

1 **Analysis of sequential active and passive arching in granular soils**

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29 **ABSTRACT:** Arching in soils has received great attention for several decades due to its significance on
30 the soil-underground structure-interaction. However, soil layers underneath such an underground
31 structure might undergo cycles of swelling and shrinking resulting in the generation of alternating
32 active and passive modes of soil-underground structure-interaction. Consequently, the stresses on
33 the underground structure and adjoining regions of ground become complex. The state of stress on
34 underground structures as a result of cycles of active and passive arching was neither explored nor
35 systematically assessed. In the present study, comprehensive investigation was carried out to
36 examine; i. the effects of direction of initial displacement to induce an initial active or passive
37 arching, ii. the behaviour of subsequent arching, iii. the effect of magnitude of initial displacement on
38 the formation of arching and iv. the influence of soil height on sequential active & passive arching.
39 The experimental results showed clearly that the magnitude of displacement of the yielding region
40 significantly affects the formation of the arch and the degree of stress redistribution. Alternating the
41 displacement of the underground inclusion exacerbated the formation of active and passive arching
42 leading to a substantial reduction in shear resistance and stress redistribution. It is noted that the
43 greatest loss in shear resistance occurs from the second cycle and remains virtually the same with
44 further cycles. Sequentially alternating displacement of the underground inclusion is found to be
45 detrimental to the formation of full active and passive arches irrespective of the burial height.

46 **KEYWORDS:** Arching of soil, Trapdoor displacement, Lateral earth pressure coefficient, Active
47 arching, Passive arching, Sequential active and passive soil arching.

48 **1. INTRODUCTION**

49 Underground structures such as buried conduits, tunnels, piled embankments, shelters and vertical
50 anchors are increasingly built and utilised for prosperity of societies all over the world. It is
51 paramount that such an underground structure is designed sustainably, efficiently and effectively.

52 One of the major uncertainties in the design is the interaction between underground structure and
53 surrounding soils which is dependent on the type and shape of structure, type of surrounding soils
54 and free field stresses. Arching mechanisms play a pivotal role in the interaction between
55 surrounding soils and underground structures/inclusions (e.g., Lee et al. 2006; Meguid et al. 2008;
56 Costa et al. 2009; Van Eekelen 2015 & Fattah et al. 2016). Depending upon the relative displacement
57 between the underground structure/inclusion and adjacent soils, redistribution of stresses would
58 occur as a result of the formation of either active or passive arching. For instance, if an underground
59 inclusion subsides, a reduction in vertical stress occurs on the yielding area or the region of the
60 underground inclusion in comparison with the anticipated undisturbed overburden pressure in the
61 free field due to active arching. The relative movement between the yielding region and the adjacent
62 less deformable regions of the ground mobilises shear stresses. The evolving shear stress tends to
63 minimise and/or prevent the settlement of the yielding part by reducing the pressure on this yielding
64 region of the inclusion as well as increasing the pressure on the relatively stationary soil regions
65 (Terzaghi 1943). In contrast, if an underground inclusion is stiffer than the adjacent soil regions, an
66 increase in the loads/vertical stress occurs on the underground inclusion alongside a reduction in the
67 stresses on the adjacent soil regions (passive arching) (Iglesia et al. 2014). The additional loads due to
68 passive mode may lead to damage of the buried structures if care is not undertaken (Clark 1971).

69 Several experimental, analytical and numerical investigations were conducted with different
70 perspectives including developing analytical equations (e.g.; Terzaghi 1943; Iglesia et al. 1999;
71 Pirapakaran and Sivakugan 2007a,b & Cui et al. 2017), studying the shape of soil arching (e.g.; Handy
72 1985 & Iglesia et al. 2014), quantifying the effect of soil type (e.g.; Stone and Muir Wood 1992; Iglesia
73 et al. 2014; Pardo and Saez 2014 & Wang et al. 2017) and studying the mode of arching (e.g.;

74 Vardoulakis et al 1981; Koutsabeloulis and Griffith 1989; Costa et al. 2009 & Dalvi & Pise 2012).
75 Studying the arching effect in granular soils was performed experimentally by Terzaghi using a
76 trapdoor test (Terzaghi 1936). Terzaghi then proposed an analytical solution based on his trapdoor
77 experimental results. It was assumed that the behaviour of the soil was within the plastic state.
78 Terzaghi's equation for plane strain situation is given by Equation 1.

$$79 \quad \sigma_v = \frac{\gamma B}{2k \tan \phi} \left(1 - e^{-2k \tan \phi \frac{H}{B}} \right) \quad (1)$$

80 where; σ_v is the vertical stress on the trapdoor, B is the trapdoor width, γ is the unit weight of
81 granular soil, ϕ is the friction angle of sand, k is the ratio between horizontal and vertical stresses and
82 H is the height of the sand bed. Later on Pirapakaran and Sivakugan (2007a, b) extended Terzaghi's
83 solution to a 3-D situation where the vertical load was placed on a rectangular trapdoor of finite
84 length and width (L x B). Although Equation 1 has been widely used in calculating the stresses on
85 yielding inclusions, it requires an accurate value for the earth pressure coefficient (k) which proves to
86 be an issue to most engineers. Terzaghi (1943) assumed that an empirical value of k equals to 1.0 for
87 practical applications whereas Krynine (1945) assumed a k value higher than the value of active earth
88 pressure based on an inclined shearing surface. Russell and Pierpoint (1997) extended Terzaghi's
89 solution by using a square arrangement of square columns supporting the embankment and
90 recommended the use of a k value equals to 1.0 as proposed by Terzaghi (1943). Russell et al. (2003)
91 suggested that the k value is to be taken 0.50. Recently, Potts and Zdravkovic (2008) showed that a
92 coefficient of lateral pressure equal to unity gave comparable results to those obtained from a plane
93 strain numerical analysis to arching over a void. Vardoulakis et al. (1981) proposed expressions for
94 the distributions of the soil loads on the trapdoor in active and passive modes based on shear bands.
95 The expression for active arching is consistent with Terzaghi's (1943) equation when $K=1.0$. However,
96 the proposed equation for passive arching involves a correction factor which was proposed to be
97 1~1.5. Tanaka and Sakai (1993) discussed the progressive failure of the arching of granular soil and
98 the scale effect experimentally and numerically and found that the earth pressure distribution in the
99 experimental results was in agreement with numerical outcome. Iglesia et al. (1999); Chevalier et al.

100 (2008, 2009, 2012) and Moradi et al. (2015) studied the behaviour of arching in soils in the plane
101 strain case during the trapdoor displacement and it was concluded that the soil arching goes through
102 a series of phases e.g. initial arch, maximum arching, recovery stage and final stage. Horgan & Sarby
103 (2002) conducted an experimental plane strain model by using a trapdoor test for two types of
104 granular materials and found the critical height for both soils to be located between 1.545 and 1.92
105 times the width between the supports. Sadrekarimi & Abbasnejad (2008) studied the effects of soil
106 density and trapdoor width on the arching of soil. The results showed that the ultimate stress on the
107 trapdoor decreased as the relative density increased. The width of the trapdoor and relative density
108 influence the formation of a stable arch.

109 Despite all the aforementioned studies, the focus was on investigating distinctive modes of arching
110 e.g. either active or passive mode separately upon isolation of external environmental influences. For
111 example, underground inclusions or structures may undergo cycles of upward and downward
112 movement due to swelling and shrinking of expansive soil layers. Expansive soil layers that exist
113 beneath the underground inclusions are prone to cycles of swelling and shrinking upon slight change
114 in moisture content. This may in turn change the arching mechanism from active to passive mode or
115 vice versa and deviate the stresses from those that were determined based on one of the two
116 recognised arching mechanisms. The focus of this paper is to investigate experimentally using the
117 well-developed trapdoor set-up various scenarios for the effect of sequentially alternating active and
118 passive arching on redistribution of stresses. This study therefore aims to i) quantify the effect of a
119 sequentially alternating arching mode on redistribution of loads exerted on underground inclusions,
120 ii) investigate the influence of displacement and soil height on the resulting stresses during
121 sequentially alternating active and passive arching, and iii) explore potential impacts for the number
122 of alternating cycles of active and passive arching on stress reduction. The results from the
123 comprehensive testing programme are presented and discussed hereafter.

124

125 **2. TESTING APPROACH**

126 The testing setup used in this study is fundamentally similar to the trapdoor setup used in previous
127 experimental studies (e.g.; Terzaghi 1936; Evans 1983; Stone 1988; Dewoolkar et al. 2007; Chevalier
128 et al. 2008; Costa et al. 2009 & Iglesia et al. 2014). Figure 1 shows a schematic drawing of the testing
129 set-up. The test setup consisted of a wooden tank with the front wall made of thick Plexiglass in
130 order to enable visual observation and measurement of the soil deformation. The utilised testing
131 tank had a length of 700 mm, a width of 250 mm and a height of 600 mm as shown in Figure 1. The
132 trapdoor with a width of 100 mm was centred and located at the base of the testing tank. The
133 trapdoor itself was designed to move downward or upward at a constant rate of 1.0 mm/min by a
134 ball screw actuator in order to release or induce pressure on the trapdoor as a result of active and
135 passive arching mechanisms respectively. A load cell was mounted to the base of the trapdoor to
136 measure the applied load on the trapdoor as shown in Figure 1. In order to avoid or minimise
137 frictional resistance and to prevent ingress of fine sand particles between the trapdoor edges and the
138 opening side walls a fibre seal that covered all four edges of the trapdoor was used.

139

140 **3. MATERIALS**

141 Sand was used as a testing material in this experimental investigation. The sand utilised in this
142 experimental study had a range of particle sizes between 410 μm and 710 μm . The important index
143 properties of the sand are summarized in the Table 1. According to BS EN ISO 14688-2:2004, the sand
144 is classified as uniformly-graded medium sand. Standard Proctor compaction tests revealed that the
145 optimum moisture content and maximum dry unit weight of the sand were 8.0 % and 16.50 kN/m^3
146 respectively. In order to prepare samples with uniform dry unit weight, a sand raining technique was
147 utilised by which dry sand was dropped from a predetermined height at a constant rate. The rate of
148 sand raining was controlled by changing the aperture size of the holes in the sand raining box base
149 whilst the dropping height was kept constant by gradually lifting the raining box upward. The unit
150 weight of the formed sand beds was measured at different heights to ensure its uniformity across the
151 whole tank. Measurements were taken at three different points at each level. Table 2 illustrates

152 values of measured dry unit weight taken from five preliminary tests. Data in Table 2 shows an
153 average dry unit weight of $16.37 \pm 0.02 \text{ kN/m}^3$ which was considered acceptable. The measured dry
154 unit weight values indicate that adopting the sand raining technique resulted in preparation of dense
155 sand beds with a dry unit weight comparable to the maximum achieved dry unit weight from the
156 standard Proctor Compaction test.

157

158 **4. TESTING PROCEDURE AND PROGRAMME**

159 A sand bed was created by pouring sand particles into the testing tank through the raining box until
160 reaching the required height. Then the surface of the sand bed was levelled off in order to avoid any
161 discrepancy in the overburden pressure. Typically, each test was initiated by moving the trapdoor at
162 a rate of 1.0 mm/min until reaching a predetermined displacement e.g. 10.0 mm. The test was then
163 temporarily stopped and movement of the trapdoor was reversed to perform the opposite stage of
164 arching. Loads on the trapdoor were recorded every 10 seconds. Each test was conducted to simulate
165 10 cycles of alternating active and passive arching.

166 Thirteen experiments were performed as illustrated in Table 3 in order for a deeper understanding of
167 the behaviour of granular soil arching in sequentially alternating active and passive modes to be
168 acquired. The first series of tests was performed on a sand bed with a thickness of 100 mm to
169 investigate the formation of monotonic active and passive arching in granular soil, the results of
170 which were used as a control. The second Seri/s included testing of two samples with a fixed sand
171 bed thickness of 100 mm to study the effect of the first arching mode on the load transfer onto the
172 inclusion as a function of sequential changes of arching mode. The third series of tests was conducted
173 to investigate the sequential active and passive arching under different trapdoor displacements of 2
174 mm, 10 mm and 20 mm respectively. The last series of experiments was devoted to the effect of
175 burial depth/sand bed thickness on the behaviour of soil arching in sequentially alternating active
176 and passive modes. Six samples of sand beds with different thicknesses were prepared and then
177 tested at the same displacement of 10 mm.

178

179 **5. RESULTS AND DISCUSSIONS**

180 Of note, data attained from the trapdoor experiments were presented as normalized load against
181 normalized displacement. The normalized load on the trapdoor is determined by dividing the
182 measured load on the trapdoor by its original value at zero displacement which is comparable to that
183 in the free field. The normalized displacement is determined by dividing the trapdoor displacement
184 by the width of the trapdoor. The normalisation of loads and displacements is adopted to enhance
185 the presentation and comparison of data sets and to show clearly the percentage changes in load
186 due to active and passive arching.

187 It is also important to note that the second and fourth series of testing underwent 10 cycles of
188 movement of the trapdoor up to a displacement of 10 mm to simulate sequential active and passive
189 arching. However, the third series of tests underwent 5 cycles of downward and upward movement
190 up to displacements of 2 mm, 10 mm and 20 mm. All measurements were taken every 10 seconds.
191 Hereafter, results are presented and discussed to clearly demonstrate the effects of underground
192 inclusion displacement and height of sand bed on the behaviour of arching of soil under sequential
193 active and passive modes.

194 **5.1. Effect of sequential active and passive arching**

195 In this section, experiments were undertaken with a sand bed of 100 mm as illustrated in Table 2.
196 Two experiments were conducted to ascertain the monotonic active and passive arching in granular
197 soils. Load measurement on the trapdoor at rest conditions prior to the onset of displacement was
198 found to be equivalent to the free field vertical stress times the area of the trapdoor. Figure 2 shows
199 the normalised load against normalised deformation for monotonic active and passive arching. Data
200 presented in Figure 2 show distinctive behaviour for granular soil during active and passive state. It is
201 important to note that minimum load achieved during yielding of the underground inclusion (active
202 arching) is 9.3 % of the original at rest load and was experienced after a settlement of 1 % of the
203 inclusion width which is consistent with previous observations by Terzaghi (1943) and Iglesia et al.

204 (2014). In contrast, the maximum load was found to be 217 % of the original at rest load and was
205 observed at a normalised displacement of 2 %. It is also worth noting that the drop rate in the load
206 during active arching is almost double the rate of increase during the passive arching to reach
207 minimum and maximum load respectively. With further displacement, a relatively stable load is
208 experienced during active and passive modes reaching a higher normalised load of 49% and a lower
209 normalised load of 163% during the active and passive modes respectively as showing in Figure 2
210 beyond a normalised displacement of 5%. This is due to the soil mass having reached the critical state
211 and soil particles being re-organised along the slip planes. The results, therefore, suggest that relying
212 on maximum and minimum loads on the inclusion as a result of complete passive and active arching
213 respectively seems to be unsustainable. Careful consideration would need to be taken during the
214 design of underground inclusions, in particular when shallow granular soil cover that is equal to one
215 width of the underground inclusion is used.

216 The next series of testing was conducted to investigate the effect of initial movement (yielding or rise
217 of trapdoor) on subsequent behaviour of soil arching. Data captured for the load on the underground
218 inclusion (trapdoor) during the initial release of pressure due to active arching or during initial
219 compression of soil mass by passive arching are presented in Figures 3-a and b respectively. The
220 monotonic active and passive relations presented in Figure 3 show typical behaviour comparable to
221 those presented in Figure 2. It was recorded that prior to the onset of tests, the soil mass seemed to
222 be at rest and the recorded load on the trapdoor was directly related to overburden pressure.
223 However, the relationships for subsequent cycles of active and passive modes are unique and
224 different from those recorded for the monotonic relationships. This suggests a clear dependence of
225 the behaviour of subsequent arching on the stress history.

226 As the underground inclusion (trapdoor) started to yield, a decreased pressure was observed due to
227 the shear resistance in the soil illustrating the development of active arching (Figure 3a). Due to the
228 initial dense packing of the sand bed with a unit weight of almost 100% of that achieved from
229 Standard Proctor Compaction test, the mass of soil above the trapdoor dilated vertically upon

230 yielding of the inclusion which was recorded by the lower surface settlement rather than the
231 trapdoor displacement. A similar interpretation was made by Villard et al. (2000) in which the rate of
232 dilation was found to be higher than the trapdoor displacement causing the soil to fill the gap under
233 the arching and thus increasing the arching effect. In contrast, the adjacent soil masses on both
234 stationary regions (left and right sides of the inclusion) would dilate horizontally preventing the soil
235 mass above the yielding inclusion from moving downwards which resulted in lowering the pressure
236 on the inclusion (trapdoor). This has occurred entirely due to the internal friction and interlocking of
237 sand particles and can be represented by the angle of friction and the angle of dilation. In contrary
238 upon rise of inclusion from a 10% yielding, passive arching started to form rapidly and gradually
239 showed an increased load on the inclusion reaching a maximum normalised load of 193% after
240 undergoing an upward normalised displacement of approximately 6%.

241 The second and subsequent relationships between normalised load and normalised displacement
242 due to cycles of active and passive arching were similar resulting in intermediate but coinciding
243 paths. During second and subsequent active modes, a minimum normalised load did not appear to
244 occur, as evidenced by the data at a normalised displacement of 1%, whereas the measured load at
245 the critical state was similar. The normalized vertical load at a normalized displacement of 1.0 %
246 during the second cycle was about four times greater than that which was observed at a normalized
247 displacement of 1.0 % during the first cycle, as can be seen in Figure 3-a. Similarly, Figure 3-b
248 illustrates that the normalised loads during the second and subsequent cycles of passive mode at a
249 normalised displacement of 2% no longer represented a peak value but were almost half of that
250 measured during the monotonic passive resistance. Careful inspection of Figure 3 illustrates that the
251 normalised load corresponding to 5% normalised displacement is the same during subsequent active
252 and passive modes irrespective of the initial direction of displacement. This indicates that during
253 alternating active and passive modes, the major and minor principal stress change directions based
254 on the direction of the inclusion's movement (trapdoor). To further explain the alteration of principal
255 stresses during the redistribution of stresses, the lateral earth pressure coefficient was determined

256 and plotted in Figure 4 as a function of inclusion's movement for various active and passive arching
257 cycles. The value of coefficient of earth pressure was calculated by the ratio of the horizontal stress
258 to the vertical stress which was determined from the measured load on the inclusion that is
259 presented in Figure 3. Evans (1983) measured the horizontal stress during trapdoor tests and found
260 that the horizontal stress remained fairly constant. It seemed therefore reasonable to assume a
261 constant value of horizontal stress which is also consistent with earlier suggestion made by Terzaghi
262 (1943) for the trapdoor test. The horizontal stress was then taken as the initial at rest. Of note, the
263 initial lateral earth pressure coefficient was determined as $k_o=1-\sin\phi$. As a result, a k_o value of 0.46 is
264 used in this investigation which is within the suggested range of 0.4-0.5 by Lambe and Whatman
265 (1969) for sand beds that were created by vertical accumulation of sand particles under no significant
266 lateral compression during sedimentation which is precisely similar to the preparation approach
267 adopted in this investigation.

268 From Figure 4, it can be seen that the coefficient of earth pressure increased with increasing the
269 downward displacement until reaching a maximum value of 3.0 at a normalized displacement of
270 0.67%. The increase in the coefficient of lateral earth pressure led to a significant reduction in the
271 vertical load on the trapdoor (underground inclusion). At this stage the soil would behave as an
272 elastic strain material mobilising the peak shear strength to provide maximum frictional resistance
273 and hence the maximum active arching would be developed (Evans 1983).

274 Despite further yielding of the trapdoor, a fairly constant coefficient of lateral pressure was recorded
275 which indicates that the rate of dilation continued but at a lower rate until reaching zero value at a
276 normalised displacement of 5%. Records of surface settlement along the centreline of the trapdoor
277 illustrated that no surface settlement was recorded until reaching a yielding of 5% as shown in Figure
278 5b. Costa et al. (2009) observed significant dilation in the soil region immediately above the trapdoor
279 at failure. A reduced K value resulted in an increased vertical load on the yielding inclusion which can
280 be attributed to a reduction in the angles of friction and dilation as a result of lowered shear strength
281 of the soil. This indicates in turn a reduced arching effect. Due to the decrease in shear strength with

282 increasing yielding of the inclusion, the soil would behave as a strain softening material (Evans 1983).
283 With additional yielding of the inclusion beyond 5%, the lateral coefficient of pressure reached a
284 constant value of unity which was recommended by a number of researchers including Terzaghi
285 (1943). Furthermore, a relatively constant load was measured on the trapdoor despite the value of
286 normalised displacement indicating that the soil mass had reached the critical state. During this
287 stage, most of inclusion yielding was transferred to the surface settlement as can be observed in
288 Figure 5-c.

289 Reversing the direction of movement at a normalised displacement of 10% led to an increase in the
290 measured load due to the formation of passive arching. The major principle stress was then in the
291 vertical direction leading to a value of lateral earth coefficient of 0.25 which is close to that
292 determined by Rankine's theory. With further cycles of active and passive mode, the coefficient of
293 lateral earth pressure stayed relatively stable at 1.0 and 0.25 for active and passive modes
294 respectively excluding the first 4% normalised displacement in each direction due to the instability in
295 the soil mass as a result of dilation and contraction.

296 Figures 5 d-h show pictures of the sand bed after cycles of active and passive modes. It can be seen
297 that soil heave is recorded and observable after completion of the first cycle of active and passive
298 mode. It may also be observed the occurrence of sand disturbance, in particular in the soil region
299 immediately above the inclusion (trapdoor). This means that the volume of soil above the trapdoor
300 was increased resulting in an imminent reduction in the sand density and shear strength. Despite
301 conduction of further cycles of active and passive modes, surface settlement was comparative
302 downward displacement indicating that no further significant change in the volume of the sand bed
303 was evident which means that the shear strength of the sand remained relatively stable. This can be
304 confirmed by the closure k values during active and passive arching as well as the improved
305 steadiness of k values in Figure 4. The results, therefore, suggest that cycles of yielding and the rise of
306 inclusion exacerbate the formation of active and passive arches causing significant changes to the
307 load transfer on the inclusion in particular during the first cycle. This could be attributed to i.

308 localisation of deformation along the same slip planes and causing shear bands as implied from the
309 physical observations taken during the tests ii. Shearing of the soil mass during the first cycle
310 reducing the shear resistance along the slip planes and iii. Permanent change in the vertical stress
311 from the previous arching mode. The volume change of sand during shearing leads to dilation or
312 contraction of the soil and hence change in density which affects the sand shear strength. Zhang et
313 al. (2011) observed that dilation leads to significant volume change and consists of reversible and
314 irreversible components. The later was found to gradually increase with continued shearing whereas
315 the reversible dilation depends upon the shearing direction. As a result, change in the angle of
316 friction is imminent due to dilatancy of the soil mass which is influenced by the shearing direction.

317

318 Figure 6 presents the results of sequential active and passive modes on a sample of dense sand with
319 a height of 100 mm over different ranges of inclusion displacements of 2%, 10% and 20%. All three
320 tests were started with yielding of the inclusion to a predetermined displacement to develop an
321 initial active arching followed by reversing the movement so that the sand bed was in a passive
322 mode. A number of cycles of active and passive mode were then performed over the predetermined
323 displacement ranges. It can be seen that irrespective of the yielding displacement, the normalised
324 load relations followed the same load-deformation path for the monotonic active mode. The
325 recorded normalised load on the inclusion is dependent on the magnitude of displacement prior to
326 reaching the relatively stable load which was measured to be around 5% normalised displacement.
327 On reversing the displacement direction for the sand bed to be in the passive mode, different paths
328 were followed up to reaching a maximum pressure on the inclusion of 180%. Subsequent cycles of
329 active and passive arching followed the same paths as those for the second cycle which were
330 consistent with previously discussed results in Figure 3. The data suggest that hysteresis in the
331 relationship between normalised load and normalised displacement exists and is dependent on the
332 displacement and route followed.

333 **5.2. Effect of burial height**

334 For the fourth series of experiments, samples of sand beds with different heights were examined to
335 investigate the effect of sand height on sequential active and passive arching. Results of tests with
336 sand bed heights of 0.50B, 1.0B, 2.0B, 3.0B, 4.0B and 5.0B where B is the width of the yielding
337 inclusion (trapdoor) were presented in Figures 7 and 8.

338 Figure 7 shows the normalised load during the initial yielding of the trapdoor. It is clear that
339 increasing the height of the sand bed leads to a substantial reduction in the load on the inclusion
340 because of the formation of a full and deep arch. The results are in agreement with those reported in
341 previous studies (e.g.; Terzaghi 1936; McNulty 1965; Ladanyi & Hoyaux 1969; Adachi et al. 1997 &
342 Iglesia et al. 2014). The data in Fig 7 also illustrate that with the increase in sand height, the relative
343 change in normalised load with increasing yield displacement reduced greatly. This could be
344 attributed to formation of a virtually stable arch which would be the case for deeply buried
345 underground inclusions.

346 Results for full cycles of active and passive modes are presented in Figure 8. Data for the passive
347 mode when the direction of movement was reversed to initiate passive mode showed different
348 features as a function of sand bed height. For shallow heights up to $H/B = 2.0$, the normalised load
349 responded quickly to the upward displacement leading to a rapid increase in the measured load. 100
350 % normalised load was observed to be reached within 1.5% of normalised displacement. However,
351 with increasing the burial height, a large movement in the range of 4% was required to reach 100%
352 normalised load. This could be attributed to the formation of a full arch in the case of high burial
353 depths leading to significant dilation of the soil region immediately above the inclusion during the
354 previous yielding and to the requirement for a large displacement to compress the soil under the
355 arch prior to the transfer of load to the soil mass in the passive mode. In other words, small burial
356 heights are only able to result in partial formation of active arching. Costa et al. 2009 noted that the
357 behaviour of active arching of soil with shallow heights ($(H/B) \leq 2$) is different from the behaviour of
358 active arching of soil with deep heights ($(H/B) \geq 2$) which is in agreement with the results presented
359 above.

360 The maximum normalised load on the passive mode is directly related to the burial depth. The data
361 illustrate that despite the increase in the number of cycles, the normalized load was relatively
362 constant regardless of the burial height of the soil as shown in Figure 8. To enhance the discussion,
363 surface settlement is plotted against the normalised soil height after the first and tenth cycles of
364 sequential active and passive arching as demonstrated in Figure 9. A significant reduction in the
365 measured settlement is experienced when the burial height increases beyond a normalised height of
366 2.50. Van Eekelen et al. (2003)'s study showed that shallow burial heights were not able to mobilize
367 shear stress noticeably and the development of soil arching was incomplete. The data suggest that
368 the critical height that is often considered to be the height at which the settlement is equal to zero, is
369 between a normalised height of 2~3. Under repeated sequential active and passive arching cycles,
370 surface settlement started to appear and increased with the number of cycles. No critical height
371 could be confirmed after ten cycles of active and passive arching due to increased surface settlement
372 as the surface settlement was recorded to be 4.0 mm after ten cycles. This means that the critical
373 height was not only dependent on the burial height but also on the number of active and passive
374 cycles, which is in line with the previous observation of a weakened arching mechanism under cyclic
375 alterations of active and passive resistance.

376 In addition, the stress reduction ratio (SRR) is determined by dividing the vertical load on the
377 trapdoor by the initial at rest overburden pressure during the active mode under repeated sequential
378 active and passive arching. If the SRR is equal to zero this means that all load was transferred to the
379 fixed sides (full arching). When SRR is equal to one this means that no arching is developed (Low et
380 al. 1994). SRR provides a useful illustration of the effect of cycle number on the maximum arching of
381 soil:

$$382 \quad SRR = \frac{\sigma_v}{\gamma H} \quad (2)$$

383 where; σ_v is the vertical pressure on the trap door, γ is the soil unit weight and H is the height of the
384 soil bed. Figure 10 presents the results of the Stress reduction ratio (SRR) with the number of cycles
385 for different heights of soil under repeated sequential active and passive arching. It can be seen that

386 most of load increase occurs in the second cycle in comparison with loads measured during the first
387 cycle. This means that arching in soil is substantially decreased during the first few active and passive
388 cycles irrespective of the sand bed height. Increasing bed height has a minor influence on the stress
389 reduction ratio. A slight effect was noted with further alteration of active and passive cycles due to
390 weakened arches. Minor reliance was also observed on the burial height as shown in Figure 10.

391

392 **6. CONCLUSIONS**

393 A comprehensive laboratory investigation was conducted to explore the effects of sequential active
394 and passive arching on the load transfer and re-distribution of stresses using the well-known
395 trapdoor test. The following conclusions can be drawn from the presented results and discussion:

- 396 1. Despite attainment of classical relationships for the normalised load during monotonic active
397 and passive modes, a significant change on the redistribution of loads occurs under
398 sequentially alteration of active and passive resistance. This highlights that relying on
399 maximum resistance and minimum loads on the inclusion as a result of complete passive and
400 active arching respectively seems to be unsustainable and requires special care.
- 401 2. The results suggested that substantial weakening of soil arching occurs during the second
402 cycle of active and passive arching onwards. This could be attributed to i. localisation of
403 deformation along the same slip planes, causing slip bands, ii. Shearing of the soil mass
404 during the first cycle reducing the shear resistance along the slip planes and iii. Permanent
405 change in the vertical stress from the previous arching mode, whether active or passive.
- 406 3. The lateral earth pressure coefficient is a good analogue reflecting changes of principal stress
407 during active and passive modes. It is clear that the suggested value of $k=1.0$ by Terzaghi
408 1943 is still appropriate for sedimentary granular materials at large displacement. Likewise, a
409 value of $k=0.25$ would appear to be reasonable for passive resistance during the passive
410 mode.

- 411 4. Increasing the displacement of the yielding inclusion had a limited effect on redistribution of
412 the loads and soil arching due to reaching the ultimate state.
- 413 5. The load on the inclusion is dependent on the magnitude of displacement prior to reaching
414 the relatively stable load. The data suggest that hysteresis in the relationship between
415 normalised load and normalised displacement exists and is dependent on the displacement
416 and route followed. Different paths are followed up to reaching maximum or minimum
417 pressure on the inclusion.
- 418 6. The critical height was affected significantly under repeated conditions of active and passive
419 modes due to the collapse and/or reduction of soil arching.
- 420 7. The results suggested that dilation of the soil improves with increasing burial height as a
421 result of formation of full arching and leading to lower loads on the inclusion during yielding,
422 improving the capacity to absorb upward displacement during the passive mode.

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558 List of tables

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Table 1. Properties of sand used in this study

Parameter	Value
d_{10} (μm)	570
d_{30} (μm)	630
d_{50} (μm)	690
d_{60} (μm)	710
Uniformity coefficient (c_u)	1.25
Coefficient of curvature (c_c)	0.98
Maximum dry Unit weight (kN/m^3)	16.50
Optimum water content (%)	8.0
Angle of friction (ϕ)	33°

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Table 2. Measured dry unit weight at different heights

Thickness of sand bed (mm)	Measurement level (mm)					Average dry unit weight (kN/m ³)
	0	100	200	300	400	
50	16.36					16.36
100	16.36					16.36
200	16.38	16.36				16.37
300	16.40	16.41	16.35			16.38
400	16.42	16.41	16.38	16.33		16.39
500	16.42	16.41	16.40	16.36	16.32	16.39

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Table 3. Summary of experimental programme

Series	Number of tests	Variable parameters	Fixed parameters
I	2	monotonic active and passive arching	$H = 100$ mm $B = 100$ mm $d = 10$ mm
II	2	initial active mode and initial passive mode	$H = 100$ mm $B = 100$ mm $d = 10$ mm $n=5$
III	3	Normalised displacement 2, 10, 20 %	$H = 100$ mm $B = 100$ mm active & passive $n=10$
IV	6	$H = 0.5B, 1B, 2B, 3B, 4B, 5B$	$d = 10$ mm $B = 100$ mm active & passive $n=5$

568 $H =$ Thickness of sand bed, $d =$ Trapdoor displacement, $B =$ Trapdoor width and $n =$ number of
569 cycles

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571 **List of figures**

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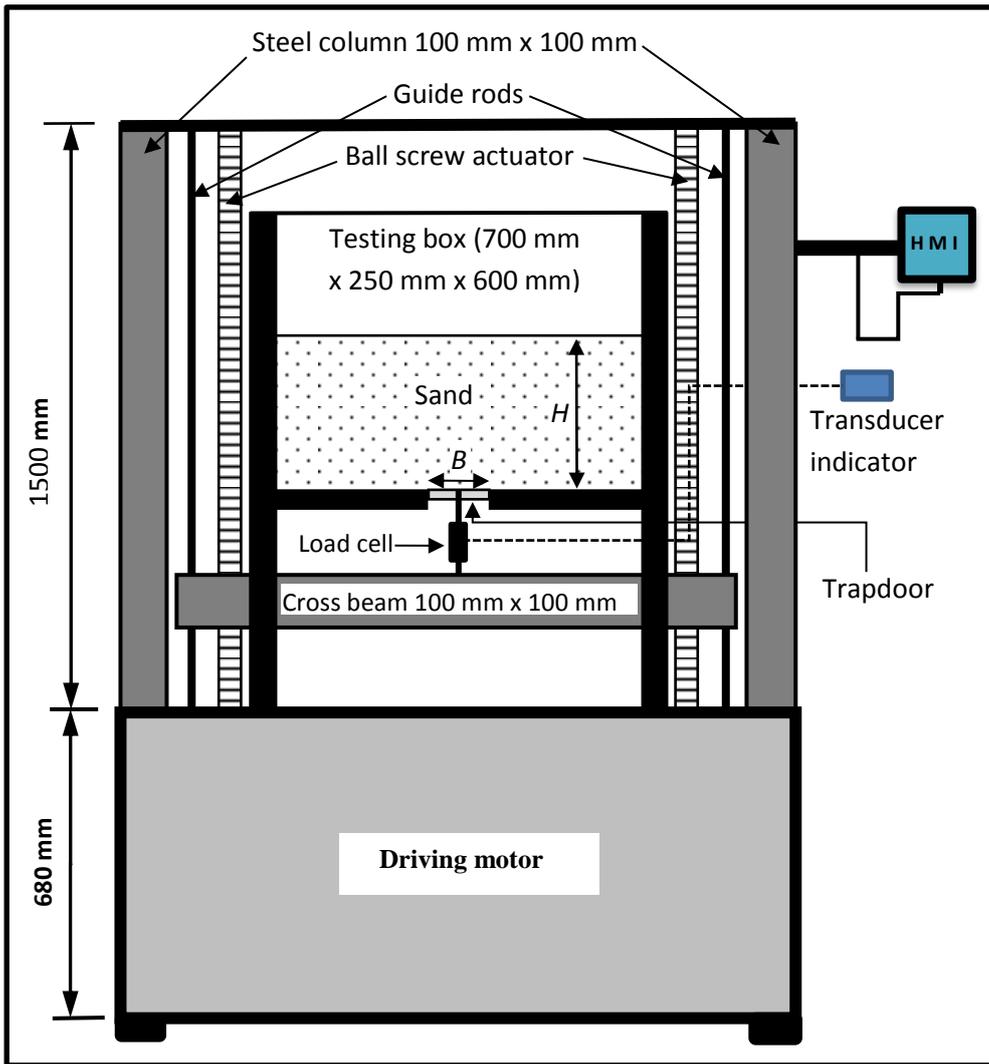
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Figure 1: Schematic drawing of the experimental set-up

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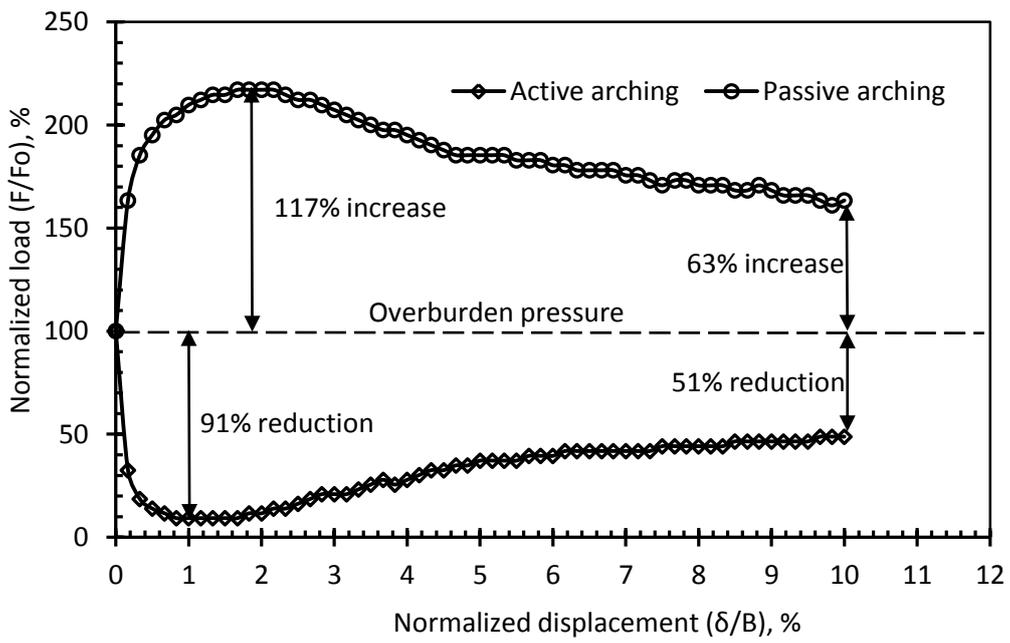
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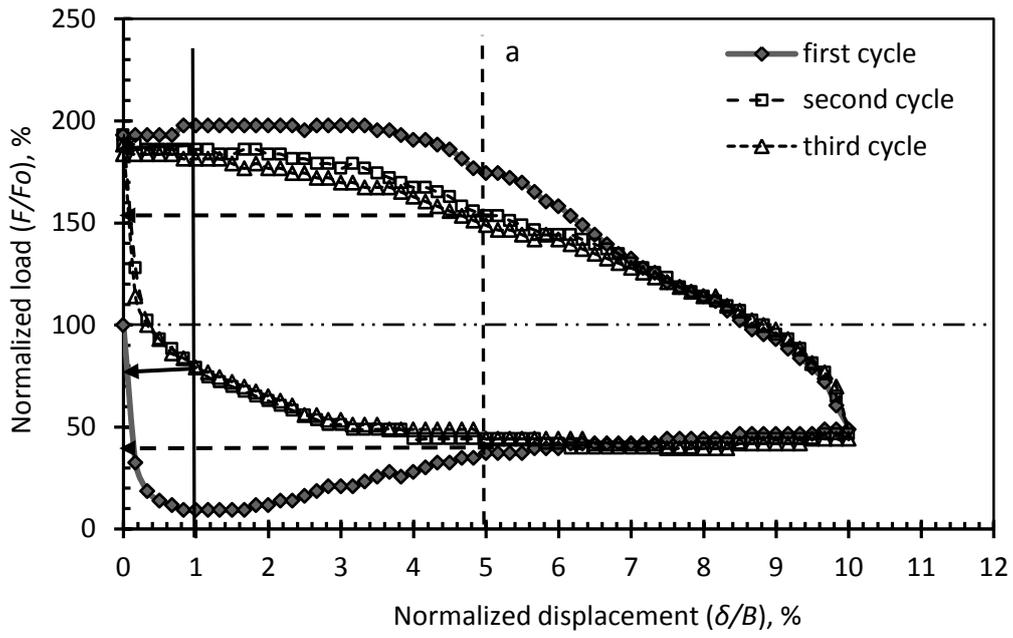
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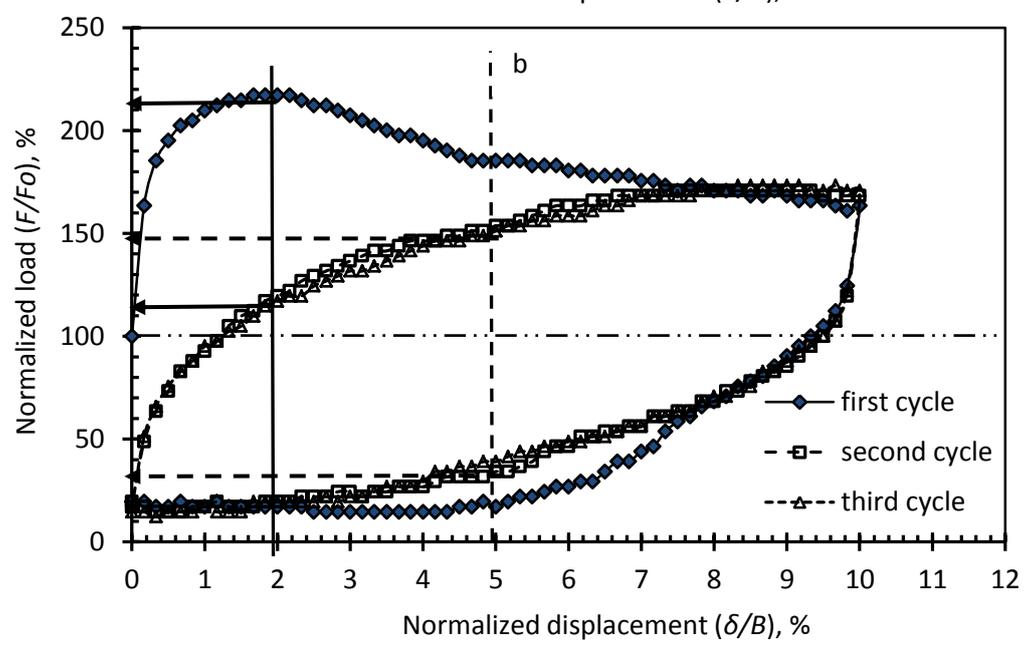
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601 Figure 2: Normalised load versus normalised displacement during monotonic active and passive
 602 arching

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606 Fig. 3: Normalised load versus normalised displacement during a. sequential active and passive
 607 arching and b. sequential passive and active arching

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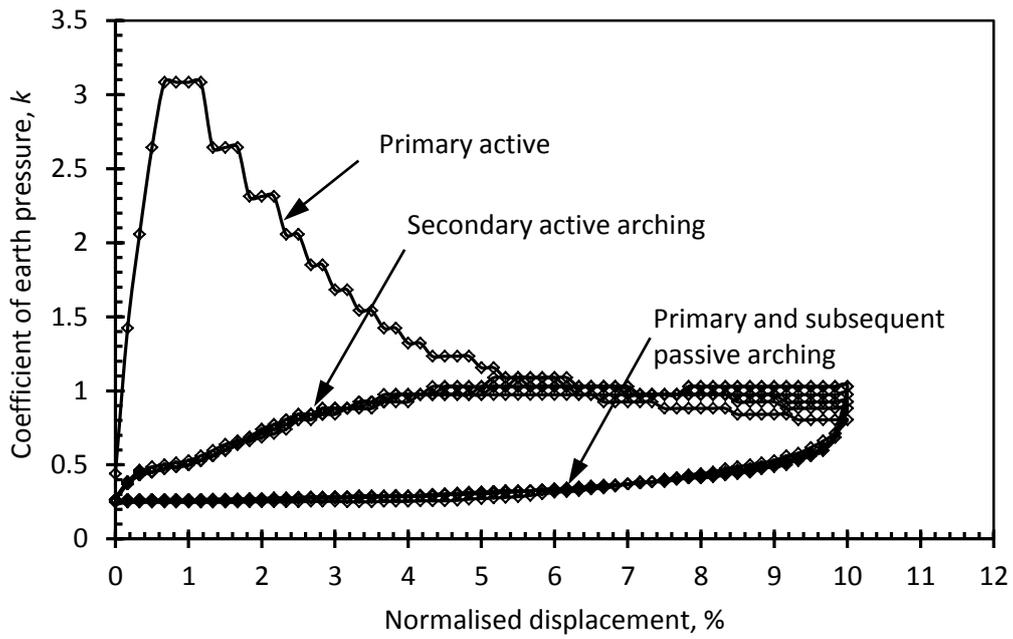
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616 Figure 4: Coefficient of lateral earth pressure as a function of normalised displacement during
 617 sequential active and passive arching

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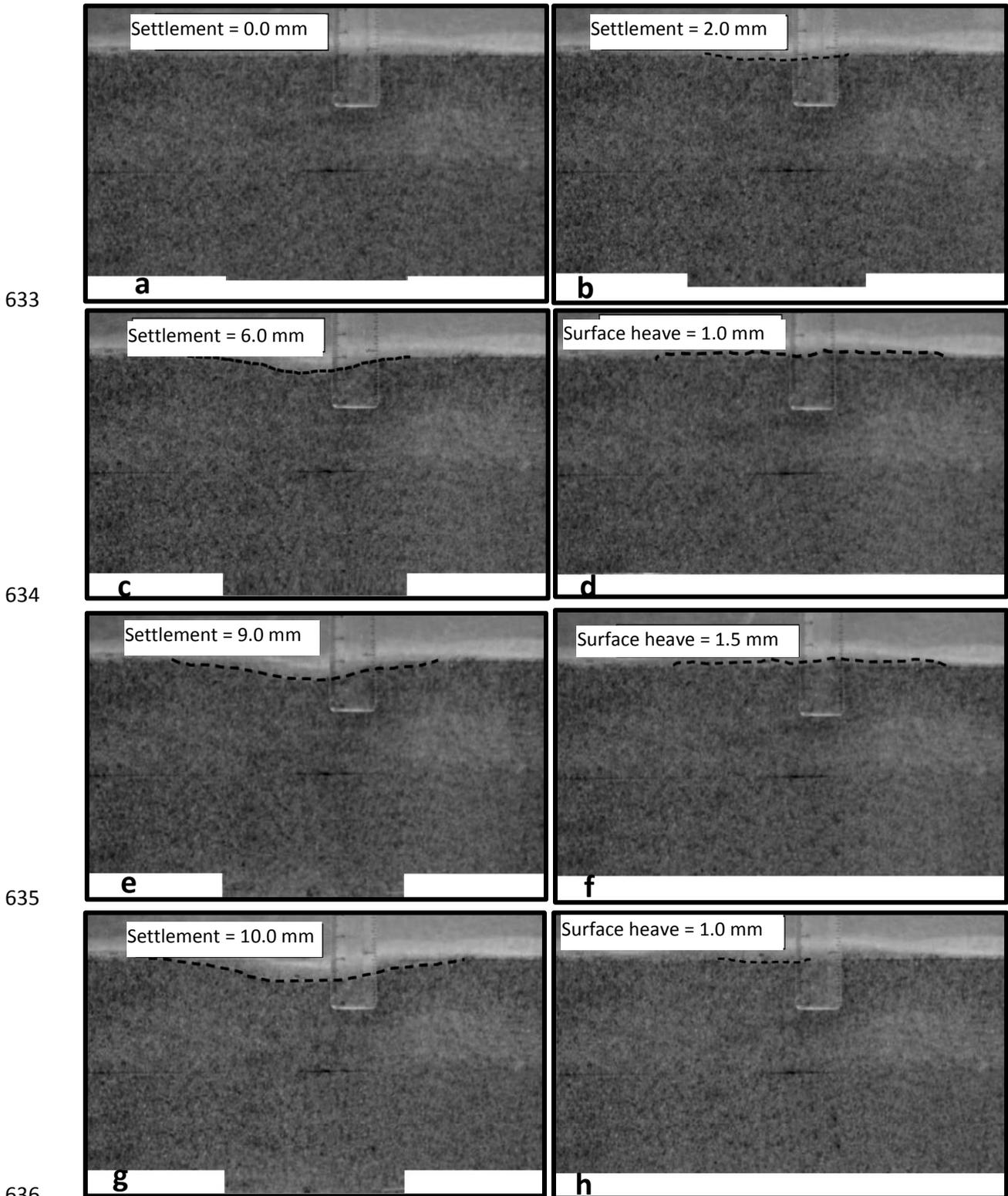
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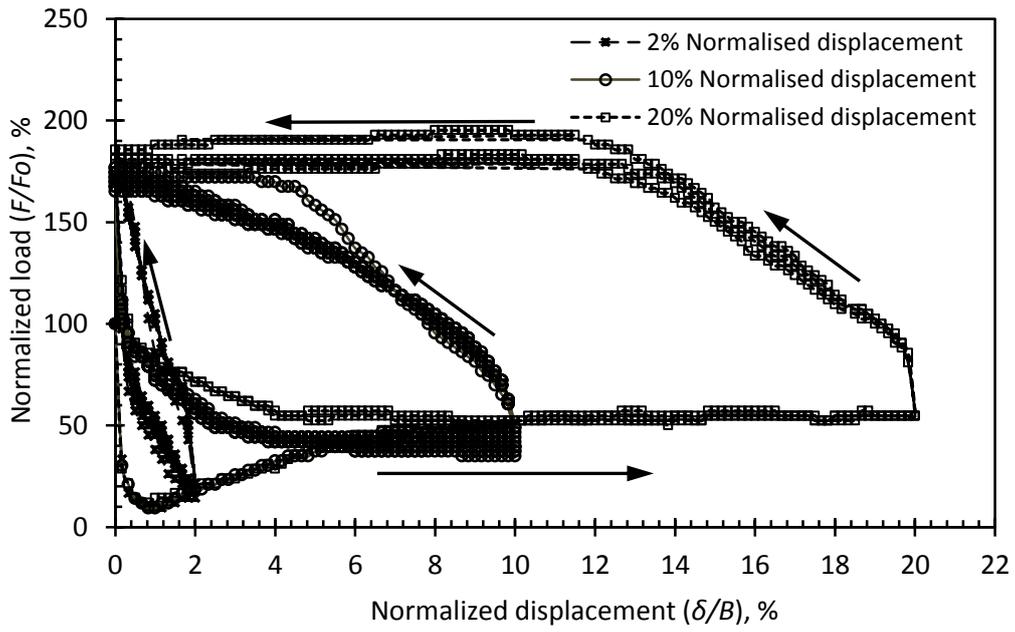
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Figure 5: Evolving of surface deformation during sequential active and passive arching

a. Active arching at normalised displacement of 2%, b. Active arching at normalised displacement of 5%, c. Active arching at normalised displacement 10%, d. Passive arching at normalised displacement of 10%, e. Second cycle of active arching at normalised displacement 10%, f. Second cycle of passive arching at normalised displacement of 10%, g. Tenth cycle of active arching at normalised displacement 10% and h. Tenth cycle of passive arching at normalised displacement of 10%.

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646 Figure 6: Relationships between normalised load and normalised displacement from cycles
647 performed at different normalised displacement

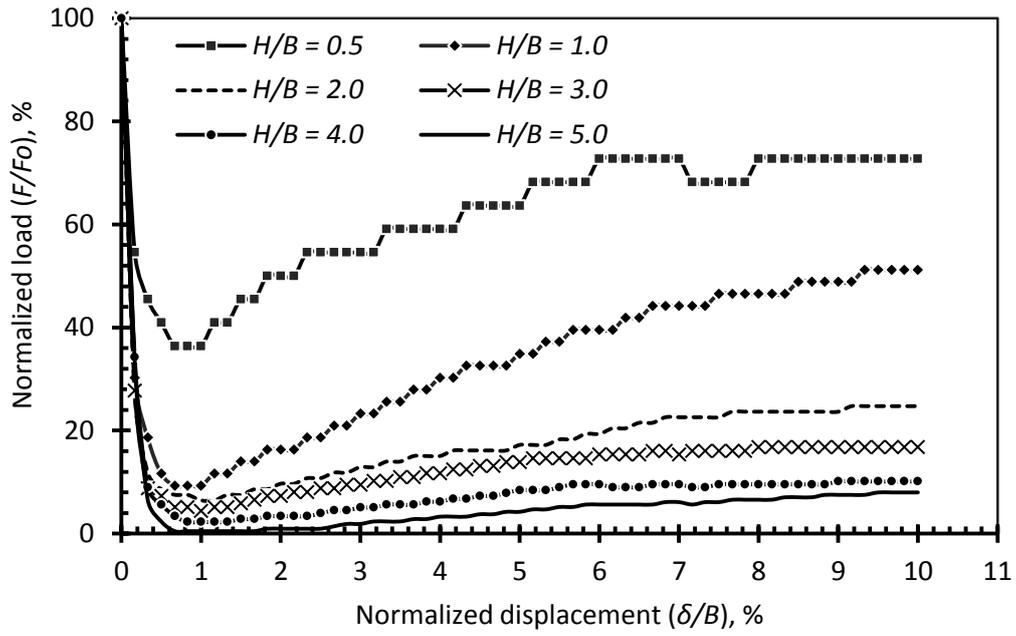
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654 Figure 7: Normalised load versus normalised displacement during initial active arching as a function
 655 of bed height.
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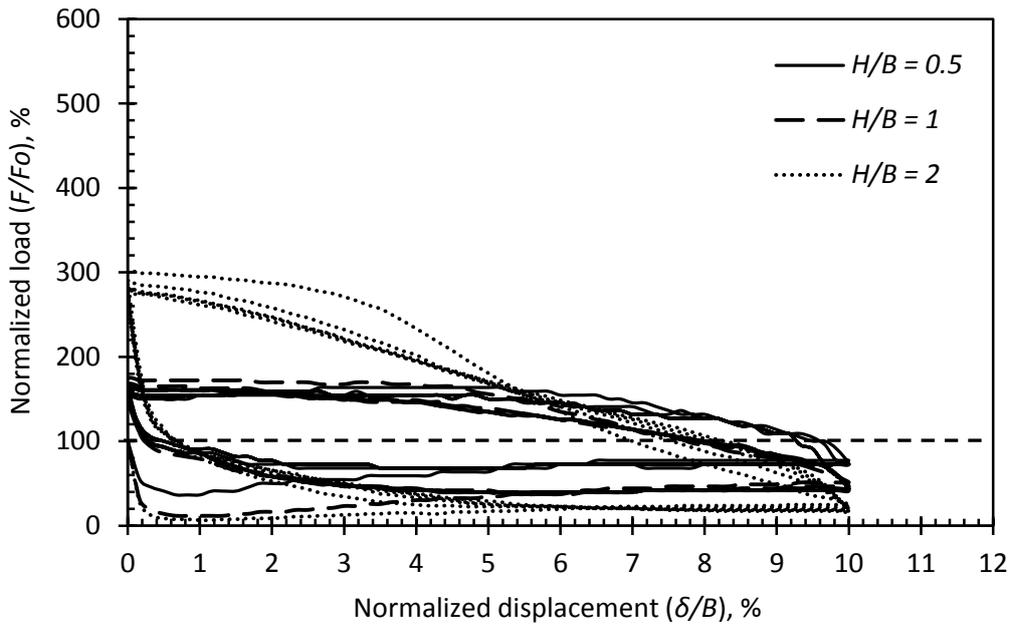
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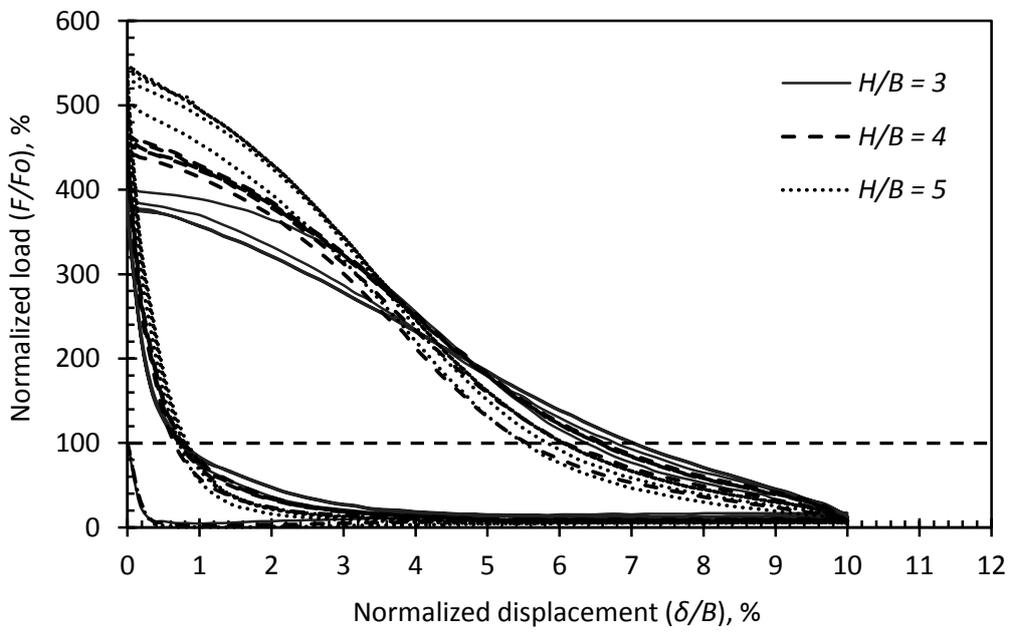
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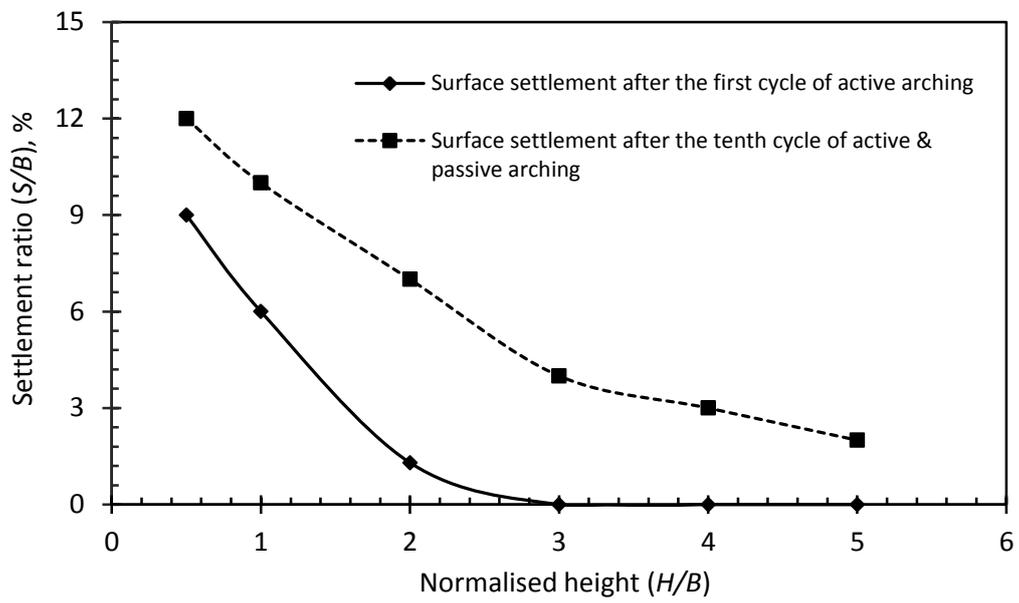
668 Figure 8: Normalised load versus normalised displacement during sequential active and passive
 669 arching

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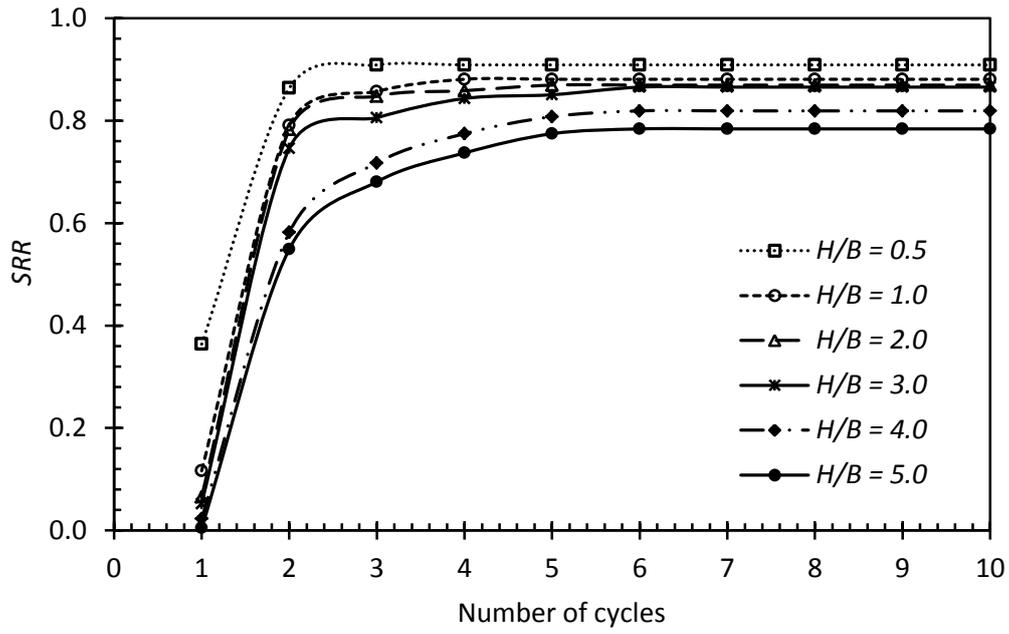
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675 Figure 9: Surface settlement as a function of normalised height after first active arching and tenth
676 cycle of active and passive arching.

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681 Figure 10: Stress reduction ratio versus cycle number of active and passive arching at 1% normalised
 682 displacement for various normalised heights.