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Ground response to tunnelling incorporating a soil reinforcement system

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Abstract

The Forepole Umbrella System (FUS) uses steel pipes installed from within a tunnel to provide a canopy above the tunnel heading that both increases stability and reduces tunnelling-induced ground movements. Although the system is known to be beneficial and has been used in a number of projects, there is little information on how key parameters including length and forepole stiffness combine to produce effective support. To investigate this, centrifuge tests incorporating the three-dimensional geometry of a tunnel heading in clay and the model FUS have been undertaken. The tunnel heading was supported by a pressurised rubber bag lining with excavation being simulated by a reduction in air support pressure. Image analysis was used to obtain subsurface ground movements and a newly developed 3D imaging system was used to measure accurately the soil surface deformations. The performance of the FUS and the influences of key FUS parameters were quantified via the settlement reduction factor. The results showed that the FUS, arranged in various settings, reduced the maximum surface settlement by 35-75%. The effects of the FUS parameters to the reinforcing effectiveness is dependent on the ratio of cover depth to tunnel diameter. An optimum design arrangement of the FUS is suggested.

*Keywords: Centrifuge modelling; Ground improvement; Tunnels & tunnelling;*
LIST OF SYMBOLS

3D three-dimensional
3DIS three-dimensional imaging system
C cover depth above tunnel
D tunnel diameter
E Young's modulus of model forepoles
FUS Forepoling Umbrella System
g acceleration due to gravity (9.81m/s²)
P unlined portion of tunnel heading
PIV Particle Image Velocity
SRF settlement reduction factor
u horizontal displacement in X direction
v horizontal displacement in Y direction
w vertical displacement in Z direction
z depth from soil surface
α filling angle
σT tunnel support pressure
σob overburden stress at tunnel centreline
σ′v0 consolidation pressure
INTRODUCTION

The reinforcing effectiveness of a Forepoling Umbrella System (FUS) on soil deformations due to open-face tunnelling in clay can be investigated using physical modelling techniques. A FUS consists of steel pipes (forepoles) installed in a canopy shape ahead of an advancing tunnel (Fig. 1) to provide structural support to the surrounding soil. As an in-tunnel measure, one of the noticeable advantages of the FUS is the immediate support from the steel pipes to reduce soil deformations at their source.

Fig. 2 illustrates a schematic diagram of a FUS and defines the main parameters of the system and a tunnel heading. The steel pipes with length $L$ are normally inserted into the ground from within the tunnel at an insertion angle $\beta$. The steel pipes are arranged along the perimeter of the upper part of the tunnel in a filling angle $\alpha$. The tunnel lining and the soil beneath the embedded length, $EL$, both act like foundations to support the steel pipes that bridge over the unlined tunnel heading $P$. The embedded length is supported by the so-called foundation effect ahead of the tunnel face as illustrated in Fig. 2. The foundation effect depends on the stiffness of tunnel lining and the undrained shear strength of soil beneath the forepoles. Case histories have demonstrated that FUS are suitable for use in a variety of ground conditions that can provide a sufficiently competent foundation effect for the forepoles such as clay (Gall and Zeidler 2008), mixed soil comprising boulders in hard sandy silt or sandy silty clay matrix (Yeo et al. 2009), claystone, mudstone and sandstone (Volkmann and Schubert 2007; Aksoy and Onargan 2010), low to medium plasticity silty clay (Wang et al. 2018), rocks (Oke 2016), sandstone–siltstone–claystone–shale sequences, gravel–sand–silt, clay-marl, limestone with shale (Ocak 2008).

The common parameters of a FUS in practice are presented in Table 1 (Volkmann and Schubert 2007). Note that in this paper, the normalised tunnel depth is represented by the dimensionless cover to diameter ratio $C/D$.

The FUS has been shown to be an efficient measure to control soil deformations due to open face tunnelling and has been used in a number of major projects such as the Victoria Station Upgrade and King’s Cross Station Redevelopment in the UK (Gall and Zeidler 2008), the Harbin
Metro Line #1 in China (Wang et al. 2018), the Istanbul Metro in Turkey (Ocak 2008), and the Fort Canning Tunnel in Singapore (Yeo et al. 2009). Field measurements and numerical analysis reported Oke (2016) showed that the Forepole Umbrella System, when used in conjunction with other soil reinforcement measures (including face bolts and soil nails), provided a reduction of approximately 20-76% surface settlement compared with the unreinforced sections. Similar to the observations made by Oke (2016), Ocak (2008) reported that the combination of several soil reinforcement measures, umbrella arch and soil nailing, reduced the magnitude of surface settlement by three compared with that in the section without soil reinforcement. However, because of the interaction of the various reinforcing techniques used, it is not possible to identify the exact contribution made by the Forepoling Umbrella System in reducing ground movements.

Although previous research has reported on the effects of the FUS, there are still limitations in understanding the influence of the FUS parameters, including forepole stiffness, EL, and $\alpha$, on the reinforcement effectiveness of the system.

Vrba and Barták (2007) used centrifuge modelling to study the effects of a FUS for a tunnel at a normalised depth $C/D=3$. In their experiments, steel plates were used to model the forepoling roof which reinforced the tunnel heading in clay. They observed significant reduction in soil settlement was provided by using the FUS. Divall et al. (2016) conducted centrifuge tests simulating a tunnel in clay incorporating a FUS in which the forepoles were modelled by resin. The normalised tunnel depth was $C/D=2$. Similar to the observations made by Vrba and Barták (2007), Divall et al. (2016) showed that the use of the FUS increased the stability of the tunnel heading and decreased the magnitude of soil settlement. It should be noted that in each research project, the material and geometry of the model forepoles was not varied. The effect of the forepole stiffness was therefore not investigated.

Volkmann and Schubert (2007) reported field measurements obtained from an inclinometer chain located on the topmost steel pipe of the FUS in the Trojane tunnel (Slovenia). The site geology consisted of faulted mudstone, claystone and sandstone (Volkmann et al. 2006). The
normalised tunnel depth was C/D=1.5. The measurement data showed that when the
embedded length $EL$ decreased, as the tunnel face advanced, the magnitude of steel pipe
deformation increased. The reason was that when $EL$ reduced, the foundation effect from the
ground beneath the FUS decreased which led to large deformation of the forepoles. This
confirmed similar findings derived from centrifuge tests reported by Vrba and Barták (2007) and
Yeo (2011).

The variations in the insertion angle, $\beta$, only caused slight differences in soil settlement as noted
by Eclaircy-Caudon et al. (2006) and hence $\beta$ is not considered as a key parameter of the FUS
and will not be investigated in this study. The effect of the filling angle $\alpha$ was investigated in a
series of plane strain centrifuge tests conducted by Divall et al. (2016). By adopting a 2D
modelling approach, this work was able to determine the effect of $\alpha$ independently from the
unsupported length $P$ and the embedded length $EL$. The test results showed that having the
forepoles distributed down to the tunnel springline or even lower can be beneficial for reducing
soil deformations and increasing tunnel stability. They concluded that tunnel stability was
improved by positioning reinforcement to prevent the development of the plastic collapse
mechanisms proposed by Davis et al. (1980).

Davis et al. (1980) suggested that C/D governs soil deformation mechanisms. Therefore, the
reinforcement effectiveness of the FUS in reducing soil movements is expected to vary at
different C/D. Thus, the influence of C/D on the effect of the FUS is an important factor that
needs to be investigated.

THE CENTRIFUGE TESTS

Test series

The centrifuge test variables, including C/D, material of the model forepole, $EL$ and $\alpha$, were
chosen so as to obtain a clearer insight into an optimal design of the FUS.

The normalised depths of C/D=1 and C/D=3 were chosen because these two are likely to result
in substantial differences in the soil deformation mechanism (Davis et al. 1979) which is an
important factor that influences the reinforcement effectiveness of the FUS (Le and Taylor 2017).

In practice, typical filling angle ranges from $\alpha=60^\circ$ to $\alpha=75^\circ$. Yeo (2011) and Le (2017) showed that even in a shallow tunnel (C/D=1), there were noticeable soil displacements above the tunnel spring line. Therefore, in the model tests, a filling angle smaller than $75^\circ$ was not chosen and instead $\alpha=75^\circ$ and $\alpha=90^\circ$ are used to assess the effect of the filling angle.

Fig. 3 presents the variables of the centrifuge experiments that comprise reference tests (no FUS) and tests incorporating a FUS. The identities indicate the variables as explained below:

- CD1 or CD3 denotes the normalised depth of the tunnel C/D=1 or C/D=3;
- R or F denotes reference test (no forepoles) or test incorporating a FUS;
- B or S denotes the model forepole material, brass or steel;
- EL0.5 or EL1 denotes the embedded length EL/D=0.5 or EL/D=1.
- A75 or A90 denotes the value of filling angle $\alpha=75^\circ$ or $\alpha=90^\circ$;
- N denotes that soil deformations were measured using the new 3D imaging system (Le et al. 2016).

All tests were conducted using the apparatus and procedures outlined below.

Test apparatus

A schematic of the centrifuge model is illustrated in Fig. 4. The model clay (Speswhite kaolin) was one dimensionally consolidated in a model container (strong box) using a hydraulic consolidometer to a vertical effective stress $\sigma'_v=175kPa$. The consolidation pressure $\sigma'_v=175kPa$ was chosen as it provided a soft clay model in which the soil deformations, induced by the simulated tunnel excavation, would be sufficiently large so that the reinforcement effects of the FUS would be observed clearly. The properties of Speswhite kaolin are presented in Table 2 (Le 2017)

The tunnel was simulated by a semi-circular cavity cut into the clay model (Fig. 4). By doing so, soil deformations on the vertical plane of symmetry of the tunnel heading could be observed
through the front perspex window. The total length of the tunnel cavity was 190mm. This was partially supported by a 165mm long tunnel lining made from a 50mm diameter 1.6mm thick semi-circular stainless steel tube. The unlined heading of length \( P = 25 \)mm was supported by a thin rubber bag supplied with compressed air pressure. The technique of using a pressurised air bag has been proved to be a successful method capable for simulating tunnel excavation in centrifuge models and the soil movements in 3D models were found to be consistent with those obtained from field measurements (Meguid et al. 2008; Le and Taylor 2018).

For each reinforced test, a total of fourteen 1mm diameter rods (brass or steel) were used to model the forepoles. The length of the rods, \( L \), was 100mm. The model forepoles were inserted around the tunnel heading via a guide produced by precision 3D printing (Fig 5).

All the tests were conducted at 125g. Applying the normal centrifuge scaling laws to the model then gives the prototype scenario described in Table 3. The 1mm diameter brass (or steel) rods under 125g have an equivalent bending stiffness as steel pipes of 135mm (or 165mm) outer diameter with an 8mm wall thickness at prototype scale (Le 2017). These sizes of forepoles are common in practice (Table 1).

**Instrumentation**

In most of the tests, surface settlement was measured by a row of displacement transducers using the principles of a Linear Variable Differential Transformer (LVDT), placed along the tunnel centreline, and the Visimet software (Grant 1998) was used to measure soil displacements at the front face of the model from images captured from the front facing camera shown in Fig. 4. In the tests CD3-R-N, CD3-F-S-EL0.5-A90-N, and CD3-F-S-EL0.5-A75-N the new 3D imaging system (Le et al. 2016) was used to measure 3D soil displacements at the model surface while GeoPIV_RG (Stanier et al. 2015) was used to measure subsurface soil movements at the front face of the model from the camera images.
The precision of 3DIS (Le et al. 2016) was shown to be within 50μm. Grant (1998) reported that the precision of Visimet was in range of 70-80μm. GeoPIV_RG was reported to have comparable measurement precision with the LVDTs (Stanier et al. 2015).

The high measurement precision offered by the imaging techniques mentioned above indicates that there is a small inherent component of friction at the interface between the Perspex window and the soil model that may affect the soil deformation mechanism. However, consistent with previous authors (Grant 1998; Divall 2013; and Le 2017) it was found that once the soil at the interface moved after overcoming the friction, it continued to displace at the same rate as the rest of the model. In addition, considerable effort was made during the model preparation to minimise the effects of this friction by using both a consistent volume of grease at the Perspex window and volume of texture material placed at the front face of the soil models (Le 2017). As a consequence, the friction at the interface was minimised and had negligible effects on the development of soil displacements in the centrifuge tests. Therefore, the displacement measurement systems used in this research are able to quantify the effects of the FUS parameters.

Two Pore Pressure Transducers (PPTs) model PDCR81 supplied by Druck Limited, Leicester, were installed within the soil model to measure the changes in pore pressure. The purpose of the transducers was to indicate when pore pressure equilibrium had been achieved in the model during centrifuge flight. These PPTs were positioned far away from the tunnel heading to minimise any effects on soil deformations induced by the simulated excavation. The air support pressure in the tunnel bag at the tunnel axis level was measured by a pressure transducer model PX600-200GV series supplied by Omega Engineering Ltd.

**Test procedure**

The models were accelerated to 125g while simultaneously increasing the air pressure inside the tunnel bag, \( \sigma_T \), to support the overburden stress at the corresponding centrifuge acceleration. The centrifuge was left running until the excess pore pressure dissipated and the clay had reached effective stress equilibrium. The tunnel excavation process was then
simulated by gradually reducing the tunnel support pressure $\sigma_T$ to zero. Data relating to the tunnel support pressure $\sigma_T$, LVDT readings and deformations of the clay model were recorded at 1 second intervals for later analysis.

From the in-flight images, it was noticed that the tunnel lining deflected when the tunnel support pressure reduced to 55kPa and 180kPa in tests with tunnel having C/D=1 and C/D=3, respectively. This was owing to the lack of hoop stiffness of the tunnel lining. The initial $\sigma_T$ was chosen to support the overburden stress near the tunnel centre-line which meant the upper part of the tunnel was over pressurised. When the tunnel pressure was increased the lining initially elongated on its vertical diameter. When the support pressure was reduced, the lining sprang back elastically to its normal shape which caused the ground above the tunnel lining to settle (Le 2017). Therefore, in order to study the effect of FUS on the ground deformations independently from deflection of the stiff lining, the results will be examined as the tunnel support pressure is reduced from $\sigma_T$=55kPa for C/D=1 tests and $\sigma_T$=180kPa for C/D=3.

RESULTS

Some of the results in this research have been reported by Le et al. (2015), Le and Taylor (2016), and Le and Taylor (2017). This section further analyses the test results to provide a clearer and broader insight on the relative effects of the FUS parameters to its reinforcing effectiveness.

The effect of using the FUS

Fig. 6 compares typical subsurface soil deformations and engineering shear strains, when $\sigma_T$ was reduced to 80kPa, in the reference test CD3-R-N (dashed lines) and the reinforced test CD3-F-S-EL0.5-A75-N (solid lines) to examine the effect of using the FUS. The pressure $\sigma_T$=80kPa was chosen because at this pressure soil deformations were large enough so that the effects of the FUS can be observed clearly.

Using a FUS led to a reduction in both magnitude and extent of the soil displacements and shear strains (Fig. 6). In the reference test, large engineering shear strains (>4%) developed at both the tunnel crown and invert. In contrast, in the test with the FUS, large shear strains did not
occur near the tunnel crown in the vicinity of the FUS. The reduction in soil movements near the
tunnel heading, delivered by the FUS, led to a reduction in ground movements in all directions
at all points at the entire top surface of the model (Fig. 7).

The maximum surface settlement is of great interest as it indicates the potential damage to near
surface structures. Fig. 8 compares the maximum surface settlement above the tunnel face in
the centrifuge tests and highlights the significant reduction in settlement delivered by the FUS.

In order to quantify the reinforcing effectiveness of the FUS, the settlement reduction factor
(SRF) defined by Equation 1 is presented in Fig. 9;

\[
SRF = \left[ \frac{(w_0 - w_r)}{w_0} \right] \times 100\%
\]  

where \( w_0, w_r \) are respectively the maximum surface settlement in the reference and reinforced
test with the same geometry and having the same tunnel support pressure;

The SRF is the settlement reduction factor (%), based on a comparison of the maximum
surface settlement in the reinforced and reference tests.

It can be seen that the SRF increased when \( \sigma_T \) decreased (Fig. 9). This is because initially the
overburden pressure, \( \sigma_{ob} \), was supported by the tunnel support pressure \( \sigma_T \). As \( \sigma_T \) was reduced,
so the stress difference (\( \sigma_{ob} - \sigma_T \)) was supported by the surrounding soil and the FUS. Thus, the
SRF became higher as the stress difference (\( \sigma_{ob} - \sigma_T \)) increased as a result of the reduction of
tunnel support pressure \( \sigma_T \). The average values of SRF, at different \( \sigma_T \) determined from Fig. 9,
are tabulated in Table 4 and will be used to examine the reinforcing effectiveness of the FUS for
different arrangements. The average values were used so as to be representative for the entire
test.

RELATIVE INFLUENCE OF THE FUS PARAMETERS

The same pre-consolidation pressure was used for the clay models and hence all the models
had similar strength and stiffness characteristics. Therefore, any significant differences in the
reinforcement effectiveness of the FUS were the result of the variation of the arrangement
including $EL/D$, $\alpha$, material of the forepoles and C/D ratios which are discussed in detail in the following sections.

**Effect of $EL/D$ with different $C/D$**

The influence of $EL/D$ on the SRF of the FUS is tabulated in Table 5. Generally, increasing the embedded length offered a greater foundation effect to the FUS which resulted in a greater SRF. It is worth noting that besides $EL/D$, there are other differences between the tests in this section including the starting point of the FUS and the radial distance from the modelled forepoles to the tunnel lining. However, the effects of these differences are negligible because the performance of the FUS is mainly dependent on the foundation effects provided by the two components: the tunnel lining, which is the same for all the tests; and the surrounding soil, which is dictated by $EL/D$. Therefore, it can be argued that the differences in the soil deformations observed in these tests were mainly due to the variation of $EL/D$.

The difference in the foundation effect between $EL/D=0.5$ and $EL/D=1$ to the FUS was reflected in the corresponding deformation of the forepoles as shown in Fig. 10. The model rods for the $EL/D=0.5$ test showed one inflexion point implying that the foundation effect was negligible and that the forepoles worked mainly as a cantilever. In contrast, the rods for $EL/D=1$ test showed two inflexion points denoting that the foundation effect was greater and the forepoles worked like beams supported at both ends and this offered a better supporting effect.

For the C/D=3 tunnels, increasing $EL/D$ by 100% (from $EL/D=0.5$ to $EL/D=1$) gave a 10% increase in SRF (CD3-F-B-EL0.5-A90 vs CD3-F-B-EL1-A90; CD3-F-S-EL0.5-A90 vs CD3-F-S-EL1-A90, see Table 5). Interestingly, for the C/D=1 tunnels (CD1-F-B-EL0.5-A90 vs CD1-F-B-EL1-A90), the same increase in $EL/D$ gave an increase of 29% in SRF which is approximately 3 times larger than that for the C/D=3 tunnels. This significant difference in the influence of $EL/D$ to the reinforcing effectiveness of the FUS for the two normalised tunnel depths suggests that the quality of the foundation effect provided by the soil beneath the FUS was different.
Figs. 11a and 11b present photographs of the reference tests having $C/D=1$ and $C/D=3$ respectively. The failure planes observed in these tests are highlighted by dashed lines. The pictures are further annotated with the outline of a potential upper bound failure mechanism suggested by Davis et al. (1980). The angles in the failure mechanism are given by:

$$\tan \theta_1 = \tan \theta_2 = \frac{1}{2 \sqrt{C/D + 1/4}}$$

$$\theta_3 = \frac{\pi}{2}$$

($\theta_1$, $\theta_2$ and $\theta_3$ are annotated in Fig. 11)

It can be seen that the upper bound mechanisms over predict the extent of the collapse zones for both tests which may reflect the fact that the upper bound mechanism is for a plane strain tunnel (long wall mining) rather than the 3D circular tunnel heading in the centrifuge tests. By way of illustration, the locations of forepoles in a FUS having $EL/D=1$ are superimposed on Fig. 11. This demonstrates that for $EL/D=1$, the forepoles in a $C/D=1$ tunnel extend beyond the shear plane (and plastic collapse mechanism) which then offers a better foundation effect compared with that for a $C/D=3$ tunnel where the forepoles would be inside the shearing plane.

This better foundation effect may explain the higher SRF of the FUS in the shallow tunnel tests.

These observations provide a clearer insight into the effect of the embedded length $EL$ to the foundation effect and the reinforcing effectiveness of the FUS. The foundation effects depend not only on $EL$ but also on the magnitude and extent of the soil deformations beneath the FUS. The implication is that the forepoles should extend beyond the expected plastic collapse mechanism which can be estimated by the simple upper bound solutions of Davis et al. (1980).

The effect of the filling angle $\alpha$ for different $C/D$

It is worth noting that, in this study, varying the filling angle $\alpha$ alters the spacing $S$ between the forepoles as the quantity of the forepoles in the reinforced tests is constant. The test results presented later in this section highlighted that at different $C/D$ ratios, the SRF delivered by the FUS heavily depends on the coverage of the forepoles in the transverse direction which is dictated by $\alpha$. Therefore, the filling angle is chosen as the key parameter for consideration, not the spacing $S$. 
Table 6 presents the SRF of the FUS for two filling angles $\alpha=75^\circ$ and $\alpha=90^\circ$ at two different normalised tunnel depths $C/D=1$ and $C/D=3$. The filling angle $\alpha=75^\circ$ outperformed $\alpha=90^\circ$ for tests with $C/D=1$ (CD1-F-B-EL0.5-A75 vs CD1-F-B-EL0.5-A90) but not for tests with $C/D=3$ (CD3-F-B-EL0.5-A75 vs CD3-F-B-EL0.5-A90; CD3-F-S-EL0.5-A75 vs CD3-F-S-EL0.5-A90).

A photograph of the tunnel heading post-test with the deformed forepoles in test CD1-F-B-EL0.5-A90 ($C/D=1$) is presented in Fig. 12-a. The upper rods had large deformations while the deformations of the lower rods were negligible. This suggests that large soil movements occurred mainly in the vicinity of the tunnel crown while near the tunnel spring line the soil displacement was small. This agrees with the collapse mechanism A suggested by Davis et al. (1980) for a shallow tunnel (Fig. 12-b). Therefore, concentrating forepoles near the tunnel crown by arranging the same quantity of forepoles within a filling angle of $\alpha=75^\circ$ outperformed $\alpha=90^\circ$ by $\approx 10\%$ in terms of SRF (Table 6).

For the $C/D=3$ tunnel (test CD3-F-B-EL0.5-A90), Fig. 13-a shows large deformations in both the upper and lower forepoles which implies that large soil displacements occurred at both the tunnel crown and near the tunnel spring line. This is relevant to the tunnel collapse mechanism D suggested by Davis et al. (1980) for a tunnel with larger $C/D$ (Fig. 13-b). Hence, arranging the same quantity of forepoles in $\alpha=90^\circ$, instead of $\alpha=75^\circ$, provided more forepoles near the tunnel spring line, where large lateral soil displacements occurred, and this resulted in a better SRF.

The effect of the forepole stiffness

Generally, for the same arrangement of forepoles, an increase in the forepole stiffness led to a higher SRF as shown in Table 7.

The increase in SRF offered by increasing the forepole stiffness (brass to steel) for $C/D=1$ tunnel was $\approx 30\%$ ($\alpha=75^\circ$) which is more significant than that for the $C/D=3$ tunnels which showed increases of approximately 10% and 20% for $\alpha=75^\circ$ and $\alpha=90^\circ$ respectively.
Interestingly, for \( C/D = 3 \) tests increasing the forepoles stiffness yielded different improved \( SRF \) for different filling angles \( \alpha \). In tests with forepoles arranged at \( \alpha = 90^\circ \) ([CD3-F-B-EL1-A90 vs CD3-F-S-EL1-A90]; [CD3-F-B-EL0.5-A90 vs CD3-F-S-EL0.5-A90-N]), the stiffness increase delivered an increase of approximately 20% in \( SRF \) (Table 7). This is about two times larger than the 10% increase in \( SRF \) for tests with \( \alpha = 75^\circ \) (CD3-F-B-EL0.5-A75 vs CD3-F-S-EL0.5-A75-N) (Table 7) which suggests that the benefit of increasing in the forepole stiffness can be maximised if the forepoles are arranged at an appropriate filling angle.

It can also be noted that by only increasing the forepole stiffness, the measured \( SRF \) was similar to that achieved by increasing the embedded length (from \( EL/D = 0.5 \) to \( EL/D = 1 \)) for \( C/D = 1 \) tunnels (test CD1-F-S-EL0.5-A90 vs CD1-F-B-EL1-A90, see Table 4). A practical application for this observation is that using forepoles with higher stiffness requires a lower \( EL/D \) and this then permits a longer excavation length which could be beneficial in terms of time saving.

**SUMMARY AND CONCLUSIONS**

The series of centrifuge tests has investigated the effects of a FUS in reducing ground movements around a tunnel heading. Data of subsurface and surface ground movements has demonstrated the benefits of using a FUS in reducing the magnitude and extent of soil deformations. The high precision measurements, including those from a novel 3D imaging system in some centrifuge tests, allowed the reinforcing effect of the FUS to be quantified and a more detailed analysis of 3D displacements at the surface to be made than has previously been possible.

The deformed model forepoles recovered after the tests revealed information on patterns and zones of movements. In the longitudinal direction, the forepoles were found to be most effective when able to mobilise a "foundation effect" at the end of the forepoles furthest from tunnel. This requires the forepoles to extend beyond the potential plastic collapse mechanism. The potential
failure mechanism can be predicted using simple upper bound solutions for a plane strain heading suggested by Davis et al. (1980).

In the transverse direction, the experimental evidence further corroborates the Davis et al. (1980) plastic failure mechanisms which suggests increased likelihood of lateral movements near the tunnel springline as $C/D$ increases. Therefore, the forepoles need to extend around the tunnel periphery into areas where significant soil movements might be expected from consideration of the plastic failure mechanism. Further studies with an $\alpha>90^\circ$ would be needed to investigate the effect of larger filling angle on the reinforcement effectiveness of the FUS for deep tunnels.

The key findings can be summarised by Fig. 14 which demonstrates the $SRF$ (from Table 4) for different ratios of $EL/D$ and $C/D$ and also for changing the stiffness of the forepoles. This chart would be useful as a guide for designing the FUS in practice.

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REFERENCES


FIGURE CAPTION

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

Fig. 2: Parameters in a tunnel heading and a FUS.

Fig. 3: Variables of centrifuge test.
Fig. 4: Schematic of the centrifuge model.

Fig. 5: 3D printed guide for inserting the model forepoles into the clay model during the modelling preparation stage at 1g.

Fig. 6: Subsurface soil deformations in test reference test CD3-R-N and reinforced test CD3-F-S-EL0.5-A75-N ($\sigma_T = 80kPa$).

Fig. 7: Soil displacements at the top of the model in tests CD3-R-N and CD3-F-S-EL0.5-A75-N(mm) ($\sigma_T = 80kPa$).

Fig. 8: Typical maximum surface settlement above tunnel face in centrifuge tests.

Fig. 9: Settlement reduction factor SRF of the FUS in different arrangements.

Fig. 10: Photos of forepoles post-test and associated schematics indicating the position of the points of inflexion relative to the model tunnel.

Fig. 11: Photos of models post-test annotated with the observed failure planes and upper bound failure mechanism.

Fig. 12: Tunnel heading and forepoles post test in test CD1-F-B-EL0.5-A90 ($C/D=1$).

Fig. 13: Tunnel heading and forepoles post test in test CD3-F-B-EL0.5-A90 ($C/D=3$).

Fig. 14: Relationship between SRF and EL/D with variation of forepole stiffness.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<td>Steel pipe diameter and wall thickness</td>
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<td></td>
<td>mm</td>
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<td>Embedded length, $EL$</td>
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</tbody>
</table>

Table 1: Parameters in a FUS (Volkmann and Schubert 2007).
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>κ</td>
<td>average gradient of swelling line in $v:\ln p'$ space</td>
<td>0.05</td>
</tr>
<tr>
<td>λ</td>
<td>gradient of compression line in $v:\ln p'$ space</td>
<td>0.19</td>
</tr>
<tr>
<td>$M$</td>
<td>stress ratio at critical state ($q':p'$)</td>
<td>0.89</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>specific volume at critical state when $p'=1$kPa</td>
<td>3.23</td>
</tr>
<tr>
<td>$N$</td>
<td>specific volume on INCL when $p'=1$kPa</td>
<td>3.29</td>
</tr>
<tr>
<td>$\phi_c'$</td>
<td>critical state angle of shearing resistance</td>
<td>23°</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>unit weight of soil (saturated for clay)</td>
<td>16.5 (kN/m$^3$)</td>
</tr>
<tr>
<td>$\gamma_w$</td>
<td>unit weight of water</td>
<td>9.81 (kN/m$^3$)</td>
</tr>
</tbody>
</table>

**Table 2.** Properties of Speswhite Kaolin (Le 2017).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model (mm)</th>
<th>Prototype (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel Diameter, $D$</td>
<td>50</td>
<td>6.25</td>
</tr>
<tr>
<td>Unlined portion, $P$</td>
<td>25</td>
<td>3.125</td>
</tr>
<tr>
<td>Cover depth $C$ ($C/D=1$)</td>
<td>50</td>
<td>6.25</td>
</tr>
<tr>
<td>Depth at tunnel CL, $z_0$ ($C/D=1$)</td>
<td>75</td>
<td>9.375</td>
</tr>
<tr>
<td>Cover depth $C$ ($C/D=3$)</td>
<td>150</td>
<td>18.75</td>
</tr>
<tr>
<td>Depth at tunnel CL, $z_0$ ($C/D=3$)</td>
<td>175</td>
<td>21.875</td>
</tr>
</tbody>
</table>

**Table 3:** Corresponding tunnel at prototype scale.
<table>
<thead>
<tr>
<th>Test</th>
<th>C/D</th>
<th>Model forepole</th>
<th>EL/D</th>
<th>α(°)</th>
<th>E (GPa)</th>
<th>SRF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD3-F-B-EL0.5-A75</td>
<td>3</td>
<td>Brass</td>
<td>0.5</td>
<td>75</td>
<td>110</td>
<td>35</td>
</tr>
<tr>
<td>CD3-F-B-EL1-A90</td>
<td>3</td>
<td>Brass</td>
<td>1</td>
<td>90</td>
<td>110</td>
<td>50</td>
</tr>
<tr>
<td>CD3-F-B-EL0.5-A90</td>
<td>3</td>
<td>Brass</td>
<td>0.5</td>
<td>90</td>
<td>110</td>
<td>42</td>
</tr>
<tr>
<td>CD3-F-S-EL1-A90</td>
<td>3</td>
<td>Steel</td>
<td>1</td>
<td>90</td>
<td>210</td>
<td>73</td>
</tr>
<tr>
<td>CD3-F-S-EL0.5-A90-N</td>
<td>3</td>
<td>Steel</td>
<td>0.5</td>
<td>90</td>
<td>210</td>
<td>62</td>
</tr>
<tr>
<td>CD3-F-S-EL0.5-A75-N</td>
<td>3</td>
<td>Steel</td>
<td>0.5</td>
<td>75</td>
<td>210</td>
<td>47</td>
</tr>
<tr>
<td>CD1-F-B-EL0.5-A75</td>
<td>1</td>
<td>Brass</td>
<td>0.5</td>
<td>75</td>
<td>110</td>
<td>53</td>
</tr>
<tr>
<td>CD1-F-B-EL0.5-A90</td>
<td>1</td>
<td>Brass</td>
<td>0.5</td>
<td>90</td>
<td>110</td>
<td>44</td>
</tr>
<tr>
<td>CD1-F-B-EL1-A90</td>
<td>1</td>
<td>Brass</td>
<td>1</td>
<td>90</td>
<td>110</td>
<td>75</td>
</tr>
<tr>
<td>CD1-F-S-EL0.5-A90</td>
<td>1</td>
<td>Steel</td>
<td>0.5</td>
<td>90</td>
<td>210</td>
<td>72</td>
</tr>
</tbody>
</table>

**Table 4**: Average value of settlement reduction factor SRF.
<table>
<thead>
<tr>
<th>Tests</th>
<th>C/D</th>
<th>$\alpha$ (°)</th>
<th>Model forepolar</th>
<th>SRF (%) $\frac{EL/D=0.5}{EL/D=1}$</th>
<th>SRF_{EL/D=1} - SRF_{EL/D=0.5} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD3-F-B-EL0.5-A90 vs</td>
<td>3</td>
<td>90</td>
<td>Brass</td>
<td>42/50</td>
<td>8</td>
</tr>
<tr>
<td>CD3-F-B-EL1-A90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD3-F-S-EL0.5-A90 vs</td>
<td>3</td>
<td>90</td>
<td>Steel</td>
<td>62/73</td>
<td>11</td>
</tr>
<tr>
<td>CD3-F-S-EL1-A90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD1-F-B-EL0.5-A90 vs</td>
<td>1</td>
<td>90</td>
<td>Brass</td>
<td>44/73</td>
<td>29</td>
</tr>
<tr>
<td>CD1-F-B-EL1-A90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5:** Relative effect of $EL/D$ with ratio $C/D$. 
<table>
<thead>
<tr>
<th>Tests</th>
<th>C/D</th>
<th>EL/D</th>
<th>Model forepole</th>
<th>$SRF(%)_{\alpha=75^\circ}$</th>
<th>$SRF(%)_{\alpha=90^\circ}$</th>
<th>$\frac{SRF_{\alpha=90^\circ} - SRF_{\alpha=75^\circ}}{%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD3-F-B-EL0.5-A75 vs CD3-F-B-EL0.5-A90</td>
<td>3</td>
<td>0.5</td>
<td>Brass</td>
<td>35</td>
<td>42</td>
<td>7</td>
</tr>
<tr>
<td>CD3-F-S-EL0.5-A75-N vs CD3-F-S-EL0.5-A90-N</td>
<td>3</td>
<td>0.5</td>
<td>Steel</td>
<td>47</td>
<td>62</td>
<td>15</td>
</tr>
<tr>
<td>CD1-F-B-EL0.5-A75 vs CD1-F-B-EL0.5-A90</td>
<td>1</td>
<td>0.5</td>
<td>Brass</td>
<td>53</td>
<td>44</td>
<td>-9</td>
</tr>
</tbody>
</table>

**Table 6:** Relative effect of filling angle in different ratio $C/D$. 
<table>
<thead>
<tr>
<th>Tests</th>
<th>C/D</th>
<th>α (°)</th>
<th>EL/D</th>
<th>SRF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brass</td>
</tr>
<tr>
<td>CD3-F-B-EL0.5-A75 vs CD3-F-S-EL0.5-A75-N</td>
<td>3</td>
<td>75</td>
<td>0.5</td>
<td>35</td>
</tr>
<tr>
<td>CD3-F-B-EL1-A90 vs CD3-F-S-EL1-A90</td>
<td>3</td>
<td>90</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>CD3-F-B-EL0.5-A90 vs CD3-F-S-EL0.5-A90-N</td>
<td>3</td>
<td>90</td>
<td>0.5</td>
<td>42</td>
</tr>
<tr>
<td>CD1-F-B-EL0.5-A90 vs CD1-F-S-EL0.5-A90</td>
<td>1</td>
<td>90</td>
<td>0.5</td>
<td>44</td>
</tr>
</tbody>
</table>

**Table 7:** Relative effect of filling angle to increase in stiffness of the forepole.
Fig. 1: Forepoling Umbrella System (after Carrieri et al. 2002)
Fig. 2: Parameters in a tunnel heading and a FUS.

- $D$: tunnel diameter
- $C$: cover depth
- $P$: unlined portion
- $EL$: embedded length
- $L$: forepole length
- $z_0$: tunnel depth
- $S$: centre to centre spacing between forepoles
- $\beta$: insertion angle
- $\alpha$: filling angle
Fig. 3: Variables of centrifuge tests.
Rubber bag containing air support pressure

Model FUS (Fig)

Front face measured by PIV/Visimet

Tunnel lining (165)

Cavity cut (190 mm)

Unlined portion, $P=25; P/D=0.5$

Rubber bag containing air support pressure

3DIS Cameras (gantry not shown)

Fig. 4: Schematic of the centrifuge model.
**Fig. 5:** 3D printed guide for inserting the model forepoles into the clay model during the modelling preparation stage at 1g.
Fig. 6: Subsurface soil deformations in test reference test CD3-R-N and reinforced test CD3-F-S-EL0.5-A75-N ($\sigma_T = 80kPa$).
Fig. 7: Soil displacements at the top of the model in tests CD3-R-N and CD3-F-S-EL0.5-A75-N(mm) ($\sigma_T = 80kPa$).
Fig. 8: Typical maximum surface settlement above tunnel face in centrifuge tests.
Fig. 9: Settlement reduction factor SRF of the FUS in different arrangements.

a) In $C/D=1$ tests

b) In $C/D=3$ tests
Fig. 10: Photos of forepoles post-test and associated schematics indicating the position of the points of inflexion relative to the model tunnel.
Fig. 11: Photos of models post-test annotated with the observed failure planes and upper bound failure mechanism.
a) Tunnel heading and forepoles post test

**Fig. 12**: Tunnel heading and forepoles post test in test CD1-F-B-EL0.5-A90 (C/D=1).

b) Upper bound collapse mechanism A for shallow tunnel (after Davis et al. 1980)
**Fig. 13.** Tunnel heading and forepoles post test in test CD3-F-B-EL0.5-A90 ($C/D=3$).

a) Tunnel heading and forepoles post test

b) Upper bound collapse mechanism D for deep tunnel (after Davis et al. 1980)
Fig. 14: Relationship between $SRF$ and $EL/D$ with variation of forepole stiffness.

Bending stiffness equivalence:
Brass rod: steel pipes with diameter of 135mm and wall thickness of 8mm
Steel rod: steel pipes with diameter of 165mm and wall thickness of 8mm.