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2 **Discrete Element Method**

3

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5 **Abstract**

6 Existing guidance on the installation of screw piles suggest that they should be installed in a pitch-
7 matched manner to avoid disturbance to the soil which may have a detrimental effect on the in-
8 service performance of the pile. Recent insights from centrifuge modelling have shown that installing
9 screw piles in this way requires large vertical compressive (or crowd) forces, which is inconsistent
10 with the common assumption that screw piles pull themselves into the ground requiring minimal
11 vertical compressive force. In this paper, through the use of the Discrete Element Method (DEM),
12 the effects of advancement ratio, i.e. the ratio between the vertical displacement per rotation to the
13 geometric pitch of the helix of the screw pile helix, on the installation resistance and in-service
14 capacity of a screw pile is investigated. The findings are further used to assess the applicability of
15 empirical torque capacity correlation factors for large diameter screw piles. The results of the
16 investigation show that it is possible to reduce the required vertical compressive installation force by
17 96% by reducing the advancement ratio and that although over-fighting a screw pile can decrease
18 the subsequent compressive capacity, it appears to increase the tensile capacity significantly.

19 **Keywords:** Installation Effects, Screw Piles, Discrete element method

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24 **1 Introduction**

25 A screw pile is a form of displacement pile, which consist of a central steel shaft with one or more
 26 helices welded to the shaft at specific intervals (Lutenegger and Tsuha, 2015) (Figure 1). Existing
 27 industrial guidance on the installation of screw piles suggests that screw piles should be installed in a
 28 pitch-matched manner (Perko 2009; BS8004 2015) to avoid disturbance to the soil that will then
 29 have a detrimental effect on post installation pile capacity. This may be for either tension or
 30 compression loading. Pitch-matched, or 'perfect', installation refers to a rate of vertical
 31 advancement of the pile per rotation, that corresponds to the distance between the helix leading
 32 edge and the end of the helix (Figure 1a). Perfect or pitch-matched installation would therefore
 33 result in an advancement ratio (AR) of 1 (Bradshaw *et al.* 2019) where the advancement ratio is
 34 defined as:

$$AR = \frac{\Delta z}{P_h} \quad (1)$$

35 where Δz is the vertical displacement per rotation and P_h is the geometric pitch of the helical plate.
 36 Within the codification of such approaches (BS8004 2015) it is normal to allow under-flighting ($AR > 1$)
 37 or over-flighting ($AR < 1$) by up to about 20% (i.e. $AR = 0.8-1.2$) but it is unclear what such variation in
 38 control would have on installation requirements and the final in-service performance of the pile. If
 39 deep foundations with similar installation methods, such as continuous flight augers (*CFA*) are
 40 considered, a different approach to the advancement ratio is adopted, which is designed to cause
 41 the least amount of disturbance during installation. Viggiani (1989) states that the ideal
 42 advancement ratio for *CFA*, to minimise disturbance, is dependent upon the geometry of the auger
 43 and is defined as

$$v_{crit} = n P_h \left(1 - \frac{D_c^2}{D_h^2} \right) \quad (2)$$

44 where v_{crit} is the critical drilling velocity, n is the rate of revolution, D_h is the diameter of the helix,
45 and D_c is the diameter of the central core of the pile (or shaft section). Equation 2 is based on
46 equating the volume of soil displaced by the pile to the volume of soil removed. This is likely to
47 minimise the change in stress of the soil surrounding the auger during its installation. If the vertical
48 velocity is greater than v_{crit} a net compression effect below the helices is produced, increasing the
49 vertical installation force and torque.

50 Shi *et al.* (2019) investigated the effect of critical drilling velocity on the installation requirements of
51 multi helix complex screw pile geometries using 1g physical modelling and the Discrete Element
52 Method (DEM). The results of their investigation show that a change in particle displacement and
53 therefore mechanism occurs when installing above and below v_{crit} . Shi *et al.* (2019) showed that it is
54 possible to reduce both the compressive installation force and torque of the screw pile by
55 decreasing the vertical velocity (by 50%) or in other words decreasing the advancement ratio (AR).
56 However, they do not comment on the post installation in-service performance of the installed pile.
57 It is also anecdotally assumed that a screw pile will screw itself into the ground if rotated under its
58 own self-weight but if this is the installation mechanism it is unclear how it would be possible to
59 maintain a constant $AR = 1$ and overcome the installation resistance, as required in BS8004:2015.
60 Bradshaw *et al.* (2019) has shown that when installing a screw pile under its own self weight an AR
61 of 0.5 is typically achieved, much lower than the pitch-matched guidance. Similarly when attempting
62 to install screw piles at $AR = 1.0$ during field testing, Richards *et al.* (2019) found that they were
63 unable to do so using conventional installation equipment due to the excessive vertical force that
64 was required. Instead, the monitored AR typically ranged between 0.8 and 0.5, which is below the
65 recommended range of 0.8-1.2.

66 The immediately apparent way to investigate this issue further would be to look at the many screw
67 pile installations undertaken to date by industry. Unfortunately, though, screw pile rigs very rarely
68 record installation rates (AR) or measure torque directly, although it is often inferred indirectly from

69 hydraulic pump pressures. Applied vertical force or “crowd” is also not recorded therefore it is very
70 difficult to investigate the effects of installation from current practice.

71 Part of the motivation for investigating screw pile installation has been the development of silent
72 offshore piling techniques for renewable energy deployment, and in particular as an alternative
73 foundation type for offshore wind and floating future wind (Davidson *et al.* 2019, 2020). To achieve
74 this, significant upscaling of typical onshore screw piles is required, resulting in quite different
75 geometry. Davidson *et al.* (2019) showed that screw piles capable of supporting a typical four-legged
76 offshore jacket structure would require significant installation torque to install (7MNm) and very
77 high vertical compressive forces to achieve pitch-matched installation (23MN). As part of this work
78 an insitu cone penetration test (*CPT*) method was developed to allow prediction of both installation
79 torque and crowd for various geometries of screw piles with pitch-matched installation (Davidson *et*
80 *al.*, 2018, 2020).

81 On attempting to validate this method against the results of other onshore studies (Gavin *et al.*
82 2013) it was found that the torque predictions performed well but the measured and predicted
83 crowd forces were much larger than could be achieved by the rigs used to install them if a pitch
84 matched approach was used. As the screw piles had been installed successfully therefore there was
85 either a flaw in the prediction methods developed or the piles were not installed in a pitch-matched
86 fashion as prescribed. On further investigation it was found that generally onshore screw pile rigs
87 had high torque capabilities but relatively low self-weights suggesting large crowd forces are not
88 encountered or applied in the field. Therefore, it was decided to investigate the effects of over
89 flighting or under flighting on screw pile installation requirements and in-service capacity using the
90 Discrete Element Method (*DEM*). The aim is firstly to resolve whether a lower AR is the likely
91 explanation for high crowd forces not being needed in practice, and secondly to assess the resulting
92 effect of AR on the subsequent vertical capacity.

93 The *DEM* technique has been successfully used previously to investigate penetration events e.g.
 94 insitu soil characterisation, pile installation behaviour and screw pile installation, based upon
 95 calibration against centrifuge tests and triaxial testing (Butlanska *et al.* 2014; Ciantia *et al.* 2016;
 96 Duan *et al.* 2018; Sharif *et al.* 2019a; Zhang *et al.* 2019).

97 An additional motivation for the study was to investigate the empirical relationship that is often
 98 adopted in practice between torque and pile capacity. It is often suggested that the torque required
 99 to install a screw pile can be predicted based upon a unique factor (K_t or K_c for tension and
 100 compression respectively) that relates the observed installation torque to pile capacity (Hoyt and
 101 Clemence 1989; Perko 2009; Tsuchi and Aoki 2010; Byrne and Houlsby 2015; Houlsby 2016). When
 102 using K_t or K_c to predict the installation torque, the pile capacity is typically is determined based
 103 upon published empirical techniques (Perko 2009; Das and Shukla 2013). It has also been proposed
 104 that the same torque relation factor (K) can be used in tension and compression, which is calculated
 105 based upon the diameter of the screw pile core (Perko 2009):

$$Q_t = TK_t \quad (3)$$

106 where Q_t is the axial tensile capacity of a screw pile and T is the installation torque at the end of
 107 installation. Perko (2009) related the K factor to the diameter of the pile central core (D_c) by fitting
 108 the following equation to model and field experiments:

$$K = 2.54D_c^{-0.9198} \quad (4)$$

109 where the units of D_c and K are m and m^{-1} respectively. Byrne and Houlsby (2015) and Houlsby
 110 (2016) developed a dimensionless torque factor (K_t^*) by including the helix diameter (D_h).

$$Q_t = \frac{TK_t^*}{D_h} \quad (5)$$

111 These authors suggested that K_t^* should tend towards a value between 8 and 10. However, on
 112 inspection of the data used by Perko (2009) to define this relationship it is apparent that there is
 113 significant scatter in the data set and that only a limited range of pile core diameters were used

114 which are far below those which may be required for offshore deployment (Davidson *et al.* 2020).
115 Lutenegger (2013) suggested that it may be incorrect to assume that a single parameter model
116 works effectively for all screw pile configurations and soils as suggested by equations (4) and (5). He
117 also suggested that correlations are often the same whether one or two helices are included.
118 Lutenegger (2019) states that where Hoyt and Clemence (1989) compared results of a large number
119 of field tension load tests in different soils the accuracy between observed and calculated values
120 (expressed as the ratio of measured to computed capacity) ranged from approximately 0.3 to 4.5,
121 suggesting considerable scatter in any individual value of K_t adopted. Lutenegger (2019) also
122 suggested that this approach is sensitive to pile geometry and number of helix plates but does not
123 comment on the effects of the installation approach (e.g. *AR*).

124 In this paper the effects of advancement ratio on the installation requirements and axial
125 performance of a single screw pile geometry installed in sand of different relative densities is
126 investigated using the Discrete Element Method. The results are used to investigate the effect of
127 advancement ratio on installation requirements, the resulting vertical load capacity and the
128 applicability of the empirical torque capacity correlation factors K_t , K_t^* , K_c and K_c^* for larger diameter
129 screw piles.

130 **2 Method adopted for DEM modelling and pile details**

131

132 The Discrete Element Method (*DEM*) is a numerical modelling framework which can be used to
133 simulate large deformation problems in granular soils (Ciantia *et al.* 2019). Rather than using a
134 continuum to model the soil, *DEM* uses discrete particles that have the ability to interact as a soil
135 body. With the application of an increased gravitational field, the *DEM* is able to act as a virtual
136 centrifuge (Ciantia *et al.* 2018; Sharif, *et al.* 2019a) when properly calibrated (as detailed in Sharif *et*
137 *al.* (2019a)), with the added benefit of using a single soil bed (particle arrangement) which can be
138 reset and used multiple times (Shi *et al.* 2019).

139 To model the installation of the large diameter plugged screw piles, Particle Flow Code 3D 5.0.35
140 (Itasca Consulting Group 2016) was used alongside a simplified Hertz-Mindlin contact model
141 (Mindlin and Deresiewicz 1953) , in which the contact stiffness is modelled using non liner springs.
142 Spherical particles are used with the rotation of the particles inhibited to capture the rotational
143 resistance of angular grains (Arroyo *et al.* 2011; Ciantia *et al.* 2019). Viscous damping is not used in
144 either of the contact models, as the simulation occurs under drained and no viscosity is needed. The
145 critical damping was also set to 0 as the simulation is conducted under quasi-static conditions. The
146 parameters for the particle -particle contact model were calibrated against laboratory triaxial tests
147 conducted at a confining pressure of 60kPa, and at relative densities of 30% and 70% in order to
148 capture both the peak and residual response of the soil. The *DEM* implementation of the triaxial
149 tests used representative element volumes (*REV*), which consist of a small cluster of around 5000
150 particles (cube with sides of 2.5mm) consolidated to the required relative densities under a confining
151 pressure of 60kPa using a stress controlled servo on all boundaries. Using *REVs* during the calibration
152 process, allowed for many iterations of the contact parameters to be tested to determine the values
153 that best reproduced the laboratory results. During shearing of the *REV*, the stress control servo was
154 maintained on the lateral boundaries at 60kPa, while the bottom boundary was fixed, and the top
155 boundary was displaced using strain-control.

156 For each change in contact model parameters, a new *REV* was created, tested and compared to the
157 physical results. The shear modulus (*G*) and the Poisson's ratio (*v*) were kept constant at 3GPa and
158 0.3 respectively and the interparticle friction (μ) was varied for each of the *DEM* triaxial tests
159 conducted. Particle rotation was inhibited in all simulations to capture the rotational resistance of
160 angular grains (Arroyo *et al.* 2011). A μ of 0.264 was able to reproduce the laboratory results (Sharif
161 *et al.* 2019a) and match the peak response of the soil, although the residual soil strength is slightly
162 higher than that of the laboratory tests. This value represents the frictional resistance between two
163 individual particles and not the soil body as a whole with none rotating particles and therefore does
164 not equate to a classical friction angle.

165 Once the particle-particle contact model parameters had been determined the particle-structure
166 contact model was calibrated against data obtained through centrifuge testing of straight shafted
167 piles (Al-Baghdadi 2017). A soil bed with the same boundary conditions and dimensions as the
168 centrifuge test was created, using the soil-soil contact model calibrated against the triaxial tests. A
169 straight shafted pile of diameter 0.5m and length 10m was then installed into the soil bed using two
170 methods. The first method was a monotonic push (i.e. no rotation of the pile) and the second
171 method was using a rotary installation at the same rotation rate as per Al-Baghdadi (2017). The
172 shear modulus (G_{pile}) and the Poisson's ratio (ν_{pile}) were kept constant at 3GPa and 0.3 respectively
173 and the interface friction coefficient (μ_{pile}) was modified in order to match the compressive
174 installation force and the installation torque reported from the centrifuge experiments. For each
175 alteration of the contact model parameters, the soil bed was reset, and the simulation repeated with
176 the new the parameters. Through this iterative process the interface friction coefficient was found
177 to be 0.16 (Sharif *et al.* 2019a). The interface friction coefficient may appear lower than expected for
178 physical model tests. This is due to the value representing the interaction of a single spherical
179 particle on the surface of the pile with, with the rotation of the particle being restricted in order to
180 model the rolling resistance of the angular soil particle.

181 The calibrated contact models were further validated, by modelling the pitch-matched installation of
182 the O2VD screw pile from Davidson *et al.* (2019). The O2VD screw pile is a dual helix screw pile, with
183 an optimised central core (lower shaft has a smaller diameter than the upper shaft) and is drastically
184 different to that of the straight shafted pile used for the previously described calibration purposes.
185 Sharif *et al.* (2019a) showed that the contact models were able to accurately reproduce both the
186 installation torque and the compressive installation force from the centrifuge tests. Further
187 validation can be seen in Figure 5e and 5f, in which the centrifuge axial response of the pitch-
188 matched U1VDB pile (Davidson *et al.* 2020) is compared to the *DEM* results of this study. From
189 Figure 5f the tensile uplift response of the centrifuge tests on the pitch matched U1VDB pile has
190 been included, The *DEM* simulation is able to match the general trend of the centrifuge results,

191 although the measured force is slightly lower in the DEM model than in the physical test. From
192 Figure 5e, the DEM is shown to replicate the load displacement curve of the pitch matched
193 centrifuge axial compressive test accurately. Further validating the contact models used within this
194 study and how they are able to capture the characteristics of the soil being modelled. Further details
195 on the calibration and validation of the contact models used within this study can be found in Sharif
196 *et al.* (2019a,b). These are outlined in Table 1 (Sharif *et al.* 2019a).

197 The sand modelled in the simulations is based upon the properties of HST95, which is a medium to
198 fine well-graded sand that is commonly used at the University of Dundee in physical modelling
199 (Davidson *et al.* 2019) and element testing. The particle size distribution (*PSD*) is the same as that of
200 HST95 sand (see Table 1) and can be seen in Lauder (2010). The behaviour and properties of the soil
201 have been previously investigated and are well documented (Al-Defae *et al.* 2013; Lauder *et al.*
202 2013).

203 The virtual soil beds for DEM analysis were created in accordance with the specification in Sharif *et*
204 *al.* (2019b). Three soil beds were created using the periodic cell replication method (Ciantia *et al.*
205 2018) and particle refinement method (McDowell *et al.* 2012), with each bed having a different
206 relative density (D_r), based upon the physical voids ratio of the sand modelled. The relative densities
207 selected were 30%, 52% and 83%, with the densest bed being consistent with the physical modelling
208 study conducted by Davidson *et al.* (2019). The soil beds used had a diameter of 40m (0.5m) and a
209 height of 32m (0.4m) (Table 2), frictionless rigid boundaries were present at the base of the soil bed
210 and surrounding the circumference. This resulted in the lateral and bottom boundaries having a
211 fixed condition, with the top boundary being free. Additional properties of the beds can be seen in
212 Table 2.. To avoid any boundary effects, the radius of the soil bed was made to be greater than the
213 $20R$ as suggested by Bolton *et al.* (1999), where R in this particular case is the radius of the pile helix
214 (i.e. the largest radius of the pile). This is supported by the finding of Sharif *et al.* (2020) who showed
215 that there was negligible increase in mean effective stress at a radial distance of $13R$ and no increase

216 at a radial distance of $20R$ when installing piles using the DEM. Additional information and detail of
217 the formation process can be found in Sharif *et al.* (2019b) and Ciantia *et al.* (2018).

218 To reduce the run-time of the simulation, a particle size distribution (*PSD*) scaling value (n_i) of 20 was
219 used at the centre of the sample with a maximum n_i of 96.5 at the boundaries. This value represents
220 the multiplier applied to the diameter of particles, so that each particle represented n_i^3 particles with
221 the bulk properties of the soil remaining the same. This methodology has previously been
222 implemented by McDowell *et al.* (2012) and Shi *et al.* (2019). The particle scaling of 20 was selected
223 based upon the minimum recommended ratio of diameter of the pile core (D_c) to the median
224 particle size (d_{50}) of 2.69 (Arroyo *et al.* 2011). It is also imperative that the screw pile pitch (P_h) is
225 considered when selecting the particle scaling, to avoid causing a blockage of particles in the helix
226 opening. A minimum ratio of the helix pitch to the maximum particle size (d_{100}) of 2.5 was
227 implemented for this study. This typically results in an average of 15 to 17 particles passing through
228 the helix pitch at any given moment (Figure 2). An example soil bed can be seen in Figure 2. Where
229 the shading of the particles represents different values of n_i . To limit the possibility of particle
230 migration between scaling zones, the increase in the *PSD* scaling value (n_i), between adjacent
231 concentric zones, is limited to 1.3 for this soil type, such that the smallest particle (d_{00}) of the larger
232 scale is smaller than the median particle in the smaller scale. This ratio is much smaller than that
233 proposed by Terzaghi (1939) and should therefore limit the possibility of particles with different
234 values of n_i merging together. Further details on soil bed formation and particle scaling criteria are
235 outlined in Sharif *et al.* (2019b). The gravitational field applied to the soil bed was set at 48g to
236 match the dry sand centrifuge tests of Davidson *et al.* (2019) which actually represented the
237 effective stress within a saturated prototype scale of 80 after the method developed by Li *et al.*
238 (2010) and validated by Klinkvort *et al.* (2013). The calculated results from the simulations were
239 scaled in accordance with centrifuge scaling laws (Garnier *et al.* 2007), such that the length is
240 multiplied by N , force by N^2 and torque by N^3 , where N is the model scaling factor ($N=80$)

241 Frictional rigid boundaries (walls) were used to model the geometry of the pile. The geometry of the
 242 screw pile used in this study is based upon the U1VDB screw pile used in the centrifuge study
 243 conducted by Davidson *et al.* (2019). The geometry selected in this research is based upon the
 244 findings of the optimisation studies of Knappett *et al.* (2014), Al-Baghdadi (2017) and Davidson *et al.*
 245 (2019). The pile has model (and prototype) dimensions as follows: core diameter (D_c) of 11mm
 246 (0.88m), a helix diameter (D_h) of 21.25mm (1.7m), a length (L) of 160mm (12.8m) and a helix pitch
 247 (P_h) of 7mm (0.56m), (Figure 1b). This results in a pile with a relatively shallow embedment depth
 248 ($H/D_h = 7$) and according to Equations 1 and 2 (Viggiani 1989) a critical advancement ratio of 0.72 for
 249 volume balance, which lies outside of the recommended 20% variation on advancement ratio for
 250 screw piles (BS8004 2015). Due to the size of the particles relative to the core diameter used in both
 251 the centrifuge tests and the DEM simulations the piles used within these studies have been
 252 modelled as closed-ended piles.

253 To determine the installation rate of the pile, for both vertical and rotational velocities, and to
 254 produce a quasi-static state, a fixed the inertial number (I) was used. The inertial number is used to
 255 define the point at which dynamic effects occur under shearing (da Cruz *et al.* 2005). To determine
 256 the limiting value for the inertial number, a sensitivity analysis was conducted, in which the
 257 compressive installation force of a pile installed at different velocities were compared. The velocities
 258 chosen result in an inertial number of 0.001, 0.01, 0.05 and 0.1. The sensitivity analysis resulted in a
 259 value of 0.01 being chosen as values higher than this resulted in an increase in compressive
 260 installation forces. The limiting value of 0.01 has been used in previous *DEM* studies to investigate
 261 pile penetration problems (Janda and Ooi 2016; Ciantia *et al.* 2019; Martinez *et al.* 2020). This value
 262 was then used to calculate the vertical and rotational velocity of the pile using Equations 6 to 9.

$$I = \dot{\gamma} d_{50} \sqrt{\rho / p_0'} \quad (6)$$

$$\dot{w} = \dot{\gamma} L_{pv} \quad (7)$$

$$\dot{\theta} = \dot{\gamma} L_{pr} \frac{2\pi}{D_h} \quad (8)$$

$$AR = \frac{2\pi \dot{w}}{\dot{\theta} P_h} \quad (9)$$

263 where $\dot{\gamma}$ is the shear strain rate, p_o' is the mean effective stress at the depth of penetration, ρ is the
 264 density of the particles, d_{50} is the median particle size in the region of penetration (core of the
 265 sample), \dot{w} is the vertical velocity in m/s, $\dot{\theta}$ is the rotational velocity in rad/s, P_h is the geometric
 266 pitch of the helix and L_p is the width of the plastic deformation zone, as discussed below.

267 The widths of the plastic deformation zone (L_p) for the vertical velocity (L_{pv}) and rotational velocities
 268 (L_{pr}) were assumed to be $3D_h$ and $4D_h$, respectively. Previous studies on the installation of straight
 269 shafted piles (Lu *et al.* 2004; Garcia - Galindo *et al.* 2018) have shown that different shearing
 270 mechanism occur when installing a straight shafted pile using rotary installation compared to a
 271 monotonic push and thus the width of the plastic deformation zone increases as AR decreases. The
 272 value of L_{pv} ($3D_h$) is based upon the region of shearing observed by Lu *et al.* (2004). The value of $4D_h$
 273 for L_{pr} was chosen based upon the results of 1g tests conducted by Garcia - Galindo *et al.* (2018) in
 274 which surface mechanisms were observed at up to $4D_c$ from the centre of a rotary installed straight
 275 shafted pile during 1g testing.

276 In this study two methods of installation were considered. The first was a screw pile installed at a
 277 constant AR (although AR varies between tests) and the second is a screw pile installed at a constant
 278 vertical compressive force equal to its own "self-weight". When installing the screw pile at a
 279 constant AR in DEM, displacement control was used. The vertical and angular velocities of the pile
 280 were calculated using Equations 6 - 9 and applied to the pile sufficiently slowly to ensure that a
 281 quasi-static regime was maintained. When installing the pile under "self-weight" (or fixed crowd)
 282 installation in DEM, a force control servo was applied. To do this the angular velocity of the pile was
 283 fixed for the entirety of the simulation and the vertical velocity was controlled through a feedback
 284 loop. The feedback loop calculated the sum of the vertical component of the contact forces between

285 the screw pile and the soil at a given moment in time and compared it to the prescribed value. If the
286 vertical force was below that which was required, the vertical velocity was increased and if the
287 vertical force was higher, the vertical velocity for the next step was decreased. The maximum
288 vertical velocity was capped near to the surface ($z < 0.5\text{m}$ only), to produce an $AR = 1$, to ensure a
289 quasi-static regime was maintained throughout the installation. The self-weight of the pile
290 considered in this study was 640kN. To obtain the axial capacity of the installed piles constant rate of
291 penetration (CRP) (Brown 2012) tests were conducted, and the installed piles were displaced
292 vertically by $0.5 D_h$ at a constant velocity of 0.1m/s and the vertical force acting on the pile was
293 continuously recorded using inbuilt commands within the software. To achieve this, the command
294 loops through all of the contacts between the particles and the pile and sums the vertical force
295 component of each contact force.

296 All simulations undertaken in this study were conducted using an Intel Xeon E5-2639v3 PC with 32GB
297 of RAM. The computational time required for fixed AR installation and axial testing ranged between
298 22 hours and 26 hours. The computational time of the self-weight installation ranged between 50
299 hours and 70 hours, reflecting the influence of the servo control. More information on the times for
300 soil bed formation are shown in Table 2.

301 **3 Results and discussion**

302

303 **3.1 Effect of AR on installation resistance**

304 The results from the installation of the pile in all of the soil densities can be seen in Figure 3. This
305 Figure highlights the large vertical crowd forces (15MN in dense sand) and torques (5MNm in dense
306 sand) that may be encountered when trying to install a screw pile designed for offshore application
307 where pitch-matched guidance is followed ($AR = 1$). It can be seen that varying the advancement
308 ratio has a significant effect on the vertical compressive force during installation with a 96%
309 reduction in force when moving from pitch matched installation to self-weight installation. During

310 self-weight installation the AR progressively reduced from 1.1 at 2m depth to 0.5 at the final depth
311 (Figure 4).

312 AR has a reduced effect on the installation torque with a pronounced effect only at the extremes of
313 under-fighting and self-weight installation, which shows an increase and reduction of torque
314 requirement, respectively (Figure 3b, 3d and 3f). This is in agreement with the *DEM* study of Shi *et*
315 *al.* (2019) as well as the 1g physical modelling studies of Shi *et al.* (2018) and Kenny *et al.* (2003),
316 who all noted a large decrease in compressive installation force and a smaller decrease in
317 installation torque when installing at lower AR values. Thus, it would seem there is potential for
318 reducing vertical load (or crowd) requirements during installation by reducing the AR to below the
319 recommended “perfect” or pitch matched installation. However, the potential effect of the
320 advancement ratio on the in-service performance must be considered.

321 The large reductions in installation force that are seen when over-fighting ($AR < 1$), in addition to
322 the anecdotal evidence that screw piles are able to screw themselves in, suggests that most if not all
323 onshore screw piles are actually over fought to some degree when installed in the field.

324 **3.2 Effect of AR on in-service compressive and tensile capacity**

325 The effect of the variation in AR on the in-service post installation capacity is shown in Figure 5 for all
326 soil densities. The markers shown in Figure 5 are for identification purposes only and do not
327 represent the data points. The data is continuously recorded during the axial capacity test and is
328 represented by the lines of the force displacement curve. If the capacity is defined in the
329 conventional manner as recommended by SPERW (Institute of Civil Engineers 2017) and AC358
330 (International Code Council 2017) as the resistance at a pile displacement equivalent to $y/D_p = 0.1$
331 (where y is the vertical displacement during axial loading) it can be seen that under fighting ($AR =$
332 1.2) results in the greatest compressive capacity in all soil densities (8MN in loose, 24MN in medium
333 dense and 33MN in dense) (Figure 5a, 5c and 5e) but also has the highest installation force
334 requirements (8MN in loose, 14MN in medium dense and 20MN in dense) (Figure 3a, 3c and 3e).

335 Low AR (over flighting $AR = 0.5$) has the worst performance in compression but the self-weight
336 installation is slightly better than this and is about 21% lower than the pitch matched installation at a
337 pile displacement of $0.1D_h$ in the medium dense and dense soil beds. Low displacement stiffness
338 (e.g. $y/D_h < 0.02$) appears to be unaffected by AR . At much greater displacements ($y/D_h > 0.3$) the
339 effect of the installation approach on compressive resistance is also less noticeable although the low
340 AR installation still results in reduced resistance. From Figure 5b, 5d and 5f the opposite is generally
341 true when considering tensile performance. In these cases, a low AR or self-weight installation
342 results in capacity and stiffness that is 43% greater than pitch matched installation at a displacement
343 of $0.1D_h$ in the medium dense and dense soils, with the loose soil bed showing an increase of up to
344 120% compared to pitch-matched installation.

345 In contrast to the compressive resistance tests the tensile resistance shows a significant drop in low
346 displacement stiffness with increasing AR . These effects are not overcome until significant uplift
347 displacements are reached ($y/D_h = 0.4$). Thus, over-flighting ($AR < 1$) can significantly reduce
348 installation requirements and has a beneficial effect on tensile performance at the expense of some
349 compressive capacity. This seems to be at odds with the assumptions of BS 8004:2015 and suggests
350 over-flighting may be beneficial for offshore screw and tension only anchor designs. These results
351 show that a low AR can reduce the vertical compressive force required for installation, as also shown
352 by Shi *et al* (2019), which assists in installation plant design where there is still a considerable need
353 for torque input, without compromising tensile capacity performance, which is controlling in the
354 design of offshore screw piles (Davidson *et al.* 2020).

355 **3.3 Summary of effects of AR on installation resistance and in-service capacity**

356 A summary of the effect of AR across all densities is shown in Figure 6. The torque and force
357 quantities have been normalised by the values for pitch-matched installation ($AR = 1$). Figure 6a and
358 6b show the installation force and torque while Figures 6c and 6d show the compressive and tensile
359 capacity, defined at $y/D_h = 0.1$. The slope of the fitted lines shows the strength of the effect of AR on
360 each quantity. By reducing AR , there is a significant reduction in compressive installation force (up to

361 61%), a reduction in installation torque (up to 35%) and compressive capacity (up to 39%), but a
362 strong increase in tensile capacity (up to 120% increase in loose and 60% in other densities) when
363 compared to the pitch-matched installation. These trends are generally consistent across all relative
364 densities. The only strong outliers in terms of density are the normalised tensile capacities for $AR < 1$
365 in loose soil, which are much greater than for the other two soil densities.

366 Figure 6c and 6d also indicate that installing screw piles between an AR of 0.8 and 1.2 does not
367 equate to a reduction in “soil disturbance”, as suggested by BS 8004: 2015, due to the significantly
368 lower tensile capacity at these AR values. However, the normalised axial capacities show that “soil
369 disturbance” is a relative term highly dependent upon whether the installed pile is to be loaded in
370 tension or compression, as indicated by the trends discussed above (Figure 6c and 6d). The
371 advancement ratio calculated using Equation 2 ($AR = 0.72$) proposed by Viggiani (1989), for *CFA* piles,
372 appears to strike a balance between compressive and tensile capacity. At this AR there is a limited
373 decrease in compressive capacity (10%) and a substantial increase in tensile capacity (27% in
374 medium dense and dense sand and 114% in loose sand), while having a beneficial effect on the
375 installation requirements when compared to the pitch matched case. This further undermines the
376 guidance from BS8004 and shows that other approaches also do not agree with the
377 recommendations of BS8004. Highlighting that there is further scope for optimisation of
378 advancement ratio depending on the required use of the screw pile.

379 **3.4 Effect of AR on soil failure mechanism during uplift**

380 To determine the cause of this large increase in tensile capacity in the loose soil bed, the average
381 particle displacement (U) during the tensile capacity test was investigated for the screw piles
382 installed at $AR=0.5$ and $AR = 1$. Figure 7 shows that a different mechanism occurs when the pile is
383 over-flighted during installation. The over-flighted screw pile ($AR = 0.5$, Figure 7a) has a larger
384 influence zone during the tensile uplift test and is developing a conical failure wedge, while the
385 pitch-matched pile ($AR = 1$ Figure 7b) results in a localised flow around mechanism, around the
386 screw pile helix, producing a lower tensile resistance.

387 This difference in mechanism during uplift between $AR = 1$ and $AR = 0.5$ in the loose soil is produced
388 by the difference in the local soil density post-installation. By extracting the radial and vertical
389 position and volume of each particle in the soil bed pre and post-installation it is possible to
390 determine the change in relative density caused by the installation of the screw pile. To calculate the
391 relative density at a given point, the soil bed is partitioned into several 3D annular cylinders (coaxial
392 cylinders) delimited by radial and vertical position as undertaken by Ciantia et al. (2019). The
393 dimensions of each annulus were determined by the particle scaling used within the region it lies,
394 such that smaller annuli are present in the core of the soil bed and larger annuli are required at the
395 boundary. The size of the annuli were chosen to give an optimal balance between resolution, which
396 decreases with increasing annulus size, and achieving a statistically representative volume which
397 requires a minimum of 60 particles (Ciantia et al. 2019). The volume of the annulus and the particles
398 residing within it are known quantities and from this a voids ratio and therefore a relative density
399 can be calculated. Comparing the relative density of each annulus pre and post installation the
400 change in relative density can be determined and assigned accordingly. The value for each annulus is
401 then plotted according to its vertical and radial position to create a contour plot, as shown in Figure
402 7c and 7d, which represent an axisymmetric averaging of the change in relative density of the soil
403 body projected on a 2D plane. Figure 7c and 7d show the change in relative density as a result of the
404 installation of the screw pile into the loose soil bed at $AR = 0.5$ and 1.0 . From Figure 7c and 7d it can
405 be seen that the installation of the pitch-matched screw pile has decreased the relative density of
406 the soil surrounding the shaft by approximately 25%, whereas for the over-flighted screw pile (AR
407 $=0.5$) there is an increase in relative density in the same region of 10%. The denser soil surrounding
408 the over-flighted screw pile increases the uplift resistance as the failure mechanism must now
409 propagate through denser soil. The increase in density also resulted in a change in the mechanism
410 from a flow around, typically seen in loose soil (Figure 7b), to a wedge type failure (figure 7a), giving
411 the over flighted screw pile a drastic increase in uplift resistance as shown in Figure 3b.

412 In the medium dense soil and the dense soil beds a similar effect was seen, where the over-flighted
413 screw pile installation ($AR < 1$) resulted in denser soil surrounding the pile post installation compared
414 to the pitch-matched or under-flighted installation. Unlike the loose case the relative density of the
415 over-flighted installation in the dense and medium dense soil did not increase with respect to the
416 initial state. The failure mechanism for all AR values in the denser soil beds resulted in a wedge type
417 failure, with the increase in tensile capacity attributed to the increase in the dilation angle of the
418 denser soil surrounding the pile post-installation. Figure 8 shows the zone of influence of the screw
419 pile during an uplift capacity test in the Dense soil bed ($D_r = 83\%$). It can be seen that the over
420 flighted screw pile had a larger zone of influence than the pitch-matched one as also seen in the
421 loose soil bed in Figure 7, in addition to an increased zone of intense displacement seen above and
422 around the helix in Figure 8 (denoted by the zones tending towards white shading). Using the
423 relative density index proposed by Bolton (1986), the dilation angle of soil at various depths were
424 calculated and integrated to create an approximated failure surface. The screw pile shown in figure 8
425 is shown in it's final position at the end of the uplift phase. Calculation of the dilation angle and the
426 derived failure surface is shown based upon the original position of the screw pile at some lower
427 depth with the failure plane assumed to propagate from the outer edge of the helix plates. It is
428 noted that the dilation angle shown here is not an input required for the DEM simulation but has
429 been added to show the similarity of the DEM observed failure mechanisms (zones tending towards
430 white shading) to other studies where it has previously been proposed that the shallow failure
431 wedge propagates upwards inclined at the dilation angle (Giampa et al. 2017; Cerfontaine et al 2019;
432 Liu et al 2012). If the in-situ pre-installation relative density and mean effective stress (p') are used, a
433 linear failure surface akin to that proposed by Giampa *et al.* (2017) is created (shown on the left of
434 figures 8a and 8b). This failure surface is simplistic in nature and lies outside the central zone of
435 intense displacement, most notably when close to the helix of the pile. When using the post
436 installation relative density and p' exported from the DEM simulations, the approximated failure
437 surface fits the outline of the zone of intense displacement closely. Particles which lie outside of this

438 failure surface show very little displacement (denoted by their dark grey shading). The failure surface
439 is non-linear, starting near vertical at the helix of the pile before expanding out to form a cone as it
440 propagates towards the surface, similar in shape to the wedge type failure observed for shallow
441 plate anchors by Liu *et al.*(2012) using digital image correlation on model scale experiments . This
442 non-linearity of the failure surface is due to the suppression of the soil dilatancy angle in the high
443 stress region close to the base of the screw pile, which reduces as it tends towards the surface. The
444 higher relative density of the soil surrounding the pile in the AR = 0.5 installation (Figure 8a), results
445 in a larger dilation angle, which manifests as a 0.5m increase in the radial extent of the wedge at the
446 soil surface. The increase in tensile capacity in Figure 5f in the denser soils is attributed to this
447 increase in the dilation angle post installation.

448 **3.5 Effect of AR on torque correlation factor**

449 Exploring the results in terms of a torque correlation factor as per Equation 3 where K_t denotes
450 tension and K_c denotes compression it can be seen that the values of K_c and K_t were not the same as
451 proposed by Perko (2009) and varied quite significantly K_c from = 5.3-6.3 and K_t from 0.7 to 2.3 (in
452 dense soil) for the large diameter plugged piles simulated here (Figures 9a and 9b). This in line with
453 the findings of Davidson et al (2020) who showed that K_c and K_t varied significantly in the results of
454 centrifuge testing of screw piles designed for offshore use ($H/D_h = 4.6 - 7.4$). Typical results from
455 centrifuge testing are shown in Figure 9 to aid comparison and to act as further evidence of previous
456 validation of the DEM approach used. Therefore, it would appear that it is not appropriate to
457 assume the same torque correlation factor for both tension and compression loading for this
458 geometry of pile and depth effect or H/D_h should be considered. Comparing the effect of
459 advancement ratio on K_c & K_t shows a marked difference where AR significantly effects K_t but there
460 is little effect on K_c for a given density. This is likely to be as a result of the very different mechanisms
461 found during tensile and compressive loading. In compression the pile has a large localised end-
462 bearing component which will be defined by the diameter of the helix with a relatively small
463 contribution from the shaft. In tension a wedge type failure was produced (Figure 8), with the angle

464 of the wedge equal to that of the dilation angle of the soil the wedge is propagating through
465 (Giampa *et al.* 2017; Cerfontaine *et al.* 2019) resulting in the capacity being primarily effected by the
466 relative embedment depth, the soil relative density and the mean effective stress post installation,
467 and by the diameter of the helix ($H/D_h = 7$ for this study). Therefore, the much higher magnitude of
468 K_c relative to K_t and the obvious difference in the values.

469 **3.6 Effect of AR on residual stresses around pile**

470 Figure 9a also shows that the K_t factor is density dependent with medium dense sand showing the
471 highest values and loose sand giving the lowest. This is due to the difference in relative density of
472 the soil that is encountered during the installation and the post installation tensile capacity tests.
473 During installation, the torque correlates directly with the applied vertical force due to the increased
474 vertical stress component of interface shearing resistance on the base and helix surfaces i.e. helix
475 torque is controlled by an interface shearing mechanism. The base of the screw pile and therefore
476 the helix is continuously penetrating into virgin soil during the installation and therefore the
477 installation torque is controlled by the initial soil conditions. In contrast to this, the tensile capacity is
478 governed by the soil state above the helix post-installation as the mechanism must propagate
479 through this. The percentage change in relative density, surrounding the helix and pile shaft, is lower
480 in the medium dense sand (18% reduction for $AR = 1$) than it is dense sand (23% reduction for $AR = 1$).
481 This difference in relative density change resulted in the medium dense soil showing a larger K_t
482 factor as the relative density of the soil controlling the installation torque and tensile capacity are
483 similar in value. Previous studies such as Jeffrey *et al.* (2016) have shown this effect through the use
484 of cone penetration tests conducted at various distances from installed cast in-situ screw piles post-
485 installation.

486 Varying AR resulted in the variation of the required vertical compressive force applied to the pile
487 head and subsequently the base of the pile, during installation. The large compressive forces
488 required during installation at higher AR values resulted in large residual stresses (Cooke 1979) (or a
489 locked in stress regime) below the pile as shown in Figure 10 which increased with increasing AR as

490 suggested by Viggiani (1989) for CFA installation and previously observed through DEM by Shi *et al*
491 (2019). The locked in stress below the helix during installation for $AR > 1.0$, preloaded the soil below
492 the helical plate resulting in a post installation compressive stiffness which was far greater than that
493 of the over-flighted case (Figure 5a,5c and 5e). For the under-flighted and pitch-matched
494 installations a region of very low stress, one helix diameter in height was seen above the helix. This
495 region of low stress resulted in the shaft of the screw pile providing very limited resistance during
496 compressive loading, as suggested by Tappenden and Segoo (2007), Mohajerani *et al.* (2014); and
497 Davidson *et al.* (2020). In the over-flighted cases, the low stress region above the helix is no longer
498 present and therefore the shaft would provide additional compressive resistance, although it should
499 be noted that the increase in shaft resistance did not counteract the decrease in stiffness attributed
500 to the reduction of locked in or residual stress below the helix.

501 When assessing the effects of the post installation residual stress field on the tensile capacity, the
502 reverse was true. The over flighted piles had a larger stiffness in tension and due to the large vertical
503 stresses observed above the helix and an increase in capacity due to the increase in dilation angle
504 (Figure 8), compared to the region of low stress found in the pitch-matched and under-flighted
505 installations. As a shallow mechanism (i.e. a wedge) was formed propagating from the helix tip to
506 the surface, the shaft had very little influence on the tensile resistance for the geometry presented
507 in this study (Cerfontaine *et al.* 2020).

508 **3.7 Effect of AR on soil movement during installation**

509 To assess how the post installation stress field and the changes in relative density of the soil
510 surrounding the pile occurred, the displacement of soil particles during the different installation
511 processes was investigated for a pitch-matched and over-flighted ($AR = 0.5$) pile. When the pile is
512 pitch-matched (or under-flighted $AR = 1-1.2$), particles were primarily displaced downwards and
513 radially (Figure 11), causing a flow-around mechanism akin to a bearing capacity failure below the
514 helix of the screw pile. The downwards movement preloaded the soil below the helix locking in the
515 high levels of vertical stress (Figure 10) increasing compressive stiffness and capacity.

516 The displacement of the particles during the installation can also be used to demonstrate how a
517 region of low relative density soil was formed around the pile shaft for pitch-matched installation.
518 Pitch-matched installation encouraged soil to move away from the shaft of the pile and around the
519 helix, momentarily forming a small cavity behind the helix which then collapsed and filled with soil
520 that was looser than the initial conditions (Figure 7d). When the screw pile was over-flighted during
521 installation ($AR < 1$) the movement of the helix encouraged soil to move through the helix rather
522 than radially around the helix (Figure 11), similar in mechanism to that of an Archimedean screw.
523 This phenomenon has previously been observed by Hird *et al.* (2008, 2011) when over and under-
524 flying a CFA tool using transparent soil analogues and by Shi *et al* (2019) when installing a screw
525 drill pile at various advancement ratios. The observations of Hird *et al* (2008,2011) show that when
526 under-flighting, particles displace downwards and radially away from the base of the CFA, in contrast
527 to the purely upward movement of the particles when the CFA tool was over-flighted during the
528 installation process. The DEM study of Shi *et al* (2019) observed particles moving predominantly in
529 the downwards direction when under-flighting and upwards when over flying, which is consistent
530 with the findings of this study.

531 The upward movement reduced the volume of soil that was displaced below and around the helix
532 and in turn produced a denser soil surrounding the shaft and helix and a reduced vertical stress field
533 below the screw pile helix post-installation. This also removed the low stress region above the helix
534 observed for pitch-matched installation. The upward movement of the soil also appeared to reduce
535 the loosening of the soil, so that it is closer to its initial conditions (Figure 7c) than in the pitch
536 matched case (Figure 7d). This in turn gave the soil a higher tensile capacity and tensile stiffness
537 (Figure 6d).

538 **3.8 Effect of AR on dimensionless torque factors**

539 The effects of the helix on the pile response suggest that it would be more appropriate to correlate
540 the K_c value with helix diameter rather than shaft diameter as proposed by Perko (2009) which is in
541 line with that proposed by Byrne & Houlsby (2015) (Figure 12b). However, it should be noted that

542 incorporating the helix diameter into K_c does not remove the large density effects that are seen in
543 this study. Although the dense and medium dense sand beds (which would be typically seen in the
544 offshore environment) produce K_c^* values within the range of those proposed by Byrne & Houlsby
545 (2015), the loose soil bed produced K_c^* below the proposed values. As previously discussed, in
546 tension the mechanism for uplift resistance was very different from that in compression because an
547 uplifting wedge was formed, propagating from the edge of the helix to the soil surface as per
548 Cerfontaine *et al.* (2019) for the relatively short pile used in this study ($H/D=7$) (Figure 13), again
549 suggesting correlation with D_h rather than D_c (Figure 12a). However, the installation torque in the
550 main is dependent on the total area of the pile elements including the shaft component which may
551 be of large diameter in offshore applications. As the values for K_t^* proposed by Byrne & Houlsby
552 (2015) are formulated on the assumption of a deep tensile mechanism, they are not appropriate for
553 screw piles at $H/D_h < 7$ where the conical uplift mechanism has been shown to form, both
554 numerically in this study (Figure 8 and 13b) and observed in centrifuge tests by Davidson *et al.*
555 (2020). This highlights the need to consider H/D_h appropriately in any analysis or prediction.

556 **3.9 Effect of pile length of torque factors**

557 Although all of the screw piles used in this study were installed to shallow relative embedment
558 depths (due to the large relative diameter of the helices required for offshore use), it is prudent to
559 note that most onshore screw piles will be installed to deeper relative embedment depths ($H/D_h >$
560 10) due to their small helix diameters. Therefore, it is assumed that the axial capacity tests used to
561 formulate Equation 3 have been based upon “deep” pile tests where a deep mechanism forms when
562 tested under tension (Figure 13d). For a screw pile, this would result in a reverse bearing capacity or
563 flow around mechanism, with an axial tensile capacity similar to that of an axial compression test.

564 To test if this is the origin of differences between onshore observations of unique K values and equal
565 values in tension and compression, four simulations of the same pile configuration (shown in Figure
566 1b) were installed to a $H/D_h = 11$ (i.e. pile core and helix diameters were kept as previous but the
567 depth of installation was increased to 18.7 m) and axially tested in the dense soil bed after

568 installation at AR values ranging between 0.5 and 1.2. Figure 14a and 14b show the K_t and K_c values
569 for all simulations conducted within the dense soil bed, the axial capacity for all results are
570 considered at the same displacement level. From Figure 14 it can be seen that when the screw pile is
571 installed to a deeper relative embedment, the torque-capacity correlation factor for compression
572 and tension are similar in magnitude ($K_t = 0.45$ $K_c = 1.11$) which explains the suggestion of similar
573 values of K_t and K_c by Perko (2009). Although AR still influences the K_t value, it is much less
574 pronounced for a deep mechanism compared to those of a shallow mechanism, as previously seen
575 when assessing K_c values. As the relative embedment depth increases ($H/D_h > 11$) it may be possible
576 that the difference between K_t and K_c becomes ever smaller, as the installation torque would
577 increase at a higher rate than that of the axial capacity and thus explaining previous assumptions of
578 similar values of K in compression and tension.

579 The above discussion highlights that for the single pile geometry investigated here that K_c is
580 relatively insensitive to AR whereas K_t is significantly affected by both AR and installation depth. This
581 suggests that torque correlation factors cannot be considered unique or a single value for a screw
582 pile geometry and depth as they can be significantly influenced by how the pile is installed i.e. under
583 or over-flighted. This is not something that is conventionally measured in commercial screw pile
584 installations and suggest that rotation and advancement rate measurements along with direct
585 torque measurement should be automated and become routinely determined in practice. It is also
586 notable that the value of K_t and K_c are not independent of soil density as current approaches would
587 suggest, with loose soils giving much lower values of K compared to medium and dense sand, where
588 the values are relatively similar (Figure 9). Thus, using analytically derived pile capacity to determine
589 installation requirements via K maybe inaccurate and using torque during installation to verify the
590 adequacy of pile installation maybe unsafe. This is especially so where larger shallow or deep piles of
591 different geometry may be required for offshore deployment in the renewable energy sector.

592 **4 Conclusion**

593 In this paper the effects of advancement ratio on the axial in service performance of a single screw
594 pile geometry has been investigated using the Discrete Element Method in sand of different relative
595 densities. The screw pile geometry is that which has been previously designed and model tested for
596 offshore renewable energy applications as a replacement for driven piles. The investigation has
597 shown that by over-fighting ($AR < 1$) a screw pile during installation, compared to installation at
598 pitch-matched ($AR = 1.0$) it is possible to reduce the installation force required significantly (up to
599 96%) and it is possible to install a screw pile under its own self-weight. The installation torque is less
600 effected by AR , but it is possible to reduce the required installation torque (up to 35%) by over-
601 fighting. The results of the in-service axial capacity tests have shown that although over-fighting
602 reduces the compressive capacity (up to 39%) of a screw pile, it is also able to significantly increase
603 the capacity and stiffness of the screw pile when loaded in tension (up to 120% in loose soil and 60%
604 in other densities). Using interparticle contact forces and particle displacements exported from the
605 DEM simulations, it has been shown that the AR chosen during installation has a significant effect on
606 the in-service behaviour of the screw pile due to the residual stress field surrounding the pile post-
607 installation.

608 The results of the investigation were then used to assess the applicability of the empirical torque
609 capacity correlation factors K_t and K_c on larger diameter screw piles for offshore renewable energy
610 deployment. The assumption that a screw pile has a single K value solely based upon its geometry
611 has been shown to be inappropriate for these larger screw piles. The results have shown that several
612 different factors contribute to both the installation torque and the ultimate capacity which have
613 previously seen little attention such as the advancement ratio, soil relative density and the relative
614 embedment depth. This implies that using analytically derived pile capacity to determine installation
615 requirements maybe inaccurate and using torque during installation to verify the adequacy of a
616 single helix pile installation maybe unsafe especially where different or larger pile geometries are
617 adopted.

618

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7 Notation list

AR	Advancement ratio
CFA	Continuous flight auger
CPT	Cone penetration test
CRP	Constant rate of penetration
d_{100}	largest particle diameter
d_{50}	median particle diameter
D_c	Diameter of screw pile central core
DEM	Discrete element method
D_h	Diameter of screw pile helix
D_r	Relative density
G	Hertz shear modulus (inter-particle contact model)
G_{pile}	Hertz shear modulus (interface contact model)
h	Depth below ground surface
H	Embedment depth from soil surface to mid-helix height
K	Empirical torque correlation factor
K^*	Dimensionless empirical torque correlation factor
L	Total Length of screw pile
L_p	Width of plastic deformation zone
L_{pr}	Width of plastic deformation zone to determine the rotational velocity
L_{pv}	Width of plastic deformation zone to determine the vertical velocity
n	Rotation rate
n_i	Particle scaling value
N	Centrifuge model scaling value
p'	Mean effective stress
p_0'	Initial mean effective stress
PCRM	Periodic cell replication method
P_h	Geometric pitch of screw pile helix
PRM	Particle refinement method
PSD	Particle size distribution
Q_c	Ultimate compressive capacity
Q_t	Ultimate tensile capacity
r	Radial distance from centre
REV	Representative element volume
T	Total installation torque
U	Average Particle displacement
v_{crit}	Critical drill velocity for a CFA pile
y	Vertical displacement during axial loading
z	Penetration depth
γ'	Effective unit weight of soil
Δz	Displacement for single rotation
δh	Vertical particle displacement
δr	Radial particle displacement
μ	Inter-particle friction coefficient
μ_{pile}	Interface friction coefficient

ν	Poisson's ratio (inter-particle contact model)
ν'	Poisson' ratio (interface contact model)
ρ	Density of particles
σ_v	Vertical stress in soil
$\dot{\gamma}$	Shear strain rate
$\dot{\theta}$	Rotational velocity
\dot{w}	Vertical velocity of pile

8 Table caption list

Table 1: HST95 sand physical and numerical properties (Sharif et al 2019a)

Table 2: Properties of soil beds used in this study at different relative densities (model scale parameters)

9 Figure caption list

Figure 1: Schematic diagram of screw pile used in this study, a) geometric properties, b) screw pile prototype dimensions. (model dimensions in brackets)

Figure 2: Example soil bed used in this study, screw pile installed to full embedment depth, 40m (0.5m) diameter and 32m (0.4m) in height. Particle shading indicates particle size distribution scaling applied ($D_r = 83\%$, $AR = 0.5$)

Figure 3: Installation requirements with depth of screw pile installed at varying advancement ratios. a) Compressive installation force ($D_r = 30\%$) b) Installation torque($D_r = 30\%$), c) Compressive installation force ($D_r = 52\%$) d) Installation torque($D_r = 52\%$), e) Compressive installation force ($D_r = 83\%$) f) Installation torque($D_r = 83\%$)

Figure 4: Evolution of advancement ratio (AR) with depth for a self-weight installed pile installed into a dense sand bed ($D_r = 83\%$).

Figure 5: Post installation axial capacity against normalised displacement. a) Compressive capacity ($D_r = 30\%$) b) Tensile capacity ($D_r = 30\%$), c) Compressive capacity ($D_r = 52\%$) d) Tensile capacity ($D_r = 52\%$), e) Compressive capacity ($D_r = 83\%$) from *DEM* study and pitched match installation results from Davidson et al. (2020) f) Tensile capacity ($D_r = 83\%$) from *DEM* study and pitched match installation results from Davidson et al. (2020)

Figure 6: Normalised results of the effects on advancement ratio and relative density on screw pile in-service performance. a) Compressive installation force, b) Installation torque, c) Compressive capacity, d) Tensile capacity. (Data at 1.0, 1.0 is offset for each relative density to allow distinction of data points)

Figure 7: Diagram of mechanism produced for different advancement ratios during tensile uplift testing in loose sand bed ($D_r = 32\%$). a) $AR = 0.5$, b) $AR = 1.0$, c) Change in relative density d) Change in relative density

Figure 8: Approximated failure surfaces calculated using the relative density index (Bolton, 1986) (left: Initial soil conditions, right: post installation conditions), superimposed over a diagram of the uplift mechanism of screw piles installed at different advancement ratios ($D_r = 83\%$) (screw pile is shown in its final position). a) $AR = 0.5$ b) $AR = 1.0$

Figure 9: Back calculated torque-capacity correlation factors compared to Equation 2 (Perko 2009) and centrifuge study of Davidson et al (2020) a) Tensile K_t b) compressive K_c

Figure 10: Residual locked in stresses at the end of installation produced by different advancement ratios

Figure 11: Comparison of particle displacement during installation between pitch matched (AR = 1.0) and over flighted (AR = 0.5) installation a) vertical displacement b) radial displacement

Figure 12: Dimensionless torque correlation factors back calculated using equation 3 in accordance with Byrne and Houlsby (2015) a) Tensile K_t^* , b) Compressive K_c^*

Figure 13: Mechanism form for installed screw piles during axial capacity testing (AR=0.5) a) compression ($H/D_h = 7$) b) tension ($H/D_h = 7$) c) compression ($H/D_h = 11$) d) tension ($H/D_h = 11$)

Figure 14: The effect of relative embedment depth and advancement ratio on torque-capacity correlation factors in a dense soil bed. a) Tension b) Compression

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Table 1: HST95 sand physical and numerical properties (Sharif et al 2019a)

HST95 silica sand property	Value
<i>Physical properties</i>	
Sand unit weight γ (kN/m ³)	16.75
Minimum dry density γ_{max} (kN/m ³)	14.59
Maximum dry density γ_{min} (kN/m ³)	17.58
Critical state friction angle, ϕ (degrees)	32
Interface friction angle, δ (degrees)	18
D ₃₀ (mm)	0.12
D ₆₀ (mm)	0.14
<i>DEM Parameters</i>	
Shear modulus, G (GPa)	3
Friction coefficient, μ (-)	0.264
Poisson's ratio, ν (-)	0.3
Interface friction coefficient [pile], μ_{pile} (-)	0.16

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Table 2: Properties of soil beds used in this study at different relative densities (model scale parameters)

Property	Loose	Medium Dense	Dense
Relative Density (%)	30	52	83
Voids ratio (e)	0.68	0.61	0.52
Height (mm)	400	400	400
Radius (mm)	250	250	250
Core PSD scaling (N_c)	20	20	20
Gravitational field	48	48	48
Number of Particles	190,000	220,000	270,000
Formation time	30 hours	25 hours	22 hours

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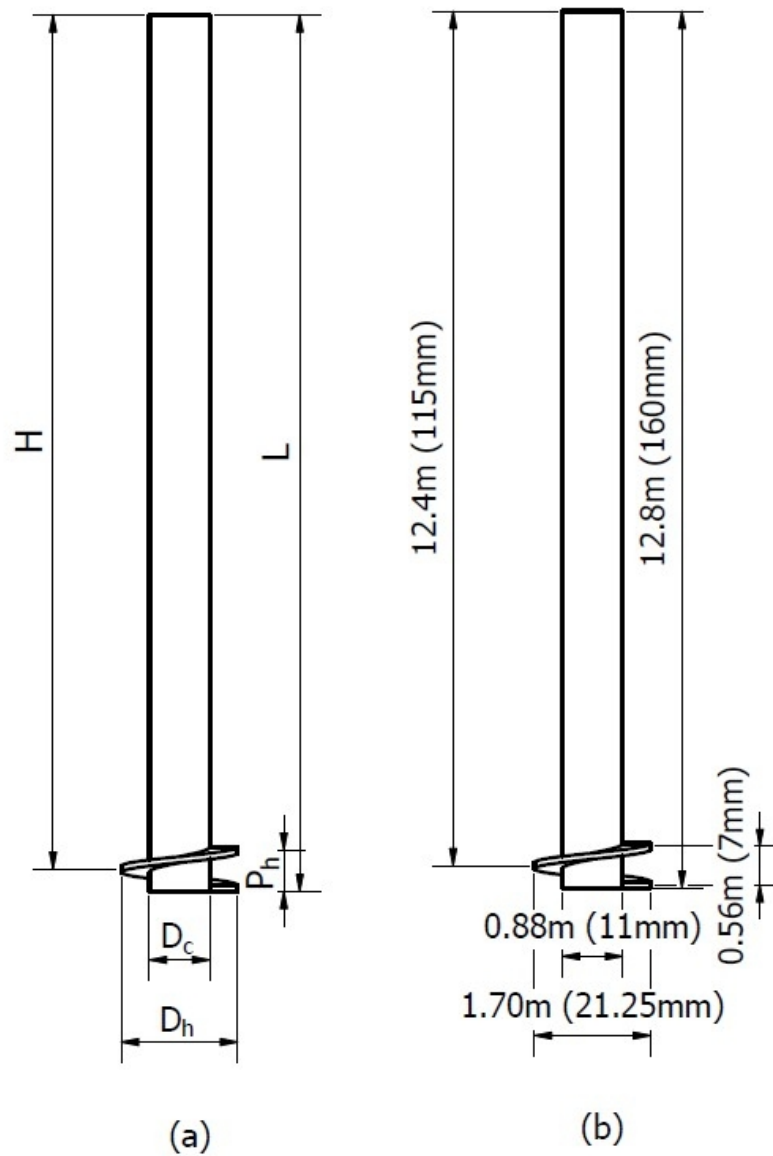


Figure 1: Schematic diagram of screw pile used in this study, a) geometric properties, b) screw pile prototype dimensions. (model dimensions in brackets)

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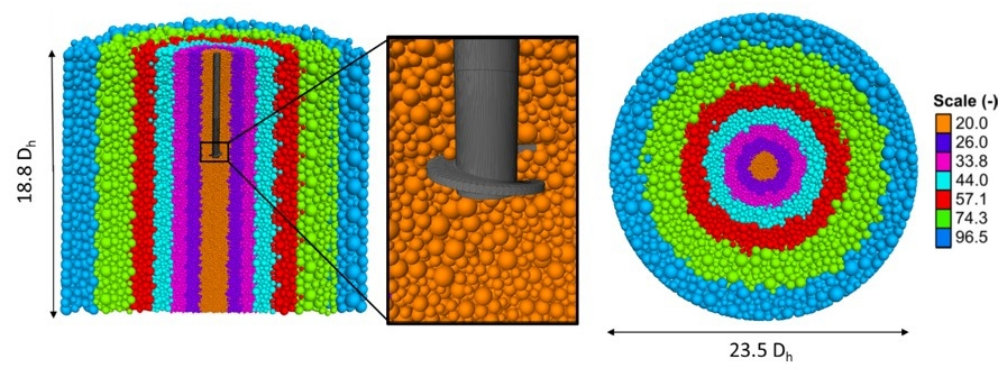


Figure 2: Example soil bed used in this study, screw pile installed to full embedment depth, 40m (0.5m) diameter and 32m (0.4m) in height. Particle shading indicates particle size distribution scaling applied ($D_r = 83\%$, $AR = 0.5$)

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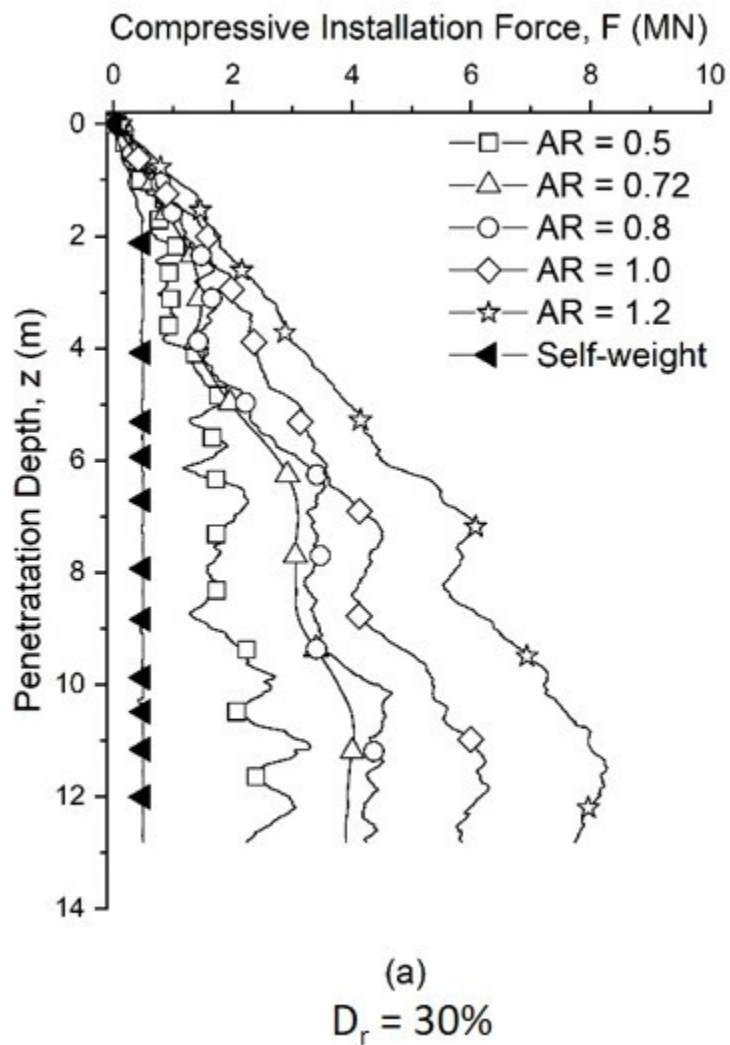


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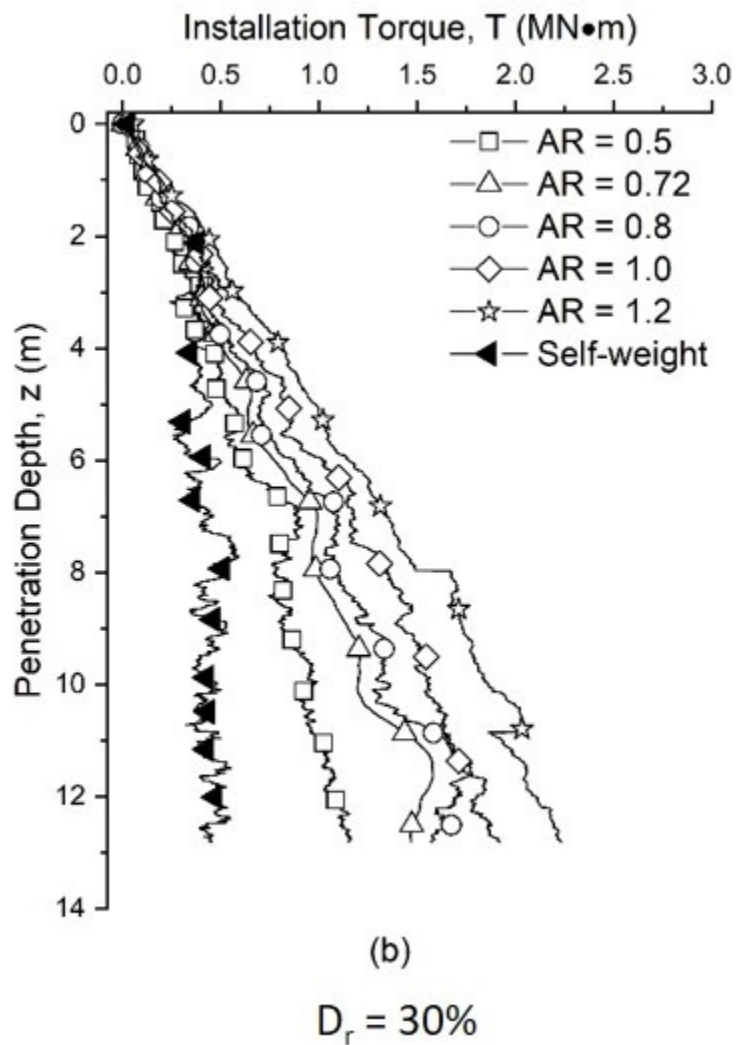
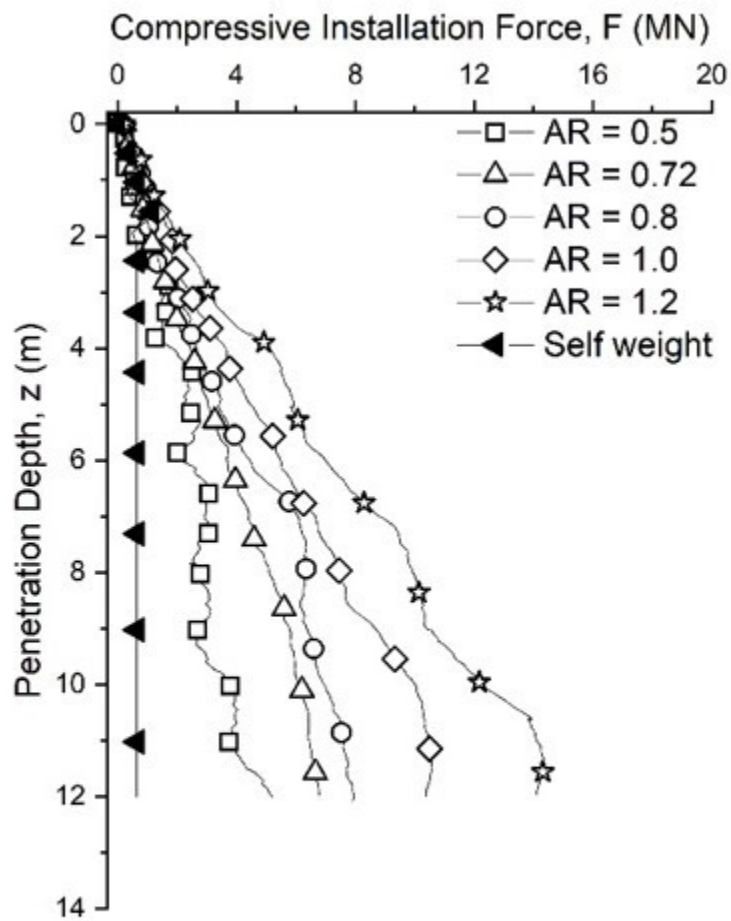


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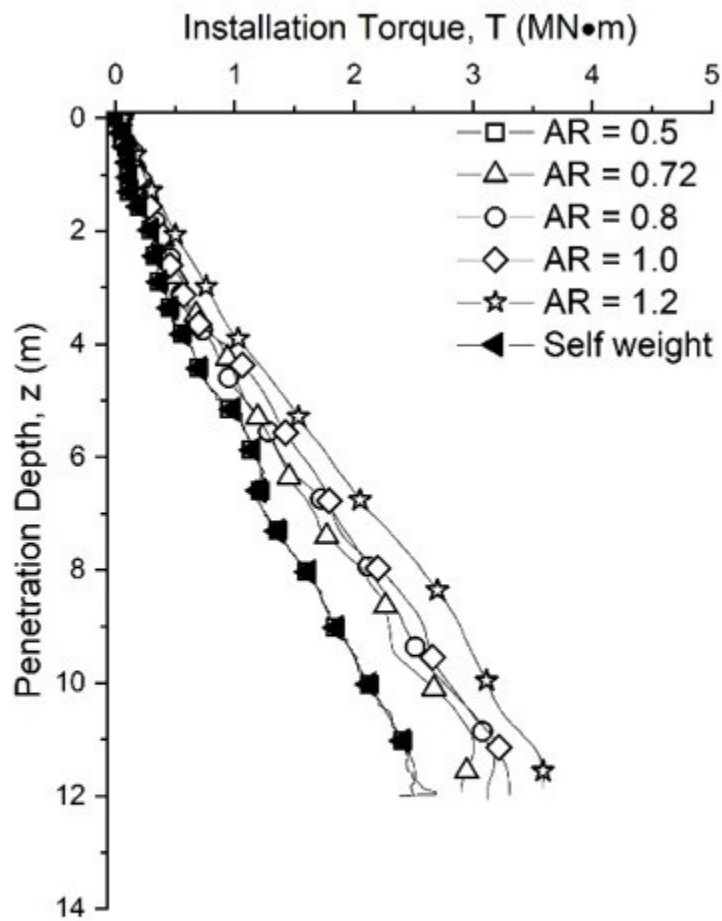
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(c)
 $D_r = 52\%$

Figure 3: Installation requirements with depth of screw pile installed at varying advancement ratios. a) Compressive installation force ($D_r = 30\%$) b) Installation torque ($D_r = 30\%$), c) Compressive installation force ($D_r = 52\%$) d) Installation torque ($D_r = 52\%$), e) Compressive installation force ($D_r = 83\%$) f) Installation torque ($D_r = 83\%$)

75x93mm (150 x 150 DPI)

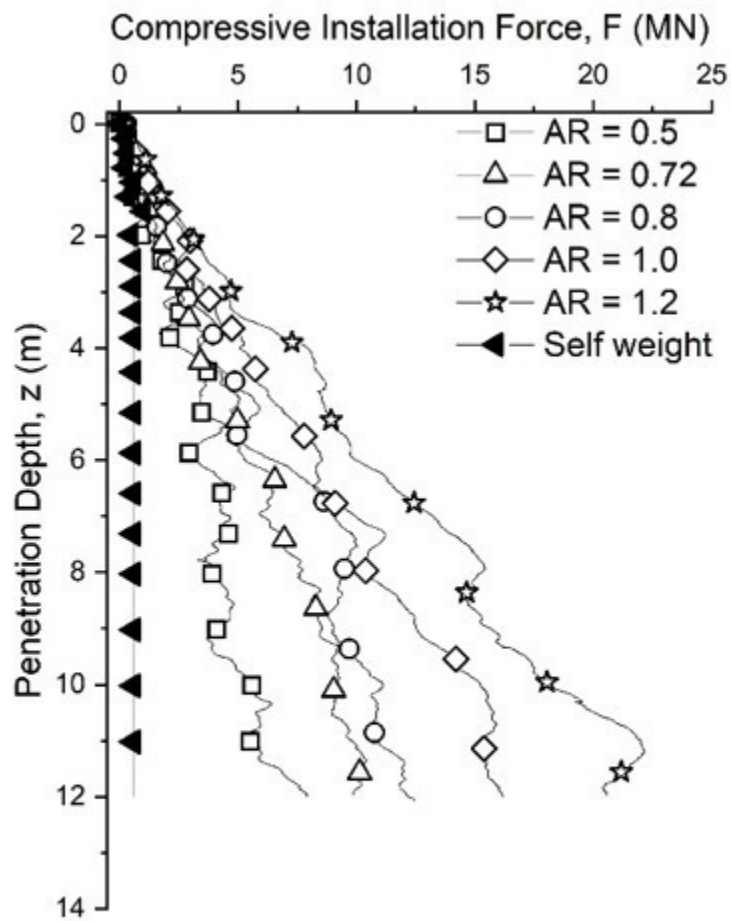


(d)

 $D_r = 52\%$

Figure 3: Installation requirements with depth of screw pile installed at varying advancement ratios. a) Compressive installation force ($D_r = 30\%$) b) Installation torque ($D_r = 30\%$), c) Compressive installation force ($D_r = 52\%$) d) Installation torque ($D_r = 52\%$), e) Compressive installation force ($D_r = 83\%$) f) Installation torque ($D_r = 83\%$)

75x93mm (150 x 150 DPI)

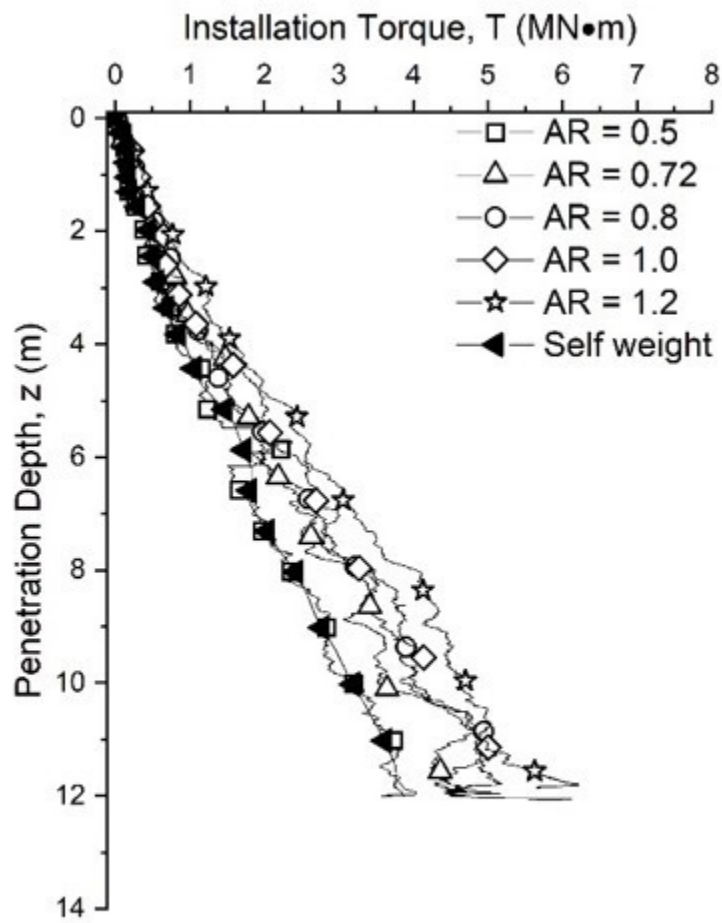


(e)

 $D_r = 83\%$

Figure 3: Installation requirements with depth of screw pile installed at varying advancement ratios. a) Compressive installation force ($D_r = 30\%$) b) Installation torque ($D_r = 30\%$), c) Compressive installation force ($D_r = 52\%$) d) Installation torque ($D_r = 52\%$), e) Compressive installation force ($D_r = 83\%$) f) Installation torque ($D_r = 83\%$)

75x93mm (150 x 150 DPI)



(f)
 $D_r = 83\%$

Figure 3: Installation requirements with depth of screw pile installed at varying advancement ratios. a) Compressive installation force ($D_r = 30\%$) b) Installation torque ($D_r = 30\%$), c) Compressive installation force ($D_r = 52\%$) d) Installation torque ($D_r = 52\%$), e) Compressive installation force ($D_r = 83\%$) f) Installation torque ($D_r = 83\%$)

75x93mm (150 x 150 DPI)

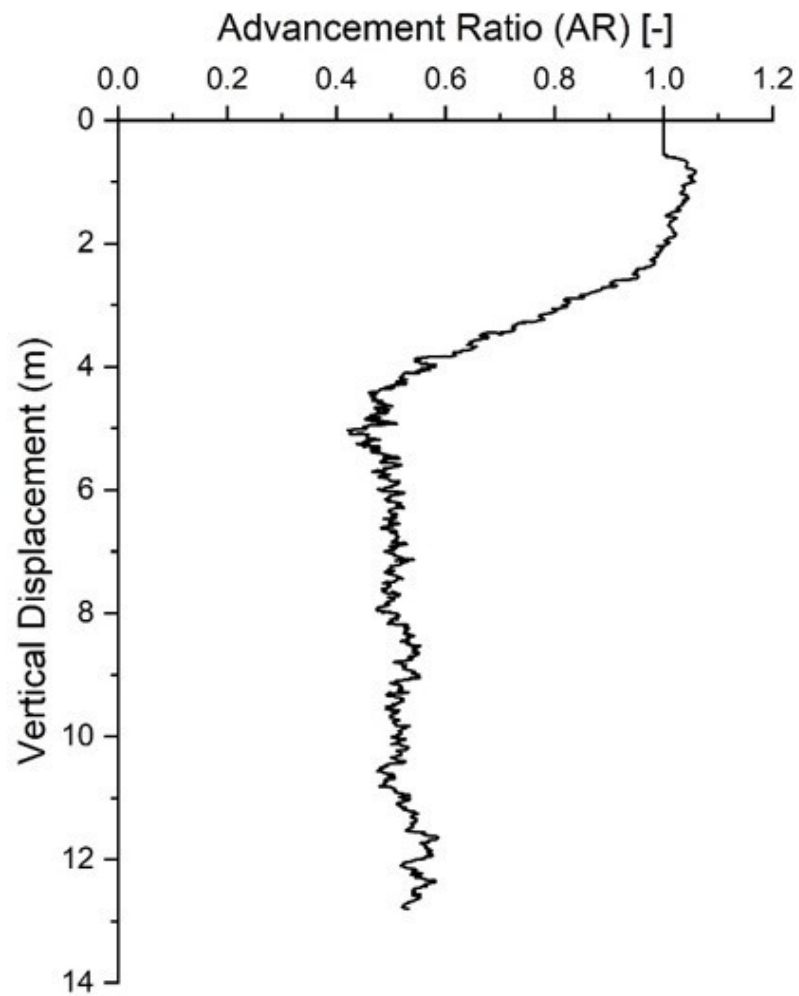


Figure 4: Evolution of advancement ratio (AR) with depth for a self-weight installed pile installed into a dense sand bed ($D_r = 83\%$).

85x107mm (150 x 150 DPI)

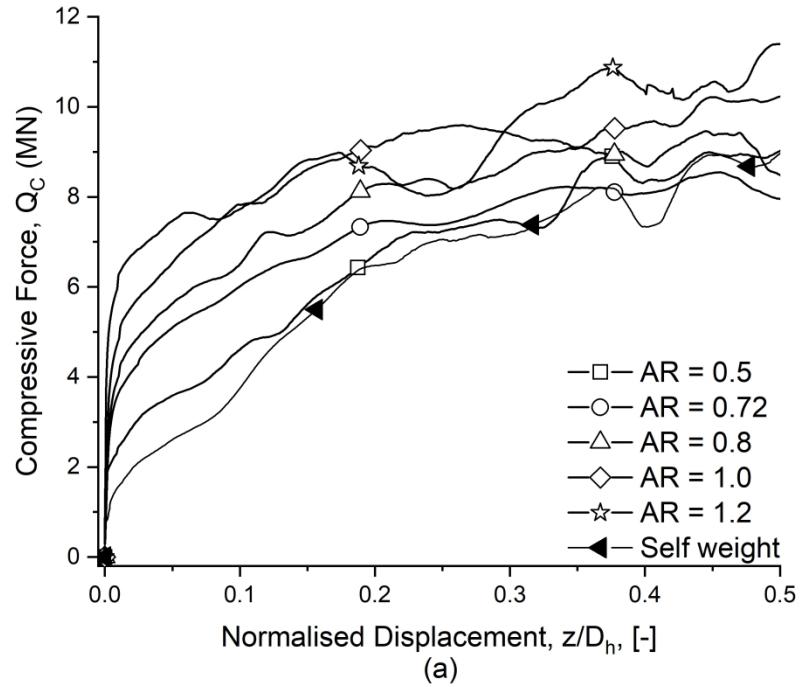


Figure 5: Post installation axial capacity against normalised displacement. a) Compressive capacity ($D_r = 30\%$) b) Tensile capacity ($D_r = 30\%$), c) Compressive capacity ($D_r = 52\%$) d) Tensile capacity ($D_r = 52\%$), e) Compressive capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020) f) Tensile capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020)

272x208mm (300 x 300 DPI)

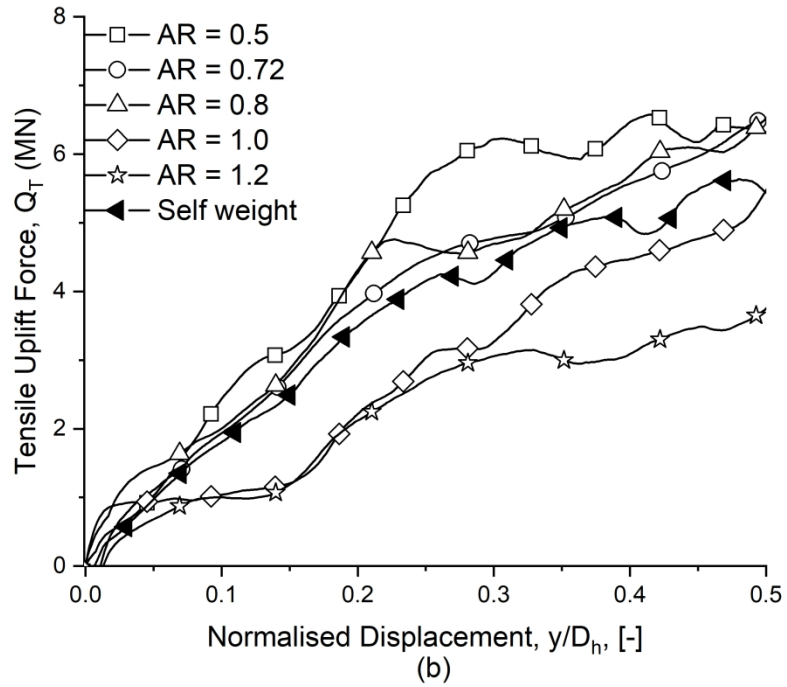


Figure 5: Post installation axial capacity against normalised displacement. a) Compressive capacity ($D_r = 30\%$) b) Tensile capacity ($D_r = 30\%$), c) Compressive capacity ($D_r = 52\%$) d) Tensile capacity ($D_r = 52\%$), e) Compressive capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020) f) Tensile capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020)

272x208mm (300 x 300 DPI)

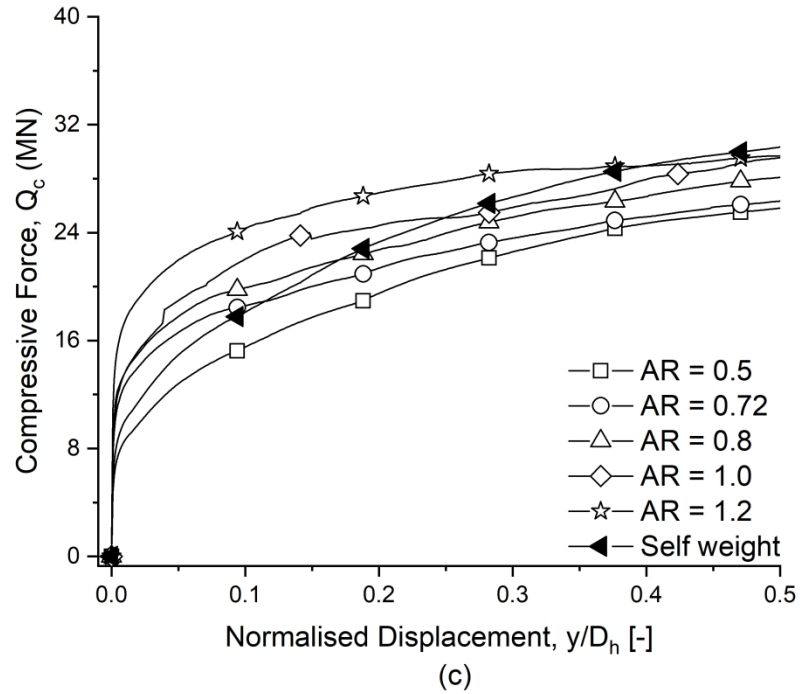


Figure 5: Post installation axial capacity against normalised displacement. a) Compressive capacity ($D_r = 30\%$) b) Tensile capacity ($D_r = 30\%$), c) Compressive capacity ($D_r = 52\%$) d) Tensile capacity ($D_r = 52\%$), e) Compressive capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020) f) Tensile capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020)

272x208mm (300 x 300 DPI)

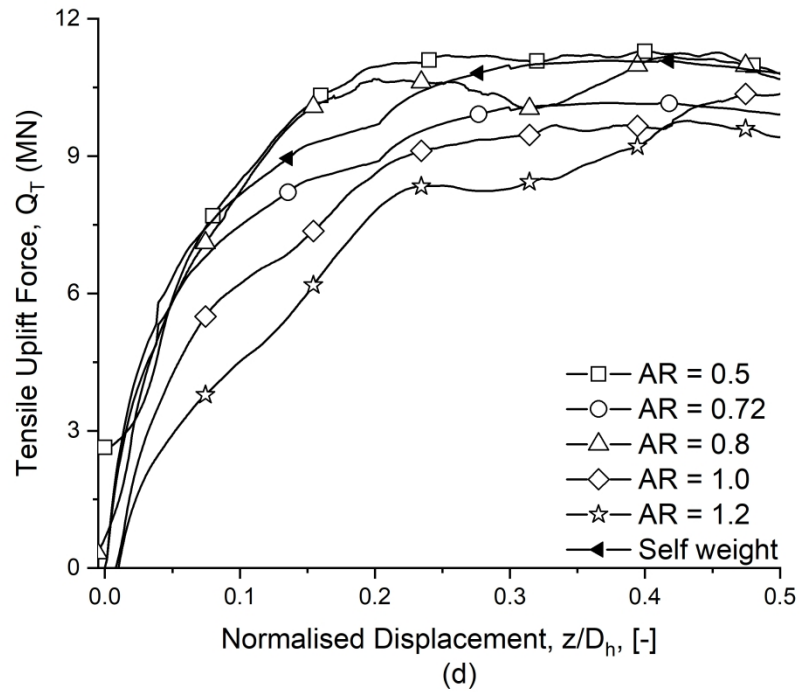


Figure 5: Post installation axial capacity against normalised displacement. a) Compressive capacity ($D_r = 30\%$) b) Tensile capacity ($D_r = 30\%$), c) Compressive capacity ($D_r = 52\%$) d) Tensile capacity ($D_r = 52\%$), e) Compressive capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020) f) Tensile capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020)

272x208mm (300 x 300 DPI)

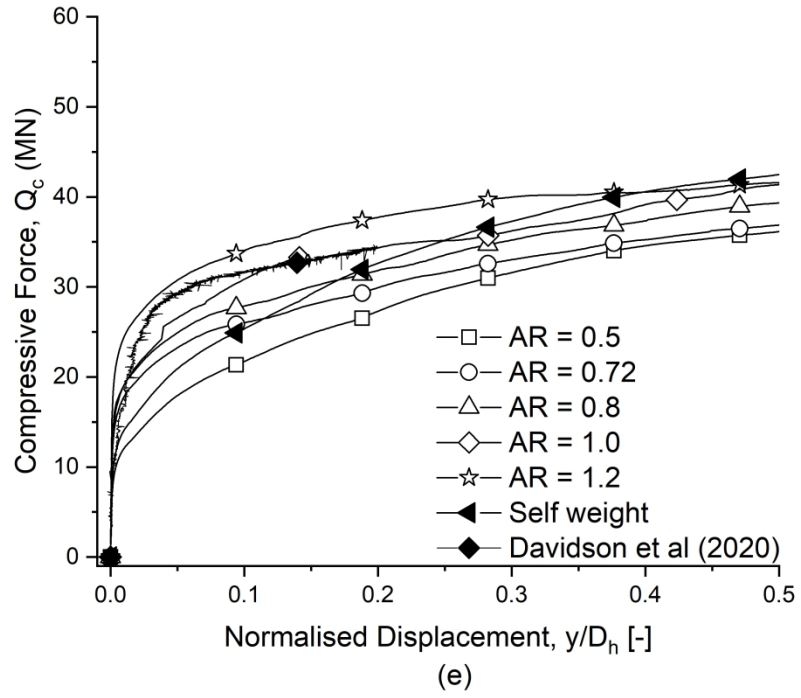


Figure 5: Post installation axial capacity against normalised displacement. a) Compressive capacity ($D_r = 30\%$) b) Tensile capacity ($D_r = 30\%$), c) Compressive capacity ($D_r = 52\%$) d) Tensile capacity ($D_r = 52\%$), e) Compressive capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020) f) Tensile capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020)

272x208mm (300 x 300 DPI)

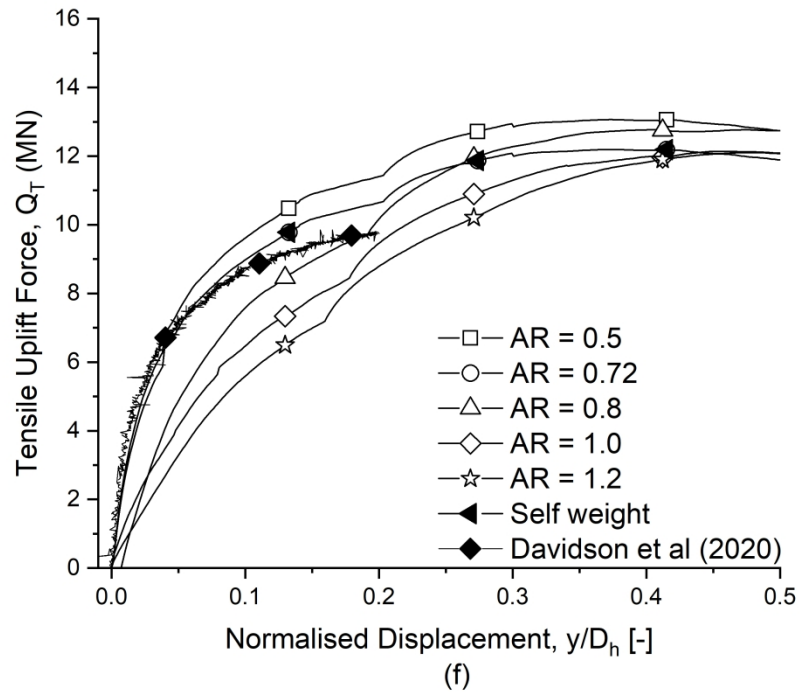


Figure 5: Post installation axial capacity against normalised displacement. a) Compressive capacity ($D_r = 30\%$) b) Tensile capacity ($D_r = 30\%$), c) Compressive capacity ($D_r = 52\%$) d) Tensile capacity ($D_r = 52\%$), e) Compressive capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020) f) Tensile capacity ($D_r = 83\%$) from DEM study and pitched-match installation results from Davidson et al. (2020)

272x208mm (300 x 300 DPI)

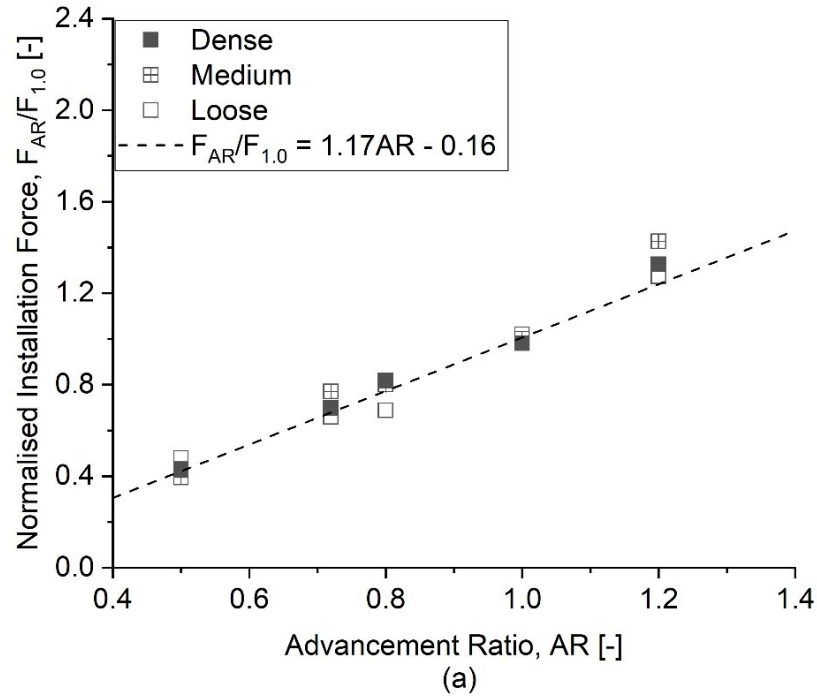


Figure 6: Normalised results of the effects on advancement ratio and relative density on screw pile in-service performance. a) Compressive installation force, b) Installation torque, c) Compressive capacity, d) Tensile capacity. (Data at 1.0, 1.0 is offset for each relative density to allow distinction of data points)

130x99mm (220 x 220 DPI)

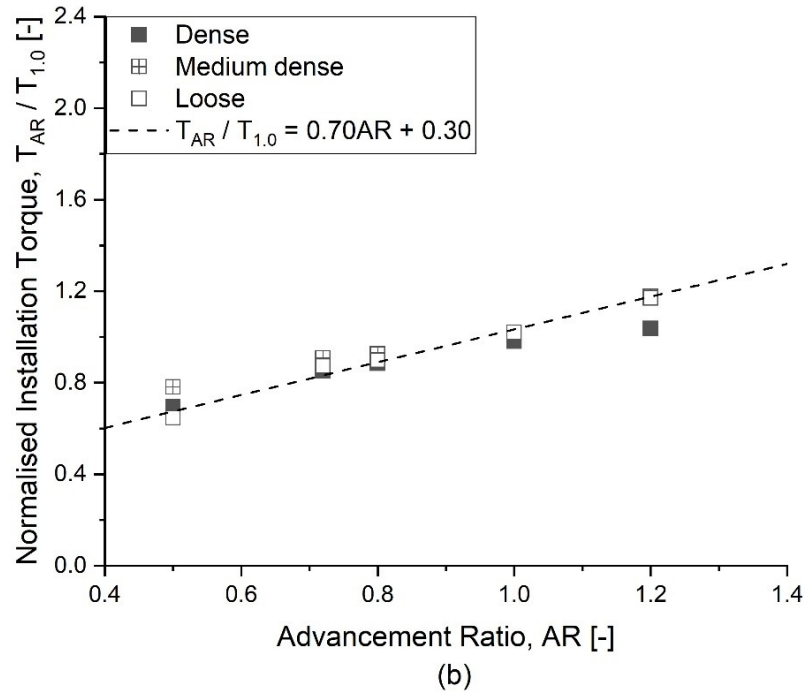


Figure 6: Normalised results of the effects on advancement ratio and relative density on screw pile in-service performance. a) Compressive installation force, b) Installation torque, c) Compressive capacity, d) Tensile capacity. (Data at 1.0, 1.0 is offset for each relative density to allow distinction of data points)

130x99mm (220 x 220 DPI)

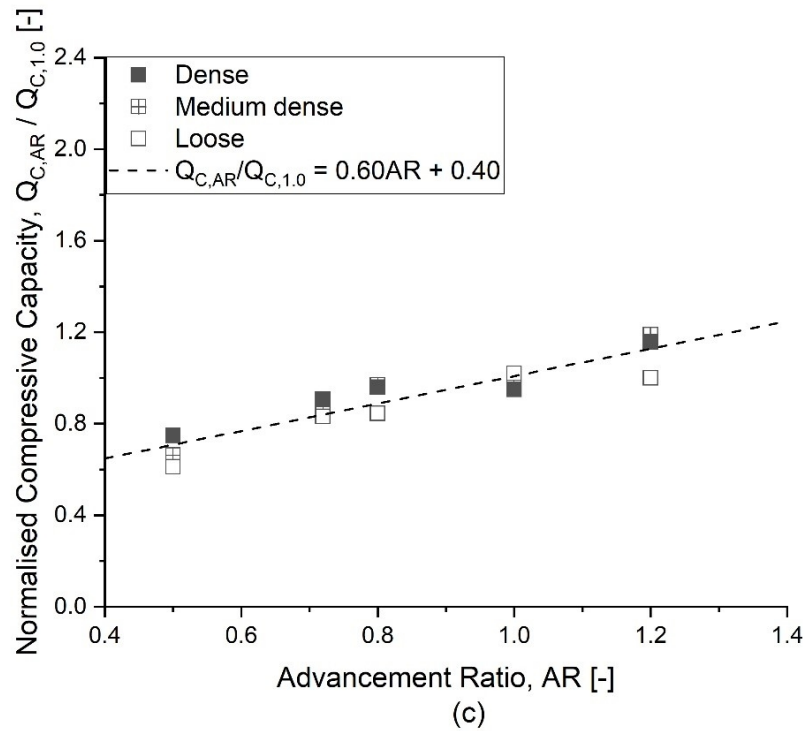


Figure 6: Normalised results of the effects on advancement ratio and relative density on screw pile in-service performance. a) Compressive installation force, b) Installation torque, c) Compressive capacity, d) Tensile capacity. (Data at 1.0, 1.0 is offset for each relative density to allow distinction of data points)

130x99mm (220 x 220 DPI)

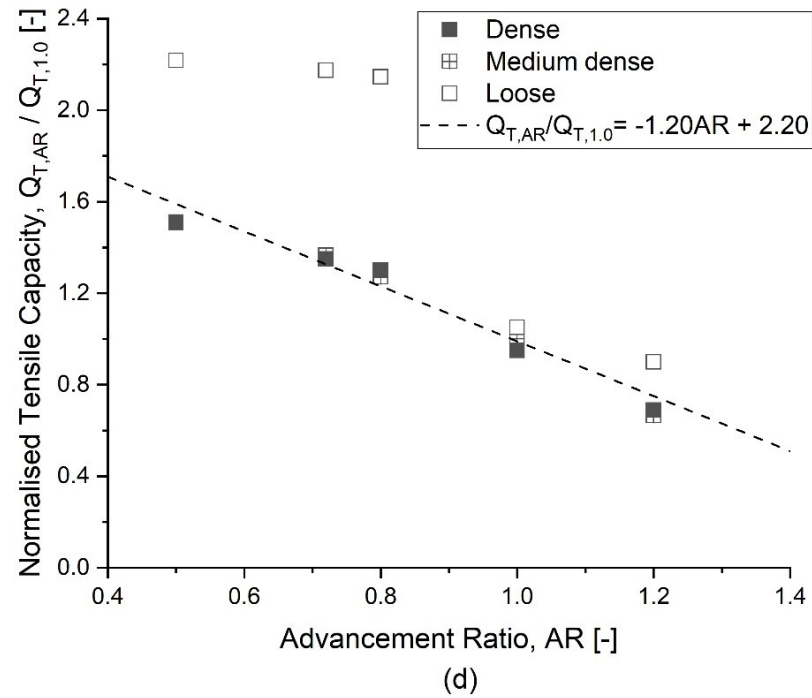


Figure 6: Normalised results of the effects on advancement ratio and relative density on screw pile in-service performance. a) Compressive installation force, b) Installation torque, c) Compressive capacity, d) Tensile capacity. (Data at 1.0, 1.0 is offset for each relative density to allow distinction of data points)

130x99mm (220 x 220 DPI)

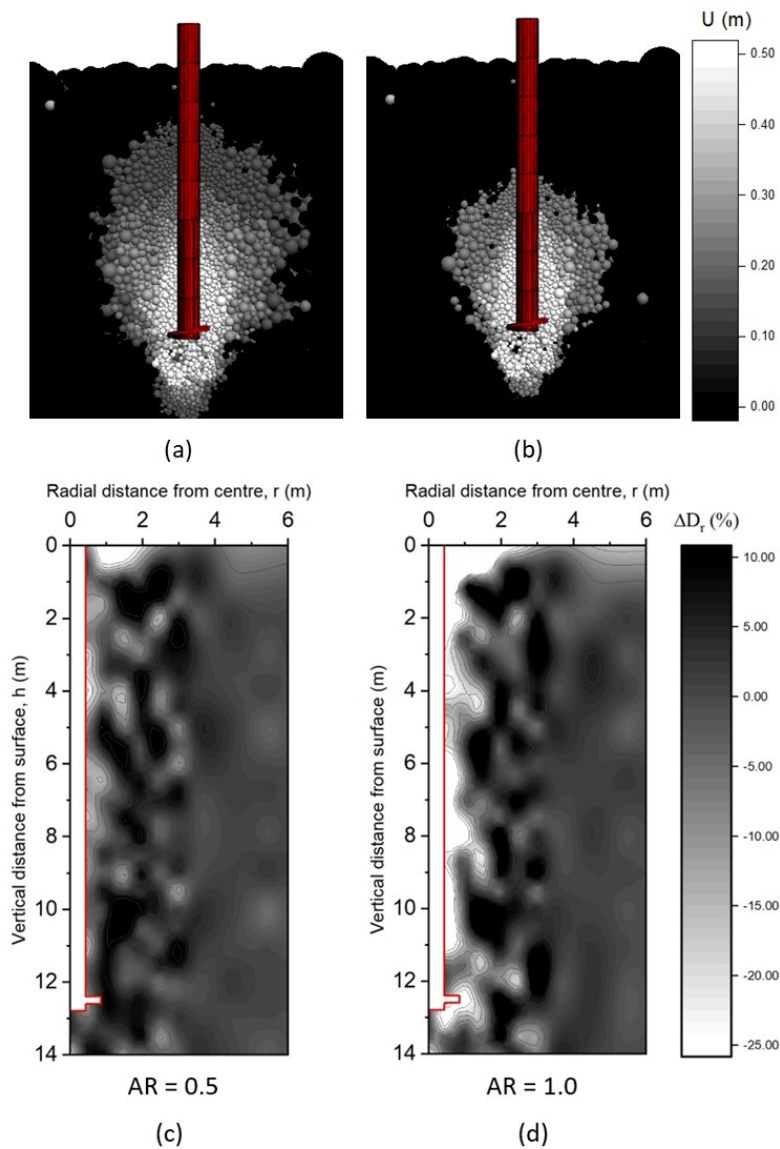


Figure 7: Diagram of mechanism produced for different advancement ratios during tensile uplift testing in loose sand bed ($D_r = 32\%$). a) AR = 0.5, b) AR = 1.0, c) Change in relative density d) Change in relative density

143x193mm (150 x 150 DPI)

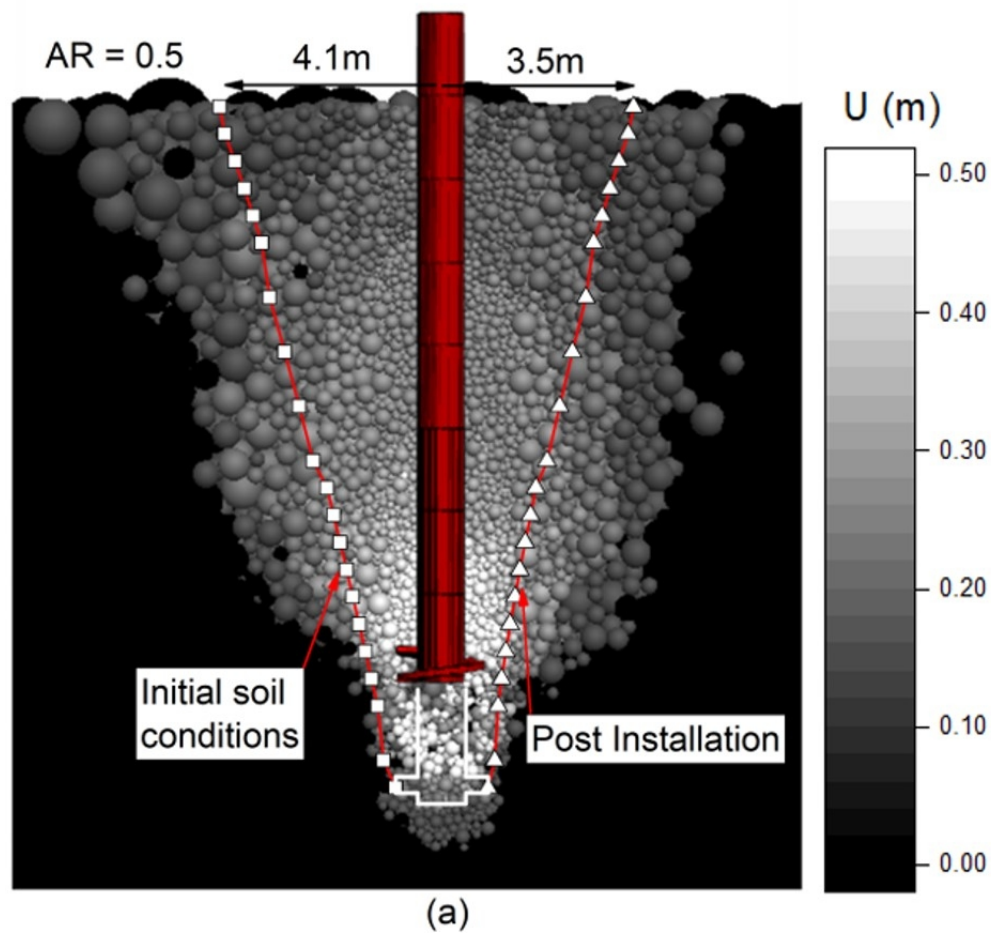


Figure 8: Approximated failure surfaces calculated using the relative density index (Bolton, 1986) (left: Initial soil conditions, right: post installation conditions), superimposed over a diagram of the uplift mechanism of screw piles installed at different advancement ratios ($D_r = 83\%$) (screw pile is shown in its final position). a) AR = 0.5 b) AR = 1.0

158x149mm (150 x 150 DPI)

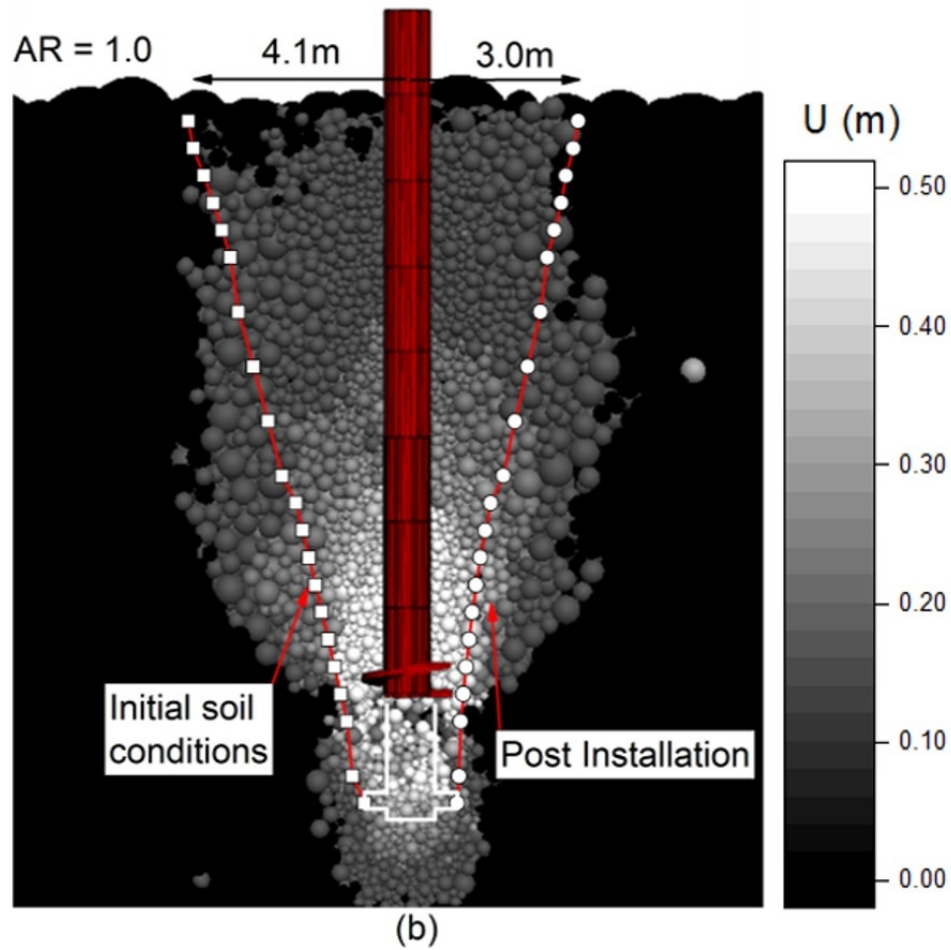


Figure 8: Approximated failure surfaces calculated using the relative density index (Bolton, 1986) (left: Initial soil conditions, right: post installation conditions), superimposed over a diagram of the uplift mechanism of screw piles installed at different advancement ratios ($D_r = 83\%$) (screw pile is shown in its final position). a) $AR = 0.5$ b) $AR = 1.0$

157x149mm (150 x 150 DPI)

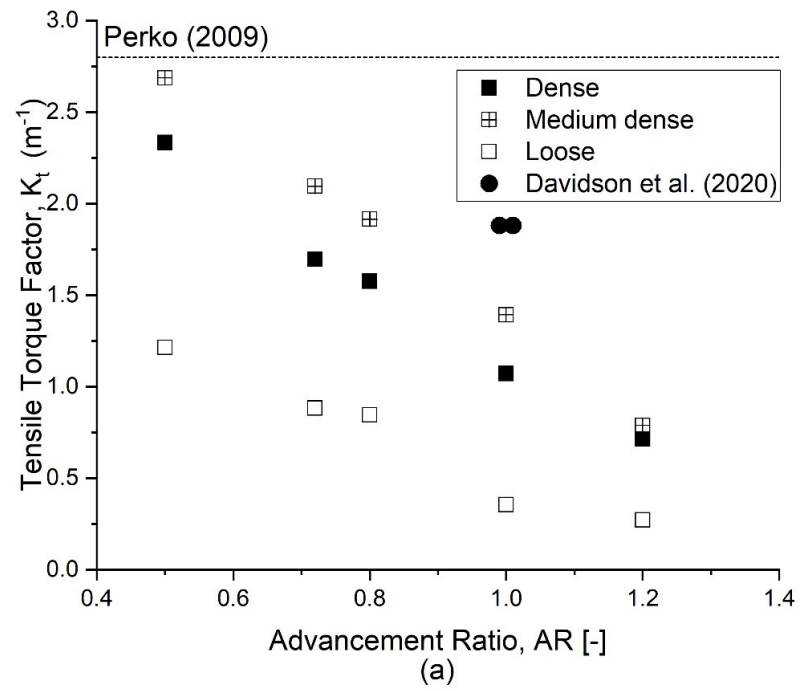


Figure 9: Back calculated torque-capacity correlation factors compared to Equation 2 (Perko 2009) and centrifuge study of Davidson et al (2020) a) Tensile K_t b) compressive K_c

143x110mm (220 x 220 DPI)

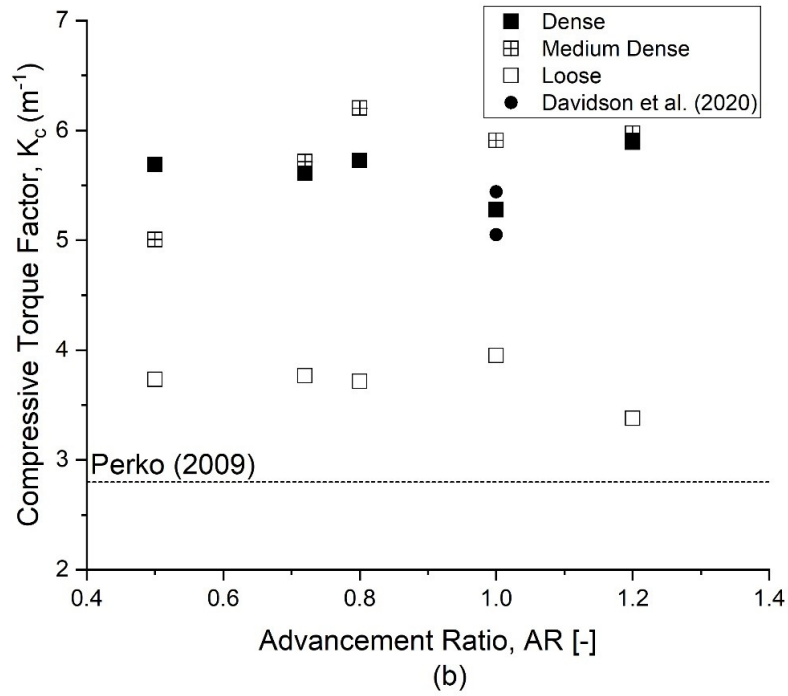


Figure 9: Back calculated torque-capacity correlation factors compared to Equation 2 (Perko 2009) and centrifuge study of Davidson et al (2020) a) Tensile K_t b) compressive K_c

143x110mm (220 x 220 DPI)

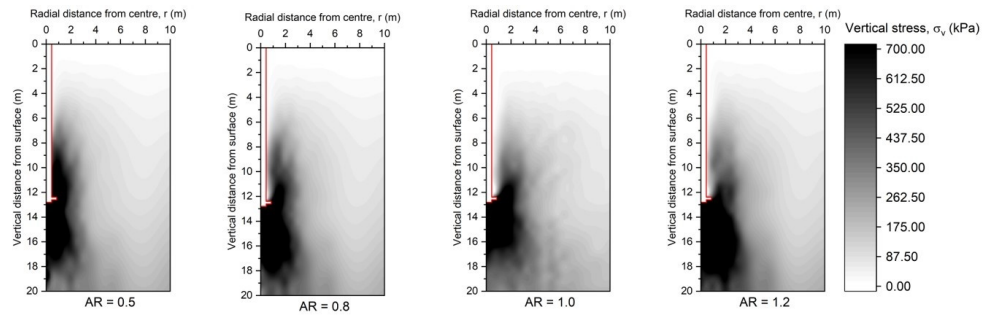


Figure 10: Residual locked in stresses at the end of installation produced by different advancement ratios

362x122mm (96 x 96 DPI)

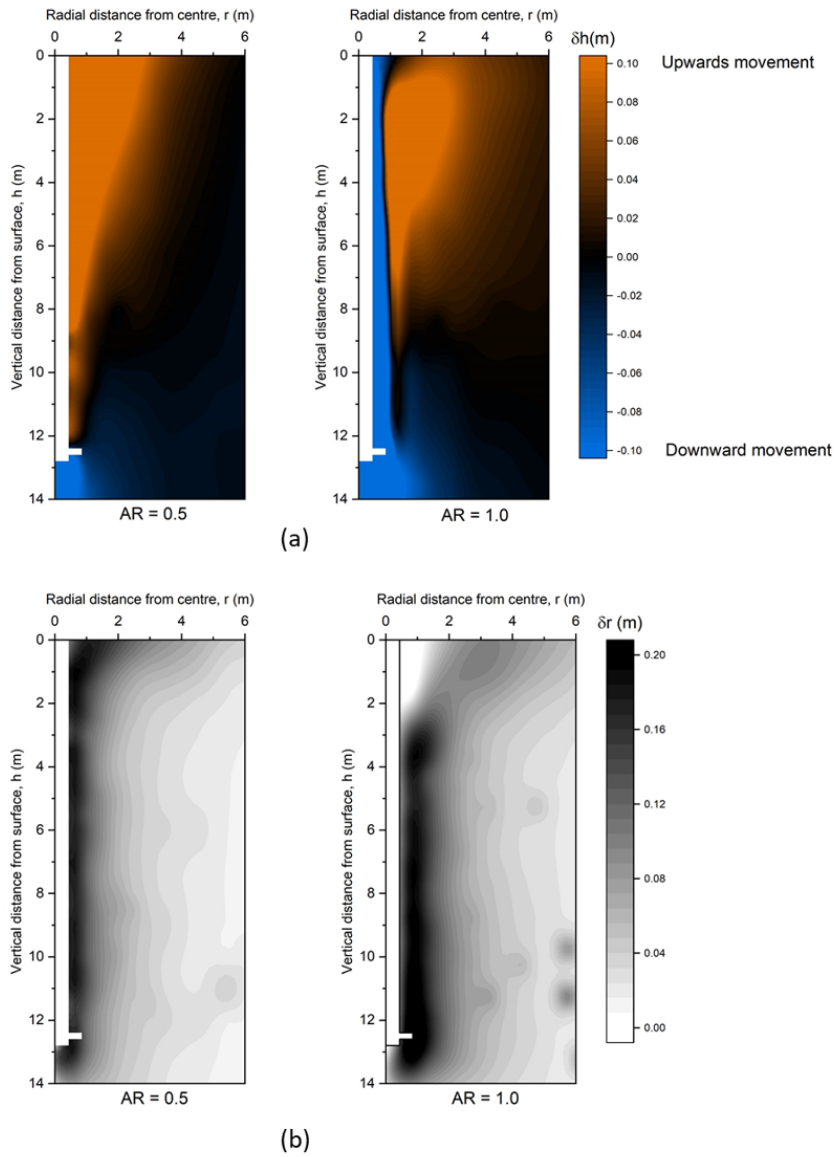


Figure 11: Comparison of particle displacement during installation between pitch matched (AR = 1.0) and over-flighted (AR = 0.5) installation a) vertical displacement b) radial displacement

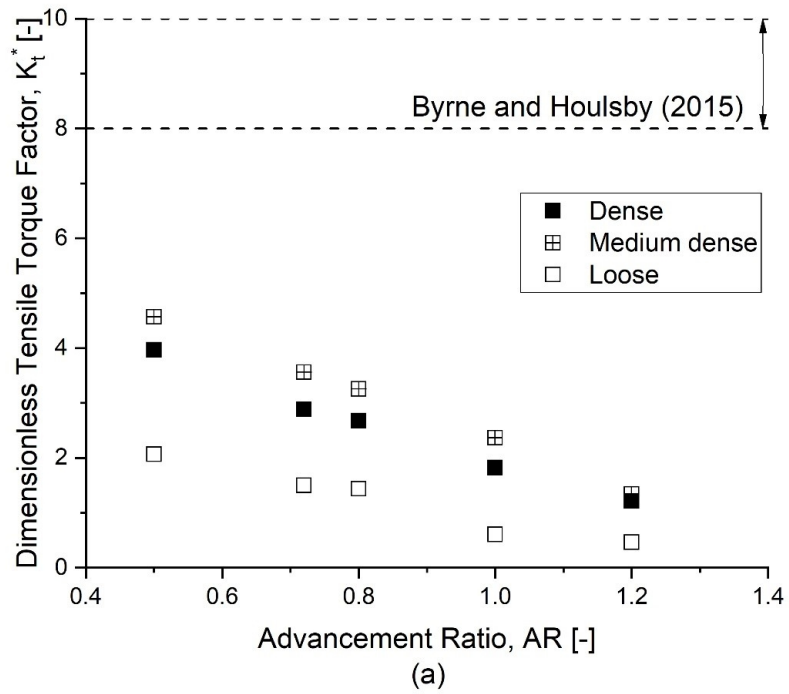


Figure 12: Dimensionless torque correlation factors back calculated using equation 3 in accordance with Byrne and Houlsby (2015) a) Tensile K_t^* , b) Compressive K_c^*

149x114mm (220 x 220 DPI)

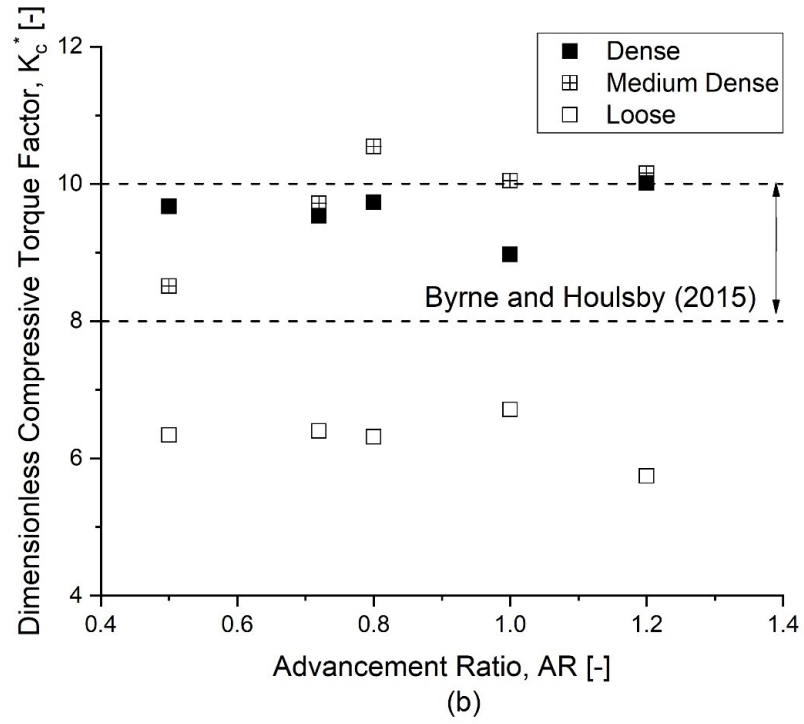


Figure 12: Dimensionless torque correlation factors back calculated using equation 3 in accordance with Byrne and Houlsby (2015) a) Tensile K_t^* , b) Compressive K_c^*

149x114mm (220 x 220 DPI)

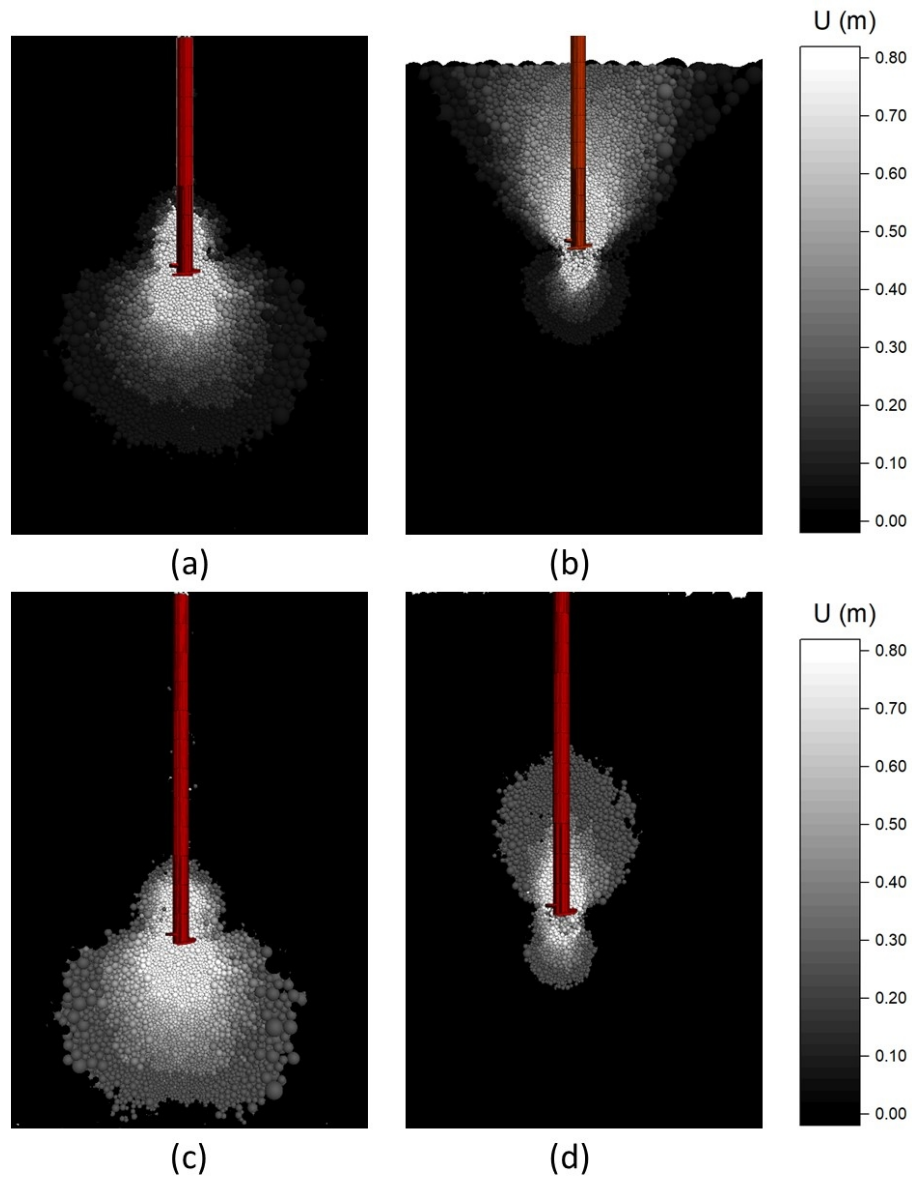


Figure 13: Mechanism form for installed screw piles during axial capacity testing (AR=0.5) a) compression ($H/D_h = 7$) b) tension ($H/D_h = 7$) c) compression ($H/D_h = 11$) d) tension ($H/D_h = 11$)

159x210mm (150 x 150 DPI)

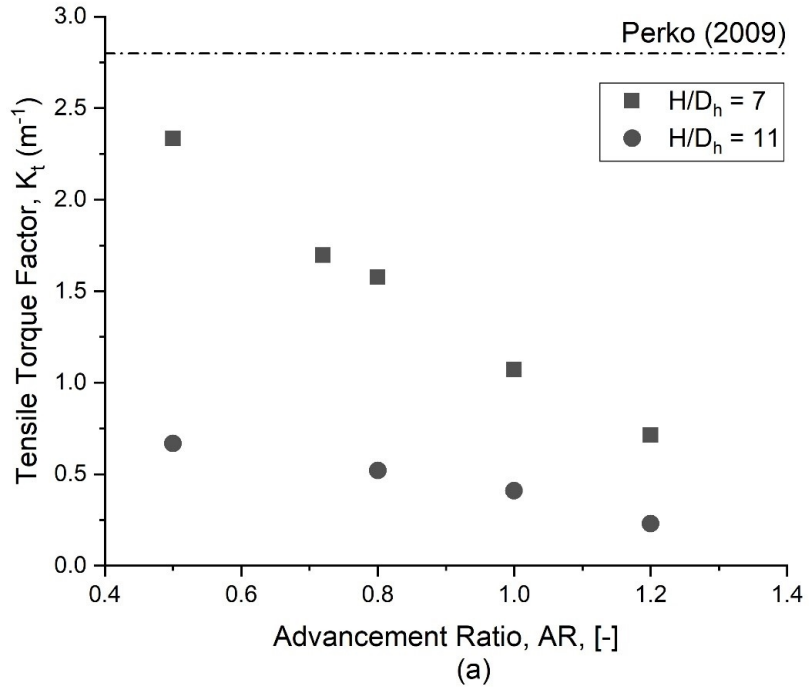


Figure 14: The effect of relative embedment depth and advancement ratio on torque-capacity correlation factors in a dense soil bed. a) Tension b) Compression

149x114mm (220 x 220 DPI)

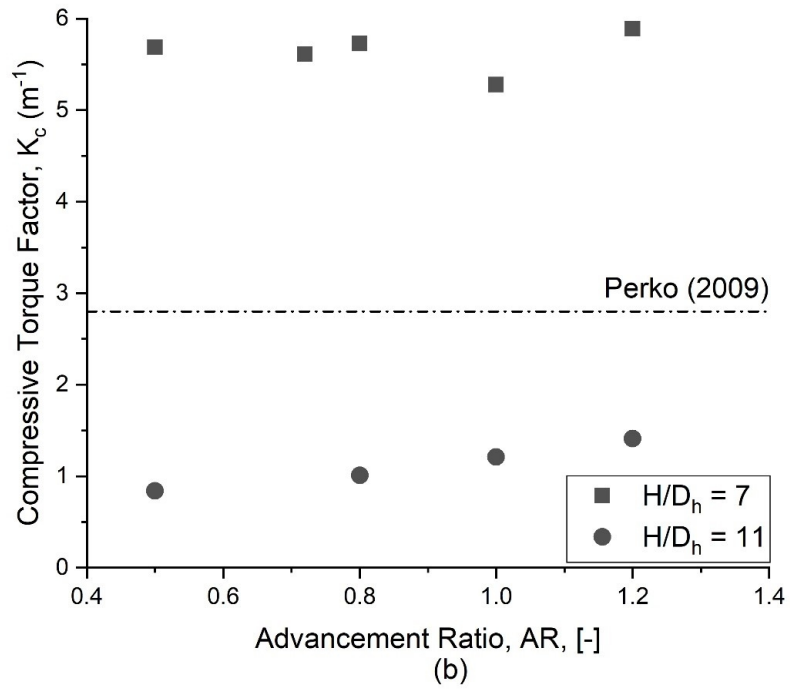


Figure 14: The effect of relative embedment depth and advancement ratio on torque-capacity correlation factors in a dense soil bed. a) Tension b) Compression

149x114mm (220 x 220 DPI)