

# INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



*This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:*

<https://www.issmge.org/publications/online-library>

*This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.*

# The reinforcing effects of Forepoling Umbrella System in soft soil tunnelling

## Les effets de renforcement du système Forepoling Umbrella dans tunneling sol mou

Binh Thanh Le, R Neil Taylor

Department of Civil Engineering, City, University of London, UK, BinhLe@city.ac.uk

**ABSTRACT:** Tunnelling inevitably induces ground deformations which may lead to damage of nearby infrastructure. A method of reducing tunnelling-induced ground movements for open-faced tunnelling is to use in-tunnel support methods such as the Forepoling Umbrella System (FUS). The FUS comprises steel pipes that provide structural support to the surrounding soil above and around the tunnel heading. A series of three-dimensional centrifuge tests modelling a reinforced tunnel heading were carried out to assess the FUS reinforcing proficiency by varying the arrangement and bending stiffness of the steel pipes at different tunnel depths. The inclusion of a FUS leads to significant reductions in both the magnitude of surface and subsurface ground movements and the overall extent of the deformed area. The tunnel depth was found to be a critical factor in designing optimum Forepoling Umbrella Systems.

**RÉSUMÉ:** Le creusement d'un tunnel induit inévitablement des déformations de terrain qui peuvent donner lieu à des endommagements des infrastructures avoisinantes. Une technique qui permet de réduire les déformations induites par le creusement de tunnel est d'utiliser des techniques de support au sein des tunnels comme la voûte parapluie (Forepoling Umbrella System FUS). La technique de la voûte parapluie utilise des tubes en acier qui fournissent un support structurel aux sols environnants situés au dessus et autour de la tête de tunnel. Une série d'essais tridimensionnels sur centrifugeuse simulant une tête de tunnel renforcé ont été effectués pour évaluer les capacités de renforcement de la technique de voûte parapluie en faisant varier l'agencement des tuyaux d'acier et la profondeur du tunnel. Les résultats montrent des réductions significatives à la fois sur l'ampleur des mouvements de terrain en surface et sous-terre et l'étendue globale de la zone déformée. La profondeur du tunnel a été démontré comme étant un facteur critique dans la conception optimale de la technique de la voûte parapluie.

**KEYWORDS:** centrifuge modelling, tunnel, soil deformations, soil reinforcement.

### 1 INTRODUCTION.

Tunnelling in soft ground inevitably induces ground deformations and is a critical issue relating to the safety of people and nearby structures especially in crowded urban areas with congested underground space. Damage to existing buildings and utilities due to tunnelling-induced ground deformations has been encountered world-wide. Therefore, systems that minimise the ground movements caused by the tunnelling process will be beneficial.

The Forepoling Umbrella System (FUS) has proved to be an efficient soil reinforcement method in open face tunnelling. The system comprises steel pipes installed from the tunnel face to form a roof above the tunnel heading (Figure 1), thereby contributing to decreasing the deformations caused by tunnelling and increasing the tunnel heading stability. One of the noticeable advantages of FUS is the immediate support after installation of the steel pipes (also termed as forepoles) that allows the excavation to be carried out with minimal waiting time.

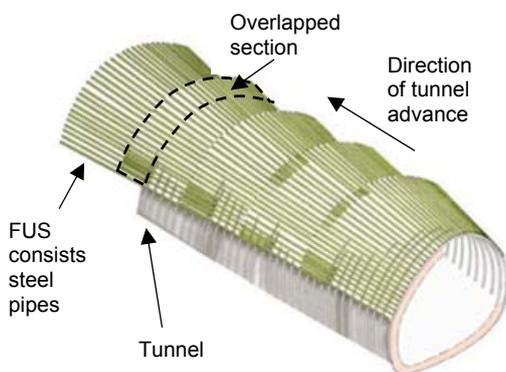


Figure 1. Forepoling Umbrella System (after Carrieri et al., 2002).

The main parameters of a tunnel heading and a Forepoling Umbrella System are illustrated in Figure 2.  $D$  is the tunnel diameter,  $C$  is the cover above the tunnel crown,  $P$  is the unlined portion of the tunnel heading.  $S$  is the centre to centre spacing between the forepoles.  $L$  is the length of the forepoles which are installed from the tunnel face at an insertion angle of  $\beta$ .  $EL$  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 (depicted in Figure 2). A minimum  $EL$  is required to maintain adequate foundation support for the steel pipes.

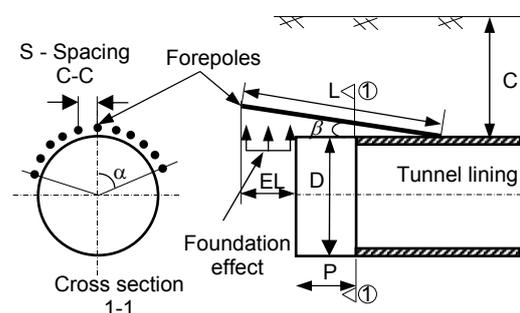


Figure 2. FUS schematic diagram.

Typical dimensions of various parameters used in a FUS in practice are presented in Table 1.

Understanding the soil deformation mechanisms is essential to achieve optimal soil reinforcement design. Upper bound collapse mechanisms proposed by Davis et al., (1980) indicate that for a shallow tunnel, soil movements tend to be concentrated at the crown of the tunnel (roof mechanism). For deeper tunnels, the soil mobilisation involves not only the crown but also the sides and invert of the tunnel.

Table 1. Typical parameters of a FUS.

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

## 2 BACKGROUND

### 2.1 Current understanding in Forepoling Umbrella System

Calvello & Taylor (1999) assessed the performance of a soil reinforcement measure by considering the reduction in soil settlement and increase in tunnel stability. The tunnel stability ratio, N, was defined by Broms & Bennermark (1967) as the difference between the overburden stress at the tunnel axis,  $\sigma_{ob}$ , and the tunnel support pressure  $\sigma_T$  expressed as a ratio of the undrained shear strength  $S_u$  as:

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

where  $\sigma_{ob} = (C + D/2) \gamma$ ,  
 $\gamma$ : unit weight of soil.

Juneja et al., (2010) used centrifuge modelling to investigate the effect of forepoling reinforcement on a tunnel face in clay. Juneja et al., (2010) found that the use of forepoles reduced the extent of the settlement trough ahead of the tunnel face while the width of the settlement trough remained unaffected.

Results from centrifuge tests and an upper bound plasticity analysis conducted by Yeo (2011) suggested a significant improvement in stability of the tunnel heading in clay can be achieved by using long and stiff forepoles. The tunnel model used by Yeo (2011) had  $C/D=1$  and the forepoles were modelled by brass rods. Inspection of the model forepoles post test showed that the top forepoles had large deformation whereas the lower forepoles had negligible deformation. That implied the majority of soil movement occurred at the tunnel crown as a roof deformation mechanism anticipated by Davis et al., (1980).

Volkman & Schubert (2007) reported the site measurement data at a tunnelling project ( $D=11m, C=15m$ ) using FUS. The geological conditions were mainly mudstone, clay stone and sandstone. The results suggested that the tunnel lining and the soil underneath the steel pipes provides foundation effects for the whole FUS system. Therefore, the reinforcing effects of a Forepoling Umbrella System depends not only on the stiffness of the steel pipes but also the strength of the surrounding soil.

Despite the research carried out to investigate the effect of FUS, understanding of the influence of the tunnel depths and the relative effects of the FUS parameters (bending stiffness,  $\alpha, EL$ ) to its reinforcing performance are still limited and form the objectives of this paper. The centrifuge modelling technique is chosen as the research methodology due to its capability in replicating the behaviour of soils (Taylor 1995). With careful selection of dimensions and materials the structural behaviour of steel pipes and their interaction with soil can also be modelled.

## 3 CENTRIFUGE MODELLING TEST SERIES

### 3.1 Centrifuge model tests

Ten centrifuge tests have been conducted to investigate the FUS effect at two different tunnel cover depths  $C/D=1$  and  $C/D=3$ . A typical model test apparatus is described in Figure 3. The

variables including  $C/D$ , forepoles arrangement and bending stiffness are presented in Table 2 and illustrated in Figure 4. In the reinforced tests, the forepoles were modelled by fourteen 1mm rods (brass or steel).

By modelling half of the tunnel, the surface and subsurface ground deformations could be observed and measured during the tests. 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  $\beta$  in all the tests were 25mm and  $5^\circ$  respectively. The tunnel cavity was supported by a compressed air pressure contained in a latex membrane lining the tunnel. The air pressure was controlled to balance the total overburden stress at the tunnel axis level. The overburden stress  $\sigma_{ob}$  for  $C/D=3$  and  $C/D=1$  tests were 360kPa and 155kPa respectively. A pressure transducer was installed at the end of the latex membrane to monitor the tunnel support pressure.

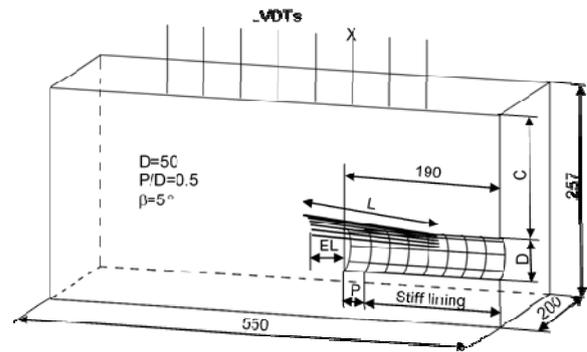


Figure 3. Centrifuge test diagram (for  $C/D=3$ )

Table 2. Test variables

Test reference					
$C/D=3$	$C/D=1$	L (mm)	EL (mm)	S (mm)	$\alpha$ (°)
2BL	8BL	100	25	1.7 – 3.4	75
				(Fig. 4)	
3BL	11BL	100	50	3	90
12BL*					
4BL	10BL	100	25	3	90
	13BL*				
5BL**	9BL**	-	-	-	-

\* Tests 12BL and 13BL used steel rods for model forepoles. \*\*5BL & 9BL are reference tests (no FUS). Other reinforced tests used brass rods.

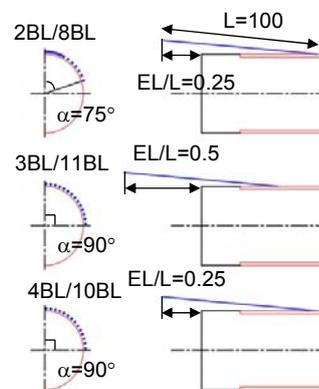


Figure 4. Forepoles arrangements in centrifuge tests

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

A guide, produced by precision 3D printing, was used to insert the model forepoles into the clay sample when the model was constructed at 1g during the model preparation (Figure 5).



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

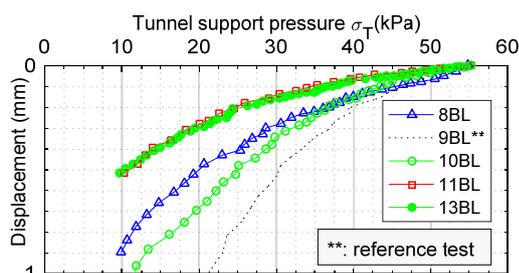
### 3.2 Centrifuge model tests

The models were accelerated to 125g while simultaneously increasing the tunnel support pressure,  $\sigma_T$ , to balance the overburden stress at the tunnel axis  $\sigma_{ob}$ . It was left running until the excess pore pressure dissipated and the clay had reached effective stress equilibrium. After the clay model reached equilibrium, the tests were started by gradually reducing the tunnel support pressure to zero to simulate the excavation process. During the tests, the surface and subsurface soil displacement and tunnel support pressure were recorded at one-second intervals for later analysis.

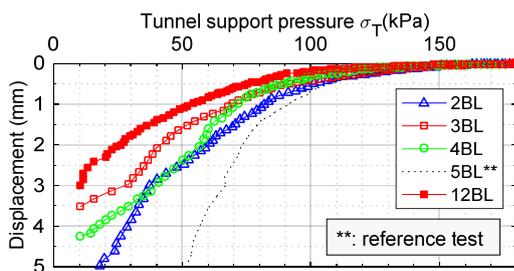
## 4 CENTRIFUGE TEST RESULTS

### 4.1 Soil displacements

Maximum surface settlement is of great concern because it indicates the potential damage to the building. Figure 6 illustrates the maximum surface settlement above the tunnel heading obtained from LVDT (marked x in Figure 3, which lies above the mid-point of the heading). For clarity, only the significant settlements at the latter stage of the tests are presented rather than from the very start of tunnel pressure reduction.



a) C/D=1 tests



b) C/D=3 tests

Figure 6. Surface settlement above the tunnel face in centrifuge tests.

Figure 7 presents the amount of ground settlement reduction delivered by the FUS,  $(S_0 - S_r)/S_0 \times 100\%$  ( $S_r$  and  $S_0$  are respectively the surface settlements in the reinforced and unreinforced tests at the corresponding tunnel support pressure). The presence of the FUS reduces the surface settlement by approximately 5%-85% at different tunnel support pressure. Increase in the bending stiffness of the steel pipe by 80% (steel compared with brass) only yielded an improvement in settlement reduction of an average of 25% for the same arrangement of forepole (13BL compared with 10BL, 12BL compared with 3BL). This implies the reinforcement effect of the FUS also depends on the strength of the surrounding soil.

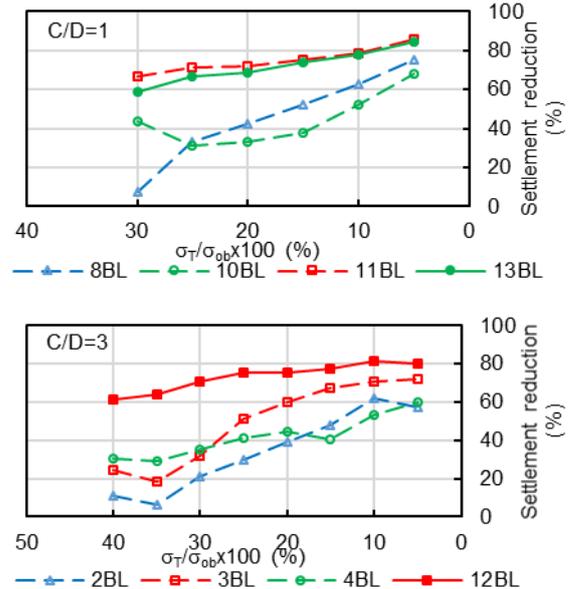
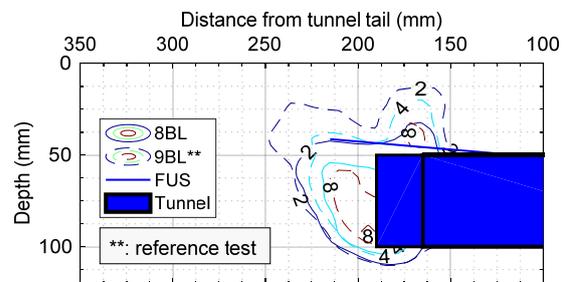
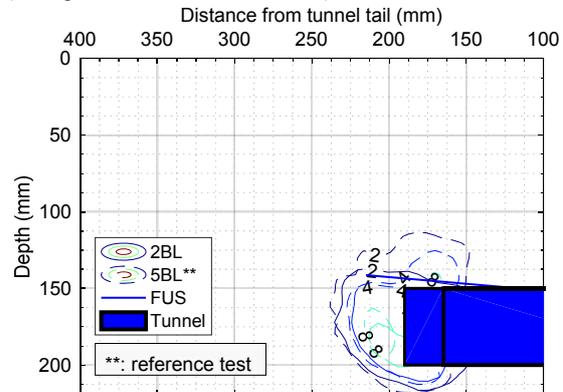


Figure 7. Settlement reduction offered by FUS.

### 4.2 Subsurface soil deformations



a) Comparison between 8BL & 9BL ( $\sigma_T$  reduced from 55 to 20kPa)



a) Comparison between 2BL & 5BL ( $\sigma_T$  reduced from 180 to 126kPa)

Figure 8. Engineering shear strain developed in the ground.

The subsurface soil deformations obtained from image analysis showed that the areas that benefit the most from the FUS are above the tunnel heading where the model rods were installed to reinforce the surrounding soil. In contrast in the areas that are far from the tunnel face or below the FUS, the effect of the FUS is less pronounced. The effect of Forepoling Umbrella System on the extent and magnitude of engineering shear strains is illustrated in Figure 8. Large engineering shear strains (> 8%) developed near the tunnel invert and tunnel heading near the stiff lining edge in the reference tests with no forepoles. However, in tests with the FUS, large shear strains only occurred near the invert of the tunnel and not at the tunnel heading where model rods were present.

#### 4.2 Tunnel stability ratio

The tunnel support pressure at collapse and the undrained shear strength of clay are used to calculate the tunnel stability at failure. 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).

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 (Mair 1979). The relationship between the undrained shear strength and OCR (Mair 1979) was used to calculate the following undrained shear strengths of clay  $S_{u1}$  and  $S_{u2}$  for tests with  $C/D=3$  and  $C/D=1$ ;

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

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

Table 3 presents the tunnel support pressure at collapse, with  $N_{TC}$ , calculated using Equation 1 and  $S_{u1}=31.5\text{kPa}$  and  $S_{u2}=28\text{kPa}$  from the Equations 2 and 3. The increase in the tunnel stability delivered by the FUS  $(N_{TC}-N_{TC0})/N_{TC0}\times 100\%$  are also tabulated ( $N_{TC}$  and  $N_{TC0}$  are respectively the tunnel stability ratios at collapse in reinforced and unreinforced tests).

Table 3 Tunnel stability ratio at collapse

Series	Test	EL/L	$\alpha$ (°)	$\sigma_{TC}$ (kPa)	$N_{TC}$	Increase in $N_{TC}$ (%)
C/D=3	2BL	0.25	75	112	7.9	6.0
	3BL	0.5	90	98	8.3	12.0
	4BL	0.25	90	107	8.0	8.1
	5BL	-	-	126	7.4	-
	12BL	0.5	90	87	8.7	16.7
C/D=1	8BL	0.25	75	15	5.0	13.8
	9BL	-	-	32	4.4	-
	10BL	0.25	90	22	4.8	8.1
	11BL	0.5	90	6	5.3	21.1
	13BL	0.25	90	10	5.2	17.9

## 5 DISCUSSION

Significant reinforcing effects delivered by using a FUS were observed from centrifuge tests (Figures 6, 7, 8). Initially, the overburden pressure was supported by tunnel support pressure  $\sigma_T$ . When  $\sigma_T$  reduced, the induced stress difference ( $\sigma_{ob} - \sigma_T$ ) was supported by the surrounding soil and the FUS. Thus, the effects of FUS became more significant when the tunnel support pressure  $\sigma_T$  reduced.

A longer embedded length (EL) provides improved support efficiency because the forepoles benefited from the greater foundation effects provided by the surrounding ground (tests 3BL and 11BL in Figures 4, 6, 7). The increase in the forepoles stiffness also improved the reinforcement effect of the FUS (tests 12BL and 13BL).

The tunnel depth was shown to be an important factor that dictates the soil mobilisation mechanisms (Davis et al., 1980) which in turn indicates a beneficial forepole arrangement. 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 soil mobilisation involves the areas at the tunnel crown and the tunnel spring line. Thus, having forepoles near the tunnel spring line is beneficial to the reinforcement effect of the FUS.

For deeper tunnels, the increase in the tunnel stability ratio was not as much as for shallow tunnels (Table 3). This can be explained by the overburden pressure in  $C/D=1$  test which was relatively small and can be supported by the structural capacity of the FUS. For the deep tunnels  $C/D=3$ , this overburden stress was much larger than it in  $C/D=1$  tests and exceeded the support capacity of the FUS hence the smaller increase in the tunnel stability. The implication is that for tunnels in clay, the strength and stiffness of forepoles may need to be increased for deep tunnels.

## 6 ACKNOWLEDGEMENT

The first author acknowledges the Vietnam government for funding his doctoral scholarship. The authors are grateful to the colleagues in the Research Centre for Multi-scale Geotechnical Engineering at City, University of 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 pile-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.
- 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.
- Volkman, 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.