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The use of impulse and stepped-frequency radar to characterize the hydric behaviour of a porous pavement structure

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ABSTRACT

This study focuses on examining the behaviour of an innovative asphalt pavement which is created as a solar energy collector, using non-destructive testing involving ground-penetrating radar. The concept of heat exchanger is based on the use of drainage asphalt in the bonding layer through which a heated fluid flows via gravity to de-ice the roadway. In order to develop hydrothermal models for a test site representing such a pavement, the saturated porous layer assumption was required when the water level in each tank (up- and down-stream of the structure) was on top of the porous layer. Two GPR techniques were tested at this test site: a ground-coupled impulse radar and an air-coupled stepped-frequency radar. The impulse GPR, a high-efficiency non-destructive testing technique which is widely used in civil engineering, provides accurate geometric information, especially for pavement investigation. In the second innovative approach, air-coupled stepped-frequency radar was combined with full waveform inversion to obtain quantitative information, while retrieving the electromagnetic properties of the successive pavement layers.

We concentrated on the early-stage water imbibition in the pavement structure, using the impulse GPR to estimate the fluid transfer velocity and both GPR techniques to verify the saturated porous layer assumption in the steady state. Ground-coupled radar could follow the water front and could capture different water-transfer behaviours in the porous asphalt layer. Our observation could be explained by

25 the vertical topology of the upper watertight interface. Air-coupled stepped-frequency GPR presented
26 similar results to ground-coupled GPR, but could quantitatively estimate also the changes within the
27 porous layer during the test.

28 ***Keywords: GPR, stepped-frequency radar, full waveform inversion, pavement, water imbibition.***

29

30

31 **INTRODUCTION**

32 In the context of climate change and road designs promoting economical and environmentally
33 friendly maintenance, innovative anti-ice road structures are necessary. The principle is to use an
34 asphalt pavement as an energy source, in order to prevent the formation of ice and snow on roads by
35 storing the solar energy captured on the road during hot periods and using this captured energy during
36 cold periods. Successful, economical and environment-friendly anti-icing techniques are needed to
37 increase road safety and mobility.

38 Various innovations for using asphalt pavements as an energy source have been studied earlier (e.g.,
39 Pan *et al.* 2015; Andriopoulos 2012), the most recent ones focusing on asphalt solar collectors (Bobes *et*
40 *al.* 2013). The present study focuses on another concept of heat exchange installations based on the use
41 of drainage asphalt in the bonding layer through which a heated fluid flows via gravity to de-ice the
42 roadway (Asfour *et al.* 2016). A full-scale experiment site was designed to test the various technologies,
43 from the supply of heat transfer fluid and the heat-transfer behaviour through the pavement structure, to
44 geothermal storage.

45 To better fit the modelling of thermal fluid flows to our experiment, non-destructive testing (NDT)
46 was performed in this test site using two ground-penetrating radar (GPR) techniques. GPR is a high-
47 efficiency NDT technique which is widely used in civil engineering (e.g., Lai *et al.* 2017). GPR

48 provides accurate geometric information, especially for pavement investigation (e.g., Saarenketo and
49 Scullion 2000; Loizos and Plati 2007).

50 This study concentrated on water imbibition at the early stage in a pavement structure.
51 Investigations were carried out using an impulse GPR with ground-coupled antennas to estimate the
52 fluid transfer velocity. Another complementary NDT was performed using static air-coupled stepped-
53 frequency radar (SFR) combined with full waveform inversion (FWI) to quantitatively estimate the
54 changes of the saturated trench in the porous layer, during the test. This innovative approach allows
55 very-high frequency investigations, offering high resolution (Dérobert *et al.* 2001) in combination with
56 calibrated wave propagation, which can be fitted with the results of an accurate forward model
57 describing the complete signal. This methodology enables retrieving the electromagnetic (EM)
58 properties of the successive pavement layers (Guan *et al.* 2017).

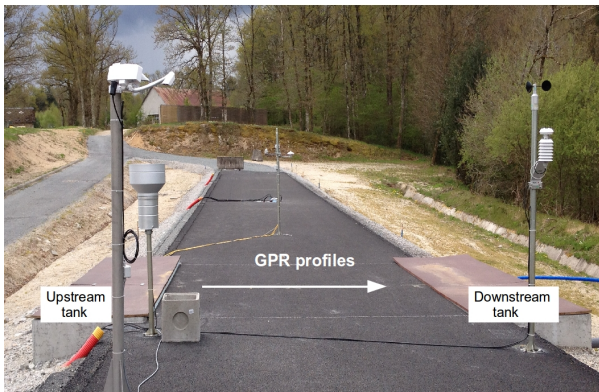
59 In the following, after a discussion on the test site, the NDT techniques and the monitoring
60 methodology will be presented. These will be followed by results and discussion.

61

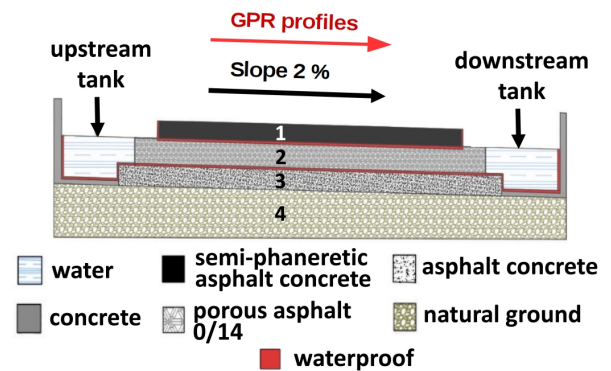
62 **POROUS PAVEMENT TEST SITE**

63 A pavement structure was built in Egletons (France) in order to experimentally validate the heat
64 exchanger function to retrieve solar energy in summer and defreeze road surfaces in winter (Fig. 1a).
65 The pavement structure is composed of three layers (Fig. 1b): a wearing course of semi-phaneritic
66 asphalt concrete 6 cm thick (WL); a bonding course of 0/14 porous asphalt 8 cm thick (PAL); and a
67 base layer of asphalt concrete 5 cm thick (BL). The porous asphalt layer has a porosity of 20%, through
68 which a fluid (water) circulates via gravitational flow because of the slope (2%). The dimensions of this
69 structure are about 3.2 m in cross section and less than 4 m in longitudinal section (traffic lane). Lateral
70 borders are made watertight to cause the water to flow in a single direction.

a)



b)



71 Fig. 1. Diagram showing the porous pavement test site and the orientation of the transverse GPR profiles

72 Two tanks, one upstream and another downstream, were built to supply and recover circulating fluid
73 in the asphalt drainage layer. Fluid circulation was maintained by a watertight seal between the porous
74 asphalt course and the underlying layer. A pump was used to control different hydraulic head losses
75 between the upstream and downstream tanks (fluid levels in the tanks). Different hydraulic regimes
76 were achieved with varying pump powers. In order to develop hydrothermal models for such a
77 pavement, we need to verify the saturated porous layer assumption when the water level in each tank is
78 on top of the porous layer.

79

80

81 **NON-DESTRUCTIVE MONITORING TECHNIQUES**

82 ***Impulse radar technique***

83 Two commercial, impulse GPR systems (SIR3000 by GSSI) were used in parallel with ground-
84 coupled 2.6 GHz antennas to limit the duration of the measurement series. The setting parameters were:
85 time range of 10 ns, 512 sampling for A-scans, frequency-band filtering 500 MHz – 5 GHz, constant

86 time gain -6 dB, and a spatial sampling of 1 cm. At center frequency of 2.6 GHz, the first two
87 interfaces, between the wearing layer and the porous asphalt layer (WL/PAL) and between the porous
88 asphalt layer and the base layer (PAL/BL), could be resolved before water inflow, at about 1 and 2.2 ns
89 respectively, due to high EM contrasts.

90 In order to accurately monitor water inflow and transfer through the porous asphalt layer, 9 parallel
91 lines in the direction of the gravity slope, with a distance of 0.5 m between the lines, were periodically
92 surveyed (transverse GPR profiles mentioned in Fig.1b). Every 7 minutes, one impulse GPR system
93 surveyed from Line 0 to Line 4, while the second impulse GPR system did the same from Line 8 to
94 Line 5. This sequence lasted about 3 minutes. After an initial series (series 0 or time T₀) of acquisition,
95 water circulation was started from the upstream tank inside the porous asphalt layer. The saturated
96 steady state was considered established after 1.5 hour, leading to 18 series of radar measurements in 115
97 minutes.

98 After two hours of a permanent saturated state maintained by a pump controlling the water flow
99 inside the pavement, the supply was stopped allowing the natural leakage of water inside the porous
100 asphalt layer to flow to the downstream tank. This second experiment led to 16 series of impulse GPR
101 measurements in 130 minutes (about every 8 minutes).

102 The objective was to pick the double travel times of radar echoes from the different interfaces,
103 mainly the water front in the porous layer during the imbibition processes, and to monitor the fluid flow
104 and verify whether the water level joins the top of the PAL or whether some air lenses remain.

105

106 ***SFR technique***

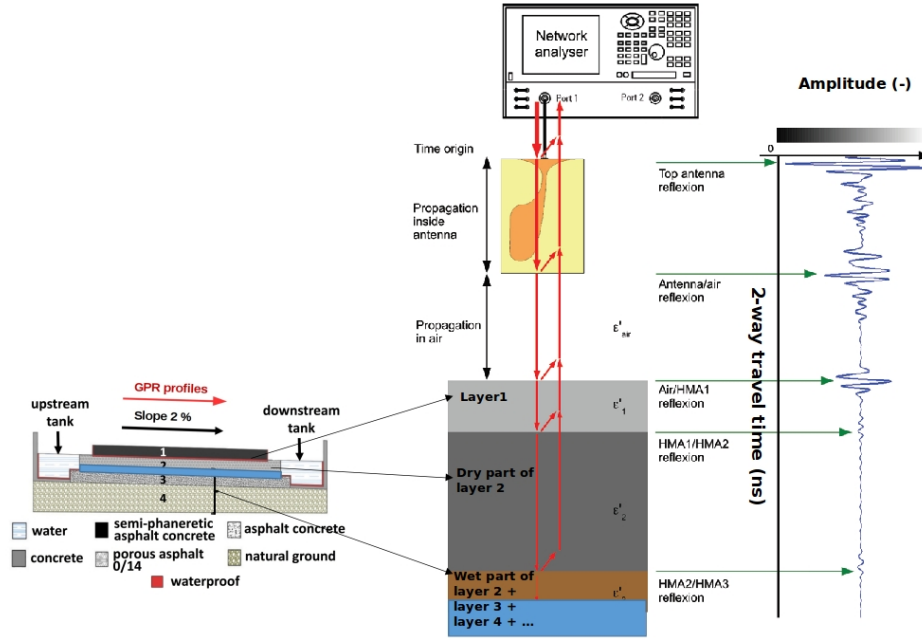
107 The second NDT method consisted of a homemade stepped-frequency radar (SFR) system with an
108 ultra-wide band (UWB), air-coupled antenna (0.8 – 8 GHz) used in near-field conditions (at 4 cm from
109 ~~the~~ the surface of the pavement structure). For this experiment, SFR measurements were performed in a

110 static mode to ensure an accurate height during the monitoring, between lines 6 and 7 at a distance of 60
111 cm from the beginning of the profiles. Data acquisition was carried out in the frequency range 0.8 – 3
112 GHz, since the antenna behaved as a dipole. SFR measurements were performed without stop during
113 each series, leading to a huge amount of data. This enabled averaging and stacking of data.

114 This particular air-coupled configuration enabled associating the data with the full-waveform GPR
115 model (Lambot *et al.* 2004, 2014). This model was used to describe the interaction between
116 electromagnetic waves and the multi-layered medium. The model is based on Green’s functions for
117 plane-layered media combined with an intrinsic representation for the antenna through global reflection
118 and transmission functions, to account for antenna effects, including antenna-medium coupling. The
119 considered pavement structure is a three-layered dispersive medium, as shown in Figure 2.

120 The dispersion in the pavement materials is described by Jonscher’s model, which has performed well
121 in describing the frequency-dependence of effective permittivity ϵ_e in materials of civil engineering
122 interest (Ihamouten *et al.* 2011). To simplify the computation and the measurement configuration in the
123 model, the spatial distribution in the near field is assumed to be constant with a single point transceiver,
124 as the antenna height is 4 cm over the studied medium. This model has been validated numerically and
125 experimentally by Guan *et al.* (2017).

126 The generalized model is described in terms of the ratio of reflected to emitted EM waves S_{II} . The
127 objective of the inversion process is to reach the best set of model parameters that minimize the
128 difference between analytical radar data S_{II}^{mod} (model) and the reference data S_{II}^{ref} (experimental data in
129 this study), in the working frequency band. This difference, generally described as a cost function, is
130 called a “residual” hereafter. Since Jonscher’s model has been chosen for the multi-layered pavement
131 structure, the model parameters of ϵ_e (integrated in Green’s function) include reference susceptibility χ_e ,
132 loss exponent n , instantaneous dielectric response ϵ_∞ , direct-current conductivity σ_{dc} , as seen in Eq. 1,
133 and the thickness h of each layer of the modelled pavement structure. This is given by,



134

135

Fig. 2. Fixed configuration of SFR on the pavement test site

136

$$\varepsilon_e(\omega) = \varepsilon_0 \chi_r \left(\frac{\omega}{\omega_r} \right)^{n-1} \left[1 - j \cot \left(\frac{n\pi}{2} \right) \right] + \varepsilon_\infty - j \frac{\sigma_{dc}}{\omega} \quad (1)$$

137

The geometry examined is simplified to 3 layers, leading to a total of 14 model parameters in the

138

analytical model: χ_e , n , ε_∞ , σ_{dc} and h of each layer. The 3 layers are WL, the dry PAL, and a virtual

139

layer composed of the saturated PAL, the BL and the natural ground (infinite thickness).

140

Due to the fact that the medium below the dry porous asphalt, during the imbibition experiment, is a

141

highly dispersive layer containing water, natural ground, etc., the entire medium below is considered as

142

an equivalent dispersive layer whose dielectric characteristics are constant from one simulated hydric

143

state to another. This hypothesis enables reducing the number of unknowns and making the inversion

144

process more robust. The water penetration depth is then estimated by inversion of SFR data at all time

145

points during the imbibition process.

146

The inversion procedure is, therefore, carried out in two steps. First, in the dry state T0, all layer

147

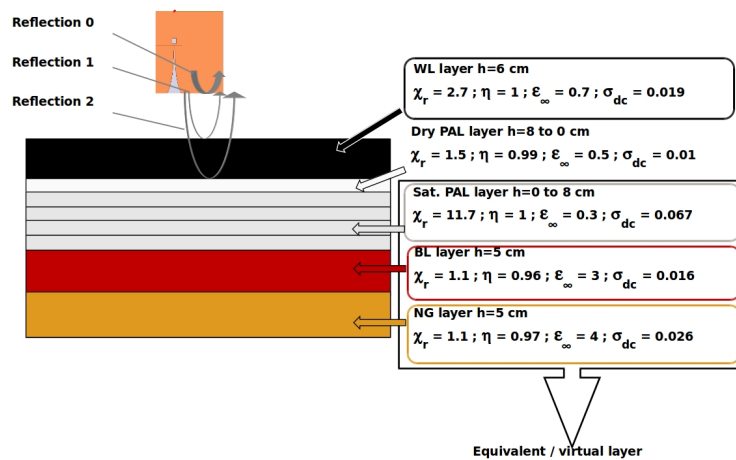
thicknesses are considered as known and the inversion of the SFR signals determines the 12 dielectric

148 parameters of Jonscher's model for the three layers (WL, dry PAL and equivalent layer). The second
 149 step of inversion considers the values of all inverted parameters from the first step as fixed and
 150 determines only the thickness of the dry porous asphalt layer. This thickness (varying theoretically from
 151 8 cm to 0 cm) is inversely proportional to the water front height in layer 2 (varying theoretically from 0
 152 cm to 8 cm).

153

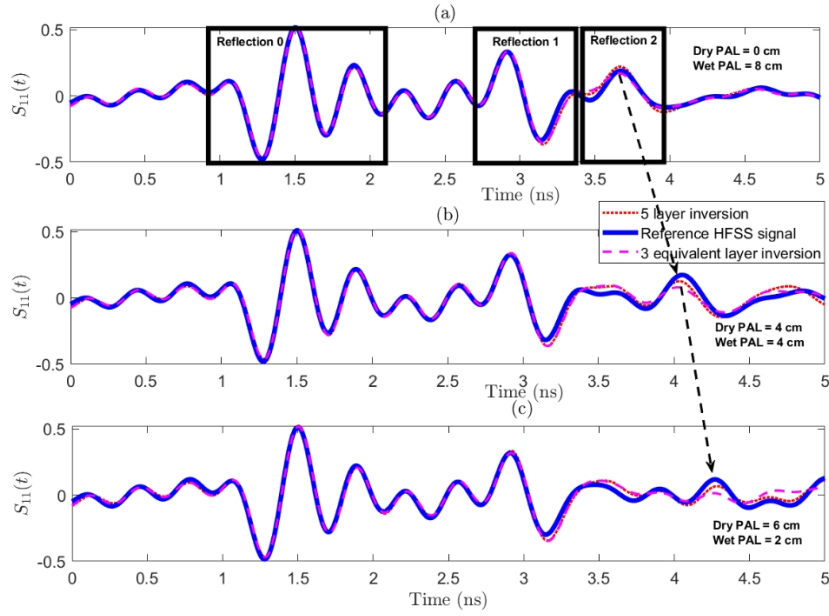
154 ***Numerical validation of the SFR inversion procedure***

155 To verify the hypothesis of an equivalent dispersive layer and evaluate its bias, we have carried out a
 156 numerical parametric study using a high-frequency simulation software (HFSS) from the ANSYS
 157 enterprise. We then compare the FWI results in terms of the residual for a complete and exact
 158 configuration made of 5 layers (Fig. 3) and for a 3-layer equivalent configuration. In considering only
 159 one medium, the values of χ_e , n , ϵ_∞ , σ_{dc} and h shown in Fig. 3 for each layer are calculated separately
 160 in the first step, using HFSS.



161

162 Fig. 3. Configuration of the SFR wave propagation numerically simulated using high-frequency simulation
 163 software (HFSS) and considering a multi-layer model representing the rise of water in the PAL



164

165 Fig. 4. Result of numerical simulation using HFSS (blue line) and FWI using 5-layered (red dotted line) and 3-
 166 layered (magenta dashed line) models, with the water level located at a) 8 cm, b) 4 cm, and c) 2 cm.

167 Fig. 4 shows an example of numerical results with a temporal representation of the HFSS reference
 168 signal (in blue), FWI signals for a 5-layer configuration (in red) and for a 3-layer equivalent
 169 configuration (in magenta) for 3 simulated hydric states (with the water front at a) 8 cm, b) 4 cm, and c)
 170 2 cm). It can be noticed that FWI can perfectly describe the near-field antenna coupling for various
 171 models. For any studied configuration, there is a close superposition of signals for the antenna internal
 172 reflections (Reflection 0), the reflection from the air/WL interface (Reflection 1) and that from the
 173 dry/saturated interface (Reflection 2). However, it can also be seen that the assumption of a 3-layer
 174 equivalent medium degrades the inversion results for Reflection 2 and for a relatively thick dry PAL.
 175 This is due to the fact that the signals corresponding to the equivalent medium are initially inverted
 176 assuming a highly dispersive medium, which considerably attenuates the waves passing through the
 177 dry/saturated PAL interface. In contrast, for the case where the dry PAL has a high thickness value
 178 (compared to the saturated PAL), the reflections from the lower interfaces (PAL/BL, BL/NG, etc.) are
 179 no longer negligible. To evaluate the generality of this bias, we present in Table 1 the FWI residuals for
 180 the two configurations examined (5 and 3 layers) for each simulated water state.

181
182

Table 1. Comparison of FWI residual for two configurations using 5-layered and 3 layered models and for each simulated water state

	FWI residual 5-layer (complete) configuration [-]	FWI residual 3-layer (equivalent) configuration [-]
Saturated PAL = 8 cm Dry Pal = 0 cm	0.2931	0.2855
Saturated PAL = 6 cm Dry Pal = 2 cm	0.3813	0.3871
Saturated PAL = 4 cm Dry Pal = 4 cm	0.3755	0.3678
Saturated PAL = 2 cm Dry Pal = 6 cm	0.4188	0.3681

183

184 The results presented in Table 1 confirm those in Fig. 4. The further we move away from the most
185 dispersive state, the higher is the residual. To evaluate the impact of a change from a residual of 0.4188
186 (5-layer inversion) to a residual of 0.3681 (3-layer equivalent inversion) on the estimated water heights,
187 in Fig. 5 we illustrate an example of the variation in residual as a function of estimated water heights (in
188 this example, Saturated PAL = 4 cm and Dry PAL = 4 cm are the references).

189 Other similar calculations (for various saturated PAL thicknesses) show an increase in the residual by
190 the same order when the error exceeds 1 cm. This confirms that the inversion results derived for a 3-
191 layer equivalent configuration, with regard to low levels of residuals, are at the precision levels of a few
192 millimeters (Fig. 5 for the saturated PAL example = 4 cm).

193

194 Fig. 5. Variation of residual with the estimated water height (in this example, saturated PAL = 4 cm and dry PAL
195 = 4 cm are the references)

196

197

198 **IMPULSE RADAR: RESULTS AND DISCUSSION**

199 *Imbibition campaign*

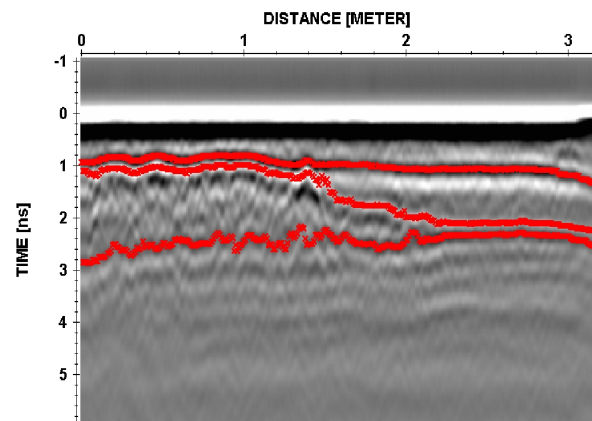
200 Transverse B-scans, confirmed by longitudinal GPR profiles made close to the tanks, show that lines
201 0 and 8 remained just outside the test site and line 1 was affected by a border. So only lines 2 to 7 were
202 processed during this campaign. Fig. 6a presents a representative raw B-scan during the water
203 imbibition process (series T3, at 16 minutes of imbibition), showing the water front between about 1.6
204 and 2.2 m, moving towards the right over time. As mentioned earlier, the original structure is clearly
205 detected, as seen in the right part of Fig. 6a. Moreover, it can be seen that the base layer (BL), above the
206 unbounded material, is laid in two stages (slightly visible interfaces at 3 and 3.4-3.6 ns), along with the
207 presence of an embedded thermal sensor located at the WL/PAL interface at about 1.40 m from the
208 beginning of the profile.

209 Use of a high center frequency of 2.6 GHz results in scattering on aggregates in the B-scan, mainly
210 visible in the saturated porous asphalt layer. This level of scattering requires an event picking process
211 which utilizes the main reflection amplitudes: the WL/PAL interface is picked considering the black
212 polarity while the water interface is picked on the white polarity, given the opposite permittivity
213 contrasts.

214 The location of the water front becomes ambiguous when the water reaches WL. This interaction
215 merging the two elementary echoes induces time shifts and amplitude modification that affect the
216 picking of both interfaces. We cannot, therefore, ensure a good correspondence between the picked
217 horizon and the WL/PAL interface. This effect is visible in the left in Fig. 6b,- the porous asphalt layer
218 being saturated. Considering the PAL to be fully saturated, the white-polarity picking of the water front
219 should replace the WL/PAL interface picking at T0 before imbibition. Moreover, WL/PAL picking
220 shown in the left side in Fig. 6b is not representative of the interface location. This step is executed only
221 to evaluate the level of disturbance in the polarity of the reflection event during monitoring.

a)

b)



222 Fig. 6. a) Raw impulse GPR B-scan, performed on Line 3 at series T3 (16 minutes of imbibition); b) Same B-
223 scan with horizons picked.

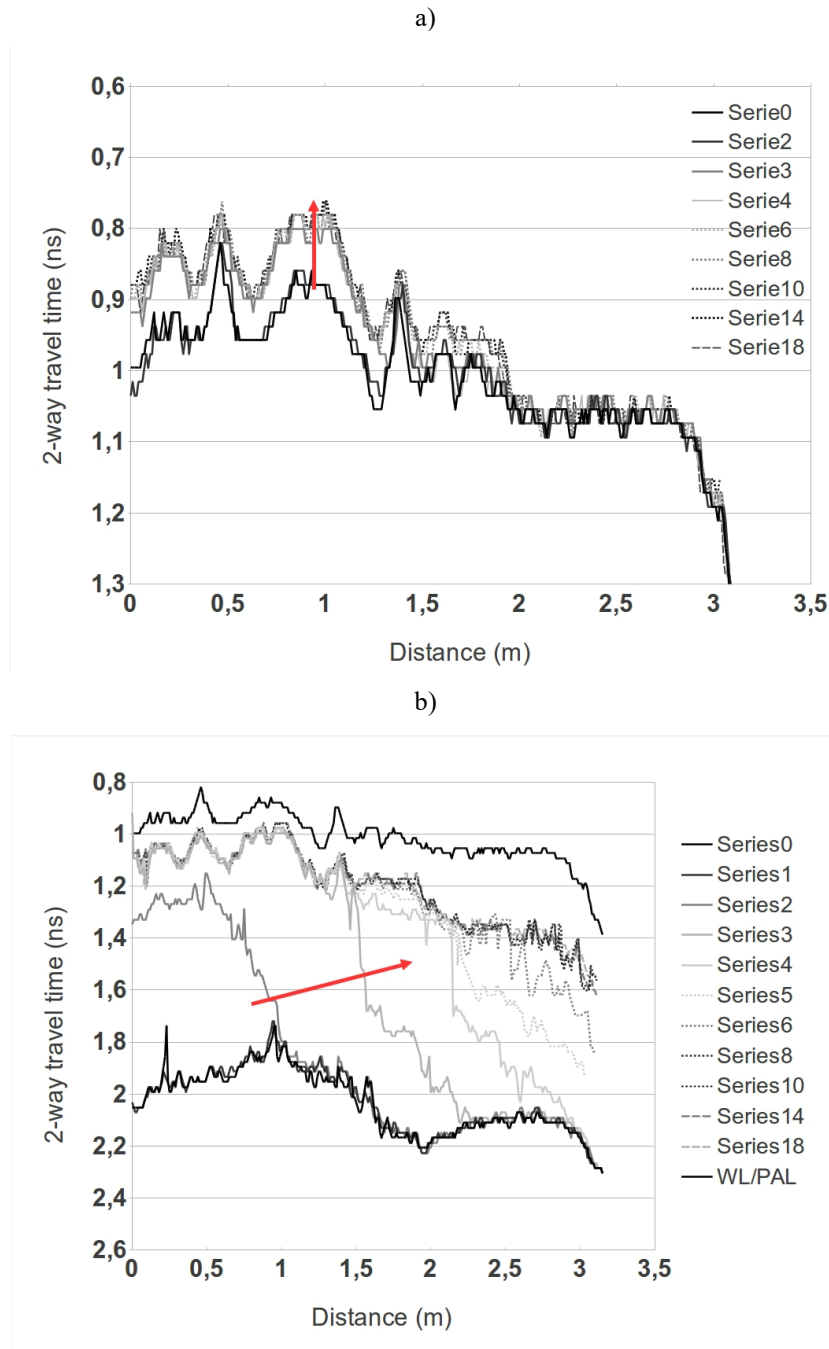
224 The following two picked interfaces (WL/PAL and water front) present a nearly half-period decay as
225 visible in Fig. 6b, thus suggesting a very thin layer of dry PAL. Nevertheless, the limited resolution
226 causing overlap of the two echoes creates a problem in picking the correct polarity and the correct
227 location, in the transition zones (before approximately 1.4 m and after 2.2 m for the case of series T3 in
228 Fig. 6b).

229 This phenomenon is similar to the third picked layer, as the first arrival (white polarity) is not visible
230 at the bottom of the saturated part (see on the left in Fig. 6b). Concerning the right part (after 2.2 m in
231 Fig. 6b), where water front has not yet reached, the visible polarity of the PAL/BL interface suggests an
232 EM property contrast decreasing with depth despite decreasing porosity. This implies some remaining
233 water at the bottom of the PAL, after the purge conducted before the imbibition campaign (not visible
234 by impulse GPR, possibly due to capillary effects masking the water). This hypothesis suggests that
235 additional caution is required in standard GPR survey, when estimating thickness of open porous layers,
236 using time picking .

237 While picking the black polarity for WL/PAL reflection during the monitoring (Fig. 7a), a time shift
238 can be seen in the left part due to the apparent saturation of the PAL. This effect becomes invisible after
239 1.4 m. At this specific location, the presence of an embedded thermal sensor, combined with the effect
240 of topography at this interface, probably explain the different behaviour of the flow path on each
241 side. This time shift after first 1.4 m is confirmed in Fig. 7b while picking the water-front reflection
242 (white polarity). Nevertheless, as mentioned above, the water front arrival time should have reached the
243 WL/PAL interface before the imbibition. This time difference (about 0.1 ns) suggests an incomplete
244 saturation in this part, although not visible on the profiles. The water flow is visible from series T2
245 (eleventh minute), going through the structure in less than 40 minutes. Moreover, our results show that
246 a complete saturation of the PAL is not reached in the steady state over the last meter.

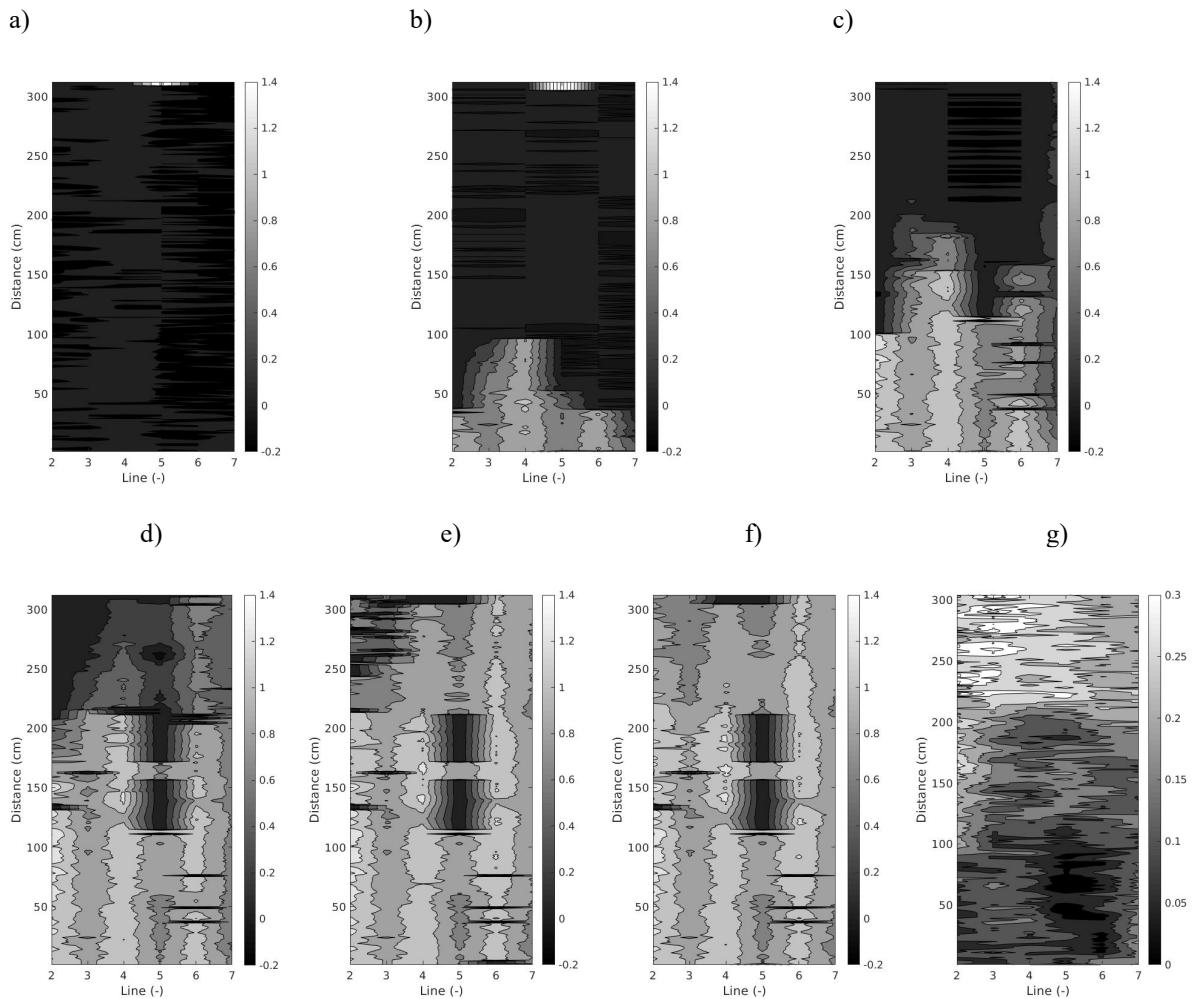
247 Monitoring of the water front is summarized in Fig. 7b, showing also the fluid transfer velocity. The
248 water front reaches the opposite side of the road in about 24 minutes (between T4 and T5). The right

249 part of the structure is then filled with water. It can be noticed that an air lens, between 1.5 and 3.2 m,
 250 remains visible in the steady state (after series T8), as the difference in the picked polarity does not
 251 explain the time shift between WL/PAL interface and the water front.



252 Fig. 7. Time picking for different series performed on Line 3: a) on the WL/PAL interface, b) for the water front
 253 entering PAL. The WL/PAL black curve corresponds to series 0.

255 Event picking was performed on every line for the water front and gathered to form a map, showing
 256 the variation of travel times due to water flow (T_0-T_i). Fig. 8 shows the progress of water flow within
 257 the first 8 series, and no more notable evolution after this time (see Fig. 8f representing a nearly steady
 258 state). It should be noted that for series T3 to T8 on Line 4, it was not possible to detect and pick the
 259 water-front reflection all along the profile. As a consequence, two dark areas remain in the maps.



260 Fig. 8. Impulse GPR monitoring showing variations of reflection travel times for the water front (in ns), a) T0-
 261 T1, b) T0-T2, c) T0-T3, d) T0-T4, e) T0-T6, f) T0-T8. g) Picking the time shift between the W/PAL interface
 262 (T0) and the water front (T8) in the steady-state flow.

263 Fig. 8g shows the remaining time shift between the W/PAL interface before imbibition and the water
264 front in the steady state. It can be seen that the PAL is not fully saturated. This is explained by the fact
265 that the edge of the downstream tank is located at the bottom of the PAL. As a consequence, the water
266 flow is not sufficient to counterbalance the water leakage in the downstream area.

267 Impulse GPR monitoring does not detect the clear air lens trapped on top of the PAL. These results
268 show the possibility of monitoring the water flow along a transverse slope, as well as along a slightly
269 longitudinal slope.

270

271 *Purge campaign*

272 During the purge and water leakage, capillary effects did not induce any sharp water front.
273 Moreover, the high EM contrasts in the PAL induced visible scattering in the B-scans (Fig. 9a) and,
274 therefore, no clear EM interface to be detected by impulse GPR. As seen in the T'16 B-scans of Line 3
275 (Fig. 9b), the visible water table was detectable after more than 1.5 hour.

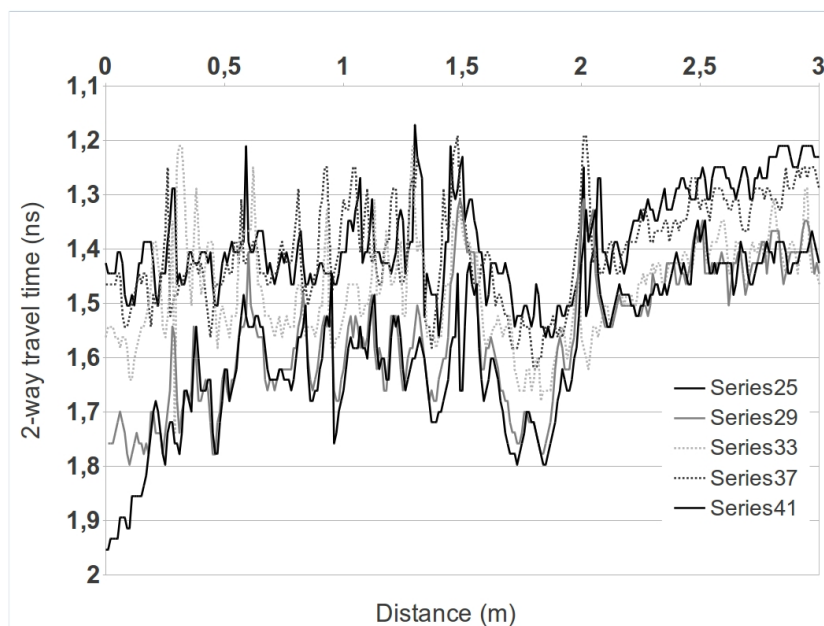
a)

b)

276 Fig. 9. GPR B-scans performed on Line 3 during the purge: a) at T'0 (series 25), b) at T'16 (series 41 – 3h).

277 The effect of water leakage on impulse GPR measurements was visible from the start, allowing time
278 picking for the bottom interface of the PAL. Average permittivity, decreasing with a decrease in the
279 average water content, increased the GPR wave velocities and hence reduced the arrival times.

280 The results are summarized in Fig. 10, showing shifts in arrival time (2-way traveltime) from
281 upstream (left part of the curves) to downstream (right part). This effect is visible around 1 hour 50
282 minutes (series 33) after the start of the purge. Dispersion in the picked travel times can be noted due to
283 the high level of scattering in the PAL (see Fig. 9a) due to high EM contrasts.



284

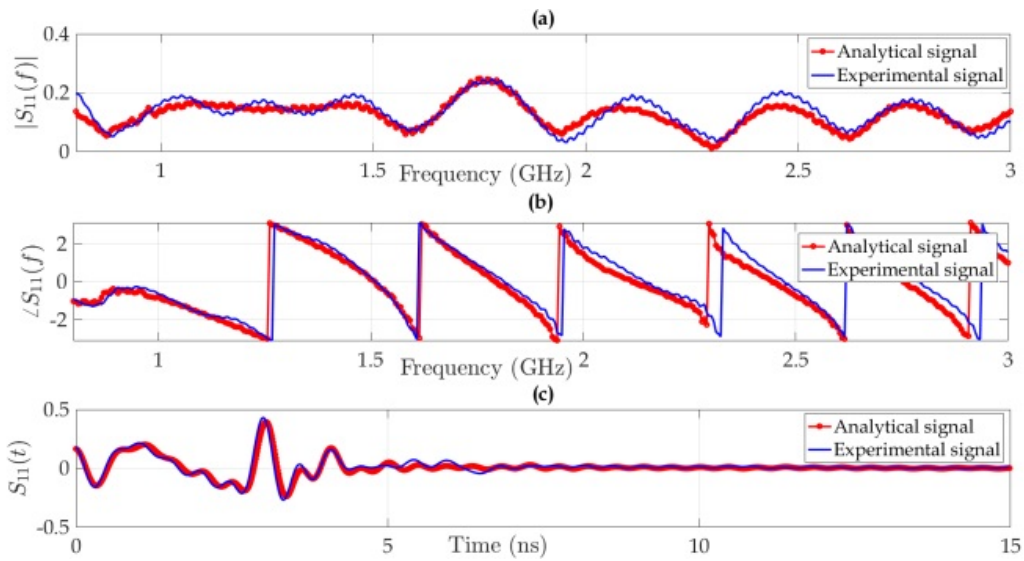
285 Fig. 10. Time picking for the PAL/BL interface for different series performed on Line 3.

286

287 SFR RESULTS AND DISCUSSION

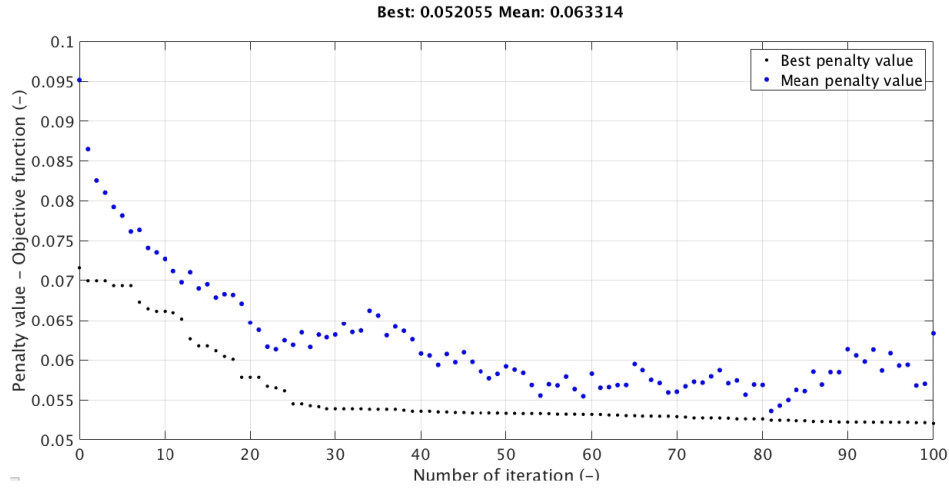
288 The SFR inversion process is detailed for the initial test time (T0) by way of an example. The
289 objective function gives a minimal value of 0.052, which indicates that the match is good in the
290 frequency domain. The correspondence between analytical (model) and experimental GPR data is
291 shown in Fig. 11.

292 Note that the small differences are due to the assumption of the so called “equivalent layer”. It
 293 should also be mentioned that the reflections in the time domain (see Fig. 11c) are hard to distinguish,
 294 as they are very similar. In this case, it is not possible to use the usual amplitude inversion in the time
 295 domain, but full waveform inversion in the frequency domain remains a powerful tool for such a case.
 296 This inversion returns a global minimum, as shown in Fig. 12. The inversion results for the
 297 experimental radar data, which shows the inverted Jonscher’s model parameters of the pavement layers,
 298 are presented in Table 2 and in Fig. 13 in terms of complex permittivities of each layer.



299

300 Fig. 11. Comparison between analytical and experimental signals, $S_{11}^{mod}(f_i, m)$ and $S_{11}^{ref}(f_i)$, at the end of inversion.

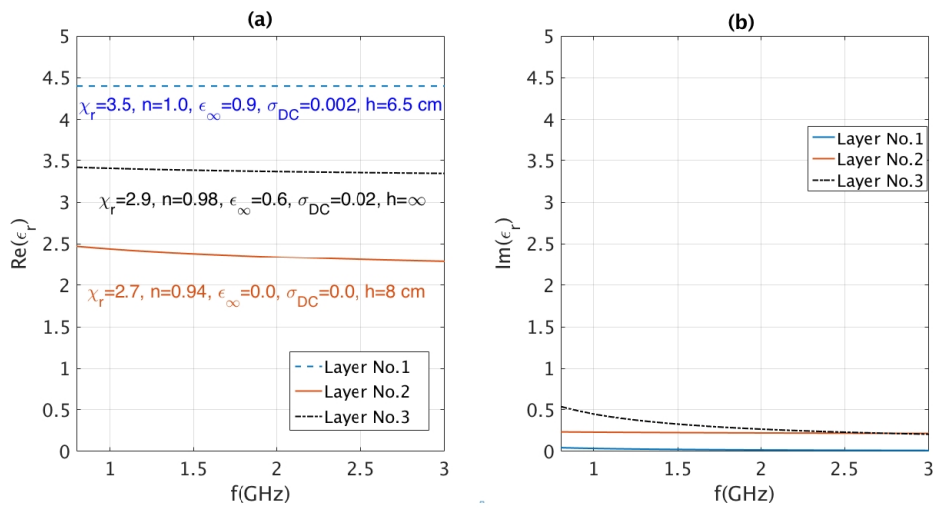


301

302

Fig. 12. Evolution of the objective function as a function of iteration number.

303



304

305

Fig. 13. Inverted effective permittivities for the three layers considered.

306

307

308

309

It should be noted that these results are obtained in the initial dry state T0, where the thicknesses of each layer are well-known. These inverted parameters (Table 2) will be considered in the rest of the experimental/inversion process as invariables (inversion input), and the inversion output will then be limited to the thickness of the dry porous asphalt layer (dry part of layer 2).

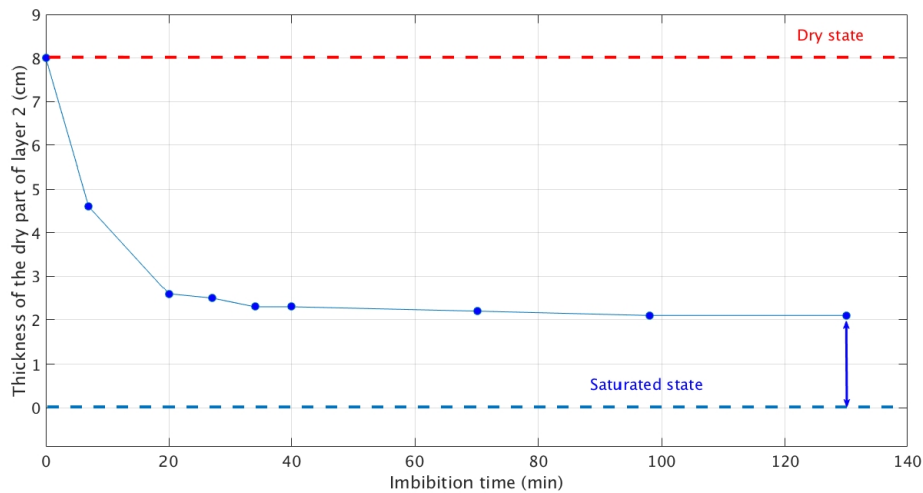
310

Table 2. FWI results for the three layers considered

Layer	χ_r	n	ϵ_∞	s_{dc}	h (known) [cm]
Layer 1	3.5	1.0	0.9	0.002	6.5
Layer 2 (dry PAL)	2.7	0.94	0.0	0.000	8
Virtual equivalent layer 3	2.9	0.98	0.6	0.020	-

311

312 Direct measurement (not shown in the present paper) at a fixed point shows the penetration of the
313 water into the material. It allowed us to follow (as with the impulse radar data) the intrusion of the
314 water front into layer 2. However, temporal time picking gives an indication of the evolution of the
315 water front but not of its exact position. We, therefore, carried out inversions of the SFR signals at times
316 T_0 , T_1 , T_3 , T_4 , T_5 , T_6 , T_{12} , T_{17} and T_{21} ($T_0 + 7$ minutes, $T_0 + 20$ minutes, $T_0 + 27$ minutes, $T_0 + 34$
317 minutes, $T_0 + 40$ minutes, $T_0 + 70$ minutes, $T_0 + 98$ minutes and $T_0 + 130$ minutes, respectively) to
318 estimate the thickness of the dry PAL (dry part of layer 2). The results showing the inverted thicknesses
319 as a function of the imbibition time are plotted in Fig. 14. It can be seen that the water penetration front
320 does not reach the interface between layers 1 and 2. In other words, water only penetrates into the
321 drainage layer up to a maximum height of 6 cm instead of the target 8 cm.



322

323

Fig. 14. Evolution of the estimated dry thickness of the PAL during monitoring.

324

These results may, however, be biased due to the different water gradients at the location of the pavement. The slope at this measurement point is in two directions. This, incidentally, explains the results of the impulse GPR measurements for Line 6. Another explanation for this time shift pertains to the initial hydric state of the pavement structure. Before T0 of the experiment, a water purge had been performed, with some humid gradients possibly remaining due to the capillary effects. This could lead to a biased estimation of the Jonscher's parameters in the initial state, for which the associated initial value of 8 cm for the thickness of layer 2 is not realistic.

331

The last explanation, which contradicts the previous one, may arise from the hypothesis of constant EM properties of the third equivalent layer (fixed for every inversion). The water flow may induce a non-negligible bias in the fixed values defining the equivalent layer 3 and then cause a bias in the estimation of the dry thickness. Even though the accuracy of the estimated thickness values may be debatable, the monitoring experiment has shown the efficiency of NDT using GPR.

336

337

CONCLUSION

338 The monitoring of water imbibition in a porous pavement structure was performed using impulse
339 radar and SFR techniques. Impulse GPR data allowed us to follow the progress of the water front
340 through picking the travel times. In parallel, static SFR measurements were continuously performed and
341 the data were inverted using an FWI scheme in the frequency domain. The impulse GPR results
342 allowed us to follow the water front and showed different behaviour for the water transfer in the PAL,
343 which could be explained by the vertical topology of the upper water-tight interface. This monitoring
344 campaign illustrated that, when estimating thickness of open porous layers using time picking of
345 reflection events, one should take- sufficient caution.

346 For the SFR measurements, a numerical parametric study was performed. This was the first step to
347 validate the hypothesis of a virtual equivalent layer. This step defined the saturated PAL, the BL and the
348 NG, thereby reducing the number of unknowns in the inversion and facilitating the convergence, while
349 limiting the number of local minima. The parameter studied here is the residual. The numerical results
350 showed that the bias caused by the equivalent thickness assumption induces an error which is much less
351 than one cm.

352 The SFR and the impulse GPR techniques offer similar results, but the SFR provides quantitative
353 information on the height of the water front inside the PAL. The two approaches have been tested and
354 adapted for monitoring water transfer in porous pavement structures.

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