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#### 1 THE INFLUENCE OF A CYCLIC LOADING HISTORY ON SOIL-GEOGRID

#### 2 INTERACTION UNDER PULLOUT CONDITION

3 G. Cardile<sup>1</sup>, M. Pisano<sup>2</sup> and N. Moraci<sup>3</sup>

4 1 Assistant Professor of Geotechnical Engineering, Ph.D. — Mediterranea University of Reggio

5 Calabria, Department of Civil Engineering, Energy, Environment and Materials (DICEAM), Italy-

6 Telephone: +39 0965 169 2213; Telefax: +39 0965 1692201, e-mail: giuseppe.cardile@unirc.it

7 (corresponding author)

8 2 Research assistant in Geotechnical Engineering, Ph.D. — *Mediterranea* University of Reggio Calabria,

9 Department of Civil Engineering, Energy, Environment and Materials (DICEAM), Italy- Telephone: +39

10 0965 169 2223; Telefax: +39 0965 1692201, e-mail: marilene.pisano@unirc.it

11 3 Full Professor of Geotechnical Engineering, Ph.D. — *Mediterranea* University of Reggio Calabria,

12 Department of Civil Engineering, Energy, Environment and Materials (DICEAM), Italy- Telephone: +39

13 0965 169 2263; Telefax: +39 0965 1692201, e-mail: nicola.moraci@unirc.it

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#### 15 ABSTRACT

16 The knowledge of soil-geosynthetic interface behaviour is a key point in the design of 17 geosynthetic-reinforced soil structures. The pullout ultimate limit state can be 18 reproduced conveniently by means of pullout tests performed with large-size laboratory 19 apparatuses, which allow studying the interaction mechanisms that develop in the 20 anchorage zone. During the service life of geosynthetic-reinforced soil structures, 21 reinforcements may be subjected to long-term cyclic vehicular loads or short-term 22 seismic loads in addition to dead loadings, such as the structure's self-weight and other 23 sustained loads. In order to study the influence of a cyclic loading history (a sinusoidal 24 function with fixed amplitude A, number of cycles N and frequency f) on the post-cyclic 25 peak pullout resistance, the writers carried out a series of multi-stage pullout tests on a 26 high density polyethylene extruded uniaxial geogrid embedded in a compacted granular

soil for different vertical effective stress  $\sigma'_v$  values. Moreover, the stability of the soilgeosynthetic interface from a point of view linked to the cyclic loading application has also been investigated. Test results showed that the design pullout resistance parameters are affected by the applied cyclic loading history for specific combined conditions (*A*, *N* and  $\sigma'_v$ ) and it should be taken into account for designing geosynthetic reinforced soil structures.

33

KEYWORDS: geosynthetics, geogrid, pullout, cyclic loading, soil-reinforcement
 interface, multi-stage test, residual strain, design parameters, apparent coefficient of
 friction, viscous properties.

### 37 1 INTRODUCTION

38 Different approaches can be used to study the seismic behaviour of geosynthetic-39 reinforced soil (GRS) structures, ranging from empirical observations of damages 40 caused on GRS works by seismic events (Carrubba and Colonna, 2000; Huang et al., 41 2003; Koseki et al., 2006; Koseki et al., 2009; Ling and Leshchinsky, 2005; Ling et al., 42 2001; Tatsuoka et al., 1995, 1997; Wartman et al., 2006; White and Holtz, 1994) to the 43 results' interpretation of tests carried out on full-scale or reduced-scale physical models 44 (Capilleri et al., 2019; El-Emam and Bathurst, 2004; El-Emam and Bathurst, 2005; 45 Izawa et al., 2004; Ling et al., 2005; Matsuo et al., 1998; Nova-Roessig and Sitar, 2006; 46 Sabermahani et al., 2009; Watanabe et al., 2003), up to theoretical studies such as 47 pseudo-static analyses (Bathurst and Cai, 1995; Biondi et al., 2013; Michalowski, 1998; 48 Motta, 1996; Nouri et al., 2006), seismic displacement analyses (Ausilio et al., 2000; 49 Cai and Bathurst, 1996a, b; Di Filippo et al., 2019; Gaudio et al., 2018; Ling et al.,

50 1997; Michalowski and You, 2000; Paulsen and Kramer, 2004) and dynamic numerical 51 methods (Hatami and Bathurst, 2000; Lee et al., 2010; Ling et al., 2004). 52 One of the parameters necessary to design GRS works by using the pseudo-static 53 approach is the apparent coefficient of friction between soil and geosynthetic, which 54 allows determining the reinforcement length and consequently the reinforced block size 55 (Abramento, 1995; Carbone et al., 2015; Jewell, 1990; Leshchinsky, 2009; Leshchinsky 56 et al., 2014; Leshchinsky et al., 1995; Moraci and Cardile, 2008; Moraci et al., 2014; 57 Moraci and Recalcati, 2006; Pavanello et al., 2018). 58 The seismic displacement analyses are performance-based approaches that originate 59 from the Newmark's sliding block method (Newmark, 1965), assuming that the soil 60 mass moves as a rigid block along a potential sliding surface, with permanent 61 displacements occurring when the forces acting on it exceed the available shear 62 resistance. Whenever the ground acceleration overcomes the critical acceleration, the 63 rigid block's permanent displacement increases and it can be considered as a measure of 64 the possible damage caused by an earthquake. The friction interaction coefficient 65 between soil and reinforcement is required also in these cases. 66 The dynamic analysis uses numerical methods such as finite element, finite difference 67 and coupled finite element-discrete element methods, which need as input constitutive 68 models capable to reproduce the stress-strain relationships for soil, geosynthetics and 69 soil-reinforcement interfaces in the best way possible so as to provide accurate results. 70 Therefore, comprehension of the soil-geosynthetic interface behaviour is extremely 71 important whichever seismic method is chosen to design GRS structures. For this 72 purpose, it is necessary to analyse the soil-geosynthetic interaction in terms of pullout 73 resistance and displacement behaviour by using pullout tests under cyclic loading

74 conditions as the more suitable tool. As things stand, few researches studied these 75 aspects on different geosynthetics-granular soil interfaces generally subject to cyclic 76 loading at frequencies up to 0.5 Hz (Min et al., 1995; Moraci and Cardile, 2009, 2012; 77 Nayeri and Fakharian, 2009; Nernheim, 2005; Raju and Fannin, 1997; Razzazan et al., 78 2018; Yasuda et al., 1992). In this context, the paper aims to expand knowledge of the 79 cyclic and post-cyclic pullout behaviour of a high density polyethylene (HDPE) 80 extruded uniaxial geogrid embedded in a compacted granular soil subject to cyclic 81 pullout loading with a higher frequency (f=1 Hz), more representative of long-term 82 vehicular loads or short-term seismic loads, varying the cyclic load amplitude and the 83 vertical effective stress. To take into account cyclic or dynamic loads potentially acting 84 on GRS structures' reinforcements in addition to sustained loadings, the pullout tests 85 were carried out using a multi-stage procedure. The influences of cyclic tensile loading 86 amplitude A, number of cycles N and vertical effective stress  $\sigma'_{\rm v}$  on the parameters 87 obtained during hysteresis loops have been analysed in depth. Moreover, the difference 88 between post-cyclic and static peak pullout resistances has also been investigated by 89 comparing pullout curves for the multi-stage tests and those for the corresponding tests 90 at constant rate of displacement.

## 91 2 EXPERIMENTAL STUDY

#### 92 2.1 Apparatus

93 The test apparatus used in the research (Cardile et al., 2016a; Moraci and Recalcati,

- 94 2006) consists of different components (Figure 1a, b, c):
- i) a pullout steel box having large dimensions (1700x600x680 mm) and walls covered
- 96 with Teflon films to avoid friction effects;

- 97 ii) a rubber flexible membrane filled with air for the application of vertical loads;
- 98 iii) a hydraulic actuator for displacement- or load-controlled pullout testing for the
- 99 application of horizontal loads;
- 100 iv) a clamping system inside the box to maintain the reinforcement specimen always
- 101 confined for the whole duration of the test;
- 102 v) a pair of metal sleeves at the front wall to avoid its stiffness effects on results;
- 103 vi) a load cell for measuring the pullout force; and
- 104 vii) six linear variable displacement transducers (LVDT) connected to six different
- 105 points of the reinforcement's specimen by means of inextensible steel wires to measure
- 106 the specimen's displacements.
- 107 Unlike the apparatus used in previous researches, the new actuator is able to simulate
- 108 pullout cyclic loadings that can reach high frequencies (up to 4 Hz).

#### 109 2.2 Test materials

110 The soil used in this research is a uniform medium sand classified as SP and A-3

111 according to USCS (ASTM D2487, 2017) and UNI EN ISO 14688-1 (2018)

112 classification systems respectively, with grain shape ranging from sub-rounded to

- 113 rounded, uniformity coefficient (U) equal to 1.96, and average grain size  $(D_{50})$  equal to
- 114 0.32 mm. The compaction of soil inside the pullout box was carried out until reaching a
- 115 dry unit weight value equal to 95% of the maximum dry unit weight ( $\gamma_{\text{dmax}} = 16.24$
- 116 kN/m<sup>3</sup>, at an optimum water content  $w_{opt} = 13.5\%$ ) obtained by AASHTO T 99 (2015)
- 117 Standard Proctor compaction tests (ASTM D698-12e2, 2012; UNI EN ISO 13286-2,
- 118 2010). Direct shear tests, performed at  $\gamma_d = 95\% \gamma_{dmax}$ , yielded values of the soil peak
- shear-strength angle  $\phi'_P$  from 48° (for  $\sigma'_v = 10$  kPa) to 42° (for  $\sigma'_v = 100$  kPa). The soil

120 shear-strength angle at constant volume  $\phi'_{CV}$  was equal to 34° (Moraci and Recalcati,

121 2006).

122 The geosynthetic used in the pullout tests is an HDPE uniaxial extruded geogrid. Its 123 mechanical behaviour was investigated by means of wide-width tensile tests (Cardile et 124 al., 2016b; Cardile et al., 2017b) in the standard atmosphere for testing  $(20\pm2^{\circ}C)$  at 125 65+5% RH) at constant strain rate (CSR) equal to 20% per minute, using index test 126 procedures (ISO 10319:2015). Additional tensile tests at CSR equal to  $\varepsilon'=0.2\%$  per 127 minute were also carried out to make comparison with the rate used in pullout tests 128 carried out at constant rate of displacement. Table 1 lists the tensile test results at 129 constant strain rates equal to 20% and 0.2% per minute.

## 130 **2.3 Test procedure**

131 The multi-stage pullout tests were performed on geogrid specimens 1.20 m long, at

132 different vertical effective stresses ( $\sigma'_v = 10, 25, 50, 100$  kPa), by using a multi-stage

133 procedure (MS) consisting of three steps (Moraci and Cardile, 2009, 2012):

• a displacement-controlled stage at constant rate of displacement (CRD) equal to 1 mm

135 per minute, reaching a fixed pullout load  $P_i$ ;

• a load-controlled cyclic stage using a sinusoidal function, with a fixed tensile loading

137 amplitude *A* and frequency *f*=1 Hz, for *N*=1000 cycles in total;

• a post-cyclic stage that is a displacement-controlled stage at CRD=1 mm per minute

139 once again, until a maximum horizontal displacement equal to 100 mm, the specimen

140 pullout or its rupture was reached.

141 Both  $P_i$  and A were chosen as a percentage of  $P_R$  that is the peak pullout resistance (per

142 unit width) obtained by pullout tests under static conditions, carried out at the same

143 confining pressure and CRD=1 mm per min. Specifically,  $P_i \approx 35\% P_R$  was adopted for

144 the first one since it could be considered as an upper bound value (taking into account

surcharge, geometry, partial coefficients to be used for the reduction of the interface

146 parameters according to several international recommendations, etc.) for those

147 representative of GRS structures' design. Moreover, in order to investigate the influence

148 in changing the cyclic loading amplitude, two different A values ( $A \approx 30\% P_R$  and

149  $A \approx 45\% P_{\rm R}$ ) were chosen for the maximum loading level falling into the range between

150  $P_i$  and  $P_R$ .

151 Table 2 lists the MS pullout test program, highlighting that the actually-made cycles

152 were lower than the planned ones for the higher applied amplitude ( $A \approx 45\% P_R$ ) at

153  $\sigma'_v < 100$  kPa due to the achievement of the clamp maximum displacement allowed by

154 this apparatus.

155 **3 ANALYSIS OF TEST RESULTS** 

156 **3.1** Cyclic stability of soil-geogrid interface

157 Accumulation of permanent strains, which occurs cycle by cycle under application of 158 non-zero mean tensile stress (ratcheting), is observed on both soil and geosynthetics 159 when a cyclic load is applied (Alonso-Marroquín and Herrmann, 2004; Calvetti and di 160 Prisco, 2010; Cardile et al., 2016b; Cardile et al., 2017b; Kongkitkul et al., 2004; Ling 161 et al., 1998; Vieira and Lopes, 2013). Likewise wide-width cyclic tensile tests, the 162 application of cyclic pullout loads involves the development of hysteresis loops during 163 the cyclic stage. 164 A cyclically stable behaviour of the polymeric reinforcement obtained by means of

- 165 wide-width cyclic tensile tests (that is, increments of residual strain decrease with
- 166 increasing number of loading cycles, Cardile et. al, 2017b) is not sufficient to assure a

167	cyclically stable pullout behaviour of the interface soil-reinforcement since the cyclic
168	loading entails geogrid's deformation as well as its pullout from the soil.
169	In order to analyse these points, the parameters obtained for each load-unload cycle are
170	listed separately depending on the reference plane. Specifically, with regard to the $P$ - $\delta$
171	plane (pullout load versus displacement of the first confined section of specimen) they
172	are (Figure 2a):
173	• Cyclic displacement's increment measured at the first confined section of
174	specimen (the specimen head attached to the clamp) and reached during each
175	cyclic loading, $\Delta \delta^h_{part,i}$ ;
176	• Cumulative cyclic displacement of the specimen's first confined section,
177	$\Delta \delta^h_i = \sum_{i=1}^N \Delta \delta^h_{part,i}$ ;
178	• Cyclic displacement's increment measured at the rear end of the
179	specimen (the last transverse rib) and reached during each cyclic loading,
180	$\Delta oldsymbol{\delta}^{e}_{part,i}$ ;
181	• Cumulative cyclic displacement of the specimen's rear end,
182	$\Delta oldsymbol{\delta}^e_i = \sum_{i=1}^N \Delta oldsymbol{\delta}^e_{part,i} \ .$
183	Regarding the <i>P</i> - $\varepsilon$ plane (pullout load versus pullout average strain), the parameters
184	obtained are (Figure 2b):
185	• Residual strains caused by cyclic loading, $\varepsilon_r$ , i.e. when the cyclic loading
186	returns to the value of the fixed pullout load $P_i$ .
187	For each of these parameters, the influence of tensile loading amplitude $A$ , number of
188	cycles N and vertical effective stress $\sigma'_{v}$ has been investigated.

189 In order to analyse the behaviour at the soil-reinforcement interface, the conceptual 190 model proposed by Moraci and Cardile (2012) has been used by applying a double-191 graph that shows the relationship between the number of cycles N and  $\Delta \delta^h$  on the top 192 part, and between  $\Delta \delta^e$  and  $\Delta \delta^h$  on the bottom one (Figure 3, Figure 4 and Figure 5). 193 The graphic representations on the top part (Figure 3a, Figure 4a and Figure 5a) allow 194 understanding when the behaviour of soil-reinforcement interface is stable/unstable 195 from a point of view linked to the cyclic loadings application. For a fixed cyclic load 196 history, the cumulative cyclic displacement of the specimen's first confined section is 197 connected both to the residual strains of the geogrid, which occur cycle by cycle under 198 application of cyclic pullout stress, and to the progressive mobilisation of the interaction 199 mechanisms along the specimen that could induce pullout failure. 200 The writers define that the soil-reinforcement interface is cyclically stable when a 201 progressive stabilisation of the interface response is observed. Specifically, this means that the curve  $N - \Delta \delta^h$  is concave upward and the cyclic displacement's increments 202  $\Delta \delta_{nart i}^{h}$  decrease with increasing numbers of cycles: the displacement accumulation rate 203 204 decreases with increasing N. Nevertheless, it is important to observe that such a 205 cyclically stable condition could be engineeringly unacceptable if the cumulative 206 displacements during the cyclic stage are larger than the allowable displacement for the 207 serviceability limit state. 208 On the contrary, the soil-geogrid interface cyclic behaviour is cyclically unstable when the cyclic displacement's increments  $\Delta \delta_{part,i}^{h}$  become constant or start to increase with 209

210 increasing numbers of cycles. In the last case, the curve  $N - \Delta \delta^h$  has an inflection point

211 becoming concave downward that is, the displacement accumulation rate increases with

212 increasing *N*, potentially precipitating the achievement of the reinforcement's limit state

of failure due to insufficient interaction resistance under pullout conditions between soiland the reinforcement.

Regarding graphics on the bottom part (Figure 3b, Figure 4b and Figure 5b), they allow
defining more in detail when the soil-geogrid interface approaches the critical condition
of pullout failure during the cyclic phase, or rather when the reinforcement is in the:

- i) load transfer phase. During this phase the active length, that is the portion of
  the geogrid specimen on which the mobilisation of interaction mechanisms
  withstands the applied load (Cardile et al., 2016a), increases with the pullout
  force until this force reaches a limit value that causes the movement of the last
  transversal bar;
- ii) pullout phase. During this phase the rear end of the geogrid begins to move
  and the active length coincides with the entire length of the specimen plus its
  elongation;

226 iii) pullout limit state. This condition happens when the displacement • 227 increments of all specimen points are the same (geogrid stops to deform). Specifically, the reinforcement is in the load transfer phase when the curve  $\Delta \delta^e - \Delta \delta^h$ 228 evolves in parallel along the  $\Delta \delta^h$  x-axis for all cycles since the specimen's rear end is 229 230 immobile. On the contrary, the reinforcement is in the pullout phase when the curve evolves inside the  $\Delta \delta^e - \Delta \delta^h$  admissible area with cyclic displacement's increments of 231 232 the specimen's rear end that are lower than the corresponding cyclic displacement's 233 increment of the specimen's first confined section for all cycles. Finally, the reinforcement is in the pullout limit state when the curve  $\Delta \delta^e - \Delta \delta^h$  becomes parallel 234 235 with the boundary line between the admissible and inadmissible areas (the

displacement's increment of geogrid's head is equal to the displacement's incrementmeasured at the rear end for all the next cycles).

## 238 3.1.1 Effect of cyclic loading amplitude

239 In order to study the influence of loading amplitude *A*, the double-graph results of MS

240 pullout tests carried out with two different loading amplitudes ( $A \approx 30\% P_R$ , 45%  $P_R$ ) at

241 the equal value of  $P_i \approx 35\% P_R$  are plotted in Figure 3a,b and Figure 4a,b for

242  $\sigma'_v = 50$  kPa and  $\sigma'_v = 100$  kPa respectively; the results are representative of all the

cases observed in the research.

In Figure 3a (
$$\sigma'_v = 50$$
 kPa), when  $A \approx 30\% P_R$  it is possible to observe a cyclically

stable behaviour of the soil-reinforcement interface during all the cyclic stage since the

246 displacement accumulation rate decreases with increasing numbers of cycles. Referring

to the results obtained with  $A \approx 45\% P_{\rm R}$ , a cyclically unstable behaviour can be

248 observed since there is an inflection point after a certain number of cycles and  $\Delta \delta_{part,i}^{h}$ 

starts to increase with increasing N (the displacement accumulation rate increases). With

250 regard to the pullout condition, Figure 3b shows that when  $A \approx 30\% P_{\rm R}$  the  $\Delta \delta^e - \Delta \delta^h$ 

curve evolves inside the admissible area but not in parallel with the boundary line (that

is, the cyclic displacement's increment measured at the rear end is lower than the cyclic

displacement's increment of the geogrid's head for all cycles), entailing that even the

last transversal rib moved; therefore, the geogrid reached the pullout phase. Instead,

255 when  $A \approx 45\% P_{\rm R}$ , an unstable pullout behaviour arises as the  $\Delta \delta^{e} - \Delta \delta^{h}$  curve

becomes parallel with the boundary line after a certain number of cycles and pullout

257 failure occurs ( $\Delta \delta_{part}^e = \Delta \delta_{part}^h$ ).

For soil-geogrid interface tested at  $\sigma'_v = 100$  kPa, a cyclically stable behaviour is noticed for both cyclic amplitudes (Figure 4a); specifically,  $\Delta \delta^h$  tends to settle towards a constant value with increasing numbers of cycles. Instead, the behaviour in terms of

261 pullout condition is different, in fact while the geogrid is in the pullout phase when

- 262  $A \approx 45\% P_{\rm R}$ , it is still in the load transfer phase when  $A \approx 30\% P_{\rm R}$  (Figure 4b) since the
- 263 curve evolves in parallel along the  $\Delta \delta^h x$ -axis for all cycles ( $\Delta \delta^e = 0$ ).

264 Therefore, with regard to the loading amplitude influence it is possible to state that, N

265 being equal, the slope of  $N - \Delta \delta^h$  decreases with increasing loading amplitude: for

266 cyclically stable interfaces, the ideal condition of  $\Delta \delta^h$  being constant (the displacement

accumulation rate is null) is reached for a number of cycles gradually decreasing with

268 decreasing applied loading amplitude, while for cyclically unstable interfaces it is

reasonable to expect that the number of cycles at which the displacement accumulation

270 rate becomes constant, or a change in the direction of curvature occurs, decreases with 271 increasing loading amplitude. In other words, the cyclic pullout behaviour of the soil-

271 increasing loading amplitude. In other words, the cyclic pullout behaviour of the soil-

272 geogrid interface starts getting worse with increasing cyclic loading amplitude.

## 273 3.1.2 The role of vertical effective stresses

274 To evaluate the influence of the vertical effective stress  $\sigma'_{v}$  applied to the soil-geogrid 275 interface, the strain behaviour has been investigated analysing MS pullout tests carried 276 out with loading amplitude  $A \approx 45\% P_R$  (the MS pullout tests at  $A \approx 30\% P_R$  are omitted 277 as they showed a similar behaviour). By observing the top part of Figure 5, the only 278 cyclically stable behaviour is obtained for  $\sigma'_v = 100$  kPa. For all the other vertical 279 effective stresses applied, when the inflection point arises the cyclic displacement's 280 increment of the specimen's head starts to increase until pullout failure. 281 On the bottom part of Figure 5 the relationship between the cumulative cyclic

displacements of the specimen's first confined section,  $\Delta \delta^h$ , and the cumulative cyclic

283 displacements of the specimen's rear end,  $\Delta \delta^{e}$ , shows an unstable behaviour in terms of

pullout condition for  $\sigma'_v = 10$ , 25 and 50 kPa since their representative curves become parallel with the boundary line between the admissible and inadmissible areas for a number of cycles that increases with increasing  $\sigma'_v$ . When  $\sigma'_v = 100$  kPa the interface is still in the pullout phase. Therefore, it is possible to observe that the increase of the vertical effective stress  $\sigma'_v$  plays a clear stabilising role.

## 289 **3.2** Residual strains and comparison with in-air results

290 Another important parameter to study the cyclic strain behaviour of the soil-

291 geosynthetic interface is the residual strain  $\varepsilon_r$ , defined as the cumulative deformation

292 mobilised in the specimen at the end of each corresponding cycle (when the cyclic

loading returns to P<sub>i</sub>), in agreement with Figure 2b. This parameter allows taking into

account the confined stiffness of the geogrid, which exhibits a different response

depending on geogrid's geometry, soil type, initial stress state and cyclic loading

history.

297 The influence of the vertical effective stress and cyclic loading amplitude is showed in 298 Figure 6a, where the residual strain (evaluated for the entire length of the geogrid, i.e. 299 apparent strain) reached at N = 10 is plotted versus the vertical effective stress for tests 300 performed at  $A \approx 30\%$   $P_{\rm R}$  and  $A \approx 45\%$   $P_{\rm R}$ . The results highlight that the residual strain 301 increases non-linearly with increasing vertical effective stress and,  $\sigma'_v$  being equal, it 302 increases with increasing loading amplitude. The choice to plot the residual strains at 303 cycle N = 10 is because tests with  $A \approx 45\% P_{\rm R}$  do not complete all cycles since pullout 304 occurred and the clamp reached the maximum displacement allowed by the apparatus, 305 as it can be observed in Figure 6b. The latter graph displays the residual strain  $\varepsilon_r$  for 306 varying numbers of cycles on a logarithmic scale, for tests carried out with loading 307 amplitude  $A \approx 45\%$  P<sub>R</sub> at different vertical effective stress values. It is possible to

308 observe that the residual strain  $\varepsilon_r$  increases with increasing numbers of cycles and, *N* 309 being equal, increases with increasing vertical effective stress. Moreover, the number of 310 cycles where the interface exhibits an instable behaviour decreases with decreasing  $\sigma'_v$ 311 (*N* = 158, 148, 20 for  $\sigma'_v = 50$ , 25, 10 kPa respectively).

312 Kongkitkul et al. (2004) stated that, for the geosynthetic reinforcement types examined 313 by them (such as the HDPE geogrids of this research), the residual strain developed 314 during a certain cyclic loading history is basically due to the loading rate effects caused 315 by the intrinsic viscous properties of the material (therefore, it is controlled by the total 316 period of cyclic loading). The nature of this residual strain is essentially the same as for 317 creep strain developing under an equivalent sustained load. The current research allows 318 studying how the soil confinement affects geogrids strain. Figure 6b points out that for 319  $\sigma'_{\rm v}$  ranging from 10 to 50 kPa the  $\varepsilon_r$  - N curve deviates from linearity in the semi-320 logarithmic graph: the strain accumulation rate starts to increase in correspondence with 321 a certain number of cycles that increases with increasing vertical effective stress, 322 highlighting viscous effects similar to the "tertiary creep" phenomenon observed in 323 tensile creep tests, that imply a possible tensile rupture of the reinforcement in case 324 pullout failure does not occur first, such as in this research. Instead, when  $\sigma'_{v} = 100$  kPa 325 the change in  $\varepsilon_r$  trend is missing since the soil confinement employs a positive effect 326 (Bathurst et al., 2004; Carrubba et al., 2000; Franca and Bueno, 2011; Kongkitkul et al., 327 2007a, b; Tatsuoka, 2008) increasing the range of numbers of cycles where the strain 328 accumulation rate remains constant (as for the secondary creep phase under sustained 329 tensile loads).

Afterwards, by considering the soil-geogrid interface tested at  $\sigma'_v = 100$  kPa and

331  $A \approx 30\% P_{\rm R}$ , 45%  $P_{\rm R}$  for which a progressive stabilisation of the interface response has

332 been observed, a comparison between their results and those obtained by wide-width 333 tensile multi-stage tests (Cardile et al., 2017b) has been made. In-air tensile tests 334 procedure was similar to the pullout one, with three different stages (two displacement-335 controlled tensile stages separated by one load-controlled cyclic stage) at the same test 336 conditions (in terms of rate of displacement, P<sub>i</sub>, A, N and f). It is more proper to analyse 337 residual strains taking into account the progressive failure mechanisms related to the 338 extensibility of the reinforcement under soil confinement; as a matter of fact, by 339 evaluating individually the residual strains of geogrid's different sections (from a 340 transversal rib to another), the results change remarkably. Figure 7 shows the residual 341 strains evaluated in the cyclic phase of the MS pullout tests for (i) the entire length of 342 the geogrid (residual apparent strains), and (ii) the geogrid's monitored portion closer to 343 its head for varying number of loading cycles at  $\sigma'_v = 100$  kPa,  $A \approx 30\%$  P<sub>R</sub> (Figure 7a) 344 and  $\sigma'_{\rm v} = 100$  kPa,  $A \approx 45\% P_{\rm R}$  (Figure 7b), and the comparison with the corresponding 345 wide-width MS tensile test (Cardile et al., 2017b). This comparison is possible only 346 because the high soil confinement (100 kPa) is preventing the pullout failure, allowing 347 the increase of the applied tensile load. The tensile load applied at the geogrid's head 348 decreases along the specimen until it becomes null (the interaction mechanisms are 349 progressively mobilised on the active length). 350 The shape of the distribution curve representing the tensile stresses along the interface

351 can be very complex, depending on: (i) boundary conditions, (ii) soil mechanical

352 characteristics, and (iii) structural, geometrical and mechanical characteristics of the

reinforcement (Bathurst and Ezzein, 2017; Cardile et al., 2014; Cardile et al., 2016a;

Moraci et al., 2017; Rahmaninezhad et al., 2019; Roodi and Zornberg, 2017; Wang et

al., 2016).Simplifying the stress curve with a triangular distribution, a comparison

356 between the in-air residual strain and the pullout residual strain evaluated for the 357 geogrid's monitored portion closer to its head can be made, as for the latter the load 358 acting on this portion is comparable with the one acting on the entire geogrid in the 359 wide-width MS tensile test (that is, the trapezoidal distribution of tensile stresses along 360 the analysed portion is comparable to a rectangular distribution with a value slightly 361 lower than the in-air one). In particular, this comparison highlights that the geogrid's 362 head strains are much higher than those obtained by in-air multi-stage tensile tests, with 363 increments at N = 1 and N = 1000 ranging from 305% to 107% for  $A \approx 30\%$  P<sub>R</sub> (Figure 364 7a) and from 258% to 84% for  $A \approx 45\%$  P<sub>R</sub> (Figure 7b) respectively. Since the load is 365 similar, this result is probably ascribable to the average test rate of pullout MS tests 366 being lower due to the soil confinement. In fact, while in the in-air tests the average test 367 rate of MS phase is almost the same for the all the points of the extensible specimen, in 368 the pullout tests the rate of MS phase decreases from the head to the free rear end due to 369 the soil confinement; therefore, this lower average test rate causes higher residual 370 strains, owing to the HDPE viscous behaviour. In the same graph, the pullout apparent 371 strains evaluated for the entire length of the geogrid are also plotted; at these conditions, 372 under the simplifying hypothesis of a triangular distribution the load acting on the 373 specimen on average is equal to a half of the load applied to the geogrid's head, acting 374 constantly along the specimen. Since both graphs (Figure 7a,b) show that the apparent 375 residual strain values are similar to those obtained by in-air MS tensile tests, it is 376 possible to state that the effects of the reduction in loading application rate during the 377 confined tests (which entail higher strains) compensate for the effects of decrease in 378 loading acting on average (which, by contrast, entail lower strains).

#### 379 **3.3** Effect of cyclic loading history on pullout resistance

380 The influence of cyclic loading history on the pullout behaviour has also been 381 investigated by comparing the pullout curves for the MS tests and those for the 382 corresponding CRD tests. The comparison is reported in Figure 8a,b for the MS pullout 383 tests at  $\sigma'_{\rm v} = 50$  kPa, with loading amplitudes equal to  $A \approx 30\% P_{\rm R}$  and  $A \approx 45\% P_{\rm R}$ 384 respectively; these tests are qualitatively representative of all those performed. The 385 pullout forces have been obtained subtracting, at the same displacement value, those 386 from tests carried out without the geogrid in order to eliminate the soil-clamp friction. 387 While in the test performed at  $A \approx 45\%$   $P_{\rm R}$  and  $\sigma'_{\rm v} = 50$  kPa the geogrid has achieved 388 the total horizontal displacement (100 mm) when N = 158 (Figure 8b), ergo the postcyclic stage being not allowed, in the test at  $A \approx 30\% P_{\rm R}$  and  $\sigma'_{\rm v} = 50$  kPa the soil-389 390 geogrid interface exhibits a cyclically stable behaviour, although it provides pullout 391 resistance values that are lower than those obtained in the CRD test carried out at the 392 same test condition (Figure 8a). Moreover, by observing the MS curve of Figure 8a it is 393 possible to highlight that the soil-geogrid interface still exhibits a very high tangent 394 stiffness when the post-cyclic stage starts, despite its test rate is lower than the one of 395 cyclic stage, where it is considerably higher on average in order to ensure the intended 396 loading amplitude. After that, the soil-geogrid interface stiffness decreases up to the 397 values obtained for the same displacement in the corresponding CRD pullout test. 398 Therefore, the interface exhibited a yielding phase, in agreement with the results of 399 Hirakawa et al. (2003) for geosynthetics tested in-air. 400 Afterwards, the remaining comparisons for all the vertical effective stresses investigated have been expressed in terms of post-cyclic peak pullout resistance  $P_{\rm R}^{\rm PC}$  (interface's 401 peak pullout resistance obtained in the MS third stage). Figure 9a illustrates  $P_{\rm R}^{\rm PC}$  values 402

403 obtained in all MS tests with  $A \approx 30\% P_{\rm R}$  normalised with respect to  $P_{\rm R}$ , for varying the 404 vertical effective stress. These results suggest that cyclic loading histories induce a 405 reduction in peak pullout resistance that increases with decreasing vertical effective 406 stresses. For these specific test conditions, the post-cyclic peak pullout resistance 407 reaches decreases up to about 28% compared to the values obtained in monotonic 408 pullout tests at the same test conditions. The higher decrease has been measured at the 409 lower investigated  $\sigma'_{v}$ , while post-cyclic pullout resistance remains almost equal to the 410 corresponding static value at the higher  $\sigma'_{v}$ . To analyse the effects of cyclic loading on the peak apparent coefficient of friction between soil and geosynthetic,  $\mu^P_{s/GSY}$ , generally 411 used in the design of reinforced earth structures, the comparison between  $\mu^{P}_{s/GSY}$ 412 evaluated under post-cyclic conditions ( $A \approx 30\% P_R$ ) and  $\mu_{s/GSY}^P$  obtained by means of 413 414 CRD pullout tests is plotted in Figure 9b for soil-geogrid interface tested at different vertical effective stresses. The experimental results show that the post-cyclic  $\mu_{s/GSY}^{P}$ 415 416 decreases with increasing  $\sigma'_{v}$ , as well as the apparent coefficient of friction under static 417 conditions, due to soil dilatancy at the interface. Moreover,  $\sigma'_{v}$  being equal, the apparent 418 coefficient of friction between soil and geosynthetic under post-cyclic conditions 419 decreases due to the effects of cyclic loading: the lower the vertical effective stress, the 420 higher the decrease (specifically, the reductions are equal to 28%, 16%, 5% and 2% for 421  $\sigma'_{\rm v} = 10, 25, 50$  and 100 kPa respectively). This result is very important as pullout limit 422 state mainly affects the shallow reinforcement levels; therefore, if this decrease is not 423 taken into account, the earth works reinforced with geosynthetics could be wrongly 424 designed.

425 To better explain the reduction of the interface design parameters in post-cyclic 426 conditions, pullout loading P for varying pullout average strain  $\varepsilon$  for the i) CRD tests 427 carried out at all the investigated  $\sigma'_{v}$  (Figure 10a); ii) the MS tests performed at 428  $\sigma'_{\rm v} = 100$  kPa,  $A \approx 30, 45\% P_{\rm R}$  and the corresponding CRD test (Figure 11a); and iii) 429 the MS tests performed at  $\sigma'_v = 50$  kPa,  $A \approx 30\%$  P<sub>R</sub> and the corresponding CRD test 430 (Figure 12a) has been plotted. Before to comment these curves, it is necessary to start 431 by making a clarification: the application of cyclic tensile loading histories on geogrids 432 tested in-air do not induce a material degradation resulting in the reduction of the 433 geosynthetic's tensile strength, according to previous researches (Cardile et al., 2017b; 434 Kongkitkul et al., 2004; Vieira and Lopes, 2013). The main goal of the present research 435 is to comprehend whether or not the behaviour under cyclic pullout conditions (hence in 436 confined conditions) involves a degradation for the soil-geogrid interface resulting in 437 the reduction of the interface parameters (therefore, a reduction of the pullout 438 resistance). For this purpose, the P -  $\varepsilon$  curves (Figure 10a, Figure 11a, Figure 12a) have 439 been plotted to represent the reinforcement's behaviour under soil confinement 440 condition (for fixed specimen length, test rate and temperature). The soil-geogrid 441 interaction provides  $P - \varepsilon$  curves that are different for varying the pullout loading 442 conditions (monotonic or cyclic) and the vertical effective stress due to both soil 443 dilatancy at the interface and the reinforcement extensibility (i.e., stiffness).  $P - \varepsilon$  curves 444 can relate to  $\delta$  -  $\varepsilon$  curves (Figure 10b, Figure 11b, Figure 12b) in order to link the 445 displacement of the specimen's first confined section  $\delta$  to the corresponding pullout 446 average strain value caused by a certain pullout load, for a fixed vertical effective stress. 447 With regard to CRD pullout tests (Figure 10b), when the soil-geogrid interface is in the 448 load transfer phase the  $\delta$ -  $\varepsilon$  curve exhibits a pseudo-linear trend ( $\sigma'_{\rm v} = 100$  kPa), which

tends to curve during the pullout phase ( $\sigma'_v = 10, 25, 50$  kPa) until reaching a vertical asymptote for pullout failure (constant average strain with increasing  $\delta$ ).  $\delta - \varepsilon$  slope clearly depends only on test rate when the soil-geogrid interface is in the load transfer phase. Once the pullout phase starts,  $\delta - \varepsilon$  slope depends even on  $\sigma'_v$  since the pullout resistances decrease with decreasing  $\sigma'_v$  (Figure 10a).

454 In pullout multi-stage tests, the first outcome arising from the observation of point 5 455 versus point 1 in Figure 11b and Figure 12b is that the cyclic loading application caused 456 both a higher geogrid's deformation (due to the geogrid's viscous effects resulting from 457 the application of a loading that can be considered constant on average over time) and a 458 higher head's displacement, with the MS  $\delta$ -  $\varepsilon$  slope of the cyclic stage increasing with 459 increasing loading amplitude (pointed out in Figure 11b by means of an arrow-shaped 460 object). This means that the displacements of geogrid's internal points (along the length 461 of the specimen) at the beginning of the MS third phase (point 5) are higher than those 462 mobilised at the same pullout load level  $P_i$  (point 1) in the corresponding static test. For 463 a better knowledge, a qualitative trend is plotted in Figure 11c and Figure 12c (square c-464 1): by comparing them, the lower the vertical effective stress, the higher the 465 displacements. These representations allow understanding how these higher 466 displacements obtained under cyclic loading move the interface towards a configuration 467 closer to pullout failure than the corresponding static test. 468 By analysing the third stage, Figure 11b and Figure 12b show that the MS  $\delta$ - $\varepsilon$  curve at 469 the beginning of this phase restarts with a trend similar to the one of CRD  $\delta$ - $\varepsilon$  curve at

470 the same strain level  $\varepsilon_{0-2} = \varepsilon_{0-5}$  (point 5 versus point 2): trends get back similar as both

471 are now displacement-controlled pullout tests at the same test rate. Specifically, it looks

472 like the CRD  $\delta \varepsilon$  curve shifts down (path 5-7) of an amount  $\delta_{2-5}$  equal to the difference

473 between the cyclic ( $\delta_{1-5}$ ) and the static ( $\delta_{1-2}$ ) displacements of the specimen's first 474 confined section reached at the same pullout average strain level (Figure 12b). 475 Moreover, during the third stage the interface tries again to mobilise the same pullout 476 strength that it would have mobilised if the cyclic stage hadn't occurred (reinforcement 477 has no degradation per se), showing a hardening curve (incremental pullout stiffness in 478 the path 5-6b is higher than the one in path 2-4, Figure 11a and Figure 12a). However, 479 this could be not possible since the cyclic loading contributed to use up more quickly 480 the geogrid's portion on which the mobilisation of the interaction mechanisms 481 withstands the applied load; that is, these cyclic loading effects (pointed out in Figure 482 11b and Figure 12b by means of an arrow-shaped object) could lead the interface a little 483 bit closer to the pullout failure, compared to an entirely monotonic loading. In fact, if 484 the development of the interaction mechanisms along the geogrid hadn't gone further, 485 the MS  $\delta$ -  $\varepsilon$  curve would have followed the "ideal" trend (dash-dot line in path 5-7, 486 Figure 12b), i.e. the difference between MS and CRD displacements of the specimen's 487 first confined section reached at the same pullout average strain level would have 488 continued to be always  $\delta_{2-5}$  (caused by the cyclic load application). Instead, the actual 489 MS  $\delta$  -  $\varepsilon$  curve deviates from the "ideal" path 5-7 due to the cyclic loading effects, 490 which cause the interface degradation; this means that the geogrid starts to deform 491 fewer when a certain head's displacement is reached, mobilising a lower pullout 492 strength. 493 These cyclic loading effects can be appreciate better by considering the displacements 494 qualitative distribution of the geogrid's internal points when  $\delta = 100$  mm has been 495 reached: Figure 11c and Figure 12c, square c-2 show that the displacements of the

496 geogrid's internal points representing 6b are higher than those representing 6a, and this

497 result is because the cyclic loading pushed towards the pullout process; in other words, 498 the geogrid starts to deform fewer approaching the pullout limit state earlier. Clearly, 499 the smaller the displacements of the geogrid's internal points, the more ideal the  $\delta - \varepsilon$ 500 trend.

501 Summarising, to reach the pullout average strain corresponding to the peak pullout 502 resistance  $P_{\rm R}$  obtained under static conditions is theoretically always possible, unless 503 pullout failure occurs first (vertical asymptote). This assertion can be explained by 504 considering a fictitious extension of the MS  $\delta$ - $\varepsilon$  curve (dashed lines, Figure 11b and 505 Figure 12b): the soil-geogrid interface has to make a further head's displacement in 506 order to achieve  $P_{\rm R}$  (i.e. the interface can mobilise  $P_{\rm R}$  with a head's displacement 507 greater than the one under static condition). For instance, the interface tested at 508  $\sigma'_{\rm v} = 100$  kPa would mobilise  $P_{\rm R}$  with both the investigated amplitudes in case it could 509 carry out the further increment plotted in Figure 11b ( $\delta_{6b-8}$  for  $A \approx 30\% P_R$  and  $\delta_{6'b-8'}$  for 510  $A \approx 45\%$  P<sub>R</sub> respectively). This result affects the peak apparent coefficient of friction between soil and geosynthetic; in fact,  $\mu_{s/GSY}^{P}$  (Figure 9b) evaluated under post-cyclic 511 512 conditions ( $A \approx 30\% P_{\rm R}$ ) is almost equal to the one obtained in the corresponding static 513 pullout test for  $\sigma'_v = 100$  kPa (only a very slight degradation of the interface occurred). 514 In case the limitation due to the clamp maximum displacement allowed by the 515 laboratory apparatus does not exist, the soil-geogrid interface analysed in this research 516 can mobilise  $P_{\rm R}$  at  $\sigma'_{\rm v} = 100$  kPa even under post-cyclic loading with amplitudes up to 517  $A \approx 45\% P_{\rm R}$ .

518 Instead, for the interface at  $\sigma'_v = 50$  kPa to reach the pullout average strain

519 corresponding to  $P_{\rm R}$  is more difficult as the head's displacement to be done is much

520 higher (this increasing with decreasing vertical effective stress): the MS  $\delta$ -  $\varepsilon$  trend is

521 curved (as well as the CRD one) as the pullout phase has been reached (Figure 12b) and 522 the displacements of the geogrid's internal points (6b trend in Figure 12c, square c-2) 523 are pushing further towards the achievement of pullout failure (that is, the cyclic loading 524 degraded the interface). This means that the pullout loading cannot increase further and, 525 consequently,  $\mu_{s/GSY}^{P}$  evaluated under post-cyclic conditions is lower than  $\mu_{s/GSY}^{P}$ 526 obtained in the corresponding CRD pullout test.

527

### 528 3.4 Nodal displacements

529 Finally, in order to explain the different behaviour of the soil-reinforcement interface 530 when the cyclic loading generates a load transfer mechanism or the pullout failure, the 531 actual distributions of the transversal rib displacements along the geogrid for different 532 numbers of cycles have been plotted in Figure 13a,b, for  $A \approx 30\% P_R$  and 533  $\sigma'_{\rm v} = 10$  and 100 kPa respectively. In Figure 13a, for vertical effective stress equal to 534 10 kPa, it is possible to observe that the reinforcement almost reached the pullout limit 535 state during the cyclic stage (two adjacent curves are parallel to each other), with the 536 third stage still being allowed (as the reached head's displacement is lower than 100 537 mm). This means that the cyclic loading entailed a significant reduction of the pullout 538 resistance during the CRD third stage, caused by higher displacements along the 539 geogrid that pushed towards the pullout failure. Since the mobilised soil shear-strength 540 angle depends on soil-geogrid relative sliding, the interaction mechanisms along the 541 interface's points (Bergado et al., 1993; Calvarano et al., 2014; Cardile et al., 2017a; 542 Dyer, 1985; Jacobs et al., 2014; Moraci et al., 2017; Palmeira, 2009; Sieira et al., 2009; 543 Zhou et al., 2012; Ziegler and Timmers, 2004) mobilised pullout strengths lower than 544 those mobilised under static conditions. These values are as close as possible to the

545 lowest that can be reached under static conditions, i.e. they are characteristic of the 546 residual phase in the pullout static curve at  $\sigma'_{v} = 10$  kPa (strain-softening pullout 547 behaviour at lower  $\sigma'_{v}$  as shown in Moraci and Recalcati, 2006). On the other hand, for 548  $\sigma'_{\rm v} = 100$  kPa, the reinforcement is still in the load transfer phase when the cyclic stage 549 is over: the interaction mechanisms developed a pullout mechanism along the active 550 length that is markedly progressive (Figure 13b). In this case, a "supply" of resistance is 551 still available in the post-cyclic stage for all the above reasons. The interaction 552 mechanisms mobilised strength values almost equal to  $P_{\rm R}$ , which happens to coincide 553 with the ultimate resistance that can be reached, as the CRD curve at  $\sigma'_v = 100$  kPa 554 exhibits a strain-hardening pullout behaviour (typical of higher vertical effective 555 stresses as shown in Moraci and Recalcati, 2006).

#### 556 4 CONCLUSIONS

The paper deals with the results of several pullout tests carried out on an HDPE geogrid-granular soil interface subjected to multi-stage loading conditions and different vertical effective stresses ( $\sigma'_v = 10, 25, 50, 100$  kPa). Cyclic and post-cyclic conditions were investigated by means of a multistage procedure, applying different cyclic loading histories characterised by a high frequency (*f*=1 Hz).

To define when the behaviour of soil-reinforcement interface is stable/unstable from a point of view linked to the cyclic loadings application, a criterion has been established. The results have showed that the soil-geogrid interface behaviour is dependent on both the cyclic loading amplitude and vertical effective stress. The stability of soil-geogrid interface during the cyclic phase starts getting worse with increasing cyclic loading 567 amplitude, entailing the possible achievement of the pullout limit state, while the 568 increasing of the vertical effective stress  $\sigma'_{\rm v}$  plays a stabilising role. 569 The analysis of the cumulative strain mobilised in the specimen at the end of each 570 corresponding cycle highlighted that it increases with increasing cyclic loading 571 amplitude and numbers of cycles and, N being equal, increases with increasing vertical 572 effective stress. By comparing the results of residual strain evaluated for the geogrid's 573 monitored portion closer to its head with those obtained by wide-width tensile multi-574 stage tests, the pullout cyclic residual strain happens to be higher since the average test 575 rate of pullout MS tests is lower due to the soil confinement. 576 With regard to pullout resistances, the results have showed that cyclic loading histories 577 can involve a reduction of the interface parameters considering a certain combination of 578 vertical effective stress and cyclic loading amplitude A, for the investigated frequency: 579 the lower the vertical effective stress, the higher the reduction, A being equal. For the 580 specific test conditions, the post-cyclic peak pullout resistance reaches decreases up to

581 28% at the lower  $\sigma'_{v}$  investigated, while it remains almost equal to the corresponding 582 monotonic value at the higher  $\sigma'_{v}$ .

583 The decreasing of the interface parameters can be explained by the progressive pullout 584 mechanism of the soil-geogrid interface: the load is transferred on a geogrid's portion 585 that increases quickly during the cyclic phase, involving a reduction of the "supply" of 586 pullout resistance during the post-cyclic phase that increases with decreasing vertical 587 effective stress and with increasing cyclic loading amplitude. To reach the static peak 588 pullout resistance  $P_{\rm R}$  is theoretically always possible even under cyclic conditions, 589 unless pullout failure occurs: the interface can mobilise  $P_{\rm R}$  with a head's displacement 590 greater than the one under static condition.

591	The preferred option to design GRS structures in the best way possible would be to use
592	peak apparent coefficients of friction between soil and geosynthetic, $\mu_{s/GSY}^{P}$ , varying
593	with the depth where the reinforcement is embedded. If it be so, since pullout limit state
594	mainly affects the shallow reinforcement levels, the $\mu^P_{s/GSY}$ reduction arising under
595	possible cyclic loading has to be taken into account. Specifically, the lower the vertical
596	effective stress, the higher the reduction.
597	

List of notation			
A	Cyclic tensile loading amplitude (kN/m)		
CRD	Constant rate of displacement (mm/min)		
CSR	Constant strain rate (%/min)		
$D_{50}$	Average grain size (mm)		
f	Frequency of cyclic load (Hz)		
GRS	Geosynthetic-reinforced soil (-)		
HDPE	High-density polyethylene (-)		
$J_{ m sec2\%}$	Secant tensile stiffness at 2% strain (0.2%/min strain rate) (kN/m)		
$J_{ m sec2\%(ISO)}$	Secant tensile stiffness at 2% strain (20%/min strain rate, STANDARD ISO 10319) (kN/m)		
$L_{R}$	Length of geogrid (m)		
MS	Multi-stage (-)		
Ν	Number of cycles (-)		
Р	Pullout load per unit width (kN/m)		
$P_i$	Pullout load (per unit width) representative of serviceability conditions (kN/m)		
$P_{R}$	Peak pullout resistance (per unit width) obtained by pullout tests under static conditions (kN/m)		
$P_{R}^{PC}$	Peak pullout resistance (per unit width) obtained by pullout tests under multi-stage conditions (kN/m)		
RH	Relative humidity (%)		
$T_{\rm max}$	Maximum tensile strength per unit width (monotonic test at 0.2%/min strain rate) (kN/m)		
$T_{\max(\mathrm{ISO})}$	Maximum tensile strength per unit width (monotonic test at 20%/min strain rate, STANDARD ISO 10319) (kN/m)		
U	Uniformity coefficient (-)		
W <sub>opt</sub>	Optimum water content (%)		
γ <sub>d</sub>	Dry unit weight (kN/m <sup>3</sup> )		
$\gamma_{d \max}$	Maximum dry unit weight (kN/m <sup>3</sup> )		
δ	Displacement of the first confined section of specimen (mm)		
$\Delta \delta^e_i$	Cumulative cyclic displacement of the specimen's rear end (mm)		
$\Delta \delta^h_i$	Cumulative cyclic displacement of the specimen's first confined section (mm)		
$\Delta {\cal S}^{e}_{{ m part},i}$	Cyclic displacement's increment of the specimen's rear end reached during each cyclic loading (mm)		
$\Delta \delta^h_{_{part,i}}$	Cyclic displacement's increment of the specimen's head reached during each cyclic loading (mm)		

	Е	Pullout average strain (%)
	$\mathcal{E}_{\max}$	Tensile strain for $T_{ m max}$ (monotonic test at 0.2%/min strain rate) (%)
	$\mathcal{E}_{\max{(ISO)}}$	Tensile strain for $T_{ m max(ISO)}$ (monotonic test at 20%/min strain rate, STANDARD ISO 10319) (%)
	E <sub>r</sub>	Residual strains caused by cyclic loading when the cyclic loading returns to Pi (%)
	ε'	Strain rate (%/min)
	$\mu^{P}_{S/GSY}$	Peak apparent coefficients of friction between soil and geosynthetic (-)
	$\sigma_{v}$	Vertical effective stress (kN/m <sup>2</sup> )
	$\phi_{n}^{'}$	Soil peak shear-strength angle (°)
	$\phi_{cv}$	Soil shear-strength angle at constant volume (°)
59	9	

## 600 Tables

$T_{\max(ISO)}$	$T_{\rm max}$	$\mathcal{E}_{\max(ISO)}$	$\mathcal{E}_{\max}$	$J_{ m sec  2\%(ISO)}$	$J_{ m sec2\%}$
[kN/m]	[kN/m]	[kN/m]	[kN/m]	[kN/m]	[kN/m]
$(\varepsilon' = 20\%)$	$(\varepsilon' = 0.2\%)$	$(\varepsilon' = 20\%)$	$(\varepsilon' = 0.2\%)$	$(\varepsilon' = 20\%)$	$(\varepsilon' = 0.2 \%)$
per minute)	per minute)	per minute)	per minute)	per minute)	per minute)
159	103.5	12.2	14.5	2454	1525

602

Test	N (planned)	N (actually- made)	σ <sub>ν</sub> [kPa]	$P_i$ [kN/m]	A [kN/m]
01	1000	1000	10	$\approx$ 35% P <sub>R</sub> (10 kPa)	$\approx 30\% P_R (10 \text{ kPa})$
02	1000	20	10	$\approx$ 35% P <sub>R</sub> (10 kPa)	$\approx$ 45% P <sub>R</sub> (10 kPa)
03	1000	1000	25	$\approx$ 35% P <sub>R</sub> (25 kPa)	$\approx 30\% P_R (25 \text{ kPa})$
04	1000	148	25	$\approx$ 35% P <sub>R</sub> (25 kPa)	$\approx$ 45% P <sub>R</sub> (25 kPa)
05	1000	1000	50	$\approx$ 35% P <sub>R</sub> (50 kPa)	$\approx 30\% P_R (50 \text{ kPa})$
06	1000	158	50	$\approx$ 35% P <sub>R</sub> (50 kPa)	$\approx$ 45%P <sub>R</sub> (50 kPa)
07	1000	1000	100	$\approx$ 35% P <sub>R</sub> (100 kPa)	$\approx 30\% P_R (100 \text{ kPa})$
08	1000	1000	100	$\approx$ 35% P <sub>R</sub> (100 kPa)	$\approx$ 45% P <sub>R</sub> (100 kPa)

# *Table 2 MS pullout testing plan.*



(a)

(b)



610

611 Figure 1. Apparatus used for pullout testing: pullout steel box (a); soil-geogrid

- 612 specimen and LVDT (b); air bag (c); clamp and sleeves (d), hydraulic actuator and
- 613 load cell (e).





617 Figure 2. Schematic representation of different parameters obtained during hysteresis

618 loops in multi-stage tests: P- $\delta$  plane (a); P- $\varepsilon$  plane (b).



622 Figure 3. Number of loading cycles versus cumulative cyclic displacement measured at

623 the first confined section of specimen (a), and  $\Delta \delta^h$  versus cumulative cyclic

624 displacement measured at the rear end of the specimen (b) for  $A \approx 30\% P_R$ , 45%  $P_R$  and

625  $\sigma'_v = 50 \, kPa$ .





628 Figure 4. Number of loading cycles versus cumulative cyclic displacement measured at

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629 the first confined section of specimen (a), and \Delta \delta^h versus cumulative cyclic
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630 displacement measured at the rear end of the specimen (b) for  $A \approx 30\% P_R$ , 45%  $P_R$  and

631  $\sigma'_{v} = 100 \ kPa$ .



634 *Figure 5. Number of loading cycles versus cumulative cyclic displacement of the* 

- 635 specimen's first confined section (a) and  $\Delta \delta^h$  versus cumulative cyclic displacement of
- 636 the specimen's rear end (b) for varying  $\sigma'_v$  at  $A \approx 45\% P_R$ .





639 Figure 6. Residual strain at loading cycle N = 10 versus vertical effective stress, for

640  $A \approx 30\% P_R$  and 45%  $P_R$  (a); and residual strain for varying number of loading cycles

641 at different vertical effective stresses and  $A \approx 45\% P_R(b)$ .



644 Figure 7. Residual strain evaluated for the entire length of the geogrid and its

645 monitored portion closer to the head, for varying number of loading cycles at

 $\sigma'_{v} = 100 \text{ kPa}, A \approx 30\% P_{R}(a) \text{ and } \sigma'_{v} = 100 \text{ kPa}, A \approx 45\% P_{R}(b), \text{ and comparison with}$ 

*the corresponding wide-width tensile tests.* 



650 Figure 8. Comparison between load-displacement trends obtained in CRD and

651 multistage conditions for tests with  $\sigma_v = 50$  kPa, at  $A \approx 30\%$   $P_R(a)$  and  $A \approx 45\%$   $P_R(b)$ 

652 respectively.



Figure 9. Normalised post-cyclic peak pullout resistance (a) and peak apparent
coefficient of friction (b) for varying vertical effective stress, considering CRD and

*multi-stage tests at*  $A \approx 30\% P_R$ .



660 Figure 10. P-  $\varepsilon$  (a) and  $\delta$ - $\varepsilon$ (b) trends obtained in CRD conditions for different vertical

*effective stresses*.



663 Figure 11. Comparison between P-  $\varepsilon$  (a) and  $\delta$ - $\varepsilon$ (b) trends obtained in CRD and

664 multistage conditions for tests with  $\sigma_v = 100$  kPa, at  $A \approx 30-45\%$  P<sub>R</sub>, and qualitative

665 distribution of the geogrid's points displacements at the same pullout load level  $P_i$  for

666 *CRD test and MS test at N=1000 (c-1) and at \delta = 100 mm for MS test following the* 

667 *"ideal" or the real path (c-2).* 



669 Figure 12. Comparison between P-  $\varepsilon$  (a) and  $\delta$ - $\varepsilon$ (b) trends obtained in CRD and

- 670 multistage conditions for tests with  $\sigma_v = 50$  kPa, at  $A \approx 30\%$  P<sub>R</sub>, and qualitative
- *distribution of the geogrid's points displacements at the same pullout load level* P<sub>i</sub> for
- *CRD test and MS test at N=1000 (c-1) and at \delta = 100 \text{ mm for MS test following the*
- *"ideal" or the real path (c-2).*



676 Figure 13. Distributions of the nodal displacements along the reinforcement for

677 different numbers of cycles, for specimens tested at  $A \approx 30\% P_R$  and  $\sigma_v = 10 kPa(a)$ ;

678  $A \approx 30\% P_R$  and  $\sigma_v = 100 kPa$  (b) respectively.

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