Analysis of strip footings on fibre reinforced slopes with the aid of Particle Image Velocimetry (PIV)

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ABSTRACT

This paper provides results of a comprehensive investigation into the use of waste carpet fibres for reinforcement of clay soil slopes. The interaction between laboratory scale model slopes made of fibre reinforced clay soil and surface strip footing load was examined. Results for the influence of two variables namely fibre content and distance between the footing edge and the crest of the slope are presented and discussed. Particle Image Velocimetry (PIV) technique was employed to study the deformation of the slope under the surface loading. The front side of the tank was made of a thick Perspex glass to facilitate taking accurate images during the loading stage. To study the stress induced in the slope under footing pressure, excess pore-water pressure and total stress increase were measured at predetermined locations within the slope. The results showed that fibre reinforcement increased the bearing resistance of the model slope significantly. For instance, inclusion of 5% waste carpet fibre increased the bearing pressure by 145% at 10% settlement ratio.

Introduction

Recently, fibre reinforced soils have been examined as a viable engineering material that could mitigate potential collapses of e.g. slopes and embankments. Polypropylene geo-fibres were used in a field trial to repair frequent failure of roadway slope in Beaumont, Texas, USA (Gregory and Chill, 1998). It was reported that the performance of the fibre reinforced slope was enhanced after the addition of fibres. In addition, Ekinci and Ferreira (2012) reported successful application of polypropylene fibres for reinforcing a partially failed embankment located along the M25, London in the UK. Fibres mobilise the tensile resistance of the host soil by interlocking soil particles and forming a composite material with a relatively coherent matrix (see for example; Jamellodin et al., 2010). However, due to the scale of the field projects and associated cost, systematic evaluation of the key parameters affecting the behaviour of fibre reinforced slopes and embankments have not been performed under controlled conditions.

Studies on the use of natural and synthetic fibres such as wool, coir, jute, steel, nylon, polypropylene, polyester, and glass as tension resisting elements have been conducted in the last few decades. Quantification of potential effects of fibres on improving the mechanical response of the reinforced soils under loading was the subject of research (see for example, Santoni and Webster 2001). Several experimentally based studies were undertaken to examine the influence of the key parameters including percentage of fibres, aspect ratio, stress level and testing conditions on the overall behaviour of fibre reinforced granular materials (e.g. Consoli et al., 1998 and 2003; Yetimoglu et al., 2005; Heineck et al., 2005; Diambra et al., 2007; Chen and Loehr, 2008; Hamidi and Hooresfand, 2013; Pino and Baudet, 2015 and Botero et al., 2015). Taking the general consensus of their findings, it is confirmed that addition of small percentage of fibres improves the stress-strain behaviour of

fibre reinforced granular soils, unconfined compression strength and ductility and reduces

post-peak strength loss. Consoli et al. (2009) observed significant increase in the load

carrying capacity of the fibre reinforced sand layers compacted to different relative densities

and subjected to plate load test. The maximum improvement was observed when the fibre

reinforced sand was compacted to a relative density of 90%. Furthermore, high degree of

improvement in the load carrying capacity was recorded at very small strain. These results

were in agreement with those of Kumar and Kaur (2012) who reported significant

improvement in the ultimate bearing capacity of a poorly graded sand bed reinforced with

randomly distributed fibres under plate load test. In a recent study, Nasr (2014) investigated

the effects of reinforcing the active zone behind a model sheet pile wall using polypropylene

fiber and cement kiln dust. Results attained experimentally and numerically confirmed an

increase in the ultimate bearing capacity and ductility of the cemented sand. Bhardwaj and

Mandal (2008) undertook centrifuge tests on fibre reinforced fly ash slopes with different

gravity ratios and concluded that there is an observable increase in the bearing capacity at

failure.

Despite the fact that the mechanical behaviour of cohesive soils is complex, addition of fibres

to cohesive soils was found to suppress excessive volume change and brittleness of the

compacted cohesive soil at failure (see for example; Maher and Ho, 1994; Kumar et al., 2006;

Estabragh et al., 201 and Correia et al., 2015). Moreover, due to the physical interaction

between fibres and the cohesive soil particles, higher unconfined compressive strength and

flexural strength, increased tensile strength and improved ductility can be achieved (Puppala

and Musenda, 2000 and Tang et al., 2007 and Tang et al., 2016). The results of Tang et al.,

(2007) illustrated that fibre-soil interaction dominantly controlled by the bonding strength

and frictional resistance between fibre and soil particles. Fibre reinforcement was also found

75   effective in reducing the number and extent of tension/desiccation cracks, supressing the

76   swelling pressure and increasing the hydraulic conductivity of low permeable clay soils (Al-

77   Akhras et al., 2008, Viswanadham et al., 2009 and Tang et al., 2012).

78

79   Most of the studies investigated the addition of virgin fibres with regular length and thickness

80   in a random fashion. However, re-use and recycling of waste fibres is receiving an increasing

81   attention in the UK and worldwide. For example, sustainable approaches for utilisation of

82   carpet waste fibres are highly favourable and are needed to avoid landfilling of 500,000

83   tonnes/annum in the UK (Mirzababaei, 2013b). The pre- and post-consumer carpet waste

84   fibres are highly variable in length and thickness of individual fibres. A few investigations

85   into reinforcement of soils using waste recycled carpet fibres were reported (Murray et al.,

86   2000, Ghiassian et al., 2004, Fatahi et al., 2012, 2013a,b and Mirzababaei et al., 2013a,b). It

87   was found that similar enhancements to the peak and residual strength of fibre reinforced

88   soils could be achieved by the addition of waste carpet fibres. Murray et al., (2000) suggested

89   that adding 3% of waste carpet fibre was feasible whereas virgin fibres was used with a

90   maximum of 1% from their laboratory tests on sandy silt soils. Based on a series of drained

91   triaxial tests on sand samples reinforced with carpet waste strips, Ghiassian et al., (2004)

92   reported good degree of improvement with either increasing strip content at constant aspect

93   ratio or increasing aspect ratio at constant strip content. Recent studies of Fatahi et al., (2012,

94   2013a) on application of virgin and carpet fibres showed that improved mechanical behaviour

95   of cement stabilised soft kaolinite can be achieved irrespective of the fibre type. The results

96   of their study showed that although both carpet fibre inclusion and cement addition are

97   effective in shrinkage reduction of clay soils, kaolinite and bentonite clay soils show

98   markedly distinctive behaviour. Carpet fibres were found to be more appropriate for

99   reinforcement of bentonite clay soils whereas cement was quite effective in kaolinite clay

100 soil. In another study Fatahi (2013b) concluded that carpet fibres reduce the shear wave

101 velocity of the cement treated clay soil specimens. However, polypropylene virgin fibres tend

102 to increase the shear wave velocity.

103

104 Although, majority of studies were performed in standard testing apparatus, studies on the

105 behaviour of footings constructed on or adjacent to fibre reinforced soil slopes are limited to

106 no single study using waste fibres. This paper therefore aims to explore feasibility and

107 efficiency of waste carpet fibre to enhance the stability of both footing and reinforced soil

108 slope. A series of laboratory scaled model soil slopes reinforced with waste carpet fibres

109 were performed under surface strip footing load. The laboratory tests focused on the effects

110 of; i. fibre content, and ii. distance between footing edge and the crest of the slope. Results

111 for bearing pressure-settlement relation, development of pore water pressure and deformation

112 of fibre reinforced slopes are presented and discussed. The deformation behaviour of the

113 model slopes is estimated using the Particle Image Velocimetry (PIV) technique.

114

115 **Materials**

116 Waste carpet fibres supplied by Carpet Recycling UK (www.carpetrecyclinguk.com) as by

117 product waste (i.e., from edge trimming). Table 1 presents the composition and general

118 properties of fibres. The average water absorption of fibres is estimated to be around 1.35%

119 based on the manufacturer's data. The length of fibres ranged from 2 mm to 20 mm with

120 diverse thicknesses from 80 μm to 1500 μm. It is clear that the proposed edge trimming

121 waste carpet fibres have a wide range of aspect ratio. Previous studies pointed out that

122 increasing the aspect ratio leads to higher fibre reinforcement effect (see, Diambra and

123 Ibriam, 2015) and for the same aspect ratio, the fibre reinforcement effect increases with

5

124   reducing the particle size (see for example, Gray and Al-Refeai, 1986). It should be noted that

125   the aim of the paper is to study the use of waste carpet fibre in stabilising weak soils.

126   The selection of fibre type and content follows from previous studies by Mirzababaei et al.,

127   (2013a,b) in which several investigations were undertaken by the authors examining the

128   workability and efficiency of utilisation of carpet waste fibre on enhancing the behaviour and

129   strength of soils. It was found that mixing of fibres with cohesive soils becomes challenging

130   if more than 5% of waste fibres is added. Nylon carpet waste fibres was mixed successfully

131   with substandard soil up to a maximum of 10 % (Miraftab and Lickfold, 2008). Therefore, a

132   decision was taken to maintain carpet fibres contents of 1%, 3% and 5% so as to relate the

133   outcomes of previous research with the current study.

134   The soil used in this study is sandy clay with liquid limit of 21.1% and plasticity index of

135   10.7%. The effective shear strength parameters (cohesion intercept and internal friction

136   angle) of the host soil were determined from consolidated undrained triaxial testing and

137   found to be 5.3 kPa and 32° respectively. A series of standard Proctor compaction tests were

138   carried out on control soil and soil samples mixed with predetermined amounts of fibres of 1

139   %, 3% and 5%. Fig.1 shows standard Proctor compaction curves for control and fibre

140   reinforced soils. The results show that continuous reduction in maximum dry unit weight and

141   slight increase in optimum moisture content was observed with further increase in fibre

142   content. This is attributed to replacement of soil grains with fibres, which have less specific

143   gravity compared to that of soil grains, and lubricating effect of absorbed water by fibres,

144   which lessens the compaction effort. Similar results have been reported by Kumar et al.,

145   (2006) and Harianto et al., (2008). However, to enable meaningful and fair comparison

146   between proposed tests, fibre reinforced slopes need to be constructed to the same dry unit

147   weight and moisture content. Compaction curves indicated that the maximum dry unit weight

148   of the soil with 5% fibre content is the lowest at 17.8 kN/m^3. This dry unit weight was then

149   set as practically achievable target in all tests. Based on data presented in Fig. 1, the

150   corresponding water content values for soils with different quantities of fibres compacted to a

151   dry unit weight of 17.8 kN/m^3 would be in the range of 16.5~17.5%. It also illustrates that at

152   a moisture content of 16.5%, there is a slight variation on dry unit weight as a function of

153   fibre content. As a result of which, compacting fibre reinforced soils with a water content of

154   16.5% would result in achieving a dry unit weight of 17.8 kN/m^3 ±3%. A series of falling

155   head permeability tests were conducted on samples of unreinforced and fibre reinforced clay

156   soil that were prepared at a dry unit weight of 17.8 kN/m^3. The attained results for the

157   coefficient of permeability are shown in Table 2. The results clearly show that fibre inclusion

158   significantly increases the permeability of the clay soil. The permeability coefficient for soil

159   sample with 5% fibre content is over fourfold that recorded for the control soil sample. In the

160   fibre reinforced soil, provided fibres are mixed evenly within the soil, they serve as multi

161   directional pathways for water to drain quicker, thus increasing the coefficient of

162   permeability. The observed behaviour is in agreement with the results reported by Maher and

163   Ho (1994) and Miller and Rifai (2004), who reported increase in hydraulic conductivity of

164   fibre reinforced soils with fibre contents beyond 1%. Coarse sand with D_{50} of 63µm is used at

165   the base of the slope. The sand was compacted to dry unit weight of 18.0 kN/m^3 at moisture

166   content of 7%. The coefficient permeability of coarse sand was determined from Constant

167   head permeability test and found to be 4.79 x 10^{-4} m/s.

168

169   **Testing Setup**

170   An automated loading machine that is controlled using a Human Machine Interface (HMI) is

171   used to study the behaviour of fibre reinforced slopes. A rigid tank with length of 800 mm,

172   height of 500 mm and width of 300 mm was designed and manufactured to facilitate this

173   study. Fig. 2 shows the laboratory setup. The front side of the tank was made of 15 mm thick

174   Perspex glass to enable observation of the failure mechanism and deformation of the slope

175   under surface loading. Based on the datasheet supplied by the manufacturer, the flexural

176   stiffness of the Perspex glass was found to be 774 $N.m^2$ which might indicate slight

177   deformation under high pressure if care is not undertaken. The tank was therefore braced by a

178   wooden frame all around to minimise/eliminate deformation of the Perspex glass sheet. The

179   back side of the tank was designed so that it provides a number of ports at predetermined

180   locations for the insertion of pressure transducers. The internal sides of the tank were covered

181   with a thin plastic sheet so as to eliminate wall friction effects.

182

183   A solid steel rigid model footing with a width of 50 mm and length of 297 mm was used to

184   simulate plane strain conditions. Load was applied in the centre of the footing through a ball

185   bearing mechanism. The footing was driven axially downwards at the rate of 1 mm/min until

186   a settlement value of 12.5 mm was recorded and the corresponding axial load was measured

187   using a 5 kN load cell. Settlement of the footing was accurately measured using two LVDT

188   mounted on both sides of the loading point. Measurements of load and settlement were

189   recorded every 20 s. To measure the induced excess pore-water pressure, two pressure

190   transducers with ceramic disc of 500 kPa air entry value were inserted into the back of the

191   slope at predetermined locations. The surface of pressure transducers' ceramic discs was

192   smeared with a saturated kaolinite paste to improve the interface between the pressure

193   transducer's ceramic disc and the compacted clay soil. Pressure transducers were saturated

194   for 72 hours prior to testing using a developed saturating cylinder to apply cycles of -90 kPa

195   (with the aid of a vacuum pump) and +1800 kPa (using a GDS pressure controller). Pressure

196   transducers were calibrated prior to use and their accuracy was found to be within ±1 kPa.

197   Three mini load cells with capacity of 700kPa and accuracy of ±0.7 kPa were also utilised for

198   measurements of the total stress at the base of the slope. Measurements from the pressure

199   transducers and load cells were recorded electronically through data acquisition system every

200   1 s.

201

202   **Experimental programme and procedure**

203   Fig. 3 shows a schematic drawing for the geometry of the model slope, locations of the strip

204   footing, load cells and pressure transducers in each series of tests. A total of 11 experiments

205   in 3 series were conducted to examine the behaviour of unreinforced and fibre reinforced soil

206   slopes with 1%, 3% and 5% fibre content. In this paper, Footing Edge Distance Ratio (FEDR)

207   is introduced as a dimensionless ratio of the distance between nearest edge of the footing and

208   crest of the slope (see, distance X in Fig. 3) over the width of the footing. Three different

209   FEDRs of 0, 1 and 3 were studied for both unreinforced and fibre reinforced model slopes.

210   All model slopes were constructed with a slope angle of 45° overlying a layer of 100 mm

211   thick compacted sand layer so as to provide a relatively stiff permeable boundary for the

212   slope and to enhance capturing the stress change at the base.

213   One of the challenges encountered in this study is how to ensure preparation of a

214   homogenous fibre reinforced soil in large quantity. Up-to-date, there is a lack of standardised

215   mixing procedure for preparation of homogeneous fibre reinforced soils (Botero et al., 2015).

216   Moist tamping and moist vibration techniques have been found effective in preparation of

217   homogeneous granular soil samples for experimental studies but they are not fairly satisfying

218   to produce isotropic distribution of fibres (Ibraim et al., 2012). Diambra et al., (2007) showed

219   that preparing coarse grained fibre reinforced soil samples by moist tamping technique results

220   in 97% of the fibres are oriented preferentially at ±45° to the horizontal axis. Results of Saad

221   et al., (2012) demonstrated that increasing the number of soil layers and compressing the soil

sample from both ends results in even distribution of fibre within the specimen, and improves the uniformity of density profile and the integrity of fibre reinforced samples. It was reported that the proposed static approach enhance the repeatability of the unconfined compression strength test results. On the other hand, Diambra and Ibraim (2014) claimed that in fibre reinforced kaolinite clay samples consolidated from slurry, the orientation of fibres is rather isotropic. Despite the fact that preparation of homogenous randomly oriented fibre reinforced soils is challenging, most of the problems could be minimised or eliminated by decreasing the amount of added fibres and increasing the water content of fibre reinforced cohesive soils (Mirzababaei et al. 2013b).

In this paper to produce a relatively homogenous mix, a rotary drum mixer was used. Dry soil and fibres were mixed initially followed by adding predetermined amounts of water upto reaching the desired moisture content. The mixing process was then continued until a uniform mixture was achieved. The geometry of the slope was marked on back wall of the tank and the model slope was subsequently constructed in five equal compacted layers of 50 mm thick by tamping technique. Before placing the following layer, the surface was scratched with a spatula and the procedure was continued until reaching the full height of slope. Once the slope was constructed, it was covered by polyethylene sheet to prevent evaporation of water from the soil slope. The slope was then left for a period of 24 hours which was found sufficient to reach equalisation of water within the slope. Samples have been extracted from different locations within the slope to examine the uniformity of density and fibre distribution. It was found that density varies within a range of ±7.3 % and fibre content is within $\pm17\%$. This highlights that further work is needed to further enhance the uniformity of fibre and density. The model footing was placed on the surface at the required FEDR. The model footing was then loaded in such way so that a settlement rate of 1 mm/min was attained in all tests.

247

PIV Technique

249 Particle Image Velocimetry (PIV) theory was first introduced by Adrian (1991) in the field of

250 fluid mechanics. The technique relies on taking images of a seeded surface and tracking the

251 movement of individual particles in consecutive images. PIV method has slightly been

252 modified to fit Geotechnical Engineering testing. PIV is advantageous over other techniques

253 since deformation of the soil can be determined non-invasively without causing any

254 disturbance to the testing process. Application of PIV method in naturally textured soils such

255 as sand with different coloured grains does not require any extra process to create pseudo-

256 texture. However, to create a suitable contrast that is recognisable when illuminated, it is

257 required to introduce texture to the surface of the clay soil by addition of dyed particles such

258 as coloured sand (White et al., 2003). In this study, the front side of slope was sprayed with

259 coloured sand so as to enhance the visibility of the slope and its deformation.

260 Dynamic Studio package (www.DantecDynamics.com) was used to perform PIV analysis on

261 the acquired images. All images in this study were taken using a Nikon D90 camera with a

262 resolution of 12M Pixel. The camera was positioned 1.0 m away with its optical axis at right

263 angle to the front surface of the tank. The size of the view field was 387.4 mm x 257.3 mm.

264 Given, the size of the images (4288x2848 pixels), the scale of the view field was determined

265 to be 0.090345 mm/pixel. To verify the accuracy of the deformation results from PIV

266 analysis, an arbitrary point A was selected at a distance of 50 mm from the centre of the

267 footing at the top surface of the slope (see, Fig. 4). The displacement of Point A was then

268 determined against a stationary point on the tank in two photographs that were taken before

269 loading and at footing pressure of 50 kPa using scaling method in AutoCAD. The results of

270 the vertical displacement of Point A is 0.3 mm whereas that given by PIV analysis is 0.29674

271 mm (see, Fig. 6). Therefore, the accuracy of the PIV technique in this study was considered

272 to be acceptable.

273

274 **Results and Discussion**

275 Data for the footing pressure and settlement, deformation of the slope, induced excess pore-

276 water pressure and the total stress increase at the base of the slope are generated and

277 discussed in this section to highlight the impact of studied parameters on the behaviour of

278 fibre-reinforced clay slopes. It should be noted that a non-dimensional Footing Settlement

279 Ratio (S/B) is utilised hereafter where; S stands for the footing settlement and B denotes the

280 footing width. The following sections are organised to discuss the effects of fibre reinforced

281 slopes that were loaded at three different FEDRs on:

282   a) Relationship between footing pressure and settlement ratio;

283   b) Contours of horizontal and vertical displacements of the slope at a footing pressure of

284   50 kPa; and

285   c) Excess pore-water pressure and total stress increase.

286 Of note, a bearing pressure of 50 kPa for analysis of the results was selected as it was found

287 to be the maximum footing pressure of the unreinforced slope. Since, images and footing

288 pressure measurements were taken every 20 s, it was straightforward exercise to select the

289 image corresponding to or very close to the required pressure for PIV analysis.

290

291 **Footing Edge Distance Ratio of three**

292 Fig. 5 shows the results of the relationships between the footing pressure and settlement ratio

293 for fibre reinforced slopes with fibre content of 0, 1%, 3% and 5%. In this series, all tests

294   were performed on the footing placed at FEDR of 3. The results clearly demonstrate that

295   addition of fibres enhances the stiffness of the fibre reinforced slopes. The figure confirms

296   the significant increase in the ultimate bearing capacity with increasing fibre content. Fibre

297   reinforced slopes with 3% and 5% fibre contents showed 85% and 145% increase in the

298   measured footing pressure at 10 % settlement ratio respectively over that attained for

299   unreinforced slope. The increase in footing bearing pressure can be attributed to the

300   reinforcement effects as a result of enhanced interlocking, higher shear strength parameters of

301   reinforced soils and higher passive resistance. The figure also suggests that as the percentage

302   of fibre increases the failure mode changes from punching shear failure on slope with 0%

303   fibre content to a general shear failure over large area at 5% fibre content. The relationship

304   between the footing pressure and settlement ratio of the 5% fibre reinforced model slopes is

305   found to be almost linear for the range of footing-settlement ratio between 3% and 25%

306   indicating elastic behaviour of the fibre reinforced material. Careful inspection of Fig. 5

307   illustrates that for the same footing pressure, less settlement/movement is experienced with

308   increasing fibre content. This is due to increased stiffness of fibre compacted soils

309   (Mirzababaei et al., 2013a) and increased number of fibre per unit volume and the

310   corresponding interfacial area (Tang et al., 2016). This is also in good agreement with

311   previous results published by Estabragh et al., (2011) on a series of undrained triaxial tests on

312   reinforced soft clay soils with nylon fibres.

313

314   Horizontal and vertical displacement contours obtained using PIV technique of unreinforced

315   and 5% fibre reinforced slopes at footing pressure of 50 kPa are presented in Fig. 6a-d

316   respectively. Of note, horizontal displacement towards the right and upward vertical

317   displacement are considered to be positive. Results presented in Fig. 6a for the unreinforced

318   clay slope show a typical deformation pattern of unreinforced soil slope in which a tendency

319 to deform laterally towards the free slope surface is high and very little deformation is

320 recorded for soil particles underneath the centre of the footing. Significant lateral deformation

321 is noticeable down to a depth of 2B. Comparing data presented in Figs. 6a and b illustrates

322 that the lateral deformation of 5% fibre reinforced slope is markedly smaller than that

323 experienced for the unreinforced slope for the same soil depth. This could be attributed to the

324 high degree of interlocking and improved shear strength parameters. As a result, the

325 reinforcing fibres transfer developed shear stresses beneath the loaded area to adjacent stable

326 soil zones resulting in a wider and deeper failure. Furthermore, existence of fibres within the

327 soil skeleton reduces the movement of soil particles due to their pull out resistance which is

328 controlled by the interfacial shear resistance at the fibre-soil interface. Therefore, the

329 reinforced soil not only result in increasing the bearing resistance due to developing larger

330 failure zone but also reduce the stress level underneath the loaded area leading to reduced

331 deformation.

332

333 Analysis of the vertical displacement contours in Fig. 6c for unreinforced soil slope illustrates

334 that settlement of the slope extends laterally to a region of ± B from the centre of the footing

335 beyond which the soil heaves in both sides. The results also indicated that significant

336 deformation occurred underneath the footing taking the shape of a bulb and extending down

337 to a depth of 2B. However, the vertical deformation pattern of fibre reinforced slope with 5%

338 fibre content is observed to be characteristically different as shown in Fig. 6d. The vertical

339 deformation is significantly lower, decreases with depth and covers larger area of the slope.

340 The soil heaved after a distance of ±2B. This illustrates that fibres integrated relatively well

341 with the soil particles to form a relatively uniform composite material that able to dissipate

342 the energy under the loaded area compared to unreinforced soil. This is in good agreement

343 with the postulation of Jamellodin et al., (2010)'s observation of significant improvement in

344   the failure deviator stress and shear strength parameters of the soft soil reinforced with palm

345   fibres.

346

347   Fig. 7 shows the evolution of excess pore-water pressure at predetermined locations as

348   presented in Fig. 3d. It is clear from Fig. 7 that zero excess pore water pressure was recorded

349   at all measurement points before the start of loading. This confirms that leaving the

350   constructed slope for 24 hrs was sufficient to reach stabilisation of water. Data recorded for

351   the excess pore water pressure show that positive excess pore water pressure is recorded in

352   the soil part of the slope that is in the left hand side of the footing irrespective of the

353   settlement ratio. In addition, unreinforced soil slope experienced higher positive excess pore

354   pressure. This is likely due to the confinement of soil in this part of the slope leading to

355   contraction of the soil. In contrast, the excess pore water pressure distribution measured in the

356   right hand side showed a slightly negative values. The observed excess pore-water pressure is

357   related to the deformation pattern and permeability of the unreinforced and reinforced soil

358   slopes at the measurement locations. For unreinforced soils in the right hand side of the

359   footing, the deformation patterns suggest that the soil is under compression leading to high

360   positive excess pressure which is further amplified by the inability of the soil to dissipate

361   excess water pressure due to its low coefficient of permeability. In contrast, the deformation

362   pattern in the part of slope to the right hand side suggests a slight dilative behaviour leading

363   to a small negative pressure measurements that are close to zero. It can be shown that fibre

364   reinforced slope with 5% fibre content resulted in less generated excess pore-water pressure

365   at both sides of the footing. This is due to the higher permeability of the fibre reinforced soil

366   compared to unreinforced soil (see, Table 2) which speeds dissipation of induced excess

367   pore-water pressure during loading.

368

Footing Edge Distance Ratio of one

A second series of tests were performed on soil slopes with 0, 1% and 3% fibre contents at FEDR of 1. Fig. 8 shows the results of load deformation behaviour of unreinforced and fibre reinforced slopes. Substantial enhancement can be observed on fibre reinforced slope with 3% fibre content. At a settlement ratio of 10%, the measured bearing pressure is 61 kPa yielding an increase of about 76% over that measured for unreinforced slope. No significant effect can be observed in the load carrying capacity for a soil slope reinforced with 1% fibres. The results of 3 % fibre is similar to those obtained for FEDR of 3 suggesting that fibre reinforced soil distribute the developed stress well over larger area. The load-deformation behaviour shown in Fig. 8 also confirms the increase in stiffness of the fibre reinforced soil with increase in fibre content.

Figs. 9a-d show horizontal and vertical displacement contour lines under the footing for unreinforced and 3% fibre reinforced slopes. Examining the deformation in the right hand side of footing shows that movement of soil particles is primarily towards the free face of the slope. As it can be seen in Fig. 9a, the lateral deformation of the unreinforced slope is still significant down to the depth of 3B. However, its vertical settlement is limited to a depth of 2B as shown in Fig. 9c. Fig. 9b clearly shows that fibre inclusion has limited the soil lateral deformation of the slope. These results are in harmony with previously report results that fibres reduce movement of soil particles and desiccation cracks due to bonding strength and frictional resistance between fibre and soil particles as suggested (Tang et al., 2007 and Tang et al., 2016). Fig. 9d demonstrates that the vertical settlement of the soil under footing load has been decreased significantly with increase in fibre content. However, the vertical settlement of the slope is not uniform compared to the deformation pattern of FEDR of 3 with

392   5% fibre content (Fig. 6d). Fig. 10 shows the excess pore-water pressure behaviour for model

393   slopes with unreinforced and 3% fibre reinforced slope measured under the footing's centre

394   (see Figure 3c). Measurement of excess pore-water pressure below the footing showed higher

395   values for unreinforced soil than reinforced soil. This is mainly due to the higher permeability

396   of the reinforced soil leading to swift drainage of pore water and dissipation of excess pore-

397   water pressure. As previously mentioned the part of the soil slope in the left hand side of the

398   footing is under compression whereas the right hand side of the slopes seems to be

399   undergoing very limited dilative behaviour.

Footing Edge Distance Ratio of zero

401   The load-settlement curves on the model slopes at FEDR of 'Zero' with fibre content of 0%,

402   1%, 3% and 5% are presented in Fig. 11. Footing pressure curves of fibre reinforced slope

403   with 3% and 5% fibre contents were significantly distinctive from those of unreinforced and

404   1% fibre content. This figure also shows significant increase in the stiffness of the fibre

405   reinforced soil with increase in fibre content. Increase in fibre content to 3% and 5% resulted

406   in 71% and 97% increase in the footing bearing pressure respectively over that of

407   unreinforced slope at footing settlement ratio of 10%. The relationship between footing

408   pressure and settlement ratio on a soil slope reinforced with 5% fibre content was found to be

409   highly linear over the measured range of settlement ratio up to 25%. Such linear elastic load-

410   deformation behaviour was also seen for the case of 5% fibre reinforced slope with FEDR of

411   3. This elastic behaviour is attributable to; i. the structure of fibre reinforced soils due to

412   addition of high percentage of fibres which are tangled around soil particles leading to

413   increased shear resistance, and ii. the overburden pressure created by settlement. These

414   results highlight that for a 5% fibre reinforced soil, fibres are still in phase 1 which is pure

415   elastic phase out of the five progressive pull out phases proposed by Zhu et al. (2014). Data

416   for 1% fibre content show no enhancement to the behaviour of fibre reinforced soil slope

417   which is consistent with those recorder at FEDR of 1. Previous studies confirmed that

418   substantial loss in the footing bearing pressure is observed as the footing location becomes

419   closer to the crest. However, utilisation of fibre as reinforcing elements spreads the generated

420   shear stresses underneath the loaded area out over larger area which contributes significantly

421   to increase in the bearing pressure in comparison with that measured for unreinforced soil

422   slope.

423

424   Data for the horizontal and vertical displacement contour lines under the footing for

425   unreinforced and 5% fibre reinforced slopes are presented in Figs. 12a-d. It is clear that the

426   horizontal and vertical deformations of unreinforced soil slope are markedly higher than

427   those experienced at lower value of FEDRs. The lateral deformation of the unreinforced slope

428   is noticeable to a depth of 3B. However, its vertical settlement is limited to the depth of 2.5B.

429   Comparing Figs. 6a, 9a and 12a demonstrates that the extent of lateral and vertical

430   deformation within the unreinforced soil has been influenced by the location of the footing

431   with respect to the slope face. With 5% fibre content, the deformation of the reinforced soil

432   slope decreased significantly showing consistently small deformation through the whole body

433   of the slope (Figs. 12b and d). The displacement patterns measured at different FEDRs for

434   unreinforced and fibre reinforced soil slopes indicate that fibres acted by holding the soil

435   particles from moving towards the slope face resulting in reduced horizontal deformation.

436   This leads to spreading the footing pressure deeper and wider area which in turn means a

437   longer failure surface, greater bearing capacity and reduced vertical deformation.

438

439   Fig. 13 shows the excess pore-water pressure behaviour of the slope with FEDR of 'zero' at

440   predetermined locations (see, Fig. 3d). Low negative excess pore-water pressure was

441   measured for unreinforced slope in the right side of the footing due to displacement of the

442   soil slope at this location towards the free slope surface (Figs. 12a and c). However, for fibre

443   reinforced slopes, the measured excess pore-water pressure at the same location was almost

444   close to zero due to its higher permeability and less deformation compared to unreinforced

445   slope. The positive excess pore-water pressure measured at left side of the footing for

446   unreinforced model slopes is indicative of compression behaviour of soil in this region. This

447   can be further explained through deformation patterns of the slope with settlement and lateral

448   deformation to the confined side of the tank (Figs. 12a and c). However, with 5% fibre

449   inclusion, the measured excess pore-water pressure is close to 'zero' due to higher

450   permeability of the reinforced soil compared to unreinforced soil.

451

452   **Total stress increase at the base**

453   Measurements for the increase in total stress were taken at three points at the base of the

454   constructed slopes as given in Fig. 3. Fig. 14 presents the measured increase in the total stress

455   at the base of the slopes on slopes tested at different values of FEDRs and fibre contents

456   under a footing pressure of 50 kPa. The data shown in this figure demonstrate that to a great

457   extent the measured stress distribution is typical in which vertical stress is high underneath

458   the centre of the loaded area and decays as measurement point moves away from the centre.

459   Furthermore, with increasing the fibre content in the soil slope transfer of stress is

460   considerably enhanced reaching deeper layers and causing considerable increase in total

461   stress below the centre point of the loaded area. The observed stress behaviour is directly

462   linked to the shear strength of the fibre reinforced soils. Previous studies (see for example

463   Mirzababaei et al., 2013a and Tang et al., 2007) reported the enhanced shear strength

464   parameters with the increased amount of fibres which in turn result in lowering the horizontal

465   shear stress and enhancing the transfer of vertical stress.

466   This is in agreement with the observed deformation pattern from PIV analysis that showed a

467   uniform deformation pattern of the fibre reinforced slope over a larger area. This proves that

468   fibres integrated relatively well with the soil particles forming a relatively uniform

469   strengthened composite material that can offer higher resistance to loads. In unreinforced soil

470   slope, the horizontal and vertical displacements are intensified over smaller areas that are

471   close to the loaded area. This would result in substantial movement of soil particles near soil

472   surface due to concentration of stress. The measured increase in total stress at the left side of

473   the footing is slightly less than that of measured at right of the footing. This could be

474   attributed to the movement of soil towards the free face of the slope and wall effects that

475   counteract the stress transfer. In addition, due to the slight variation of density and fibre

476   content across the slope, stress transfer would be influenced.

477

478   **Coupled effect of the footing location and fibre content**

479   To summarise the coupled effect of FEDR and fibre content on the footing bearing pressure,

480   a 3D graph has been plotted and presented in Fig. 15. Of note, all bearing pressure

481   measurements were taken at a settlement ratio of 10%. This figure shows that pronounced

482   effect for fibre addition is clear making it an efficient technique to overcome potential loss in

483   the bearing pressure for footings constructed in close proximity to slope faces. High degree of

484   bearing pressure enhancement is observable irrespective of the footing edge distance ratio in

485   comparison with those attained on unreinforced soil slope. Fig. 16 shows cross sections of the

486   failed area on unreinforced soil and reinforced soil with 5% fibre content. The results

487   indicated clearly that fibres integrated and interlocked well with the soil particles forming a

488   relatively homogenous reinforced soil. There are no visible cracks observed on fibre

489   reinforced soil. Nevertheless, very clear punching shear failure is noticeable on unreinforced

490   soil slope. These suggest that on fibre reinforced soils there is high degree of stress transfer to

491   adjacent and deeper areas that are more stable which in turn leads to wider and deeper failure

492   surface. Hence the footing deformation reduces substantially with the increase in fibre

493   content.

494   **Scale and boundary effects**

495   Due to difficulties and associated cost to load full scale model footings under controlled

496   conditions to failure, studies based on experimental models are commonly performed.

497   Although, the whole system is scaled down to a laboratory scale, the use of such models are

498   useful to acquire deeper understanding of the behaviour of slopes and foundations on or close

499   proximity to the slope face (see for example; Choudhary et al., 2010 and Castelli and Lentini,

500   2012). Careful design of the laboratory scaled models is required to ensure that the observed

501   behaviour can be extrapolated to larger scale. However, it is likely that scale effect might

502   cause some influence on experimentally attained results (Vesic, 1973). Key parameters for

503   consideration in small scale fibre reinforced soil slopes include footing size, particle size

504   distribution, density, fibre aspect ratio, wall friction and boundary conditions.

505

506   Recently Toyosawa et al., (2013) stated that there is no effect for the model footing size on

507   the bearing capacity if the ratio of footing diameter to particle size is more than 50. Earlier

508   reporting suggested the ratio of footing width to particle diameter has to be more than 200 to

509   eliminate scale effects (see for example; Habib, 1974). In this study, the ratio of the footing

510   width to the median diameter of the sandy clay material is close to 250 which is satisfactory.

511   Considering the aspect ratio and length of fibre, Diambra and Ibriam (2015) concluded that to

512   achieve the desired effect of fibres, the aspect ratio is required to be between 10 and 100 and

513   fibre length is at least 10 times the average particle size which have been met in the current

514   study. However, controlling the aspect ratio and fibre length of waste is extremely difficult.

515   So, it seems reasonable that further experimentations are needed to increase understanding of

516   fibre reinforced effects with variable fibre aspect ratio and fibre length.

517

518   Jayasree et al., (2012) based on numerical simulations suggested that wall effects could be

519   reduced by increasing tank width to footing width ratio and reducing angle of friction

520   between soil and tank sides. In this study, all tests were performed under plain strain

521   conditions in a tank with a length and width of 16 and 6 times the width of footing to reduce

522   wall effects and to provide some flexibility in positioning the footing with respect to the slope

523   face. The tank sides are covered by plastic sheet to minimise wall effects. Centrifugal

524   compression tests on fibre reinforced slopes would be recommended to provide deeper

525   understanding of the real behaviour.

526

527   **Conclusions**

528   A comprehensive and systematic laboratory study into the effects of fibre content and footing

529   edge ratio on the behaviour of slope under surface loading was undertaken. Particle image

530   velocimetry technique was employed to investigate the deformation pattern of the slope

531   throughout the experiments. Excess pore-water pressure behaviour and total stress increase at

532   predetermined locations within the slope were also measured using a set of instrumentations.

533   Based on the experimental analysis, the following conclusions can be made:

534 • Fibre reinforcement enhanced the bearing resistance of the model slopes significantly.
535 The footing pressure on 5% fibre reinforced model slope showed 145% improvement
536 over that attained on unreinforced model slope at footing edge distance ratio of 3.

537 • The use of fibres increased the strength of the reinforced soil slope due to the
538 interlocking of the soil particles with fibres resulting in a reduced deformation of the
539 slope in both vertical and lateral directions. Moreover, fibres enhanced the integrity of
540 the slope and prevented occurrence of tension cracks at failure. The stiffness of the
541 slope increased significantly with increase in fibre content that resulted in less
542 deformation of fibre reinforced slopes for the same footing pressure.

543 • In fibre reinforced model slopes, degree of stress transfer is higher which is attributed
544 to enhanced shear strength and confinement.

545 • In general, addition of 1% Fibres showed insignificant improvement in the footing
546 bearing pressure for all footing edge distance ratios.

547 • Fibre reinforced slopes with 5% fibre showed high degree of elastic behaviour so that
548 the footing pressure-settlement ratio relationships was almost linear over the range of
549 settlement ratio upto 25%.

550

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677

678   List of tables

679   Table 1: properties of waste carpet fibres

680   Table 2: permeability coeficients