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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;**

1	LIST OF SYMBOLS
2	3D three-dimensional
3	3DIS three-dimensional imaging system
4	C cover depth above tunnel
5	D tunnel diameter
6	E Young's modulus of model forepoles
7	FUS Forepoling Umbrella System
8	g acceleration due to gravity (9.81m/s ²)
9	P unlined portion of tunnel heading
10	PIV Particle Image Velocity
11	SRF settlement reduction factor
12	u horizontal displacement in X direction
13	v horizontal displacement in Y direction
14	w vertical displacement in Z direction
15	z depth from soil surface
16	α filling angle
17	σ_T tunnel support pressure
18	σ_{ob} overburden stress at tunnel centreline
19	σ'_{v0} consolidation pressure
20	

21 INTRODUCTION

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

28

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

43

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

47

48 The FUS has been shown to be an efficient measure to control soil deformations due to open
49 face tunnelling and has been used in a number of major projects such as the Victoria Station
50 Upgrade and King's Cross Station Redevelopment in the UK (Gall and Zeidler 2008), the Harbin

51 Metro Line #1 in China (Wang et al. 2018), the Istanbul Metro in Turkey (Ocak 2008), and the
52 Fort Canning Tunnel in Singapore (Yeo et al. 2009). Field measurements and numerical
53 analysis reported Oke (2016) showed that the Forepole Umbrella System, when used in
54 conjunction with other soil reinforcement measures (including face bolts and soil nails), provided
55 a reduction of approximately 20-76% surface settlement compared with the unreinforced
56 sections. Similar to the observations made by Oke (2016), Ocak (2008) reported that the
57 combination of several soil reinforcement measures, umbrella arch and soil nailing, reduced the
58 magnitude of surface settlement by three compared with that in the section without soil
59 reinforcement. However, because of the interaction of the various reinforcing techniques used, it
60 is not possible to identify the exact contribution made by the Forepoling Umbrella System in
61 reducing ground movements.

62

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

66

67 Vrba and Barták (2007) used centrifuge modelling to study the effects of a FUS for a tunnel at a
68 normalised depth $C/D=3$. In their experiments, steel plates were used to model the forepoling
69 roof which reinforced the tunnel heading in clay. They observed significant reduction in soil
70 settlement was provided by using the FUS. Divall et al. (2016) conducted centrifuge tests

71 simulating a tunnel in clay incorporating a FUS in which the forepoles were modelled by resin.

72 The normalised tunnel depth was $C/D=2$. Similar to the observations made by Vrba and Barták
73 (2007), Divall et al. (2016) showed that the use of the FUS increased the stability of the tunnel
74 heading and decreased the magnitude of soil settlement. It should be noted that in each
75 research project, the material and geometry of the model forepoles was not varied. The effect
76 of the forepole stiffness was therefore not investigated.

77

78 Volkmann and Schubert (2007) reported field measurements obtained from an inclinometer
79 chain located on the topmost steel pipe of the FUS in the Trojane tunnel (Slovenia). The site
80 geology consisted of faulted mudstone, claystone and sandstone (Volkmann et al. 2006). The

81 normalised tunnel depth was $C/D=1.5$. The measurement data showed that when the
82 embedded length EL decreased, as the tunnel face advanced, the magnitude of steel pipe
83 deformation increased. The reason was that when EL reduced, the foundation effect from the
84 ground beneath the FUS decreased which led to large deformation of the forepoles. This
85 confirmed similar findings derived from centrifuge tests reported by Vrba and Barták (2007) and
86 Yeo (2011).

87

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

98

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

103

104 THE CENTRIFUGE TESTS

105 *Test series*

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

108

109 The normalised depths of $C/D=1$ and $C/D=3$ were chosen because these two are likely to result
110 in substantial differences in the soil deformation mechanism (Davis et al. 1979) which is an

111 important factor that influences the reinforcement effectiveness of the FUS (Le and Taylor
112 2017).

113

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

118

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

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

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

129

130 *Test apparatus*

131 A schematic of the centrifuge model is illustrated in **Fig. 4**. The model clay (Speswhite kaolin)
132 was one dimensionally consolidated in a model container (strong box) using a hydraulic
133 consolidometer to a vertical effective stress $\sigma'_{v0}=175\text{kPa}$. The consolidation pressure
134 $\sigma'_{v0}=175\text{kPa}$ was chosen as it provided a soft clay model in which the soil deformations, induced
135 by the simulated tunnel excavation, would be sufficiently large so that the reinforcement effects
136 of the FUS would be observed clearly. The properties of Speswhite kaolin are presented in
137 **Table 2** (Le 2017)

138

139 The tunnel was simulated by a semi-circular cavity cut into the clay model (**Fig. 4**). By doing so,
140 soil deformations on the vertical plane of symmetry of the tunnel heading could be observed

141 through the front perspex window. The total length of the tunnel cavity was 190mm. This was
142 partially supported by a 165mm long tunnel lining made from a 50mm diameter 1.6mm thick
143 semi-circular stainless steel tube. The unlined heading of length $P=25\text{mm}$ was supported by a
144 thin rubber bag supplied with compressed air pressure. The technique of using a pressurised air
145 bag has been proved to be a successful method capable for simulating tunnel excavation in
146 centrifuge models and the soil movements in 3D models were found to be consistent with those
147 obtained from field measurements (Meguid et al. 2008; Le and Taylor 2018).

148

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

152

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

158

159 *Instrumentation*

160 In most of the tests, surface settlement was measured by a row of displacement transducers
161 using the principles of a Linear Variable Differential Transformer (LVDT), placed along the
162 tunnel centreline, and the Visimet software (Grant 1998) was used to measure soil
163 displacements at the front face of the model from images captured from the front facing camera
164 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
165 new 3D imaging system (Le et al. 2016) was used to measure 3D soil displacements at the
166 model surface while GeoPIV_RG (Stanier et al. 2015) was used to measure subsurface soil
167 movements at the front face of the model from the camera images.

168

169 The precision of 3DIS (Le et al. 2016) was shown to be within 50 μ m. Grant (1998) reported that
170 the precision of Visimet was in range of 70-80 μ m. GeoPIV_RG was reported to have
171 comparable measurement precision with the LVDTs (Stanier et al. 2015).

172

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

185

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

193

194 *Test procedure*

195 The models were accelerated to 125g while simultaneously increasing the air pressure inside
196 the tunnel bag, σ_T , to support the overburden stress at the corresponding centrifuge
197 acceleration. The centrifuge was left running until the excess pore pressure dissipated and the
198 clay had reached effective stress equilibrium. The tunnel excavation process was then

199 simulated by gradually reducing the tunnel support pressure σ_T to zero. Data relating to the
200 tunnel support pressure σ_T , LVDT readings and deformations of the clay model were recorded
201 at 1 second intervals for later analysis.

202

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

213

214 RESULTS

215 Some of the results in this research have been reported by Le et al. (2015), Le and Taylor
216 (2016), and Le and Taylor (2017). This section further analyses the test results to provide a
217 clearer and broader insight on the relative effects of the FUS parameters to its reinforcing
218 effectiveness.

219 *The effect of using the FUS*

220 **Fig. 6** compares typical subsurface soil deformations and engineering shear strains, when σ_T
221 was reduced to 80kPa, in the reference test CD3-R-N (dashed lines) and the reinforced test
222 CD3-F-S-EL0.5-A75-N (solid lines) to examine the effect of using the FUS. The pressure
223 $\sigma_T=80\text{kPa}$ was chosen because at this pressure soil deformations were large enough so that the
224 effects of the FUS can be observed clearly.

225

226 Using a FUS led to a reduction in both magnitude and extent of the soil displacements and
227 shear strains (**Fig. 6**). In the reference test, large engineering shear strains (>4%) developed at
228 both the tunnel crown and invert. In contrast, in the test with the FUS, large shear strains did not

229 occur near the tunnel crown in the vicinity of the FUS. The reduction in soil movements near the
 230 tunnel heading, delivered by the FUS, led to a reduction in ground movements in all directions
 231 at all points at the entire top surface of the model (**Fig. 7**).

232

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

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

238

$$SRF = [(w_0 - w_r)/w_0] \times 100\% \quad (1)$$

239

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

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

244

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

253

254 RELATIVE INFLUENCE OF THE FUS PARAMETERS

255 The same pre-consolidation pressure was used for the clay models and hence all the models
 256 had similar strength and stiffness characteristics. Therefore, any significant differences in the
 257 reinforcement effectiveness of the FUS were the result of the variation of the arrangement

258 including EL/D , α , material of the forepoles and C/D ratios which are discussed in detail in the
259 following sections.

260

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

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

271

272 The difference in the foundation effect between $EL/D=0.5$ and $EL/D=1$ to the FUS was reflected
273 in the corresponding deformation of the forepoles as shown in **Fig. 10**. The model rods for the
274 $EL/D=0.5$ test showed one inflexion point implying that the foundation effect was negligible and
275 that the forepoles worked mainly as a cantilever. In contrast, the rods for $EL/D=1$ test showed
276 two inflexion points denoting that the foundation effect was greater and the forepoles worked
277 like beams supported at both ends and this offered a better supporting effect.

278

279 For the $C/D=3$ tunnels, increasing EL/D by 100% (from $EL/D=0.5$ to $EL/D=1$) gave a 10%
280 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-
281 EL1-A90, see **Table 5**). Interestingly, for the $C/D=1$ tunnels (CD1-F-B-EL0.5-A90 vs CD1-F-B-
282 EL1-A90), the same increase in EL/D gave an increase of 29% in SRF which is approximately 3
283 times larger than that for the $C/D=3$ tunnels. This significant difference in the influence of EL/D
284 to the reinforcing effectiveness of the FUS for the two normalised tunnel depths suggests that
285 the quality of the foundation effect provided by the soil beneath the FUS was different.

286

287 **Figs. 11a and 11b** present photographs of the reference tests having $C/D=1$ and $C/D=3$
 288 respectively. The failure planes observed in these tests are highlighted by dashed lines. The
 289 pictures are further annotated with the outline of a potential upper bound failure mechanism
 290 suggested by Davis et al. (1980). The angles in the failure mechanism are given by;

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

$$\theta_3 = \pi/2 \quad (3)$$

291 (θ_1 , θ_2 and θ_3 are annotated in **Fig. 11**)

292

293 It can be seen that the upper bound mechanisms over predict the extent of the collapse zones
 294 for both tests which may reflect the fact that the upper bound mechanism is for a plane strain
 295 tunnel (long wall mining) rather than the 3D circular tunnel heading in the centrifuge tests. By
 296 way of illustration, the locations of forepoles in a FUS having $EL/D=1$ are superimposed on **Fig.**
 297 **11**. This demonstrates that for $EL/D=1$, the forepoles in a $C/D=1$ tunnel extend beyond the
 298 shear plane (and plastic collapse mechanism) which then offers a better foundation effect
 299 compared with that for a $C/D=3$ tunnel where the forepoles would be inside the shearing plane.
 300 This better foundation effect may explain the higher SRF of the FUS in the shallow tunnel tests.

301

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

307

308 *The effect of the filling angle α for different C/D*

309 It is worth noting that, in this study, varying the filling angle α alters the spacing S between the
 310 forepoles as the quantity of the forepoles in the reinforced tests is constant. The test results
 311 presented later in this section highlighted that at different C/D ratios, the SRF delivered by the
 312 FUS heavily depends on the coverage of the forepoles in the transverse direction which is
 313 dictated by α . Therefore, the filling angle is chosen as the key parameter for consideration, not
 314 the spacing S .

315

316 **Table 6** presents the *SRF* of the FUS for two filling angles $\alpha=75^\circ$ and $\alpha=90^\circ$ at two different
 317 normalised tunnel depths $C/D=1$ and $C/D=3$. The filling angle $\alpha=75^\circ$ outperformed $\alpha=90^\circ$ for
 318 tests with $C/D=1$ (CD1-F-B-EL0.5-A75 vs CD1-F-B-EL0.5-A90) but not for tests with $C/D=3$
 319 (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).
 320

321 A photograph of the tunnel heading post-test with the deformed forepoles in test CD1-F-B-
 322 EL0.5-A90 ($C/D=1$) is presented in **Fig. 12-a**. The upper rods had large deformations while the
 323 deformations of the lower rods were negligible. This suggests that large soil movements
 324 occurred mainly in the vicinity of the tunnel crown while near the tunnel spring line the soil
 325 displacement was small. This agrees with the collapse mechanism A suggested by Davis et al.
 326 (1980) for a shallow tunnel (**Fig. 12-b**). Therefore, concentrating forepoles near the tunnel
 327 crown by arranging the same quantity of forepoles within a filling angle of $\alpha=75^\circ$ outperformed
 328 $\alpha=90^\circ$ by $\approx 10\%$ in terms of *SRF* (**Table 6**).

329

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

336

337 *The effect of the forepole stiffness*

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

340

341 The increase in *SRF* offered by increasing the forepole stiffness (brass to steel) for $C/D=1$
 342 tunnel was $\approx 30\%$ ($\alpha=75^\circ$) which is more significant than that for the $C/D=3$ tunnels which
 343 showed increases of approximately 10% and 20% for $\alpha=75^\circ$ and $\alpha=90^\circ$ respectively.

344

345 Interestingly, for $C/D=3$ tests increasing the forepoles stiffness yielded different improved SRF
346 for different filling angles α . In tests with forepoles arranged at $\alpha=90^\circ$ ([CD3-F-B-EL1-A90
347 vs CD3-F-S-EL1-A90]; [CD3-F-B-EL0.5-A90 vs CD3-F-S-EL0.5-A90-N]), the stiffness increase
348 delivered an increase of approximately 20% in SRF (**Table 7**). This is about two times larger
349 than the 10% increase in SRF for tests with $\alpha=75^\circ$ (CD3-F-B-EL0.5-A75 vs CD3-F-S-EL0.5-
350 A75-N) (**Table 7**) which suggests that the benefit of increasing in the forepole stiffness can be
351 maximised if the forepoles are arranged at an appropriate filling angle.

352

353 It can also be noted that by only increasing the forepole stiffness, the measured SRF was
354 similar to that achieved by increasing the embedded length (from $EL/D=0.5$ to $EL/D=1$) for
355 $C/D=1$ tunnels (test CD1-F-S-EL0.5-A90 vs CD1-F-B-EL1-A90, see **Table 4**). A practical
356 application for this observation is that using forepoles with higher stiffness requires a lower EL/D
357 and this then permits a longer excavation length which could be beneficial in terms of time
358 saving.

359

360 SUMMARY AND CONCLUSIONS

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

368

369 The deformed model forepoles recovered after the tests revealed information on patterns and
370 zones of movements. In the longitudinal direction, the forepoles were found to be most effective
371 when able to mobilise a “foundation effect” at the end of the forepoles furthest from tunnel. This
372 requires the forepoles to extend beyond the potential plastic collapse mechanism. The potential

373 failure mechanism can be predicted using simple upper bound solutions for a plane strain
374 heading suggested by Davis et al. (1980).

375

376 In the transverse direction, the experimental evidence further corroborates the Davis et al.
377 (1980) plastic failure mechanisms which suggests increased likelihood of lateral movements
378 near the tunnel springline as C/D increases. Therefore, the forepoles need to extend around the
379 tunnel periphery into areas where significant soil movements might be expected from
380 consideration of the plastic failure mechanism. Further studies with an $\alpha > 90^\circ$ would be needed
381 to investigate the effect of larger filling angle on the reinforcement effectiveness of the FUS for
382 deep tunnels.

383

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

387

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392

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 456 pp.33-38.
- 457 **FIGURE CAPTION**
- 458 **Fig. 1:** Forepoling Umbrella System (after Carrieri et al. 2002)
- 459 **Fig. 2:** Parameters in a tunnel heading and a FUS.
- 460 **Fig. 3:** Variables of centrifuge test.

- 461 **Fig. 4:** Schematic of the centrifuge model.
- 462 **Fig. 5:** 3D printed guide for inserting the model forepoles into the clay model during the
463 modelling preparation stage at 1g.
- 464 **Fig. 6:** Subsurface soil deformations in test reference test CD3-R-N and reinforced test CD3-F-
465 S-EL0.5-A75-N ($\sigma_T = 80kPa$).
- 466 **Fig. 7:** Soil displacements at the top of the model in tests CD3-R-N and CD3-F-S-EL0.5-A75-
467 N(mm) ($\sigma_T = 80kPa$).
- 468 **Fig. 8:** Typical maximum surface settlement above tunnel face in centrifuge tests.
- 469 **Fig. 9:** Settlement reduction factor SRF of the FUS in different arrangements.
- 470 **Fig. 10:** Photos of forepoles post-test and associated schematics indicating the position of the
471 points of inflexion relative to the model tunnel.
- 472 **Fig. 11:** Photos of models post-test annotated with the observed failure planes and upper bound
473 failure mechanism.
- 474 **Fig. 12:** Tunnel heading and forepoles post test in test CD1-F-B-EL0.5-A90 ($C/D=1$).
- 475 **Fig. 13:** Tunnel heading and forepoles post test in test CD3-F-B-EL0.5-A90 ($C/D=3$).
- 476 **Fig. 14:** Relationship between *SRF* and *EL/D* with variation of forepole stiffness.

Parameter	Unit	Value
Steel pipe diameter and wall thickness	mm mm	70-200 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

Table 1: Parameters in a FUS (Volkman and Schubert 2007).

Symbol	Parameter	Value
κ	average gradient of swelling line in $v:\ln p'$ space	0.05
λ	gradient of compression line in $v:\ln p'$ space	0.19
M	stress ratio at critical state ($q': p'$)	0.89
Γ	specific volume at critical state when $p'=1\text{kPa}$	3.23
N	specific volume on INCL when $p'=1\text{kPa}$	3.29
ϕ'_c	critical state angle of shearing resistance	23°
γ	unit weight of soil (saturated for clay)	16.5 (kN/m ³)
γ_w	unit weight of water	9.81 (kN/m ³)

Table 2. Properties of Speswhite Kaolin (Le 2017).

Parameter	Model (mm)	Prototype (m)
Tunnel Diameter, D	50	6.25
Unlined portion, P	25	3.125
Cover depth C ($C/D=1$)	50	6.25
Depth at tunnel CL, z_0 ($C/D=1$)	75	9.375
Cover depth C ($C/D=3$)	150	18.75
Depth at tunnel CL, z_0 ($C/D=3$)	175	21.875

Table 3: Corresponding tunnel at prototype scale.

Test	<i>C/D</i>	Model forepole	<i>EL/D</i>	$\alpha(^{\circ})$	<i>E</i> (GPa)	<i>SRF</i> (%)
CD3-F-B-EL0.5-A75	3	Brass	0.5	75	110	35
CD3-F-B-EL1-A90	3	Brass	1	90	110	50
CD3-F-B-EL0.5-A90	3	Brass	0.5	90	110	42
CD3-F-S-EL1-A90	3	Steel	1	90	210	73
CD3-F-S-EL0.5-A90-N	3	Steel	0.5	90	210	62
CD3-F-S-EL0.5-A75-N	3	Steel	0.5	75	210	47
CD1-F-B-EL0.5-A75	1	Brass	0.5	75	110	53
CD1-F-B-EL0.5-A90	1	Brass	0.5	90	110	44
CD1-F-B-EL1-A90	1	Brass	1	90	110	75
CD1-F-S-EL0.5-A90	1	Steel	0.5	90	210	72

Table 4: Average value of settlement reduction factor *SRF*.

Tests	C/D	α (°)	Model forepoles	SRF (%)		$SRF_{EL/D=1} - SRF_{EL/D=0.5}$ (%)
				EL/D=0.5	EL/D=1	
CD3-F-B- EL0.5 -A90 vs CD3-F-B- EL1 -A90	3	90	Brass	42	50	8
CD3-F-S- EL0.5 -A90 vs CD3-F-S- EL1 -A90	3	90	Steel	62	73	11
CD1-F-B- EL0.5 -A90 vs CD1-F-B- EL1 -A90	1	90	Brass	44	73	29

Table 5: Relative effect of *EL/D* with ratio *C/D*.

Tests	<i>C/D</i>	<i>EL/D</i>	Model forepole	<i>SRF</i> (%)		<i>SRF</i> _{$\alpha=90^\circ$} - <i>SRF</i> _{$\alpha=75^\circ$} (%)
				$\alpha = 75^\circ$	$\alpha = 90^\circ$	
CD3-F-B-EL0.5- A75 vs CD3-F-B-EL0.5- A90	3	0.5	Brass	35	42	7
CD3-F-S-EL0.5- A75-N vs CD3-F-S-EL0.5- A90-N	3	0.5	Steel	47	62	15
CD1-F-B-EL0.5- A75 vs CD1-F-B-EL0.5- A90	1	0.5	Brass	53	44	-9

Table 6: Relative effect of filling angle in different ratio *C/D*.

Tests	C/D	α (°)	EL/D	SRF (%)		$\frac{SRF_{steel} - SRF_{brass}}{SRF_{brass}}$ (%)
				Brass	Steel	
CD3-F- B -EL0.5-A75 vs CD3-F- S -EL0.5-A75-N	3	75	0.5	35	47	12
CD3-F- B -EL1-A90 vs CD3-F- S -EL1-A90	3	90	1	50	73	23
CD3-F- B -EL0.5-A90 vs CD3-F- S -EL0.5-A90-N	3	90	0.5	42	62	20
CD1-F- B -EL0.5-A90 vs CD1-F- S -EL0.5-A90	1	90	0.5	44	72	28

Table 7: Relative effect of filling angle to increase in stiffness of the forepole.

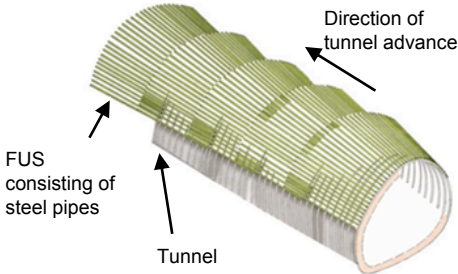


Fig. 1: Forepoling Umbrella System (after Carrieri *et al.* 2002)

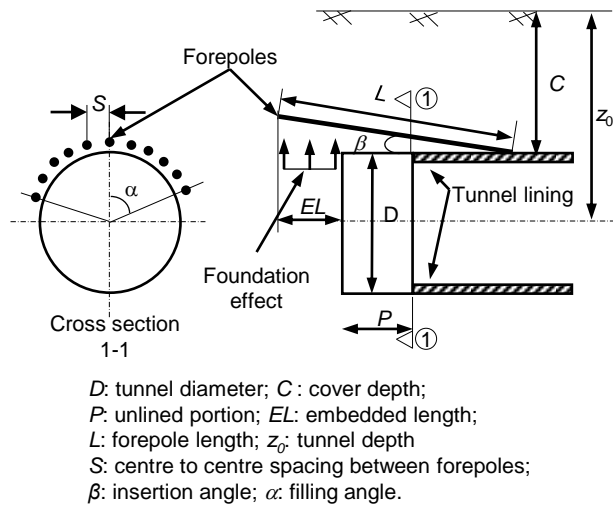


Fig. 2: Parameters in a tunnel heading and a FUS.

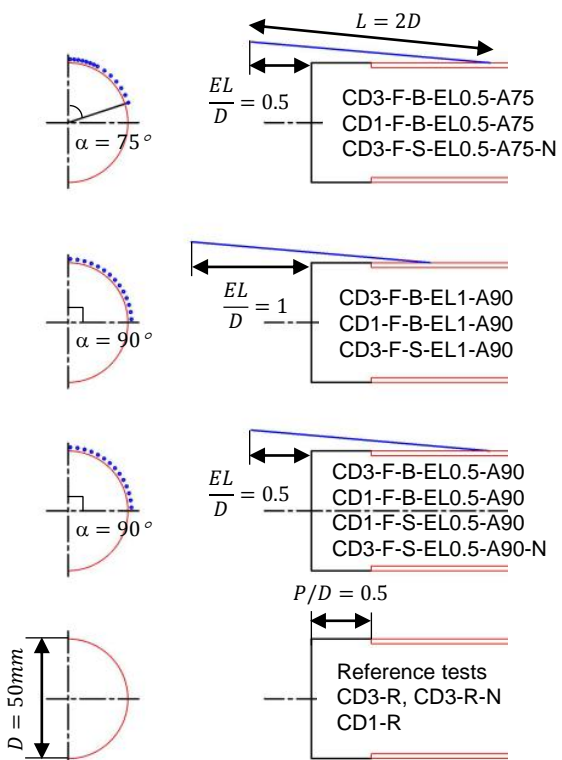


Fig. 3 : Variables of centrifuge tests.

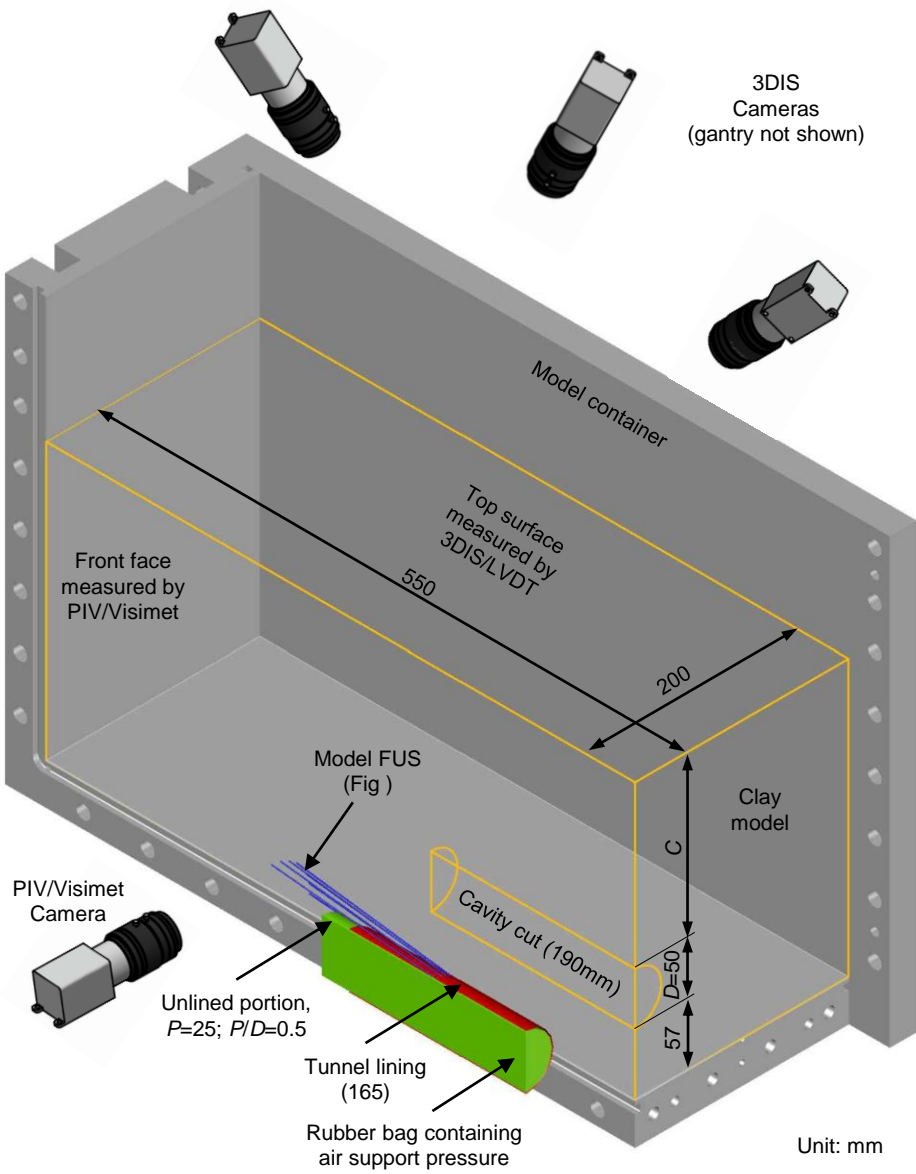


Fig. 4 : Schematic of the centrifuge model.

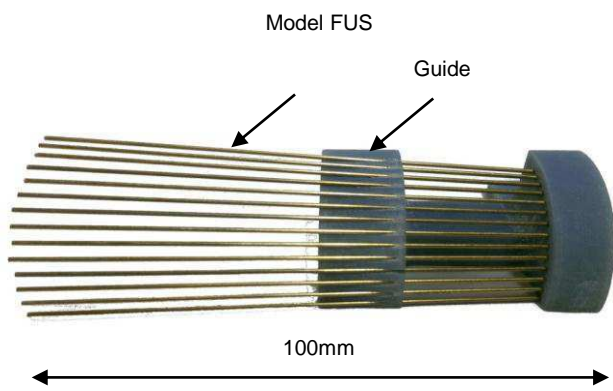
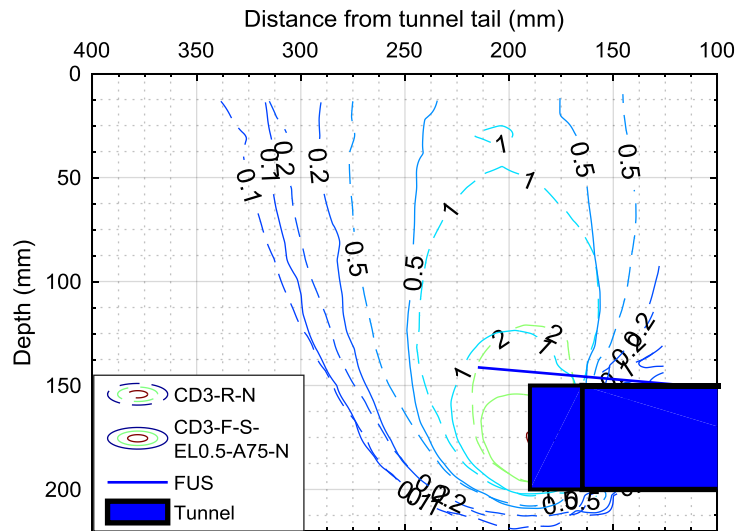
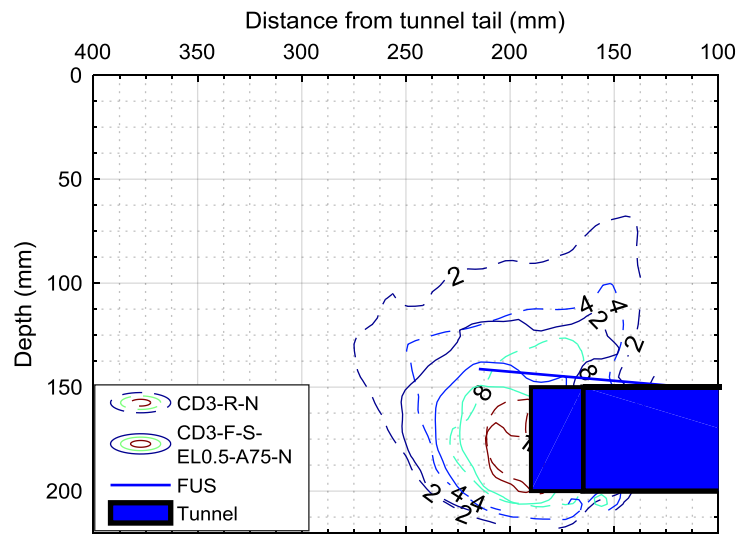


Fig. 5: 3D printed guide for inserting the model forepoles into the clay model during the modelling preparation stage at 1g.

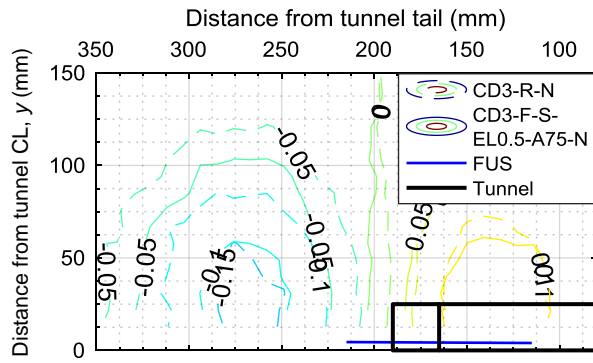


a) Resultant soil displacements (mm).

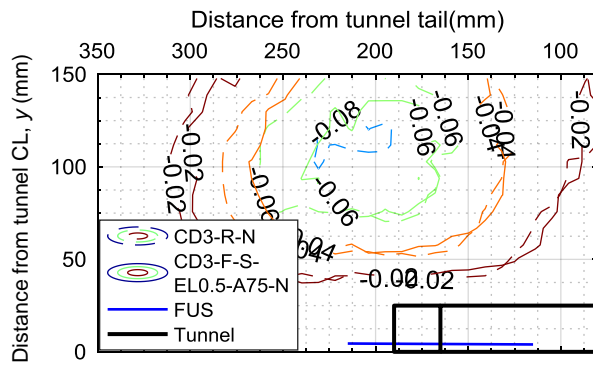


b) Engineering shear strains (%).

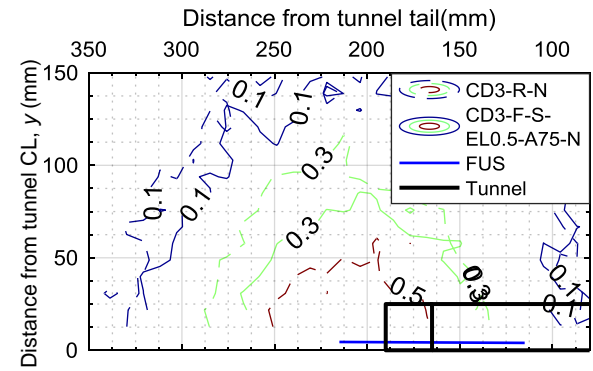
Fig. 6: Subsurface soil deformations in test reference test CD3-R-N and reinforced test CD3-F-S-EL0.5-A75-N ($\sigma_T = 80kPa$).



a) Horizontal soil displacements, u .

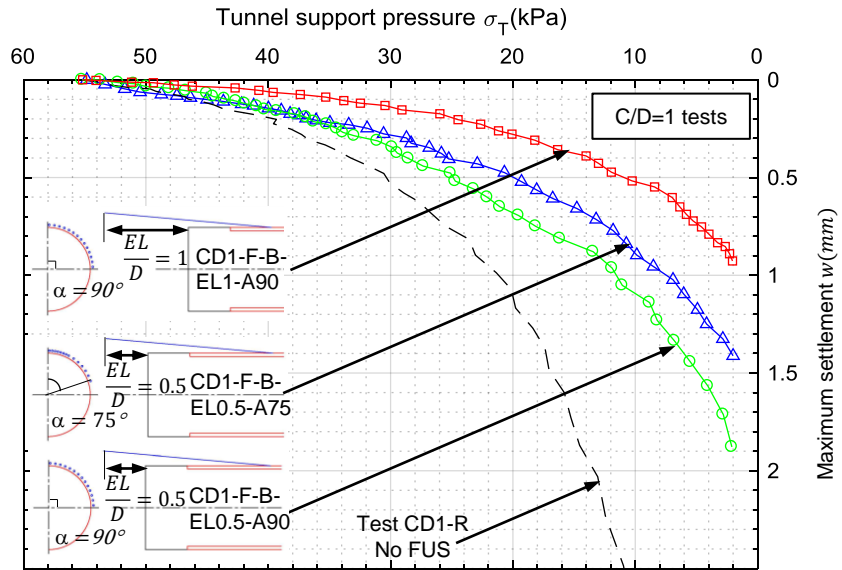


b) Horizontal soil displacements, v .

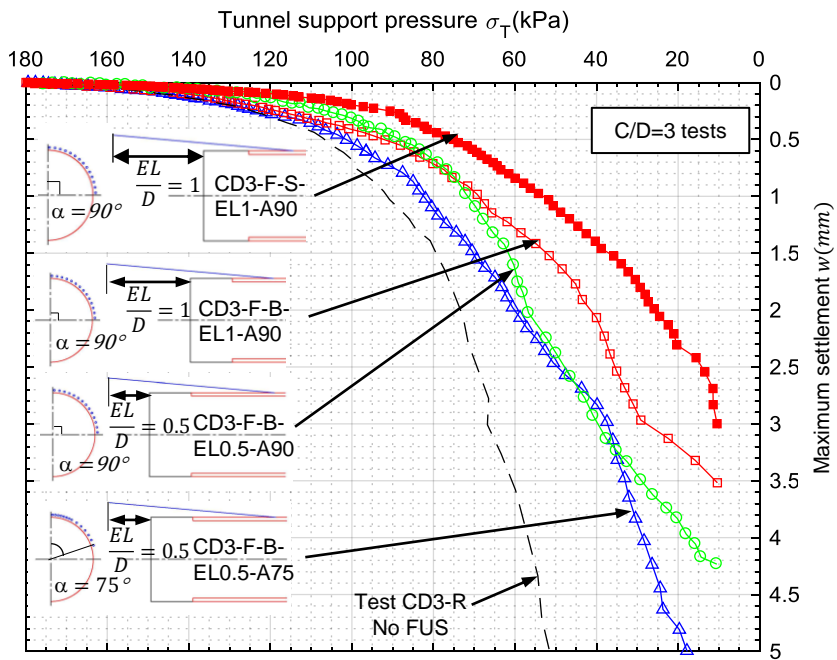


c) Vertical soil displacements, w .

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

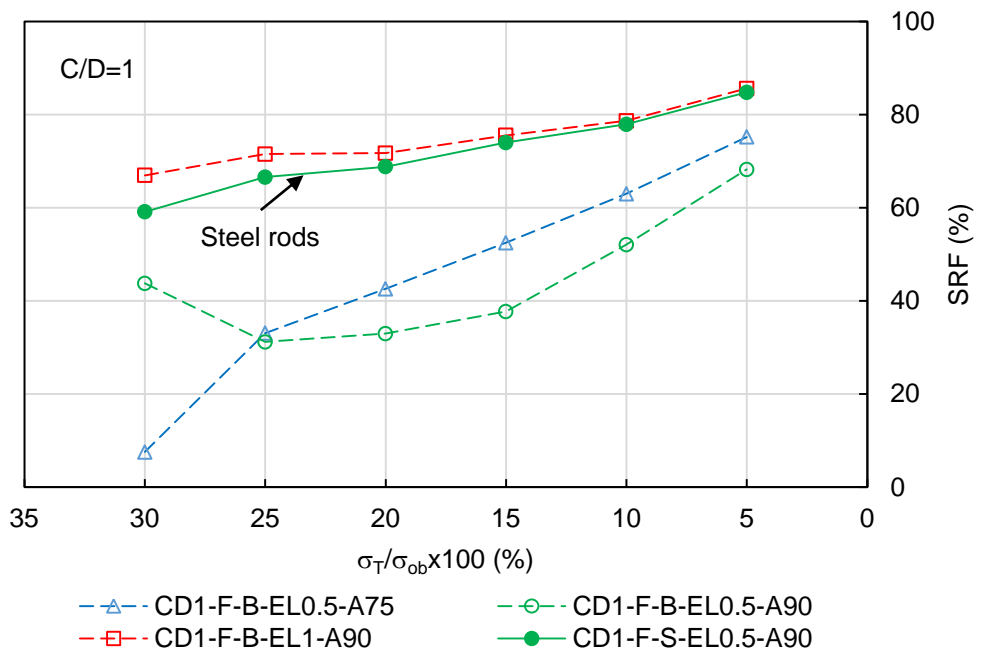


a) In $C/D=1$ tests.

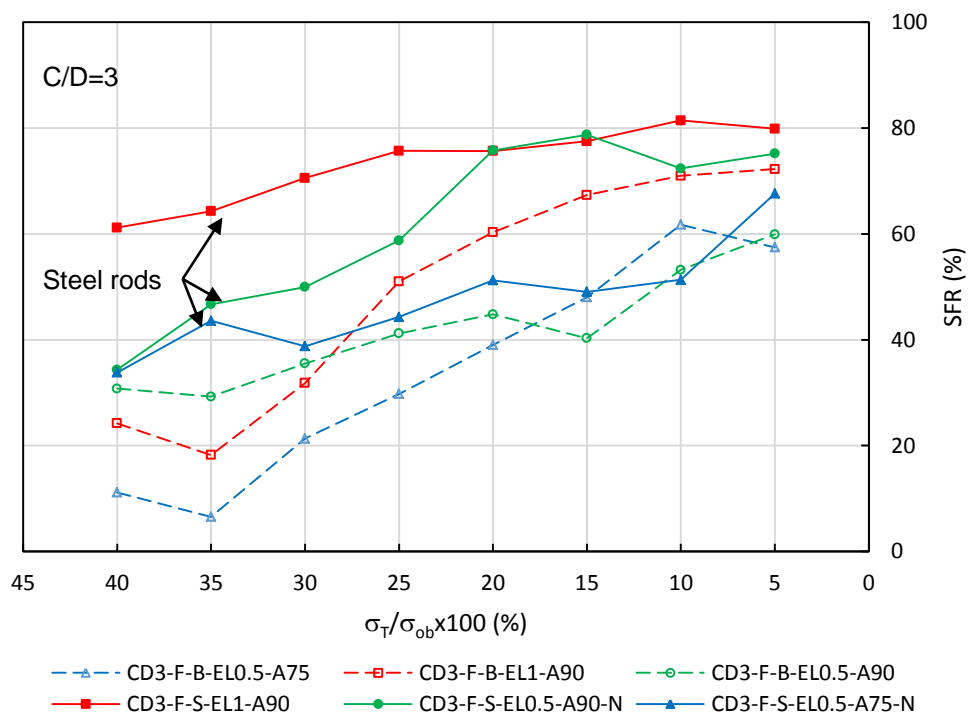


b) In $C/D=3$ tests.

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



a) In $C/D=1$ tests



b) In $C/D=3$ tests

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

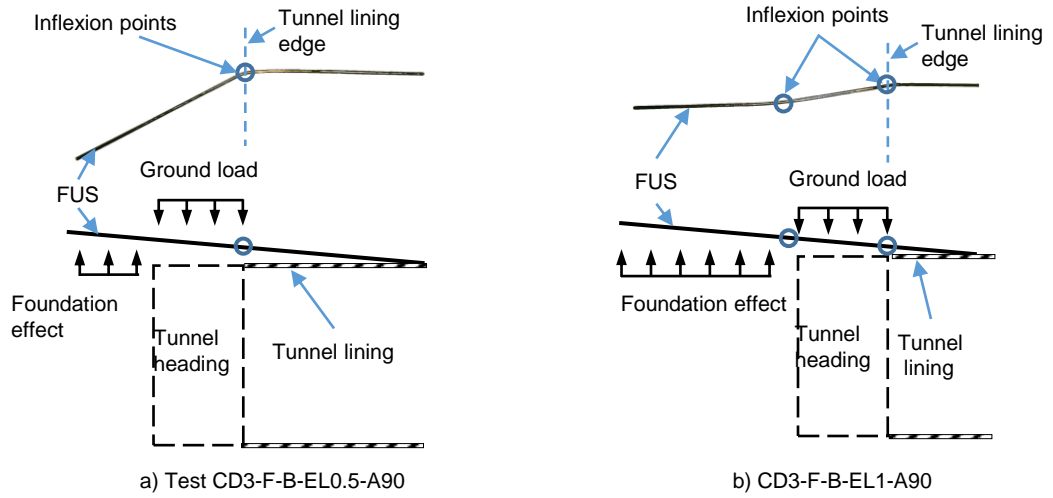
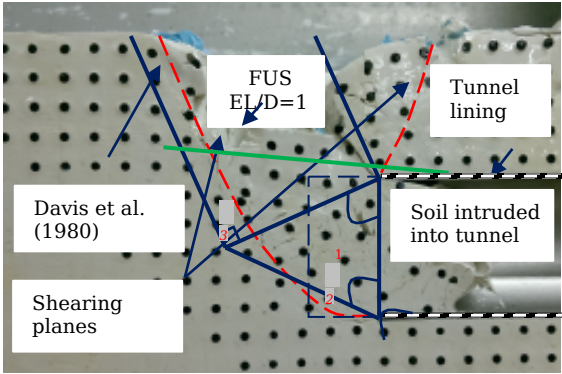
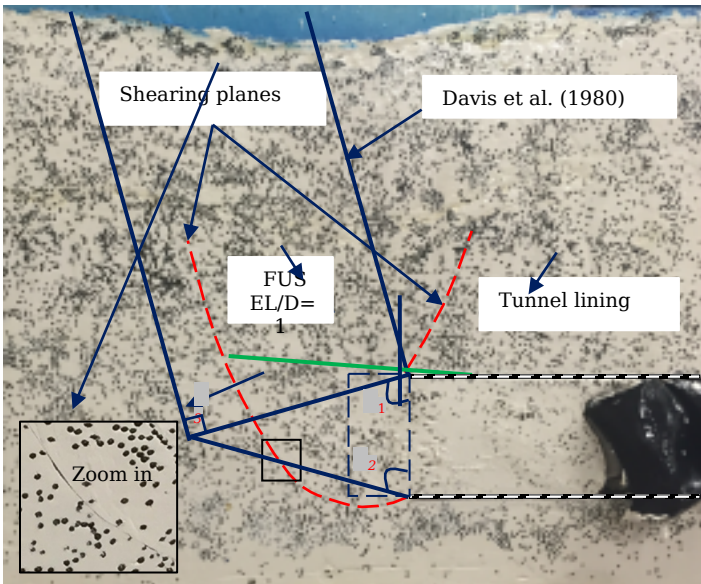


Fig. 10: Photos of forepoles post-test and associated schematics indicating the position of the points of inflexion relative to the model tunnel.

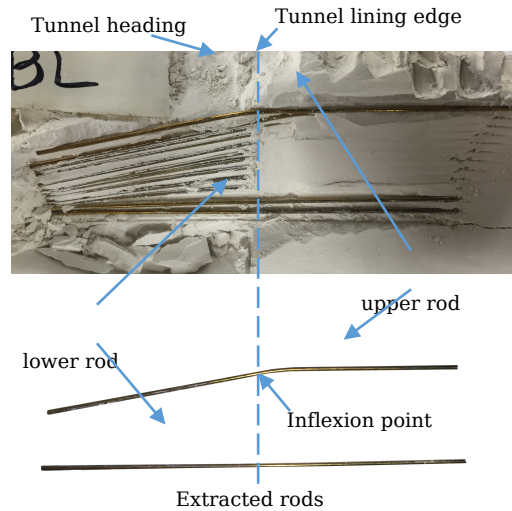


a) Test CD1-R

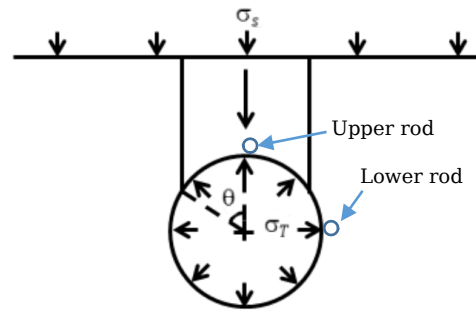


b) Test CD3-R-N

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

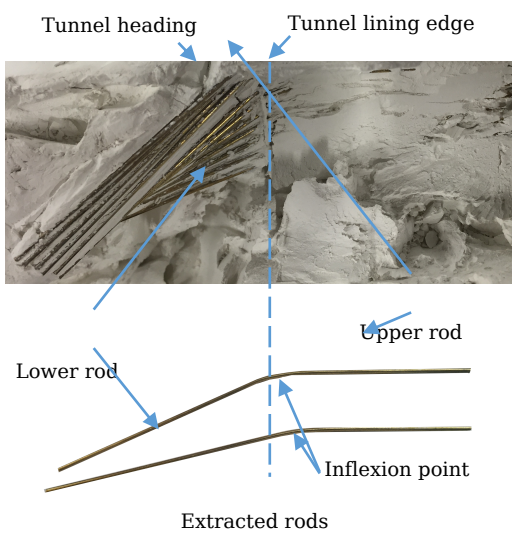


a) Tunnel heading and forepoles post test

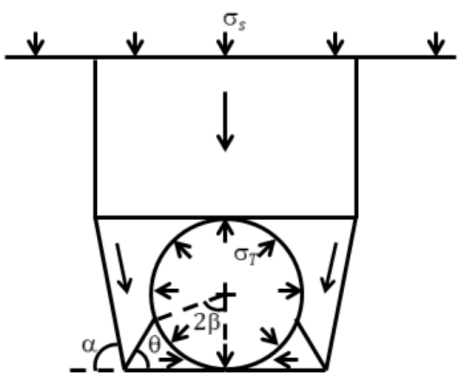


b) Upper bound collapse mechanism A for shallow tunnel (after Davis et al. 1980)

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

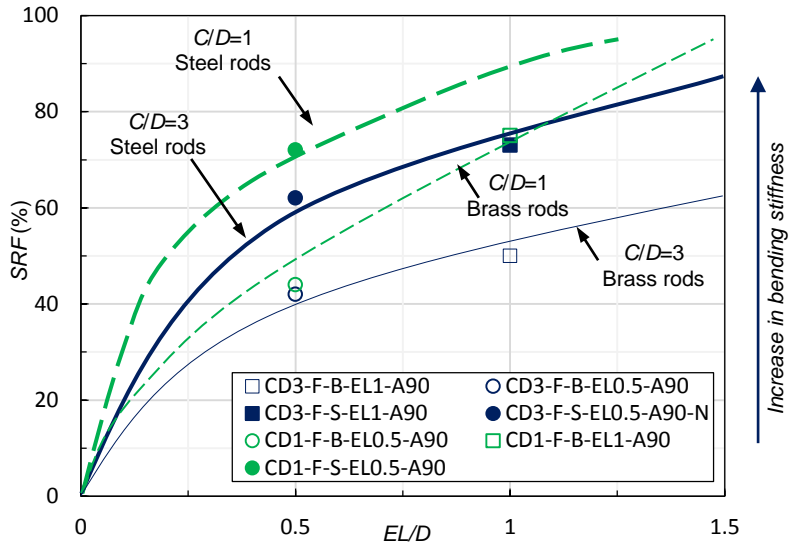


a) Tunnel heading and forepoles post test



b) Upper bound collapse mechanism D for deep tunnel (after Davis et al. 1980)

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



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.

Fig. 14: Relationship between *SRF* and *EL/D* with variation of forepole stiffness.