A study on the reinforcing capabilities of Forepoling Umbrella System in urban tunnelling

B.T. Le and R.N. Taylor
City University London, London, United Kingdom

ABSTRACT: Adequate heading stability is crucial to the safe construction of any tunnel. Insufficient support will lead to ground movements which have the potential to cause damage to existing infrastructure. Congested urban environments have led to a requirement to minimise these tunnelling-induced deformations. Forepoling Umbrella Systems (FUS) have proved to be a beneficial soil reinforcement measure for controlling ground movements due to NATM tunnelling in urban areas. However, there is limited understanding of the influence of tunnel geometry and FUS parameters on its reinforcing efficiencies. A series of centrifuge tests has been conducted to investigate the benefits of FUS using different arrangements of steel pipes placed in a model tunnel heading at various depths. The results show the importance of the steel pipes near the tunnel spring-line and the embedded lengths on the reinforcing effects of forepoles. In addition, relative benefits of forepole location and embedded length are shown to vary as the soil cover above the tunnel changes.

1 INTRODUCTION

1.1 *Urban tunnelling in soft soil conditions*

Tunnel construction inevitably induces ground deformations and potentially causes damage to surrounding structures. In congested urban areas with soft soil conditions, this becomes a critical issue relating to the safety of people, buildings and services. Therefore, reducing ground movements due to tunnelling and their effects is a requirement for all new construction and can be addressed by in-tunnel reinforcement measures.

For tunnel construction involving short lengths of excavation (e.g. connecting existing tunnels), non-circular sections (e.g. an enlargement at a station), open face tunnelling is normally chosen over a tunnel boring machine. In open face tunnelling, the main source of ground movements is the tunnel heading deformation due to the stress relief (Mair & Taylor 1997). Easy access in open face tunnelling enables soil reinforcement measure such as forepoles to be added in the tunnel heading to control ground deformations.

1.2 *Forepoling Umbrella System*

The Forepoling Umbrella System (FUS) comprises steel pipes installed from the tunnel face to form a roof above the tunnel heading (Figure 1). Therefore, the FUS contributes to decreasing the deformations caused by excavation and increasing the stability of the tunnel heading. One of the noticeable advantages of FUS is the immediate support after installation of the steel pipes. This allows the excavation to be carried out with minimal waiting time.

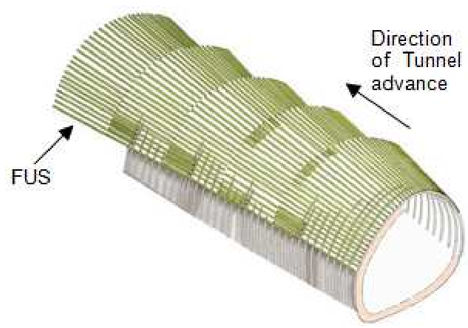


Figure 1. Forepoling Umbrella System (after Carrieri et al. 2002).

Figure 2 presents a schematic diagram of a FUS where D is the tunnel diameter, C is the cover above the tunnel crown, P is the unlined portion of the tunnel heading and S is the centre to centre spacing between the steel pipes used as forepoles. L is the length of forepoles which are installed from the tunnel face at an insertion angle of β. EL is the embedded length of the forepoles into the soil in front of the tunnel face. The soil beneath the embedded length of the forepoles acts like a foundation to support the steel pipes as they bridge over the structurally unsupported tunnel heading and this is known as the foundation effect. A minimum EL is required to maintain an adequate foundation effect to the steel pipes to support the tunnel heading. Typical dimensions of various parameters used in a FUS are presented in Table 1.

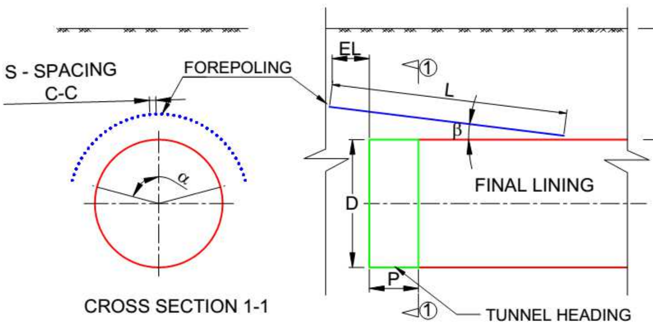


Figure 2. FUS schematic diagram.

Table 1. Typical parameters of a FUS.

Parameter	Unit	Value
Steel pipe diameter and wall thickness	mm mm	70-80 4-8
Steel pipe length, L	m	12-18
Embedded length, EL	m	3-6
Insertion angle, β	°	5-7
Filling angle, α	°	60-75

The actual values chosen for the parameters in Table 1 depend on the tunnel geometry, ground conditions and support required. However, understanding the effects of the parameters to achieve an optimal design of FUS is still limited. The following section reviews the current understanding on the effect of Forepoling Umbrella System.

2 BACKGROUND

2.1 *Assessment aspects on the efficiency of FUS*

In order to understand the reinforcing efficiency of the FUS in different tunnel geometries and forepole arrangements, it is necessary to have an assessment scale. Calvello & Taylor (1999) quantified the efficiency of soil reinforcement measures using the vertical ground surface settlement and the tunnel stability ratio.

Measuring vertical ground surface settlement due to tunnelling in centrifuge model tests is straightforward by the means of instrumentation such as LVDTs and image analysis technique.

The stability ratio, N, was defined by Broms & Bennermark (1967) as the difference between the overburden stress at the tunnel axis, σ_{ob}, and the tunnel support pressure expressed as a ratio of the undrained shear strength S_u as:

$$N = [\sigma_{ob} - \sigma_T]/S_u \qquad (1)$$

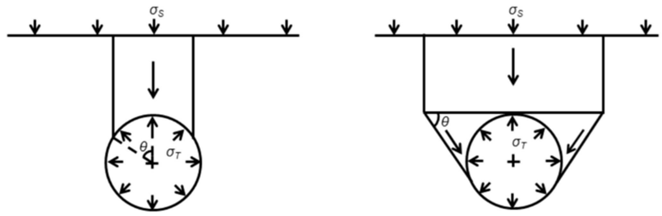
where:

$\sigma_{ob} = \gamma(C + D/2)$,
γ: unit weight of soil,
σ_T: tunnel support pressure.

2.2 *Mode of transverse ground movements due to tunnelling*

Understanding the soil deformation mechanism is important since the forepoles can then be positioned appropriately to reduce the soil deformations and increase the tunnel stability.

Davis et al. (1980) proposed upper bound collapse mechanisms for the transverse plane strain section of a tunnel. These mechanisms indicate that for a shallow tunnel, soil movements tend to be concentrated at the crown of the tunnel. For deeper tunnels, the soil mobilisation involves not only the crown but also the sides and bottom of the tunnel. Figure 3 presents the two mechanisms that will be used to interpret the model test results.



(a) Roof mechanism (b) Roof and side mechanism
Figure 3. Upper bounds mechanisms (after Davis et al. 1980)

2.3 *Previous studies on the Forepoling Umbrella System*

Calvello & Taylor (1999) found that the presence of spile reinforcement placed in the tunnel face delivered significant reduction in ground movement and the affected area at the ground surface. The stability of the tunnel was also increased.

Juneja et al. (2010) reported that the use of forepoles reduced the length of the settlement trough ahead of the tunnel face while the width remained unaffected.

Results from centrifuge tests and an upper bound plasticity analysis conducted by Yeo (2011) suggested a significant improvement of the tunnel heading stability can be achieved by using very long and stiff forepoles.

Volkmann & Schubert (2007) reported the site measurement data of a tunnel construction using a steel pipe roof. The results suggested that the soil underneath the steel pipes provides a foundation effect for the whole FUS system. As a consequence, the reinforcing effects of a Forepoling Umbrella System depends on not only the stiffness of the steel pipes stiffness but also the strength of the surrounding soil. A similar suggestion on the foundation effect was also made by Carrieri et al. (2002).

Le et al. (2015) investigated the effect of using FUS in different arrangements with EL and α as the variables while the length of steel pipes and the cover depth C were unchanged. It was found that a longer EL provided an improved reinforcing effect. More forepoles near the tunnel spring line reduced the lateral ground displacements and hence reduced the overall settlement at the ground surface and increased the tunnel stability.

Tunnel depth is one of the essential features that govern tunnelling-induced ground deformations and is therefore likely to have a major impact on the reinforcing efficiency of the FUS. The next section discusses the experimental parameters and the methodology used to investigate the relative effects of the cover depth C, the embedded length EL and the filling angle α.

3 CENTRIFUGE MODELLING TEST SERIES

3.1 *Centrifuge modelling principle*

The ground surface settlement and the tunnel stability explicitly relate to the behaviour of soil in different tunnel geometries and the corresponding influence caused by the steel pipes.

In situ ground deformation behaviour is governed by the stress generated by the self-weight of the soil. Centrifuge modelling techniques can produce a large inertial radial acceleration to generate a proper self-weight effect in a small-scale model to be equivalent to a full scale prototype. The well-established centrifuge scaling laws are useful when choosing suitable dimensions and materials to replicate the behaviour of, for example soil and steel pipe forepoles. Given these advantageous capabilities, the centrifuge modelling technique was chosen as the research methodology.

3.2 *Centrifuge model tests*

Eight centrifuge tests have been conducted to investigate the FUS effect at two different tunnel cover depths C/D=1 and C/D=3.

The model clay (Speswhite kaolin) was one dimensionally consolidated to a vertical effective stress, σ'_{vo}, of 175kPa. The tests were conducted at 125g.

Figure 4 illustrates the model test apparatus. By modelling half of the tunnel, the surface and subsurface ground deformation could be observed and measured during the test with minimal boundary effects. The stiff tunnel lining was modelled by a half section of a stainless steel tube. The model tunnel diameter, D, was 50mm. The unlined portion P and the insertion angle β in all the tests were 25mm and 5^0 respectively. The tunnel cavity is supported by a compressed air pressure contained in a latex membrane lining the tunnel. The air pressure is controlled to balance the total overburden stress at the tunnel axis level. A pressure transducer was installed at the end of the latex membrane to monitor the support pressure.

A guide, precisely produced by 3D printing, was used to insert the brass rods (model forepoles) into the clay sample when the model was constructed at 1g (Figure 5). According to the centrifuge scaling law, the brass rods have the bending stiffness equivalent to the steel tubes of 114mm diameter with 8mm wall thickness at prototype.

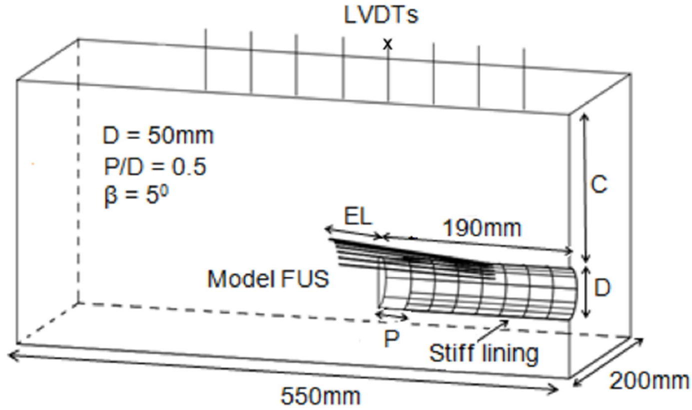


Figure 4. Model test apparatus.

Figure 5. Insertion guide, high precision produced by 3D printing.

The variables C, EL and α used in the tests are summarised in Table 2 and illustrated in Figure 6.

Table 2. Test variables

Test reference					
C/D=3	C/D=1	L (mm)	EL (mm)	S (mm)	α(°)
2BL	8BL	100	25	1.7 – 3.4 (see text)	75
3BL	11BL	100	50	3	90
4BL	10BL	100	25	3	90
5BL	9BL	-	-	-	-

There were no forepoles in the reference tests 5BL and 9BL. In tests incorporating a FUS, the same quantity of fourteen 1mm brass rods were used to model the forepoles. In tests 2BL and 8BL, the distributions of the brass rods were concentrated around the tunnel crown (i.e. the spacing between the eight upper rods was 1.7mm but the six lower rods had a spacing of 3.4mm). In tests 3BL, 4BL, 10BL and 11BL all the rods were evenly spaced at 3mm.

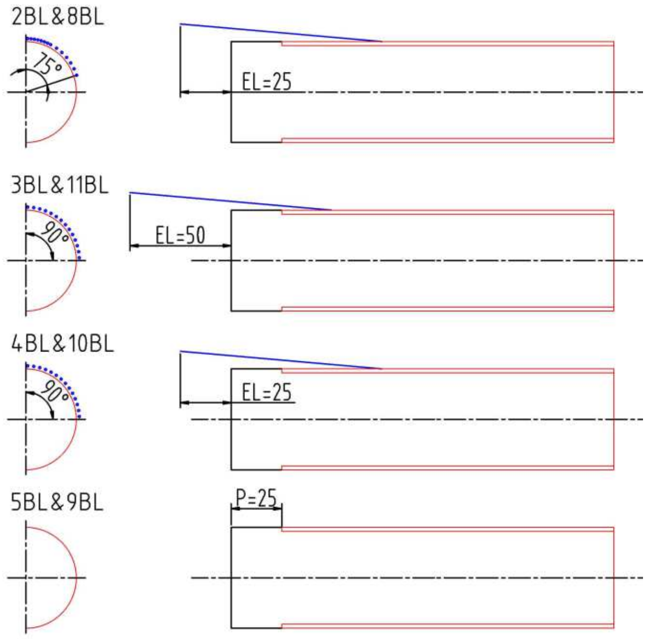


Figure 6. Forepole arrangements in the two series.

3.3 *Test procedure*

The models were accelerated to 125g while simultaneously increasing the tunnel support pressure, σ_T, to balance the overburden stress at the tunnel axis σ_{ob}. It was left running until the excess pore pressure dissipated and the clay had reached effective stress equilibrium. The overburden stress σ_{ob} for C/D=3 and C/D=1 are 360kPa and 155kPa respectively.

After the clay model reached equilibrium, the tests were started by gradually reducing the tunnel support pressure to zero. This technique has been shown to be successful in simulating tunnelling induced ground movements (e.g. Mair 1979).

During the tests, the surface settlements (measured using linear variable differential transformers, LVDTs) and tunnel support pressure were recorded at one-second intervals for later analysis.

4 RESULTS

4.1 *Surface settlement*

Figures 7 and 8 show the vertical surface settlement directly above the tunnel face obtained by an LVDT (marked as x in Figure 4) during the reduction of the tunnel support pressure. It is evident that FUS provide noticeable reduction on the ground surface settlement. The following sections discuss the results in more detail.

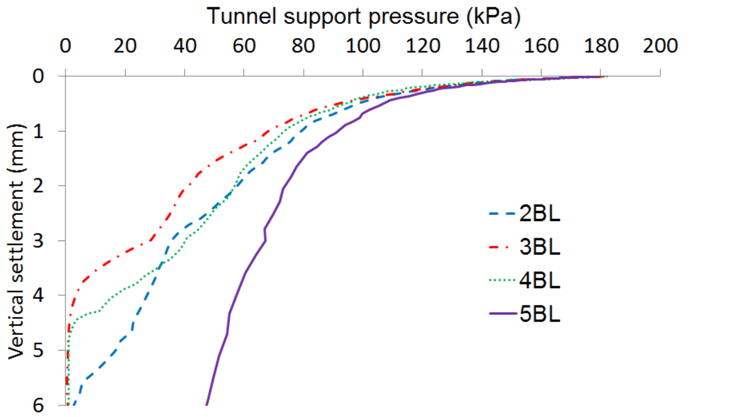


Figure 7 Vertical surface settlement above the tunnel face in series C/D=3.

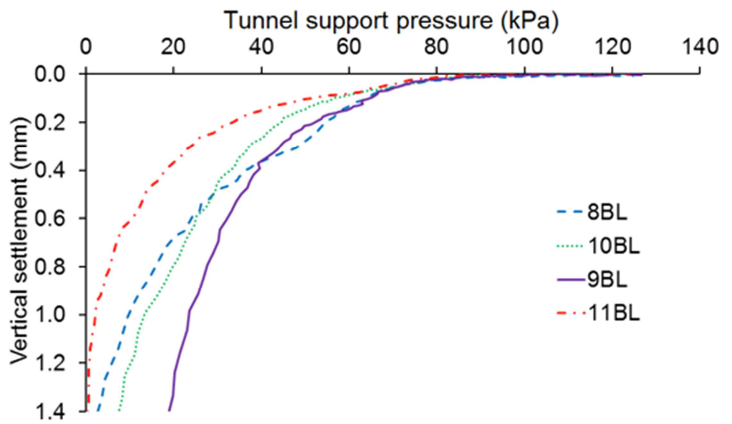


Figure 8 Vertical surface settlement above the tunnel face in series C/D=1.

4.2 *Tunnel stability ratio*

Two parameters are needed for the tunnel stability ratio calculation (Equation 1): the tunnel support pressure at collapse and the undrained shear strength of clay.

The stage at which there is a significant increase in the rate of settlement with reduction in tunnel support pressure is used to define failure and thus the tunnel support pressure at collapse (Mair 1979).

Mair (1979) suggested that most of the elements of clay around and above the tunnel in three-dimensional heading tests experience extension stress paths during the reduction of tunnel support pressure. Therefore, the undrained shear strength of one-dimensionally consolidated kaolin in triaxial extension is deemed the relevant strength for these three-dimensional tunnel heading tests. The relationship between the undrained shear strength and OCR (Mair 1979) was used to calculate the undrained shear strength of clay S_{u1} and S_{u2} in C/D=3 and C/D=1 as below;

$$S_{u1} = 0.18\sigma'_{vo} \quad (2)$$

$$S_{u2} = 0.16\sigma'_{vo} \quad (3)$$

Table 3 presents the stability ratios at collapse, with N_{TC}, calculated using Equation 1 and S_u from the Equations 2 and 3.

Table 3 Tunnel stability ratio at collapse

Series	Test	S_u(kPa)	σ_{TC}(kPa)	N_{TC}
C/D=3	2BL	32	105	8.6
	3BL	32	95	8.9
	4BL	32	102	8.7
	5BL	32	119	8.2
C/D=1	8BL	28	14	5.3
	9BL	28	36	4.5
	10BL	28	27	4.9
	11BL	28	1	5.8

4.3 *Effect of FUS presence*

Table 4 presents the increase in the tunnel stability delivered by the FUS $(N_{TCr}–N_{TC0})/N_{TC0}$x100 ($N_{TCr}$ and N_{TC0} are respectively the tunnel stability ratios at collapse in reinforced and unreinforced tests). The tunnel stability ratio increases from approximately 5-30% moving from deep tunnels to shallow tunnels.

Table 4. Increase in tunnel stability at collapse

Series	Test	Increase in N_{TC} (%)	EL/L	α (°)
C/D=3	2BL	4.9	0.25	75
	3BL	8.5	0.5	90
	4BL	6.1	0.25	90
C/D=1	8BL	17.8	0.25	75
	10BL	8.9	0.25	90
	11BL	28.9	0.5	90

Figure 9 presents the amount of ground settlement reduction delivered by the FUS, $(S_0–S_r)/S_0$x100 (S_r and S_0 are respectively the surface settlements in the reinforced and unreinforced tests at the corresponding tunnel support pressure). For both cover depths, the presence of the FUS reduces the surface settlement by approximately 13%-82% when the tunnel support pressure σ_T is equivalent to 40%-5% of the overburden pressure σ_{ob}. Initially, the overburden pressure was supported by the tunnel support pressure. When the tunnel support pressure reduced, the induced stress difference ($\sigma_{ob} – \sigma_T$) was supported by the surrounding soil and the FUS. As a result, the effects of FUS become more significant when the tunnel support pressure σ_T reduces.

The same consolidation pressure was used for all the tests hence the difference in the reinforcement efficiency of the FUS results from the arrangement of the forepoles and the tunnel depth. The two following sections discuss further details of the effects of EL, α and C.

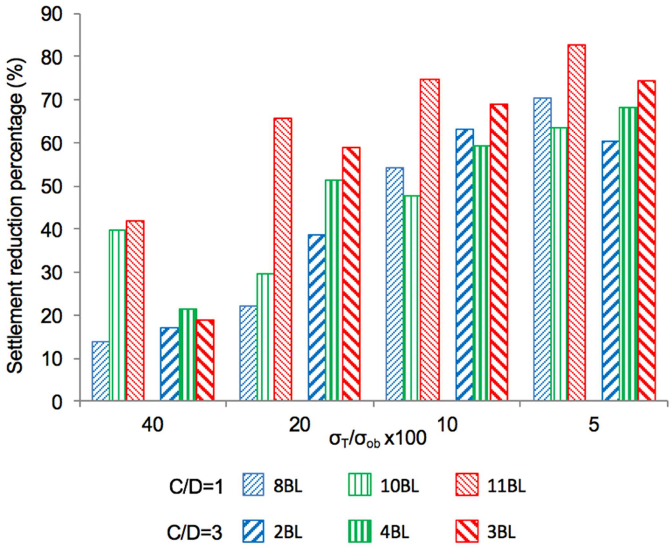


Figure 9. Settlement reduction delivered by FUS.

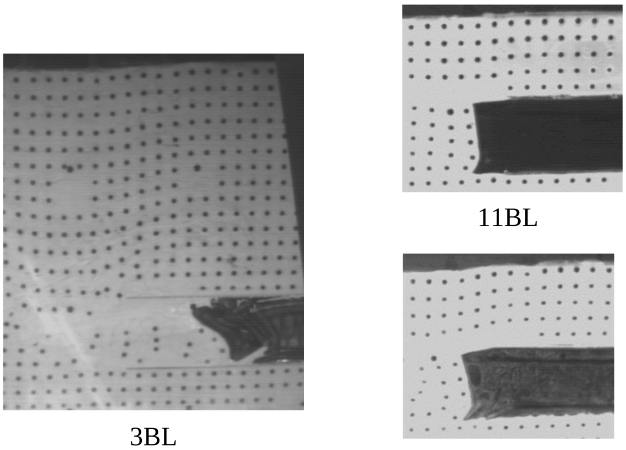
4.4 *The effects of the embedded length EL*

FUS with a longer embedded length EL (Figure 6) have a much better foundation support effect as there is a larger soil area to support the forepoles. As a consequence, the longer EL delivered improved soil reinforcement reflected by the reduction in surface settlement (Figures 7 & 8) and the increase in tunnel stability ratio (Table 4) in both test series. This validates the foundation effect proposed by Volkmann & Schubert (2007) and Carrieri et al. (2002).

4.5 *The effects of the tunnel cover depth C and the filling angle α*

Figure 10 shows typical images of the models for different C/D ratios at the end of the test when the tunnel support pressure was reduced to zero. For deep tunnels (C/D=3, e.g. test 3BL), the clay filled the tunnel lining at the end of all the tests. Similar mechanisms were observed in shallow tunnels in tests 9BL (no reinforcement) and 10BL (even distribution of FUS). However, in test 11BL (longer EL) and 8BL (forepoles distributed more at the crown, α=75°), the clay did not intrude into the tunnel lining. It is evident that the large overburden stress in the deep tunnels exceeded the structural support provided by the FUS. Whereas, in the shallow tunnel tests, the overburden stress is smaller and can be supported by the forepoles. This is also reflected via the increase in tunnel stability ratio delivered by FUS in shallow tunnels (8.9-28.9%) which is more significant than the increase for the deeper tunnels (4.9-8.5%).

In the deep tunnel series, it can be seen that the amount of surface settlement reduction (Figure 9) and increase in tunnel stability (Table 4) due to the FUS in test 4BL (α=90°) was larger when compared with test 2BL (α=75°). It denotes the importance of having sufficient forepoles near the tunnel spring line to reduce the lateral soil movement. However, in shallow tunnel tests, the forepoles arrangement in test 8BL (α=75°) generally has a better reinforcing effect when compared with test 10BL (α=90°). It indicates that for shallow tunnels the presence of forepoles at the crown have a more significant reinforcing effect.



3BL 11BL 8BL

Figure 10. In-flight images at the end of selected model tests when σ_T was 0kPa.

It is necessary to note that the lateral soil displacement was not measured in the centrifuge tests and the above interpretations were made in accordance with the the ground deformation mechanisms proposed by Davis et al. (1980) together with the available measurements. Evidently, having forepoles distributed in the areas where soil is predicted by the plastic collapse mechanism to have major ground movement maximises the reinforcing effectiveness of the FUS.

5 SUMMARY

The results obtained from the centrifuge model tests show the significant reinforcing effects delivered by using a FUS.

The results also highlight the relative effects of the tunnel cover depth and the forepole arrangements to achieve an optimal FUS design. The benefits of having the FUS are reflected in the significant reduction of the ground surface settlements in both deep and shallow tunnels and improvement in tunnel stability ratio in shallow tunnels. In deep tunnel, the increase in the tunnel stability ratio was not as much as in shallow tunnels. Longer embedded lengths (EL) provide improved support efficiency.

The cover-to-diameter ratio was shown to be an important feature that governs the soil mobilisation mechanisms which in turn indicates a beneficial distribution of forepoles. For relatively shallow tunnels, the soil mobilisation mechanism is concentrated at the tunnel crown. Therefore, the presence of forepoles above the tunnel crown is more effective. For deep tunnels, the plastic collapse mechanism extends to the sides of the tunnel and thus forepoles near the tunnel spring line proved to be important in reducing the settlement.

6 ACKNOWLEDGEMENT

The authors are grateful to the colleagues in the Research Centre for Multi-scale Geotechnical Engineering at City University London for their support.

7 REFERENCES

Broms, B.B. & Bennermark, H. 1967. Stability of clay in vertical openings. *J. Soil Mechanics and Foundation Division.* American Society of Civil Engineers **93**, SM1: 71-94.

Carrieri, G., Fiorotto, R., Grasso, P. & Pelizza, S. 2002. Twenty years of experience in the use of the umbrella-arch method of support for tunnelling. *Proc. 4th Int. Workshop on Micropiles*, Venice.

Calvello, M. & Taylor, R.N. 1999. Centrifuge modelling of a spile-reinforced tunnel heading. *Proc. 2nd Int. Symp. Geotechnical Aspects of Underground Construction in Soft Ground*. Tokyo.

Davis, E.H., Gunn, M.J., Mair, R.J & Seneviratne, H.N. 1980. The stability of shallow tunnels and underground openings in cohesive material. *Géotechnique* **30**, No. 4: 397-416.

Juneja, A., Hedge, A., Lee, F.H. & Yeo, C.H. 2010. Centrifuge modelling of tunnel face reinforcement using forepoling. *Tunnelling and Underground Space Technology* **25**: 377-381.

Le, B.T., Divall, S. and Taylor, R.N. (2015). The effect of a forepole umbrella system on the stability of a tunnel face in clay. *16th European Conference on Soil Mechanics and Geotechnical Engineering*, 13 Sep 2015, Edinburgh, Scotland

Mair, R.J. 1979. *Centrifugal modelling of tunnelling construction in soft clay*. PhD Thesis, University of Cambridge

Mair, R.J. & Taylor, R.N. 1997. Theme lecture: Bored tunnelling in the urban environment. *Proc. 14th Int. Conf. Soil Mechanics and Foundation Engineering*, Hamburg. Balkema, Rotterdam.

Taylor, R.N. 1995. *Geotechnical Centrifuge Technology*. Blackie Academic and Professional, Glasgow.

Volkmann, G.M. & W. Schubert 2007. Geotechnical Model for Pipe Roof Supports in Tunneling. In *Proc. of the 33rd ITA-AITES World Tunneling Congress, Underground Space - the 4th Dimension of Metropolises, Volume 1.* Prague, Czech Republic.

Yeo, C.H. 2011. *Stability and collapse mechanisms of unreinforced and forepole-reinforced tunnel headings*. PhD Thesis, National University of Singapore.