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1 Drag anchor behaviour in soft clay deposits: Model investigation in transparent clay
2 surrogate and analytical predictions

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36

37 **ABSTRACT**

38 As the offshore energy industry begins to develop wind farms in areas of deeper water, the
39 use of traditional foundations such as shallow foundation and driven hollow steel tube piles
40 becomes uneconomical. The deployment of floating turbines and continued development of
41 novel/efficient anchoring systems for these structures will be an important factor in the
42 continued growth of the sector. This paper presents an investigation carried out as part of a
43 proof-of-concept for a novel 'Bi-Wing Anchor'. This design will allow a plate anchor to be
44 dropped through the water column and then penetrate the seabed under its own weight. The
45 anchor will then be dragged causing it to embed further into the seabed and provide a greater
46 holding capacity. This paper focuses on experimental as well as analysis of the drag
47 embedment behaviour during the installation and pull-out phases. The physical modelling
48 investigations were carried out in a transparent clay-surrogate which enabled observation of
49 the anchor's orientation during installation. The predictions using analytical modelling showed
50 good agreement with the observed behaviour at varying embedment ratios.

51 Keyword: Bi-Wing Anchor, anchor kinematics, clay surrogate

52

53 INTRODUCTION

54 The offshore wind energy industry is developing installation techniques in areas of deeper
55 water, which necessitates the development of efficient and reliable foundation systems. To
56 deploy wind turbines in these areas, the use of floating structures and mooring lines that are
57 anchored to the seabed is becoming the most economically feasible option (Musial et al. 2004;
58 Karimirad and Torgeir 2012; Barooni et al. 2023). To anchor mooring lines to the seabed,
59 various anchoring options such as driven pile, suction caissons, and drag embedded anchors
60 (DEA) are often used by the offshore oil and gas industry (Randolph and Gourvenec 2011).
61 In recent past new, anchoring systems like dynamically installed torpedo anchor (Richardson
62 2008; O'Loughlin et al. 2013) and suction embedded plate anchor (Dove et al. 1998; Wilde et
63 al. 2001; Yang et al. 2012) has been deployed in some offshore structures. In deep water,
64 selection of anchors is primarily driven by cost differences. Drag embedded anchors are an
65 effective and attractive option due to their low installation costs and high holding capacity
66 relative to their self-weight. The offshore oil and gas industry has made use of these drag
67 embedded anchors for permanent (as well as temporary) moorings. Various experimental (
68 Liu et al. 2010; Shin et al. 2011; O'Loughlin et al. 2014; Balck and O'Loughlin 2015; Yu et al.
69 2015; Lai et al. 2020; Liu et al. 2021; Fanning et al. 2023) and analytical (O'Neill *et.al.* 2003;
70 Aubeny and Chi 2010; Liu et al. 2010; Liu et al. 2012; Aubeny and Chi 2014; Zhang et al.
71 2014; Tong et al. 2020; Han et al. 2023) studies have been reported on the subject. The pullout
72 capacity of these anchors largely depends on factors such as soil type, embedment depth,
73 and the orientation of the fluke. For optimal penetration, DEA anchors must be accurately
74 positioned on the seabed before initiating drag embedment. However, environmental forces
75 can sometimes prevent precise initial placement, introducing uncertainty in the final
76 embedment depth and, consequently, affecting the anchor's pullout capacity. Additionally,
77 embedment depth is typically estimated using semi-empirical methods, which may yield
78 unreliable predictions across varying soil conditions. This uncertainty can be addressed

79 through proof load testing of the anchor (DNV-RP-E302; Aubeny 2018), although such testing
80 is often costly.

81 Limit equilibrium approach has been adopted to predict the drag anchor behaviour, for
82 example by: Stewart (1992); Neubecker and Randolph (1995); Neubecker and Randolph
83 (1996a,b,c); O'Neill et al. (2003) proposed a plasticity model which used yield loci to express
84 the combined horizontal and vertical loads and moments which cause failure of the soil
85 surrounding the anchor. Aubeny and Chi (2014) further modified the O'Neill et al. (2003)
86 considering shank resistance.

87 Recently, various innovative anchor systems have been proposed, such as helical pile
88 anchors (Byrne and Houlsby 2015; Ullah et al. 2023) dynamically installed plate anchor, DIPA
89 (Flores 2016; Ying et al., 2020) and dynamically embedded plate anchors, DEPLA (O'Loughlin
90 et al. 2014; Blake and O'Loughlin et al. 2015). The helical pile anchors substantially reduce
91 the cost of installations compared to the driven pile and suction caissons. Similarly, DEPLA
92 and DIPA bring more reliability on the penetration of plate anchor. For the installation, DEPLA
93 and DIPA use the concept of a torpedo anchor as well as DEA, which is why it is sometimes
94 also referred to as a hybrid anchor system. Usually, the DEPLA is consists of plate anchor
95 and torpedo like central shaft or follower. The DEPLA is released from a designated height
96 above the seabed, like a torpedo anchor. After installation, the follower or central shaft is
97 retracted, and the plate is then keyed to the required position. In DIPA installation, there are
98 two stages. In the first stage, the anchor (without any follower) freefalls from a designated
99 height from the seabed, which results in self-penetration. In the subsequent stage, anchor
100 dragging is carried out in a manner like to that of a conventional DEA.

101

102 The work presented in this article was carried out as part of a project developing a concept for
103 a novel "bi-wing anchor". The concept of the bi-wing anchor is comparable to that of a DIPA.
104 The bi-wing refers to spilt fluke and two fluke arrangement which have been used in this study.
105 Figure 1 shows the scale model bi-wing anchor used in this investigation. The gap between

106 flukes will decrease the side friction during penetration, resulting in a greater self-penetration
107 of the anchor. At the same time, the bearing resistance (pull-out capacity) of the anchor will
108 not be affected significantly by the gap due to the bridging effect between the flukes (Fanning
109 et al. 2023). The installation method for bi-wing anchors is similar to that of the DIPA, which
110 has demonstrated a high success rate in achieving the targeted anchor embedment (Lai et al.
111 2020; Liu et al. 2021). Therefore, it is reasonable to anticipate that bi-wing anchors will achieve
112 a similar anchor embedment performance. Physical testing and analytical modelling were
113 carried out to understand and interpret the drag embedment behaviour for the anchor. The
114 physical model tests were carried out in a transparent clay-surrogate which also served as a
115 proof-of- concept for the proposed anchor system and allowed the direct observation of the
116 anchor during installation. The use of transparent clay enabled continuous tracking of the
117 anchor's movement and orientation during installation. Observations during testing were then
118 used in the development the mathematical model for the drag embedment behaviour of this
119 anchor.

120 **BI-WING ANCHOR CONCEPT**

121 Figure 2 outlines the installation procedure for a possible field application. The plate anchor
122 can be dropped from a height above the seabed and it would initially embed into the soil under
123 the force of its own self-weight (Stage-1). Upon application of tension in the mooring line,
124 keying of the anchor would then begin until the anchor has rotated to an orientation which
125 would allow the anchor to begin further embedding during dragging (Stage-2). Until this point
126 the fluke and shank can be held closed by a coupling mechanism designed by Flores (2016).
127 As the anchor fluke rotated, the mechanism will release and allow the fluke and shank to open
128 (Figure 1b), enabling drag embedment of the anchor to take-place. Dragging the anchor would
129 cause the anchor fluke to rotate towards a horizontal orientation and embed further into the
130 soil (Stage-3). This will enable the anchor to develop a higher holding capacity. The Bi-wing
131 anchor's two-stage (Stage 1 and stage -3) anchor embedment is the major advantage over
132 the conventional DEA. This concept was developed in collaboration with University of Texas,

133 University of Rhode Island, and University College Dublin. The main advantage of a bi-wing
134 anchor is its reliability during embedment due to the initial installation stage, and lighter weight,
135 without decreasing pullout capacity. More information on the pullout capacity of the Bi-wing
136 anchor can be found in Fanning (2020) and Fanning et al. (2023).

137 **EXPERIMENTAL MODELLING**

138 **Anchor model and mooring line**

139 The model anchor is shown in Figure 1 which was fabricated using mild steel. The total length
140 and width of the anchor model were 70mm and 60mm respectively. All other dimensions of
141 the model are shown in Figures 1 and 3. The length, width and thickness of the front and rear
142 flukes were [26mm x 60mm x 2mm] and [17mm x 43mm x 2mm] respectively. The two flukes
143 were connected by a 5mm x 6mm member (connection section) and the spacing between the
144 two anchor flukes was 27mm. The shank of the anchor was attached to the connecting section
145 and the point of attachment was based on the centre of gravity. The anchor's mooring line
146 was made of 3mm diameter nylon coated-steel fishing wire. The mooring line and anchor were
147 attached using wire-clamps. Since this is a small-scale model investigation, the test results
148 are presented in nondimensional scaling formation which is discussed in Appendix-1. The
149 geometric scale ratio (n) and stress ratio (N) were calculated to be 42:1 and 35:1 respectively.
150 The length of the prototype fluke is 2.94m and its width is 2.52m respectively.

151 **Transparent clay-surrogate**

152 The tests were carried out in a transparent clay material called laponite-RD. Visualizing the
153 horizontal, vertical, and rotational movements of the drag anchor improves the interpretation
154 and understanding of its behavior in soft clay. Transparent clay has been used for various
155 physical model tests, such as the installation of torpedo anchors (Ads et al. 2020), drag anchor
156 installation (Beemer and Aubeny 2012), penetrometer installation (Lehane and Gill 2004), pile
157 driving (Ni et al. 2010) and strain field evaluation (Liu and Iskander 2010). The geotechnical
158 properties of laponite are like to those of a soft clay (Wallace and Rutherford 2015; Almikati et

159 al. 2023). The laponite is a highly compressible material compared to normal clay soil,
160 therefore an equivalent soil that matches its properties would be Bentonite Clay (Almikati et
161 al. 2023). The slurry for making test-bed was mixed at a ratio of 4% by weight of laponite to
162 water. To enhance the transparency of the sample, intrusion of air into the slurry during mixing
163 was limited as any presence of air bubbles within the testbed will reduce the transparency of
164 the material Wallace and Rutherford (2015). The laponite and water were mixed in a specially
165 manufactured vacuum chamber having a 20 litre capacity to remove air voids in in the slurry
166 before commencing the test-bed preparation. The basic characteristics of laponite used in this
167 investigation are presented in Table 1, which are consistent with the observation previously
168 reported in Almikati et al. (2023). Multiple batches of laponite slurry were mixed in a vacuum
169 chamber before being placed in the testing chamber in order to build the test-bed. To delay
170 the rate of gelation of the slurry, an additive called “sodium pyrophosphate decahydrate” was
171 used and the process was carried out in a temperature-controlled room (20°C).

172 **Testing chamber and clay bed preparation**

173 The anchor tests were carried out in a chamber which had internal dimensions of 1.0m by
174 0.3m by 0.75m (Figure 4). The front and back of the chamber were made of clear acrylic which
175 allowed the visualization of the anchor performance during installation. Drainage provisions
176 were made on the base of the chamber to allow for any excess pore water pressure to
177 dissipate. In addition, to enhance the strength of the clay slurry, a vacuum pressure of 30kPa
178 was applied on this drainage line (drained water was collected via a chamber) on an
179 understanding that the effective stress at the base could be increased by the same amount
180 (Nanda et al. 2017). Added facilities also included: (a) the bottom of the chamber was also
181 lined with a filtration sheet to ensure the suction did not extract any laponite particles from the
182 slurry during consolidation. (b) the top of the slurry was also lined with a filter sheet and a
183 surcharge of 3kPa was also applied on the surface. During consolidation, a nominal head of
184 water was maintained above the test-bed to avoid drying of the slurry. Due to time constraints

185 of the project, the slurry was left to consolidate for three months. After consolidation, the
186 surcharge was removed from the surface of the test-bed.

187 **Testing arrangement and instrumentation**

188 A diagram of the equipment used for bi-wing anchor drop and dragging is shown in Figure 4.
189 A 2m long drop guide (a box section with a slot on one side) was used to ensure the anchor
190 would maintain a vertical orientation while falling and impact at a precise location on the
191 testbed. This guide can be clamped to the container at various locations to enable multiple
192 drops to be carried out. The bi-wing anchor was held in place using a pin which was manually
193 removed at the start of each test.

194 A geared, 15V DC motor attached on the other side of the test-bed was used to apply pull-out
195 force on mooring line. This mooring line was passed through a pulley (located at the bottom
196 of the frame) and connected to the shank of the bi-wing anchor. This arrangement can be
197 moved along the length of the box so that the bi-wing anchor can be pulled-out vertically after
198 dragging. The miniature In-line load cell (Applied Measurement, UK: Accuracy 0.1N, full
199 capacity 250N) was located at an appropriate position to measure the pull-out force required
200 during the entire process.

201 Two cameras were used to record the bi-wing anchor-fall. A high-speed camera was used to
202 record the bi-wing anchor drop and initial penetration into the sample at 500fps (frame per
203 sec). A second camera (less fps) was used to record the drag and pull-out stages of the bi-
204 wing anchor, which was kept at the same position throughout testing to minimise any changes
205 in the view of the bi-wing anchor in multiple tests. The transparent front and back faces of the
206 testing chamber enabled the use of backlighting to improve the clarity of the images taken
207 during the test. The front face of the container was annotated with markers at centres of
208 200mm which were used to carry out image correction. This helped to account for any
209 distortion due to the camera lens characteristics. The images captured during the anchor
210 installation were digitized in AutoCAD using a suitable scale factor, defined as the ratio of the

211 distance between markers in the image to their actual physical separation. Key tracking points
212 on the anchor included the shackle point, the outer tips of the fluke, and the junction between
213 the shank and fluke. Through this digitization process, the coordinates of each tracking point
214 were extracted for subsequent analysis. The digitization achieved an accuracy of 1.2 mm. The
215 depth of the anchor below the mudline (z_0 or z) was measured between the soil surface and
216 the point of connection between the shank and fluke. A T-bar was used to determine the
217 strength profile. This T-bar was manufactured for the purpose of this research using the
218 techniques reported by Nanda et al. (2017). This T-bar was driven into the soil-bed using a
219 motor with a rack and pinion setup.

220 **Test procedure**

221 Cameras were located in place and focused on the vertical centreline of the test-bed. The
222 cameras were then set on “recording”, and the anchor was dropped by removing the pin from
223 the guide. The anchor fluke and the shank would be closed during the free-fall penetration as
224 shown in Figures 2, 1a, and 4. After completion of the initial penetration, the high-speed
225 camera was removed and the mooring line was wrapped through the pulley and connected to
226 the load cell. The process of keying and dragging the anchor was then initiated by using the
227 motor to pull the mooring line at a rate of 3mm/s. As load was applied to the mooring line, the
228 fluke and shank opened as shown in Figures 2, 1b and 4. This allowed the anchor to embed
229 further into the clay bed and rotate towards a horizontal orientation (Figure 4), which required
230 about 750 mm of horizontal travel. The anchor dragging process was continuing until it began
231 moving vertically upward direction. Upon completion of the drag, the motor frame was
232 relocated so that the anchor could be pulled vertically at a rate of 3 mm/s. Upon the completion
233 of the tests, two T-bar tests were carried out in undisturbed areas of the soil-bed to obtain a
234 strength profile.

235 The drop and drag phases of this process can be watched in the video link: bit.ly/3Z7Cw0l
236 The recorded videos were split into individual images and image tracking was used to track
237 the movement of the front and rear ends of the anchor and the tip of the anchor's shank during

238 dragging. The positions of these three points were then plotted as cartesian coordinates and
239 used to determine the orientation of the anchor's fluke and shank for comparison with the
240 analytical model.

241 **EXPERIMENTAL OBSERVATIONS**

242 **Shear strength profile**

243 Figure 5 shows the undrained shear strength profile of the test-bed measured using the T-Bar.
244 A value of T-bar factor of 12 was used to determine the undrained shear strength c_u (Low et
245 al. 2010; Nanda et al. 2017). The rate of penetration of the T-bar was 3 mm/sec, which results
246 in undrained penetration (Lunne et al. 2011; Nanda et al. 2017). It is clear that the strength
247 profile is not uniform as one would expect in a normally consolidated clay bed. The increased
248 strength at the top and bottom of the test-bed is attributed to the surcharge and negative pore
249 water pressure applied during the formation. It appears that the clay is not fully consolidated.
250 The approximate time required for 90% consolidation (for the size of the test-bed) was
251 calculated to be about 1 year assuming the coefficient of consolidation of Iaponite as
252 approximately $0.017\text{m}^2/\text{year}$ (Wallace and Rutherford 2015). Nevertheless, the observed
253 strength profile was modelled using a series of sub-sections as shown in Figure 5 and they
254 were incorporated in the analysis.

255 **Installation**

256 Two tests were carried out: Test 1 (1m fall) and Test 2 (2m fall). Figures 6(a), 6(b) and 6(c)
257 show the position of the bi-wing anchor at different stages during the installation. The impact
258 velocities of the anchor on the test-bed in Test 1 and Test 2 were 3.6 m/sec and 5.4 m/sec
259 respectively (based on the digital data). Figure 6(a) shows the anchor position after completion
260 of the drop installation. This resulted in vertical embedment ratio (depth of penetration/length
261 of anchor) was 0.7 for test 1 and that for test 2 was 2.4. Figure 6(b) shows the position of the
262 anchor after the keying process, during which it shifted in both horizontal and vertical (upward)

263 directions. In this process, the normalised horizontal displacement $\left(\frac{x}{L_f}\right)$ recorded for Test-1
264 and Test-2 was 0.36 and 0.4, respectively. Similarly, the vertical upward movement $\left(\frac{y}{L_f}\right)$ was
265 0.15 for Test-1 and 0.3 for Test-2. Figure 6(c) presents the final position of the anchor after
266 the completion of anchor dragging process. The resulting embedment ratios for Test-1 and
267 Test-2 were 2.7 and 3.7, respectively.

268 The embedment depth of an anchor is influenced by the impact energy at the seabed
269 (O'Loughlin et al. 2013; Tong et al. 2020). A higher impact energy generally leads to deeper
270 anchor penetration. This impact energy can be increased by raising the anchor's velocity,
271 mass, or both. In the case of hybrid anchors or DIPAs, greater impact energy can be readily
272 achieved by enhancing the impact weight through the use of a retrievable booster (Tong et al.
273 2020; Liu et al. 2021).

274 A typical torpedo anchor penetration is two to three times the anchor length and reached the
275 seabed at a velocity of 25 to 35 m/s (Randolph and Gourvenec 2011). According to the scaling
276 law provided in Appendix-1, the impact velocity of the prototype in Test-2 is 35 m/s.
277 Comparatively, the proposed anchor achieves a greater final penetration ratio than a torpedo
278 anchor. Unlike torpedo anchors, where pull-out resistance is mainly derived from skin friction,
279 the proposed anchor primarily relies on bearing resistance to generate pull-out resistance.

280 **Loading**

281 In the analysis, the horizontal and vertical displacements and the rotation of the anchor were
282 normalised by the fluke length L_f (Figures 7(a) and 7 (b)). After completion of the dynamic
283 installation (drop installation) of the anchor, the anchor flukes were orientated at angles of 84
284 and 85 degrees to the horizontal for Tests 1 and 2 respectively. It is assumed that rotation of
285 the anchor during dynamic installation is due to the asymmetric shape of the anchor caused
286 by the fluke/shank coupling mechanism as shown in Figures 2 to 4. The greater embedment

287 depth achieved by the anchor in Test 2 allowed the anchor to rotate a greater amount than in
288 Test 1. During keying of the anchor, the fluke rotated angles of 32 and 45 degrees for Tests 1
289 and 2 respectively. This difference is due to the greater installation depth of the anchor in Test
290 2 and the fluke/shank coupling mechanism. The mechanism opened when the resultant forces
291 from the mooring line at the shackle caused it to slide to an open position. Upon completion
292 of the keying stage, the anchor fluke was orientated at angles of 52 and 40 degrees to the
293 horizontal for Tests 1 and 2 respectively. The fluke/shank coupling mechanism also opened
294 at this stage and some amount of horizontal ($\frac{X}{L_f} = 0.36$ to 0.4) and vertical displacement
295 ($\frac{X}{L_f} = 0.15$ to 0.3) could have occurred in both tests. The point at which keying was completed
296 is indicated on Figures 6(b) and 7a. It was determined that keying of the anchor was completed
297 when the angle between the fluke and shank had reached a value of 60 degrees. In the
298 conventional DEA, the angle between the fluke and shank in soft clay is in the order of 50
299 degrees (Aubeny et al. 2018). After the fluke and shank had opened, the anchor began to
300 drag into the test-bed.

301 Figure 7(a) shows the trajectory of the anchor during drag installation for both tests, where
302 Figure 7(b) shows the trajectory of the anchor with the orientation and position of the anchor
303 fluke overlaid on the graph. By the completion of drag installation during Test 1, the anchor
304 had reached an embedment ratio of 2.7 with the fluke at an orientation of 9 degrees to the
305 horizontal. For Test 2, the anchor reached an embedment ratio of 3.7 (Figure 7) and an
306 orientation of 5 degrees to the horizontal plane. In a full-scale model, the projected embedment
307 in Test 1 and Test 2 can be as high as 7.9m and 10.9m respectively based on 42: 1 scale.

308 Figure 8 shows the normalised anchor holding capacity (P_N) or pullout resistance measured
309 during keying and drag embedment of the anchor plotted against the normalised horizontal
310 displacement of the anchor. The anchor force (holding capacity) was normalised by the fluke
311 area and the shear strength of the soil-bed at the centre of the anchor (point 'O' in Figure 9,
312 more details on this figure below). The point at which the coupling opens is apparent by the

313 sudden drop in holding capacity as indicated for both tests. The normalised holding capacities
314 during keying are lower than expected. This was due to the low shear strength of the sample
315 and variation in strength along the depth of the test-bed. During further dragging, holding
316 capacities increased as the anchor rotated towards the horizontal.

317 **Mathematical Modelling**

318 In the following section, an analytical model for the drag trajectory is presented. The model
319 makes use of observations from the tests carried out as well as limit equilibrium and plasticity
320 models. The load and moment acting on an anchor during the process of drag installation are
321 shown in Figure 9(b). The chain experiences tensions of T_a at the shackle point and T_0 at the
322 seabed. These tension forces subtend angles of θ_T and θ_0 at the shackle and seabed
323 respectively. The values T_a and θ_T are one of the main parameters which control the
324 embedment behaviour of an anchor. Since both T_0 and θ_T are directly measured from
325 experiment, the interrelationship between T_a , T_0 and θ_T will be evaluated and various input
326 parameters which are influencing the chain anchor system shall be recalibrated for bi-wing
327 drag anchor. Anchor dragging kinematics has been previously predicted using interaction
328 models (O'Neill et.al. 2003; Elkhatib and Randolph 2005; Aubeny and Chi 2014). The drag
329 anchor kinematics depends on the change in θ_T and θ_p and both these angles have been
330 measured in this investigation. To predict the kinematics of the bi-wing drag anchor, a modified
331 interaction model is required as it follows two-stage embedment and consists of split fluke
332 configuration. The mathematical modelling may be used to predict the anchor embedment
333 during anchor dragging (Stage-3, Figure 2).

334 During the initial drop penetration (Stage-1) of the anchor into the soil, the fluke and shank
335 were secured in one plane by a coupling mechanism. After the completion of the drop
336 penetration, the anchor was orientated at an angle to the horizontal, θ_p (shown in Figure 9a),
337 of between 81° and 85° . Upon application of a load to the mooring line, keying of the anchor
338 initiated in which the anchor went through a small amount of displacement and a large rotation

339 in the plane of the fluke. The proposed anchor consists of two flukes. For sake of simplicity an
 340 equivalent fluke was considered in the analysis. The area of equivalent fluke is equal to the
 341 total area of both the flukes and length is fluke is equal to L_f (Figure 9a). The effect of shank
 342 resistance to anchor penetration not included in anchor trajectory prediction.

343 **Anchor capacity**

344 **Chain-anchor system:** Using limit equilibrium models, Neubecker and Randolph (1995)
 345 proposed the following relationship which determined the tension force applied by the chain
 346 at the shackle point relative to the tension applied at the seabed surface:

$$347 \quad T_\alpha = T_0 e^{\mu(\theta_T - \theta_0)} \quad (1)$$

348 where,

349 T_α = tension in the chain at shackle point

350 T_0 = tension in the chain at soil surface

351 θ_T = the angle subtended by the chain to horizontal at shackle point

352 θ_0 = angle subtended by the chain to horizontal at soil surface

353 μ = frictional coefficient

354 The frictional coefficient, μ is the ratio between the shear stress (τ) and normal stress (Q)
 355 stress acting along the chain element. Using the parameter "effective chain width" Degenkamp
 356 and Dutta (1989) proposed values for the shear stress (f) and normal stress (Q). Using these
 357 parameters, the expression for μ becomes:

$$358 \quad \mu = \frac{\tau}{Q} = \frac{E_s b \alpha c_u}{E_b b N_c c_u} \quad (2)$$

359 where,

360 E_s = effective chain width in sliding factor

361 E_b = effective chain width in bearing factor

362 b = chain diameter

363 α = adhesion factor

364 c_u = undrained shear strength

365 N_c = bearing capacity factor

366 In soft clay, skin friction is approximately equal to c_u (Neubecker and Randolph 1995).
 367 Therefore, the value of α may be considered as one (i.e., 1.0 in soft clays). Using these
 368 values, Eq.(2) can be simplified to obtain Eq.(3).

$$369 \quad \mu = \frac{3.2}{N_c} \quad (3)$$

$$370 \quad N_c = 5.14 \left(1 + 0.2 \frac{z}{E_b b} \right) \quad (4)$$

371 The bearing capacity factor, N_c can be obtained by using Skempton's equation (Skempton,
 372 1951). Eq.(4) represents the bearing capacity factor for the chain where the depth below the
 373 mudline is represented by z . The minimum and maximum values of N_c vary between 5.14 at
 374 the mudline and 7.6 at a depth of $z = 6b$ or 2.4 times the effective width in bearing (Degenkanp
 375 and Dutta, 1989). Using these values, the coefficient of friction described in Eq. (3) will be
 376 likely to vary in a range of 0.6 to 0.4. Assuming the tension force applied at the mudline was
 377 horizontal ($\theta_0 = 0$) during dragging, Eq. (1) becomes:

$$378 \quad T_a = \frac{T_0}{e^{-\mu\theta_T}} \quad (5)$$

379 Neubecker and Randolph (1995) proposed the relationship between the tension at the shackle
 380 point, the angle at the shackle and average-bearing resistance from the seabed to anchor
 381 location shown in Eq. (6).

$$382 \quad T_a \frac{\theta_T^2}{2} = zQ \quad (6)$$

383 where Q is the average bearing resistance and z , is the depth between the soil surface and
 384 the shank- fluke connection point. By replacing the value of Q in Eq. (6) with the parameters
 385 from Eq. (2),

$$386 \quad T_a \frac{\theta_T^2}{2} = z E_b b N_c \left(c_{u0} + kz/2 \right) \quad (7)$$

387 By substituting Eq. (5) into Eq. (7) and after simplification,

$$388 \quad \theta_T^2 = \frac{2G^* (1 + c_u^* z^* / 2) z^*}{T_0^* e^{\mu \theta_T}} \quad (8)$$

$$389 \quad G^* = \frac{E_b b N_c}{b_0} \quad (8.a)$$

$$390 \quad c_u^* = \frac{kz_0}{c_{u0}} \quad (8.b)$$

$$391 \quad T_0^* = \frac{T_0}{c_{u0} b_0 z_0} \quad (8.c)$$

$$392 \quad z^* = \frac{z}{z_0} \quad (8.d)$$

393 where,

394 b_0 = Width of chain at the mudline

395 N_c = Bearing capacity factor

396 k = Gradient of the undrained shear strength as the depth from the soil surface increases

397 z_0 = Depth of anchor at the beginning of anchor dragging which is measured between the soil
 398 surface and the point of connection between the shank and fluke

399 c_{u0} = Undrained shear strength of soil at the depth z_0

400 G^* , c_u^* , T_0^* , and z^* = Dimesiionless parameters

401 Eq. (8) shows that θ_T depends on the shear strength of soil, effective chain width, tension in
 402 the chain and the bearing capacity factor. Using Eq.(8), θ_T can be predicted during anchor
 403 dragging as the parameters for shear strength and k can be pre-determined before anchor
 404 dragging and the value of T_0 can be measured during the dragging of the anchor. As shown
 405 in Figure 5, the variation of shear strength along the depth of the sample was nonlinear in the
 406 tests used for this analysis. In order to address this variation of the shear strength, the profile
 407 was divided into small sections with each section having a constant k value. Thereafter the
 408 equivalent k_{eq} value was determined as defined in Eq.(9).

$$409 \quad k_{eq} = k_1 \left(\frac{z_1}{z_0} \right) + k_2 \left(\frac{z_2}{z_0} \right) + k_3 \left(\frac{z_3}{z_0} \right) + \dots \quad (9)$$

410 where $z_1, z_2, z_3 \dots$ are the thicknesses of each section. The addition of these values will give
 411 the total depth of anchor from the seabed. By substituting Eq.(9) into Eq.(8)

$$412 \quad \theta_T^2 = \frac{2G^*(1+c_u^*/2)z^*}{T_0^* e^{\mu\theta_T}} \quad (10)$$

$$413 \quad c_u^* = \frac{k_{eq}z_0}{c_{u0}} \quad (10.a)$$

414 By using Eq. (7), the expression for θ_T can be rewritten using G^* and c_u^* from Eq.(8.a) and Eq.
 415 (8.b).

$$416 \quad \theta_T = \sqrt{\frac{G^*z^*(2+c_u^*z^*)}{T^*}} \quad (11)$$

$$417 \quad T^* = \frac{T}{c_{u0}b_0z_0} \quad (11.a)$$

418 Eq 11 can be used to determine θ_T if the tension in the anchor line is known. Figure 10 shows
 419 the comparison between the measured and predicted values of θ_T for Tests 1 and 2. A
 420 noticeable difference in the observed and predicted values can be seen for both the tests. For
 421 the analysis, the values of E_s and E_b were taken as 8 and 2.5 respectively as recommended
 422 by Degenkamp and Dutta (1989). The error in the predictions may be due to the use of an

423 inappropriate value of average bearing capacity (Q). Due to the novel anchor shape and
 424 installation method used in this research, the parameters influence the Q may need to be
 425 recalibrated using the observation from the model testing.

426 Degenkamp and Dutta (1989) carried out experimental work using samples with shear
 427 strengths of 4.2 kPa. They found that E_b increases with increasing embedded chain length
 428 and the values of E_s varied in the range of 5.5 to 12. For a given value of E_b a reverse analysis
 429 was carried out by changing the value of N_c until the difference between the observed and
 430 predicted value of θ_T was less than 0.001. The ratio between E_s and E_b was maintained
 431 constant at 3.2 as the average values of E_s and E_b being 8 and 2.5 respectively. The value
 432 of E_b was used in above analysis is in the range of 0.5 to 2.5. The above analysis suggested
 433 that the N_c value depends up on the orientation of mooring line, depth and E_b . Figure 11(a)
 434 presents value of N_c at various values of θ_T and E_b . The N_c increases with the increased in
 435 depth of embedment, θ_T and E_b . Degenkamp and Dutta (1989) suggested E_b increases with
 436 an increase in the embedded, however E_b value close to one would be a better approximation
 437 while mooring line is a wire. Based on the above observation a revised expression for average
 438 bearing resistance has been proposed in Eq.(12).

$$439 \quad Q = E_b b N_{c1} D_i \beta_i \left(c_{u0} + \frac{kz}{2} \right) \quad (12)$$

$$440 \quad D_i = \left[1 + A \left(\frac{z}{b E_b} \right) \right] \quad (12a)$$

$$441 \quad \beta_i = \frac{B_i \theta_i}{147} \quad (12b)$$

$$442 \quad N_k = N_{c1} D_i \beta_i \quad (12c)$$

443 where D_i and β_i consider the average effect of depth and inclination of mooring line on bearing
 444 resistance respectively. The θ_i is the average inclination or bending of mooring line. The value
 445 of N_{c1} is 5.1. The value of B_i observed from back calculation is 0.65. The value of A is 0.1

446 when the first stage of anchor penetration is less than 1.5 times the fluke length (L_f) and 0.05
 447 for rest of the cases. Figure. 11(b) shows the comparison between observed and predicted N_k
 448 value using Eq. 12c.

449 A reasonable prediction of θ_T can be made by replacing Eq.(12 c) with N_c in Eq.(2) and at
 450 value of $E_b = 1$. The dotted line in Figure 10 represents the prediction of θ_T using Eq.11 and
 451 Eq.12.

452 **Mechanics of the fluke**

453 The forces and resulting moment acting on the anchor fluke during dragging are shown in
 454 Figure 9(b). The length of entire fluke is L_f and its centroid is located at a distance L_{fc} from
 455 the rear of the anchor. The angle of the fluke relative to the horizontal plane is labelled as θ_p .
 456 During installation, the fluke experiences normal and tangential forces distributed across its
 457 surface. In order to simplify the analysis, the distributed loads were converted to equivalent
 458 point loads. The forces F_n and F_t are the equivalent normal and tangential loads acting on the
 459 fluke respectively. Using force equilibrium, the normal and tangential loads acting on the fluke
 460 as a result of the load from the mooring line can be defined in terms of T_a , θ_T and θ_p as
 461 shown in Eq.(13) and Eq.(14).

$$462 \quad F_n = T_a \sin(\theta_T + \theta_p) \quad (13)$$

$$463 \quad F_t = T_a \cos(\theta_T + \theta_p) \quad (14)$$

464 Using the relationship between T_a and θ_T derived in Eq.(8), F_n and F_t can be determined using
 465 equations (13) and (14) once the value of θ_p is known. The moment acting at the centroid of
 466 the fluke can be derived in term of T_a , θ_T and θ_p as

$$467 \quad M = T_a \{ \sin(\theta_T + \theta_p) [L_s \cos \theta_s - L_{fc} + L_{fl}] - \cos(\theta_T + \theta_p) [L_s \sin \theta_s] \} \quad (15)$$

468 where

469 L_s = length of the shank

470 L_{fc} = distance between the fluke centroid and the rear edge of the fluke (Figure 9a)

471 L_{fl} = length of second half of fluke (Figure 9a)

472 θ_p = angle of the fluke relative to the horizontal plane

473 θ_s = angle between the shank and fluke

474 In Equations (13) to (15) the effect of the shank resistance was not included. Many studies
 475 assume that the fluke governs the anchor kinematics because it produces a large proportion
 476 of the capacity and for this reason leave it out of their analysis.

477 **ANCHOR DRAGGING KINEMATICS**

478 ***Yield function for fluke***

479 The loads and moment applied to the anchor continually change during the drag installation
 480 of an anchor. An interaction model can be used to express the interaction between the loads
 481 and moment as shown in Eq. (16). This model was originally developed by Murff (1994) for
 482 shallow foundations. This approach has been successfully applied to plate anchor dragging
 483 problems in multiple studies such as O'Neill et.al. (2003); Elkhatib and Randolph (2005);
 484 Aubeny and Chi (2014).

$$485 \left(\frac{F_n}{F_{n(max)}} \right)^q + \left[\left(\frac{M}{M_{max}} \right)^m + \left(\frac{F_t}{F_{t(max)}} \right)^r \right]^{\frac{1}{p}} = 1 \quad (16)$$

486 The proposed drop drag anchor consist of split fluke therefore the Eq. (16) needs further
 487 modification. Eq. (16) has been modified and expressed as a yield function f for anchor
 488 movement as shown in Eq. (17).

$$489 f = \alpha_1 \left(\frac{F_n}{F_{n(max)}} \right)^q + \alpha_2 \left[\left(\frac{M}{M_{max}} \right)^m + \left(\frac{F_t}{F_{t(max)}} \right)^r \right]^{\frac{1}{p}} - 1 = 0 \quad (17)$$

490 In these equations m, r, q and p are interaction coefficients. $F_{n(max)}$, $F_{t(max)}$ and M_{max} are the
 491 failure values for pure normal, tangential (or shear) and moment loading respectively. The α_1
 492 and α_2 are the new parameter named as modification factor which capture the effect of split
 493 fluke. These coefficients are unique values for a particular anchor type. Usually, interaction
 494 coefficients are determined by applying the technique of least square fitting to Eq. (17) with
 495 the results of finite element analysis. However, in the current study, θ_T and θ_p could be
 496 observed from the experiment. This allowed the experimental results to be used for the least
 497 square fit with Eq.(17). The failure loads and moment can be determined by using suitable
 498 bearing capacity factors as described in Equations (18) to (20).

$$499 \quad F_{n(max)} = N_{n(max)} c_u A_f \quad (18)$$

$$500 \quad F_{t(max)} = N_{t(max)} c_u A_f \quad (19)$$

$$501 \quad M_{max} = N_{m(max)} c_u A_f L_f \quad (20)$$

502 A_f , $N_{n(max)}$, $N_{t(max)}$ and $N_{m(max)}$ are the fluke area, bearing factors for pure normal load,
 503 tangential load and moment.

504 **Anchor displacement**

505 The displacement behaviour of the anchor was analysed by considering the displacement of
 506 the anchor across incremental distances from point A to point B as shown in Figure 12. It was
 507 assumed that only plastic displacement occurred in the system. Due to the anchor dragging,
 508 anchor moved a small distance, ΔS between points A and B, and the corresponding horizontal
 509 and vertical distances are ΔX and ΔY respectively. The angles θ_T and θ_p were designated as
 510 θ_{T1} and θ_{p1} at point A and θ_{T2} and θ_{p2} at point B. By applying the associated flow rule to
 511 Eq.(17), the fluke displacement and rotation can be expressed as:

$$512 \quad \delta h = \lambda \frac{\partial f}{\partial F_t} \quad (21)$$

$$513 \quad \delta v = \lambda \frac{\partial f}{\partial F_n} \quad (22)$$

$$514 \quad L_f \delta \beta = \lambda \frac{\partial f}{\partial (M)} \quad (23)$$

515 where λ is the dimensionless flow parameter, δh represents a small displacement parallel to
 516 the fluke and δv is the displacement normal to δh . In Figure 12, the displacements δv and δh
 517 are represented by AC and BC respectively. The values δv and δh can be presented in terms
 518 of the angle ψ as shown in Eq.(24).

$$519 \quad \psi = \tan^{-1} \left(\frac{\delta v}{\delta h} \right) \quad (24)$$

520 The $\frac{\delta v}{\delta h}$ can be obtained from equations (21) and (22):

$$521 \quad \frac{\delta v}{\delta h} = \frac{qp\alpha_1}{\alpha_2 r \left[\left(\frac{M}{M_{max}} \right)^m + \left(\frac{F_t}{F_{t max}} \right)^n \right]^{\left(\frac{1}{p-1} \right)}} \left(\frac{F_{t max}}{F_{n max}} \right) \frac{(F_n/F_{n max})^{q-1}}{(F_t/F_{t max})^{r-1}} \quad (25)$$

522 Similarly, the ratio between the rotational and tangential movement can be derived from Eq.
 523 (21) and Eq. (23):

$$524 \quad \frac{\delta \beta L_f}{\delta h} = \frac{m \left(\frac{M}{M_{max}} \right)^{m-1}}{r \left(\frac{F_t}{F_{t max}} \right)^{r-1}} \left(\frac{F_{t max}}{M_{max}} \right) \quad (26)$$

525 Eq. (24) and Eq. (26) are used to predict the theoretical trajectory of anchor embedment. By
 526 combining these two equations with Eq.(11), the change in the value of θ_T and θ_p during
 527 anchor dragging can be obtained. Inclusion of three unknowns in Eq. (25) and Eq. (26), a
 528 numerical solution needs to be employed for prediction of the anchor trajectory.

529 **Anchor trajectory prediction method**

530 The previous sections outlined the development of mathematical relationships for the various
 531 aspects of anchor dragging. The following sections outline how these relationships were used
 532 to predict the anchor trajectory during dragging. In this study, the predicted trajectory of the

533 anchor indicated the location of the fluke-shank connection point changing during installation.
 534 The computation of anchor trajectory was carried out by small increment in T_0 and θ_T , and
 535 calculating the corresponding θ_p . The anchor parameters such as $\Delta\theta_p$, $\Delta\theta_T$ and δh were then
 536 determined for each anchor advancement and this process was continued until θ_p was close
 537 to horizontal.

538 **Suggested procedure for prediction of anchor drag embedment behaviour**

- 539 1. All parameters of the anchor and chain after completion of stage 2 should be known.
 540 These parameters include tension in the chain at seabed (T_0), angle at the shackle
 541 point (θ_T), angle of the fluke relative to the horizontal (θ_p) and depth of anchor
 542 embedment (z_0) after stage 2. Also determine the $F_{n(max)}$, $F_{t(max)}$ and M_{max} .
 543 2. Increase a small amount in T_0 and θ_T . Determine the T_a using Eq (7). The θ_p shall be
 544 determined from solving the Eq (17).
 545 3. Determine θ_T using Eq. (11) where T_a is equal to that obtained from step 2.
 546 4. Compare the θ_T obtained from step 2 and step 3. If the difference is significant then
 547 repeat step 2 with a new values of T_0 and θ_T .
 548 If the θ_T obtained from step 2 and step 3 are in good agreement, determine the value
 549 δv , δh , $\delta\beta$, ψ and ΔS using Equations (24) to (26).
 550 5. The anchor trajectory (Δx and Δy) is then calculated using equations (27) and (28)
 551 below.

$$552 \quad \Delta x = \Delta S \cos(\theta_{p1} - \psi) \quad (27)$$

$$553 \quad \Delta y = \Delta S \sin(\theta_{p1} - \psi) \quad (28)$$

- 554 6. Repeat steps 2 to 5 for another small increase in T_0 and θ_T from its just previous value
 555 and this process will be continue up to a point where the value of θ_p approaches zero
 556 meaning the anchor has reached a horizontal orientation and will not embed any
 557 further.

558 **Analytical results and discussion**

559 ***Input parameters***

560 From the analysis presented in the previous sections, the following input parameters are
561 required for the prediction of the dragging behaviour of an Bi-wing anchor:

- 562 a) Maximum bearing capacity factors of fluke in pure loading ($N_{n(max)}$, $N_{t(max)}$ & $N_{m(max)}$)
- 563 b) Interaction coefficients m, r, p and q
- 564 c) Anchor dimensions and initial orientation
- 565 d) Mooring line parameters, b and E_b ,
- 566 e) Shear strength profile of the soil bed
- 567 f) The α_1 and α_2 are the modification factor due to the split fluke

568 ***Maximum bearing capacity factor of fluke ($N_{n(max)}$, $N_{t(max)}$ & $N_{m(max)}$)***

569 In this study, the values of $N_{n(max)}$, $N_{t(max)}$ & $N_{m(max)}$ were taken as 10, 3.8 and 1.5
570 respectively. Aubeny and Chi (2014) summarised the bearing capacity factors used for various
571 anchor types. The range of values for $N_{n(max)}$, $N_{t(max)}$ & $N_{m(max)}$ were 11.78 to 12, 1.8 to 4.39
572 and 1.49 to 1.65 respectively.

573 ***Interaction coefficients (m, r, p, q) and Parameter α_1, α_2***

574 The use of a transparent soil bed allowed the interaction coefficients to be determined by
575 applying a least square fit to the observations made during testing. It was observed that the
576 interaction factors are also deepened on the depth of anchor penetration after completion of
577 stage 2 or keying. The values m, r, p and q were determined as 0.8, 1.7, 8.5 and 2.5 for test 1
578 as well as test 2. Aubeny and Chi (2014) reported values of m, r, p and q which ranged from
579 1.26 to 2.58, 3.72 to 4.19, 1.09 to 1.57 and 1.74 to 4.43 respectively. The interaction coefficient
580 observed in this study could be attributed to the shape of the anchor being examined and the

581 interaction between the two anchor flukes. The modification factors α_1 and α_2 due to the split
582 fluke may be considered as 1.3 and 1.1 respectively.

583

584 *Anchor dimensions and initial orientation*

585 The anchor dimensions and initial orientation are summarised in Table 1. The initial orientation
586 of the anchor would need to be predicted by analysing the keying process of the anchor.
587 Various models exist which analyse the keying behaviour of anchors such as Yang et al.
588 (2012). As this study focused on analysing the drag behaviour of the anchor, the initial
589 orientation observed during testing was used in the analysis. The initial orientation was taken
590 from the point at which the keying process had stopped and continued loading of the mooring
591 line caused the anchor to move parallel to the fluke.

592 *Mooring line parameters, N_k , θ_i , b and E_b*

593 The diameter of the mooring line used in testing was 3mm. The N_k value can be determined
594 from Eq. 12 (c). θ_i is the θ_T of the previous step. The ratio between E_s/E_b remained constant
595 at a value of 3.2. The value of E_b may consider one for cable-type mooring lines.

596 *Shear strength of soil strata*

597 The shear strength profile of the soil used in testing is shown in Figure 4. By using equations
598 (9) and (10), the varying shear strength profile was considered in the analysis.

599 The model parameter values presented in this section are based on a limited number of
600 experiments and may vary with changes in soil type or other geotechnical conditions.

601 **Validation**

602 Using the mathematical model detailed above, the drag embedment behaviour of the anchor
603 observed during Test 1 and test 2 were compared with the predicted behaviour. A comparison

604 of the observed and predicted drag trajectory is shown in Figure 13. As previously stated, the
605 plotted point correlates to the position of the connection between the fluke and shank and all
606 displacements were normalised by the fluke length. The predicted trajectory of the anchor
607 shows good agreement with the observed behaviour. By the end of the dragging process, the
608 deviation in results for the vertical embedment depth was below 5%.

609 A likely reason for this error could be the angle of the mooring line at the sample surface. As
610 the anchor gets closer to the pulley, the angle of the mooring line at the surface is no longer
611 zero and this results in a greater component of vertical load being applied to the anchor than
612 expected in the analysis. This would explain why the anchor deviated from the predicted
613 behaviour. Similar behaviour was observed in the centrifuge modelling carried out by Elkhatib
614 et al. (2002). A similar deviation from the trajectory predicted by the model presented by
615 Neubecker and Randolph (1996a) and Neubecker and Randolph (1996c) was observed in
616 their work.

617 The theoretical prediction suggests that vertical embedment of the anchor would only stop
618 after θ_p reaches zero. However the vertical embedment of the anchor during testing stopped
619 when θ_p was in the range of 10^0 to 5^0 . This suggests the increased vertical load applied to
620 the anchor due to the location of the pulley caused the anchor to stop embedding.

621 Figure 14 shows the observed and predicted values of T_0 plotted against the normalised
622 vertical embedment depth of the anchor for test-1 and test-2. These graphs show predicted
623 values of T_0 closely follow the values observed throughout the dragging process. Figures 13,
624 and 14 show that the proposed mathematical model provides a reasonably good prediction
625 for the anchor trajectory and the T_0 of the mooring line of anchor. To predict anchor trajectory
626 (stage-3) readers need c_u profile and orientation of anchor just before dragging. Further testing
627 would be required in order to prove if the error in prediction of the vertical embedment depth
628 is as a result of the limitations of the testing arrangement.

629

630 **CONCLUSIONS**

631 Modelling of the installation procedure for the 'Bi-wing Anchor' concept was successfully
632 carried out in a transparent clay surrogate. The use of a transparent clay bed enabled direct
633 observation of the anchor and mooring line during testing. The use of a transparent material
634 simplified the analysis of the anchor's behaviour. The Bi-wing Anchor can penetrate more than
635 3.5 times the fluke length. The initial free fall embedment of the anchor helps anchor to
636 penetrate deeper during the dragging process.

637 The analytical model showed good agreement with the observed drag behavior of the anchor
638 at different free fall embedment ratios. Compared to the commonly used drag anchor, the Bi-
639 wing anchor provides greater reliability in anchor penetration during anchor dragging attributed
640 to its initial free fall embedment. The performance of the Bi-wing Anchor is encouraging, but
641 more study is required to fully understand the anchor rotation, split fluke behavior, and model
642 input parameters.

643 **DATA AVAILABILITY**

644 Data generated or analysed during this study are available from the corresponding author
645 upon reasonable request.

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649 **Appendix-1**

650 The applicability of 1-g model test results depends on the scaling relationship adopted during
651 the test. The initial stress levels in the field should be correlated to those of the 1-g model test
652 through a scaling relationship. This investigation employed laponite as the foundation material,
653 which is not soil. Thus, to apply the scaling rule, the laponite should first be converted to an

654 equivalent soil, and thereafter, the geometric scale ratio (n) and stress scale ratio (N) shall be
 655 determined. For scaling relationships, the approach suggested in Altaee and Fellenius (1994)
 656 has been implemented to derive the scale ratios. It was considered that the initial state of 1-g
 657 model soil and prototype soil should be on the same line in e - $\ln(p')$ space and parallel to the
 658 normal compression line (NCL). Usually, in normally consolidated clay, the NCL is parallel to
 659 the critical state line (CSL). Thus, the slope of the line representing the initial state of the model
 660 and prototype is equal to that of the CSL. Furthermore, the test condition is undrained and the
 661 scale ratios are interrelated. The void ratio relationship between the model and prototype can
 662 be expressed as

$$663 \quad e_m = e_p + \lambda_c \ln(N) \quad (A-1)$$

664 e_m = void ratio of 1-g model soil

665 e_p = void ratio of full scale soil

666 λ_c = slope of critical state line (CSL)

667 $N = \text{Stress ratio} = \left(\frac{\sigma'_m}{\sigma'_p} \right)$, σ'_m = effective stress model, σ'_p = effective stress prototype

668 The ratio between the density of model soil and prototype soil can be expressed as

$$669 \quad \frac{\gamma'_m}{\gamma'_p} = \frac{N}{n} = \frac{1+e_p}{1+e_m} = \frac{1+e_p}{1+e_p+\lambda_c \ln(N)} \quad (A-2)$$

670 $n = \text{geometric scale ratio} = \frac{L_m}{L_p}$, L_m = linear dimension model, L_p = linear dimension prototype

671 γ'_m = density of model soil

672 γ'_p = density of prototype soil

673 Almikati et al. (2023) observed that laponite is a highly compressible material, and the closest
 674 equivalent soil would be a very soft soil with a high percentage of Montmorillonite clay mineral
 675 (Bentonite). The properties of equivalent soil (model soil) were derived from the work of

676 Chenari et al. (2018), where the soil content 44% of Bentonite. The void ratio, density,
 677 compression index, c_u and λ_c of equivalent model soil is 3.5, 11kN/m³, 0.67, 2 kPa and 0.26
 678 respectively. Using Eq. A-1 and Eq. A-2, the geometric scale ratio (n) and stress ratio (N) are
 679 calculated as 42:1 and 35:1 respectively. The prototype fluke length, maximum width, and
 680 total depth of embedment are 2.94m, 2.52m, and 10.88m respectively. Some of the scaling
 681 relations are given below

682 Table A-1. Scaling relationships

Properties	Model	Full scale prototype
Linear dimension	n	1
Area	n^2	1
Volume	n^3	1
Impact Velocity	\sqrt{n}	1
Stress	N	1
Force	Nn^2	1

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692 **Notation**

- 693 M : Moment
- 694 N : Stress ratio
- 695 Q : Normal stress or Bearing resistance
- 696 b : Chain diameter
- 697 f : Yield function
- 698 k : Gradient of the undrained shear strength as the depth from the soil surface increases
- 699 n : Geometric scale ratio
- 700 m, r, q and p : Interaction coefficients
- 701 z : Vertical depth below mudline
- 702 A_f : Fluke area
- 703 P_N : Normalised anchor holding capacity
- 704 b_0 : Width of chain at the mudline
- 705 c_u : Undrained shear strength
- 706 c_{u0} : Undrained shear strength of soil at the depth z_0
- 707 D_i : Depth effect of mooring line
- 708 E_s : Effective chain width in sliding factor
- 709 E_b : Effective chain width in bearing factor
- 710 F_n : Normal loads acting on the fluke
- 711 F_t : Tangential loads acting on the fluke
- 712 $F_{n(max)}$: Failure values for pure normal Loading
- 713 $F_{t(max)}$: Failure values for pure tangential (or shear) lading
- 714 e_m = void ratio of 1-g model soil
- 715 e_p = void ratio of full scale soil
- 716 k_{eq} : Equivalent gradient of undrained shear strength
- 717 L_m = linear dimension model,
- 718 L_p = linear dimension prototype
- 719 L_s : length of the shank
- 720 L_{fc} : Distance between the fluke centroid and the rear edge of the fluke (Figure 9a)

- 721 L_{fl} : Length of second half of fluke (Figure 9a)
- 722 L_f : Fluke length
- 723 M_{max} : Failure values for pure moment loading
- 724 N_c : Bearing capacity factor
- 725 N_{c1} : Is a nondimensional constat equal to 5.1
- 726 $N_{n(max)}$: Bearing factors for pure normal load
- 727 $N_{t(max)}$: Bearing factors for pure tangential load
- 728 $N_{m(max)}$: Bearing factors for pure moment load
- 729 T_a : Tension in the chain at shackle point
- 730 T_0 : Tension in the chain at soil surface
- 731 z_0 : Depth of anchor at the beginning of anchor dragging
- 732 δh : Small displacement parallel to the fluke
- 733 δv : Small displacement normal to δh
- 734 ΔS : Distance between two successive anchor movement
- 735 G^* , c_u^* , T_0^* , T^* and z^* : Dimesiionless parameters
- 736 α : Adhesion factor
- 737 α_1 and α_2 : Modification factor
- 738 β_i : Effect of depth and inclination of mooring line
- 739 γ'_m = Density of model soil
- 740 γ'_p = Density of prototype soil
- 741 θ_i : Average inclination or bending of mooring line
- 742 θ_T : The angle subtended by the chain to horizontal at shackle point
- 743 θ_0 : Angle subtended by the chain to horizontal at soil surface
- 744 θ_p : Angle of the fluke relative to the horizontal plane
- 745 θ_s : Angle between the shank and fluke
- 746 μ : Frictional coefficient
- 747 λ : Dimensionless flow parameter
- 748 λ_c = slope of critical state line (CSL)
- 749 σ'_m = effective stress model

750 σ'_p = effective stress prototype

751 τ : Shear stress

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754 **Competing interests**

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756 The authors declare there are no competing interests.

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958 Figure Captions

959 Figure 1: (a) Drop/drag anchor model with fluke and shank closed and (b) with fluke and shank
960 open.

961 Figure 2: The installation procedure for the bi-wing anchor with separate stages highlighted.
962 Stage 1-drop, stage 2-keying and stage 3-drag embedment.

963 Figure 3: Bi-wing anchor.

964 Figure 4; Diagram of testing arrangement.

965 Figure 5: Sample shear strength profile with gradients used for sample profile in numerical
966 analysis marked as K_x .

967 Figure 6: Drop/drag anchor at different stages during test: (a) immediately after dropping, (b)
968 fluke and shank opened after keying and (c) anchor after completion of dragging (test 2.)

969 Figure 7: (a) Anchor drag profiles during Tests 1 and 2. (b) change in orientation of fluke with
970 the dragging.

971 Figure 8: Mooring line load during anchor drag and keying. Normalised load plotted against
972 and horizontal displacement of anchor.

973 Figure 9: (a) Geometry components of anchor (b) Load and moment acting on an anchor
974 during the drag installation.

975 Figure 10: Comparison between the measured and predicted values of θ_T during drag
976 embedment for tests 1 and 2.

977 Figure 11: (a). Values of N_k at different values of E_b and θ_T . (b). A comparison between
978 observed and predicted N_k value.

979 Figure 12: Parameters used for analysis of incremental anchor displacement between two
980 points.

981 Figure 13: Observed and predicted trajectory of anchor.

982 Figure 14: Observed and predicted T_0 against the normalised vertical embedment.

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