Numerical Analysis of Pipe Roof Reinforcement in Soft Ground Tunnelling

W.L.Tan and P.G. Ranjith

School of Civil & Environmental Engineering, Nanyang Technological University, Singapore 639798
Phone: 65-67905267, Email: cranjith@ntu.edu.sg

ABSTRACT

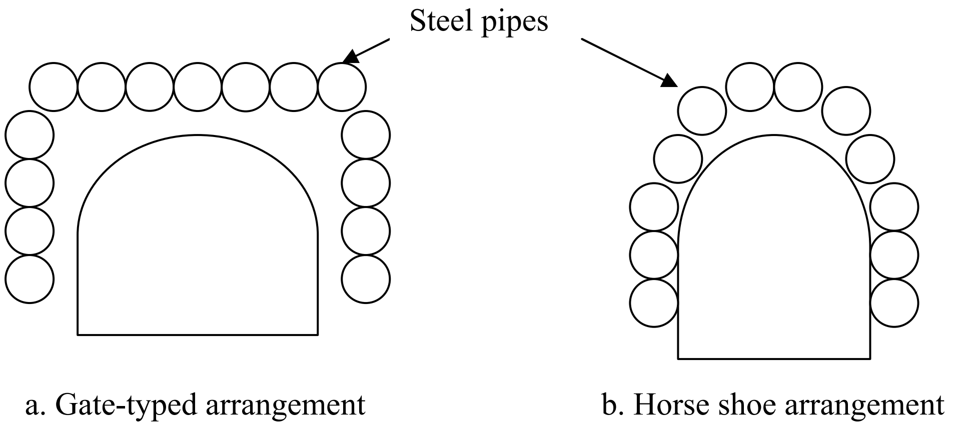
Tunnel displacement causes deformation of the ground between the tunnel and the ground surface and hence results in subsidence at the ground surface. Jacked steel pipes are used to form a reinforced layer between the driven tunnel and the soil mass above the tunnel to reduce the potential surface settlement. The paper discusses the potential of using jacked steel pipes around a tunnel to enhance the stability of the tunnel prior to tunnel excavation.

The analysis was carried out to investigate: (a) the convergence at the tunnel cavity and the deformation at the tunnel face, and (b) surface settlement after the installation of the steel pipe roof. An explicit finite difference analysis (Fast Lagrangian Analysis of Continua, FLAC) was employed to evaluate the effect of the steel pipe roof on ground surface settlement and deformation at the tunnel face. The numerical results indicate that the tunnel roof formed by the steel pipes provide a restraining effect on the tunnel induced displacement and helps to reduce the tunnel deformation and corresponding ground surface settlement. Ground settlement directly above the crown could reduce by 40-50% of the settlement produced without any pipe reinforcement.

1. INTRODUCTION

Ground surface settlement due to tunnelling in soft ground is a major concern in all aspects of tunnel design. The surface settlement is caused by a combination of ground loss at the tunnel, which includes the ground loss at the tunnel face, convergence of the tunnel cavity and the closure of the physical gap between the concrete lining and the ground.

Ground loss at the tunnel is consequentially translated into an equivalent surface depression especially in cohesive soil and tunnelling in shallow ground (Attewell et al., 1986). The effect of settlement due to shallow and soft ground tunnelling is hazardous to nearby buildings, infrastructures and existing services. A new method of reinforcing tunnel excavation and reducing the effect of ground loss at the tunnel is to create a boundary of high stiffness between the ground surface and the tunnel. In order to enhance soil property before tunnelling, steel pipes can be jacked over the projected tunnel crown either in a gate typed or horse-shoe typed arrangement to form a layer of reinforced ground between the proposed tunnel core and the ground surface as shown in Figure 1. The reinforced layer prevents the flow of soil into the tunnel at the periphery and at the face when the TBM is driven through. Consequently, ground surface settlement is reduced substantially as the translation of the movement of the ground loss at the tunnel is reduced by the reinforced layer of steel pipes. Subsequently, concrete lining can be installed to further enhance the stability of the tunnel cavity.



a. Gate-typed arrangement

b. Horse shoe arrangement

Figure 1. Pipe roof reinforcement

2. FIELD STUDIES

The pipe roof method has been utilised primarily in Japan for construction of underground rail stations (Satoh et al., 1996). Moreover, it has been widely used for construction of small diameter tunnels in the US (Rhodes and Kauschinger, 1996). However, this method has in fact been used in the early 1960s in Belgium for the construction of the Antwerp Metro station (Hoste, 1980). Pipe diameters varied for all projects and are determined based on field experience of the engineers. To the author's knowledge, there are few theoretical and numerical analyses regarding the effect of the steel pipe roof in restricting ground surface settlement. However, field evidences drawn from the actual tunnel projects have supported the conclusion that the pipe roof method does in fact reduce the surface settlement. This method can also draw similar comparison to the forepiling or umbrella arch method used to reinforce tunnels in rocks whereby fibre glass pipes are inserted into pre-drilled holes around the tunnel crown (Barisone et al., 1982).

3. NUMERICAL STUDIES

Matsumoto et al. (2001) described the usage of large diameter steel pipes jacked into the tunnel periphery and then grouted at the Satsuma Tagami Tunnel in Japan. They simulated it with a two dimensional finite element code which showed that the pipe roof method satisfied the predicted allowable settlement. Tunnel face pre-reinforced with sub horizontal pipes has gained prominence in recent years and the fundamental working mechanism of the pipes is rather similar to that of the steel pipe roof in terms of applicability and functionality. Peila et al. (1996) conducted a three dimensional finite element analysis to study the behaviour of tunnel face reinforced with horizontal fibre glass pipes. They found that the pipes had a positive reinforcing effect on the face stability in the form of a reduction of the displacements and the plastic zone extension. In addition, Yoo and Shin (2000) conducted a parametric study on the effect of reinforcing layouts on the deformation behaviour of the tunnel face and drew a conclusion that there existed an optimum reinforcing layout to reduce the deformation of the tunnel for a given tunnel geometry and ground condition.

4. EFFECTS OF TUNNELLING INDUCED GROUND MOVEMENT

The effect of tunnelling induced ground movement on nearby services such as water and gas pipelines has always been the focus of numerous studies conducted by Bracegirdle et al. (1996), Attwell et al. (1986) and Mair et al. (1996). Potential damage studies were conducted to evaluate the extent of impending damage to services. There are fundamentally two types of ground movement that the steel pipes experience. The lateral ground movement due to the vertical downward movement of the ground perpendicular to the tunnel drive develops axial bending on pipes. Secondly, the longitudinal ground movement parallel to the tunnel drive also causes the pipe to develop compressive strains as the soil pushes the pipe in the direction of the tunnel face. The part of the ground behind the tunnel face develops tensile stresses which reinforced the soil behind the tunnel face and tends to resist the impending movement of the soil towards the open tunnel face. Thus, deformation at the tunnel face is substantially reduced. The stability of the pipes are provided by the installation of struts in the tunnel during driving and also by the anchorage provided by the ground behind the tunnel face. Subsequently, sufficient stand up time is provided for tunnel linings to be installed.

5. TWO DIMENSIONAL NUMERICAL ANALYSIS

The following analysis demonstrates the effect of steel pipe reinforcement to support a tunnel that is excavated in cohesive soil under shallow overburden. The problem investigated is a circular tunnel of 6m diameter and normalised depth (ratio of depth of tunnel to tunnel diameter) of 2.5. The overburden soil is cohesive clay with a friction angle of 27 degrees and a cohesion of 40 kPa. The density of the soil is 1900kg/m3 and a Poisson's ratio of 0.49 is assumed. Figure 2 shows boundary conditions applied in the model. In the analysis, a mesh of 120 x 60 zones was generated and a Mohr Coulomb failure criterion was used to model the behaviour of tunnel. The tunnel was unlined and not restrained by any structural support system except steel pipe roof. The radial deformation was allowed around the tunnel periphery and it was assumed that stress release around the tunnel cavity was the only source of ground movement. The face deformation was not taken into account due to the plane strain analysis. The steel pipe roof was installed prior to any tunnel excavation and the following cases were studied:

Case 1A – installation of 38 nos. of steel pipes with 0.5m diameter in a gate typed arrangement. Nearest pipe has a distance of 1.5m to the tunnel periphery.

Case 1B – installation of 21 nos. of steel pipes with 1.0m diameter in a gate typed arrangement. Nearest pipe has a distance of 1.5m to the tunnel periphery.

Case 1C - installation of 14 nos. of steel pipes with 1.5m diameter in a gate typed arrangement. Nearest pipe has a distance of 1.5m to the tunnel periphery.

Case 2A – installation of 26 nos. of steel pipes with 0.5m diameter in a horse shoe arrangement. Nearest pipe has a distance of 1.0m to the tunnel periphery.

Case 2B – installation of 15 nos. of steel pipes with 1.0m diameter in a horse shoe arrangement. Nearest pipe has a distance of 1.0m to the tunnel periphery.
Case 2C - installation of 10 nos. of steel pipes with 1.5m diameter in a horse shoe arrangement. Nearest pipe has a distance of 1.0m to the tunnel periphery.

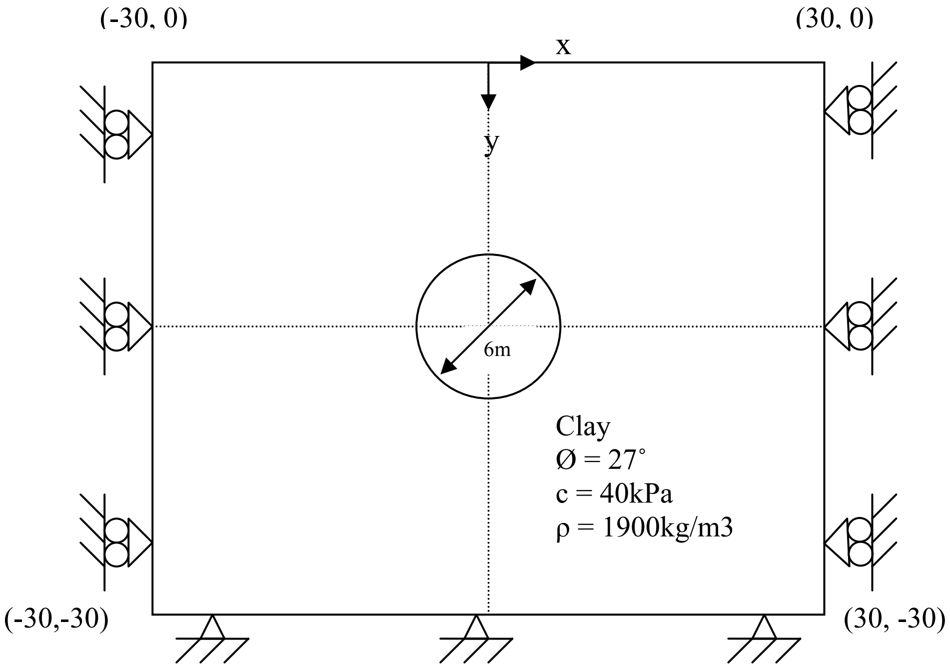
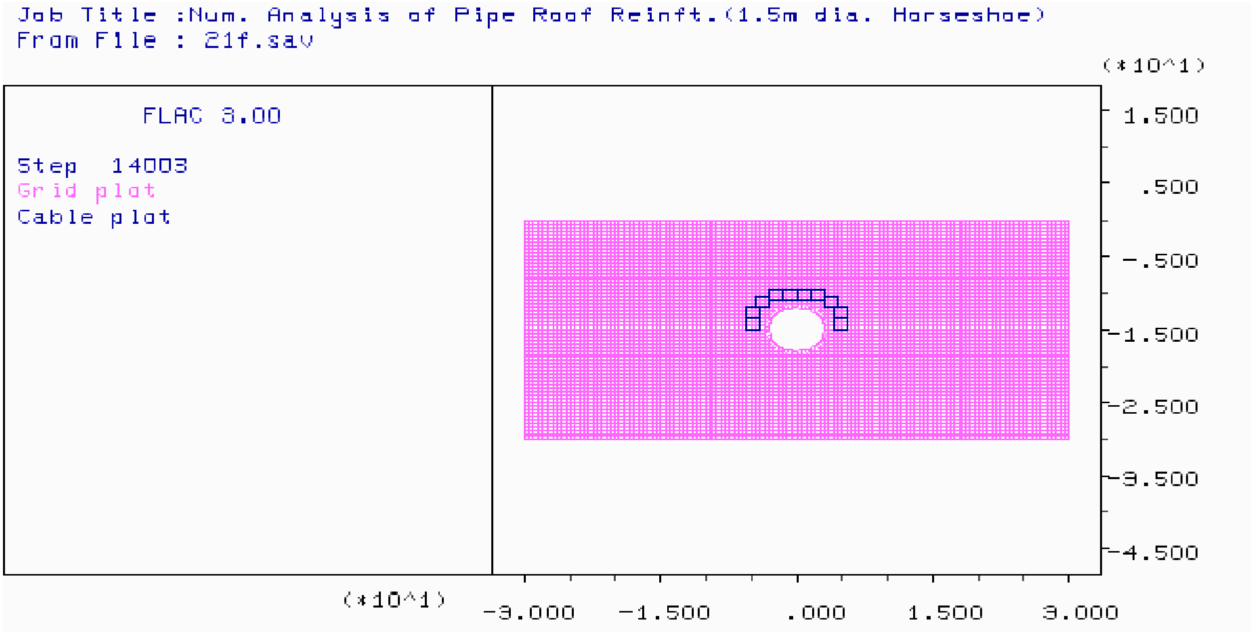


Figure 2. Boundary conditions employed in the numerical study.

There are no inter-pipe spacing and pipes are in contact with the adjacent pipes. The horse shoe pipe arrangement was modelled in such a way as to minimise the distance to the tunnel periphery. Pipes were installed from tunnel springline to tunnel crown as shown in Figures 3a and 3b.


Job Title :Num. Analysis of Pipe Roof Reinft.(1.5m dia. Horseshoe)
From File : 21f.sav

FLAC 3.00

Step 14003
Grid plot
Cable plot

Figure 3a. Finite difference mesh for horse shoe arrangement of pipes.

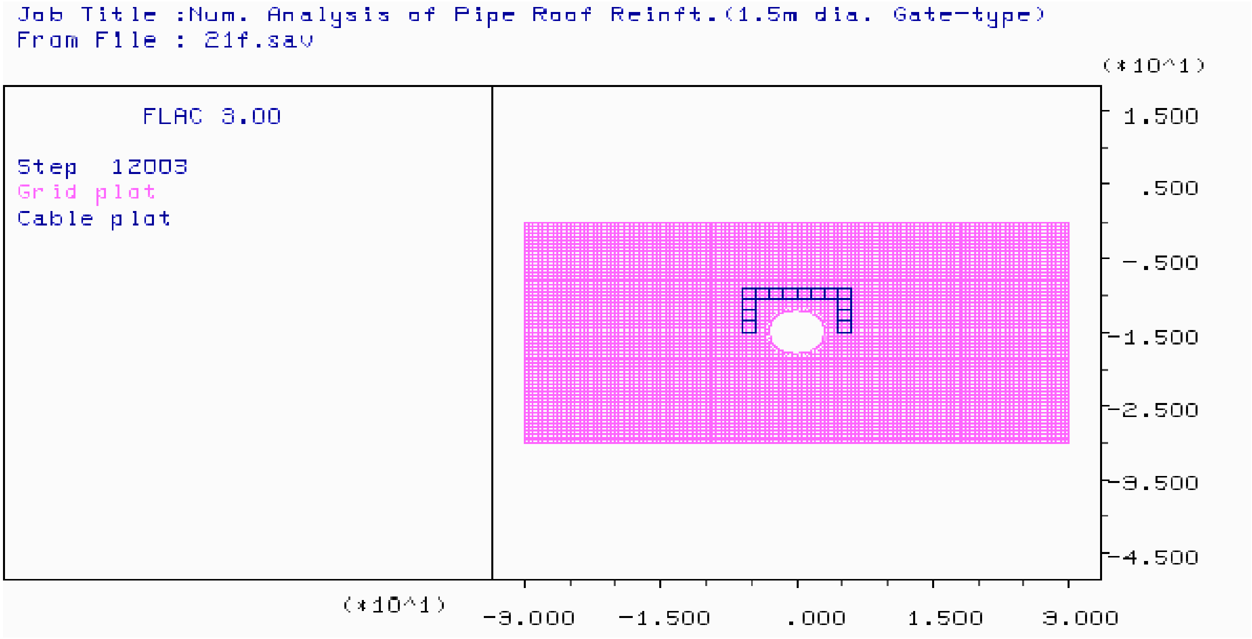


Figure 3b. Finite difference mesh for gate type arrangement of pipes.

The steel pipe reinforcements were modelled using cable elements. The cables have a thickness of 0.015 metres. The yield strength of the pipes is 320MPa and its modulus of elasticity is 70GPa. The soil was assumed to be homogenous and isotropic. The ratio of horizontal to vertical stress was chosen as 0.6.

The steel pipes were installed in a gate typed or horse shoe arrangement as shown in Figure 3a and 3b respectively. Subsequently, the tunnel was excavated. The excavation face was advanced instantaneously and the equilibrium of the model was observed.

6. RESULTS AND DISCUSSIONS

Figures 4a and 4b illustrate the reinforcing effect of the steel pipe roof on the ground surface settlement for a gate type and horse shoe type arrangements. It shows that the steel pipes reinforcement, when used as a structural support system effectively reduce the ground surface settlement up to 50%. The significant reduction could be a result of the formation of a reinforced zone of soil mass around the tunnel periphery. The steel pipes increase the effective cohesion in the soil mass around the tunnel periphery and hence the vertical and horizontal tunnel closures are reduced.

It can also be observed that when the gate type arrangement produces less surface settlement as compared to the horse shoe type of arrangement. Although less pipes are used for the horse shoe arrangement and hence it is an economical design, but surface settlement is larger for each category of pipe diameters. Numerical results also show that 0.5m steel pipes installed in a gate typed arrangement reduce surface settlement more than other pipe diameters. However for a horse shoe arrangement, 1.5m diameter pipes produce the least surface settlement. Figure 5 shows the variation of pipe diameter with ground surface settlement.

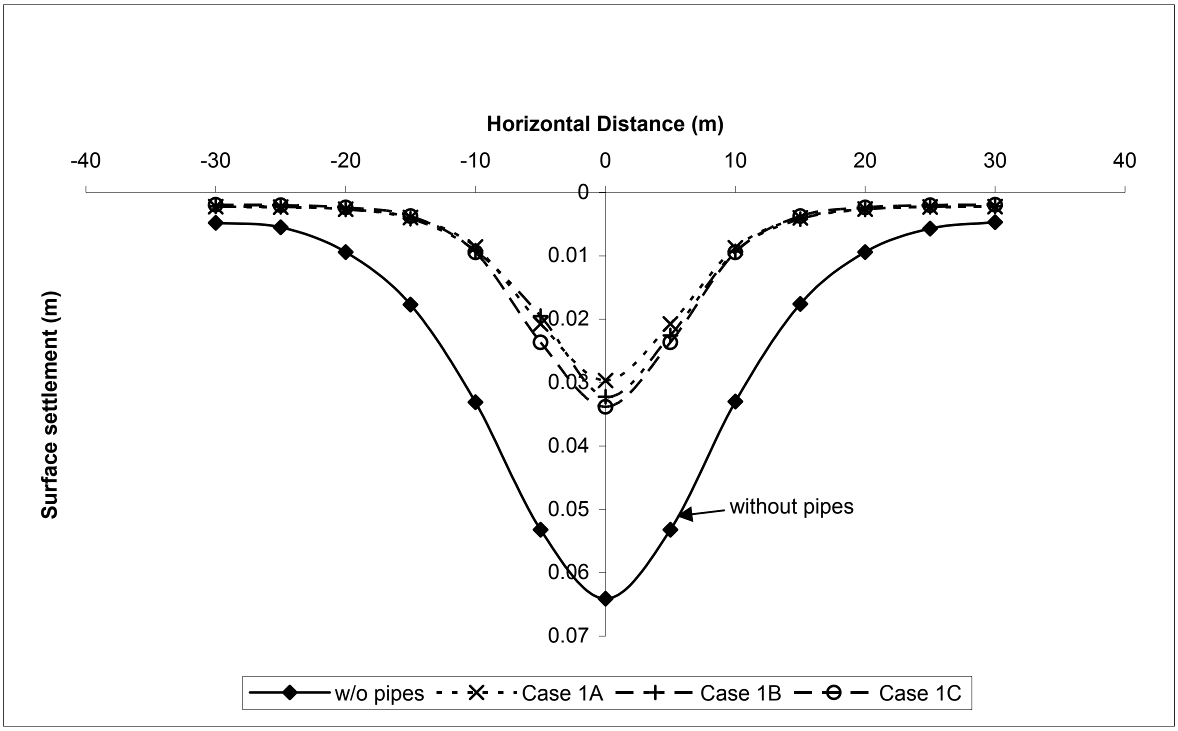


Figure 4a. Effect of pipe roof reinforcement on surface settlement for different pipe diameter (Gate type arrangement).

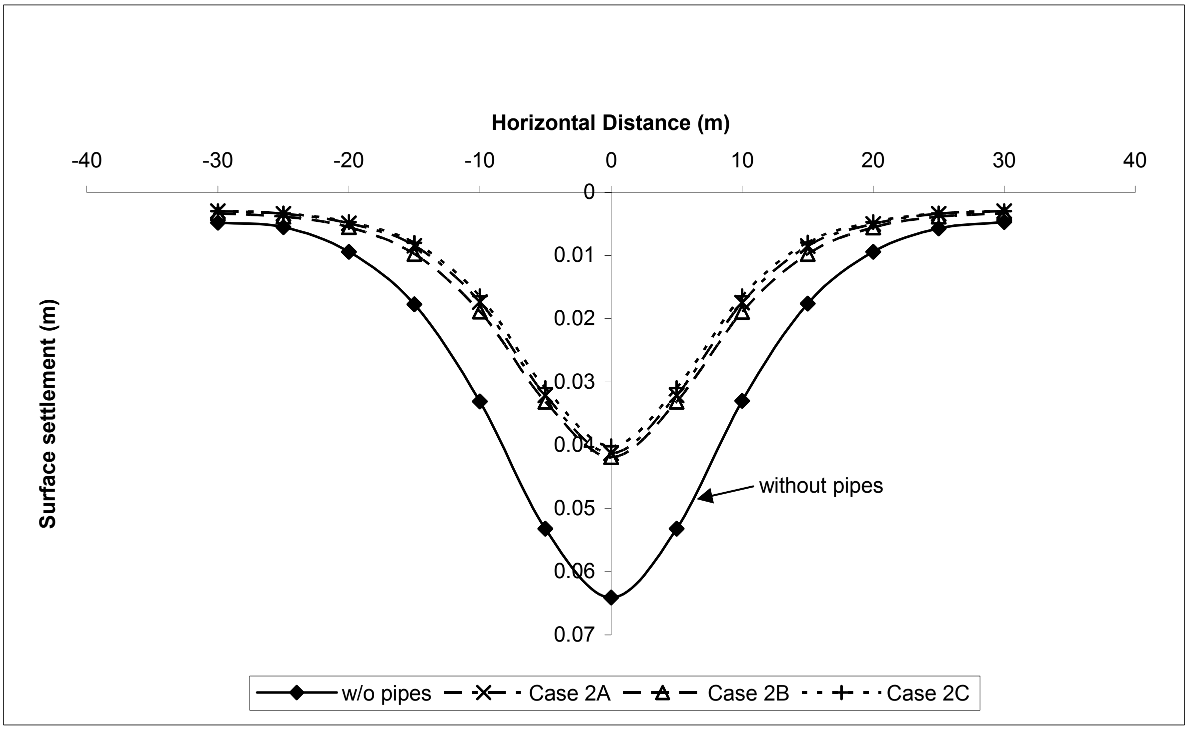


Figure 4b. Effect of pipe roof reinforcement on surface settlement for different pipe diameter (Horse shoe arrangement).

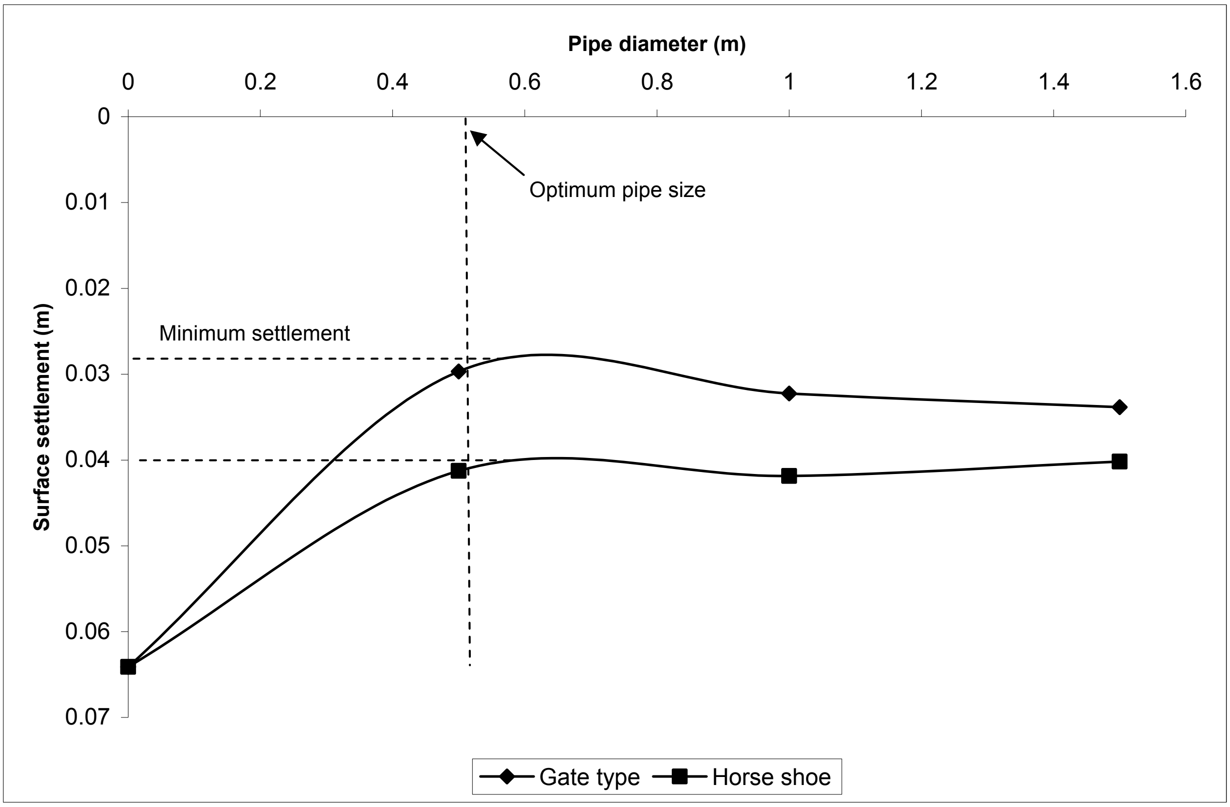


Figure 5. Variation of pipe diameter with ground surface settlement.

It can be seen from Figure 5 that optimum pipe size is 0.5m arranged in a gate typed manner around the excavated tunnel periphery. Pipe diameters that are less than 0.5m will be less effective in curbing the tunnel convergence considering the tolerance of the steel pipe in withstanding bending and buckling.

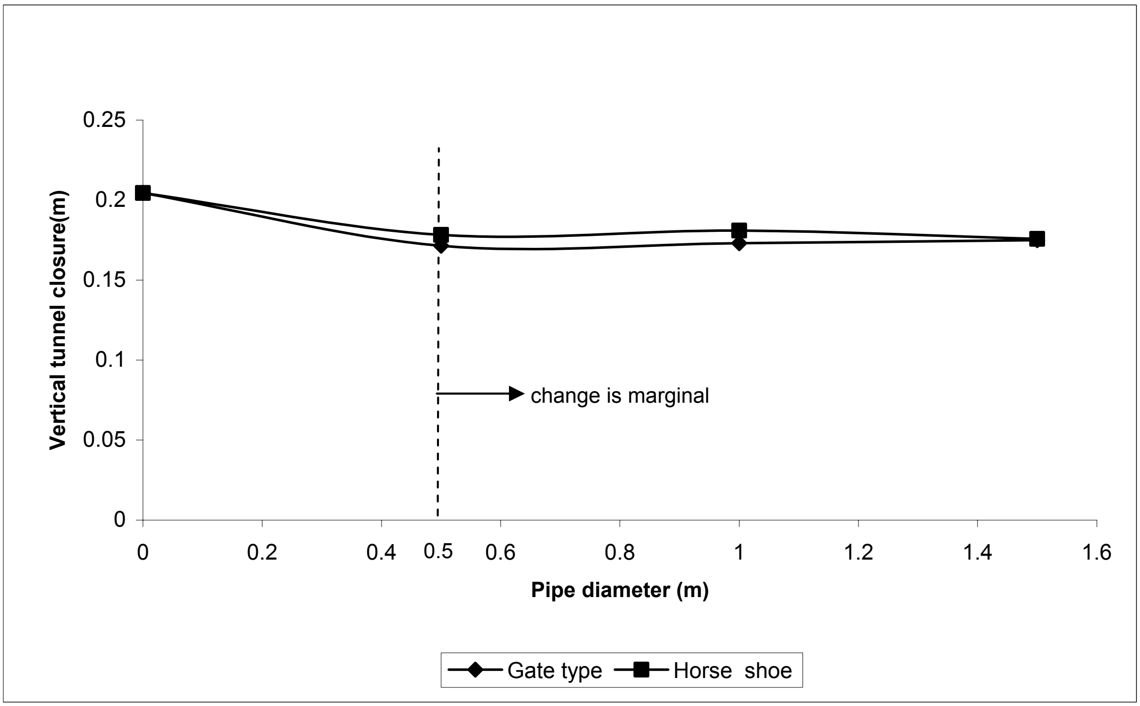


Figure 6a. Vertical tunnel closures with pipe diameter variations.

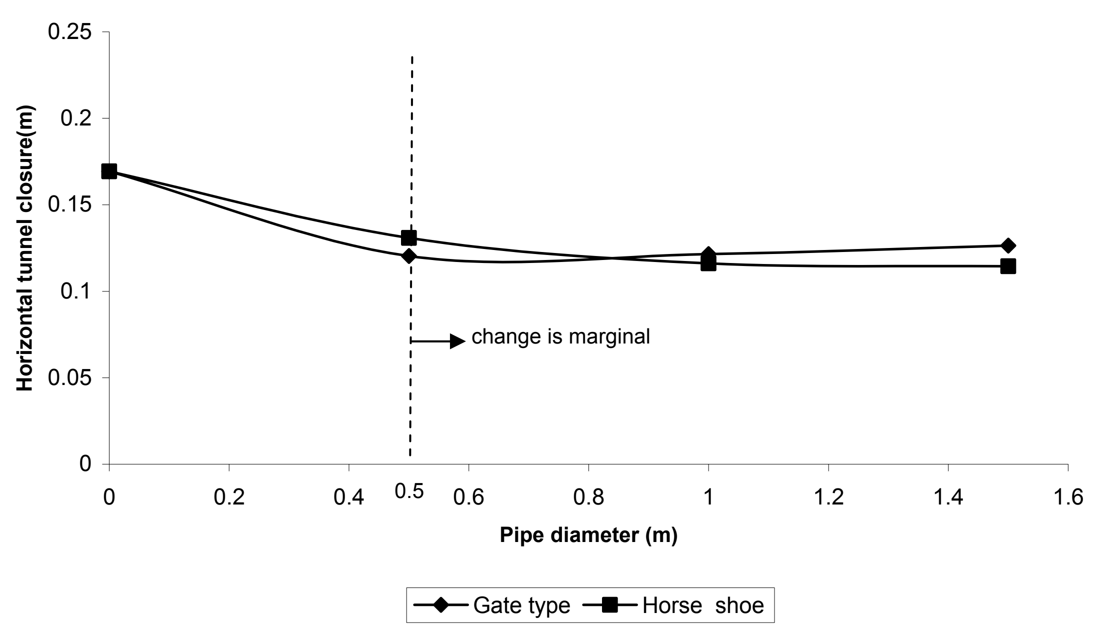


Figure 6b. Horizontal tunnel closures with pipe diameter variations.

Vertical and horizontal tunnel closures are also analysed in the study and results are plotted as shown in Figure 6a and 6b, respectively. The plots present that vertical and horizontal deformations at the tunnel crown and springline, display a trend of decrement when the pipe roof reinforcement is installed. This shows that the loss of ground at the tunnel has decreased and thus, the ground surface settlement also decreases. Residual vertical and horizontal tunnel closures are observed when the pipe diameter exceeds 0.5m.

The analysis was further explored for two different soil conditions:
(1) Cohesion = 0, friction angle = 27˚ and,
(2) Cohesion = 60kPa, friction angle = 35˚.

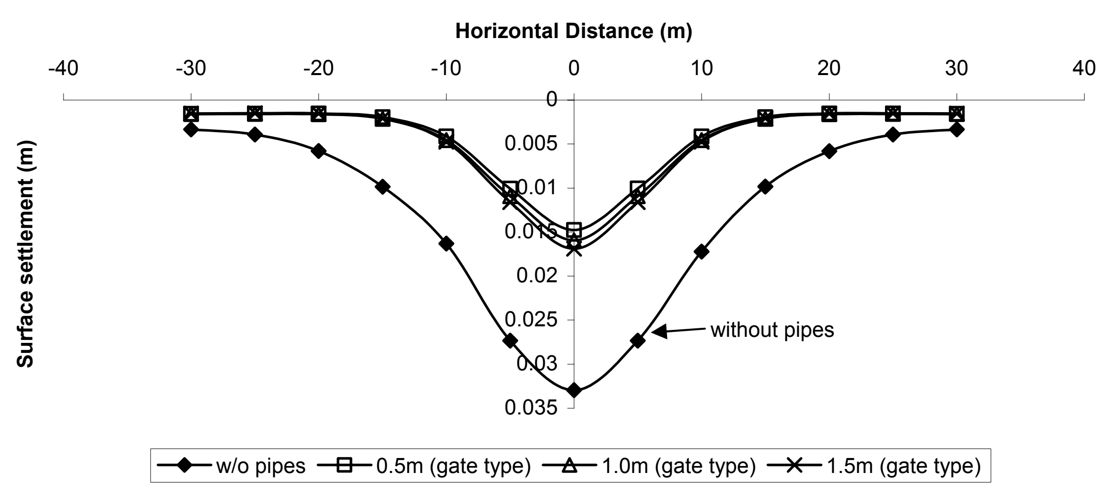


Figure 7. Surface settlement of steel pipe reinforced soil with cohesion = 60kPa, friction angle =35˚.

Results from Figure 7 show that for a more cohesive soil, the steel pipes reinforcement will exhibit similar reinforcing capability to reduce surface settlement up to 50%. Vertical and horizontal tunnel closures also show similar trends of reduction when pipe reinforcement are installed. However, a study on cohesionless soil indicates that steel pipe reinforcement is unsuitable as soil failure occurs instantaneously after installation and subsequent excavation of tunnel. Hence, it can be concluded that the pipe roof reinforcement works remarkably well in cohesive soil condition.

7. CONCLUSIONS

The behaviour of steel pipe roof reinforcement installed prior to tunnel excavation was studied using a two dimensional finite difference method. In comparison to the horse shoe arrangement, the gate type pipe arrangement is more effective in reducing ground surface settlement. Findings of the study suggest that the optimum size of steel pipe is approximately 0.5m diameter with a thickness of 0.015m. The pipe roof reinforcement is also found to be unsuitable for cohesionless soil condition. Two dimensional analyses only provided an approximation of the actual tunnel behaviour. The analysis must be supplemented by considering the longitudinal effect from a three dimensional or axisymmetric analysis since the face deformation also contributes to tunnel closures or loss of ground at the tunnel. In addition, choice of tunnel boring machines, tunnelling methods, pipe joints and workmanship should also be major considerations in the derivation of an accurate prediction of the loss of ground at the tunnel and the surface settlement.

REFERENCES

Attewell, P.B., Yeates, J. and Selby, A.R. (1986). "*Soil movements induced by Tunnelling*", Chapman and Hall, New York.

Barisone, G., Pigorini, B. and Pelizza, S. (1982). "Umbrella Arch method for tunnelling in difficult conditions- Analysis of Italian cases", *Proceedings of the 4th Congress International Association of Engineering Geology*, New Delhi, Vol. 4, pp.15-27.

Bracegirdle, A., Mair, R.J., Nyren, R.J. and Taylor, R.N. (1996). "A methodology for evaluating potential damage to cast iron pipes induced by tunnelling", *Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds.), 1996*, Balkema, Rotterdam, pp. 659-664.

Hoste, G.R. (1980). "Metro works in Antwerp, Belgium: use of a 6.50m diameter bentonite shield for the tunnels and pipe jacking for the stations", *Proceedings of Eurotunnel '80*, Basle, pp. 28-32.

Itasca Consulting Group (1991). "FLAC User Manual – Version 3.0", Minneapolis.

Mair, R.J., Taylor, R.N. and Burland, J.B. (1996). "Prediction of ground movements and assessment of the risk of building damage due to bored tunnelling", *Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds.), 1996*, Balkema, Rotterdam, pp. 713-718.

Matsumoto, Y., Kurose, N., Inoue, T., Kurazono, M. and Nodomi, K. (2001). “New pre support method using pipe roof by semi shield and chemical grouting for shirasu fill”, *Modern Tunnelling Science and Technology, Adachi et al. (eds.)*, Swets & Zeitlinger, pp.751-756.

Peila, D. (1994). “A theoretical study of reinforcement influence on the stability of a tunnel face”, *Geotechnical and Geological Engineering*, Vol. 12, pp. 145-168.

Rhodes, G.W. and Kauschinger, J.L. (1996). “Microtunnelling provides structural support for large tunnels with shallow cover”, *North American Tunnelling 1996*, Balkema, Rotterdam, pp. 443-449.

Satoh, S., Furuyama, S., Murai, Y. and Endoh, T. (1996). “Construction of a subway tunnel just beneath a conventional railway by means of a large-diameter long pipe-roof method”, *North American Tunnelling 1996*, Balkema, Rotterdam, pp. 473-481.

Yoo, C.S. and Shin, H.K. (2000). “Behaviour of tunnel face pre-reinforced with sub horizontal pipes”, *North American Tunnelling 2000*, Balkema, Rotterdam, pp. 463-468.