Numerical investigations into development of seabed trenching in semi-taut moorings

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43 **in semi-taut moorings**
44

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46 **ABSTRACT**

47 Field observations of semi-taut mooring systems have shown severe trench development in

48 front of suction caissons. Trenches extend back from where the chain emerges from the seabed

49 under ambient mooring loads to relatively close to the caisson, and with depths approaching the

50 padeye depth. To help understand the process, a Coupled Eulerian-Lagrangian (CEL) approach

51 has been used to apply cyclic loading to a mooring chain system, treating the chain as a series

52 of linked cylindrical elements and the soil as a strain-softening Tresca material. The chain

53 extended through the soil into the water column, and cyclically changing boundary conditions

54 were applied to the far-end of the chain to reflect a typical mooring layout and metocean

55 conditions. In spite of rather idealized conditions, with loading restricted to the vertical plane

56 of the chain and no consideration of hydrodynamic effects, a stable trench profile developed

57 after only a few cycles of loading. The chain profile straightened during the cycles, with the

58 section nearest to the padeye gradually cutting deeper into the soil and with the amplitude of

59 cyclic motions of the chain, and hence tendency for a trench to form, increasing at shallower

60 depths. The magnitude of soil resistance acting on the chain reduced by increasing cycles, with

61 particularly low resistance in the zone where the trench was most developed. The long-term

62 longitudinal profile of trenching was predicted based on the current modelling, and was found

63 comparable to that inferred from field observations, even without consideration of

64 hydrodynamic and out-of-plane effects.

65 **Keywords:** Anchor chain; trenching; coupled Eulerian–Lagrangian; strain-softening; finite

66 element analysis

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67 **INTRODUCTION**

68 The phenomenon of mooring chain trenching – the generation of a 'trench' or void around the

69 chain in the seabed due to operational chain movements - was first discovered during a due-

70 diligence inspection of the suction anchors of the Serpentina floating production storage and

71 offloading system (FPSO) offshore Equatorial Guinea (Bhattacharjee et al. 2014). The

72 inspection, conducted after ten years of operation, revealed large trenches that extended from

73 the seabed and almost reached the embedded padeye of the suction anchor (Figure 1(c)). This

74 was considered to threaten the reliability of the anchor system (Alderlieste et al. 2016; Arslan

75 et al. 2015; Sassi et al. 2018) and all anchors were replaced utilizing a larger mooring radius.

76 Since the first report of significant seabed trenching associated with the mooring chain

77 (Bhattacharjee et al. 2014) there has been widespread industrial interest, as summarized below.

78 *Observations of trenching and trench morphology*

79 The findings from the Serpentina FPSO inspections (Bhattacharjee et al. 2014) are summarized

80 in Figure 1. Steep sided trenches were observed in front of the suction caissons (Figure 1(a),

81 (b)), with the tensioned chain completely detached from the trench base. Significant motion of

82 the mooring chains was observed in operating swell conditions and identified as the primary

83 cause of trench formation. A schematic of the longitudinal profile of the trenches and the

84 surveyed dimension ranges (Bhattacharjee et al. 2014) are shown in Figure 1(c).

85 After the Serpentina trenching observations came into the public domain, accurate bathymetry

86 inspections of seabed trenches were conducted for the moorings of five FPSOs and off-loading

87 terminal buoys in the Gulf of Guinea. Colliat et al. (2018) presented longitudinal and transversal

88 trench profiles and statistically related trench development with the mooring-line loads.

89 Initiation of trenching started near the touch-down-point where the most significant chain

2

90   motions occurred, and progressed towards the anchor as a result of chain motions and trench

91   wall collapses.

92   Other observations concerning trench evolution were obtained from laboratory floor and

93   centrifuge tests (Sassi et al. 2017). However, fully-developed trenches were not established due

94   to the relatively small time-scale of testing, the small tension amplitudes applied to the chain,

95   and the absence of out-of-plane chain movements or appropriate hydrodynamic modelling.

96   ***Investigation of trenching mechanisms and driving factors***

97   Sassi et al. (2017) described the development of trenching in two stages: formation of the trench

98   with a relatively high trenching rate; and stabilization of the trench with a low trenching growth

99   rate. For the first stage, the trenching rate was linked to the maximum chain tension, with the

100   trenching rate increasing with tension level. During that stage, soil cutting caused by 'flattening-

101   out' of the initial inverse catenary of the embedded chain, together with soil degradation, was

102   proposed as the dominating mechanism. For the second stage, hydrodynamic effects and trench

103   collapse were suggested to explain regressive development of a tunnel and trench back towards

104   the anchor. Accordingly, a time-based 2D analytical tool was developed (Versteele et al. 2017)

105   incorporating chain-soil interaction, soil erosion and trench wall stability.

106   O'Neill et al. (2018) presented back-calculations of the Serpentina mooring line configurations,

107   from the FPSO fairlead down to the anchor padeye, based on analytical solutions for anchor

108   chains (Neubecker and Randolph 1995), considering various load ranges, different mooring

109   setups and soil properties. Cutting of the chain into soil and lifting up during extreme load

110   conditions were postulated as the primary mechanisms driving the formation of anchor chain

111   trenches. The results showed initial trench formation around the chain near the mudline,

112   although the predicted trench profiles were still far from reaching the limiting geometry of the

113   Serpentina trenches. This was attributed to 'secondary' trench formation mechanisms

114   concerning trench collapse and hydrodynamic-related effects not considered in those

115   calculations.

116   ***Motivations and scope of present study***

117   Most of the previous studies of trench development involved direct observations from the field

118   or model tests, providing useful information about the relationship between chain configuration

119   and open trench profile. However, the methods have not addressed chain-soil interaction

120   directly from a geotechnical viewpoint (i.e. soil resistance to the chain, and soil remolding due

121   to chain cutting), although chain-soil interaction is acknowledged as the underlying mechanism

122   for trench development. The analytical tool of (Versteele et al. 2017) predicted trench initiation

123   from the geometry of estimated chain profiles at the extreme load ranges, but their model was

124   phenomenological in nature, without attempting to quantify progressive remolding of soil under

125   repeated loading from the chain.

126   Consequently, there is still limited knowledge of the trench formation process in the public

127   domain. The numerical work reported in this paper aims to address this gap in knowledge by

128   investigating directly chain-soil interaction during the cyclic loading of a semi-taut mooring

129   system.

130   The Coupled Eulerian-Lagrangian (CEL) finite-element approach is used here to model the

131   large-deformation problem of a chain cutting cyclically through soil. The approach has been

132   shown (e.g. Kim et al. 2015; Sun et al. 2019a; Zhao and Liu 2016) to capture chain-soil

133   interaction during tensioning of an embedded chain, including incorporation of strain softening

134   to capture soil remolding during chain movement (Sun et al. 2019b). In the analyses presented

135   here, only in-plane cyclic motions of chain in undrained conditions are considered, without

136   consideration of lateral excursions of the mooring line. Hydrodynamic effects, including water

137   entrainment, erosion and scouring of the seabed soil were also not considered in the analyses.

138   These simplifications were made in order to allow detailed investigation of the geotechnical

139   chain-soil interaction aspects of this very complex offshore geotechnical issue.

140   The chain system response is investigated by modelling a multi-segment chain which cuts

141   through a softening soil domain cyclically due to the application of a range of practical

142   operational mooring line tensions and angles arising from metocean-induced vessel

143   movements. The behavior of selected chain segments is analyzed to understand how different

144   parts of the embedded chain interact with the seabed during cycling, deforming and remolding

145   the surrounding soil. Distributions of the soil resistance along the chain at different stages of

146   cyclic loading are presented together with implications for the predicted limiting geometry of

147   the trench (within the assumptions made in the numerical analyses). The numerically derived

148   trench is then compared with centrifuge test data for similar soil conditions and evidence from

149   field data, and conclusions are then drawn.

150   **FINITE-ELEMENT MODEL**

151   *Modelling software and approach*

152   All finite element analyses were carried out with the coupled Eulerian-Lagrangian (CEL)

153   approach provided in Abaqus (Dassault Systèmes 2014). The approach used (except for the

154   loading scheme) and parameters selected were as described by Sun et al. (2019a, b).

155   Consequently, only brief details of the methodology are given here.

156   *Chain geometries*

157   The chain was modelled as a string of equally spaced, rigid cylindrical segments, connected

158   using 'LINK' connector elements provided in Abaqus (Figure 2a). Three geometric variables -

159   the length l_s and the diameter d_s of each segment, and the space between adjacent segments, s_s

160   - govern the dimensions of the model chain. In the current analyses, l_s was taken as 1 m, with

161   s_s and d_s being 0.1 m and 0.25 m respectively.

162 The CEL model was designed to represent a standard $5d_b$ studless chain as shown in Figure 2a.

163 Each link pair of the $5d_b$ studless chain was idealized as one bar segment together with one

164 spacing, i.e, $l_s + s_s = 6d_b = 1.1$ m, giving $d_b \sim 0.18$ m for this model. This gives $d_s/d_b = 0.25/0.18$

165 $= 1.39$ for the configuration adopted, which must be considered when interpreting the soil

166 resistances obtained from the CEL simulations (Sun et al. 2019a).

167 The global chain model comprised 40 segments (giving a total length of 43.9 m) as shown in

168 Figure 2b. The fixed anchor point ('padeye') was set to 9 m below the soil surface (the anchor

169 depth at Serpentina (Bhattacharjee et al. 2014). Four chain segments, selected for detailed

170 analysis later, are highlighted and numbered #2, #13, #18 and #25 counting from the padeye.

171 The cyclic motion of the chain was implemented by applying a varying force at appropriate

172 inclination angles at the far end of the chain, as detailed later in this paper.

173 *Soil domain*

174 The soil was assumed to be fully undrained during chain tensioning and cyclic loading;

175 consequently total stress analyses were performed. The initial (undisturbed) undrained soil

176 strength was assumed to increase linearly with depth z, according to $s_{u0} = 2 + 1.2z$ kPa, with the

177 effective soil weight γ' being 2.4 kN/m^3. These values correspond with typical properties

178 (specifically the high shear strength ratio $s_{u0}/\gamma'z$, which is expected to be a favorable condition

179 for the stability of trench walls) of seabed sediments offshore West Africa (Ehlers et al. 2005).

180 The effects of parametric variations of soil properties were not investigated herein due to the

181 massive computational expense required for each analysis.

182 The soil was modelled as a linear elastic-perfectly plastic material, obeying the Tresca yield

183 criterion, but extended here to capture the progressive softening of clay. The undrained shear

184 strength at individual Gauss points was modified immediately prior to re-meshing according to

185 the accumulated absolute plastic shear strain ξ, according to (Einav and Randolph 2005):

186
$$s_u = \left[\delta_{rem} + (1 - \delta_{rem}) \, e^{-3\xi/\xi_{95}} \right] s_{u0} \qquad (1)$$

187   The models the degradation of soil strength according to an exponential function of cumulative

188   plastic shear strain, ξ (ξ_{95} representing the value of ξ for 95% strength degradation), from intact

189   to fully remolded strength, $\delta_{rem}s_{u0}$ (δ_{rem} being the inverse of sensitivity S_t). A user subroutine

190   was implemented in Abaqus to track the evolving soil strength profile. In the present analyses,

191   ξ_{95} and δ_{rem} were taken as 10 and 0.2 (giving an equivalent S_t of 5, typical of highly structured

192   West African soils).

193   The Young's modulus E was taken as $500s_u$ and Poisson's ratio as 0.49 to approximate

194   incompressible soil response for undrained conditions. The regular mesh comprised 8-noded

195   linear brick elements with reduced integration (EC3D8R in the Abaqus element library). A

196   central fine mesh volume (with a minimum mesh size $L_e = 0.35d_s$) was used in the domain

197   encompassing the predicted chain trajectory during the simulation.

198   ***CEL model setup***

199   A global view of the CEL model is presented in Figure 2b together with the detailed chain

200   model illustrated at the bottom of the figure. The total length of the soil domain was taken as

201   57.7 m, and the out-of-plane thickness as $30d_s$ (7.5 m) to avoid boundary effects, with the line

202   of symmetry along the vertical axial of the chain used to halve the domain size. A layer of

203   'void' with height $2l_s$ (2 m) was prescribed above the soil surface to accommodate possible

204   upward soil movement during the periodic tensioning process.

205   The anchor chain was assumed to be weightless and initially 'wished-in-place' in the post-

206   installation configuration shown in Figure 2b. Ignoring the chain weight has been shown to

207   make negligible difference to the chain response, especially given the strength intercept of

208   2 kPa at the soil surface (Sun et al., 2019a, b). A vertical section was fully embedded and

209   attached to the padeye, and a horizontal section was laid on the seabed (with the centerline level

210   at the mudline). The chain had boundary conditions of full displacement (but not rotational)

211   fixity at the padeye (leading to tension T_a applied at an angle θ_a to the horizontal at the padeye)

212   reacting to tension T_m applied at an angle θ_m at the 'dragging point'. Note that the chain tension

213   and angle do not change between mudline intersection and dragging point since the chain is

214   weightless.

215   The chain was first loaded horizontally at the seabed assuming a slack catenary of the mooring

216   line during pre-tensioning (increasing T_m gradually maintaining θ_m zero), and then tensioned

217   with periodically increasing and decreasing mudline loads and load inclinations to the

218   horizontal. The relationship between the mudline tension and inclination angle (i.e. T_m-θ_m

219   relationship) was selected to model the global behavior of a practical mooring setup as

220   discussed below.

221   ***Loading scheme based on a practical mooring setup***

222   The boundary conditions for loading the chain (i.e. applied T_m and θ_m for the chain) in the CEL

223   model were chosen to reflect a real mooring configuration, decoupling the mooring line section

224   through the water column from the embedded chain section and assuming a fixed touch-down

225   point on the seabed, consistent with engineering design practice. The mooring configuration

226   was designed to recreate approximately the Serpentina mooring (Bhattacharjee et al. 2014;

227   O'Neill et al. 2018) shown in Figure 3a. The length of mooring line in the water was set as

228   1000 m from the fixed touch-down point (with tension T_m and angle θ_m), up to the fairlead (with

229   tension T_s and angle θ_s) connecting to the floating facility with a corresponding water depth of

230   475 m (averaging the depths reported for Serpentina). As illustrated in Figure 3a four sections

231   make up the whole 1000 m line with different buoyant weights w_{mooring}, sourced from Vryhof

232   (2015) according to the types of chain and wire rope used in the Serpentina mooring system

233   (Bhattacharjee et al. 2014).

234   With the assumption of constant water depth and length of the mooring line suspended in water,

235   the relationship between T_m and θ_m for increasing fairlead movements (i.e. increasing T_s) was

236   deduced by integrating the equilibrium equations of the mooring line (see Figure 3a) over the

237   whole length from the touch-down point to the fairlead, following Faltinsen (1993). The derived

238   mudline tension T_m ranges from 640 kN (with mudline angle $\theta_m = 0°$) to 2860 kN (with angle

239    $\theta_m = 22°$) with the relationship shown on Figure 4. This range of mudline tension falls within

240   the design range (500 kN for pre-tensioning, and a maximum value of 3000 kN considering the

241   extreme conditions) adopted by O'Neill et al. (2018) based on the Serpentina moorings.

242   The derived configurations of the mooring line are plotted on the left of Figure 3b together with

243   the changing tension and angle at two ends of the line. A mudline chain angle, θ_m of 0° with T_m

244   = 640 kN was designated as the completion of the pre-tensioning stage, while $\theta_m = 10°$ ($T_m =$

245   980 kN) and $\theta_m = 22°$ ($T_m = 2860$ kN) were selected as the lower and upper limits respectively

246   for cyclic loading of the mooring line. The lower limit (θ_m of 10° and T_m of 980 kN) during

247   cycling was selected to correspond to the normal operational condition of the mooring line. The

248   lateral movement (drift) of the floating facility during cyclic loading condition is indicated on

249   the right of Figure 3b. The maximum load is generated by 17 m of drift from the virtual

250   completion of pre-tensioning and 7 m of movement from the operational ($\theta_m = 10^o$) condition.

251   This displacement range is comparable to the analyses of O'Neill et al. (2018) (26 m drift due

252   to a larger tension range of $500 \leq T_m \leq 3000$ kN).

253   Figure 4 shows the non-linear mudline tension – mudline chain angle relationship obtained

254   from the above in-water chain analyses. The relationship compares reasonably with the

255   analytical solution by O'Neill et al. (2018), who considered a constant length of mooring line

256   (942 m) with depths of seawater and padeye being 436 m and 9 m, respectively.

257   Using the relationship in Figure 4, the loading sequence in the CEL modelling consisted of the

258   following stages:

259   1. During pre-tensioning the mudline tension T_m was increased linearly with time from 0

260   to 640 kN while θ_m remained zero.

261   2. For the first loading step (labelled 'Load #1'), both T_m and θ_m were increased from

262   640 kN to 2860 kN (θ_m increasing from 0° to 22°).

263   3. The load was reduced (in stage 'Unload #1') until $T_m = 980$ kN ($\theta_m = 10°$).

264   4. Repeated loading (Load #2, #3 etc.) and unloading (Unload #2, #3 etc.) were

265   implemented alternately between the same limits of mudline tension and mudline angle

266   as for cycle 1.

267   Seven cycles of loading between the lower and upper limits were completed. The tremendous

268   computational cost for the CEL model meant that approximately 60 days of analysis time was

269   required on a fast server to run these seven cycles.

270   **RESULTS**

271   *Chain system response*

272   Figure 5a presents the mudline and padeye tensions T_m and T_a against simulation time from the

273   initial pre-tensioning phase through the eight loading and seven unloading cycles. During pre-

274   tensioning, the chain tension at the anchor padeye, T_a, is only slightly smaller than the mudline

275   tension T_m. The small difference ($T_a/T_m \approx 0.97$) reflects the low mobilization of frictional chain

276   resistance because of the combined effects of high mobilization of normal resistance over most

277   of the chain (Sun et al. 2019a) and the greater reduction in frictional resistance than normal

278   resistance during remolding (Sun et al. 2019b). For the subsequent cyclic loading, T_a is within

279   1% of T_m.

280   Figure 5b plots the corresponding changes of the mudline and padeye angles θ_m and θ_a with

281   simulation time. The variation of the chain angle at the mudline, θ_m, is a saw-toothed response

282   as specified by the load scheme. In contrast, the chain angle at the padeye θ_a decreased

283   significantly through the complete pre-tensioning (to P on Figure 5b) and Load #1 (L_1) phases

284   with a gradually decreasing rate, as the chain cut through the soil to the fully loaded geometry.

285   It then reduced further in shallow steps with marginal decreases in chain angle at the end of

286   each loading phase. The padeye angle θ_a decreased continuously, becoming smaller than the

287   mudline θ_m on application of Load #6 and subsequent cycles of maximum load application.

288   Figure 6 shows the configurations of the chain at the completion of selected loading and

289   unloading stages with dots representing the positions of the chain link elements. In the figure,

290   black represents the end of pre-tensioning (P on Figure 5), red shows the end of loading (L_1)

291   and unloading (U_1) stages of the first cycle, and blue shows the equivalent stages for the seventh

292   cycle. For the stages where much of the chain was moving downwards and so penetrating

293   deeper into the soil, e.g. during pre-tensioning and the subsequent unloading stages, the chain

294   became less curved with cycle number (i.e. having less of an inverse catenary shape) with the

295   difference of the chain angles at the padeye and mudline becoming smaller. During each load-

296   up cycle, the chain straightened, apart from the deeply embedded section very close to the

297   padeye, with the chain becoming straighter in each subsequent cycle so that by loading #7, θ_m

298    $\approx \theta_a$ (as already pointed out on Figure 5b). Overall, as cycling proceeded, the chain penetrated

299   deeper into the seabed (e.g. comparing the difference between the blue and the red profiles in

300   Figure 6).

301   ***Observation of the numerical trenching phenomenon***

302   The numerically-generated trench is shown in Figure 7 for five different stages, P, L_1, U_1, U_7

303   and L_8 (as annotated in Figure 5a). The grey regions indicate that the Eulerian domain is

304   completely filled with soil material, and the black regions indicate gap formation. Further

305   insight is provided in Figure 8, which shows cross-sections normal to the plane of the chain for

306   two positions along the chain (with the chain indicated as a blue half circle). The elevations in

307   Figure 7 show the initial lifting up of soil above the trench (L_1), together with the start of an

308   opening below the chain, with partial collapse of the lifted soil at the unload points. With

309   increasing cycles the trench becomes more developed, with the chain near the mudline (beyond

310   about segment #15) essentially moving within an open trench, while a smaller tunnel develops

311   in the mid-region (difficult to see in Figure 7, but extending from about segment #13 to #15).

312   The cross-sectional views (Figure 8(a) and (b)) at the centroids of segments (#18 and #23)

313   confirm the trench opening near the mudline during the initial chain lifting (stage L_1) and then

314   the development of the trench (in stages L_1 to L_8). The trench develops as the chain moves up

315   and down between loading and unloading stages whilst progressively penetrating the trench

316   bottom downwards during unloading.

317   The limitations of the CEL analyses, without consideration of hydrodynamic effects, water

318   entrainment and out-of-plane motions, do not allow full trench development, or the observed

319   breadth of the open trenches (reaching 50% of the trench depth) reported by Colliat et al. (2018).

320   Instead, cells partially filled with remolded soil remain above the chain (see Figure 8).

321   However, the main processes and consequences of trench development are clear, even within

322   the quite limited number of loading cycles that were feasible computationally.

323   ***Response of chain at selected segments***

324   *Overall displacements*

325   To understand how different parts of the chain interact with the seabed, the accumulation of

326   two displacement components (locally normal and axial to the chain axis) are plotted for four

327   selected chain segments in Figure 9, with the segment locations indicated in Figure 6 and Figure

328   7. The graphs start from the 'wished-in-place' installed configuration (i.e. the beginning of the

329   simulation) until the completion of Load #4 (L_4).

330   The accumulated displacement graphs show the domination of the normal movement for

331   segment #2 (near the padeye) due to the constraint at the padeye (which precludes any axial

332   chain movement, but allows chain rotation), while axial movements dominate normal

333   movements closer to the dragging point (e.g. for segment #25). The accumulated axial

334   displacement of the four segments remained almost constant after L_1, irrespective of the axial

335   movements during pre-tensioning, reflecting a relatively taut configuration of the chain during

336   cycling.

337   *Normal displacements*

338   In contrast to the axial displacements, the normal displacements of the four segments show

339   distinctive responses during cycling after the initial increase of normal displacement, with the

340   chain cutting through the soil, during pre-tensioning. The tension-displacement responses

341   during all seven loading cycles are plotted in detail in Figure 10, with the loading stage of each

342   curve presented in black and the unloading stages in magenta.

343   The normal movement of segment #2 (near the padeye) increases 'step-wise' with reducing

344   step heights with increasing numbers of cycles (Figure 10a). No significant movement occurs

345   during unloading stages, while normal displacement increases mainly during the later stage of

346   each loading, reducing progressively with cycle number.

347   The normal displacement of segment #13 (about half way between the padeye and the seabed

348   surface) increases (cutting further downwards into the soil) during the first half of each loading

349   stage, then decreases (being lifted up) over the second half of the loading stage before increasing

350   further during unloading of the chain (see Figure 10b). Interestingly the cyclic range of normal

351   displacement increases with cycle number even though there is a reduction in the cumulative

352   cycle-by-cycle chain segment movement. This reflects the development of a gap or tunnel

353   around that part of the chain.

354   Segments #18 and #25 (see Figure 10c and d), which are near the seabed surface, show more

355   conventional cyclic motion with alternate directions of movement during unloading and loading

356   with the cyclic amplitude not changing very much. In this zone, the very low soil resistance,

357 reflecting trench development and, for segment #25, elevation above the mudline, results in

358 much greater displacement amplitudes than for the deeper chain segments.

359 *Normal resistances*

360 The relationships between normal resistance and displacement for the selected segments are

361 presented in Figure 11, with black lines represent loading stages and magenta unloading.

362 Normal soil resistances are shown normalized by the ultimate normal seabed resistance, Q_{ult},

363 for non-softening soil at the instantaneous chain depth.

364 The ultimate resistance Q_{ult} ($= N_{b,ult}d_b s_{u0} = 19 d_b s_{u0}$) was derived based on monotonic penetration

365 analyses for a deeply embedded multi-segment chain section in non-softening soil (Sun et al.

366 2019a), benchmarked by Degenkamp and Dutta (1989). For simplicity, the 'deep' ultimate

367 resistance was adopted for the normalization even for the shallow part of the chain. In softening

368 soil with sensitivity $S_t = 5$, the post-peak steady-state normal resistance (for monotonic chain

369 movement in deep conditions) was $0.68 Q_{ult}$ (Sun et al. 2019b) and this will theoretically reduce

370 to $0.2 Q_{ult}$ for fully remolded conditions. Lower resistance will be obtained near the seabed

371 surface or as gapping develops.

372 In current design methods (Degenkamp and Dutta 1989; Neubecker and Randolph 1995), the

373 soil resistance to the chain is conventionally decomposed as two independent components, the

374 normal resistance Q and 'frictional' resistance F, which are expected to react in opposition to

375 the normal and axial incremental displacements. Consequently, positive normal resistance is

376 defined as that corresponding to downward movement of the chain (as would occur during the

377 initial tensioning), and negative resistance the result from upward movement. The frictional

378 resistance during chain cycling remained close to zero as the axial movement became

379 insignificant after Load #1 (see Figure 9) and is not considered further.

380 The behavior of segment #2 (Figure 11a) indicates that this section of chain gradually penetrates

381 deeper into the seabed with increasing cycles and that the normal seabed resistance gradually

382 reduces. The cyclic response shows increasing seabed resistance during the loading phases

383 during which there is downward plastic penetration of the chain into less disturbed soil, with

384 slight upward movement during chain unloading that lead to sharp drops in normal resistance.

385 During the small upward movements there appears to be no detachment of the chain from the

386 underlying soil, since the net resistance remains positive. Although the cumulative chain

387 movement is downwards, the soil resistance reduces gradually with increasing cycle number

388 from approximately $Q/Q_{ult} = 0.6$ at L_1 (which is broadly consistent with the 0.68 expected for

389 the first movement for $S_t = 5$ soil) to $Q/Q_{ult} \approx 0.35$ for L_7, which reflects increasing remolding

390 of soil around the chain. Further cycles are expected to continue to reduce Q/Q_{ult} during the

391 loading phases as the soil continues to remold.

392 Segments #13, #18 and #25 experience two-way oscillation of normal resistance, reaching

393 maximum positive resistance (against downward movement) partway through each loading

394 cycle as reflected in the changes in normal displacement direction shown on Figure 11. The

395 maximum uplift resistance is reached towards (or at) the end of the chain loading (i.e. at L_1, L_2

396 etc.). For all three segments the cyclic range of normalized resistance decreases continuously,

397 reflecting a decrease in penetration resistance from an initial value of $Q/Q_{ult} \approx 0.68$ down

398 towards $Q/Q_{ult} \approx 0.4$, while the uplift resistance decreases in magnitude from $Q/Q_{ult} \approx -0.4$ down

399 to -0.32 to -0.35 for segments #13 and #18. For segment #25, a maximum uplift resistance was

400 $Q/Q_{ult} \approx -0.1$ partway through the loading stage, but reduced towards zero by the end of loading.

401 These responses reflect the combined effects of soil remolding for the deeper conditions, and

402 gapping and trench development during uplift, particularly for segment #25.

403 The chain response in the vicinity of segment #25 appears similar to that of a vertically

404 oscillating steel catenary riser in the touchdown (Bridge et al. 2004; Randolph and Quiggin

405 2009). This part of the chain lifts out of the soil during each cycle, experiencing a small amount

406 of uplift resistance $(-0.1 < Q/Q_{ult} < 0.1)$ until the chain fully loses contact with the seabed (when

407    $Q \approx 0$). During reduction in tension, the chain segments repenetrate the seabed, pushing initially

408   into remolded soil before coming into contact with 'new' soil. In each cycle, the chain

409   penetrates slightly further into the seabed at the end of unloading with penetration resistance

410   decreasing from $0.6Q_{ult}$ to $0.5Q_{ult}$ with each cycle (and still reducing at U_7).

411   *Soil resistance profiles*

412   Figure 12 presents depth profiles of normal soil resistance at the completion of the loading

413   (plotted on the left) and unloading (plotted on the right) phases of each cycle.

414   The normal resistance curves at the completion of the loading phases show three types of chain-

415   soil interaction:

416   (i)   For the deeply embedded segments near the padeye (where the chain moves

417   downwards during system tensioning), positive seabed resistance is mobilized. This

418   reduced with number of cycles because of remolding. Segment #2 shows this

419   behavior.

420   (ii)   Further away from the padeye, the soil resistance is negative because the chain

421   moves upwards at the end of tensioning. The resistance stays approximately

422   constant with depth due to the deep uplift mechanism, although for any given

423   segment the resistance gradually reduced with cycle number. Segment #13 shows

424   this type of behavior, which appears to correspond to the 'tunneling' mechanism

425   identified earlier in Figure 7.

426   (iii)   For chain segments near the mudline the absolute value of the negative (uplift) soil

427   resistance during chain loading gradually reduces towards zero due to mobilization

428   of shallow uplift resistance mechanisms and gradual trench development. Slight

429   uplift resistance was generated even for some segments above the mudline because

430   of soil lifted by the chain. Segments #18 and #25 show this behavior, which

431   corresponds to the trenching zone identified earlier in Figure 7.

Numerical investigations into development of seabed trenching
in semi-taut moorings
Sun et al.
November 2019

432   As cycling proceeded, the depth range of the positive (penetration) resistance section reduced,

433   i.e. the transition to cyclic penetration and uplift resistance moves deeper, with the maximum

434   normal resistance in this section reducing from $0.6Q_{ult}$ to just below $0.4Q_{ult}$. The seabed

435   resistance reverses (resisting uplift) during Load #2 for segment #11, Load #4 for segment #9

436   and Load #6 for segment #8, reflecting the transition point moving gradually closer to the

437   padeye with increasing number of cycles. The changing depth of this transition point with

438   numbers of cycles is shown on the left side of Figure 12, with the depth ranges of each observed

439   mechanism identified.

440   In contrast, the normal resistance profiles at the completion of each unloading phase shown on

441   the right of Figure 12 show that resistance remains positive for the whole chain length because

442   the whole chain is moving downwards at the end of each unloading phase (as can be seen in

443   Figure 10). Within the first two unloading events, the magnitude of the soil resistance near the

444   padeye reduces to just above $0.1Q_{ult}$ with the near-mudline resistance remaining between 0.5

445   and 0.6 of the ultimate intact resistance (apart from a zone within the top 0.5 m of the seabed

446   where resistance reduced to almost zero on unloading). With increasing cycles, the resistance

447   at all depths reduces, although this happens increasingly slowly as the seabed surface is

448   approached because the chain moves progressively into 'new' soil as it works its way down

449   into the seabed. It is postulated that, if sufficient cycles were conducted, the ultimate condition

450   of the normal resistance during chain unloading might be for none of the segments below the

451   mudline to mobilize more than about $0.1Q_{ult}$ considering the near-surface and gapping effects

452   for soil in different embedment depths.

453   **IMPLICATIONS FOR TRENCHING**

454   Figure 13 brings together the findings about loadings and displacements on individual chain

455   segments and observations about seabed geometry changes (particularly trench and gap

456   formation) as a result of chain movements. For each cycle (with L_8 shown in Figure 13), three

457   sections of the seabed are identified:

458   (a) a 'trenching' zone (from the seabed to about 3 m) where a shallow uplift mechanism

459   prevails, the resistance on the chain reverses direction during system loading and

460   unloading and a trench is generated with soil at the seabed surface elevated. The extent

461   of this zone appears to be governed by the chain oscillating upwards and downwards

462   during system loading (as hypothesized by O'Neill et al. (2018)) and where shallow

463   chain uplift mechanisms (with gap formation beneath the chain) occur (the value of z/d_s

464   where this occurs may be estimated knowing $\gamma'd_s/s_u$, e.g. Merifield et al. (2009)).

465   (b) a 'tunneling' zone (from about 3 m to 6.5 m for L_8) where the soil resistance reverses

466   during loading and unloading, but the local uplift mechanism is local rather than

467   reaching the mudline. A small 'tunnel' is generated above and below the chain due to

468   detachment behind the chain during movement (see Figure 13). The depth of the

469   tunneling zone increases with number of cycles (see Figure 12).

470   (c) a 'remolding' zone (from the padeye to 6.5 m for L_8) where the soil resistance remains

471   below the chain although small chain movements gradually remold the soil around the

472   chain and the resistance reduces with numbers of cycles. Gapping was not observed in

473   this zone.

474   If water entrainment and hydrodynamic effects (with scour) are included, the soil around the

475   'shallow uplift' section of the chain is likely to be transported away with time. Furthermore, the

476   soil opening in the 'tunneling' section provides an additional water ingress path, which is likely

477   to lead to scour and softening of this zone and so this zone is also expected to trench with time.

478   The lowest depth of the tunneling zone in the CEL analysis was observed to increase during

479   cycling with no equilibrium position achieved in the eight cycles modelled. The rate of tunnel

480   development is likely to accelerate in reality as soil is removed though hydrodynamic effects,

481   and with out of plane excursions of the chain. Consequently, trenching is expected to occur

482   progressively down towards the padeye.

483   The trenching process discussed above is compared with the field observations from

484   Bhattacharjee et al. (2014) and with the centrifuge observations from Sassi et al. (2017). The

485   lowest extent of the 'tunnel' zone in the CEL analyses (for only eight cycles) approaches the

486   depth of the trench in the field observation. Furthermore, the end of centrifuge test geometry

487   (with 1000, small amplitude cycles) appears qualitatively similar to the numerical result. Both

488   provide confidence in the simulation method despite the simplifications made.

489   With the help of the analytical solutions of the embedded chain by Neubecker and Randolph

490   (1995), a predicted limiting configuration of chain at minimum tension was derived with the

491   assumption that the normal soil resistance was reduced to $0.1Q_{ult}$ with no friction mobilized

492   based on the previous discussion with reference to Figure 11 and Figure 12. This is shown on

493   Figure 13 and is compared with the inferred longitudinal profile of trenches by Bhattacharjee

494   et al. (2014). The difference can be attributed to 'secondary' trenching mechanisms including

495   hydrodynamic transportation (O'Neill et al. 2018). The analytical prediction for the limiting

496   trench geometry based on CEL modelling results shows an improvement compared with the

497   previous results by O'Neill et al. (2018) even without consideration of hydrodynamic effects.

498   **CONCLUSIONS**

499   Abaqus CEL was utilized to analyze the behavior of a mooring chain embedded in the seabed

500   during cyclic loading of a semi-taut mooring system. The analysis allowed identification of

501   patterns of cyclic chain movements and chain-soil interaction and provided a quantitative basis

502   for understanding how chain trenching develops.

503   The embedded section of the chain demonstrated three different types of mechanisms, which

504   were described as 'trenching', 'tunneling' and 'remolding'. In the 'trenching' section the chain

505   lifted the soil above the chain, opening up a 'slot' in the seabed with the chain penetrating

506   slightly further into the seabed during each unloading stage. The adjacent 'tunneling' section

507   of the chain opened a smaller gap above and below the chain. Both zones were associated with

508   seabed uplift resistance mechanisms during tensioning of the chain.

509   Once hydrodynamic effects and out of plane motion of the chain are considered (neither of

510   which were modelled in the analysis), the combined 'trenching' and 'tunneling' zones are likely

511   to define the final extent of chain trenching. The lower extent of the tunneling zone moved

512   closer to the padeye with number of cycles, suggesting that some degree of trenching will

513   progress down the chain to the padeye during operation. Water entrainment will also contribute

514   to growth of the trench.

515   Finally, all chain segments were observed to move down into the soil during chain unloading,

516   remolding the soil and reducing the seabed penetration resistance and leading ultimately to an

517   almost straight chain (i.e. with minimal soil resistance) throughout loading cycles. The chain

518   profile during unloading, assuming fully remolded soil resistance, approximates the extent of

519   the trenching zone and appears to agree closely with observations by (Bhattacharjee et al.

520   (2014)).

521   Despite the limitations of the 2D in-plane motion of the chain analyzed, the small number of

522   cycles (limited by computational expense) and the lack of consideration of hydrodynamic

523   effects and other aspects such as out of plane motion and water entrainment, all of which would

524   lead to further growth of the trench, the CEL analysis led to significant improvement in

525   understanding the chain trenching process.

526   **DATA AVAILABILITY STATEMENT**

527   All data, models, or code that support the findings of this study are available from the

528   corresponding author upon reasonable request.

529 **ACKNOWLEDGEMENTS**

540 **REFERENCES**

541 Alderlieste, E. A., Romp, R. H., Kay, S., and Lofterød, A. (2016). "Assessment of Seafloor
542 Trench for Suction Pile Moorings: a Field Case." In *Proc., Offshore Technology Conference*,
543 Offshore Technology Conference.

544 Arslan, H., Peterman, B. R., Wong, P. C., and Bhattacharjee, S. (2015). "Remaining Capacity
545 of the Suction Pile due to Seabed Trenching." In *Proc., The Twenty-fifth International
546 Offshore and Polar Engineering Conference*, International Society of Offshore and Polar
547 Engineers.

548 Bhattacharjee, S., Majhi, S. M., Smith, D., and Garrity, R. (2014). "Serpentina FPSO Mooring
549 Integrity Issues and System Replacement: Unique Fast Track Approach." In *Proc., Offshore
550 Technology Conference*, Offshore Technology Conference.

551 Bridge, C., Laver, K., Clukey, E., and Evans, T. (2004). "Steel catenary riser touchdown point
552 vertical interaction models." In *Proc., Offshore Technology Conference*, Offshore Technology
553 Conference.

554 Colliat, J.-L., Safinus, S., Boylan, N., and Schroeder, K. (2018). "Formation and Development
555 of Seabed Trenching from Subsea Inspection Data of Deepwater Gulf of Guinea Moorings."
556 In *Proc., Offshore Technology Conference*, Offshore Technology Conference.

557 Dassault Systèmes (2014). *ABAQUS 6.14 Analysis User's Manual*, Simulia Corp, Providence,

558 RI, USA.

559 Degenkamp, G., and Dutta, A. (1989). "Soil resistances to embedded anchor chain in soft

560 clay." *Journal of Geotechnical Engineering*, 115(10), 1420-1438.

561 Ehlers, C. J., Chen, J., Roberts, H. H., and Lee, Y. C. (2005). "The origin of near-seafloor

562 crust zones in deepwater." In *Proc., Proc. Int. Symp. on Frontiers in Offshore Geotechnics:*

563 *ISFOG*, 927-934.

564 Einav, I., and Randolph, M. F. (2005). "Combining upper bound and strain path methods for

565 evaluating penetration resistance." *International Journal for Numerical Methods in*

566 *Engineering*, 63(14), 1991-2016.

567 Faltinsen, O. (1993). *Sea loads on ships and offshore structures*, Cambridge university press.

568 Kim, Y., Hossain, M. S., and Wang, D. (2015). "Dynamically Installed Anchors: Performance

569 of embedded mooring chain profile in clay." *Frontiers in Offshore Geotechnics III*, Meyer,

570 ed., Taylor & Francis Group, London, 881-886.

571 Merifield, R. S., White, D. J., and Randolph, M. F. (2009). "Effect of surface heave on

572 response of partially embedded pipelines on clay." *Journal of Geotechnical and*

573 *Geoenvironmental Engineering*, 135(6), 819-829.

574 Neubecker, S. R., and Randolph, M. F. (1995). "Profile and frictional capacity of embedded

575 anchor chains." *Journal of geotechnical engineering*, 121(11), 797-803.

576 O'Neill, M., Erbrich, C., and McNamara, A. (2018). "Prediction of Seabed Trench Formation

577 Induced by Anchor Chain Motions." In *Proc., Offshore Technology Conference*, Offshore

578 Technology Conference.

579 Randolph, M., and Quiggin, P. (2009). "Non-linear hysteretic seabed model for catenary

580 pipeline contact." In *Proc., ASME 2009 28th International Conference on Ocean, Offshore*

581 *and Arctic Engineering*, American Society of Mechanical Engineers, 145-154.

582 Sassi, K., Kuo, M. Y. H., Versteele, H., Cathie, D. N., and Zehzouh, S. (2017). "Insights Into

583 the Mechanisms of Anchor Chain Trench Formation." In *Proc., Offshore Site Investigations*

584 *and Geotechnics Conference, Society for Underwater Technology, SUT OSIG, London, UK*,

585 10-12.

586 Sassi, K., Zehzouh, S., Blanc, M., Thorel, L., Cathie, D., Puech, A., and Colliat-Dangus, J.-L.

587 (2018). "Effect of Seabed Trenching on the Holding Capacity of Suction Anchors in Soft

588 Deepwater Gulf of Guinea Clays." In *Proc., Offshore Technology Conference*, Offshore

589 Technology Conference.

590   Sun, C., Feng, X., Bransby, M. F., Neubecker, S. R., Randolph, M. F., and Gourvenec, S.

591   (2019b). "Numerical investigations of the effect of strain softening on the resistance to

592   embedded mooring chains." *Applied Ocean Research*, 92, 101944.

593   Sun, C., Feng, X., Neubecker, S. R., Randolph, M. F., Bransby, M. F., and Gourvenec, S.

594   (2019a). "Numerical study of mobilized friction along embedded catenary mooring chains."

595   *Journal of Geotechnical and Geoenvironmental Engineering* 145(10), 04019081.

596   Versteele, H., Kuo, M. Y. H., Cathie, D. N., Sassi, K., and Zehzouh, S. (2017). "Anchor

597   Chain Trenching–Numerical Simulation of Progressive Erosion." In *Proc., Offshore Site*

598   *Investigations and Geotechnics Conference, Society for Underwater Technology, SUT OSIG,*

599   *London, UK*, 10-12.

600   Vryhof (2015). "Anchor Manual 2015." *Global Maritime Vryhof Anchors*.

601   Zhao, Y., and Liu, H. (2016). "Numerical implementation of the installation/mooring line and

602   application to analyzing comprehensive anchor behaviors." *Applied Ocean Research*, 54, 101-

603   114.

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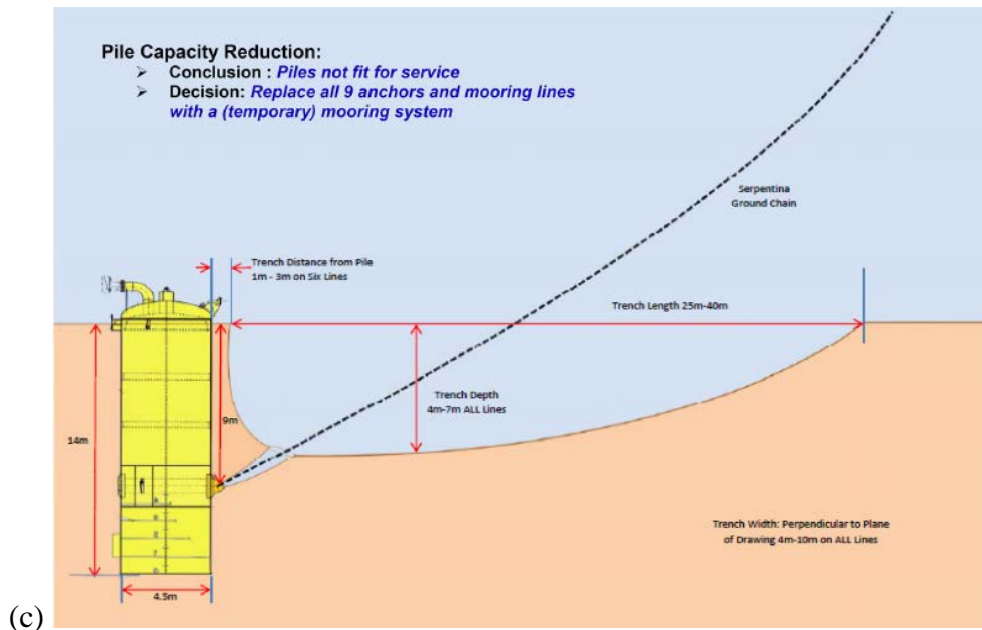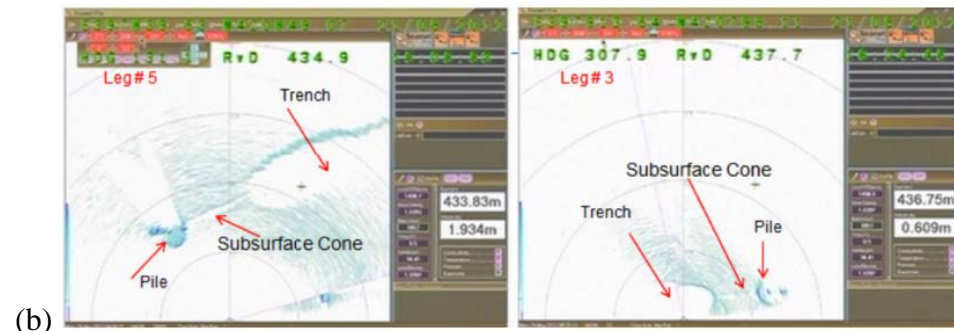
605   **Figure captions**

606   Figure 1. Surveys and schematic of the seabed trench at Serpentina FPSO (Bhattacharjee et
607   al., 2014): (a) ROV images of seabed trenching in the vicinity of the suction caisson; (b)
608   Sonar showing proximity of trenches to suction caissons; (c) Schematic of the trench with
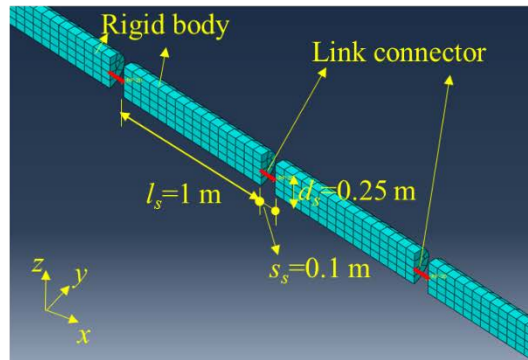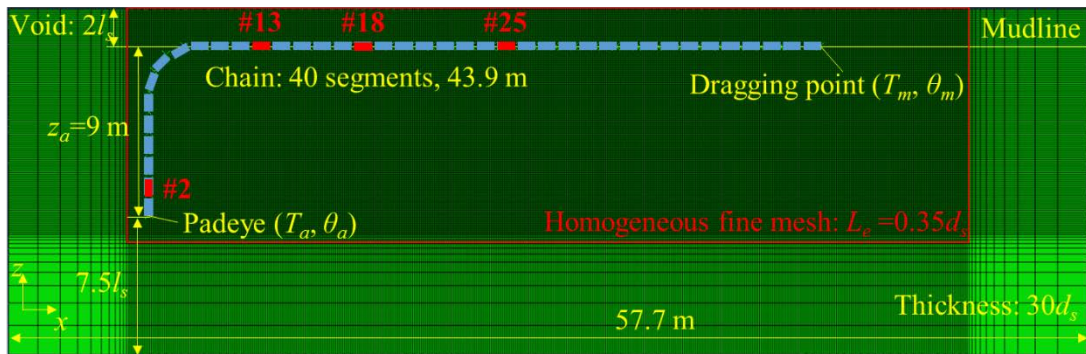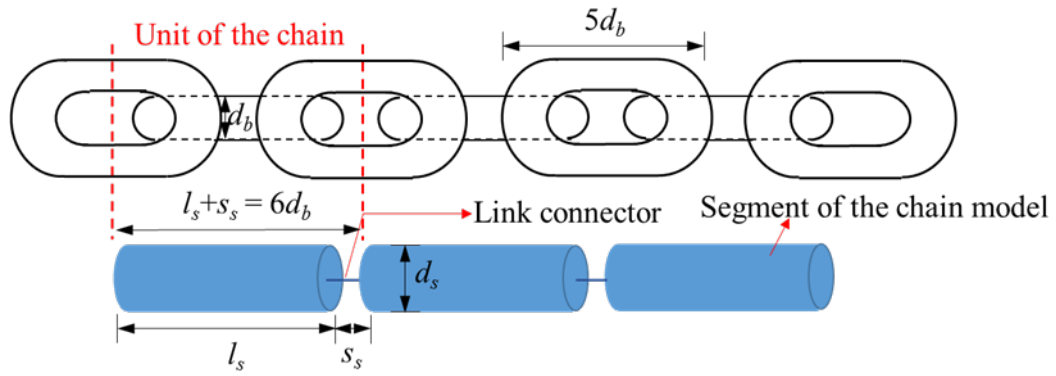609   surveyed dimensions.

610   Figure 2. CEL modelling of the embedded chain: (a) Chain model representing $5d_b$ studless
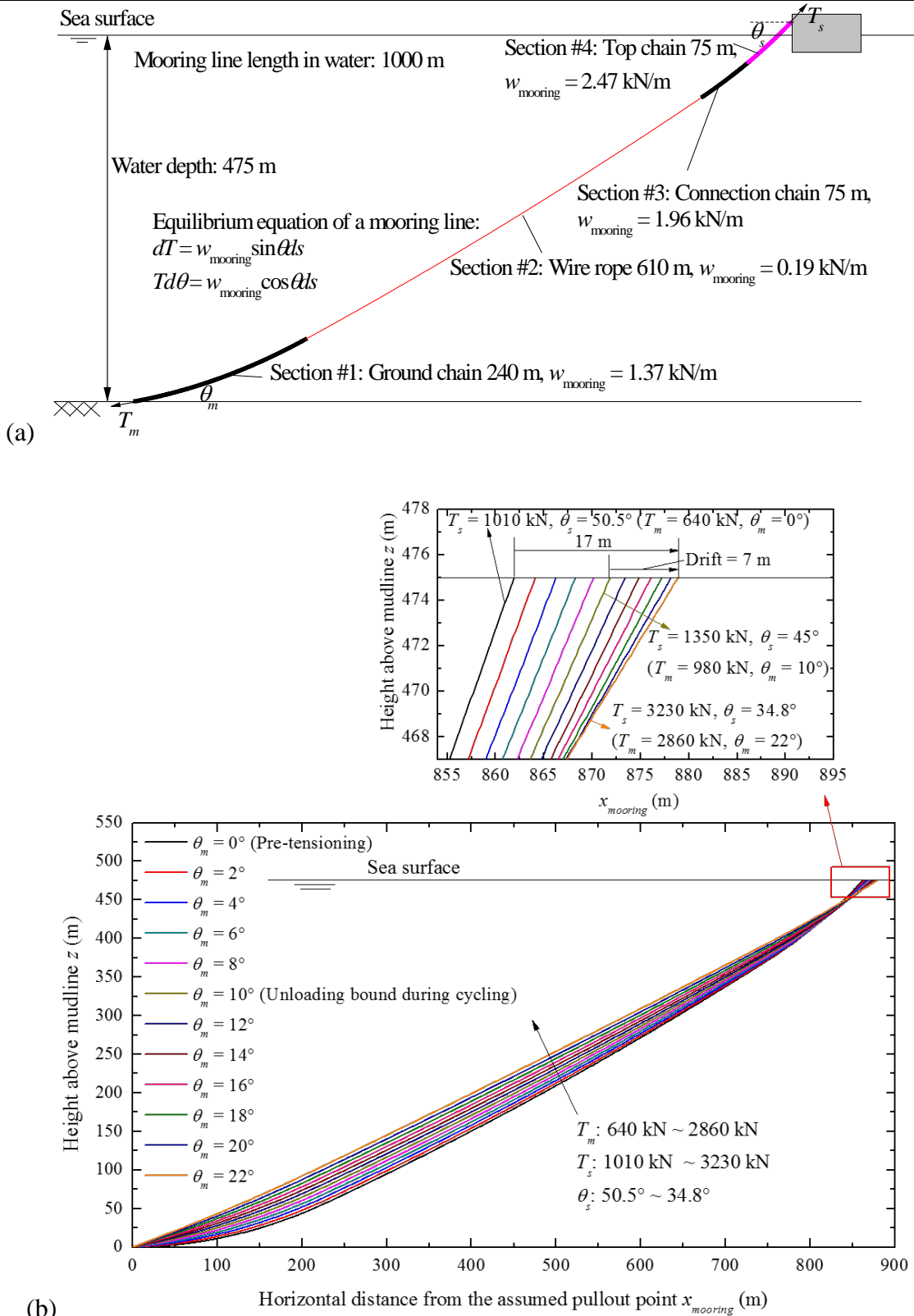611   chain; (b) FE model setup.

612   Figure 3. Setup of the mooring line for CEL modelling work: (a) A practical example of a
613   mooring line in the seawater; (b) Configurations of the mooring line and the corresponding
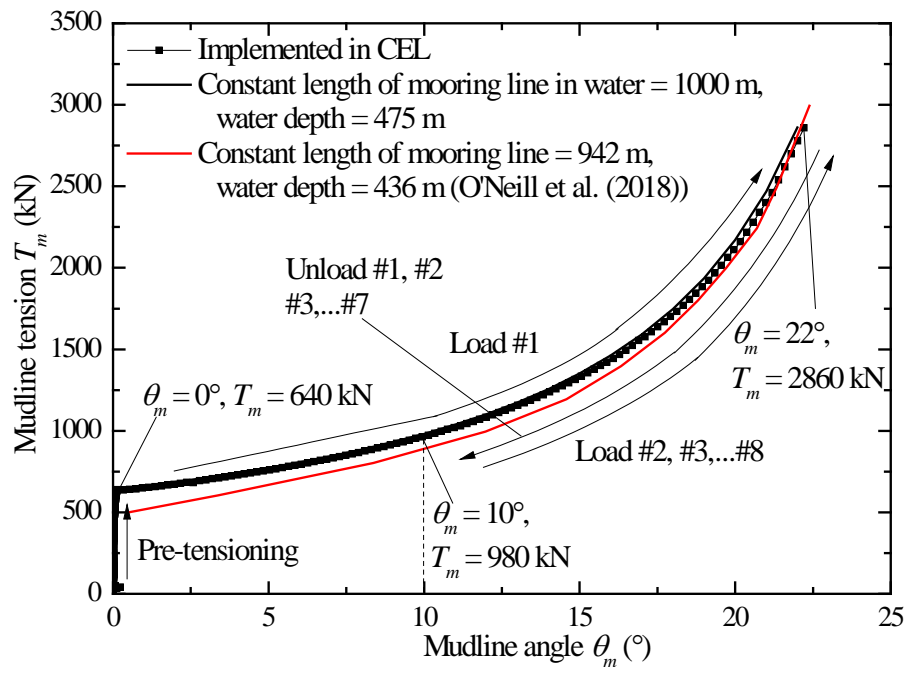614   boundaries of the tension and angle.

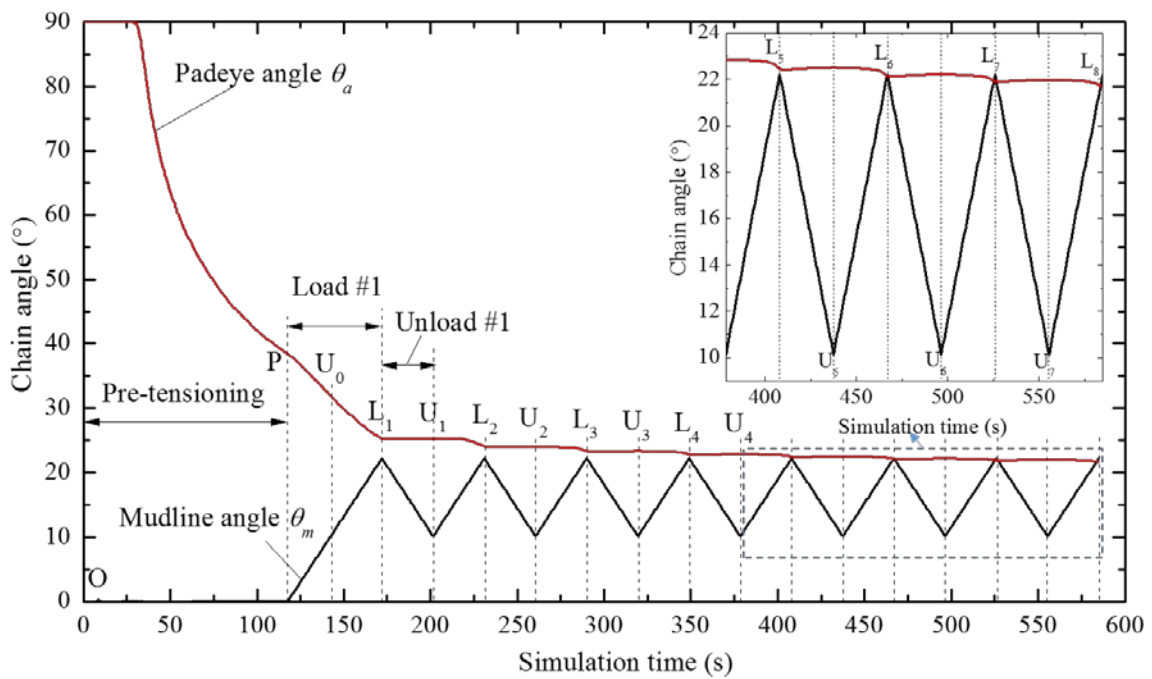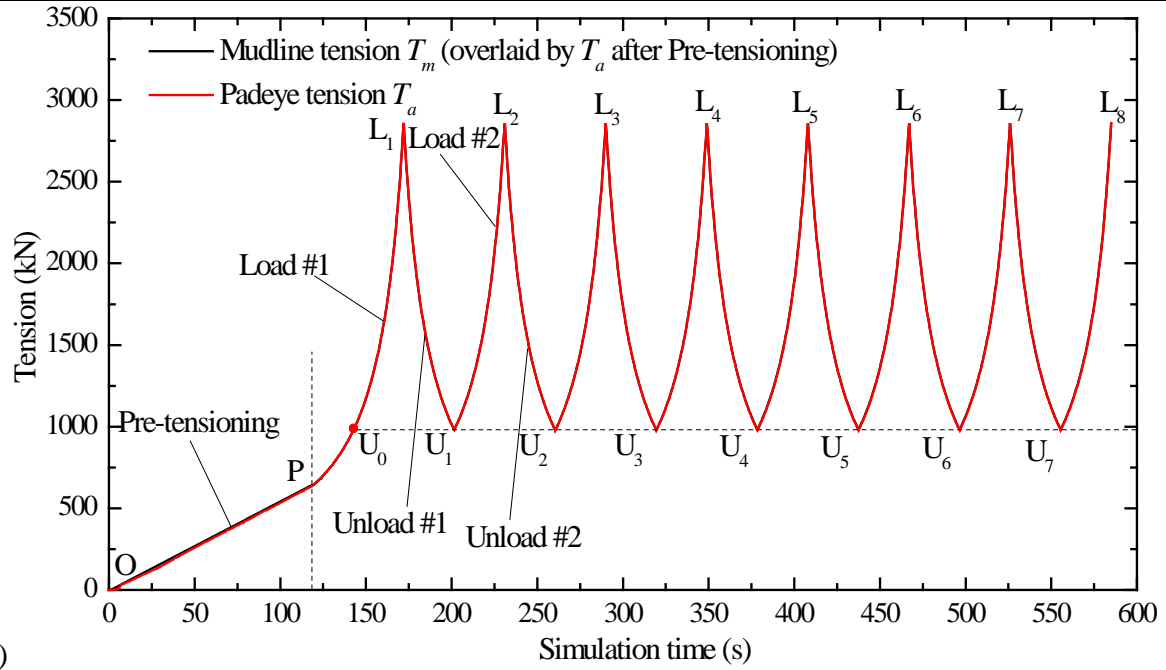615   Figure 4. Load input from the mooring line in the seawater.

616   Figure 5. Tensions and angles of the chain during the complete simulation: (a) Mudline and
617   padeye tension; (b) Mudline and padeye angles.

618   Figure 6. Comparison of the configurations of the embedded chain at selected instants during
619   cyclic loading.

620   Figure 7. Volume fraction of soil at selected instants during cyclic loading.

621   Figure 8. Cross-sectional views of the volume fraction of soil at selected instants during
622   cyclic loading.

623   Figure 9. Accumulated displacement of selected chain segments (from pre-tensioning to Load
624   #4): (a) Segment #2; (b) Segment #13; (c) Segment #18; (d) Segment #25.

625   Figure 10. Variation of normal displacement during cyclic loading for selected chain segments
626   (a) Segment #2; (b) Segment #13; (c) Segment #18; (d) Segment #25.

627   Figure 11. Normal resistance-displacement response for selected chain segments: (a) Segment
628   #2; (b) Segment #13; (c) Segment #18; (d) Segment #25.

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633

634 (a)

635 (b)

636 (c)

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641   (a)

642   (b)

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644   chain; (b) FE model setup.

Sea surface

Mooring line length in water: 1000 m

Section #4: Top chain 75 m, $w_{mooring} = 2.47$ kN/m

θ_s T_s

Water depth: 475 m

Section #3: Connection chain 75 m, $w_{mooring} = 1.96$ kN/m

Equilibrium equation of a mooring line:
$$dT = w_{mooring} \sin\theta ds$$
$$Td\theta = w_{mooring} \cos\theta ds$$

Section #2: Wire rope 610 m, $w_{mooring} = 0.19$ kN/m

Section #1: Ground chain 240 m, $w_{mooring} = 1.37$ kN/m

θ_m

T_m

645   (a)

646   (b)

647   Figure 3. Setup of the mooring line for CEL modelling work: (a) A practical example of a

648   mooring line in the seawater; (b) Configurations of the mooring line and the corresponding

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650

651

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657

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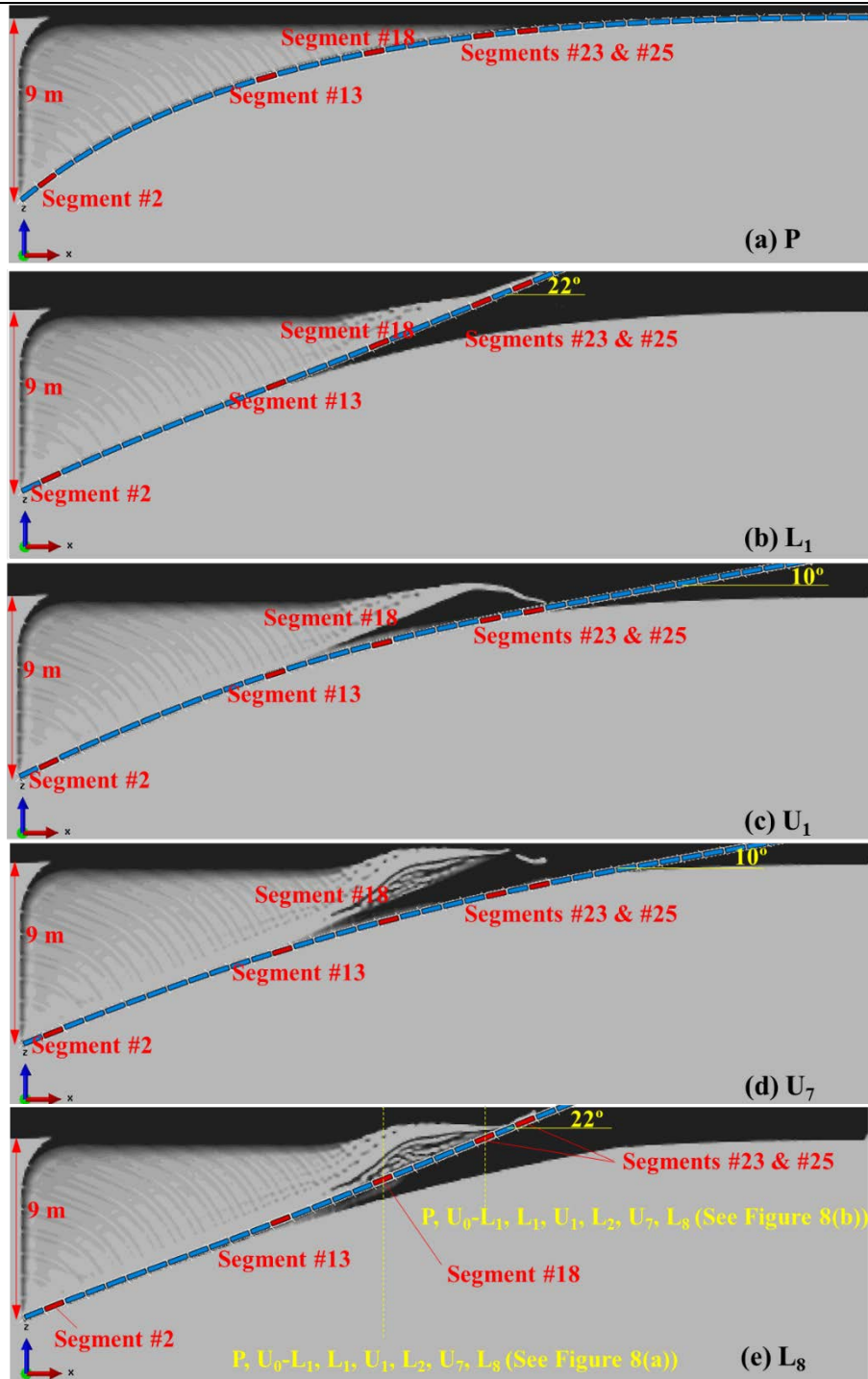
659 cyclic loading.

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666   Figure 7. Volume fraction of soil at selected instants during cyclic loading.

667

(a) Through the centroid of segment #18

668

(b) Through the centroid of segment #23

669   Figure 8. Cross-sectional views of the volume fraction of soil at selected instants during

670   cyclic loading.

671

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674

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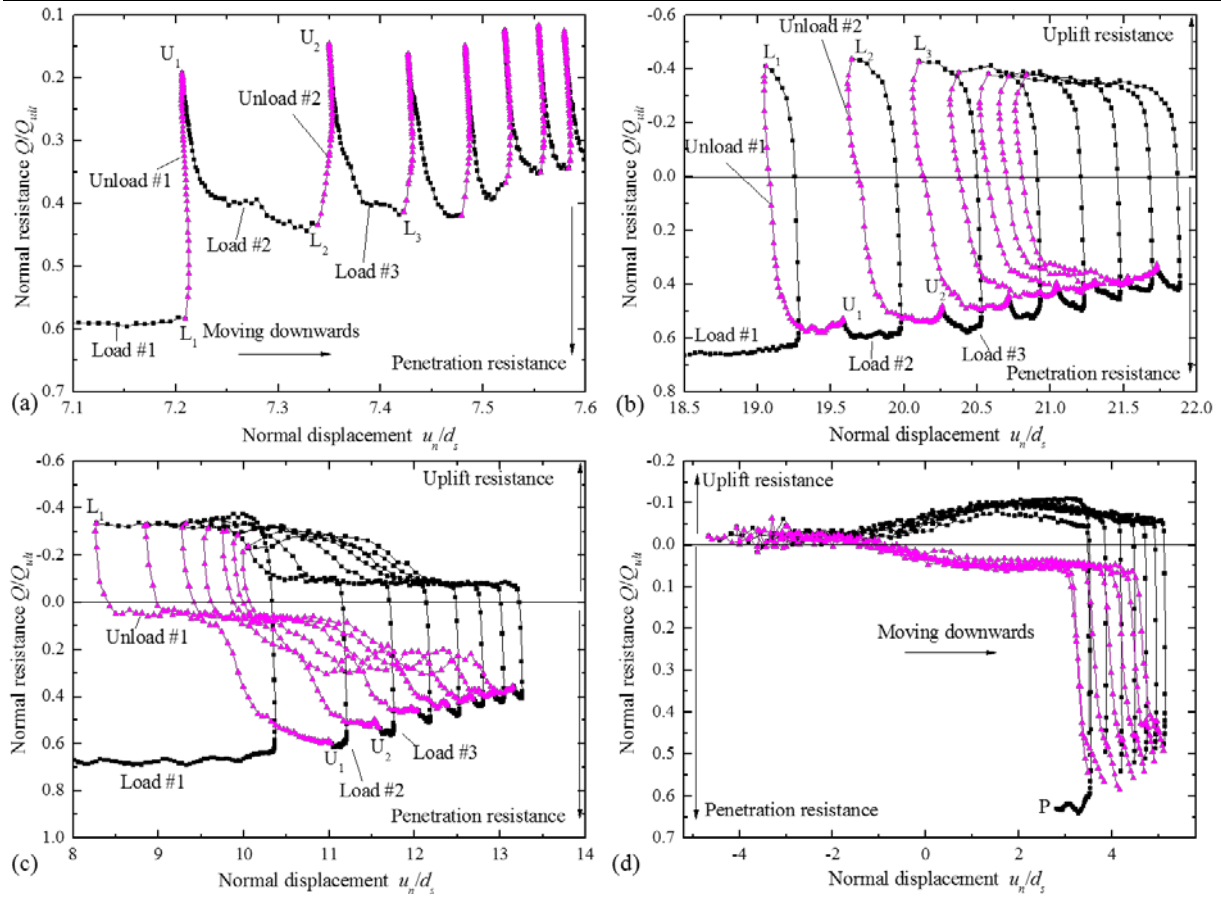676   segments (a) Segment #2; (b) Segment #13; (c) Segment #18; (d) Segment #25.

677

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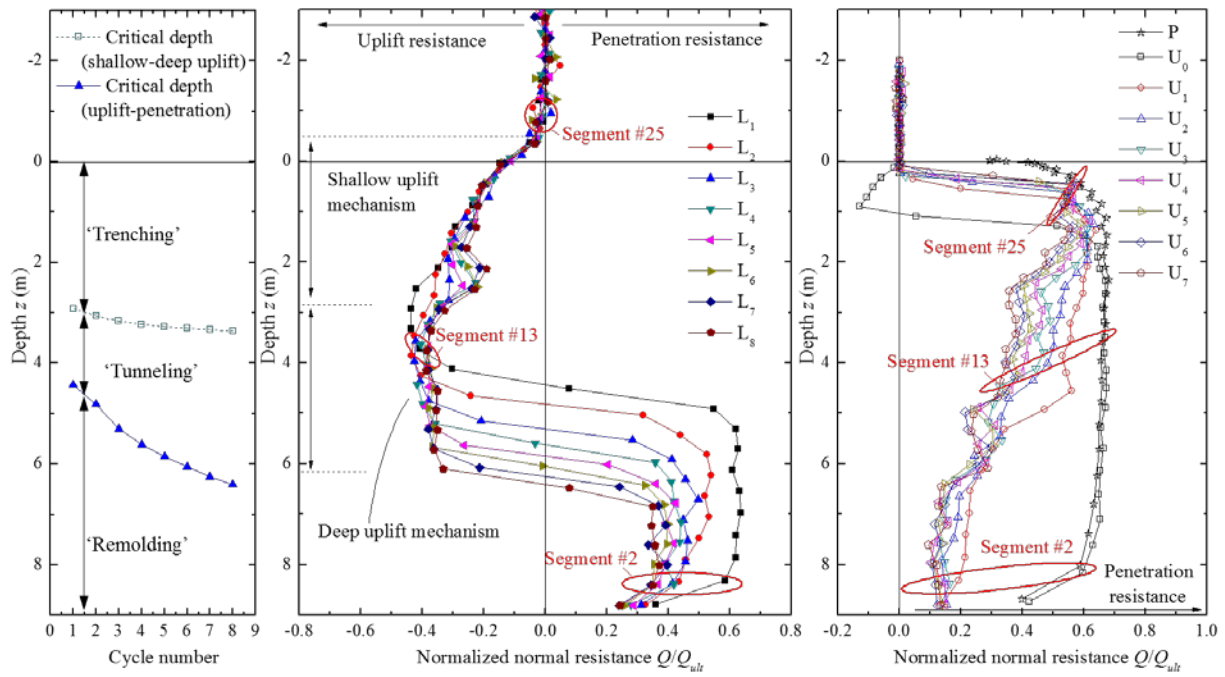679   #2; (b) Segment #13; (c) Segment #18; (d) Segment #25.

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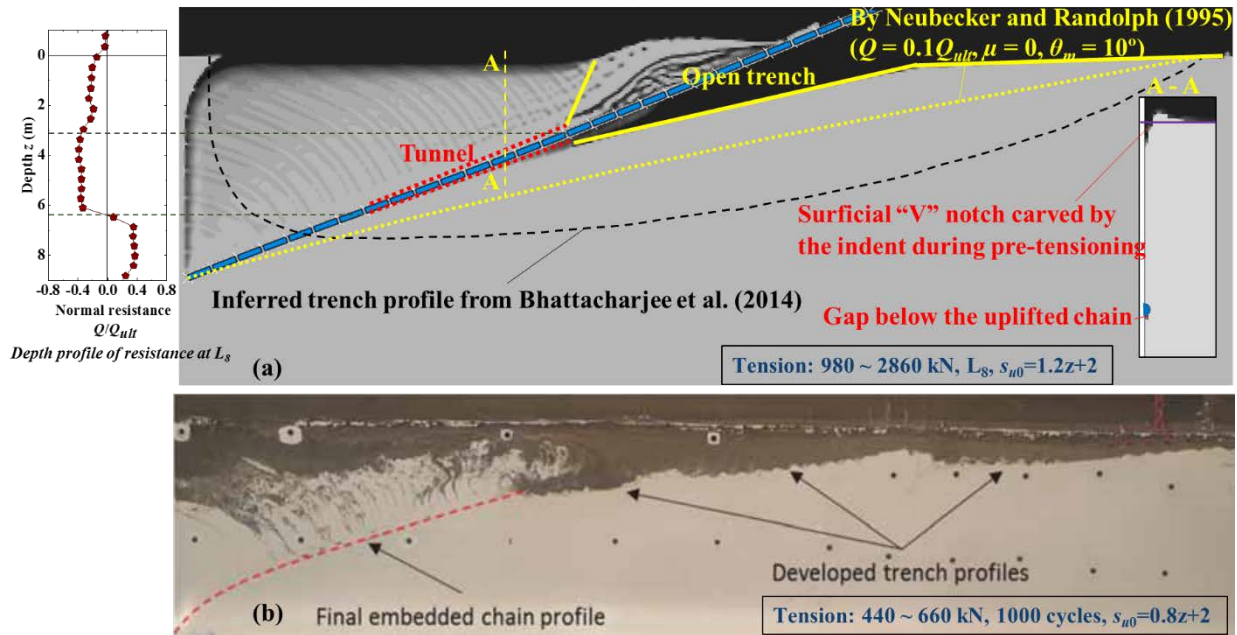
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