University of Southern Queensland

Faculty of Engineering and Surveying

Stability of Underground Tunnelling Using Relaxation Techniques

A dissertation submitted by

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In fulfilment of the requirement of

Courses ENG4111 and ENG 4112 Research Project

Towards the degree of

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Abstract

This project involves the investigation, development and verification of two numerical models aimed at predicting the settlement profiles caused by the process of underground tunnelling in soft cohesion less soils using the computer program Fast Lagrangian Analysis of Continua (FLAC). The numerical models created will investigate the settlement profiles caused by the tunnelling process from a transverse and longitudinal cross sectional view using a relaxation process employed in FLAC. Any major problems that arose during the model development will be analysed, discussed any the possible remedies will either be discussed for future work or applied where possible.

The basic approach of this project was to research the two situations under investigation, develop the appropriate models in FLAC, verify these models though comparison with reputable published paper and analyse the results from a series of parametric studies.

The main focus of the investigation was to develop new models for the two problems utilising a relaxation technique employed in FLAC. Few problems were encountered in the development of these models – mainly from the ability of FLAC to accurately model cohesion less soil structures.

The completion of this project has adequately demonstrated that FLAC is able to be utilized to develop models for the two different tunnel heading profiles. However, it was recognised that the circular tunnel heading was model would require further development to accurately model cohesion less soil structures.

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26/10/11

Date

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Chapter 1 – Introduction

Throughout the years a considerable amount of investigation has been made into underground construction in soft soils. However, even with these investigations being completed and with many analytical and empirical models have being developed it is widely recognised that there is no generally accepted or valid method for predicting ground subsidence caused by the shield tunnelling process prior to construction. This investigation aims to develop two numerical models using Fast Lagrangian Analysis of Continua (FLAC), which is an explicit finite difference computer program, used for engineering mechanics computations widely used in geotechnical engineering. FLAC will be used to investigate the situations of the volume loss around the circular tunnel heading (transverse) cross-section and the full tunnel heading (longitudinal cross-section) collapse. In turn the investigation will validate and analyse the models through comparison with existing techniques, models and results. The models will in turn hopefully provide an insight into the possible problems that may arise whilst developing such numerical models and be analysed and corrected where possible.

This chapter will provide an overview of the project, which will include: a background into the shield tunnelling process and the volume losses associated with this process, the current empirical numerical models used for model verification and the specific geotechnical problems that are being analysed and the objectives of this investigation. In addition a brief outline of the succeeding chapters will also be provided.

1.1 – Background of Shield Tunnelling Process

This section provides a brief description of the shield tunnelling process. There are many ways that the construction of tunnels in soft soils can be completed ranging from hand excavation all the way to the tunnel boring machines (TBM) which utilise cutting edge shield tunnelling technology. These types of TBM are particularly efficient when used in soils that are too soft or fluid to remain self supporting and stable during the time it takes to line the tunnel with a support structure whether it is of concrete, cast iron or steel. In turn the shield of the TBM acts as a temporary support structure for the tunnel whilst being excavated. In modern day TBM they consist of a shield which is usually in the form of a large metal cylinder and trailing support mechanisms. The rotating cutting wheel is located at the front end of the shield, followed by a chamber which contains either the excavated soil as a mixed slurry or left as is, behind this can be seen the hydraulic jacks that are used to support and push the TBM forward. The use of shield tunnelling has shown to be a very effective way to excavate in soft soils, however no matter the quality of the workmanship or the technology used in the shield tunnelling machine there will always some sort of overlying ground subsidence that will occur. This is acceptable in rural areas however becomes a major issue when tunnelling in urban areas particularly when excavating a tunnel whose buried depth is quite low and in turn very close to the surface.

In urban tunnelling there are almost always special requirements in place to have no or very little ground surface disturbance. This is because any major ground surface disturbance could result in damage to the overlying structures resulting in financial costs along with the potential loss of life. The major type of overlying subsidence that occurs is caused by insufficient pressure at the face of the tunnel. This subsidence is normally controlled through the use of positive face control which with correct operation and well documented ground conditions can result in a reduction of the risk of surface subsidence. This being said it should be noted that whilst the ground subsidence caused by insufficient face pressure can be significantly reduced or completely removed, there are some ground losses that are involved in the tunnelling process that are impossible to control.

1.2 – The Problems

The first problem that is being investigated is the settlement profile caused by the ground loss around the circular heading of the tunnel. An example of this surface settlement profile caused by ground loss is shown below:

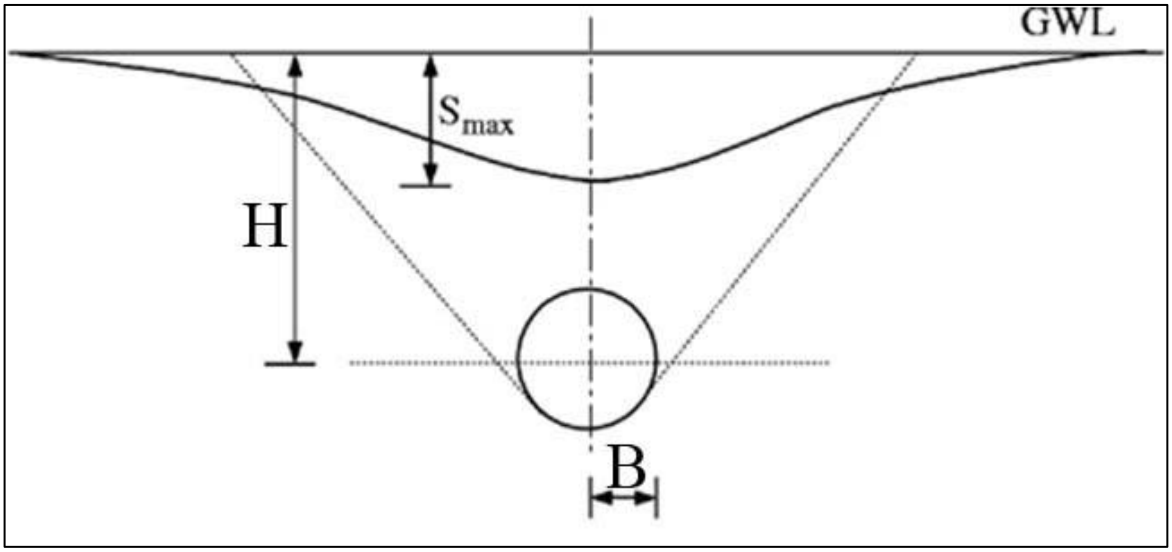


Figure 1-1: Definition of settlement profile

In this investigation a circular tunnel heading with specific geometric properties to be comparable with reputable previous studies will be modelled in FLAC. The tunnel will be lined with the reaction force that is necessary to completely support the tunnel so that no ground subsidence occurs. From here these reaction forces are slowly released in 5% increments until there are no reaction forces present and a full tunnel collapse situation is reached. The results of the settlement profiles produced by the different stages of relaxation in FLAC will then be compared against the Gaussian distribution curve. Peck (1969) amongst others proposed that the surface settlement profile can be estimated through an empirical method by using the Gaussian distribution curve. From a series of parametric studies the aim will be to create a series of design charts showing the percent relaxation required in FLAC that adequately simulates a certain percent volume loss.

The second investigation involves simulating a full collapse of a tunnel heading due to insufficient pressure at the face. In this situation the reaction forces necessary to support the tunnel heading will be found and relaxed in 5% increments until all reaction forces have been completely removed. This will emulate insignificant pressure at the face of the tunnel heading and therefore simulate a full tunnel collapse. This is a very important investigation as a full tunnel collapse results in substantial overlying ground subsidence. Though the use of parametric studies the main purpose of this investigation is to calculate the extent at which the overlying ground is affected and the affect that the H/B ratio and friction angles has on the surface settlement. This study will include the investigation of the effect of these parameters on both length and the depth of ground subsidence caused by the full tunnel collapse.

1.3 – Aims and Objectives

In the preparation of this project the specifications showed that there was to be 4 different geotechnical problems to be modelled. However, because of time constraints it was necessary to revise this goal and it was decided that only two different geotechnical problems were to be modelled. Through revision it was found that the initial scope of the project was most probably too extensive and in turn would not allow for a thorough investigation of all 4 cases.

The main objectives of this project were to develop models of the geotechnical problems under analysis applying the relaxation technique to the certain situations. The models would then be analysed and the results critically compared against the results of those from reputable sources to verify and or allow adjustment of the models and in turn highlight any significant problems that arise through developing these types of models using the FLAC software.

In a very broad sense there are five main goals of the project which are:

- Researching background information on the problems and modelling these situations
- Developing the model to allow parametric studies
- Verifying the model
- Analysing the results
- Documenting and presenting the finding

1.4 – Outline of Dissertation

This section will provide a brief overview of the information that is contained within the chapters of this dissertation. This chapter introduces the broad concepts covered by this dissertation and the subsequent chapters will address in detail the aims and objectives that have been introduced in this chapter.

Chapter 1 – This chapter introduces the concepts that will be addressed in the following chapters. It gives a broad overview of what points will b covered within the project which include the aims, objectives along with a brief introduction into the key topics.

Chapter 2 – The second chapter discusses the uses of FLAC, its advantages, disadvantages and the reasoning behind why FLAC was chosen to be used.

Chapter 3 – This chapter discusses the problem of the settlement profiles induced from ground losses from circular tunnel headings including the background information and research, methodology, results, analysis and conclusions. The chapter also contains results from parametric studies performed for various H/B ratios and soil friction angles. Areas in which future work could be made are also discussed.

Chapter 4 -This chapter discusses the problem of the full tunnel heading collapse including the background information and research, methodology, results, analysis and conclusions. The chapter also contains results from parametric studies performed for various H/B ratios and soil friction angles. Areas in which future work could be made are also discussed.

Chapter 5 – The final chapter summarises the aims, objectives and any conclusions that were obtained from the research. It will also summaries the future potential work that could be completed following the discussions in the previous chapters.

Chapter 2 – FLAC Overview

From the ITASCA website "FLAC is a two-dimensional explicit finite difference program for engineering mechanise computation. This program simulates the behaviour of structures built of soil, rock, or other materials that may undergo plastic flow when their yield limits are reached" (Itasca 2011).

FLAC contains the powerful built-in programming language FISH (short for FLACish) which enables the user to write their own function to increase the usefulness of FLAC.

For the purpose of this dissertation the research was completed solely in FLAC 2D meaning that all computations were calculated in two directions being i and j. It was noted that a 3 dimensional version of FLAC is available however given the lack of time to learn the foreign computer language combined with the complexity of using this program and the increased solution time it was decided to use the 2 dimensional version of FLAC, FLAC 2D.

2.1 – Advantages and Disadvantages of using FLAC

Common to any numerical modelling program they will all have their own specific advantages and disadvantages. A few of the obvious advantages and disadvantages of FLAC that were noted during this investigation are shown below:

Advantages:

- Through some research it was found that FLAC is a very commonly used numerical modelling program and therefore was somewhat easier to find specific examples on how to use this computing language
- Editing the FLAC files may be done in a text editor like notepad
- The full license of the program FLAC 4.0 was available through the University of Southern Queensland
- Has the option of being controlled through a graphical user interface or through the command line

Disadvantages:

- To obtain a thorough understanding of the programming that is involved in FLAC takes a reasonable period of time, however this would be similar to any other computing language
- In order to accurately and effectively write programs in FLAC requires some experience

- Because of the lack of experience using the program all results obtained from FLAC had to be carefully analysed to ensure that the outputs made logical sense

Chapter 3 – Circular Tunnel Heading

The first model to be developed investigated the situation of circular tunnel heading. More specifically the settlement profiles caused by volume losses attributed to insufficient face pressure and ground losses around the tunnel boring machine or TBM.

The first use of the shield tunnelling process in which the tunnels were excavated by hand and support was gained from timber and brick linings was for the construction of the Brunel's Thames Tunnel between 1825 and-1843 (Skempton and Chrimes (1994)). From here, through the advancements of tunnelling equipment and techniques combined with the stringent guidelines that exist in urban tunnel construction means that now more than ever accurate modelling of the surface settlement caused by the tunnelling process is an absolute necessity. The development of accurately modelling of this situation will allow engineers to be able to accurately predict the surface subsidence before the tunnelling process begins giving the engineers more confidence when faced with the task of predicting the surface settlement caused by the process.

This being said as the shield tunnelling process has been in use for around 180 years there have been many different investigations over the years involving mainly the empirical and analytical approaches. As a result of this there are many published papers that can be used to obtain background information as well as program verification for this investigation.

In this chapter the background of the circular tunnel heading problem is discussed with particular attention being paid to the causes of ground subsidence overlying the tunnel as well as the relationship between the Gaussian distribution curve and the surface settlement profiles. Following this the methodology for this problem will be discussed along with the: model development, results and analysis and the parametric study performed on the H/B ratios and soil friction angles for the tunnel. Finally a brief discussion will be completed recommending the possibility for future work in this area.

3.1 – Background of the Circular Tunnel Heading Problem

As the world becomes ever more urbanised with the rapid expansion of cities and towns both upwards and outwards there has been seen an equivalent increase in demand for the construction of services and transportation. Tunnels have been seen to provide an effective alternative to routing these services on the surface and in turn are essential components of these development schemes. Following this, tunnelling has been seen to represent a major portion of the project expenditure.

The advancement in tunnelling construction methods over the years has resulted in a significant reduction in construction time and a consequent decrease in construction costs. However even with these modern construction techniques and technology it is widely known in the industry and backed up by SUN Zong-jun et al. (2008) that it is extremely difficult to completely prevent the occurrence of ground subsidence even when the use of the advanced shield tunnelling machines is employed. From here it can be said that these deformations can have a negative and potentially harmful effect on the road foundations and buildings overlaying the tunnel. Furthermore this highlights the importance of considering these deformations in the design of the tunnel and the need for a reliable model to be developed to help predict these settlements.

Currently in today's modern construction techniques when excavating tunnels in soil especially soft soils, it almost always causes subsidence of the ground overlying the tunnel. As said before when constructing tunnels the ground settlement is always assessed as excessive settlements may present a risk of damage to surface structures or buildings.

When considering the source of ground settlements there are generally 3 main contributing causes. These are:

1. Ground movement into excavation which consists of the subsidence as a result of the construction of tunnels beneath the ground. This settlement occurs immediately and is often termed ground loss or volume loss.
2. Deformation of surrounding soil due to stress change which is considered a long term deformation and is caused because of the alteration of the soil stress/strain behaviour that is caused by excavation
3. Consolidation of the surrounding soil due to underground water table lowering which is another long term deformation and is once again caused by the excavation process.

Currently in urban tunnelling in soft ground it is found that shield tunnelling machines are used, these machines are used to minimise the amount of settlement that occurs when tunnelling. With proper structural and waterproof lining, settlement due to the stress and groundwater level changes as mentioned previously can be greatly minimised. This being said, even with these shield tunnelling machines there are still some ground losses that occur during the excavation process that cannot be avoided.

These volume losses can occur in three places:

1. At the face due to insufficient pressure at face of tunnelling machine
2. over the shield because the tunnel is always over excavated to have a gap in between the shield and the surrounding soil
3. And at the tail void in which soil may move to fill the gap between surrounding soil and segmental lining.

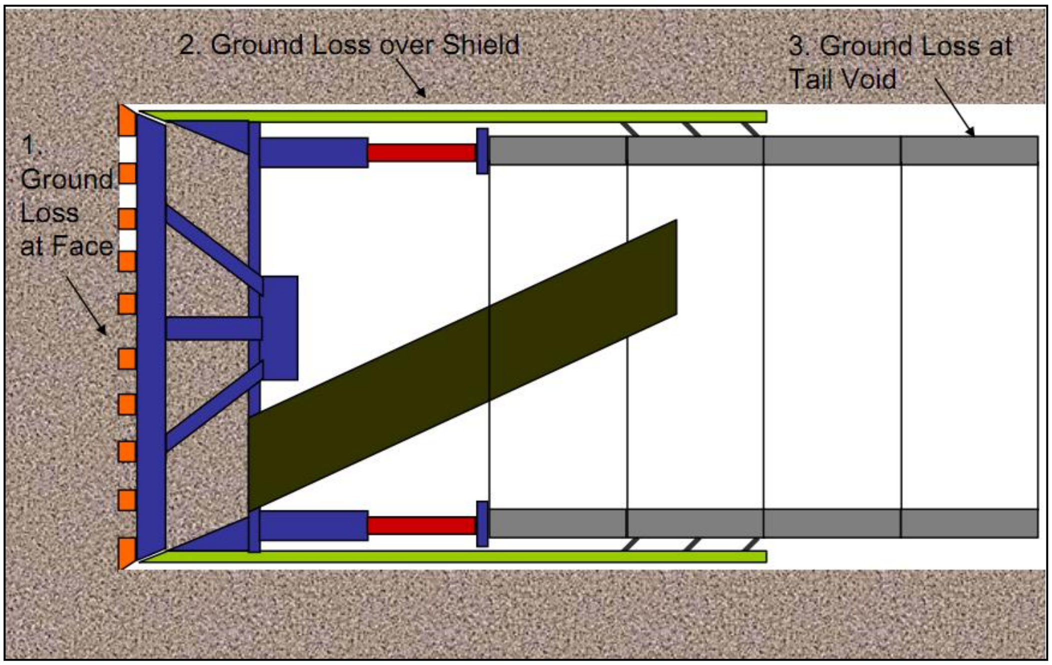


Figure 3-1: Definition of ground losses

This is the volume loss that can be seen over the top of the tunnel and is a percentage of the tunnel surface area. Therefore assuming that no change in the volume of the ground has occurred, the ground loss is defined as the ratio of the volume of surface settlement to that of the theoretical volume of the excavated tunnel. Figure 3-1 details the typical forces acting on the shield tunnelling machine and the three different locations for possible volume losses.

In this investigation the volume loss caused by the 3 situations that are described above is the main area of focus. For the purpose of this dissertation a volume loss of 3 percent was used to represent the total volume loss attributed to the 3 situations described above. This value was chosen as it is mentioned by Sugiyama et.al (1999) that a predicted volume loss of 1 percent was predicted for a construction process that employs a high degree of settlement control that has been achieved by good construction techniques including such methods as controlling the face pressure and immediately grouting the tail void and therefore greatly reducing the effects of two of the three causes of ground losses. In turn it was decided that a volume loss of 3 percent would accurately depict a shield tunnelling process that has not employed these techniques and therefore represent a regular shield tunnelling process.

3.1.1 – The Design Process

Unfortunately, as a result of the advancements in tunnelling technology the theoretical advancements has not been kept up to date and in turn there is currently no generally accepted or valid method for predicting ground subsidence prior to construction. As suggested by Tan (2006) the study of surface subsidence is currently limited to mainly empirical solutions based on field studies and in turn there is a significant lack of analytical and numerical studies that have been carried out. It was also suggested by Tan (2006) that the available analytical solutions perhaps are not completely sufficient to accurately represent many complex ground conditions and therefore a comprehensive analytical solution combined with numerical modelling is necessary to model the effect of surface subsidence due to tunnelling in soft ground.

As mentioned previously the majority of the methods that are used for estimating surface subsidence are of an empirical nature and based on mainly observations made in the UK (Tan 2006).In turn the most common method to estimating the settlement profile caused by tunnelling is by estimating a parameter which is used to define the distance between the tunnel centre and the point of inflection of the settlement trough of a normal distribution curve. Peck (1969) originally proposed that the surface settlement profile can be determined through an empirical method through the use of a Gaussian curve. However it was later established that this method does underestimate the actual deformations in certain soil types. From here it was noticed that the significant limitation of this model was the fact that they required the expected ground loss volume in order to accurately depict the expected settlement profile. This ground loss volume is usually given as the percentage of the volume of surface settlement in comparison to the theoretical volume of the excavated tunnel.

3.1.2 – Empirical Solutions

Mair et al. (1996) and O'Reilly and New (1982) have all describe the possible applications of the Gaussian distribution as a tool in providing a method for prediction for horizontal and vertical movements due to the construction of tunnels. However the limitations of these estimations have been recognised and in turn backed up by Ahmed and Iskander (2010) and suggest that predicting the magnitude of ground loss is extremely difficult, especially in the case of shield tunnelling because of the various components that cause the excavated volume to be larger than the theoretical volume, including such losses as: face losses, ground disturbance and tail void closure.

Due to the obvious amount of uncertainties that exist in the prediction of settlement profiles which are mentioned above. It highlights the importance of obtaining sufficient and appropriate analytical data to validate the numerical solution that is being created. Research has shown that there is a comparative lack of information regarding studies on longitudinal movement compared to that of lateral movement studies. That being said Romo and Diaz (1981) developed a finite element method to find the stress and deformation of different degrees of face yielding and established a relationship between safety factor, stability ratio and surface settlement at different depths that are attributable to face yielding. Given below is the equation that can be used to calculate the tunnelling induced ground settlement along a tunnel alignment due to face yielding as the tunnel progress between two points.

$$w_x = \left(0.0083 - 0.0014\frac{Z}{H}\right)(\sigma_h - p)(F_1)(Z + D)\left(\frac{\varepsilon_f}{\sigma_f}\right)$$

Where:

w_x = the settlement at a distance x from the initial point of reference
Z = H + D/2
H = tunnel depth above the crown
D = tunnel diameter
σ_h = initial horizontal stress at tunnel axis,
σ_f = mean compressive soil strength from ground surface to depth of tunnel invert
p = fluid pressure at excavation face
ε_f = mean axial strain at failure of soil samples from ground surface to depth of tunnel invert

F1 = function related to x/ (Z+D)

Following this a less complicated and much more widely used equation in the industry to predict ground settlement was initially proposed by Peck (1969) and further simplified by O'Reilly and New (1982). It was proposed that the surface settlement distribution could be determined by using the normal probability Gaussian distribution curve. The properties of the normal probability function and its relationships to the dimensions of the tunnel and the settlements caused can be seen in figure 3-2 below:

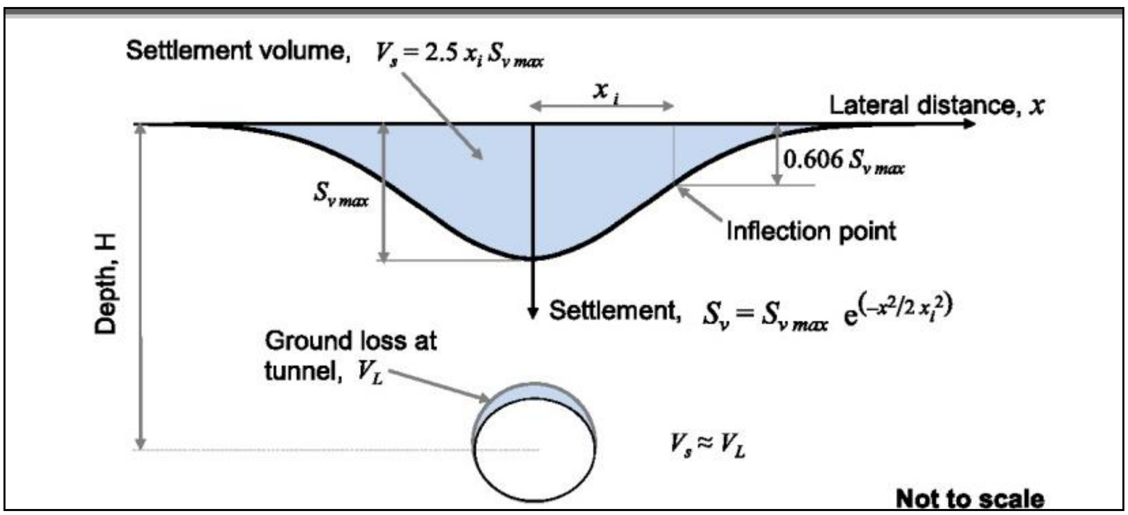


Figure 3-2: Properties of Gaussian function related to surface settlement prediction

O'Reilly and New proposed that the surface settlement could be predicted using the formula:

$$S_v = S_{v\,max} e^{\left(-\frac{x^2}{2x_i^2}\right)}$$

Where:

Sv	= The surface settlement profile given at any point x
Sv max	= The maximum surface settlement
x	=distance away from centreline of tunnel
xi	=K z (where K is a constant depending on material properties and Z is the depth to the centreline of the tunnel from the surface)

Because these functions are empirical formulas and in turn means that these results have been established because of timely filed observation work it highlights the need for more accurate numerical solutions. However, the prediction of these settlements through numerical modelling has proposed a challenge for engineers over the years because of the vast range of factors that influence tunnelling induced ground movement. Tan and Ranjith (2006) have recognised this and in turn stated that it is almost impossible to incorporate every single factor that influences deformation of the ground as a result of tunnelling into a theoretical solution for predicting settlement. In turn as part of their study they created a comprehensive list of these influencing factors.

This being said, it highlights the importance of having a numerical solution that accurately depicts the soil properties in which the tunnel construction is being completed in. It also highlights the fact that one model cannot adequately cater for the many different types of soil structures and in turn needs the ability to be adjusted to accurately model the cast range of soil properties in which tunnels are being constructed in today. With so many different possible combinations for construction of tunnels including different: soil types, soil properties, tunnel requirements and construction methods it demonstrates the complexity of this task at hand.

3.1.3 – Analytical Solutions

Currently in France the analysis of the convergence of the tunnel wall is completed by using the Convergence-Confinement method (Panet, 1995). This is done by using a two dimensional representation of the three-dimensional deformation pattern around the opening. New (2007) suggests that this is done by applying a fictitious tunnel support pressure. From here a magnitude which is adjusted in proportion to a stress release coefficient. The magnitude of this coefficient is varied to account certain construction/site specific properties which include such things as: behaviour of the ground at the tunnel face, the distance of installation of the support system behind the face, the construction method and quality of the workmanship. From here equilibrium is reached within the ground mass after it has been disturbed by the excavation works. It is suggested that following this the results can be analysed using two conventional techniques being analytical methods and the finite element method (FEM). It was found that this method of predicting the surface settlement has the same basic principles of the method that is being applied in this investigation to be modelled in FLAC.

From here it has been established that these analytical solutions are based on simplifying many key properties which include such things as: geometry, ground layering and defining the boundary and initial conditions. It was found that a generous amount of work has been done in the field on defining new stress fields as a result of excavation and consequently that not a huge array of work has been done in the field of evaluating the distribution of the ground movements caused by excavation. This is mainly because of the complexity of work involved in such predictions.

This being said numerical techniques such as finite element and finite difference method analysis can account for much more complicated systems which can involve many different layers and complex boundary conditions. The only problem with such 3 dimensional analyses is once again because of the complex nature of this type of analysis and in turn this form of analysis has very commonly seen to have been resorted back to the simpler 2 dimensional analyses and therefore reducing the potential to use this technique.

New (2007) suggest that in practice empirical methods are most commonly used. From here these methods are combined with analytical methods or finite element methods and in turn calibrated with data that has been gathered from previous cases. It is also suggested that these methods can be used to great accuracy when site conditions are well known and well calibrated parameters are used. This technique was firstly introduced by Schmidt (1969) and Peck (1969) and in turn further developed in the 1980's through a series of studies related to tunnelling in homogeneous ground in London soils. Amongst others this work has been completed by (Attewell et al., 1986 O'Reilly, 1988, O'Reilly and New, 1982 and Bower, 1994)

From the studies that have completed in this area it was found that had these methods do have some inherent problems. These include such things as when determining surface deformation for shallow structures the models can sometime miss-represent the width of the surface settlement and in turn the magnitude of the surface settlements could be underestimated.

It has been seen that there is both accurate and practical uses of empirical methods backed up with appropriately calibrated analytical or numerical methods. However shortcomings have been seen to arise in the use of semi-empirical methods and numerical methods with limitations on uses for particular geometries especially to do with shallow tunnels. For the objectives of this dissertation fully numerical methods will be used to predict the tunnel settlement and compared with the standard distribution curve propose by O'Reilly and New for comparison of results.

3.2 – Methodology

To enable validation through comparison of results it was necessary to create a text file that utilized a user friendly set up in a way that a parametric study could be easily implemented. This was done so that the results could be compared to previous studies that had been completed in this field whether it is of the empirical or analytical nature as it is quite obvious that not all tunnels that have been constructed over the years have had the same geometry and geotechnical properties. Because the choice to create a text file that can be easily modified to match previous studies it has allowed us to compare results from a much wider field of results.

The model for the circular tunnel heading was created in a text file that was compatible with FLAC software. To allow FLAC to distinguish which part of the grid space represented the circular tunnel heading the model of the circular tunnel heading was firstly marked by a value of one into the location of an extended array that matched the i and j locations of the marked gird points. From here the extended array was searched for a value of 1 and set the flag to indicate a mark with a FISH function. Following this, x and y reaction force of the marked grid points were found and stored in two separate extended arrays. From here the reaction forces at the tunnel lining are reduced in 5 % increments as this value was believed to give a good balance of accuracy and time usage. From here the vertical displacements are stored in a table for each relaxation step until the reaction forces have been completely relaxed and therefore representing a completely collapsed tunnel heading. Figure 3-3 below shows a plot from FLAC of the grid showing the marked gird points indicated by yellow circles representing the tunnel lining.

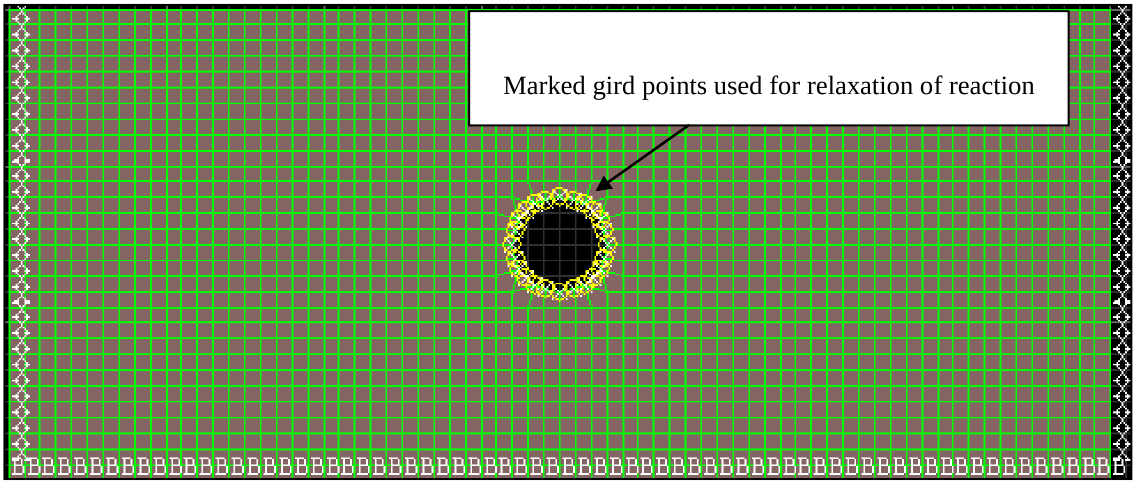


Figure 3-2: Definition of marked grid points

For this problem the solution was reached by running the FLAC program until the reaction forces were completely removed. By running the FLAC program until the relaxation forces were completely relaxed (simulating full tunnel collapse) it allowed for a study to be completed that involved comparing the different settlement profiles for the different relaxation percentages. From here these profiles were compared to the standard distribution curve that was proposed by O'Reilly and New that had been calibrated to match the same soil properties (namely cohesion) and percent volume loss of the model.

Once the settlement profiles for the various range of relaxation percents had been plotted it enabled the investigation of the percent of relaxation required to adequately represent the surface settlement caused by a 3 percent volume loss. Finally the investigation required the repetition of this process in order to obtain the percent relaxation required to represent settlement profile for different values of H/B ratios and soil friction angles. These results were analysed and presented as a design chart for percent relaxation required to be applied to the FLAC mode given particular H/b ratios and soil friction angles.

3.3 - Model Development

The first step of this investigation was to establish the model dimensions, gird geometry, tunnel interface with the surrounding soil, boundary conditions and determine appropriate material properties and the specific parameters that will be studied.

3.3.1 – Model Dimensions

The dimensions of the model was a crucial element as if the model was not large enough it would not be able to accurately display the extents of the settlement profile and may potentially affect the reliability of the results. It was also noted that for comparison with previous analytical models the formulas were dependent on model size. This being said, the dimensions of the tunnel was critical as the greater the tunnel radius the greater the tunnel area and in turn given the same percent volume loss would result in greater ground loss. It was also noted that as the buried depth was increased, the maximum surface settlement decreased and the width of the surface settlement increased. In turn through an iteration process a model dimension of 30 by 70 was chosen however the FLAC code was created in such a way to allow easy manipulation of this value and this value was chosen as it was deemed to provide a good mix of accuracy whilst not increasing the program running time to significantly. Figure 3-4 shows the dimensions used for the model on the next page.

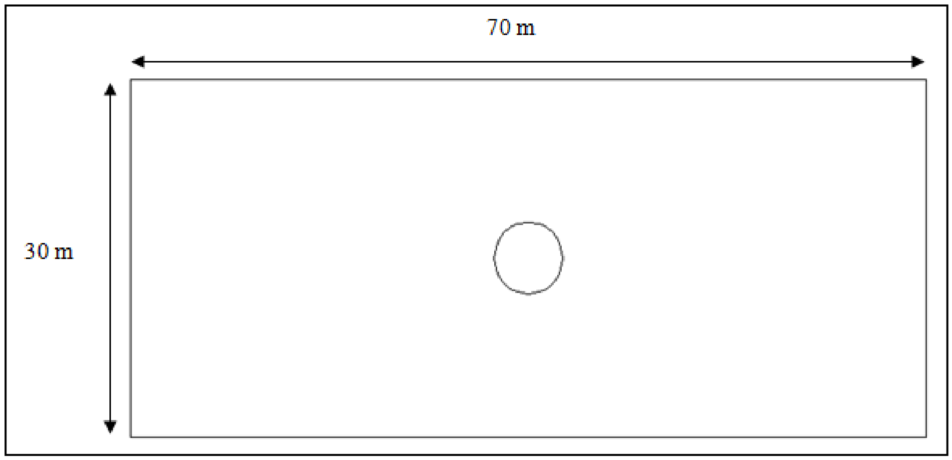


Figure 3-4: Circular tunnel heading dimensions

3.3.2 – Materials

Material properties were chosen to simulate sand and included the use of Mohr-coulomb plasticity material was used to simulate the entire fill of the model. It was necessary to assume more specific properties of each material, these are listed below:

Fill Properties:

- Mohr-Coulomb material $(c - \phi)$
- Density 1900kg/m^3
- Shear modulus 5.46 MPa
- cohesion = 0
- g = 9.81 m/s^2
- friction angle = 30, 35, 40 degrees

- $\gamma = 11.7\ kN/m^3$

3.3.3 – Boundary Conditions

In order to accurately represent the volume loss caused by the tunnelling process it was necessary to ensure that the model's boundary conditions were an accurate representation of reality. In turn the interface with the tunnel lining was left free in the X and Y directions, the vertical walls of the grid were fixed in the X direction only allowing vertical displacement, the horizontal base of the grid was fixed in both the X and Y directions and the surface of the soil fill was modelled as 'free' to allow all natural movement of the surface. Figure 3-5 below shows the boundary conditions that have been discussed above.

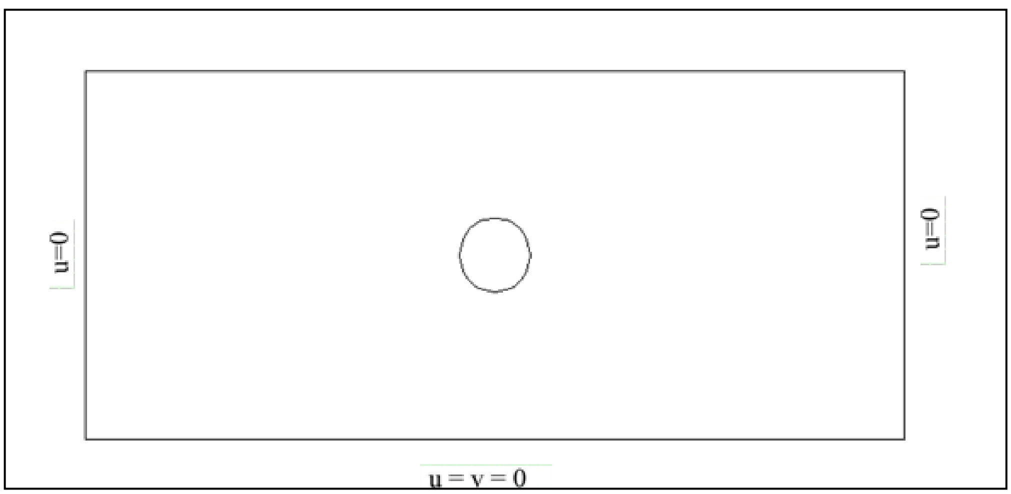


Figure 3-5: Boundary conditions

The first stage of model verification took place very early in the model development as it was necessary to ensure that the boundary conditions accurately represented a real life situation. This was done by firstly analysing the displacement vectors ensuring that the boundary conditions applied were applied in the correct spots ensuring the no soil has not been displaced where it is not meant to displace and secondly that the boundary conditions were not causing any extra soil stress of that that can be expected meaning that the boundary conditions were only holding the soil in place and therefore not providing any extra capacity to the soil. The results of these plots can be seen in figure 3-6 below:

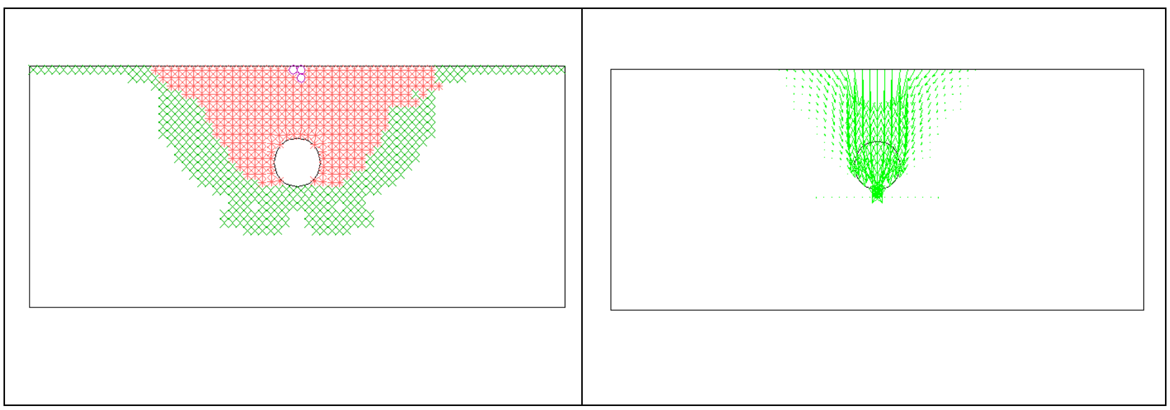


Figure 3-6: Demonstration of boundary conditions

The plot above shows a completely collapsed tunnel to over exaggerate any errors that may exist in the FLAC coding. As it can be seen from the figure above the boundary conditions have had no effect on the soil structure. The plot on the left clearly indicates that no the soil has been plastically deformed below the level of the bottom of the tunnel (red shading). This figure also shows a continuous plastic state (green shading) across the surface of the grid space continuing all the way down to the depth of the tunnel heading. The plot on the right shows the displacement vectors for the particular case highlighting the ‘free’ surface at the top of the grid space. The plot also proves that the reaction forces have been completely relaxed as the displacement vectors in green have moved the entire way through the existing tunnel lining (outlined in black).

3.3.4 – Parameters

The main parameter that is under investigation was the percent relaxation required to attain the specific 3% volume loss. Values for this percent relaxation were determined for a range of H/B ratios and soil friction angles.

3.4 – Results Analysis

This section looks at critically analysing the results from the model created in FLAC to determine whether the behaviour of the structure, method of relaxation and fill properties are realistic. In this section particular attention will be paid to the most generally and widely accepted empirical models that were derived by Peck (1969) and O'Reilly and New (1982).

3.4.1– Typical Output

The figure below shows a typical graph of the settlement profile from FLAC. This was created by completely relaxing the forces acting on the tunnel lining. The figure below shows the surface settlement caused by completely removing all of the reaction forces acting around the tunnel. This has resulted in a reasonably clear picture of the movement of the soil for a complete tunnel collapse. The figure below is for a tunnel radius of 3 meters friction angle of 30 degrees and a H/B ratio of 5.

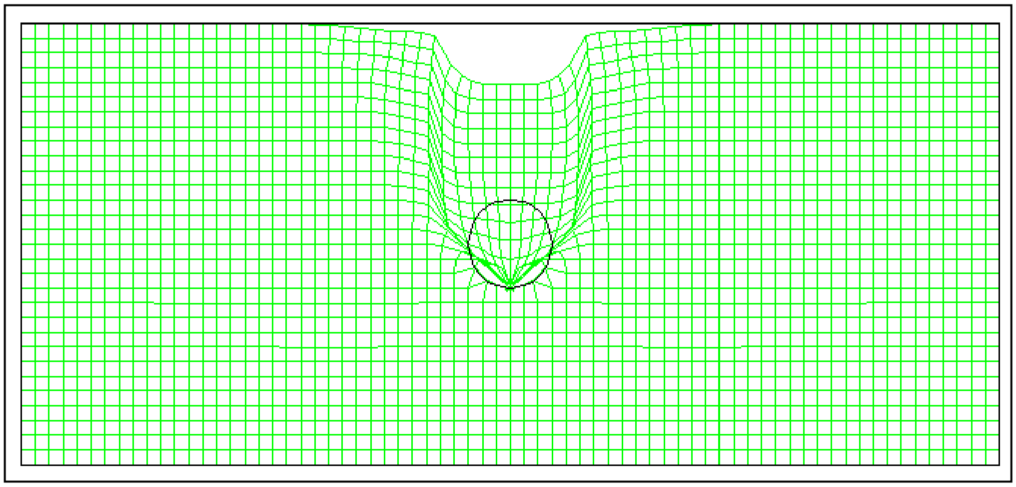


Figure 3-7: Typical exaggerated grid displacement

From figure 3-7 above it can be seen that there is a gap created between the deformed grid space and the boundary. The gap between the deformed grid space and the boundary is defined as the percent volume loss. By relaxing the reaction forces around the tunnel lining the result is the soil structure slowly moving into the existing tunnel heading. This phenomenon is highlighted by the exaggerated distorted grid space that is shown above in which the soil above tunnel has slowly moved into the heading.

Figure 3-8 shows a typical contour of the shear strain rate for a tunnel radius of three meters and H/B ratios from 2 to 8. It is noted that there are no notable peaks in the shear strain rate and that all of contours on the plot are a continual progression of one another. By comparing the various shear strain rates it can be seen that as the tunnel is placed deeper within the grid space that the shear strain rates are both of greater intensity and have a wider area of effect. This is backed up by Eberl et al. (2006) where a study involving the analysis of internal strains in MATLAB showed similar relationship between tunnel depth and shear strain rates. In turn it was considered that this would be acceptable for the final mesh.

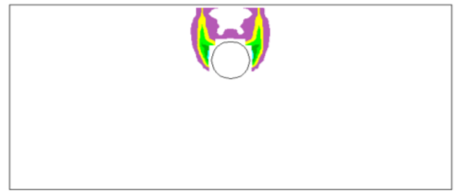
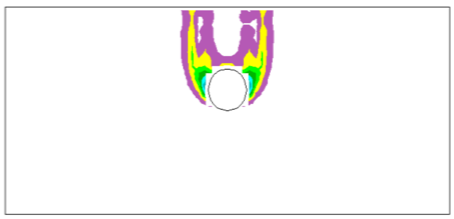
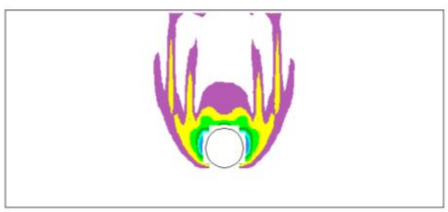
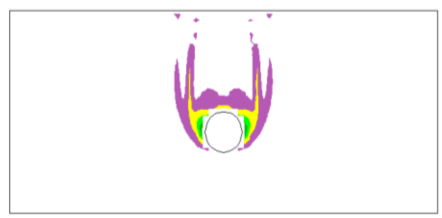
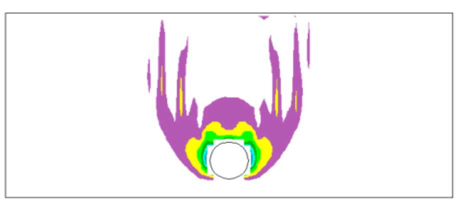
H/B	2	3
Shear Strain Rate		
H/B	4	5
Shear Strain Rate		
H/B	6	7
Shear Strain Rate		
H/B	8	
Shear Strain Rate		

Figure 3-8: Comparison of shear strain rates

To further validate the accuracy of this model it was compared against the empirical formula proposed by O'Reilly and New (1982). The following figure is a plot showing the deformation profile created by using the settlement equations that were proposed by O'Reilly and New (1982) versus the settlement profiles caused by a prescribed amount of tunnel reaction force relaxation. The empirical equation for the settlement at a distance x away from the centreline of the tunnel is given as:

$$S(x) = S_{max} e^{\left(\frac{-x^2}{2i^2}\right)}$$

Where i was later simplified to:

$$i = kZ \qquad \text{(O'Reilly and New)}$$

$$Z = the\ distnace\ from\ the\ tunnel\ centreline\ in\ meters$$

k
$= is\ a\ constant\ that\ varies\ depending\ on\ soil\ type\ and\ is\ equal\ to\ 0.2\ to\ 0.3\ for\ cohesionless$

$soils\ above\ the\ water\ table\ and\ 0.4\ for\ stiff\ clays\ to\ around\ 0.7\ for\ soft\ clays$

$$S_{max} = \frac{V_s}{2.5i}$$

Where:

$$V_s = A\, V_L$$

Where:

- Vs is the volume of the settlement trough
- V_L is the percent volume loss
- A is the tunnel cross section area.

For a 3 percent volume loss and H/B ratio of 5 the comparison of the empirical model proposed by O'Reilly and New using a k value of 0.3 and the proposed settlement achieved with a relaxation of 50% and 55% can be seen in figure 3-8 below. The blue settlement pattern was achieved using O'Reilly and News formula stated on the previous page whilst the red and green profiles were achieved by prescribing a relaxation of 50 and 55 percent respectively.

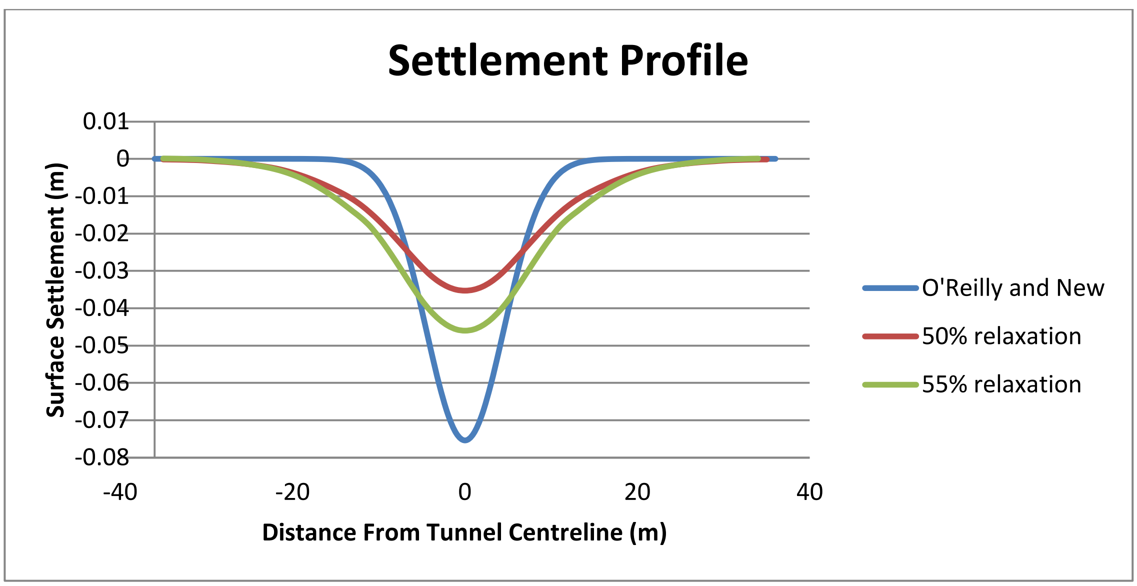


Figure 3-9: Comparison of results with empirical formula

It was found by linear interpolation it was found that a relaxation of 51.83% was needed to achieve the 3% volume loss. This being said it was immediately obvious that the settlement profile proposed by O'Reilly and new was vastly different than the one created in FLAC. It can be seen from the above figure that the settlement trough proposed by O'Reilly and New is much deeper and narrower then the settlement profile that has been created in FLAC. It can also be said that this profile that was created using O'Reilly and News empirical formula was created using a k value of 0.3 which is on the outer limit for cohesion less soils above the water table.

It was found that by increasing the constant K and in turn representing cohesion less soil above the water table, through to the stiff clays and all the way to soft clays that the settlement trough continued to widen whilst the maximum depth of the subsidence decreased. The figure below shows the relationship between the settlement profiles by varying K.

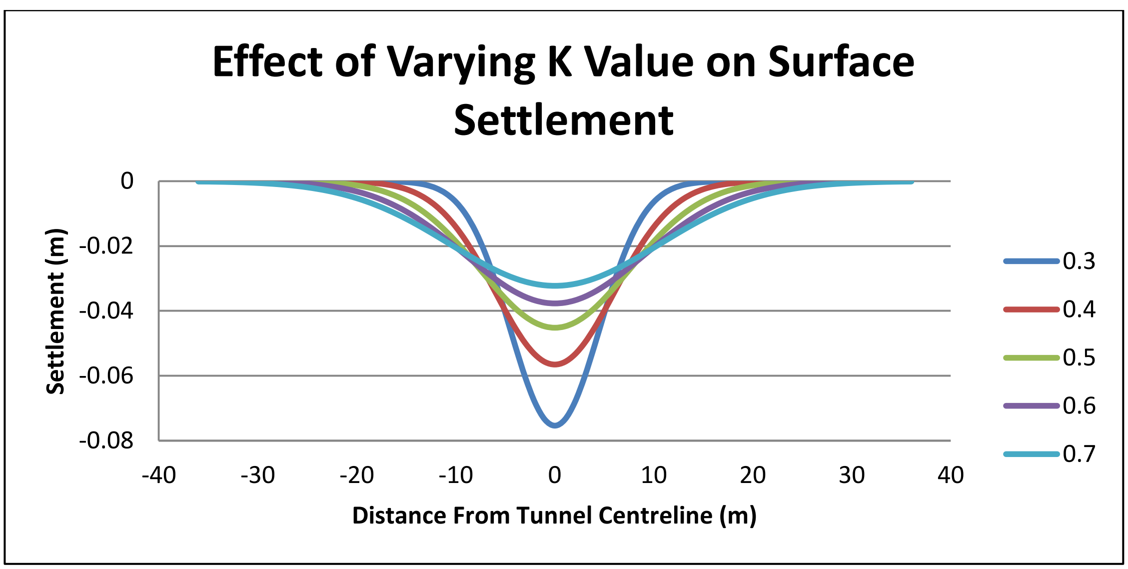


Figure 3-10: Effect of varying K on the displacement profile

Through careful analysis of the settlement profiles created in FLAC with the settlement profiles created using the empirical formula proposed by O'Reilly and New it was found that the surface settlement profiles created in FLAC best fitted the curve that used a K value of 0.6. Therefore it can be said that even though the material properties that were used were chosen to accurately model cohesion less (dry sand) structure that the model still seemed to be modelling a situation that resembled a medium- soft clay.

From here as it was found that settlement profile created by FLAC was one that closely resembled a medium-soft clay it was decided that to carry out a study in FLAC utilizing soil properties that resembled those of clay. Continuing on from this the results were compared with O'Reilly and News empirical solution with the results being shown below.

For a 3 percent volume loss and a H/B ratio of 8 the comparison of the empirical model proposed by O'Reilly and New and the proposed settlement pattern achieved with 50% and 55% relaxation can be seen in figure 3-8 below. The blue settlement pattern was achieved using O'Reilly and News formula stated on the previous page whilst the red and green profiles were achieved by prescribing a relaxation of 50 and 55 percent respectively. It was noted that even though from the plot it could be said that a relaxation of 51.5% would give a better fit to the empirical solution however this would result in modelling a volume loss of 4% whilst the 50% relaxation is resulting in 3.02% volume loss and therefore will be considered to be an accurate representation of the amount of relaxation required to accurately represent the 3% volume loss.

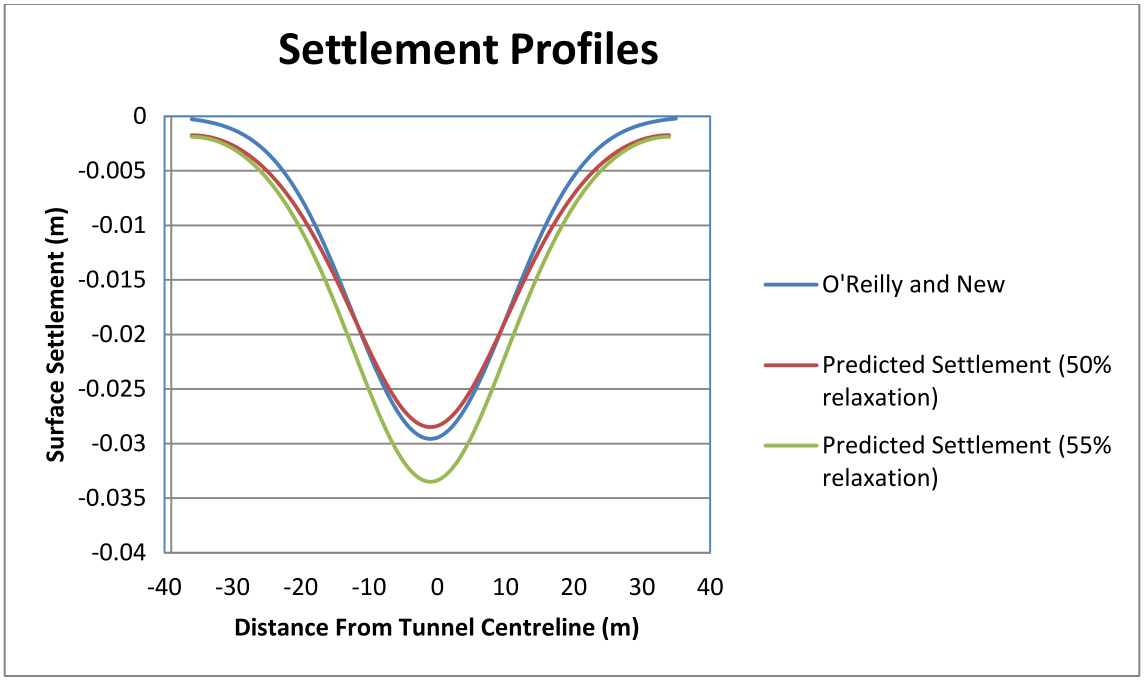


Figure 3-11: Typical settlement profile output

It can be seen above that the empirical model that was initial proposed by Peck and Schmidt very closely resembles the settlement profile that was created in FLAC using a relaxation of 50%. On conclusion from this and considering the fact that this empirical equation was initially proposed by Peck and Schmidt (1969) and has been simplified and modified through various studies over many years since it was firstly proposed along with the fact that these formulas are continually being used to predict ground settlements to verify both new empirical and numerical models and in turn hold great credibility when considering the level of accuracy provided by these formulas.

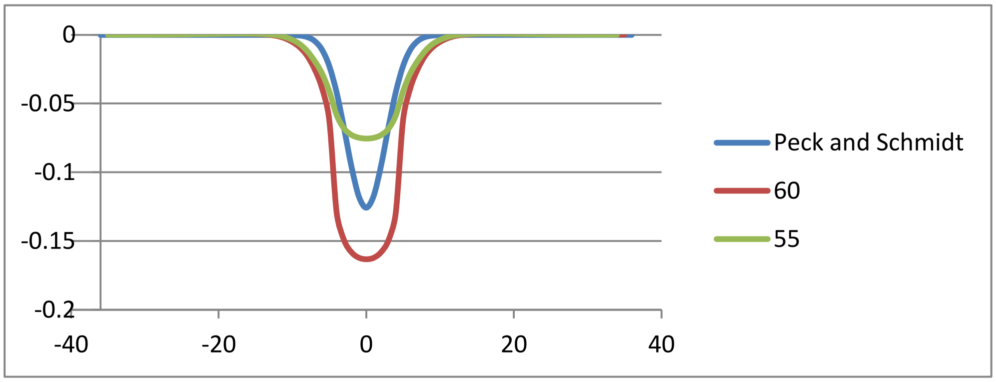
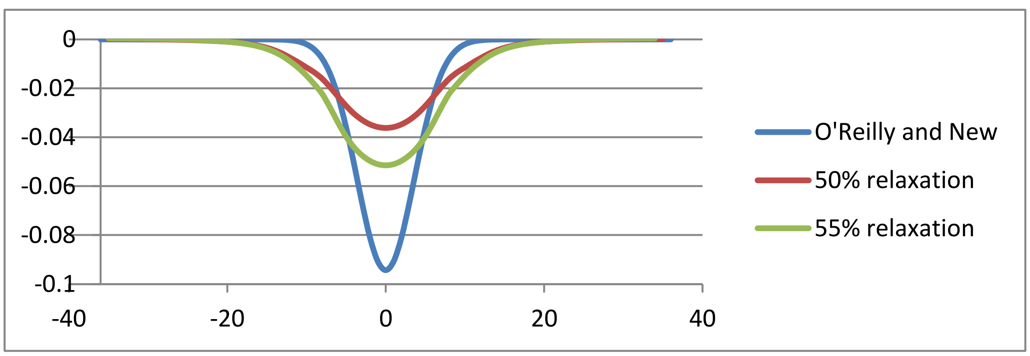
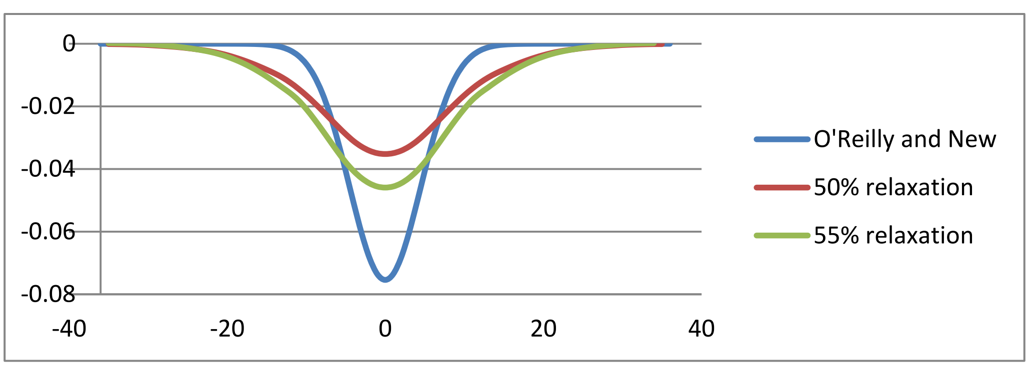
It can be said that the FLAC code that has been created to represent the settlement troughs thorough the use of the relaxation technique caused by tunnelling is an accurate representation of such cases and in turn will be used with confidence for the future parametric studies in the following sections for the analysis with the clay type soil structure.

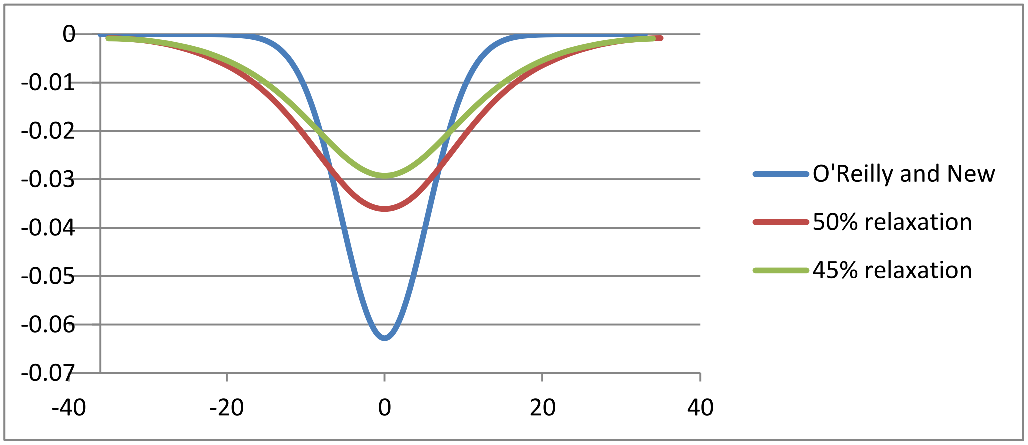
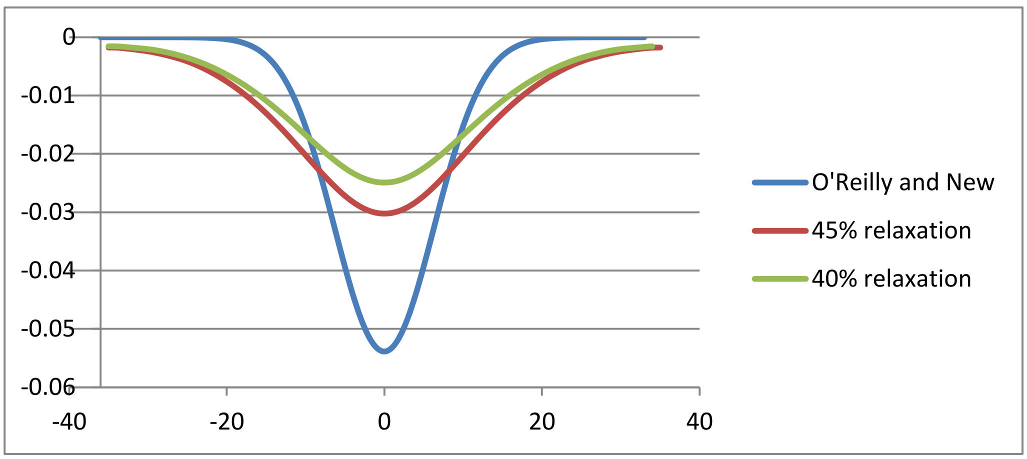
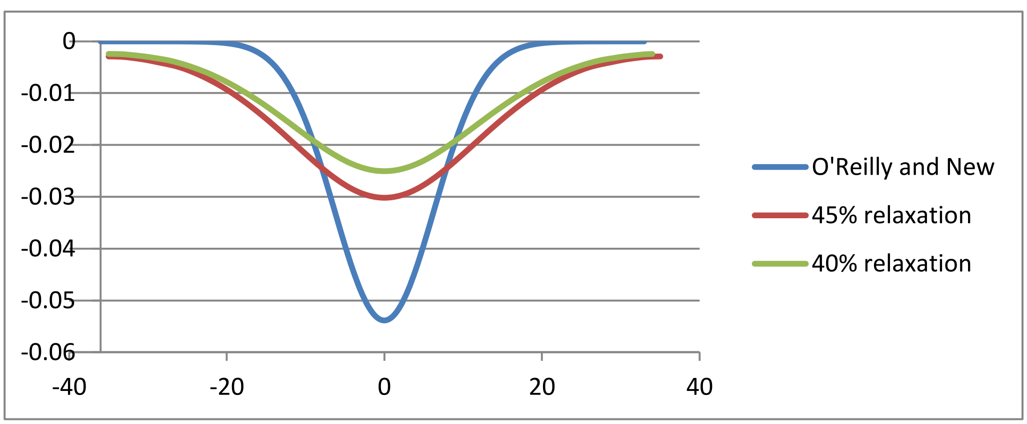
Even though the results were not as expected a parametric study was completed for the cohesion less soil structure for which the results can be seen in section 3-5. From here, comparisons will be made with published papers and conclusions will be drawn on the effectiveness of the plots created in FLAC. The following section also shows a smaller study completed in FLAC to show the potential use for the code for modelling clay type (with cohesion) soil structures.

3.5 – Parametric Study

Design charts can provide an enormous benefit to engineers whilst undertaking designs specifically those within tight time restraints. In turn it is extremely difficult to accurately predict the settlement profiles as this normally requires complex site specific numerical modelling. Therefore to increase the benefit of this study, it was decided to complete a parametric study on the model such that percent relaxations (for use in the FLAC code) may be determined for various H/B ratios and soil friction angles. In turn the designer will be able to select a site/job specific H/B ratio and soil friction angle and from these two key parameters will be able to select the percent relaxation to apply to the FLAC code to accurately represent the settlement profile that will occur.

The following table provides the percent relaxation (located on the right hand side of the table) required to reach the desired 3% volume loss for soil friction angles of 30, 35 and 40 degrees. The graphs in the table below shows a comparison of the results between the present study and the results derived from the equation formulated from by O'Reilly and New. The H/B ratio is given along the left hand side of the table, the percent relaxation required to reach 3% volume loss is given along the right hand side of the table and all measurements on both axis are given in metres with the y axis being the amount of settlement and the x axis being the distance from the tunnel centreline.

H/B	Plot of settlement profile for friction angle of 30 degrees	
3		57
4		55
5		51.8

6	0 -0.01 -0.02 -0.03 -0.04 -0.05 -0.06 -0.07 -40 -20 0 20 40 O'Reilly and New 50% relaxation 45% relaxation	47.2
7	0 -0.01 -0.02 -0.03 -0.04 -0.05 -0.06 -40 -20 0 20 40 O'Reilly and New 45% relaxation 40% relaxation	43
8	0 -0.01 -0.02 -0.03 -0.04 -0.05 -0.06 -40 -20 0 20 40 O'Reilly and New 45% relaxation 40% relaxation	40

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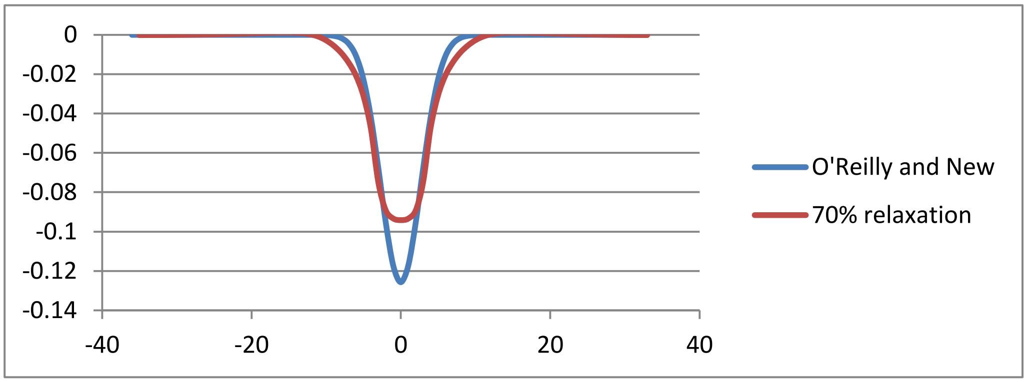
<tr><td>3</td><td>
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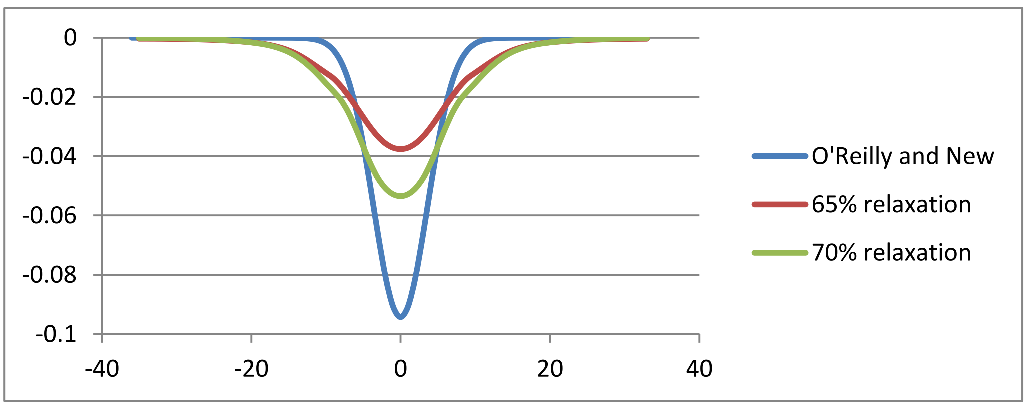
<tr><td>4</td><td>
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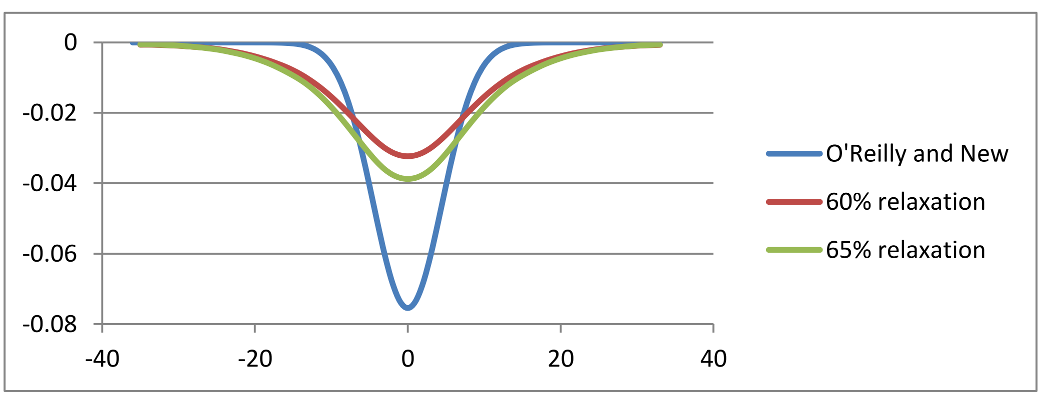
<tr><td>5</td><td>
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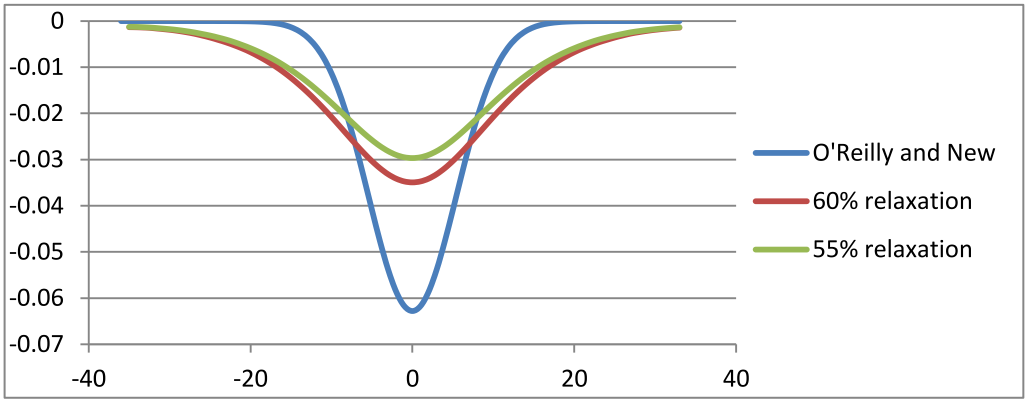
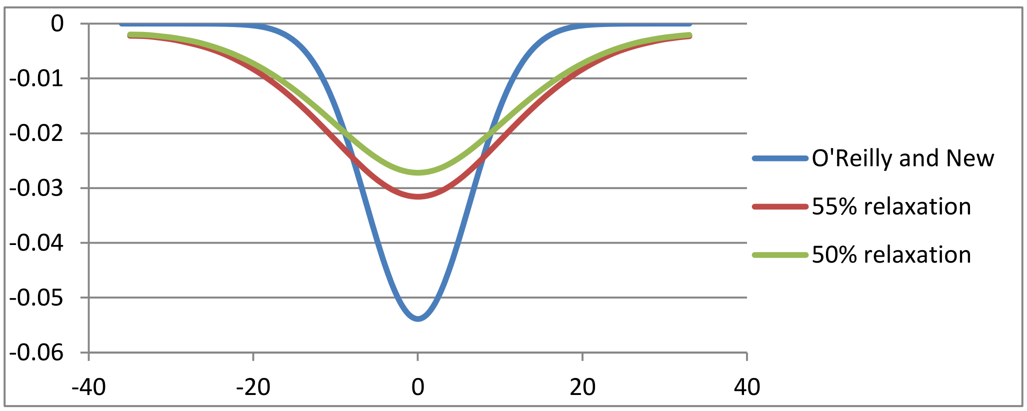
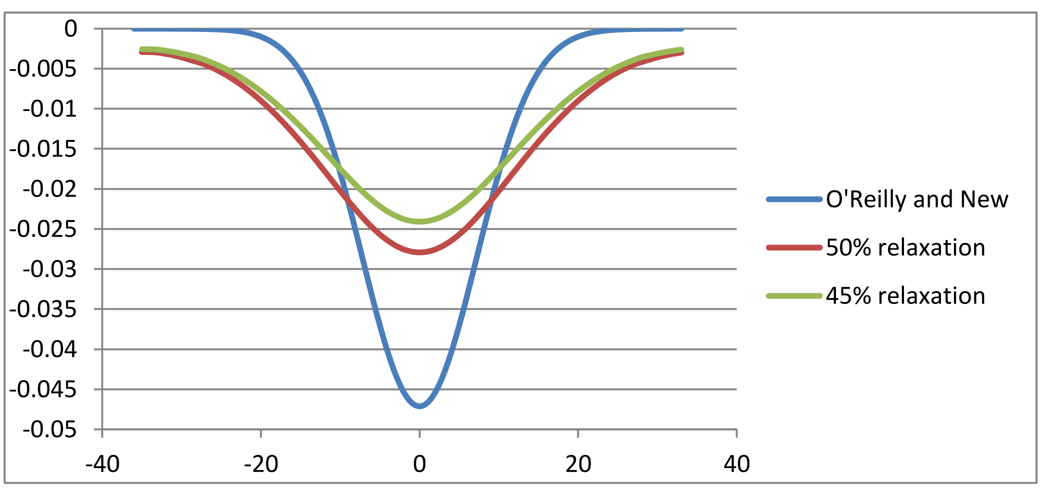
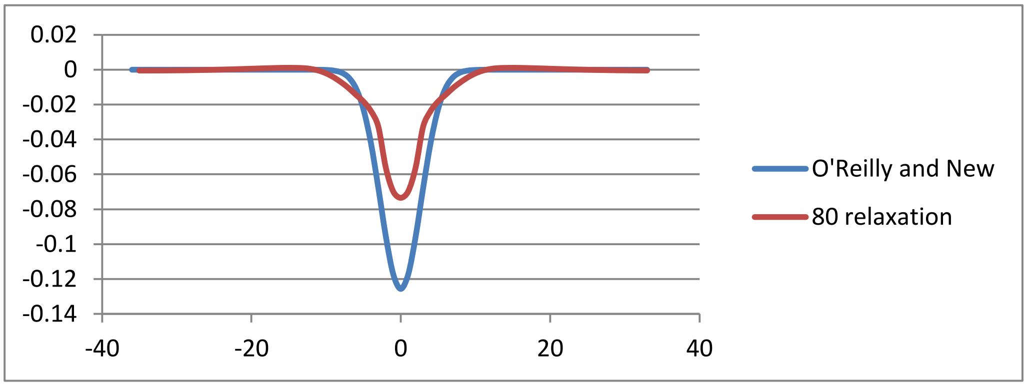
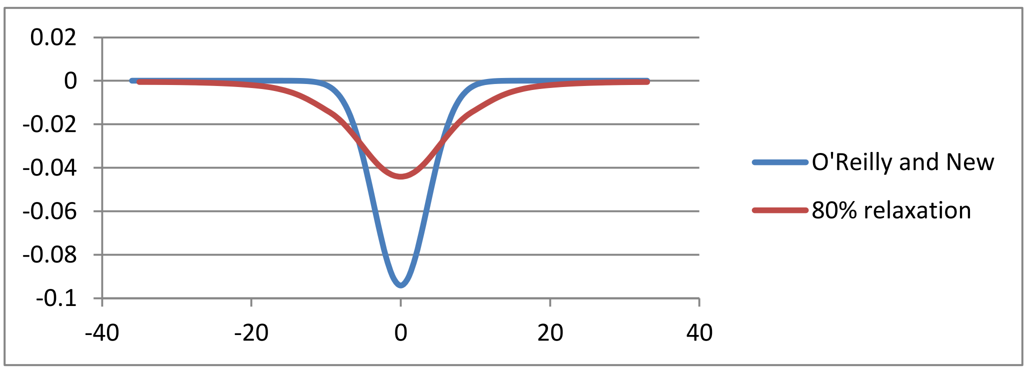
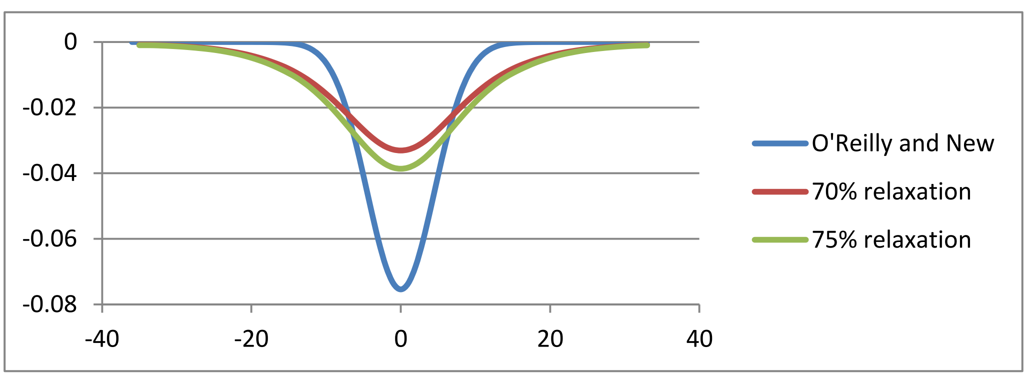
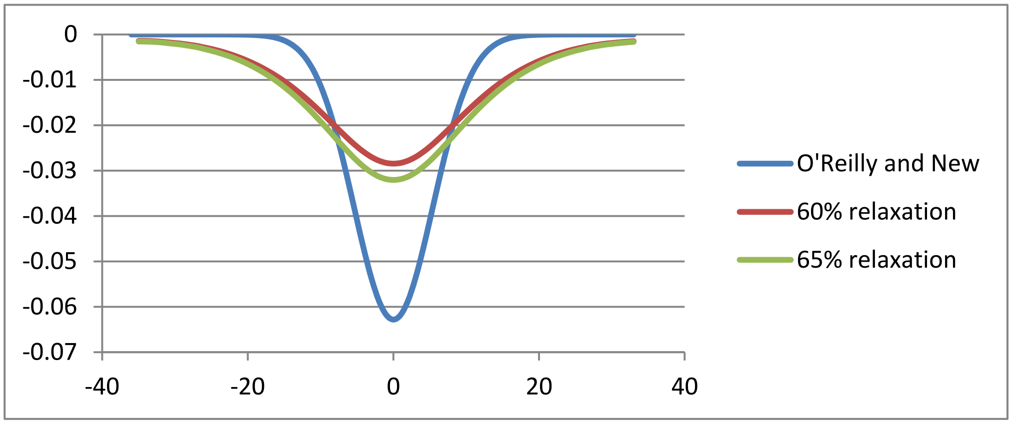
6		56.6
7		50.4
8		46.5

H/B	Plot of settlement profile for friction angle of 40 degrees	
3		N/A
4		N/A
5		73.9

<table>
<tr><td>6</td><td>
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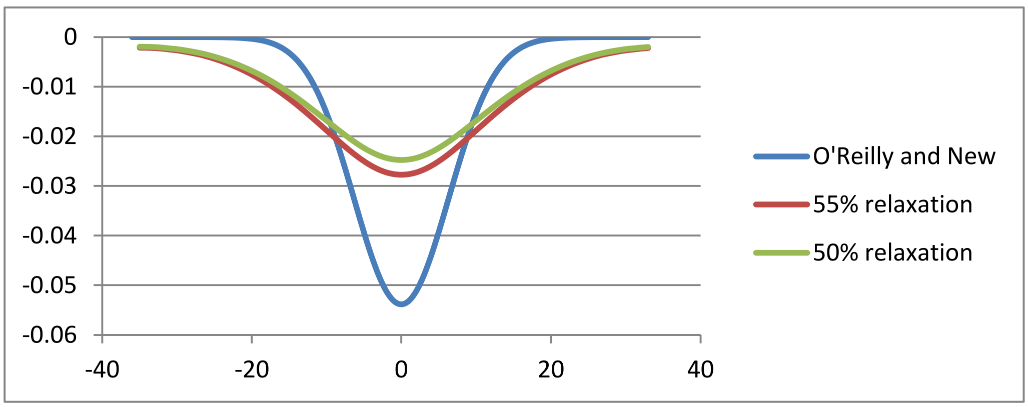
<tr><td>7</td><td>
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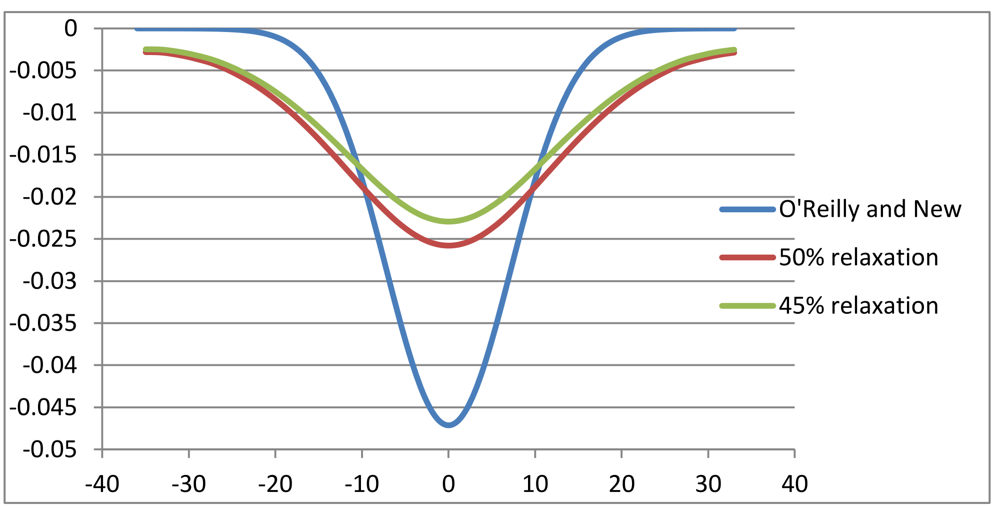
<tr><td>8</td><td>
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</table>

Figure 3-12: Comparison of results with empirical formula

From the figures above it can be seen that the results from FLAC have completely different settlement profiles of those compared with O'Reilly and New. However, the general trend of settlement profile as the H/B ratios increases coincides with O'Reilly and New in that as the tunnel is buried deeper within the soil the settlement profiles tend to become broader and shallower. This proves that the model created in FLAC does hold some creditability however it highlights that the model created does not accurately represent the cohesion less (dry sand) case that was trying to be modelled. This being said the following plot displays the linear relationship between the H/B ratio and the percent relaxation required to reach the desired 3 percent volume loss for the three different friction angles.

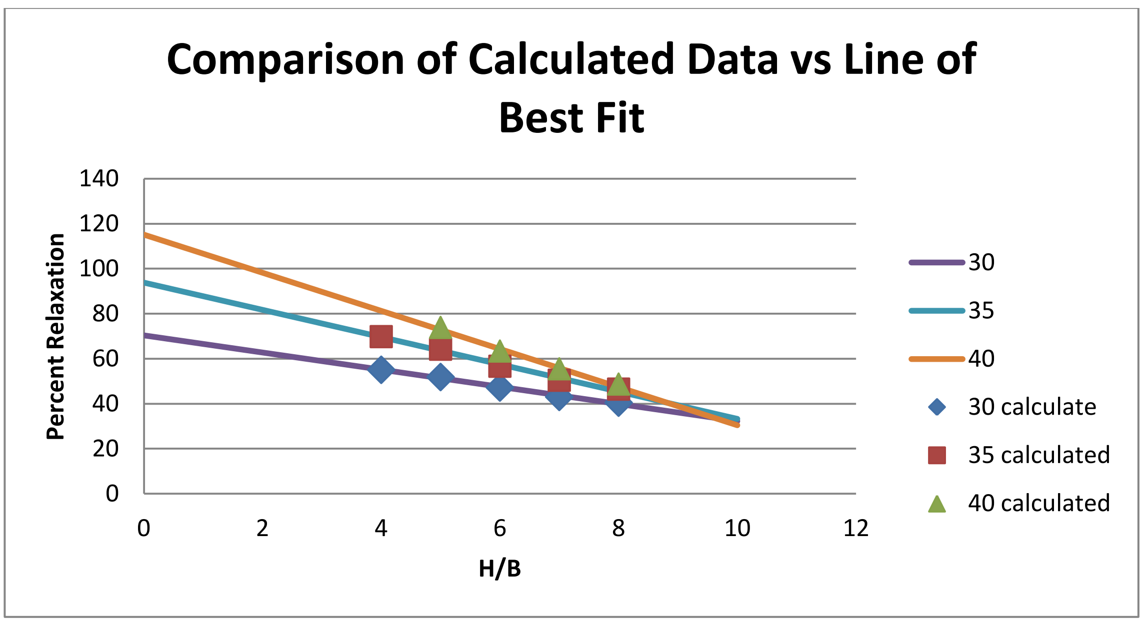


Figure 3-13: Line of best fit applied to data from FLAC

Through the analysis of this chart it was found that a linear line of best fit represented the data quite well. It was found that the formula for determining the percent relaxation required to simulate the 3 percent volume loss given the H/B ratio (x) can be given as:

For cohesion less soil with a friction angle of 30 degrees:

$$Percent\ relaxation\ required = -3.8011x + 70.303$$

For cohesion less soil with a friction angle of 35 degrees:

$$Percent\ relaxation\ required = -6.0423x + 93.749$$

For cohesion less soil with a friction angle of 40 degrees:

$$Percent\ relaxation\ required = -8.3375x + 114.56$$

Therefore from these equations the following design chart was created:

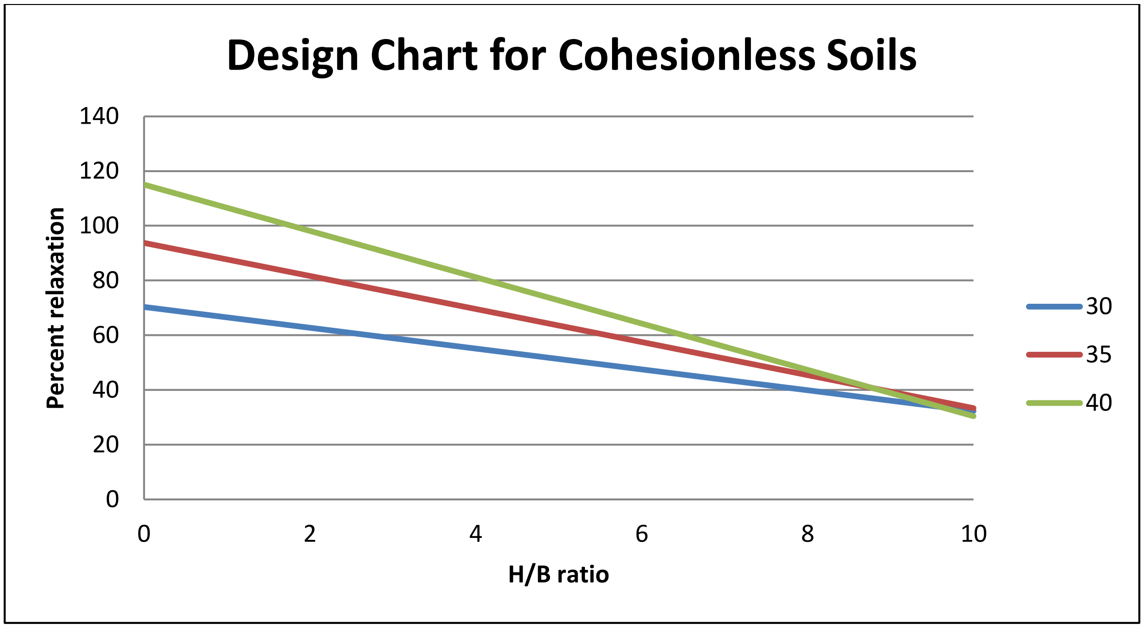
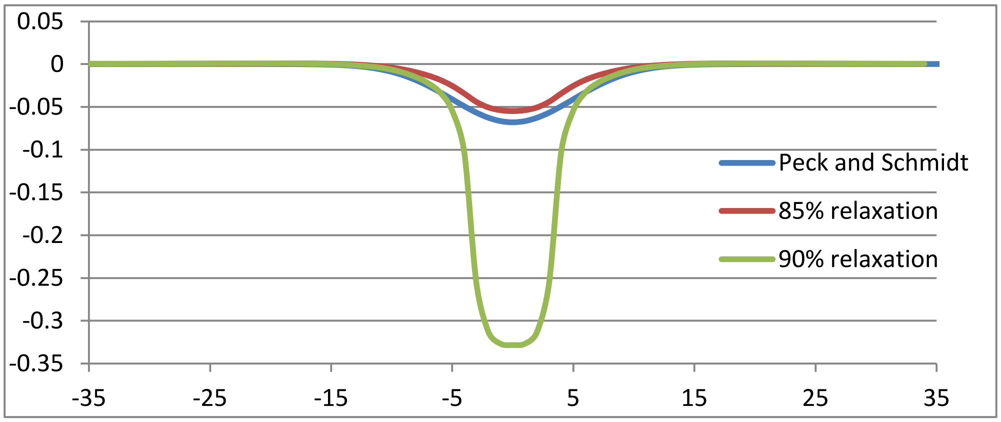


Figure 3-14: Design chart for percent relaxation required

As discussed in section 3-4 it was found that the FLAC model was creating settlement profiles that resembled a soil structure of soft-medium clay. From here it was decided to carry out a small study on the effectiveness of the FLAC model to predict ground settlement caused by the shield tunnelling process in the soft-medium clay. It should be noted that for this model the soil properties were changed to more accurately simulate this soft-medium clay soil structure. In turn a cohesion of 20 kPa was chosen along with appropriate values of shear and bulk modulus to accurately model a soft-medium clay soil structure.

The following table provides the percent relaxation (located on the right hand side of the table) required to reach the desired 3% volume loss. The graphs in the table below shows a comparison of the results between the present study and the results derived from the equation formulated from by O'Reilly and New (1982). The H/B ratio is given along the left hand side of the table whilst all measurements on both axis are given in metres.

<table>
<tr><th>H/B</th><th>Plot of settlement profile</th><th></th></tr>
<tr><td>3</td><td>
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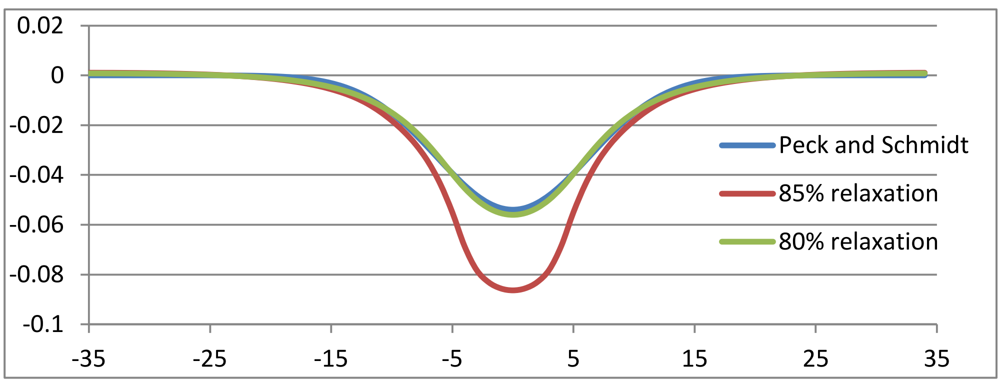
<tr><td>4</td><td>
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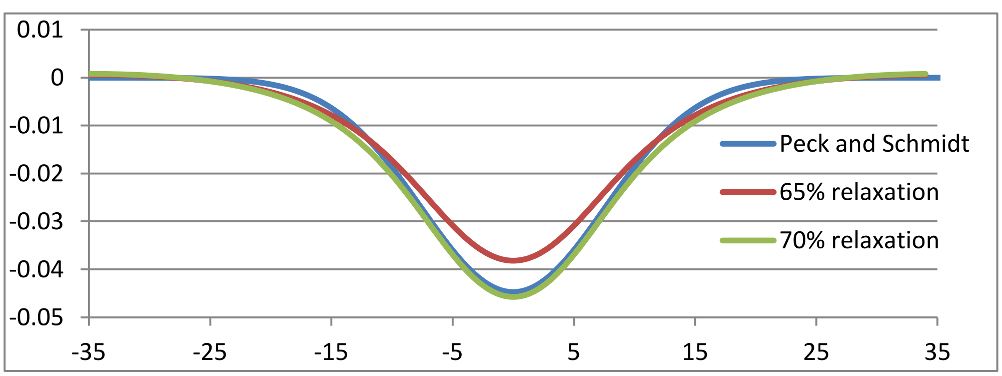
<tr><td>5</td><td>
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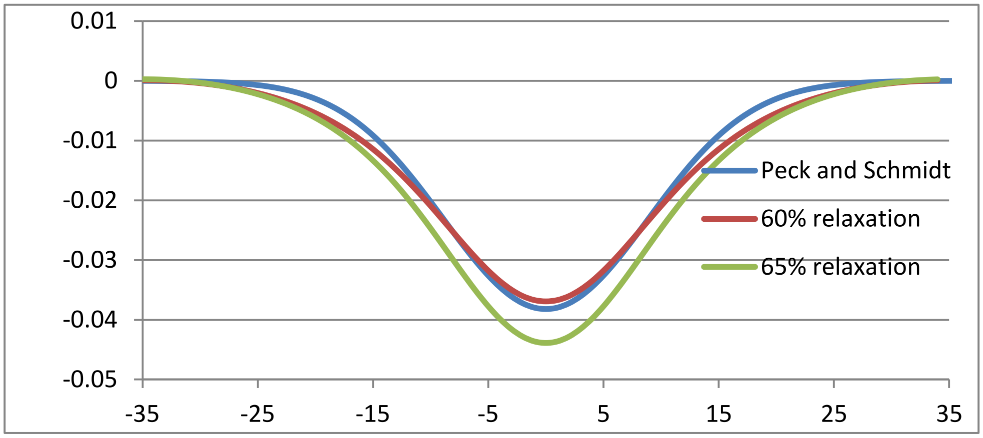
<tr><td>6</td><td>
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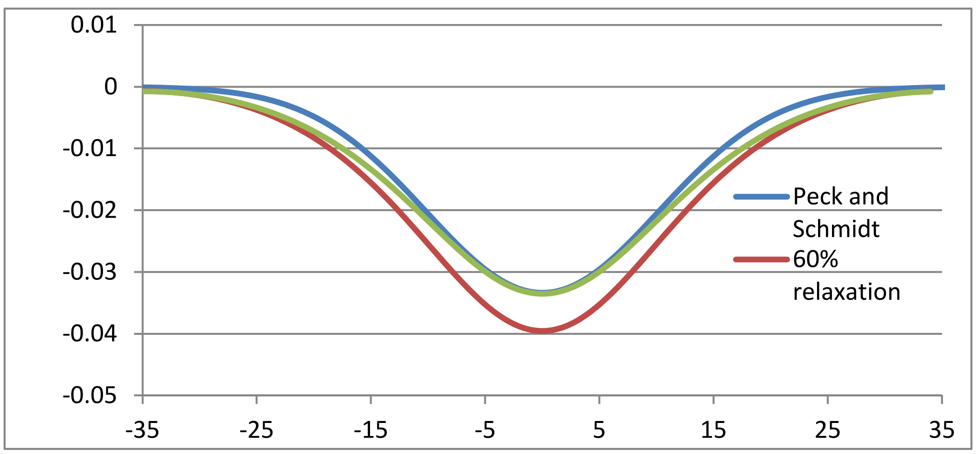
<tr><td>7</td><td>
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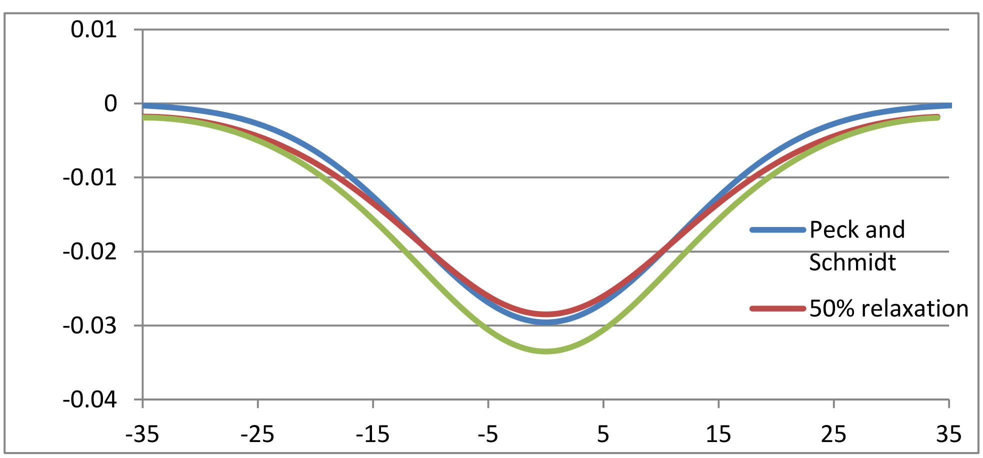
<tr><td>8</td><td>
</td><td>51.5</td></tr>
</table>

Figure 3-15: Comparison of results for clay type material

The plots above indicate that the model developed appears to provide accurate results across all ranges of C/D ratios. It was found that the model was extremely accurate ($\pm$ 3%) in representing the settlement profiles in between the two inflection points (depth of 0.606 of the maximum settlement) and still provided reasonably accurate results outside of these inflection points. It can also be seen from the above plots that as the H/B ratio increases the settlement trough widens and the maximum depth of the settlement decreases which is consistent with Cording (1991). Figure 3-9 presents the findings of the percent relaxation required to reach the desired 3% volume loss given different H/B ratios and shows the increase of percent relaxation required as the H/B ratio decreases.

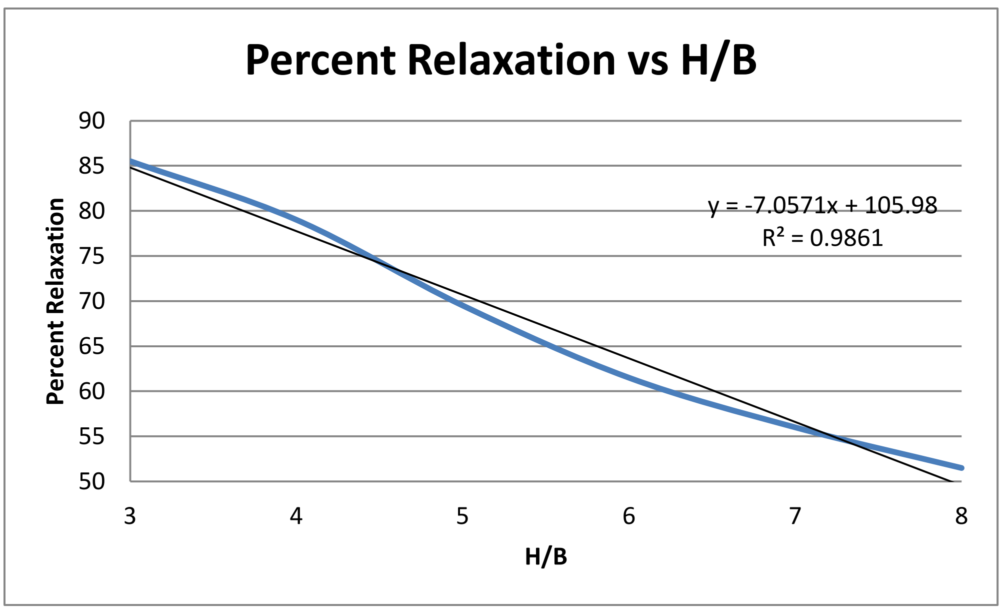


Figure 3-16: Findings from parametric study

It can be seen from the above plot that the relationship between H/B ratio and the Percent relaxation required is almost linear. By fitting a linear line of best fit in excel the formula for the percent relaxation required to obtain a 3 percent volume loss given a particular H/B ratio is given as:

$$Percent\ relaxation\ required = -7.0571\left(\frac{H}{B}\right) + 105.98$$

It should also be noted that the R-squared value for this formula was 0.9861 which is regarded as a very good fit of the line to the given data and therefore would suggest that it would be appropriate to suggest a linear relationship between H/B ratio and percent relaxation.

By comparing the four design curves (3 from the cohesion less soil and 1 from the soil with cohesion) it was concluded that changing the cohesion value in FLAC did not have a great effect on the settlement profile. However, from the background research that was conducted in section 3-1 it was found that this was not as expected as there was a clear difference between sandy/granular (cohesion less) type soils and clay (with cohesion) type soils which was not displayed in the numerical modelling. The presence of this phenomenon may highlight a problem that FLAC has in accurately modelling cohesion less soil structure. This being said investigation into FLAC's ability to accurately model this problem is outside of the scope of the research and will not be further investigated.

Through careful analysis of the above figure it was noted that the model may be over estimating the width of the settlement trough especially for higher (>6) H/B ratios. It can be seen in the above figure for an H/B ratio of 8 that the settlement profile created by the model significantly over estimates the potential width of the settlement trough. It was also noted that given lower values of H/B ratios (<6) that a slight rise in the soil was experienced as the settlement trough extended towards the outer extents of the model.

Through the analysis of the results in FLAC it was found that there was an uplift force generated once the tunnel was excavated and the relaxed reaction forces were applied. In the cases in which the buried depth was much lower a situation known as heaving was occurring. It was found that is due to the stress relief effect of excavated soil in a homogeneous soil structure (Chow, L 1994). Furthermore, it was found that as the buried depth of the tunnel was increased the effect of the uplift on the over lying soil was much less. This can be attributed to the fact that the as the tunnel is buried deeper it means that the loading points in which the reaction forces are applied to are further away from the soil surface and in turn have a lesser affect (Chow, L 1994).

It was found that this large uplift force is being generated because of a situation known as ovalisation. During a normal shield tunnelling process once the soil clears the tailpiece of the shield tunnel the soil then propagates into the tail void behind the shield. Following this the weight of the lining combined with the weight of the overlying soil would cause the lining to rest on the excavated surface (Lee et al. 1992). This being said it is now realised that numerical model that has been developed does not actually represent the complete shield tunnelling process. It was found that this model is actually representing situation of when the soil clears the tailpiece of the tunnel shield however before the lining has been installed and thus explains the large uplift force that has been occurring.

By installing a lining after the tailpiece clears the tunnel shield it would result in the weight of the soil combined with the weight of the lining pushing downwards onto the bottom of the excavated surface. In turn this would highly reduce the effect of the uplift force acting on the soil structure and in turn the positive surface displacement generated because of the stress relief that is caused when excavating the tunnel would be greatly reduced. It is now understood that as the reaction forces acting on the tunnel lining are slowly reduced that this creates the formation of a situation known as ovalisation. This conclusion was reached by analysing the applied reaction forces in FLAC and critically evaluating the way in which the relaxation technique gradually reduces the tunnel reaction forces.

As stated in section 3-2 the settlement profiles are created by firstly obtaining the necessary reaction forces needed to assure that no displacement occurs. From here the reaction forces in the tunnel lining are gradually reduced until they reach full relaxation (complete collapse). Through the analysis of the shield tunnelling process compared to the way in which the relaxation technique that has been applied to this situation it has been concluded that without installing the lining after relaxing the reaction forces that the FLAC model is representing the situation prior to the installation of the lining. Firstly, it was thought that this model would not have practical application because of the uplift that was occurring. However after careful consideration it was decided that all stages of the subsidence caused by the shield tunnelling process needs to be calculated in order for the full effect to the shield tunnelling process to be fully understood and therefore this model still provides the designer with a powerful tool to predict surface subsidence before the installation of the lining is completed and presents an interesting task for engineers in the future to further develop this model.

This being said through a series of parametric studies that can be seen in section 3.5 it can be established that even though this model represents the situation prior to the installation of the lining, given a greater buried depth this model closely resembles the settlement profiles proposed by O'Reilly and New (1982).

As described above, when given low H/B values and low amounts of relaxation results in the horizontal surface uplifting. This phenomenon was analysed and the following suggestions were made to correct this uplift occurring.

1. Fixing of x and y boundaries on the lower half of the tunnel.
    - This would result in no uplift occurring as through the entire modelling process the bottom half of the tunnel would remain completely fixed. Another method that would have the same affect of fixing the lower half of the tunnel boundaries would be by only modelling the top half of the tunnel. This would result in no uplift being caused as there is obviously no soil structure present below the tunnel however this would not be an accurate representation of the settlement that occurs during the shield tunnelling process and therefore would not provide much practical use
2. Changing the underlying soil structure to a stiffer material.

- Changing the underlying soil structure to a stiffer material would result in a significant reduction in the magnitude of the uplift and therefore more closely represent the settlement profile because of the resultant decrease in magnitude of uplift caused by the unloading of the tunnel reaction forces. This being said it would be difficult to choose appropriate material properties to use in this area to accurately model.

3. Installing an artificial lining after applying the 'relaxed' reaction forces
    - After relaxing the tunnel reaction forces by installing an artificial lining in FLAC this would result in a more accurate representation of the situation of the progression of the shield tunnelling machine through the soil structure. By installing this lining after relaxing the tunnel reaction forces this would in turn model the situation more accurately as the weight of the overlying soil would act downwards on top of the installed lining causing the lining to settle down onto the bottom of the excavated surface and therefore reducing the affect of the uplift by counter acting this force with the weight of the overlying soil.

By analysing these specific remedial actions to lower the effect of the uplift on the horizontal surface of the soil it was decided that option number three would yield the most realistic results. This being said modelling this situation is outside the scope of this dissertation and will therefore not be investigated any further. In turn because of the close resemblance of the relationship between the H/B ratio and the percent relaxation to a linear relationship it was decided to provide an equation displaying this relationship rather than a design chart as it is believed that this formula will both save more time and be more use to potential designers using this model. Therefore given a certain H/B ratio the percent relaxation required to model 3% volume loss is given as:

For cohesion less soil with a friction angle of 30 degrees:

$$Percent\ relaxation\ required = -3.8011x + 70.303$$

For cohesion less soil with a friction angle of 35 degrees:

$$Percent\ relaxation\ required = -6.0423x + 93.749$$

For cohesion less soil with a friction angle of 40 degrees:

$$Percent\ relaxation\ required = -8.3375x + 114.56$$

For soils with cohesion and friction angle of 30 degrees:

$$Percent\ relaxation\ required = -7.0571 \times \left(\frac{H}{B}\right) + 105.98$$

3.6-Further Work

The problem that is proposed by predicting the surface settlement caused by underground tunnelling has been a case of great interest to engineers and researchers because of the rapid increase in use of tunnels over the years and the subsequent lack of accurate methods of predicting these settlements that occur.

This investigation has focused primarily on the prediction of the surface settlement profiles caused by the shield tunnelling process in purely homogeneous cohesion less soils for a friction angle of 30-40 degrees. It should be noted that obviously in reality there are not many situations in which pure homogeneous soil structures exist and that the friction angles studied in this analysis are only a small amount of the friction angles which exist in soil types around the world. Therefore it can be said that this model could be further modified to represent multiple layer soil structures with varying friction angles and different values of cohesion to be applicable to a wide range of situations.

In conclusion it can be said that this model could be further modified to represent a variety of soil structures and used to predict the surface settlements caused by the shield tunnelling process. Therefore it can be said by altering specific soil properties it would be possible to analyse the following situations:

- Analysis with varying soil cohesion values
- Analysis with varying soil friction angles
- Analysis with multiple (non-homogeneous) soil layers
- Analysis with varying Shear and Bulk Modulus

These suggestions along with the proposals put forward in section 3-5 of:

- Installing artificial tunnel liners in FLAC to generate more realistic results
- Non- homogeneous soil structure analysis
- Restraining the bottom half of the tunnel
- Changing the underlying soil structure to a stiffer material to reduce the uplift forces
- Analysing FLAC's suitability to modelling cohesion less soil structures

Would all be useful studies that could be completed by modifying the model that has been created for this particular analysis. Additionally, further investigation into the situation that was presented by modelling a purely cohesion less soil type in this analysis could be investigated to try and justify whether or not modelling purely cohesion less soil structures provides a problem for FLAC.

3.7 Chapter Conclusions

This investigation was successful in using FLAC to model the surface settlement profile created by the shield tunnelling process. It was found that the model was un-successful in predicting the surface settlement profile in cohesion less soils but presented adequate results when modelling this situation in soils with cohesion. This investigation highlighted the possibility that FLAC may not accurately model cohesion less soil structures when modelled using the relaxation technique applied in this investigation.

It was found that for the model representing a soil with cohesion was able to produce accurate results inside the bounds of the inflection points of around ($\pm$ 3%) and still provided reasonably accurate results outside of these inflection points when compared to the results derived from O'Reilly and New (1982) empirical formula. From this investigation it was found that the Gaussian distribution curve can be a helpful tool when trying to predict the surface settlement profile however it requires in depth knowledge of the underlying soil properties and good knowledge of the way in which the K values change as the soil properties changes to allow an appropriate value of K to be chosen to accurately simulate the surface settlement caused by the tunnelling process prior to construction.

Chapter 4 –Tunnel Heading Failure

The second problem that has been undertaken for this project is to analyse the failure profile of a tunnel heading from a longitudinal perspective. When tunnelling it is vital to know what effects that a complete tunnel collapse may have on the surface of the overlying soil. It has been recognised that even though tunnelling is a 3 dimensional problem there is still value in analysing this 2 dimensional model. This is backed up when considering the increased difficulties that arise when constructing a 3 dimensional model not to mention the increased computation time. It is suggested that through the use of a combination of both FLAC codes created for these two situations the user will be able to arrive at a solution that provides an adequate solution to the problem of predicting tunnelling induce ground settlements. It should be noted that even though this section is looking mainly at the surface displacement profile given a full tunnel collapse, it will be discussed later on how the FLAC code will be able to be adjusted to allow for tunnelling induced ground settlement prediction.

4.1 – Background

The face stability analysis of a circular tunnel particularly those driven by a pressurized shield has become of considerable interest over the recent years as shield tunnelling is now being used extensively over the world for tunnelling in urban environments to reduce the overlying subsidence that can be caused by the tunnelling process. This issue has been studied extensively by (Broms and Bennermark, 1967 Augarde et al. 2003 and Klar et al.) for the case of purely cohesive soils and has been studied for soils without cohesion by (Leca Dormieux 1990 Eisentein and Ezzeldine 1994 and more recently by Mollon et al. 2010) just to mention just a few. These works have been completed through a wide variety of techniques including empirical, numerical and analytical models.

It was firstly noted that there was a significant lack of previous research that had been completed that discussed the affect that varying the soil friction angle and C/D ratio had on the width and magnitude of the surface settlement. From here it became evident that the majority of the background research was needed to be completed needed to be done in the field of determining the critical failure mechanism for the use of model verification.

It was noted by Chambon and Corte (1994) that regardless the tunnel depth or diameter all failure envelopes were bulb shaped. It was also noted that any strains that were developed were localised along the surface of the area bounded by the bulb shaped failure envelope. Chambon and Corte discussed that the strains were limited by a vertical plane passing through the tunnel face and by a concave envelope that starts near the floor and extends a half diameter in front of the face. This then rejoined the vertical plan at a height of approximately one diameter above the face. One important factor which was noted was the fact that given deeper tunnels, the bulb was seen to close because of a force transfer to the crown of the tunnel caused by a situation known as ‘arching’.

From here similar failure mechanisms have been noticed by Leca and Dormieux (1990). It was found that there were clear similarities between their upper bound solution and experimental results. This was for a case of loose sand with a C/D = 1.0 (Buried Depth/Diameter) and it was noticed that the failure area surface in front of the face of the tunnel matched almost exactly for both cases. This being said it was also noted that the failure are observed from the limit analysis did not extend up as high when compared with the results derived from the centrifuge. It was found that this may be attributed to the continual progression of the failure mechanism in the unsupported ground once the face collapse had occurred. The result of this comparison is shown on the next page in figure 4-1:

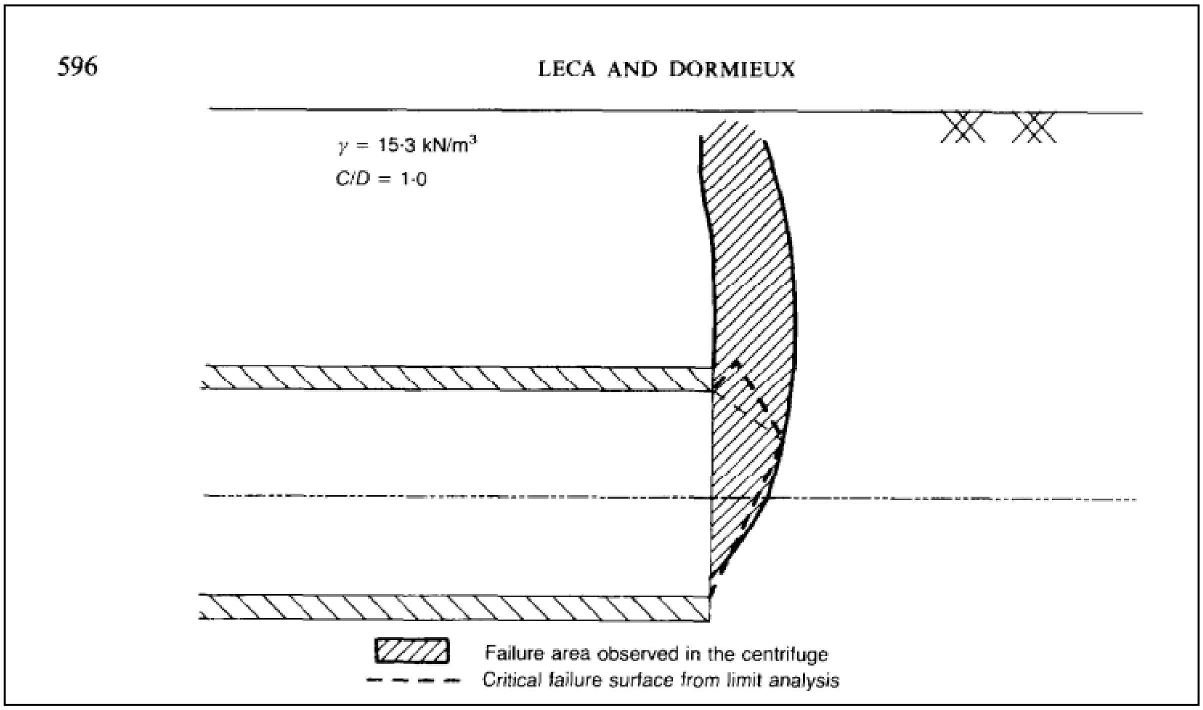


Figure 4-1: Definition of failure area

Augarde et al. (2003) found that by increasing the soil unit weight resulted in the velocity profile over the heading becoming less uniform. It was also noted by increasing the depth of tunnel resulted in greater velocities at the tunnel heading and in turn reduced velocities at the top. From these studies it was found that there is a trend showing that the deeper the tunnel (greater C/D ratio) the less chance there is of the failure mechanism reaching the surface. This assumption seems to be in agreement from many studies including Chambon and Corte (1994) and Leca and Dormieux (1990).

4.2 – Methodology

Similar to the previous model development, suitable results for comparison had to be obtained. In turn the results of this investigation were validated through comparisons with previous studies of failure mechanisms. This resulted in numerous studies being chosen for comparison as it was found that there was somewhat of a lack of information regarding effect of the full tunnel collapse on the surface settlement. It was found that the basis of the information was completed in the field of determining critical failure surface and the investigation of the critical face pressure. Therefore this resulted in the results being taken from many different studies including those done by Chambon, Corte (1994) and Leca and Dormieux (1990) and Augarde et al. (2003).

After the selection of which studies were appropriate for comparative use it was necessary to develop the model in FLAC. As mentioned previously the results will have been taken from various sources and in turn different sources may be using different material properties. Thankfully the model was created in such a way to allow easy manipulation of key parameters and therefore comparison of results with other sources will be done the exact same material properties where possible.

The FLAC model used to determine the failure mechanism for the tunnel heading closely resembles the model that was used in the previous chapter. However, some key parameters had to be changed which mainly involved changing the boundary conditions along with the region in which the relaxation forces will be applied. It was found that the model was not required to include the tunnel floor or the soil beneath the tunnel as it was found from the literature review that that the failure mechanism did not extend below the bottom of the tunnel. This was combined with the fact that including these elements in the analysis would increase the solution time to justify the exclusion of these lower elements..

A Similar process was used in this model as the one developed for the previous chapters investigation in that the face of the tunnel was mapped with a value of 1 (using the INI command) into the locations of an extended array that matched the i and j locations of the marked grid points. From here the extended array was searched for a value of 1 and set the flag to indicate a mark with a FISH function. From here the x and y reaction forces of the marked grid points (tunnel lining) were stored in extended arrays using another fish function. From here the reaction forces at the tunnel are reduced in 5% increments, applied to the marked grid points and the vertical displacement are stored in a table until the reaction forces are completely relaxed in turn representing a complete tunnel collapse.

4.3 - Model Development

The model development process closely resembled the process that was used in the previous chapter. This involved establishing specific values for boundary condition, materials and dimensions that are (where possible) the same as the models that have been developed in the study used for model verification which as mentioned above is from by Chambon, Corte (1994) and Leca and Dormieux (1990) and Augarde et al. (2003).

4.3.1 – Model Dimensions

As mentioned above for model verification, to be comparable with the published data of Chambon, Corte (1994) and Leca and Dormieux (1990) and Augarde et al. (2003) there were numerous models that needed to be created.

Through the revisions of the published papers from the above authors it was decided to use a C/D ratio of one. This value was chosen obviously as each of the three authors presented that failure condition for a C/ D ratio of 1. It was also noted that as these papers did investigate other C/D ratios for the full failure condition if needed the model will be adjusted to adequately resemble these conditions. Therefore an overall length of the model was chosen to insure that when the full collapse of the tunnel was simulated that the majority of the surrounding soil was able to adequately yield and displace without any contact to the model boundary. +

In turn, though an iteration process the boundary conditions were placed wide enough to ensure that the extents to which the tunnel heading failure would influence the surrounding soils would be adequately modelled without interference from the boundary conditions. The length of the tunnel heading was also chosen on this principle to ensure that any stresses and strains were adequately modelled by allowing a clear distance from any stresses and strains that were developed to be confined to the extent of the boundaries. It was found that this proposal would result in a large solution time because of the amount of elements needed to model the situation. Through an iteration process involving the analysis of the width of the soil that was affected along with the solution time to complete this task following model dimensions were chosen:

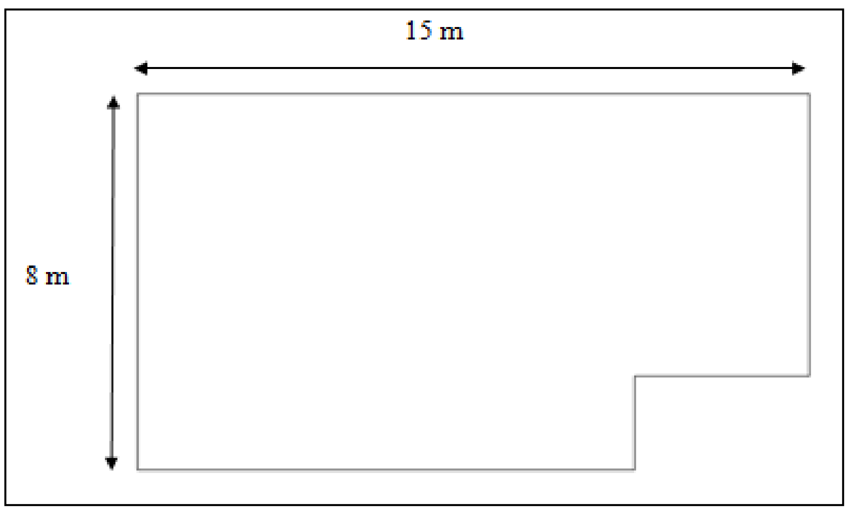


Figure 4-2: Model Dimensions

To allow adequate comparison of the results produced in FLAC a tunnel radius of 2 metres was chosen. The C/D ratio was increased by simply adding more grid spaces on top of the tunnel. Figure 4-2 above shows the model dimensions for a C/D ratio of 3.

4.3.2 – Materials

Material properties were chosen to be compatible with the existing solutions for Leca and Dormieux (1990). In turn the use of a Mohr-Coulomb cohesions-less fill was chosen. The reason why Leca and Dormiex soil properties were chosen was because of a lack of information from the other papers. In turn for model verification the following properties of each material are listed below:

- Mohr Coulomb material
- Density = 1500 kg/m^3
- g = 9.81 m/s^2
- γ =16.1 kN/m^3
- Shear modulus = 7.43 MPa
- c' = 0 Pa

4.3.3 – Boundary Conditions

In order for the FLAC model to realistically model the situation under study, the boundary conditions must be accurate representations of reality. Research into previous studies showed that the selection of boundary conditions were not always consistent between different investigations.

The boundary condition in dispute was the horizontal extents of the model. From Augarge et al (2003) it was suggested that the horizontal extents should only be vertically fixed (V=0) however Sloan and Assadi (1994) suggest that the extents should be fully fixed (u=v=0). This was based on the assumption that the extents are modelled far enough away from the tunnel heading to have no influence on the results.

Therefore in this model the horizontal extents will be modelled as vertically fixed (u=0). Given the nature of the problem it was chosen because as noted by Sloan and Assadi (1994) it was assumed that the extents were further enough away from the tunnel heading to have no influence on the results and in an act to try and produce accurate results and not relying on the assumptions used in defining the model length it was decided to adopt this boundary condition.

Another problem that arose in the selection of boundary conditions was the selection the method of support for the roof of the tunnel. It was proposed by Augarge et al. (2003) that even though mines are supported along the entire length of the tunnel in close intervals to prevent collapse that this does not mean that the tunnel roofs will be completely rigid. However in an act to simplify this analysis the tunnel roof was assumed to be rigid. This decision was based on the fact that this assumption has been made previously and produced reasonable results (Augrade et al. 2003, Slaon and Assadi 1994).

4.3.4 – Parameters

The main parameter that is under investigation was the length of the area effect overlying the collapsed tunnel heading and the magnitude of the maximum settlement created by a full tunnel collapse. Values for this length of subsidence and magnitude of maximum settlement were determined for a range of tunnel diameter C on buried depth

D ratios (C/D) and friction angles. Following this a parametric study was completed for a range of friction angles given ranging C/D ratios.

4.4 – Results Analysis

This section looks at critically analysing the results from the outputs created from the model that was developed to determine whether the behaviour of the structure, method of relaxation and fill is realistic. In this section particular attention will be paid to analysing the displacement profiles found by Augarde et al. (2003) and failure mechanisms proposed by Mollon (2001).

4.4.1 – Typical Output

The figure below shows a typical displacement plot output from FLAC for a C/D ratio of 1 and 5. As stated previously these values were chosen because they are the same that have been used in previous studies and were used to allow easy comparison of results. It can be seen in the figure below that for the C/D ratio of 1 the displacement vectors extend to around 1-1.5 of the diameter in front of the tunnel heading whilst the case for the C/D ratio of 5 displacement vectors extend to around 2.5-3 of the diameter in front of the tunnel heading. This phenomenon has been highlighted by Augarde et al. (2003) and the comparison of the two results can be seen below:

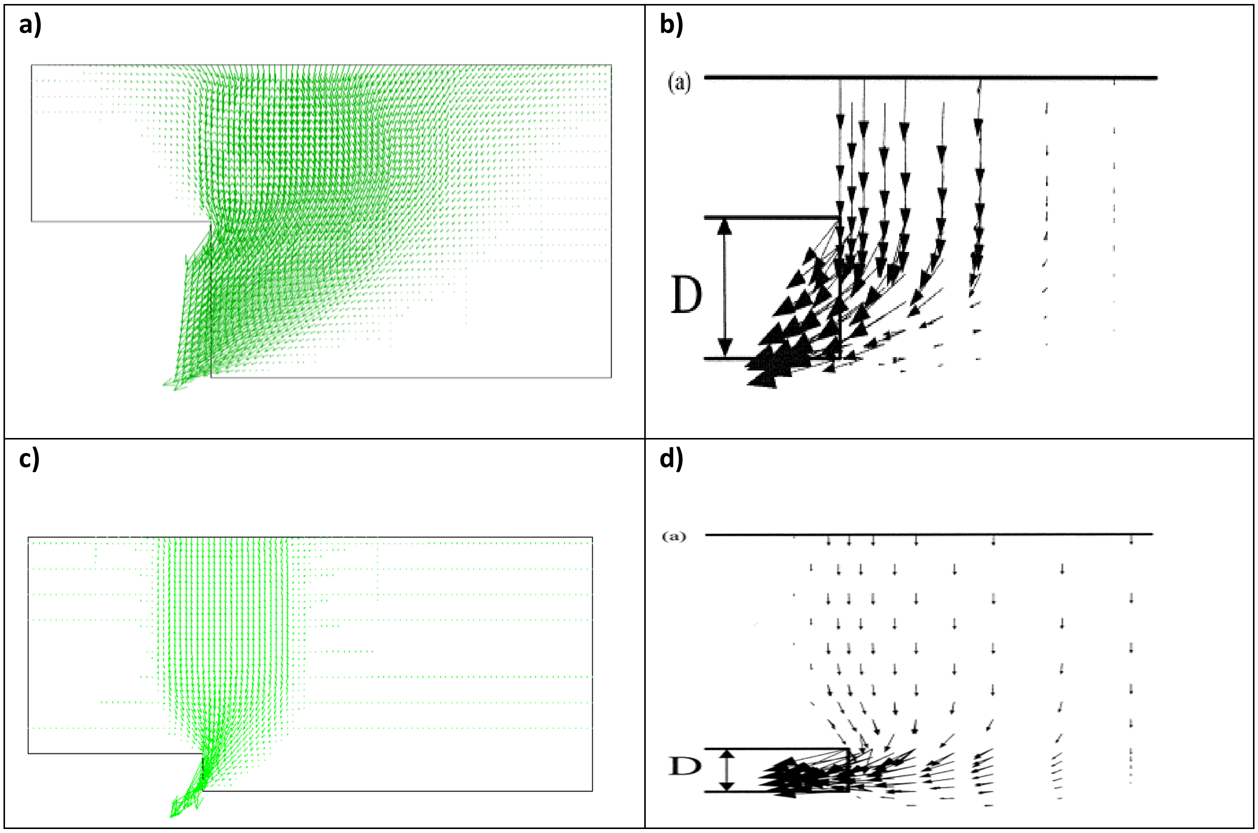


Figure 4-3: Displacement profiles from:
C/D ratio of 1: a) Dudley (2011), b) Augarde et al. (2003)
C/D ratio of 5: c) Dudley (2011), d) Augarde et al. (2003)

Figure 3-4 shows a plot from FLAC displaying the typical of contours of maximum shear strain rate. There is a notable peak in the shear strain rate at the bottom and top corners of the tunnel heading. This was to be expected as in between this top and bottom corner is where the soil is progressing through and in turn would produce higher shear strain rates because of the contact of the soil and corners of the tunnel heading.

Figure 4-4: Contours of shear strain rate

Figure 3-5 below illustrates the state shear strain ratio for the failure mechanism of the tunnel of a C/D ratio of 2 and a friction angle of 30 degrees. It can be seen by comparing the two figures that the failure mechanism that has been proposed by Mollon et al. (2011) is very similar to the mechanism that has been attained from the FLAC model that has been created for this study.

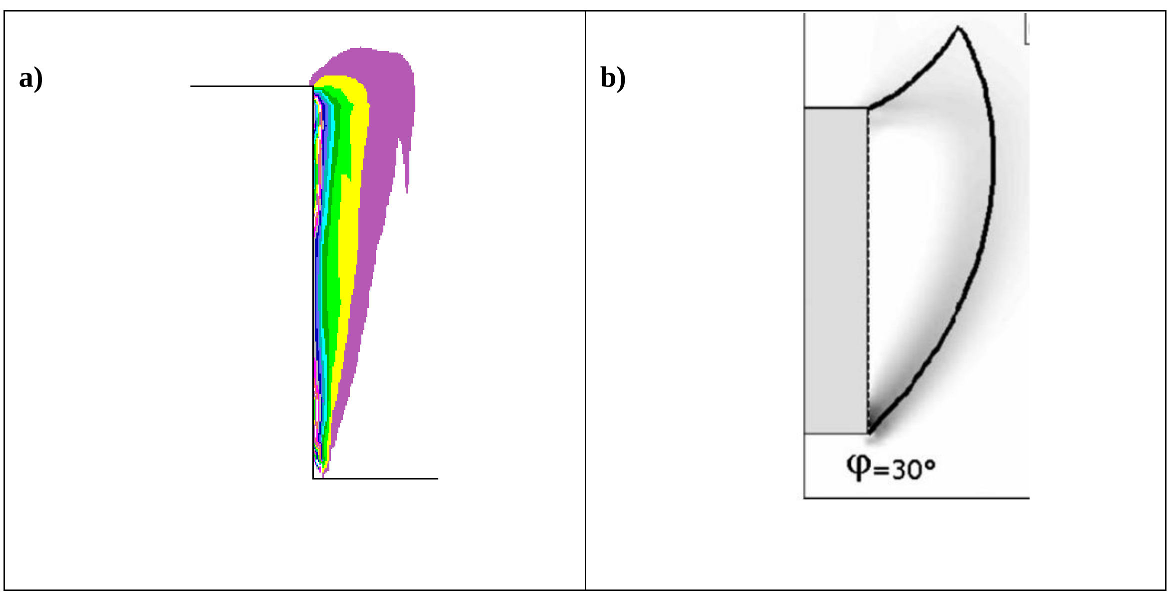


Figure 4-5: Comparison of failure mechanism from: a) Dudley (2011) and b) Mollon et al. (2011)

4.5 – Parametric Study

As discussed before understanding the potential effects that a full tunnel collapse can have on overlying structures is a very important tool to engineers. Therefore to increase the benefit of this study a parametric study should be performed on the model such that the horizontal length which is affected by the tunnel collapse may be determined for various friction angles and C/D ratios. The following diagram illustrates the influence of the angle of friction and C/D ratios on the horizontal surface displacement.

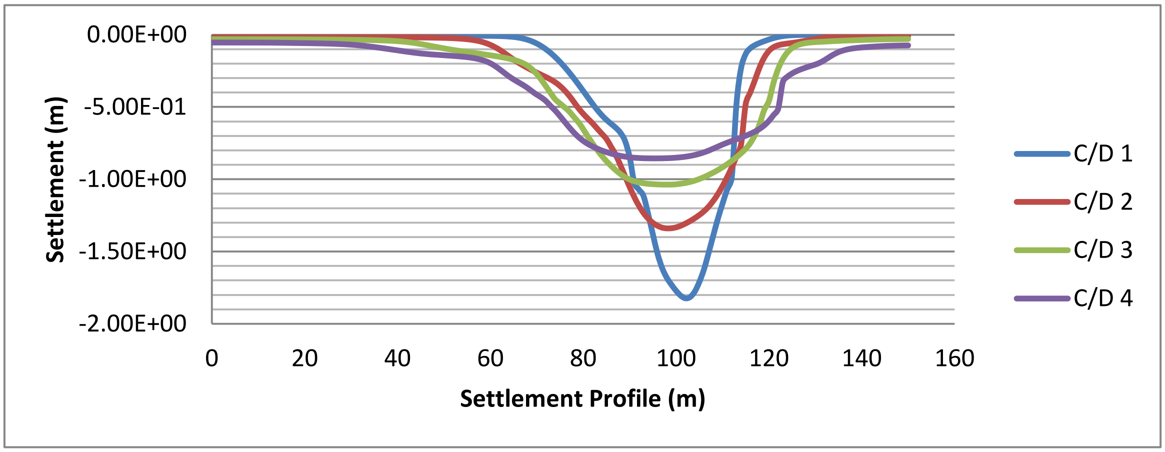
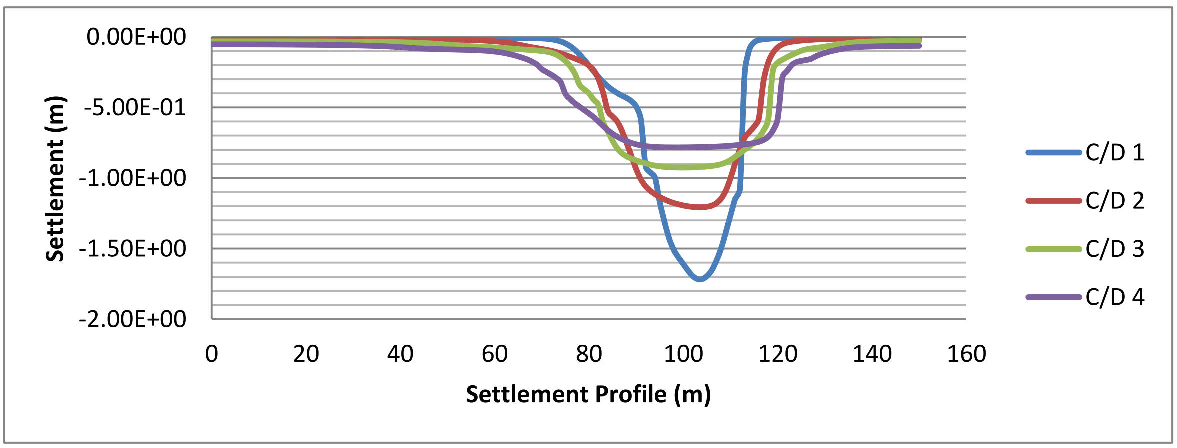
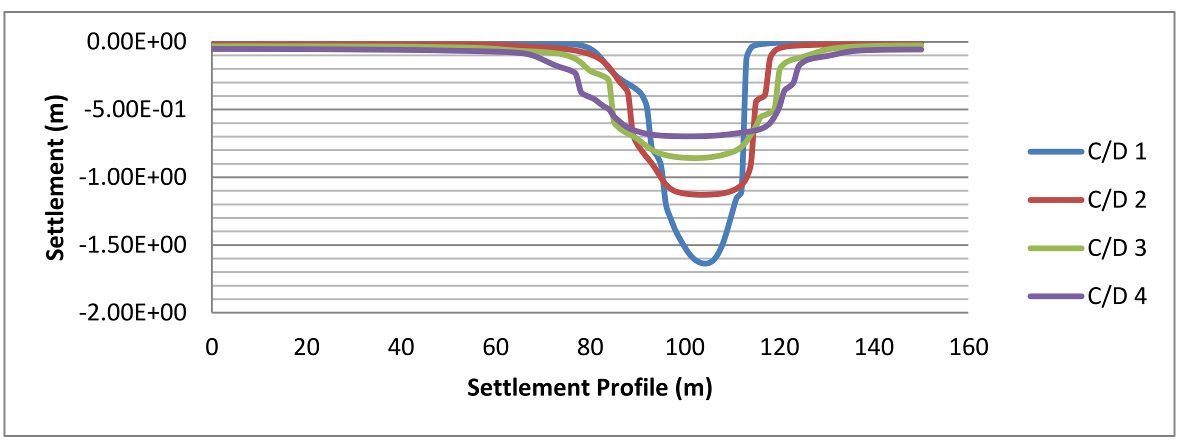
ϕ	Settlement Profile
30	
35	
40	

Figure 4-6: Comparison of settlement profiles

It can be seen from the above plots that both C/D ratio and soil friction angle has a very large effect on the width and magnitude of the surface settlement. It shows that given an increasing C/D ratio causes the length of settlement in front of the tunnel heading to increase whilst the maximum depth of the settlement decreases.. It can also be seen from the figure (however not as obvious) that as the C/D ratio increases the length of settlement behind the tunnel heading increases. The occurrence of a shallower settlement profile given higher C/D values is consistent with the study completed in section 3.5.

It was found that the decrease in the magnitude of the surface settlement as the C/D ratio increases was caused by a situation known as arching. Arching is a situation in which pressure from a yielding mass of soil is transferred onto adjoining stationary parts (Terzaghi (1943). This means that the soil becomes somewhat ‘self supporting’. It was also proposed by Terzaghi (1943) that the arching effect increases as buried depth increases which seems to be the case for the longitudinal cross section. This being said it was also noted by Terzaghi (1943) that if the tunnel is located at great depths that the arching effect cannot extend beyond a certain elevation D1 however the analysis of this proposal is not within the scope of this investigation.

Following this the figure above also indicates that as the soil friction angle increases the length of the settlement profile both in front and behind the tunnel heading is significantly decreased. This means that given a higher friction angle results in a much narrower width of settlement above the tunnel heading.

In an act to further demonstrate the effect of varying the C/D ratio and soil friction angles has on the full tunnel collapse figure 4-7 was created which shows the y displacement contours given various values for C/D ratio and soil friction angle.

These diagrams show that given an increasing friction angle results in a reduction of the horizontal distance in front of the heading that is affected by the tunnel collapse combined with a subsequent decrease in the magnitude of the y displacement contours for all of the cases. This results in the surface settlement decreasing in width as the friction angle increases.

It can also be seen that by increasing the C/D ratio it causes similar changes to increasing the soil friction angle accept with a much more significant way. It can be seen by increasing the C/D ratio results in significantly less displacement of soil in the vertical direction and increases the horizontal distance in front of the heading of the tunnel that is affected by the tunnel collapse. Therefore these diagrams show that given a larger friction angle of the soil results in a narrower settlement pattern and significantly lower levels of soil displacement. The diagrams also indicate that given a larger C/D ratio results in both a wider settlement pattern and lower maximum magnitude of soil displacement.

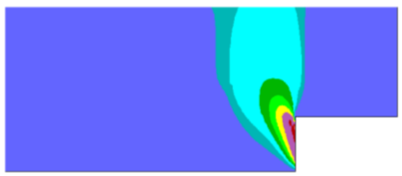
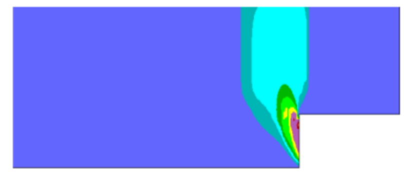
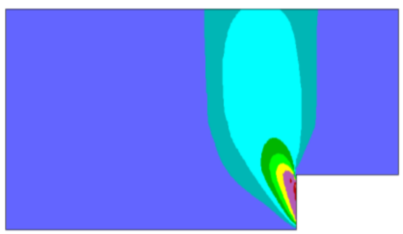
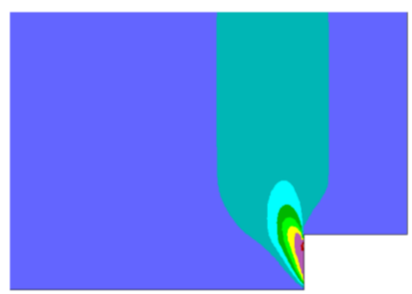
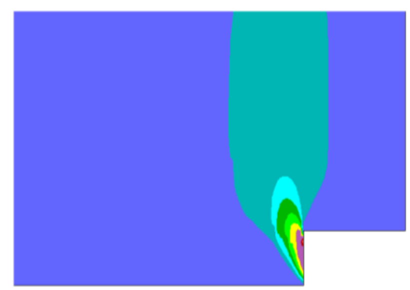
ϕ	30	35	40
C/D = 1			
C/D = 2			
C/D = 3			
C/D = 4			

Figure 4-7: Comparison of y-displacement contours

From here it was necessary to analyse the data that created these plots to provide important information on the actual width of the surface subsidence and the depth of the maximum surface subsidence that was created. For the purpose of this study it was assumed that any value below 0.06 m would not be considered. This is because it was found in the *Subsidence Engineers Handbook* (NCB, 1975) that a settlement of greater than 0.06m would result in a moderate impact classification. Therefore it was considered that any settlement less then this value would not have an extreme effect on the overlying structures. Therefore the table 4-1 below contains a summary of the findings from this parametric study.

	Friction angle 30		Friction angle 35		Friction angle 40	
	Length of subsidence (m)	Max Subsidence (m)	Length of subsidence (m)	Max Subsidence (m)	Length of subsidence (m)	Max Subsidence (m)
C/D						
1	54	-1.82	38	-1.72	32	-1.64
2	62	-1.34	54	-1.21	43	-1.13
3	82	-1.04	79	-0.927	66	-0.857
4	>128	-.856	>120	-0.783	104	-0.698

Table 1-1: Summary of results

From table 4-1 it can be seen that there is a definite correlation between friction angle and both length of the subsidence created as well as the maximum depth of the subsidence that occurs during a full tunnel heading collapse. There is also a clear relationship that has developed between varying C/D ratio and length of subsidence as well as the maximum subsidence that has occurred.

It can be concluded that as the friction angle of the soil increases that both the wodth of the subsidence as well as the depth of the maximum subsidence decreases, therefore increasing the angle of friction has a negative relationship on both the width of the subsidence as well as the depth of the maximum subsidence created. Similar to the increasing friction angle, as the C/D ratio increases it can be seen that the maximum surface settlement that occurs decreases however the width of settlement that occurs increases.

As expected, it was found that the relationship between the change in the surface settlement profiles by varying the buried depth and the soil friction angle from this investigation produced similar results to the investigation in section 3-5. The occurrence of this situation as well as the similarities in the results from this investigation compared to previous published work has resulted in a high level of confidence for the accuracy of this investigation.

4.6- Further Work

Through the investigation involved in this dissertation it became evident that there is a wide array of geotechnical problems in which the relaxation technique utilised in FLAC could be employed in. The possible applications in which the relaxation technique could be applied to are and not limited to:

- Slotted Wall Situation
  - The slotted wall case models a situation in which an excavation has been made for a building foundation for example and a concrete wall has been installed vertically to withstand the earth pressure. For whatever reason whether it be because of incorrect vibration or construction technique, the slotted wall can fail somewhere along the length of the vertical wall resulting in injury of possible death. The relaxation technique could easily be employed to model this situation and is in fact quite similar to the longitudinal tunnel heading problem accept that the soil would be moving direction out of the side wall of the model rather than having to move around the tunnel lining to flow out of the hole. This technique would be able to model the failure mechanism of the slotted wall and could be used to model many other situations given the correct application of this technique.
- Trapdoor situation
  - The trapdoor situation can be broadly described as s situation of a cavity beneath a homogenous layer of purely cohesive soil, from here the

overburden fails and result a section of soils falls into the trapdoor. This trapdoor situation has many applications including the failure of tunnel roofs or mine workings. The relaxation technique would be able to model the collapse mechanism of the trapdoor and would be extremely efficient in modelling the effect that this collapse has on the surface. Similar to the slotted wall situation the relaxation technique would be able to model the surface settlement and the movement of soil given different values of trapdoor support pressure.

- Sinkhole situation
    - The sinkhole situation is basically an extension of the trapdoor problem and is surface settlement caused because of overburden collapsing where the support is removed. The relaxation technique would be able to be applied to the sinkhole situation to reach similar results that could be derived for the trapdoor situation.

4.7 – Chapter Conclusions

This investigation has been successful in using FLAC software to model the relaxation technique employed to simulate the collapse of the tunnel heading problem. FLAC was able to develop the model used for the investigation of the effect of the full collapse on the surface settlement. It was found that the model not only was able to predict the surface settlement but was found to have some application in defining the failure mechanism of the tunnel heading problem which has already been investigated using other techniques.

It was found that as the C/D ratio increased the width of the settlement profile increased and the magnitude of the maximum surface settlement decreased. This being said it was found that the friction angle had a negative relationship with the width of the surface settlement as well as the maximum depth of the surface settlement. This means that given an increasing friction angle results in a narrower and shallower surface settlement profile. It was found that this occurrence was due to a situation that is known as arching. It was also found that there is a significant lack of information regarding the prediction of this type of longitudinal cross-section surface settlement when compared to the amount of data available for the transverse cross-section and highlights the potential for future work to be done in this area

Chapter 5 – Conclusions

Individual chapter conclusions can be found in their relevant sections however this chapter provides the conclusions of the entire project. From this the relative achievements of the objectives stated in Chapter 1 are evaluated and topics for future work are summarised in brief.

5.1 Achievement of Objectives

The aims and objectives for this dissertation can be seen in section 1.3 along with the specific specifications provided in Appendix A. The objectives as listed in the project specification were:

1. Research numerical modelling of soft ground tunnelling
2. Using FLAC, simulate various relaxation techniques for single tunnel with various soil types and tunnel depth on tunnel diameter ratios
3. Simulate partial and full tunnel collapse and comparing with Gaussian curve to both validate and predict settlement patterns.
4. Analyse and evaluate certain relaxation forces to cause certain amount of % volume loss.
5. Compare and critically analyse numerical modelling to real life physical environments
6. Create the ability for full user interface control allowing alteration of some key parameters
7. Using knowledge from previous model apply similar principles to the application and investigation of full tunnel collapse with respect to tunnel headings
8. Using FLAC model, predict volume loss and settlement patterns for tunnel heading problem.

Time permitting:

9. For different soil types investigate settlement patterns using FLAC for two parallel tunnel problem

It was found that completing the objectives that were outlined in the specifications was a much larger task than expected. Because of time constraints it was found that the original specification involved a very broad area of study including investigating the effect of changing wide array of soil properties and in turn was found to be an unrealistic target. From here, the study was narrowed down to model only a few key parameters and thus providing a more in depth study on the affect of changing these properties was achieved.

The investigation was successful in finding suitable research material for the circular tunnel heading problem however it proved difficult to find research material relating specifically to predicting the settlement in front of the tunnel heading, however it was found that the model was able to be verified using other methods. Numerical models were able to be developed for the two problems and it was found that the circular tunnel heading model was not able to accurately model the cohesion less soil structure. Through investigation it was found that the soil structure that was being modelled closely resembled a clay type soil structure rather than the cohesion less soil structure that was being aimed for.

This being said, the analysis that was completed by altering the model to match soil properties to those of medium strength clay was found to be successful and produced results to within 3% to those produced by Peck and Schmidt (1969) and O'Reilly and New (1982) for the values confined within the bounds of the inflection points of the settlement curve. It can be concluded that the investigation was successful in predicting the surface settlement profile for the case in soils with cohesion (clay) however was unsuccessful in producing reliable results for the cohesion less soil type (sand) however reasoning for why this occurred and alternative methods to effectively model this situation were discussed. The investigation for the tunnel heading was successful and it was found to produce results comparable to Mollon et al. (2011) and Augarde et al. (2003) for verification.

Parametric studies were completed for each of the problems with the circular tunnel heading problem producing reasonable results for the material with cohesion and for the tunnel heading problem when modelling the cohesion less material.

The completion of this project has shown the usefulness of using FLAC for developing numerical models to analyse the geotechnical problems that have been completed in this dissertation. The investigation was not completely set-backs however it was found that they were able to be controlled and explanation for these occurrences were analysed. Any issues that were not able to be fixed were highlighted in an act to try and encourage further development of these models in turn allowing other engineers to learn from the errors that occurred. As a result it will hopefully provide a valuable starting point in determining accurate methods to correct these errors.

5.2 – Further Work

As stated in the previous chapters there is a wide range of possibilities for future work that may be undertaken to either create new models to represent different problems and elaborate or improve on the investigations that have been undertaken in this project. These suggestions have been discussed within the relevant chapters and a summary of these possibilities can be seen below:

Circular Tunnel Heading

- Installing artificial tunnel liners in FLAC to generate more realistic results
- Non- homogeneous soil structure analysis
- Restraining the bottom half of the tunnel
- Changing the underlying soil structure to a stiffer material to reduce the uplift forces

Tunnel heading

- Slotted wall problem
- Trapdoor problem
- Sinkhole problem
- Analysis of the different stages of unloading
- Alternate soil properties (clay)
- Analysis of failure mechanism

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Appendix A – Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SUVERYING

ENG 4411/4412 Research Project

PROJECT SPECIFICATION

FOR: **Samuel Charles Dudley**

TOPIC: Stability of Underground Tunnelling

SUPERVISORS: Dr Jim Shiau

ENROLEMENT: ENG 4111-S1, D, 2011

ENG 4112-S2, D, 2011

PROJECT AIM: This project seeks to investigate the settlement profiles that occur because of instability of the face pressure during underground tunnelling.

PROGRAMME: Issue A, 21st March 2011

1. Research numerical modelling of soft ground tunnelling
2. Using FLAC, simulate various relaxation techniques for single tunnel with various soil types and tunnel depth on tunnel diameter ratios
3. Simulate partial and full tunnel collapse and comparing with

Gaussian curve to both validate and predict settlement patterns.

4. Analyse and evaluate certain relaxation forces to cause certain amount of % volume loss.
5. Compare and critically analyse numerical modelling to real life physical environments
6. Create the ability for full user interface control allowing alteration of some key parameters
7. Using knowledge from previous model apply similar principles to the application and investigation of full tunnel collapse with respect to tunnel headings
8. Using FLAC model, predict volume loss and settlement patterns for tunnel heading problem.

Time permitting:

9. For different soil types investigate settlement patterns using FLAC for two parallel tunnel problem

10. Using FLAC for different soil types investigate settlement patterns for full collapse of 'trap door' problem

AGREED (student) (supervisor)

Date: 22/03/2011 Date: 22/03/2011