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1 Analysis of strip footings on fibre 2 reinforced slopes with the aid of 3 Particle Image Velocimetry (PIV)

4 Mehdi Mirzababaei; PhD, Lecturer; Central Queensland University, Melbourne Campus,
5 Victoria, Australia

6 Mostafa Mohamed*; PhD, Senior Lecturer, Faculty of Engineering and Informatics,
7 University of Bradford, UK

8 Mohsen MirafTAB, PhD, Professor, Institute for Materials Research and Innovation,
9 University of Bolton, UK

10 *Corresponding author (Email: m.h.a.mohamed@bradford.ac.uk)

11 **ABSTRACT**

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

24

25 **Introduction**

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

38

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

50 fibre reinforced granular soils, unconfined compression strength and ductility and reduces
51 post-peak strength loss. Consoli et al. (2009) observed significant increase in the load
52 carrying capacity of the fibre reinforced sand layers compacted to different relative densities
53 and subjected to plate load test. The maximum improvement was observed when the fibre
54 reinforced sand was compacted to a relative density of 90%. Furthermore, high degree of
55 improvement in the load carrying capacity was recorded at very small strain. These results
56 were in agreement with those of Kumar and Kaur (2012) who reported significant
57 improvement in the ultimate bearing capacity of a poorly graded sand bed reinforced with
58 randomly distributed fibres under plate load test. In a recent study, Nasr (2014) investigated
59 the effects of reinforcing the active zone behind a model sheet pile wall using polypropylene
60 fiber and cement kiln dust. Results attained experimentally and numerically confirmed an
61 increase in the ultimate bearing capacity and ductility of the cemented sand. Bhardwaj and
62 Mandal (2008) undertook centrifuge tests on fibre reinforced fly ash slopes with different
63 gravity ratios and concluded that there is an observable increase in the bearing capacity at
64 failure.

65

66 Despite the fact that the mechanical behaviour of cohesive soils is complex, addition of fibres
67 to cohesive soils was found to suppress excessive volume change and brittleness of the
68 compacted cohesive soil at failure (see for example; Maher and Ho, 1994; Kumar et al., 2006;
69 Estabragh et al., 201 and Correia et al., 2015). Moreover, due to the physical interaction
70 between fibres and the cohesive soil particles, higher unconfined compressive strength and
71 flexural strength, increased tensile strength and improved ductility can be achieved (Puppala
72 and Musenda, 2000 and Tang et al., 2007 and Tang et al., 2016). The results of Tang et al.,
73 (2007) illustrated that fibre-soil interaction dominantly controlled by the bonding strength
74 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, suppressing 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

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/m³. 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 $17.8 \text{ kN/m}^3 \pm 3\%$. 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 $63\mu\text{m}$ 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 $4.79 \times 10^{-4} \text{ m/s}$.

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 $\pm 1 \text{ kPa}$.
197 Three mini load cells with capacity of 700kPa and accuracy of $\pm 0.7 \text{ kPa}$ 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 $\pm 45^\circ$ to the horizontal axis. Results of Saad
221 et al., (2012) demonstrated that increasing the number of soil layers and compressing the soil

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

231 In this paper to produce a relatively homogenous mix, a rotary drum mixer was used. Dry soil
232 and fibres were mixed initially followed by adding predetermined amounts of water upto
233 reaching the desired moisture content. The mixing process was then continued until a uniform
234 mixture was achieved. The geometry of the slope was marked on back wall of the tank and
235 the model slope was subsequently constructed in five equal compacted layers of 50 mm thick
236 by tamping technique. Before placing the following layer, the surface was scratched with a
237 spatula and the procedure was continued until reaching the full height of slope. Once the
238 slope was constructed, it was covered by polyethylene sheet to prevent evaporation of water
239 from the soil slope. The slope was then left for a period of 24 hours which was found
240 sufficient to reach equalisation of water within the slope. Samples have been extracted from
241 different locations within the slope to examine the uniformity of density and fibre
242 distribution. It was found that density varies within a range of $\pm 7.3\%$ and fibre content is
243 within $\pm 17\%$. This highlights that further work is needed to further enhance the uniformity of
244 fibre and density. The model footing was placed on the surface at the required FEDR. The
245 model footing was then loaded in such way so that a settlement rate of 1 mm/min was
246 attained in all tests.

247

248 **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 $\pm B$ 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 $\pm 2B$. 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

369 **Footing Edge Distance Ratio of one**

370 A second series of tests were performed on soil slopes with 0, 1% and 3% fibre contents at
371 FEDR of 1. Fig. 8 shows the results of load deformation behaviour of unreinforced and fibre
372 reinforced slopes. Substantial enhancement can be observed on fibre reinforced slope with
373 3% fibre content. At a settlement ratio of 10%, the measured bearing pressure is 61 kPa
374 yielding an increase of about 76% over that measured for unreinforced slope. No significant
375 effect can be observed in the load carrying capacity for a soil slope reinforced with 1% fibres.
376 The results of 3 % fibre is similar to those obtained for FEDR of 3 suggesting that fibre
377 reinforced soil distribute the developed stress well over larger area. The load-deformation
378 behaviour shown in Fig. 8 also confirms the increase in stiffness of the fibre reinforced soil
379 with increase in fibre content.

380 Figs. 9a-d show horizontal and vertical displacement contour lines under the footing for
381 unreinforced and 3% fibre reinforced slopes. Examining the deformation in the right hand
382 side of footing shows that movement of soil particles is primarily towards the free face of the
383 slope. As it can be seen in Fig. 9a, the lateral deformation of the unreinforced slope is still
384 significant down to the depth of 3B. However, its vertical settlement is limited to a depth of
385 2B as shown in Fig. 9c. Fig. 9b clearly shows that fibre inclusion has limited the soil lateral
386 deformation of the slope. These results are in harmony with previously report results that
387 fibres reduce movement of soil particles and desiccation cracks due to bonding strength and
388 frictional resistance between fibre and soil particles as suggested (Tang et al., 2007 and Tang
389 et al., 2016). Fig. 9d demonstrates that the vertical settlement of the soil under footing load
390 has been decreased significantly with increase in fibre content. However, the vertical
391 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.

400 **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

551 **References**

552 Adrian, R.J. (1991). "Particle imaging techniques for experimental fluid mechanics. Annual
553 Review of fluid Mechanics", 23, 261-304.

554 Al-Akhras, N.M., Attom, M.F., Al-Akhras, K.M., Malkawi, A.I.H. (2008). "Influence of
555 fibres on swelling properties of clayey soil" Geosynthetics International Journal, 15(4), 304-
556 309

557 Bhardwaj, D.K., Mandal, J.N. (2008). "Centrifuge modelling on fibre reinforced fly ash
558 slope" In: proceedings of the 4th Asian Regional Conference on Geosynthetics, Shanghai,
559 China.

560 Botero, E., Ossa, A., Sherwell, G., and Ovando-Shelley, E. (2015). "Stress-strain behavior of
561 a silty soil reinforced with polyethylene terephthalate (PET)" *Geotextiles and*
562 *Geomembranes*, 43(4), 363-369.

563 Castelli, F and Lentini, V. (2012). "Evaluation of the bearing capacity of footings on slopes".
564 *Int. J. of Physical Modelling in Geotechnics*, 12(3), 112-118.

565 Chen, C.W. and Loehr, J.E. (2008). "Undrained and drained triaxial tests of fibre-reinforced
566 sand" In: *Proceedings of the 4th Asian Regional Conference on Geosynthetics*. Shanghai,
567 China, 114-120.

568 Choudhary, A.K., Jha, J.N. and Gill, K.S.(2010)." Laboratory investigation of bearing
569 capacity behaviour of strip footing on reinforced flyash slope". *Geotext and Geomemb.*, 28,
570 393-402.

571 Consoli, N.C., Casagrande, M.D.T., Thome, A.R., Dalla Rosa, F. and Fahey, M. (2009).
572 "Effect of relative density on plate loading tests on fibre-reinforced sand" *Geotechnique*,
573 59(5), 471-476.

574 Consoli, N.C., Corte, M.B., Festugato, L. (2012). "Key parameter for tensile and compressive
575 strength of fiber-reinforced soil lime mixtures" *Geosynth. Int.*, 19(5), 409-414.

576 Consoli, NC., Prietto, M., Ulbrich, A. (1998). "Influence of fibre and cement addition on
577 behavior of sandy soil" *J. of Geotechnical Engineering*, 124(12), 1211-1214.

578 Consoli, N., Casagrande, M., Prietto, P., and Thomé, A. (2003). "Plate Load Test on Fiber-
579 Reinforced Soil." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-
580 0241(2003)129:10(951), 951-955

581 Correia, A., Venda Oliveira, P., and Custódio, D. (2015). "Effect of polypropylene fibres on
582 the compressive and tensile strength of a soft soil, artificially stabilised with
583 binders" *Geotext. Geomemb.*, 43(2), 97-106.

584 Diambra, A. and Ibraim, E. (2015). "Fibre-reinforced sand: interaction at the fibre and grain
585 scale" *Geotechnique* 65 (4), 296-308.

586 Diambra, A., Ibraim, E. (2014). "Modelling of fibre-cohesive soil mixtures" *Acta*
587 *Geotechnica*, 9, 1029-1043.

588 Diambra, A., Russell, A.R., Ibraim, E. and Muir Wood, D. (2007). "Determination of fibre
589 orientation distribution in reinforced sands" *Geotechnique*, 57(7), 623-628.

590 Ekinci, A. and Ferreira, P.M.V. (2012). "The undrained mechanical behaviour of a fibre-
591 reinforced heavily over-consolidated clay" *ISSMGE-TC 211 International Symposium on*
592 *Ground Improvement*, Bruxelles.

593 Estabragh, A., Bordbar, A., Javadi, A. (2011). "Mechanical Behaviour of a Clay Soil
594 Reinforced with Nylon Fibres" *J. of Geotechnical and Geological Engineering*, 29, 899-908.

595 Fatahi, B., Fatahi, B., Le, T.M. and Khabbaz, H. (2013b). "Small-strain properties of soft clay
596 treated with fibre and cement" *Geosynthetics International*, 20(4), 286-300.

597 Fatahi, B., Khabbaz, H. & Fatahi, B. (2012). "Mechanical characteristics of soft clay treated
598 with fibre and cement" *Geosynthetics International J.*, 19(3), 252-262.

599 Fatahi, B., Le, T.M., Fatahi, B., Khabbaz, H. (2013a). "Shrinkage Properties of Soft Clay
600 Treated with Cement and Geofibers" *Geotechnical and Geological Engineering J.*, 31, 1421-
601 1435.

602 Ghiassian, H., Poorebrahim, G. and Gray, D. (2004). "Soil Reinforcement with Recycled
603 Carpet Wastes" *Waste Management & Research J.*, 22(2), 108-114.

604 Gray, D. H. and Al-Refeai, T. O. (1986). "Behaviour of fabric- versus fiber-reinforced sand"
605 J. Geotech. Engng, ASCE 112(8), 804-820.

606 Gregory, G.H. and Chill, D.S. (1998). "Stabilization of earth slopes with fibre reinforcement"
607 Proceedings of the sixth International conference on geosynthetics, Atlanta, Georgia, 1073-
608 1078.

609 Habib, P.A. (1974). "Scale Effect for Shallow Footings on Dense Sand" J. of the Geotech.
610 Eng. Division, ASCE, 100 (1), 95-99.

611 Hamidi, A., Hooresfand, M. (2013). "Effect of fiber reinforcement on triaxial shear behaviour
612 of cement treated sand". Geotext. Geomemb., 36, 1-9.

613 Harianto, T., Hayashi, S., Du, Y.J., Suetsugu, D. (2008). "Effects of Fiber Additives on the
614 Desiccation Crack Behavior of the Compacted Akaboku Soil as A Material for Landfill
615 Cover Barrier" J. of Water Air Soil Pollut., 194(1), 141-148

616 Heineck, K., Coop, M., and Consoli, N. (2005). "Effect of Microreinforcement of Soils from
617 Very Small to Large Shear Strains" J. of Geotechnical and Geoenvironmental Engineering,
618 131(8), 1024-1033.

619 Ibraim, E., Diambra, A., Russell, A.R., Muir Wood, D. (2012). "Assessment of laboratory
620 sample preparation for fibre reinforced sands" Geotext. Geomemb., 34, 69-79.

621 Jamellodin, Z., Talib, Z., Kolop, R., Noor, N. (2010). "The effect of oil palm fibre on strength
622 behaviour of soil" In: 3rd SANREM conf., kota kinabalu, Malaysia; 3-5 August.

623 Jayasree, P. K., Rajagopal, K., and Gnanendran, C.T. (2012). "Influence of Sidewall Friction
624 on the Results of Small-Scale Laboratory Model Tests: Numerical Assessment" Int. J.
625 Geomech., 2012, 12(2): 119-126.

626 Kumar A., Kaur A. (2012). "Model tests of square footing resting on fibre reinforced sand
627 bed" *J. of Geosynthetic International*, 19(5), 385-392.

628 Kumar, A., Walia, B.S. and Mohan, J. (2006). "Compressive strength of fibre reinforced
629 highly compressible clay" *Construction and Building Materials*, 20, 1063-1068.

630 Maher, M.H. and Ho, Y.C. (1994). "Mechanical properties of kaolinite/fibre soil composite"
631 *J. of Geotechnical Engineering*, 120(8), 1381-1393.

632 Miller, C. J. and Rifai, S. (2004). "Fiber reinforcement of waste containment soil Liners" *J. of*
633 *Environmental Engineering*, 130(8), 891-895.

634 Mirafatab, M. & Lickfold, A. (2008). "Utilization of carpet waste in reinforcement of
635 substandard soils" *Journal of Industrial Textiles*, 38(2), 167-174.

636 Miranda Pino, L. and Baudet, B. (2015). "The effect of the particle size distribution on the
637 mechanics of fibre-reinforced sands under one-dimensional compression". *Geotext.*
638 *Geomemb.*, 43(3), 250-258.

639 Mirzababaei, M., Mirafatab, M., Mohamed, M. and McMahon, P. (2013a). "Unconfined
640 compression strength of clays with waste carpet fibres" *J. of Geotechnical and*
641 *Geoenvironmental Engineering*, 139(3), 483-493.

642 Mirzababaei, M., Mirafatab, M., Mohamed, M. and McMahon, P. (2013b). "Impact of waste
643 carpet fibres on swelling properties of compacted clays" *J. of Geotechnical and Geological*
644 *Engineering*, 31(1), 173-182.

645 Murray, J. J.; Frost, J. D. and Wang, Y. (2000). "Behaviour of a sandy silt reinforced with
646 discontinuous recycled fibre inclusions" *Transportation Research Record J.*, 1714(1), 9-17.

647 Nasr, A.M. (2014). "Behavior of strip footing on fiber-reinforced cemented sand adjacent to
648 sheet pile wall" *Geotext. Geomemb.*, 42(6), 599-610.

649 Puppala, A.J., Musenda, C. (2000). "Effects of Fiber Reinforcement on Strength and Volume
650 Change in Expansive Soils" *Transportation Research Record J.*, 1736, 134-40.

651 Saad, S., Mirzababaei, M., Mohamed, M., Miraftab, M. (2012). "Uniformity of density of
652 compacted fibre reinforced clay soil samples prepared by static compaction", *The 5th*
653 *European Geosynthetics Congress, Valencia, Spain.*

654 Santoni, R.L., and Webster, S.L. (2001). "Airfields and road construction using fibre
655 stabilization of sands" *J. of Transport Engineering*, 127(2), 96-104.

656 Tang, C., Shi, B., Gao, W., Chen, F., and Cai, Y. (2007). "Strength and mechanical behavior
657 of short polypropylene fiber reinforced and cement stabilized clayey soil" *Geotext.*
658 *Geomembr.* 25(3), 194-202.

659 Tang, C., Shi, B., Cui, Y., Liu, C., and Gu, K. (2012). "Desiccation cracking behaviour of
660 polypropylene fibre-reinforced clayey soil. *Can. Geotech. J.*, 49: 1088-1101.

661 Tang, C., Wang D., Cui, Y., Shi, B., and Li, J. (2016). "Tensile strength of fibre-reinforced
662 soil" *J. of Materials in Civil Engineering, ASCE*, 8(7), 04016031-13.

663 Toyosawa, Y., Itoh, K., Kikkawa, N., Yang, J. and Liu, F. (2013)." Influence of model
664 footing diameter and embedded depth on particle size effect in centrifugal bearing capacity
665 tests" *Soils and Foundations*, 53(2), 349-356.

666 Vesic, A. (1973)."Analysis of ultimate loads of shallow foundations". *J. of Soil Mechanics*
667 *and Foundations Division ASCE*, 94(SM3), 661-688.

668 Viswanadham, B.V.S., Phanikumar, B.R. and Mukherjee, R.V. (2009). "Swelling behaviour
669 of a geofibre-reinforced expansive soil" *Geotext. Geomemb.*, 27, 73-76.

670 White, D. J., Take, W. A. and Bolton, M. D. (2003). "Soil deformation measurement using
671 particle image velocimetry (PIV) and photogrammetry", *Geotechnique*, 53(7), 619-631.

672 Yetimoglu, T., Inanir, M., Inanir, O. (2005). “A Study on Bearing Capacity of Randomly
673 Distributed Fiber-Reinforced Sand Fills Overlying Soft Clay” Geotext. Geomemb., 23 (2),
674 174-183.

675 Zhu, H., Zhang, C., Tang, C., Shi, B. and Wang B. (2014) “Modelling the pullout behaviour
676 of short fiber in reinforced soil. Geotext. Geomemb., 42: 329-338.

677

- 678 List of tables
- 679 Table 1: properties of waste carpet fibres
- 680 Table 2: permeability coefficients

Table 1: Properties of waste carpet fibres

Fibre Type	Specific Gravity*	Water Absorption* (%)	Composition (%)	Specific Tensile Modulus* (GPa/gr/cm³)
Polypropylene	0.90	Nil	60	0.27~0.44
SBR Latex	0.99	-	20	-
Nylon	1.14	4.1-4.5	15	0.40~0.70
Wool	1.32	13-15	5	0.27~0.40

*Recommended by the manufacturer

Table 2: Permeability coefficients of clay samples with different percentages of fibre

Fibre content %	Permeability (m/sec) x 10 ⁻¹⁰
0	2.27
1	4.15
3	4.99
5	9.92

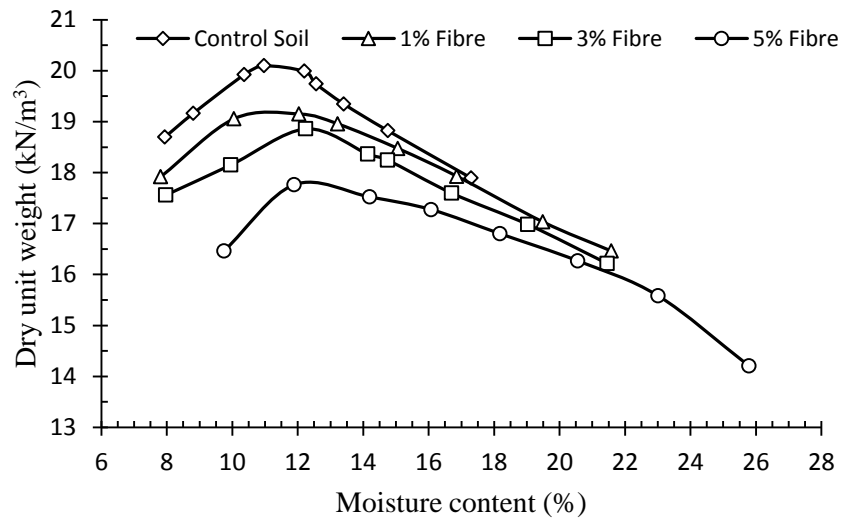


Fig. 1. Standard Proctor compaction curves of control and fibre reinforced soils

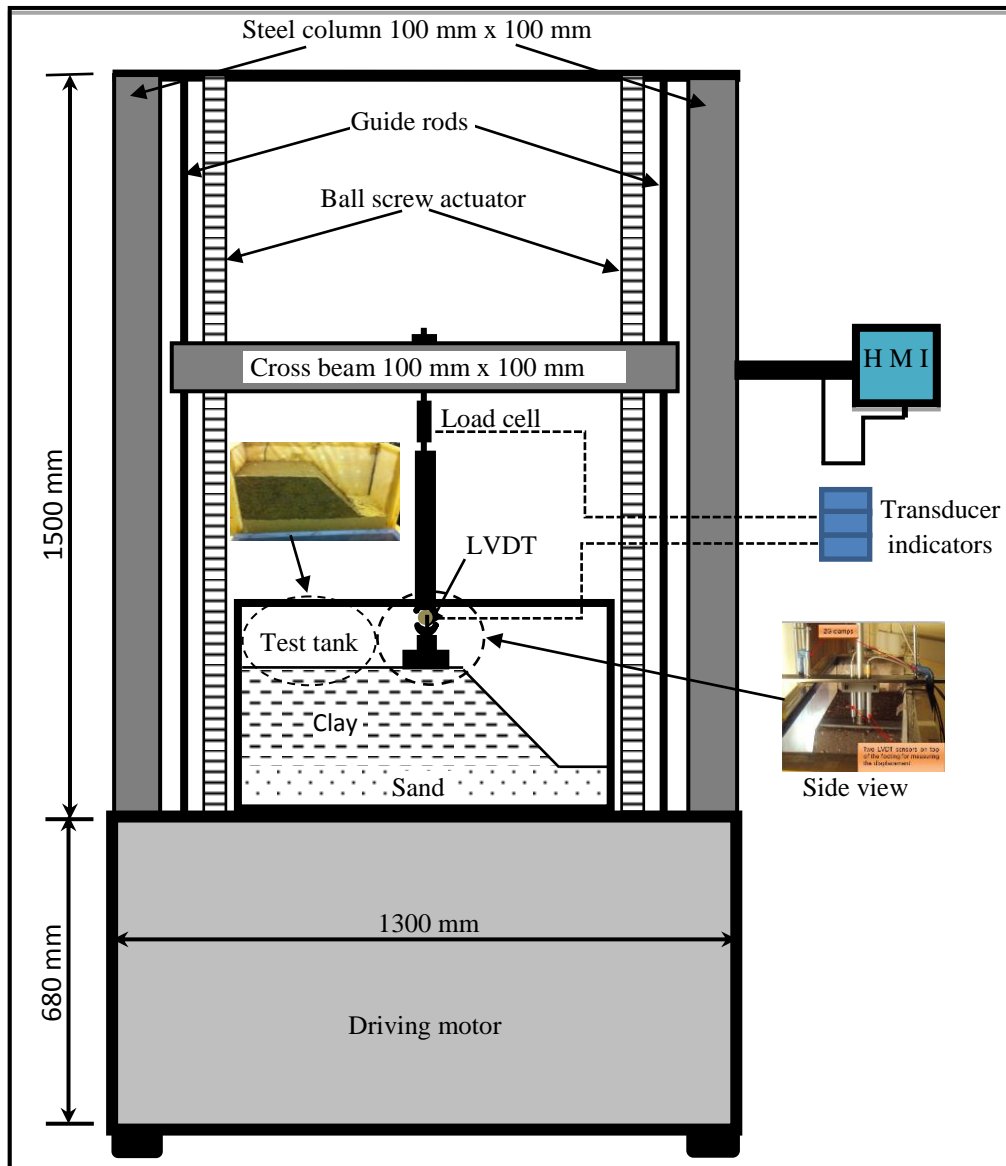


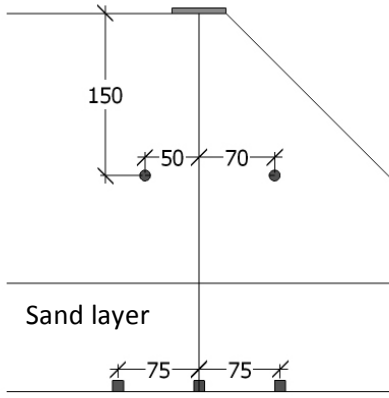
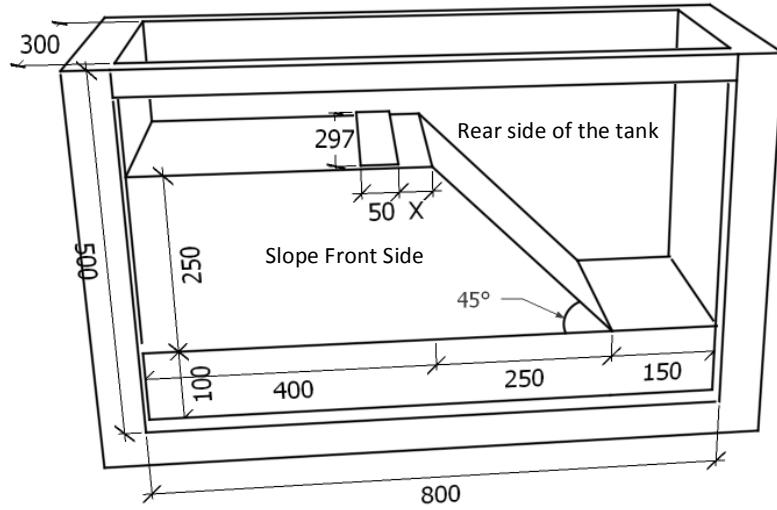
Fig. 2. Schematic drawing of the experimental set-up

a) 3D view of the setting

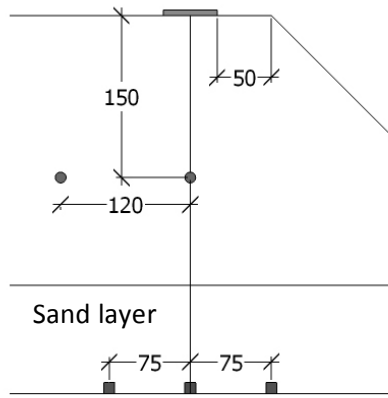
- Location of pressure transducers on the rear side of the tank

- Location of pressure cells on the base of the box

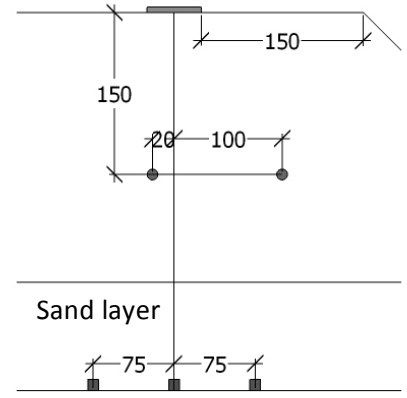
* All dimensions are in mm



b) FEDR (X/B): 0



c) FEDR (X/B): 1



d) FEDR (X/B): 3

Fig. 3. Geometry of the model slope

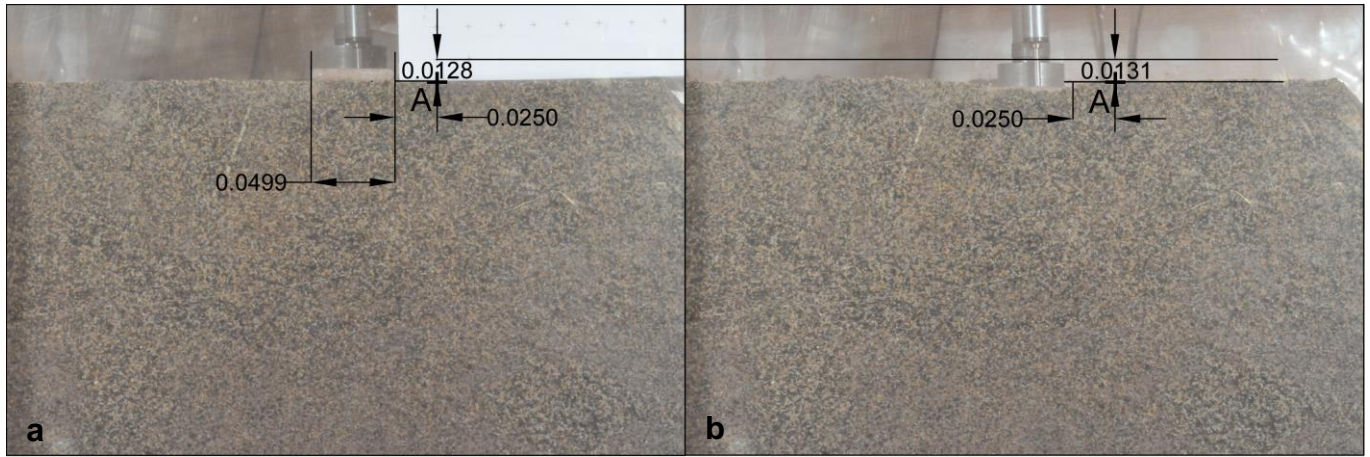


Fig. 4. Vertical distance (m) between point A and a known position
a) before loading b) after loading at 50 kPa footing pressure (FEDR = 3)

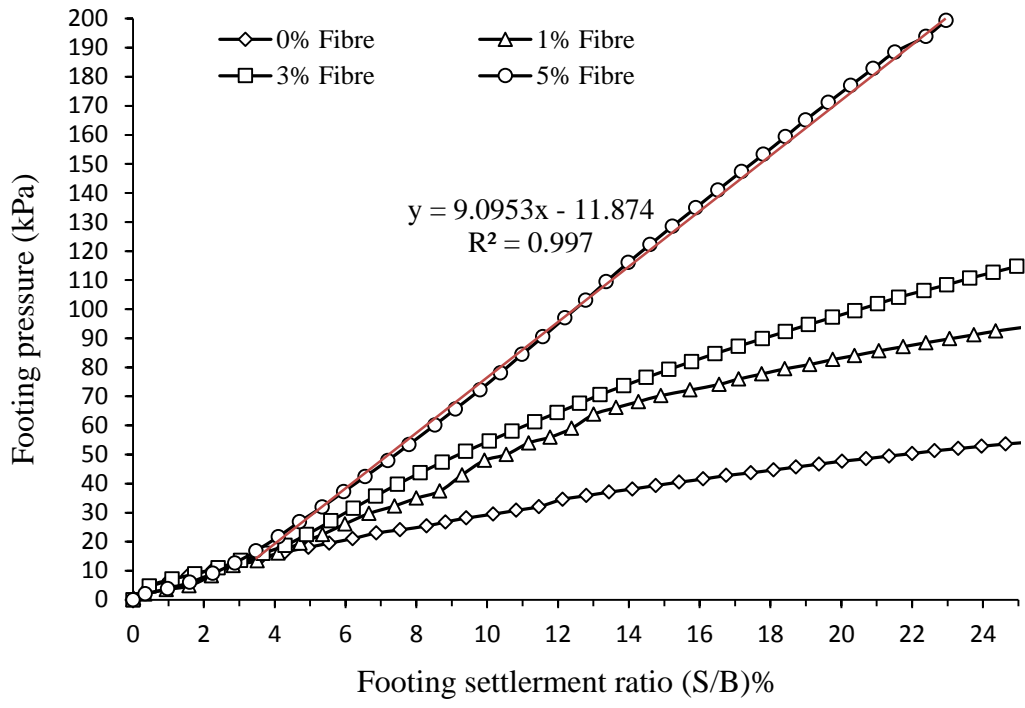


Fig. 5. Footing pressure curves versus footing settlement ratio (FEDR = 3)

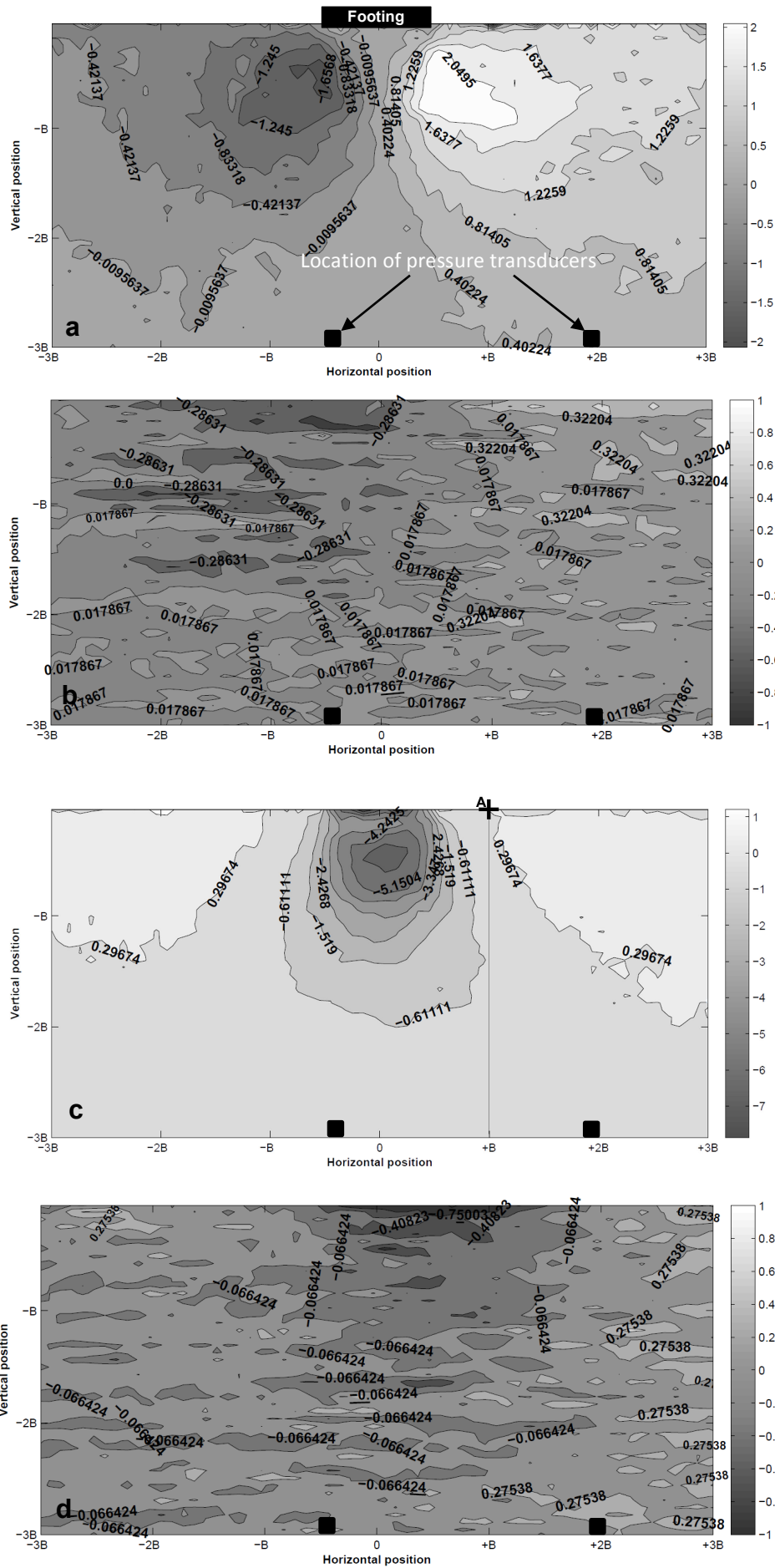


Fig. 6. Contours of horizontal (a & b) and vertical (c & d) displacement (mm) under footing pressure of 50 kPa for FEDR = 3: a,c) 0% fibre b,d) 5% fibre

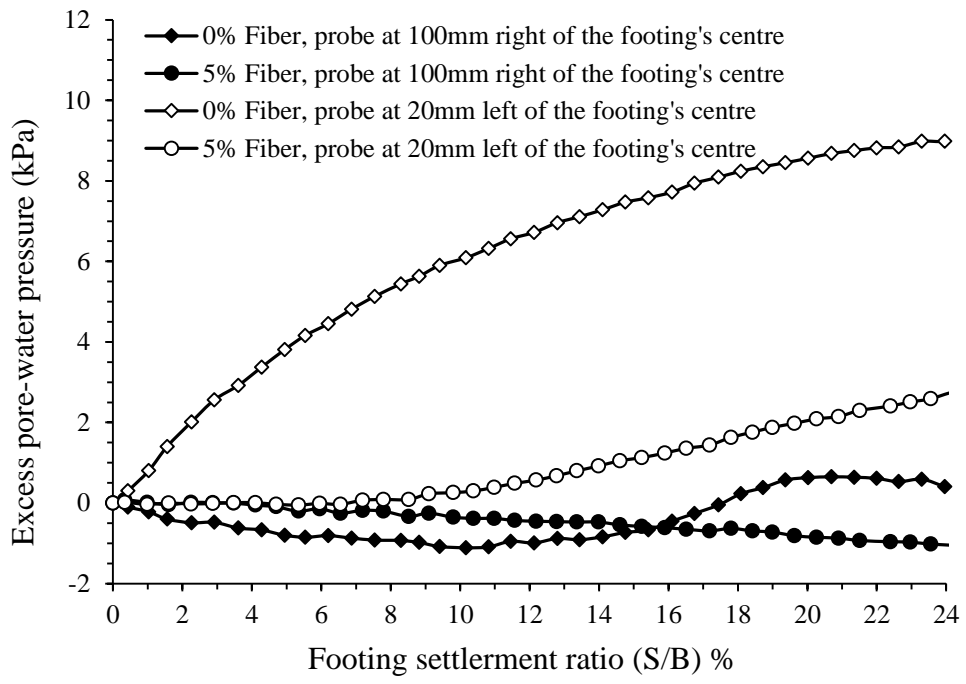


Fig. 7. Pore-water pressure curves versus footing settlement ratio (FEDR = 3)

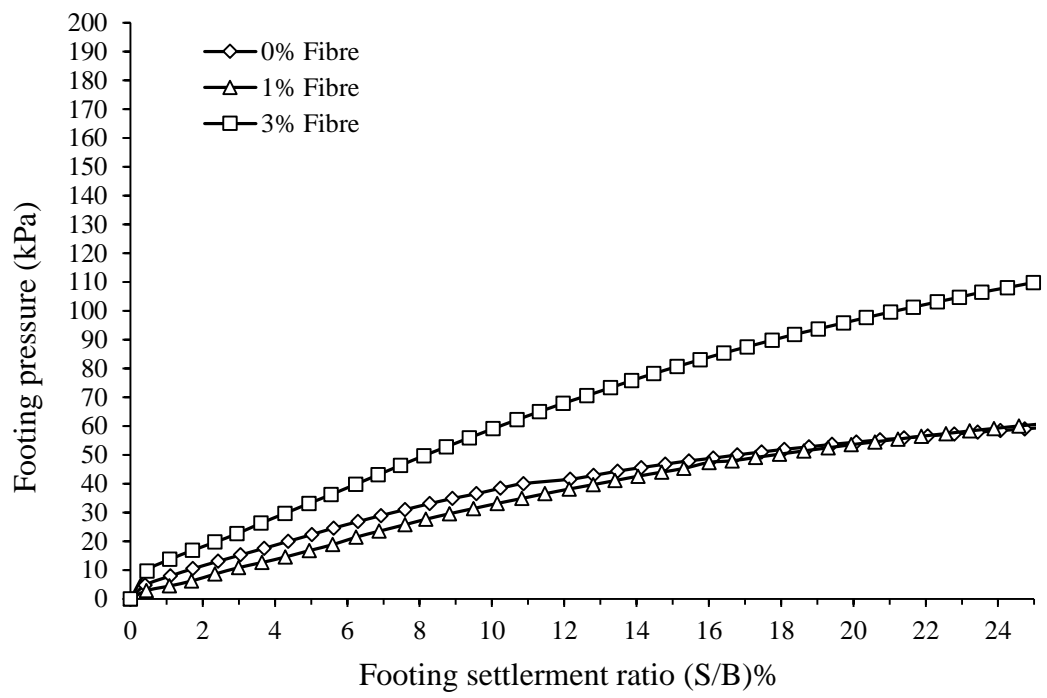


Fig. 8. Footing pressure curves versus footing settlement ratio (FEDR = 1)

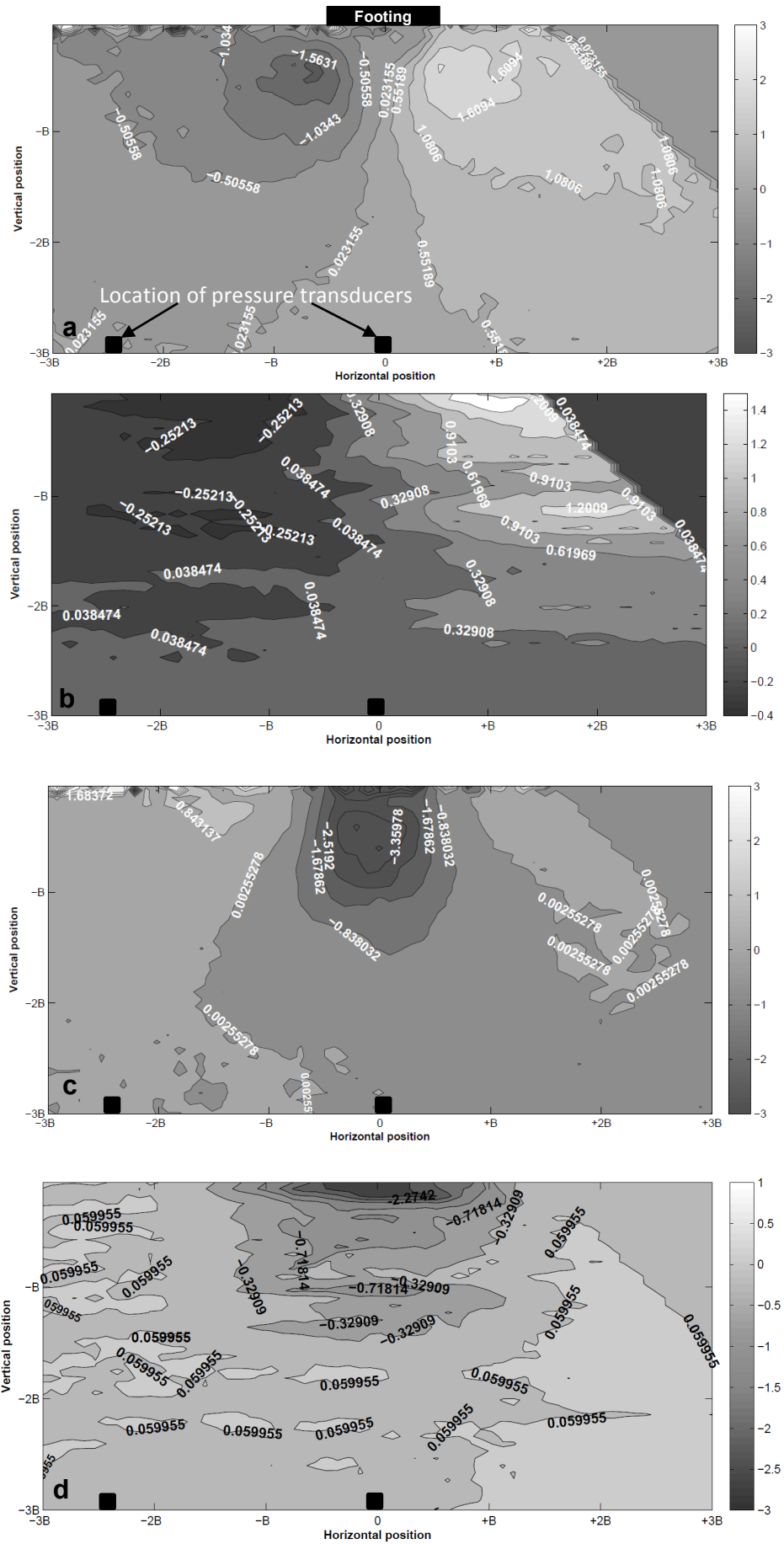


Fig. 9. Contours of horizontal (a & b) and vertical (c & d) displacement (mm) under footing pressure of 50 kPa for FEDR = 1: a,c) 0% fibre b,d) 3% fibre

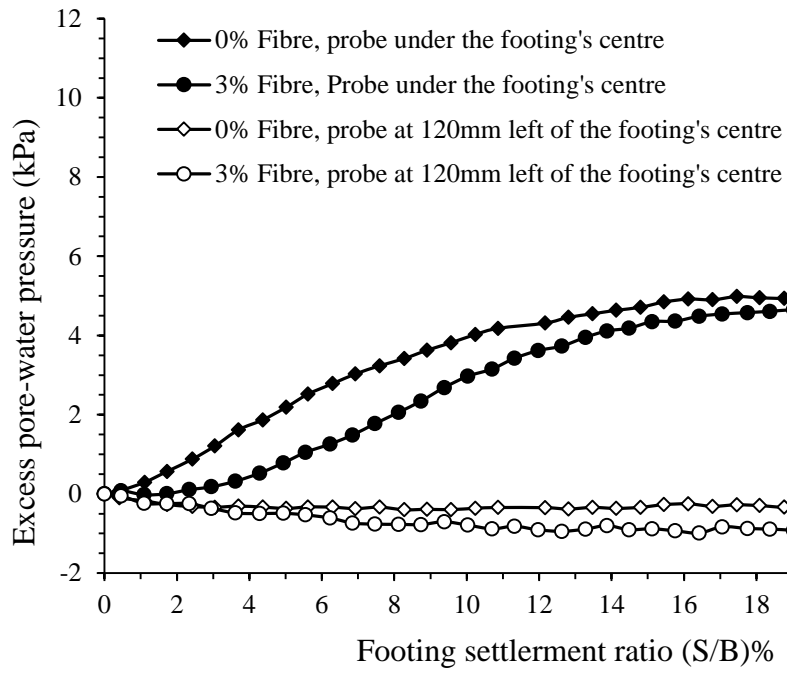


Fig. 10. Pore-water pressure curves versus footing settlement ratio (FEDR = 1)

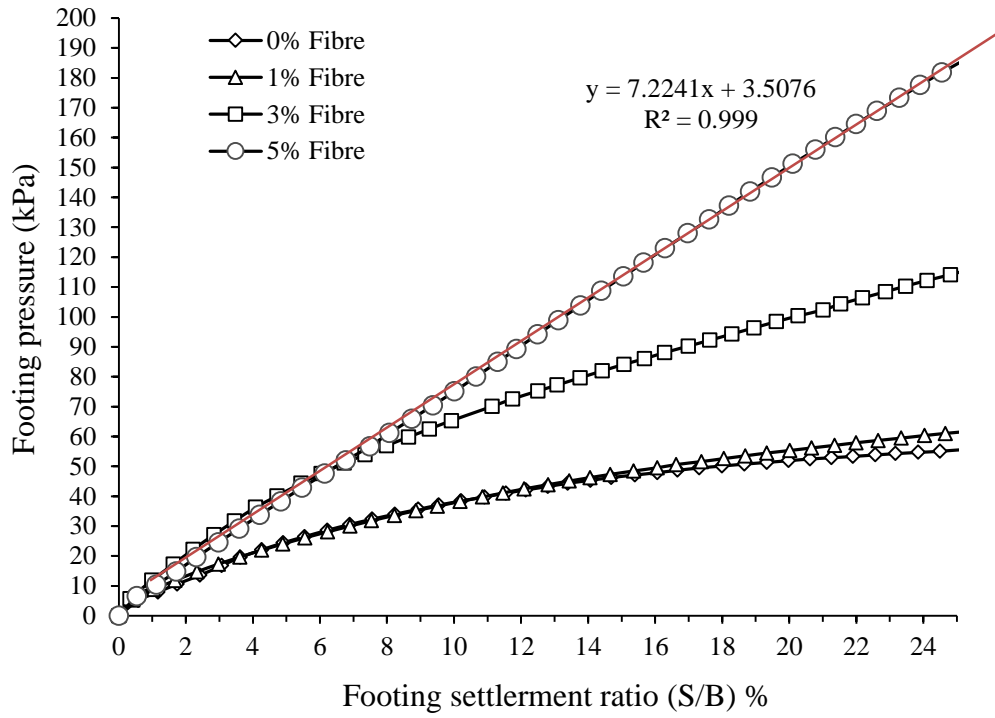


Fig. 11. Footing pressure curves versus footing displacement ratio (FEDR = 0)

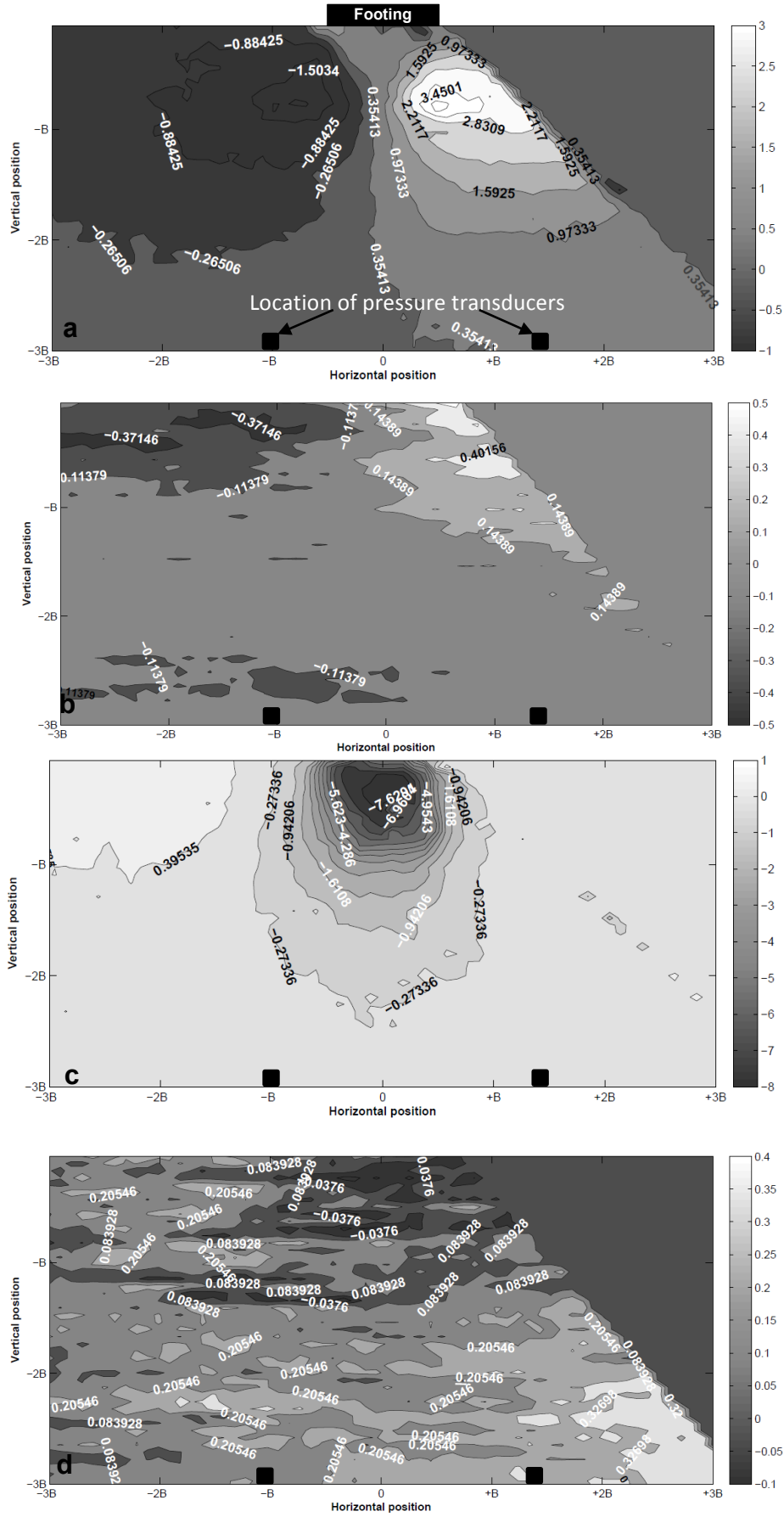


Fig. 12. Contours of horizontal (a & b) and vertical (c & d) displacement (mm) under footing pressure of 50 kPa for FEDR = 0: a,c) 0% fibre b,d) 5% fibre