

1 **New insight into cavitation mechanisms in high capacity tensiometers**
2 **based on high-speed photography**

3

4

5

Mendes J., Buzzi O.^a

6

7 **Affiliation/Address:** Priority Research Centre for Geotechnical and Materials Modelling, The
8 University of Newcastle, Callaghan, 2308, New South Wales, Australia

9

10 Joao.Mendes@newcastle.edu.au

11 Olivier.Buzzi@newcastle.edu.au

12 ^a: Corresponding author. Tel: +61249215454/Fax:+61249216991

13

14 **Abstract**

15

16 The high capacity tensiometer developed by Ridley and Burland (1993) is a
17 milestone of experimental unsaturated soil mechanics. This device, which relies
18 on development of tension in an enclosed water body, permits direct
19 measurement of negative water potential. Many tensiometers have been built
20 since 1993; all being based on the same principle although the design might
21 slightly differ from the original one. In particular, the common characteristic is a
22 very small water reservoir as this latter is believed to be the location of bubble
23 nucleation, phenomenon referred to as cavitation that impedes the sensor from
24 functioning properly. Many have studied cavitation and different explanations or
25 cavitation mechanisms have been proposed. However, all the considerations put
26 forward were derived without being in a position to capture what happened
27 inside the water reservoir at cavitation. This is now achieved with the new
28 tensiometer specifically designed to see inside the water reservoir during
29 suction measurement. For the first time, cavitation has been captured via high-
30 speed photography and the mechanisms of cavitation can be explained on
31 physical evidence. The first outcome is that it is possible for a high capacity
32 tensiometer to function to its full range with a large water reservoir. Then, the
33 analysis of high-speed photographs revealed that the bubbles triggering
34 cavitation are nucleated in the ceramic and make their way to the water
35 reservoir. Cavitation occurs only when the air phase reaches the water reservoir.

36

37 **Keywords:** Cavitation, Tensiometer, High-speed cameras, Suction, Bubble

38

39 **1) Introduction**

40

41 Water potential, commonly called suction when in the negative range, is known
42 to significantly affect the mechanical response and hydraulic behaviour of soils.

43 This is one reason why measurement of water potential is a key aspect of
44 experimental research in soil mechanics. While gaging positive water pressure is
45 not problematic, measuring suction proves difficult. A broad range of techniques

46 has been developed (see different techniques in Fredlund and Rahardjo, 1993)

47 but the one retaining attention in this paper is the high capacity tensiometer
48 developed by Ridley and Burland (1993). This device, depicted in Figure 1b of

49 the next section, allows direct measurement of negative water potential since
50 tension is developed in the water enclosed in the reservoir and the ceramic.

51 Since 1993, many other models of tensiometers have been developed, all based
52 on the same principle (Guan & Fredlund, 1997; Meilani et al., 2002; Tarantino

53 and Mongiovì, 2002; Take and Bolton, 2003; Lourenço et al., 2008; Cui et al.,
54 2008; among others). Although it is, on paper, a simple sensor to use, getting it to

55 function to its full range can pose some issues. Indeed, water under tension is
56 prone to cavitation, phenomenon first observed by Berthelot (1850) and that,

57 when it occurs, prevents the sensor from working any longer.

58

59 According to the literature on the subject, cavitation can be delayed by adequate
60 preparation of the sensor including use of de-aired water, application of vacuum,

61 cycles of pressurization and even cycles of cavitation (e.g. Marinho and Chandler,
62 1994). There is also a general consensus on the fact that the design of the

63 tensiometer itself has a role to play. In particular, the need to minimize the size

64 of the water reservoir is regarded as fundamental: all high capacity tensiometers
65 presented in the literature have a water reservoir less than about 10 mm³. This
66 special care comes from the perception that cavitation takes place in the
67 reservoir due to heterogeneous nuclei as explained by Marinho et al. (2008).

68

69 However, Tarantino and Mongiovi (2001) put forward another cavitation
70 mechanism where they suppose that water break down actually initiates in the
71 ceramic, not in the reservoir. Today, there is still no clear answer as to where
72 cavitation actually takes place because of a lack of experimental evidence. All
73 conclusions tend to be drawn from analysis of the sensor response rather than
74 direct observation of the cavitation mechanism inside the device (e.g. Lourenço
75 et al., 2011).

76

77 This paper presents a tensiometer that was designed to observe cavitation inside
78 the water reservoir during suction measurement. For the first time, cavitation
79 has been captured via high-speed photography and the mechanisms of cavitation
80 can be explained on physical evidence. Some results validating the new design
81 are firstly presented, followed by the analysis of the sequence of high-speed
82 photographs. The paper concludes with a model for cavitation in a tensiometer.

83

84 **2) Experimental facilities**

85

86 **2.1) Details of the new tensiometer**

87

88 **FIGURE 1.**

89

90

91 Two high capacity tensiometers were built at the laboratory of the Centre for
92 Geotechnical and Materials Modelling of The University of Newcastle. The
93 objective of the study being to visualize the cavitation within a tensiometer, a
94 translucent perspex body was combined to a water reservoir far larger than the
95 recommended volume. Indeed, the reservoir can hold 1100 mm³ of water as
96 opposed to less than about 10 mm³ (Ridley and Burland, 1993; Guan and
97 Fredlund, 1997; Meilani et al., 2002; Tarantino and Mongiovì, 2003; Lourenço et
98 al., 2006). Two tensiometers were built, one with a 15 bar air entry value
99 ceramic and one with a 5 bar ceramic. Both were equipped with the same type of
100 pressure sensor (capacity 3.5 MPa, accuracy ± 10 kPa). The 5 bar tensiometer is
101 shown in Figure 1a.

102

103 **2.2) Preparation and testing**

104

105 The tensiometers were prepared by following the typical steps evoked in the
106 literature (e.g. Marinho and Chandler, 1994): use of de-aired water, application
107 of vacuum, saturation and cycles of pressurization. Different pressurization
108 values were used, as per Table 1. As for testing the tensiometers, it simply
109 consisted of exposing the device to air-drying, which is referred to as a “pulling
110 test”.

111

112 Cavitation is characterised by apparition of air bubbles in a liquid phase, a
113 phenomenon that takes place quickly. For example, micro bubbles have been

114 observed to appear within microseconds (Vincent et al., 2012). Preliminary
115 testing with the new tensiometers showed that the bubbles accompanying
116 cavitation were visible at the naked eye in the large water reservoir.
117 Consequently, high-speed cameras (Optronis, CR600) were deemed sufficient to
118 capture the apparition of air bubbles in the water reservoir during testing. A low
119 frame rate was initially used (50 frames per second or fps) but this was
120 progressively increased to 7000 fps. Most of the tests were done at 2000 fps, the
121 reason being that the higher the frame rate, the lower the accuracy and the lower
122 the recording time. 2000 fps was found be an acceptable compromise. Table 1
123 summarizes the different frame rates used throughout the testing.

124

125 For tests 1 to 10, suction was recorded via a data logger DT80 with a relatively
126 low sampling rate (1 data point every 3 seconds).

127

128 The objective of the last test (#11) was to verify the concomitance of bubble
129 appearance in the water reservoir and cavitation, which requires
130 synchronisation of suction measurements and high-speed photographs. For that
131 purpose, a high rate logger capable of recording 2000 data per second (USB
132 Compact DAQ system from National Instruments 9234) was preferred to the
133 DT80. The National Instruments logger was only used for the last test because of
134 the noise generated when combined to the tensiometer: the accuracy in suction
135 measurement dropped to about ± 90 kPa.

136

137 For test 11, synchronisation of data was achieved via a LED, the status of which
138 (on/off) can be detected from the logger (voltage) and from the high-speed

139 cameras (light). Exact matching was later confirmed through the internal clock of
140 the logger and the high-speed cameras.

141

142 One pulling test was performed on the 15 bar tensiometer in order to
143 demonstrate that the sensor can work to its full capacity despite the large
144 reservoir. This test did not require use of high-speed cameras. The actual study
145 on cavitation was done on the 5 bar tensiometer only in order to minimize the
146 damage to the tensiometer. Indeed, the 5 bar tensiometer requires lower
147 magnitude of pressure to achieve saturation meaning that its perspex body is
148 less likely to crack under the cycles of pressurization and multiple testing.

149

150 **TABLE 1.**

151

152 Note that the calibration of the tensiometers (performed in the positive range)
153 was checked before each test.

154

155 **3) Results and discussion**

156

157 **3.1) Validation of the new design**

158

159 Figure 2 shows the sharp decrease in pressure recorded by the tensiometers
160 HCTP2 and HCTP3 when exposed to air. The first noticeable result of this study
161 is that the maximum suction sustained by both tensiometers is equal or greater
162 than the nominal air entry value of the ceramics: about 920 kPa for HCTP2 and
163 1520 kPa for HCTP3 (Figure 2). The possibility for suction to exceed the nominal

164 air entry value of the ceramic has already been observed (e.g. Tarantino and
165 Mongiovi, 2001; Marinho and Chandler, 1994) and is explained by successive
166 cycles of pressurization and cavitation (Tarantino and Mongiovi, 2001).

167

168 The results here obtained demonstrate that the perception held by the
169 community regarding the size of the water reservoir is somehow incorrect: high
170 capacity tensiometers can function to their full range with a large reservoir
171 provided the preparation of the sensor is adequate. This finding considerably
172 simplifies the manufacturing process of tensiometers and provides the
173 opportunity to observe possible changes in the water reservoir during or
174 following cavitation.

175

176 Note that the large volume is not significantly detrimental to the saturation time
177 of the tensiometers. From a totally dry state, it takes about three days under 2
178 MPa of pressure to be in a position to measure 1 MPa of suction and an extra five
179 days under 3.45 MPa of pressure allowed to reach 1.5 MPa. Any subsequent use
180 requires only about a day of pressurization.

181

182 **FIGURE 2.**

183

184 **3.2) High-speed photographs of cavitation**

185

186 **All the photographs presented in the following were taken with the**
187 **tensiometer placed horizontally, which was the position of test. The slight**
188 **angle visible on some photographs actually reflects a slightly inclined**

189 **position of the camera. The horizontal position was chosen to avoid any**
190 **preferential direction from or towards the ceramics due to gravity. Note**
191 **that the final location of the bubbles in the reservoir has little influence on**
192 **the overall results.**

193

194

195 Figure 3 shows all the results obtained with tensiometer HCTP2 (5 bar). For test
196 8, the sharp decrease of suction is interrupted by cavitation at a value lower than
197 the air entry of the ceramic. In the light of all the tests performed, this cavitation
198 is attributed to the presence of gas nuclei in the water reservoir (dissolved in the
199 water or on crevices of the reservoir walls) that the pressurization procedure did
200 not suffice to get rid of.

201

202 Although this type of cavitation is possible in case of inadequate sensor
203 preparation, it is not the scope of the paper. Attention is herein focused on the
204 cavitation occurring after suction has reached or exceeded the nominal air entry
205 value of the ceramic, which is illustrated in Figure 3 for all other tests but test 8.

206

207 **FIGURE 3.**

208

209

210 The evolution of suction in time in Figure 3 is quite peculiar: the peak value of
211 suction is not followed by straight cavitation nor by a plateau but by a slight
212 relaxation during a variable time (up to 8 minutes) before cavitation occurs.

213 Some explanations about this behaviour will be provided in a later section.

214

215 As detailed previously, sequences of high-speed photographs were taken for all

216 these tests, some of which are presented below to elaborate the discussion.

217 Firstly, Figure 4 presents a sequence occurring inside the water reservoir for test

218 4 at 2000 fps. A bubble emerges from the ceramics within 0.5 ms (Figure 4b) and

219 makes its way to the highest point of the reservoir (Figure 4c). At the end of the

220 process (about 4s, Figure 4d), a large number of bubbles have accumulated.

221 These do not come from the ceramics but from air that was dissolved in the

222 water reservoir.

223

224 **FIGURE 4.**

225

226 This mechanism, which was similarly observed for tests 2 and 3, suggests that

227 cavitation could be driven by the ceramic since the first bubble to appear in the

228 reservoir comes from the stone. However, it is not trivial to assess from Figure 4

229 whether the bubble has formed from a nucleus lodged on the surface of the

230 ceramic surface or inside the ceramic.

231

232 Sequences of photographs obtained for tests 5, 6, 7 and 9 at 2000 fps (not shown

233 here for the sake of brevity) suggest that the phenomenon might actually be due

234 to nuclei located on the surface of the reservoir walls, including the surface of the

235 ceramic. Indeed, the photographs reveal bubbles appearing, at the same time,

236 from both the ceramic side and the sensor side of the reservoir.

237

238 On one hand, this would be consistent with the crevice model depicted by
239 Marinho et al. (2008) but on the other hand, one question remains unanswered:
240 why, in Figure 2, can suction be maintained during a certain time after having
241 reached a peak?

242

243 The frame rate was further increased up to 7000 fps in order to provide
244 elements of answer.

245

246 Figure 5 (test 10) reveals an interesting mechanism that was not visible at 2000
247 fps: a bubble first emerges from the ceramic in 0.14 ms (bottom right corner,
248 Figure 5b) but this latter largely disappears back in the ceramic in the next frame
249 (Figure 5c at $t=0.28\text{ms}$). In the meantime, some change in colour suggests
250 nucleation of a bubble close to the tip of the pressure sensor. The reason why the
251 initial bubble would partly be drawn backwards in the ceramic is still unknown.
252 Then, two bubbles can be seen: one from the pressure sensor (where the change
253 in colour was observed) and one from the ceramic, located at a higher position
254 than where the first bubble appeared. This occurred at 0.43 ms but the
255 photograph at $t = 2.57\text{ ms}$ that is of better quality is showed here (Figure 5d).

256

257 This sequence suggests that concomitant occurrence of bubbles from the two
258 sides of the reservoir, as observed for tests 5, 6, 7 and 9 at 2000 fps is likely, in
259 fact, to be preceded by the arrival of a bubble from the ceramic.

260

261 **FIGURE 5.**

262

263

264 This observation corroborates the view of Tarantino and Mongiovi (2001) who
265 stated that bubbles start to form within the ceramic. Indeed, pressurizing the
266 nuclei in water is easier than in the ceramic where a three-phase interaction
267 prevails. Consequently, nuclei in the ceramic are likely to be bigger than those in
268 the reservoir, and bubbles would grow preferably in the porous stone. However,
269 Figure 11 in Tarantino and Mongiovi (2001), and the related discussion, suggest
270 that the cavitation mechanism takes place only in the stone, which is
271 contradicted by the upcoming results.

272

273 A final test (number 11), conducted with synchronization of high speed cameras
274 at 2000 fps and high rate logger (2000 data/s) via a LED (visible in Figure 6),
275 showed that although bubbles might initially appear in the ceramic, it is only
276 when the air phase reaches the reservoir that cavitation occurs. Evidence is
277 shown in Figure 6 where values of suction are given for each frame. The abrupt
278 drop in suction coincides with the appearance of a bubble in the water reservoir.
279 In addition, it is interesting to see that the maximum value of suction has been
280 sustained for at least 13.75 seconds before cavitation occurred, meaning that the
281 peak suction was reached without occurrence of a bubble in the water reservoir.

282

283 **FIGURE 6.**

284

285 Following from the analysis of the high-speed photographs, a mechanism for
286 cavitation is proposed: as per Tarantino and Mongiovi (2001), it is considered
287 that some convex air-water interface exist during pressurization (Figure 7a). As

288 suction is applied, menisci turn concave and the air cavities progressively grow
289 without significant interaction (Figure 7b). Then it can be hypothesised that, at
290 some stage, the different cavities start interacting and joining together creating
291 some re-adjustment in pressure or relaxation, as they do not necessarily all have
292 the same menisci curvature. The air cavity eventually reaches the interface
293 between water reservoir and the ceramic (Figure 7c) at which stage small
294 bubbles appear in the reservoir triggering cavitation (Figure 7d). Quite quickly,
295 small bubbles gather into larger ones (Figure 7e). According to the mechanism
296 described, the time between peak suction and cavitation, observed in Figure 2, is
297 the time required for the agglomerated air cavities within the ceramic to reach
298 the water reservoir. A sharp response with no plateau or relaxation might be
299 observed if the air cavities start to form close to the water reservoir.

300

301 While high-speed cameras are useful to visualize the chain of events taking place
302 in the water reservoir, considerations about mechanisms inside the ceramic are
303 only speculative. At this stage, it is still difficult to capture the microstructure of
304 the ceramic with the three-phase interaction.

305

306 **FIGURE 7.**

307

308 **Conclusions**

309

310 High capacity tensiometers have been developed to allow direct measurement of
311 suction. Since the initial design from Ridley and Burland (1993) many
312 tensiometers have been proposed, although all based on the same principle. In

313 particular, the scientific community agrees on the need to minimize the volume
314 of the water reservoir in order to measure suction close to the air entry of the
315 ceramic. Also, discussions have arisen in the literature about cavitation
316 mechanisms but, so far, conclusions were based on the response of the sensor
317 rather than actual observation of the cavitation inside the water reservoir. For
318 the first time, in this study, high capacity tensiometers were built of translucent
319 perspex with water reservoirs at least 100 times larger than the typical
320 recommended volume. This combination permits to visualize the cavitation
321 inside the tensiometer, phenomenon that was captured by high-speed cameras.
322 The following conclusions can be drawn from this study:

323

- 324 • It is possible for a high capacity tensiometer to function to its full range
325 with a large water reservoir, provided that the preparation procedure is
326 adequate (de-aired water, vacuum, cycles of pressurization).
- 327 • Sequence of high-speed photographs revealed that, when suction reaches
328 or exceeds the nominal air entry value of the ceramic, cavitation is due to
329 the appearance of bubble(s) into the water reservoir.
- 330 • The bubbles triggering cavitation are nucleated in the ceramic and make
331 their way to the water reservoir. Indeed, the crevice model applied to the
332 ceramic wall does not explain the time gap between the peak suction and
333 cavitation.
- 334 • A mechanism for cavitation has been proposed based on the
335 understanding gained from the high-speed photographs.

336

337 **References**

338

339 Berthelot M. (1850). Sur quelques phénomènes de dilatation forcée des liquides.

340 Annales de chimie et Physique, 30(3), 232-237.

341

342 Cui, Y.J., Tang, A., Mantho, A., and De Laure, E. (2008). Monitoring Field Soil

343 Suction Using a Miniature Tensiometer. Geotechnical Testing Journal 31(1). 95-

344 100.

345

346 Fredlund, D.G. and Rahardjo, H. (1993) Soil Mechanics for Unsaturated Soils.

347 Wiley-Interscience Publications.

348

349 Guan Y., Fredlund D.G. (1997) Use of the tensile strength of water for the direct

350 measurement of high soil suction. Canadian Geotechnical Journal, 34(4): 604-

351 614.

352

353 Lourenço, S.D.N., Gallipoli, D., Toll, D.G. and Evans, F.D. (2006). Development of a

354 Commercial Tensiometer for Triaxial Testing of Unsaturated Soils, Proc. 4th Int.

355 Conf. on Unsaturated Soils, Phoenix, USA, Geotechnical Special Publication No.

356 14, Reston: ASCE, vol. 2, 1875-1886.

357

358 Lourenço S.D.N., Gallipoli D., Toll D.G., Augarde C., Evans F., Medero G. (2008)

359 Calibrations of a high-suction tensiometer. Géotechnique, 58(8), 659-668.

360

361 Lourenço, S.D.N, Gallipoli D., Toll D.G., Augarde, C., Evans, F. (2011). Cavitation in

362 high suction tensiometers: effect of temperature, time of use and stone drying. In

363 Unsaturated Soils: theory and practice. Proceedings of the 5th Asia Pacific
364 Conference on Unsaturated Soils, 429-435.
365

366 Marinho, F.A.M., and Chandler, R.J. (1994). Discussion: a new instrument for the
367 measurement of soil moisture suction. *Géotechnique*, 44(3), 551-556.
368

369 Marinho, F. A. M., Take, W. A., and Tarantino, A. (2008). Measurement of Matric
370 Suction Using Tensiometric and Axis Translation Techniques. *Geotechnical and*
371 *Geological Engineering*, vol. 26(6), 615-631.
372

373 Meilani, I., Rahardjo, H., Leong, E.-C. and Fredlund, D.G. (2002). Mini suction
374 probe for matric suction measurements, *Canadian Geotechnical Journal* 39,
375 1427-1432.
376

377 Ridley, A.M. and Burland, J.B. (1993) A new instrument for the measurement of
378 soil moisture suction. *Géotechnique* 43(2), 321-324.
379

380 Take, W.A. and Bolton, M.D. (2003) Tensiometer saturation and the reliable
381 measurement of soil suction. *Géotechnique*, 54(2), 159-172.
382

383 Tarantino, A. and Mongiovì, L. (2001). Experimental procedures and cavitation
384 mechanisms in tensionmeter measurements. *Geotechnical and Geological*
385 *Engineering*, 19, 189-210.
386

387 Tarantino, A. and Mongiovi, L. (2002). Design and construction of a tensiometer
388 for direct measurement of matric suction. In: Proceedings of 3rd international
389 conference on unsaturated soils, Recife, vol. 1, 319-324.

390

391 Tarantino, A. and Mongiovi, L. (2003). Calibration of tensiometer for direct
392 measurement of matric suction, *Géotechnique*, 53(1), 137-141.

393

394 Vincent O, Marmottant P, Quinto-Su PA, Ohl CD. (2012). Birth and growth of
395 cavitation bubbles within water under tension confined in a simple synthetic
396 tree. *Phys Rev Lett*. 108(18):184502 Epub.

397

398

399

400

401

List of Captions

402

403

404 **TABLE 1:** Details of the tests performed: pressurization values and high-speed
405 camera frame rate.

406

407 **FIGURE 1:** (a) Tensiometer developed by Ridley and Burland (1993) at Imperial
408 College. (b) Perspex tensiometer built at The University of Newcastle, 5 bars
409 ceramics, 3.5 MPa sensor, 1100 mm³ water reservoir.

410

411 **FIGURE 2:** Tests 1 and 2: Evolution of suction measured by HCTP2 (5 bar AEV)
412 and HCTP3 (15 bar AEV) in time as the tensiometers are exposed to air.

413 Maximum sustained suctions of about 920 kPa and 1520 kPa.

414

415 **FIGURE 3:** Tests 2, 4, 5, 8 and 10: Evolution of suction measured by HCTP2
416 (5bar) in time as the tensiometer is exposed to air-drying. The time between
417 peak suction and cavitation (visible on tests 4 and 10) is referred to as delay.

418

419 **FIGURE 4:** Sequence of high speed photographs for test 4 (2000 fps).

420

421 **FIGURE 5:** Sequence of high-speed photographs for test 10 (7000 fps).

422

423 **FIGURE 6:** a) to d) Sequence of high-speed photographs for test 11 (2000 fps).

424 e): Measurement of suction at time of cavitation.

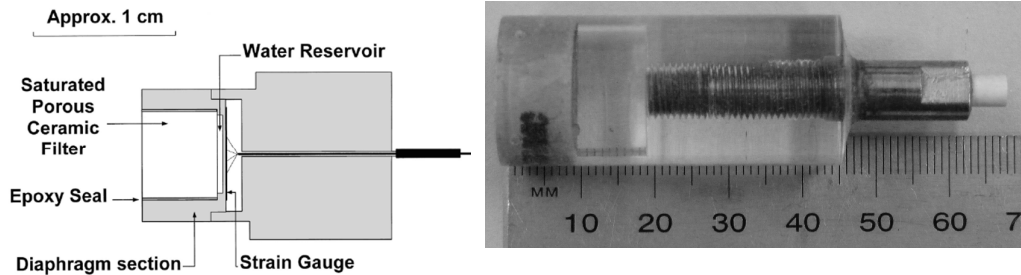
425

426 **FIGURE 7:** Mechanism for cavitation in a high capacity tensiometer. The sketch
427 represents the water reservoir (with the back wall) and the ceramic (not to
428 scale). In white is the air phase, light grey is the water and dark grey are the solid
429 particles (referred to as S.P) constituting the ceramic. The dotted circle is a close-
430 up of an idealised crevice. (a): Air-water interface exist during pressurization;
431 (b): Agglomeration/expansion of the cavities under suction application; (c): Air
432 cavities reach the water reservoir; (d): Small bubbles form in the reservoir
433 triggering cavitation; (e): small bubbles gather into larger ones.
434

Table 1: Details of the tests performed: pressurization values and high-speed camera frame rate.

Test No.	Sensor	AEV (bars)	Saturation pressure (kPa)	Camera Frame rate (Fps)
1	HCTP3	15	3450	None
2	HCTP2	5	750	50
3	HCTP2	5	750	500
4	HCTP2	5	750	2000
5	HCTP2	5	2000	6000
6	HCTP2	5	2000	2000
7	HCTP2	5	2000	2000
8	HCTP2	5	0*	2000
9	HCTP2	5	2000	2000
10	HCTP2	5	2000	7000
11	HCTP2	5	2000	2000

* - tensiometer was saturated, cavitated and immersed in water without further pressurisation.



(a)

(b)

Figure 1: (a) Tensiometer developed by Ridley and Burland (1993) at Imperial College. (b) Perspex tensiometer built at The University of Newcastle, 5 bars ceramics, 3.5 MPa sensor, 1100 mm³ water reservoir.

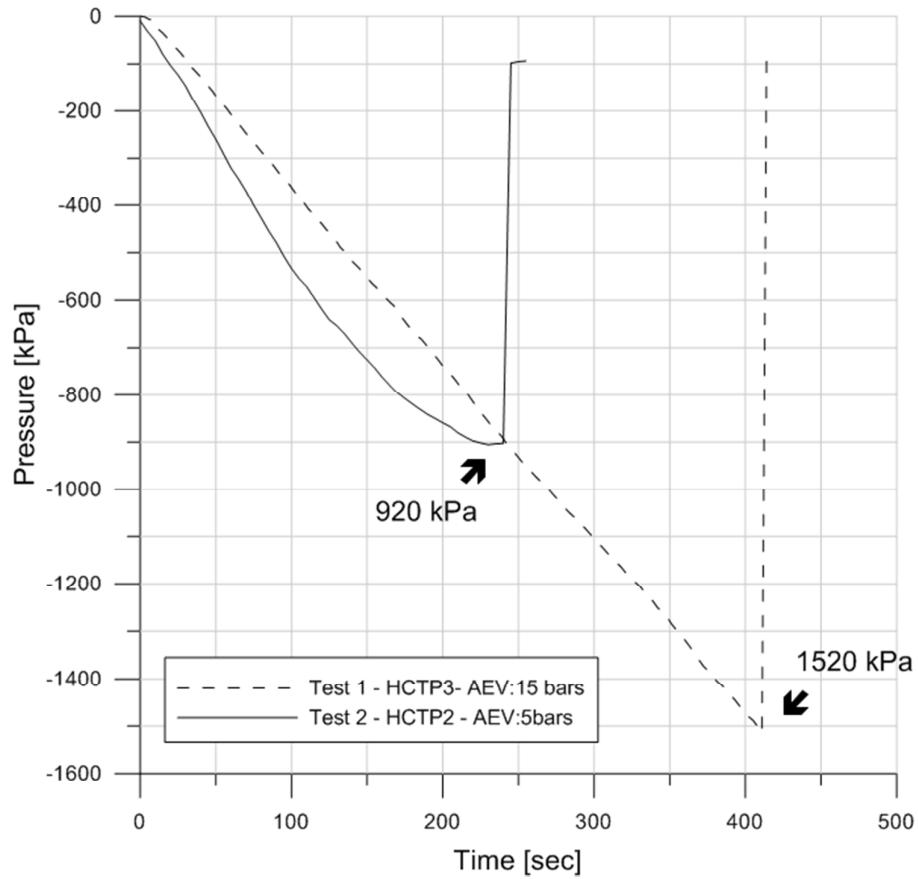


Figure 2: Tests 1 and 2: Evolution of suction measured by HCTP2 (5 bar AEV) and HCTP3 (15 bar AEV) in time as the tensiometers are exposed to air. Maximum sustained suctions of about 920 kPa and 1520 kPa.

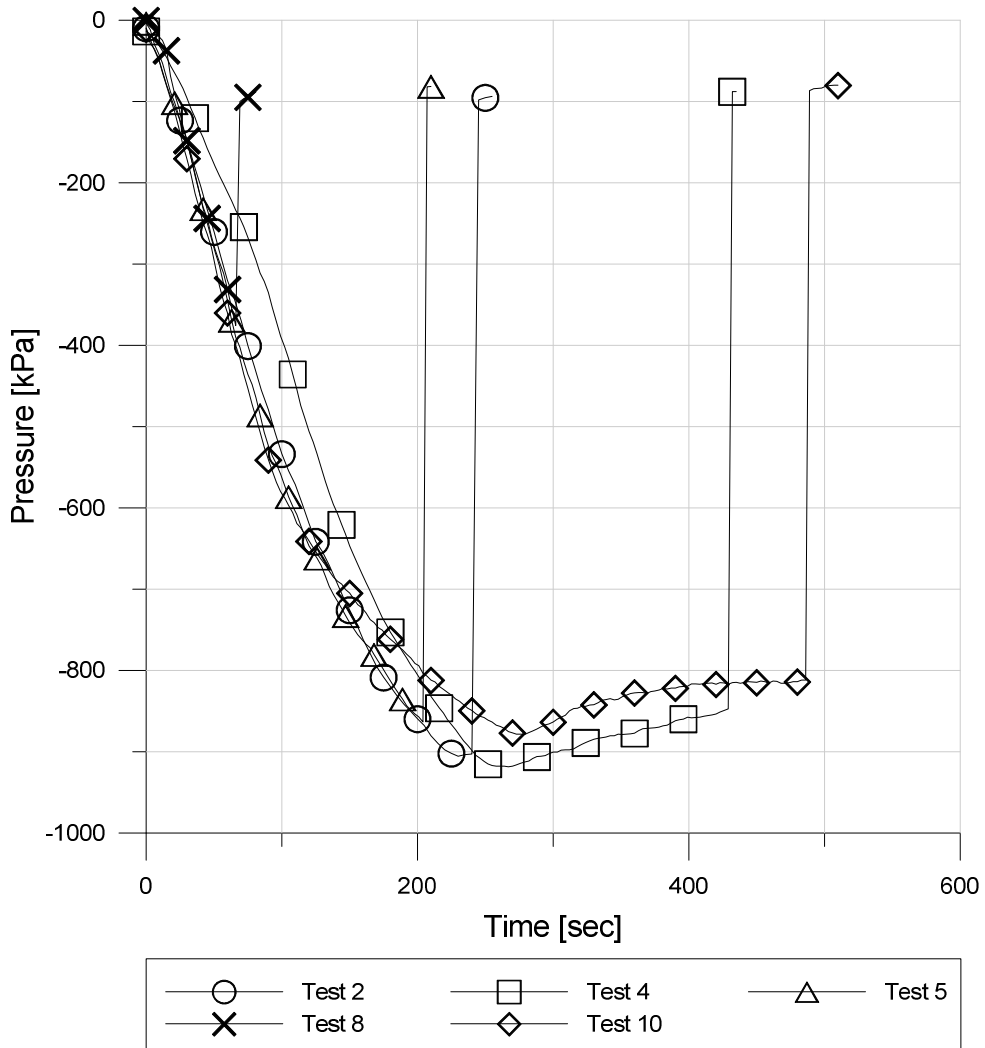
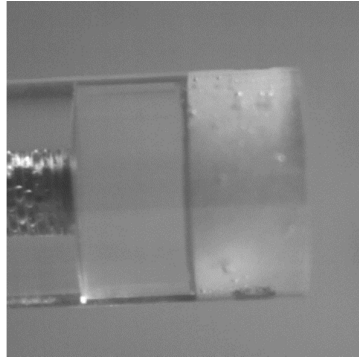
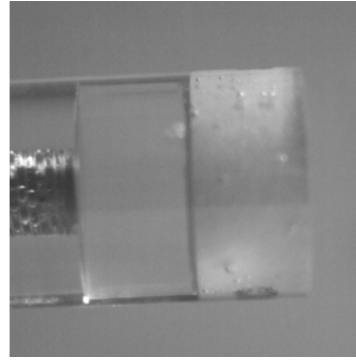


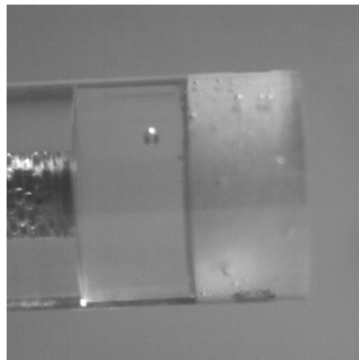
Figure 3: Tests 2, 4, 5, 8 and 10: Evolution of suction measured by HCTP2 (5bar) in time as the tensiometer is exposed to air-drying. The time between peak suction and cavitation (visible on tests 4 and 10) is referred to as delay.



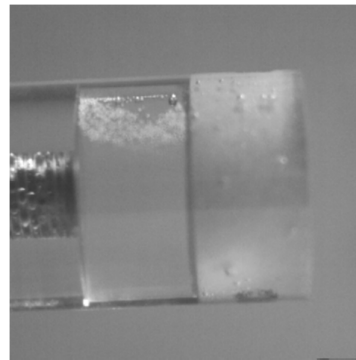
a) Initial state, $t=0s$



b) Small bubbles emerging from the ceramic, $t=0.5\text{ ms}$



c) Small bubbles have agglomerated into a large bubble, $t=5.5\text{ ms}$.



e) Final state after more bubbles have formed, $t=4.4s$

Figure 4: Sequence of high speed photographs for test 4 (2000 fps).

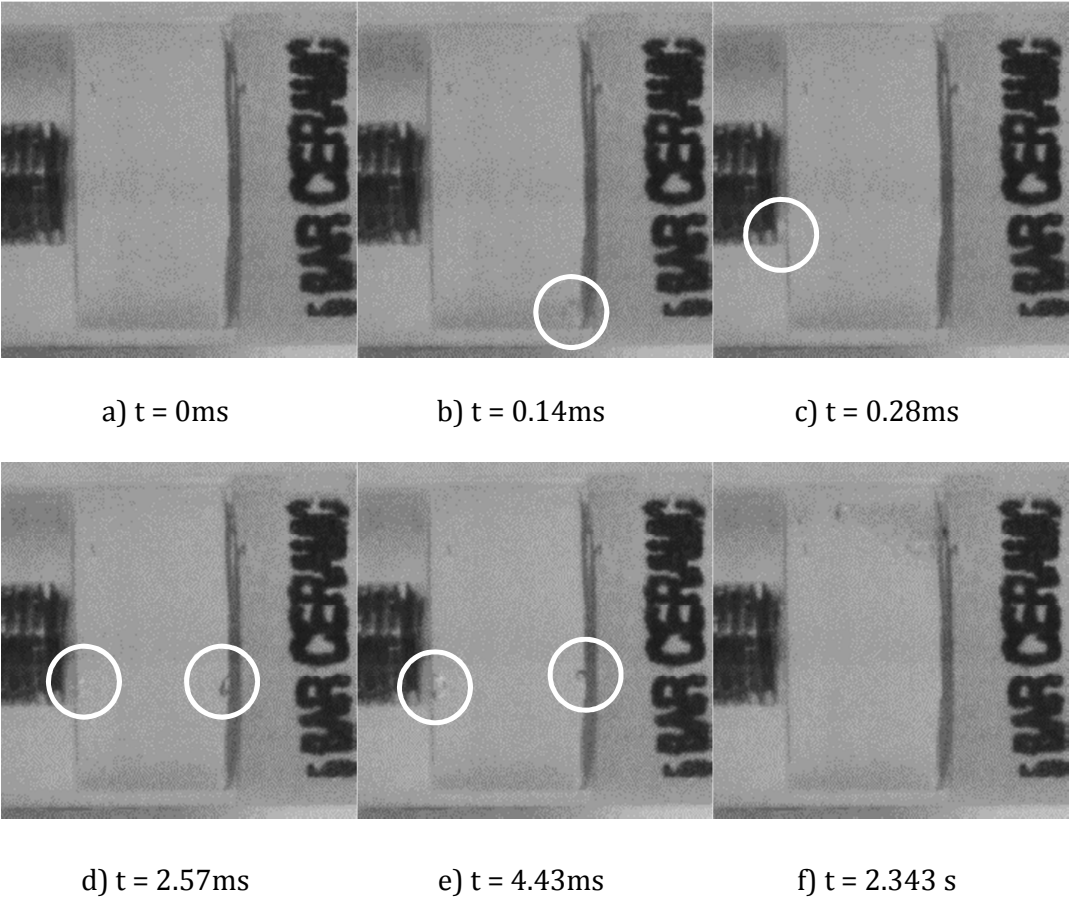
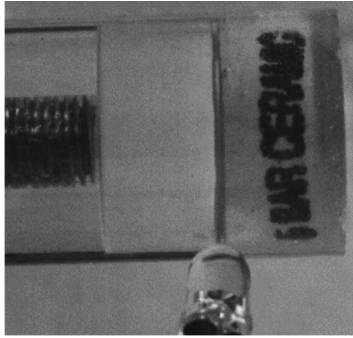
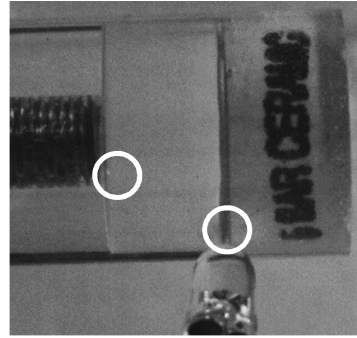


Figure 5: Sequence of high-speed photographs for test 10 (7000 fps).



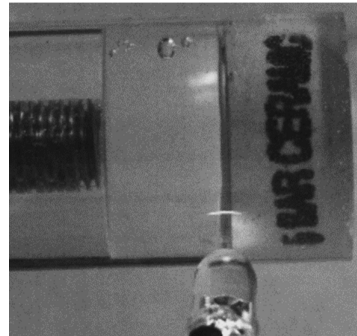
a) Initial state pre cavitation
 $t = 0$ s or $t_{log} = 13.7585$ s
 suction ≈ 800 kPa



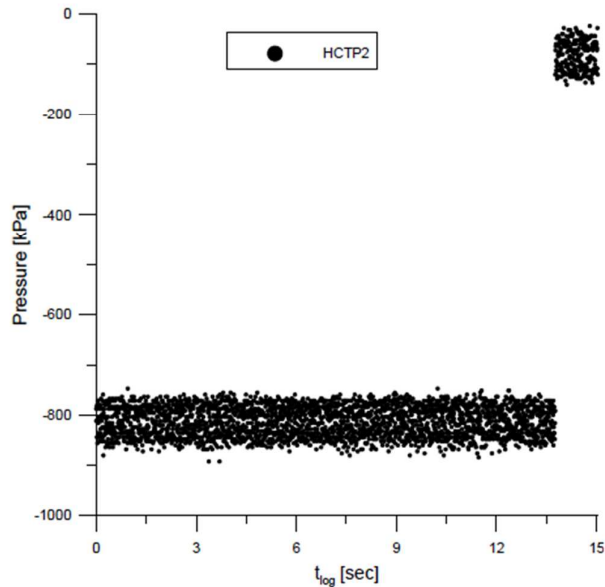
b) Bubble emerging from the ceramics
 and crevice
 $t = 0.5$ ms or $t_{log} = 13.7590$ s
 suction ≈ 100 kPa



c) Bubbles that emerged from
 ceramics and crevice
 $t = 22.5$ ms or $t_{log} = 13.7610$ s
 suction ≈ 100 kPa.



d) Final state
 $t = 0.64$ s or $t_{log} = 14.3990$ s
 suction ≈ 100 kPa



e)

Figure 6: a) to d) Sequence of high-speed photographs for test 11 (2000 fps). e): Measurement of suction at time of cavitation.

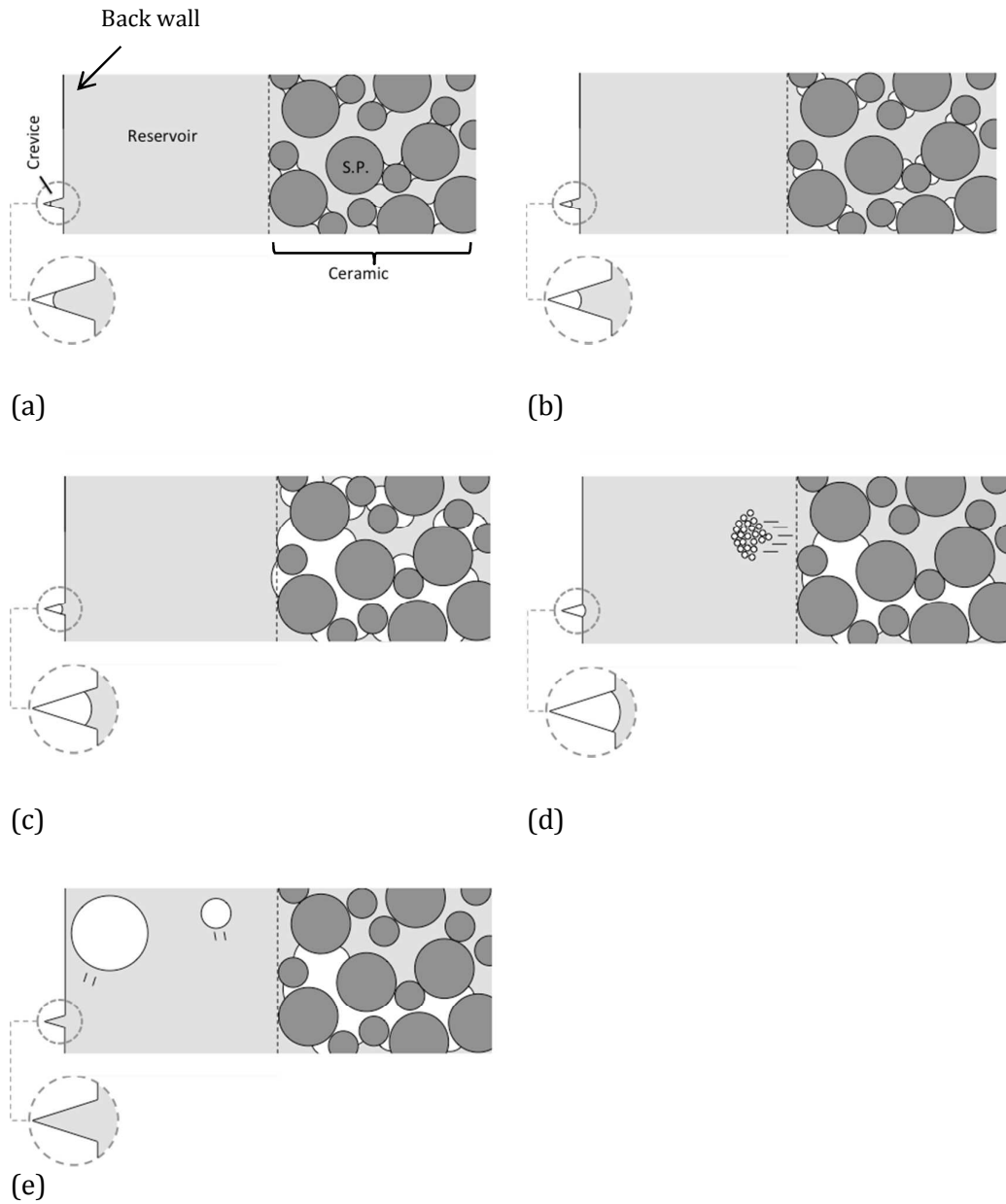


Figure 7: Mechanism for cavitation in a high capacity tensiometer. The sketch represents the water reservoir (with the back wall) and the ceramic (not to scale). In white is the air phase, light grey is the water and dark grey are the solid particles (referred to as S.P) constituting the ceramic. The dotted circle is a close-up of an idealised crevice. (a): Air-water interface exist during pressurization; (b): Agglomeration/expansion of the cavities under suction application; (c): Air cavities reach the water reservoir; (d): Small bubbles form in the reservoir triggering cavitation; (e): small bubbles gather into larger ones.