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Effective Vs and Vp characterization from Surface Waves streamer data along river embankments.

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ABSTRACT

River embankments are linearly extended earth structures built for river flood protection. Their continuity and uniformity are fundamental prerequisites to ensure and maintain their protection efficiency. Weakness points usually develop in localized areas where geotechnical variability is present in the embankment body or in the underlying subsoil. Given their significant length, and the localized nature of weakness points, the characterization of river embankments cannot therefore rely on local geotechnical investigations but requires the application of efficient and economically affordable methods, able to investigate relevant lengths in a profitable way. This is even more essential when the investigations are conducted near, or in foresee of, significant flood events, when timing of the surveys is essential. In this paper the application of a procedure (W/D procedure) for the seismic characterization of river embankments, specifically designed for surface waves streamer data, is presented. The W/D procedure allows the combined definition of 2D shear (Vs) and compressional (Vp) wave velocity models and can be developed in order to be automated as a fast imaging tool. Its application to the characterization of a test site (Bormida river embankment, Piedmont Region, Italy) is presented. It is also shown that the obtained results are comparable to standard seismic processing approaches with the advantage of reduced survey time and increased efficiency, giving preliminary results directly in the field.

Article Highlights:

- Effective Vs and Vp information are extracted from surface waves streamer data;
- An automated procedure for the seismic characterization of river embankments was developed;
- The procedure is demonstrated comparable to standard seismic processing approaches;
- Advantages in survey time and efficiency is highlighted.

Keywords: surface waves, seismic characterization, river embankments.

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38 **1. INTRODUCTION**

39 River embankments are linearly extended earth structures constructed to serve as flood control
40 systems during large rain events. A proper characterization of the embankment body is essential to
41 verify its uniformity and to monitor the occurrence of possible integrity losses which could
42 undermine its stability. In recent years, frequency and magnitude of extreme flood events have been
43 rapidly increasing in Central America, Southern Europe, and in Italy because of climate change.
44 Moreover, the poor maintenance of hydraulic structures, mostly reaching their design service life,
45 makes the adoption of specific interventions of paramount international relevance.

46 Given the significant length extension of these structures, and the localized nature of weakness
47 points, the characterization cannot rely only on local geotechnical investigations but requires the
48 application of efficient and economically affordable methods, able to investigate the whole
49 embankments in a profitable way. Moreover, geotechnical investigations usually require invasive
50 procedures (such as boreholes, penetration tests, etc) that are both expensive and time-consuming.
51 With this respect non-invasive, rapid and cost-effective methods are desirable to identify higher
52 potential hazard zones.

53 Among the available non-invasive geophysical methods (Chao et al., 2006; Bergamo et al., 2016;
54 Takahashi et al., 2014; Sentenac et al., 2018), the seismic ones have peculiar advantages for the soil
55 characterization. Seismic velocities, and particularly shear wave velocity (V_s), are directly related
56 to the dynamic stiffness of the material, which is an important mechanical parameter for the
57 recognition of soil layers. Moreover, in the field of geotechnical engineering, huge research effort
58 has been spent on the correlation of V_s to parameters obtained from standard geotechnical tests. Site
59 specific and general correlations exist to porosity, plasticity index, to the shear modulus at higher
60 strains and to standard geotechnical in situ tests such as cone penetration, standard penetration and
61 dilatometer tests (e.g. Kramer, 1996; Samui, 2010; Foti et al., 20014).

62 Among the seismic methods the multichannel analysis of surface waves (MASW), based on the
63 Rayleigh wave dispersion curve (DC) analysis, is considered the most effective for the
64 determination of V_s profiles. This method can be efficiently applied to seismic streamer data
65 dragged along embankments and overall linear earth structures. This allows the determination of
66 several V_s profiles to offer an almost 2D representation of the velocity field. Several literature
67 applications of this methodology are available along embankments, river dykes and earth dams (e.g.
68 Lutz et al., 2011; Lane et al., 2008; Min and Kim, 2006). Eventually, MASW surveys can be used
69 in combination with geoelectrical and geotechnical methods to allow for more complete
70 characterization (e.g. Samyn et al., 2014; Busato et al., 2016; Bièvre et al., 2017; Rahimi et al.,
71 2018; Arato et al. 2020).

72 The main limitations of this methodology are related to the high non-linearity of the DC inversion
73 procedure and to the lack of compressional wave velocity (V_p) information. Several global
74 inversion approaches have been proposed for the DC inversion (e.g. [Socco and Boiero, 2008](#)), with
75 the aim of tackling the problem of non-uniqueness of the solution. More elaborated inversion
76 strategies for reconstructing 2D shear wave velocity sections including waveform information (e.g.
77 wave-equation dispersion inversion (WD), [Li et al., 2017](#), or multi-objective waveform inversion
78 (MOWI), [Pan et al., 2020](#)) have been also proposed. Nevertheless, all these approaches are highly
79 time consuming, particularly for increasing number of DCs to be analysed, and can be adopted only
80 in the post-processing stage, not allowing for an effective in situ characterization. The lack of V_p
81 information can also be a disadvantage since V_p is known to be correlated with saturation levels
82 and related Poisson ratio of the materials. This last could be indeed an important parameter to be
83 determined along river embankments, to complete the characterization.

84 To overcome these limitations, the application of a new procedure ([Socco et al., 2017](#); [Socco and](#)
85 [Comina, 2017](#)) for the analysis of Rayleigh wave fundamental mode DC is adopted in this paper.
86 This procedure is based on the relationship between Rayleigh wave wavelength and investigation
87 depth (W/D procedure) and exploit the higher sensitivity of the DCs to time-average shear wave
88 velocity ($V_{s,z}$) than to layered velocity profiles and the sensitivity of the Rayleigh wave skin depth
89 to V_p . The W/D procedure allows the determination of both 2D V_s and V_p sections from the DCs
90 using a direct data transform approach. The relationship between the wavelength of the Rayleigh
91 wave fundamental mode and the investigation depth (W/D relationship) is estimated through a
92 reference V_s and $V_{s,z}$ profile and used to directly transform all DCs into V_s profiles. The sensitivity
93 of the W/D relationship to Poisson ratio is moreover exploited to obtain also V_p profiles along the
94 studied embankment. The procedure has already demonstrated its reliability both on synthetic and
95 real data, producing V_s and V_p models which allow a reliable waveform matching in comparison to
96 benchmarks ([Khosro Anjom et al., 2019](#)) and effective full waveform inversion starting models
97 ([Teodor et al., 2020](#)).

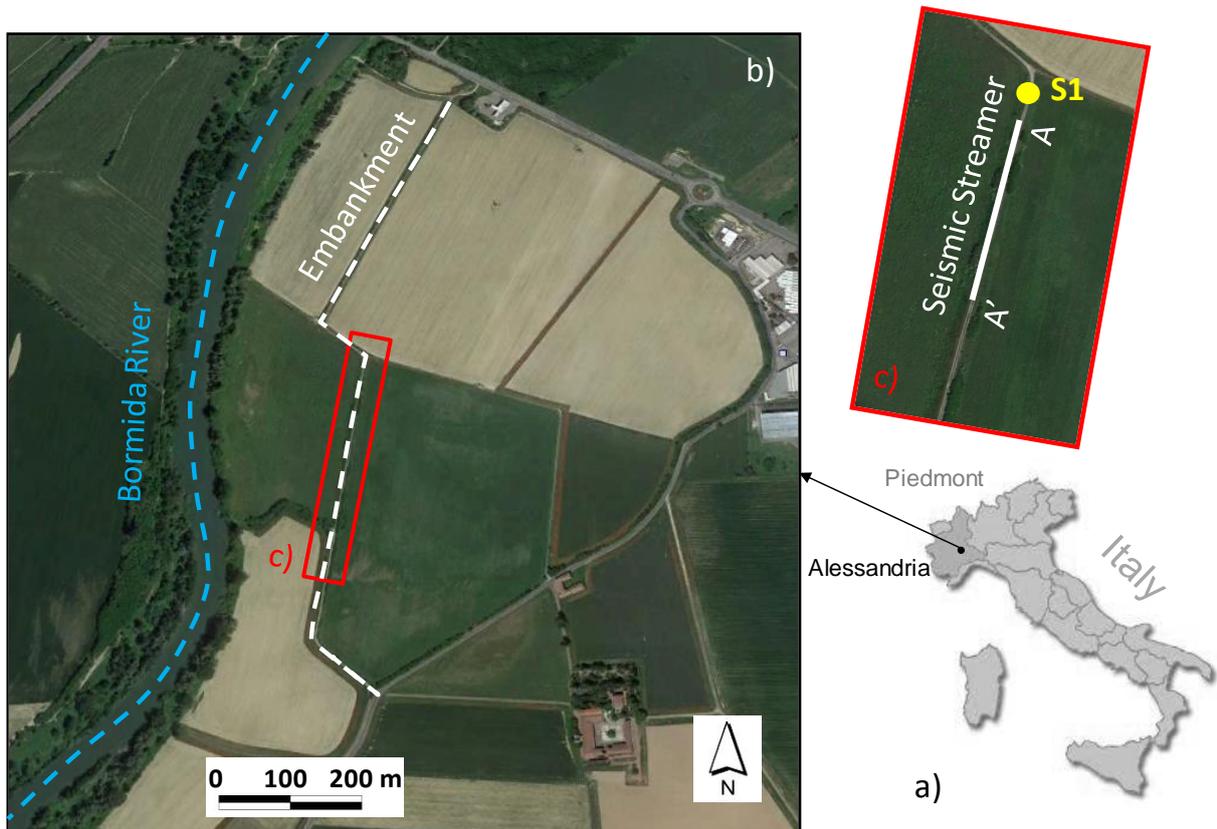
98 Another significant advantage of the proposed W/D procedure is that, being a data transform
99 approach, it does not have particular computational requirements. In principle, it could therefore be
100 applied also during in situ measurement campaigns for a fast imaging of the seismic properties of
101 the studied embankment. This products a strong reduction of survey time and increased efficiency.
102 In this paper, the procedure is specifically implemented for surface waves streamer data and its
103 application to the characterization of a test site (Bormida river embankment, Piedmont Region,
104 Italy) is presented. It is shown that the obtained results are comparable to standard seismic

105 processing approaches with the advantage of reduced survey time and increased efficiency, and that
106 preliminary results can be obtained directly during in situ measurements.

107

108 2. TEST SITE AND EXECUTED SURVEYS

109 The test site investigated in this paper is the right embankment of the Bormida river, east of the city
110 of Alessandria, in Spinetta Marengo municipality, Piedmont Region, NW Italy (Figure 1). The
111 embankment is separated from the river by the presence of a 200 m wide floodplain that serves as
112 expansion area during floods (Figure 1). The top of the embankment rises about 9 m from the free
113 surface of the river, and about 3 m from the floodplain. The soil composition of the embankment
114 (embankment body and foundation) was obtained by available geotechnical tests: a borehole,
115 executed on the top of the embankment in correspondence of an embankment curve (S1, in Figure 1
116 inlet) and a dynamic penetration super heavy test (DPSH) executed in the proximity of the borehole.
117 Both the borehole and DPSH interested embankment body and foundation soil till about 16 m
118 depth.



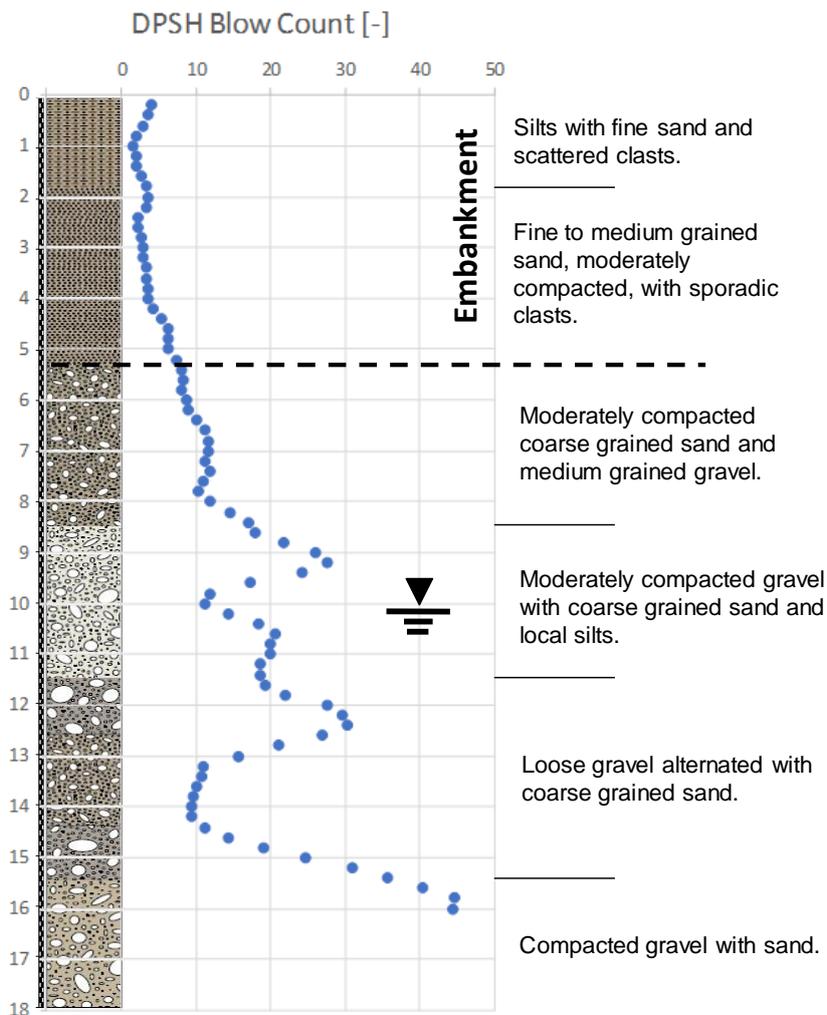
119

120 **Figure 1 – Location of the test site: a) north western Italian Po plain, Piedmont region, near the city of**
121 **Alessandria, b) detail of the studied embankment and c) executed surveys.**

122 The geotechnical setting (Figure 2) can be synthesized as constituted by silts with fine sands and
123 scattered clasts changing to fine to medium grained sands, moderately compacted, with sporadic

124 clasts, up to about 5.3 m depth (embankment body) overlaying a coarse sand and gravel formation
125 moderately to medium compacted with intercalated silts and local compaction reduction with depth.
126 At the moment of execution of the borehole (November 2007) the water table was reported at about
127 10 m depth from the embankment top; given the height of the river, the water table is therefore
128 supposed to be fed by the river and its elevation strictly dependent on the water level within the
129 river.

130 As it can be observed in the stratigraphic log, the transition from embankment body to natural
131 subsoil does not appear to be particularly sharp. This can be an indication that the construction
132 procedure did not involved relevant reworking of the first subsoil and that lateral differences in
133 depth and nature of this contact could be present along the embankment. Taking as reference the
134 DPSH result, local eventual differences along the embankment body will be investigated using
135 seismic streamer data dragged along a specific portion of the embankment (Figure 1).



136

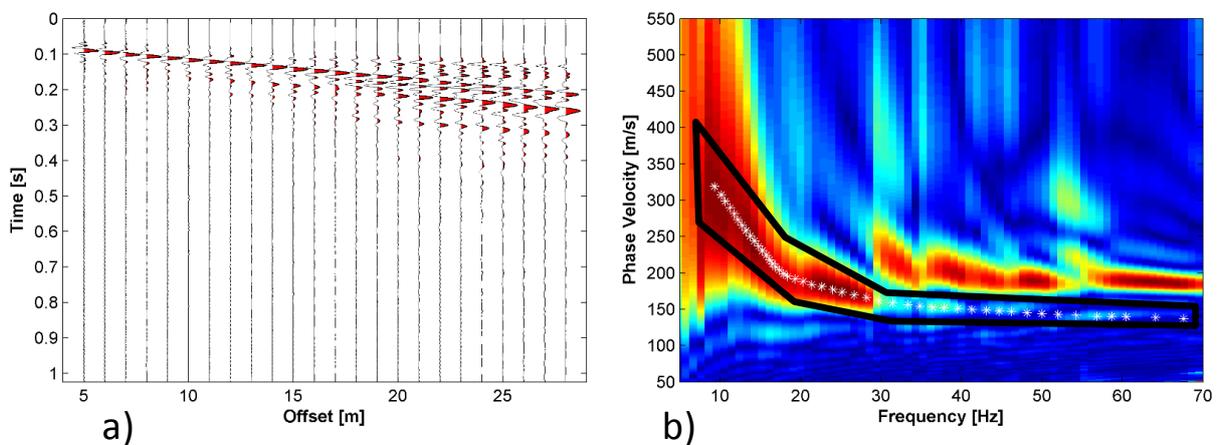
137 **Figure 2 – Stratigraphic log and geotechnical description of the encountered formations with evidence**
138 **of the DPSH results.**

139 An embankment sector of about 90 m, south with respect to the S1 borehole (Figure 1), was
140 investigated in May 2019 with a seismic land streamer constituted of 24, 4.5 Hz vertical geophones
141 mounted on coupling sliders at 1 m spacing. The streamer was dragged by a pick-up truck and was
142 moved along the studied reach at 2 m steps; for each moving step a single seismic shot was
143 registered. The seismic source was a 40 kg accelerated mass mounted on the pick-up back; a 5 m
144 source offset was adopted in the acquisitions. The streamer was connected to a DaQLink IV
145 (Seismic Source, 2016) acquisition device on the pick-up truck, storing the data in a survey laptop
146 and eventually applying pre-processing steps. Seismograms were acquired with a 0.5 ms sampling
147 interval, -50 ms pretrig and 1.024 s total recording length. A total of 45 seismograms were therefore
148 acquired during the survey. On these data several processing steps were applied for the definition of
149 2D Vs and Vp models with the proposed W/D procedure.

150

151 3. METHODOLOGY

152 An example seismic shot is reported in Figure 3a. The used source and streamer setup allowed the
153 acquisition of high-quality data, with clear evidence of surface waves dispersive pattern and also
154 particularly evident first arrivals of compressional waves.



155

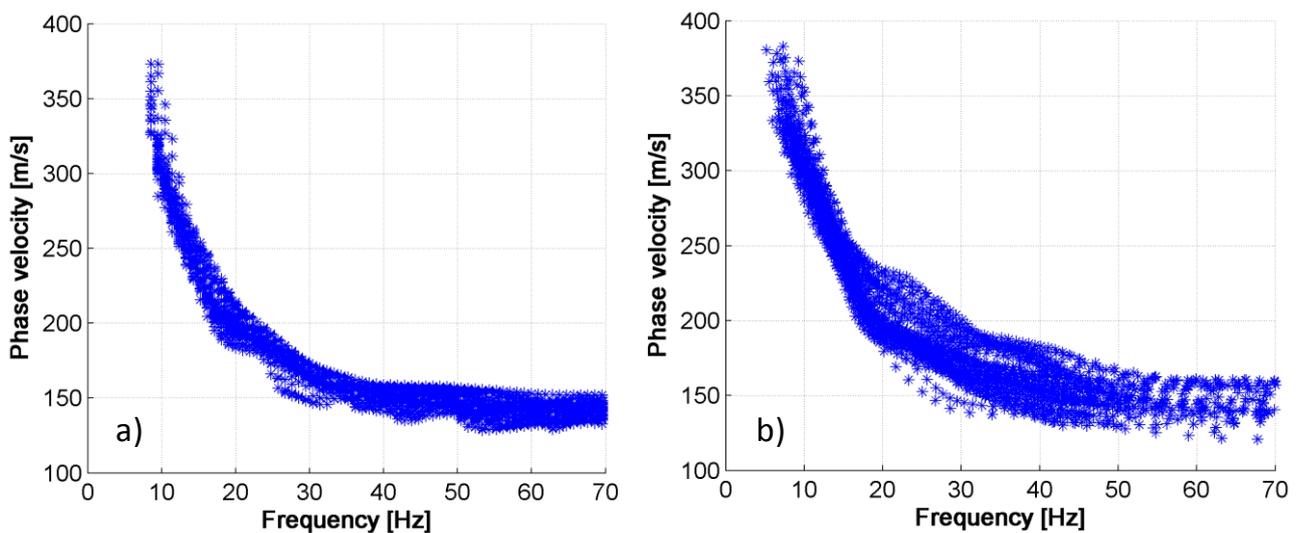
156 **Figure 3 – Data processing procedures on acquired seismograms: a) example seismic shot, b)**
157 **dispersion curve extraction with evidence of the applied mask (black line) and selected high energy**
158 **maxima (white asterisks).**

159 DCs extraction was performed with two different procedures: first, the dispersion image for each
160 seismogram was obtained by means of a phase-shift approach (Park et al., 1998) implemented in
161 MATLAB® routines. The phase-shift approach has demonstrated to maintain very good
162 performances even when a limited number of traces is considered (Dal Moro et al., 2005).
163 Alternatively, to further improve the accuracy of dispersion measurement, a multi-channel

164 nonlinear signal comparison (MNLSC, [Hu et al., 2019](#)) can be adopted, producing high and
165 adjustable resolution among a wide detected frequency range.

166 On the dispersion image the zone pertinent to the fundamental mode propagation was selected with
167 a mask (black line in [Figure 3b](#)) and energy maxima were automatically searched within this area
168 (white asterisks in [Figure 3b](#)). The mask selected for the first shot can be either automatically used
169 for all the following shots (automatic procedure) or partially adjusted to follow eventual variations
170 in the energy distribution (semi-automatic procedure). In the first case a rough, but fully automated,
171 DCs selection is obtained, in the second case a more refined, but more time consuming, analysis is
172 allowed, to better evidence eventual lateral variations. On both these selected DC groups eventual
173 smoothing and manual outlier removal can be applied to obtain more continuous and reliable
174 curves.

175 In [Figure 4](#) the resulting DCs selected for all the shots from automatic and semi-automatic
176 procedures are reported. For some of the shots a transition of the absolute energy maxima towards
177 higher modes was observed in the high-frequency range (e.g. frequencies higher than 30Hz in
178 [Figure 3b](#)). Nevertheless the fundamental mode can still be followed as local maxima thank to the
179 adopted mask that allowed to isolate the correct portion of the dispersion image to be considered,
180 excluding the higher modes from the maxima searching. It can be evidenced that the DC ranges are
181 very similar with corresponding velocity transition. Nevertheless, the semi-automatic procedure
182 ([Figure 4b](#)) shows higher variability for the medium-high frequency range (shallower layers) as a
183 result of the application of a variable mask. Most of the results reported in the paper refer to the
184 DCs selected with this approach. In the discussion section some comparisons are however presented
185 with the results obtainable with the automatic procedure also.



186

187 **Figure 4 – DCs selected for all the shots: a) automatic procedure and b) semi-automatic procedure.**

188 The application of the W/D procedure to the extracted DCs requires the knowledge of a single V_s
189 and $V_{s,z}$ reference profile along the seismic line together with its associated DC. This profile can be
190 either extracted from the data themselves, by performing the inversion of a representative DC
191 among the ones extracted, or it can be obtained by independent seismic or geotechnical data.

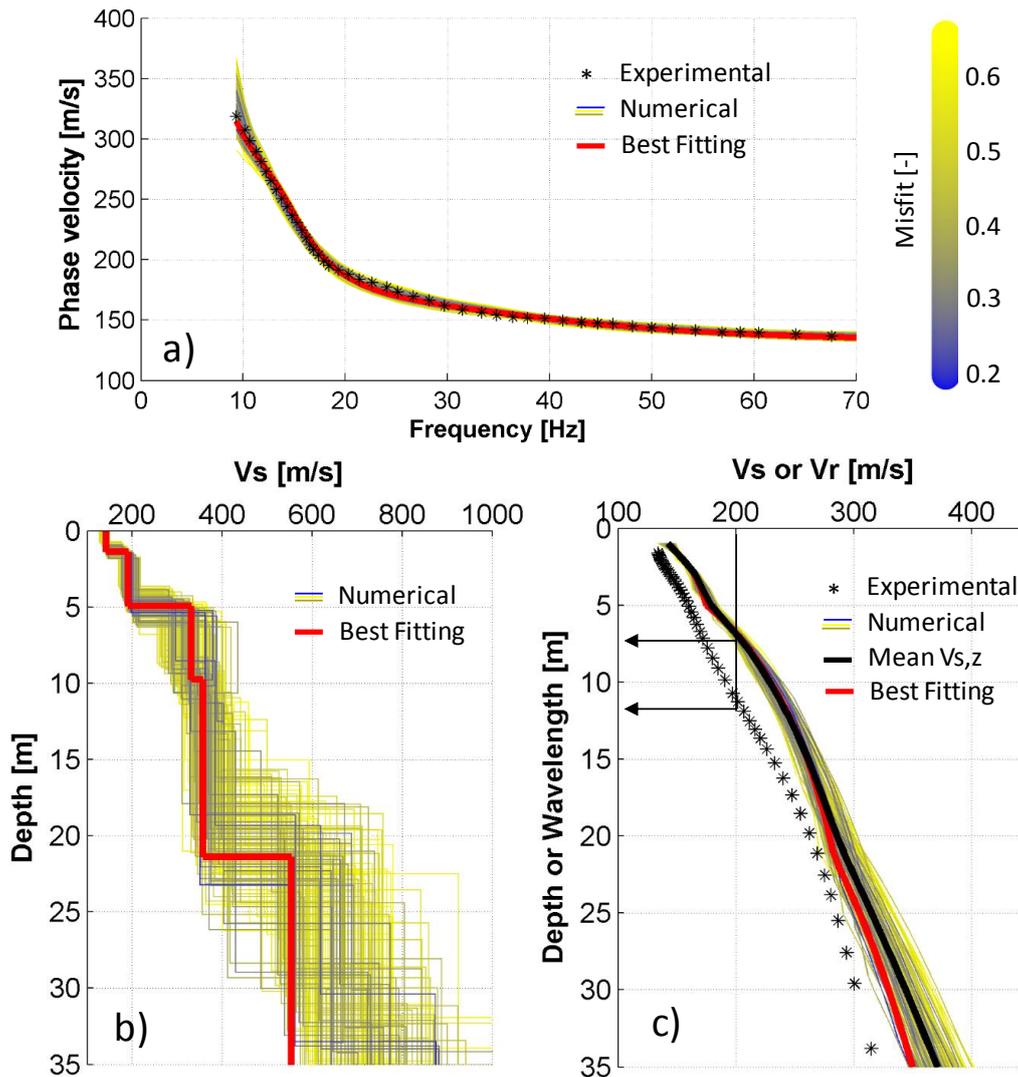
192 In this paper the first method was adopted using a Monte Carlo Inversion (MCI) algorithm (Socco
193 and Boiero, 2008) which efficiently limits potential non-uniqueness of the solution and results in
194 reliable V_s and $V_{s,z}$ profiles. The inversion implies the definition of a wide model space by
195 selecting ranges for each model parameter (V_s , thicknesses and the Poisson ratio of each layer) and
196 performing random sampling (10^5 profiles) among these ranges. Please note that, in order to allow
197 for the W/D procedure to be applied, also Poisson ratio of each layer is considered as a model
198 parameter, contrary to what usually performed in the inversion of DC curves.

199 Example application of the inversion process to the DC reported in Figure 3b, which was selected
200 as reference, is reported in Figure 5. It can be observed that the set of statistical equivalent profiles
201 selected from the MCI assess the presence of a contrast at the bottom of the embankment around 5
202 m depth (Figure 5b). This set of profiles, and their correspondent numerical DCs, is represented in
203 Figure 5 with a relative misfit representation based on the absolute difference between each profile
204 misfit and the best fitting one (in red in Figure 5).

205 It can also be noted that the higher variability in terms of V_s profiles (Figure 5b) strongly reduces
206 when the time average shear wave velocity is considered ($V_{s,z}$, in Figure 5c). With this respect the
207 best selected profile (in red in Figure 5c) and the mean of the statistical set (in black in Figure 5c)
208 almost superimpose for the top portion of the profile. Socco and Comina (2015) have already shown
209 that the non-uniqueness of the DC inversion very slightly affects the estimation of time-average
210 velocity, and hence, the $V_{s,z}$ obtained from inverted profiles is very robust. Nevertheless, given the
211 increased uncertainty at the bottom of the profile, the following analyses were limited to 20 m
212 depth, which is enough for investigating both the embankment and a significant portion of the
213 foundation subsoil at the studied test site.

214 Using the reference V_s and $V_{s,z}$ profiles and all the extracted DCs, the proposed data transform
215 procedure is then applied as following: i) the estimated $V_{s,z}$ and its corresponding DC are used to
216 compute the reference W/D relationship; ii) the reference W/D relationship is used to transform all
217 DCs into $V_{s,z}$ models; iii) an apparent Poisson ratio is estimated using the reference W/D
218 relationship and the reference V_s model; iv) using the apparent Poisson ratio, each $V_{s,z}$ profile is
219 transformed into a $V_{p,z}$ profile; v) all the reconstructed $V_{s,z}$ and $V_{p,z}$ profiles are transformed into
220 V_s and V_p profiles with an interval velocity analysis.

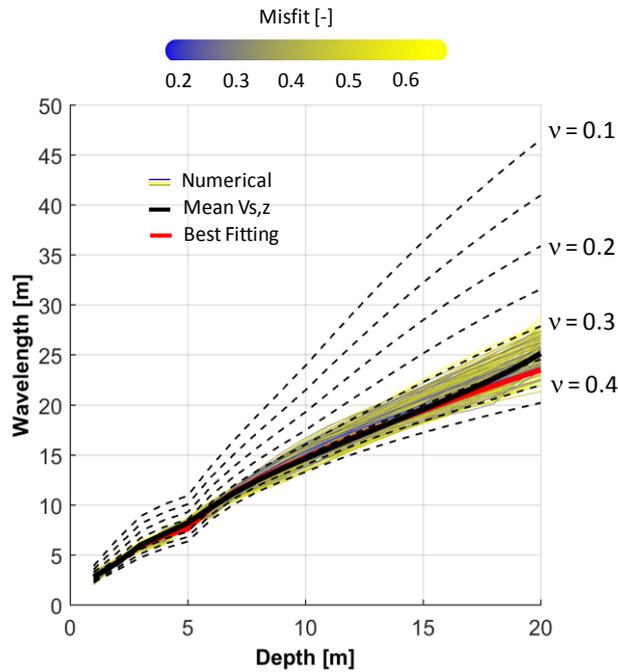
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222

223 **Figure 5 – MCI of the reference DC curve: a) experimental and numerical dispersion curves b) best**
 224 **fitting profile and set of statistically equivalent profiles and c) experimental dispersion curve as a**
 225 **function of wavelength, time average velocities of best fitting profile and statistically equivalent**
 226 **profiles with their mean.**

227 Steps i) and iii) of the procedure require more explanations. The meaning of the W/D relationship is
 228 represented in [Figure 5c](#): for each $V_{s,z}$ value, the wavelength (W) at which the phase velocity (V_r)
 229 of the DC is equal to the $V_{s,z}$ (see the arrows in [Figure 5c](#)) is searched for each depth (D). With all
 230 the W/D pairs at which $V_{s,z}$ and phase velocity are equal a relationship is obtained (W/D
 231 relationship). This relationship is represented in [Figure 6](#) for the best fitting profile (in red), for the
 232 mean of the statistically equivalent profiles (in black) and for all the statistically equivalent profiles.
 233 Consistency of the extracted W/D relationships is evidenced.



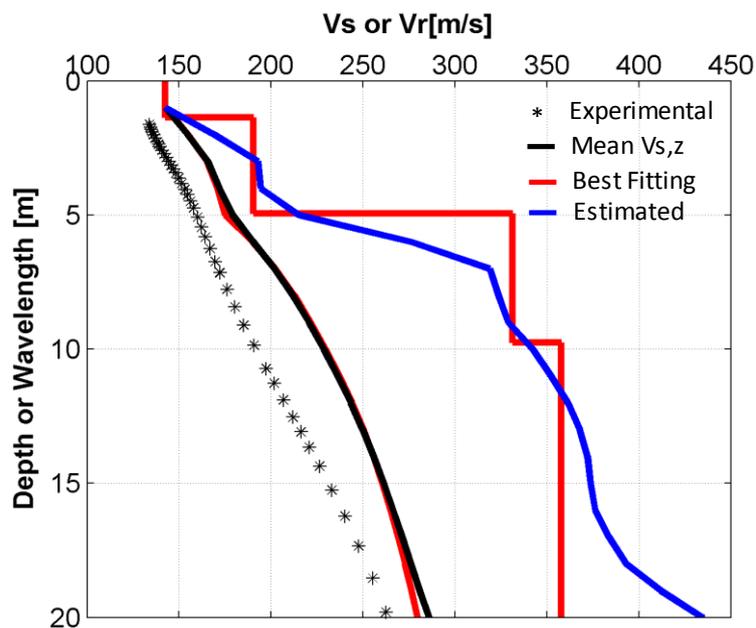
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235 **Figure 6 – The W/D relationship for the reference DC for the best fitting profile (in red), for the mean**
 236 **of the statistically equivalent profiles (in black) and for all the statistically equivalent profiles**
 237 **compared with the ones obtained with different Poisson ratio values. Reference Poisson ratio values**
 238 **are indicated on the right of the plot.**

239 This relationship represents the surface waves' skin depth for increasing wavelengths and has been
 240 demonstrated (Socco and Comina, 2017) to be influenced by the Poisson ratio of the formation.
 241 With the reference V_s and $V_{s,z}$ profiles it is therefore possible to build different synthetic W/D
 242 relationships by changing the value of the Poisson ratio (ν) of the layers (assumed constant for all
 243 the layers). These synthetic W/D relationships are reported in Figure 6 (dashed black lines) for
 244 some example values of the Poisson ratio. It can be noted that Poisson ratio acts on the slope of
 245 W/D relationship. In particular, the slope decreases when Poisson ratio increases. Therefore the
 246 slope of the experimentally determined W/D relationship contains information on the actual Poisson
 247 ratio of the formation. The actual apparent Poisson ratio profile of the formation can be therefore
 248 searched by associating to each depth the value of Poisson ratio that corresponds to the linear
 249 interpolation between the upper and lower nearest synthetic W/D relationships. In this way an
 250 apparent Poisson ratio profile with depth can be obtained for the reference DC. This profile can be
 251 later used to transform all the $V_{s,z}$ profiles into $V_{p,z}$ profiles allowing for a 2D V_p section to be
 252 later computed.

253 An example application of the W/D procedure to the reference DC is reported in Figure 7. It can be
 254 observed that the $V_{s,z}$ of the best fitting profile (continuous red line in Figure 7) and the mean $V_{s,z}$
 255 of the statistical set (continuous black line in Figure 7) almost superimpose for the first 20 m depth.

256 It can be also noted that the W/D procedure allows the estimate of a V_s model (in blue in Figure 7)
 257 very near to the best fitting one (layered red line in Figure 7) obtained from the MCI of the DC. The
 258 model obtained with this procedure has also the advantage of not making any assumption with
 259 respect to the number of layers of the profile. For this reason, it can result smoother with respect to
 260 the layered profile but also more correspondent to the actual geotechnical situation below the
 261 embankment. Particularly, it can be observed that the transition from embankment body to bottom
 262 layers with this estimated profile appear to be more correspondent to what evidenced in the DPSH
 263 results (Figure 2) with respect to the sharp interface evidenced by the MCI result.



264
 265 **Figure 7 – Application of the W/D procedure to the reference DC for V_s profile determination and**
 266 **comparison with the best fitting result (both in term of layered velocity model and $V_{s,z}$) from MCI.**

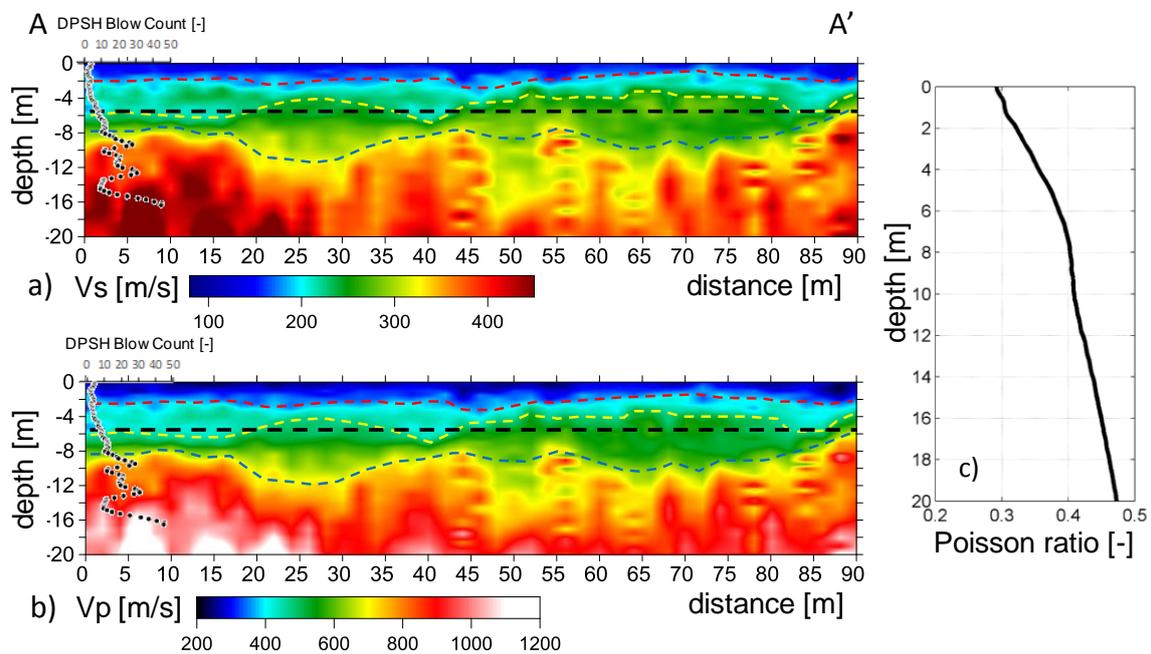
267 All the V_s and V_p profiles estimated with the W/D procedure are then interpolated along the studied
 268 embankment to allow for a 2D visualization of the V_s and V_p velocities distributions. The data
 269 gridding was performed in Surfer (Golden software) with an interpolation grid of 2 m in the
 270 horizontal direction (equal to the acquisition step) and of 0.5 m in the vertical direction.

271 To validate the velocity models obtained with the application of the W/D procedure the obtained
 272 results are benchmarked against standard seismic processing approaches. For V_s , all the dispersion
 273 curves extracted were inverted with a laterally constrained inversion (LCI) approach (Auken and
 274 Christiansen, 2004; Socco et al., 2009). For this inversion, the same number of layers of the MCI
 275 was assumed. For V_p , processing was carried out by picking the first breaks on each acquired
 276 seismogram, picked first breaks were then interpreted in tomographic approach with the use of the
 277 software Rayfract (Intelligent Resources Softwares Inc.).

278

4. RESULTS

279 Results of the application of the W/D procedure are reported in Figure 8. Particularly, the V_p result
 280 is obtained from the V_s one with the application of the apparent Poisson ratio obtained from the
 281 W/D procedure. This last is assumed constant through the whole profile and therefore the resulting
 282 V_p velocity field is a transformation of the V_s one with similar properties. Both V_s and V_p sections
 283 can discriminate the transition from the shallow silts and sands to the bottom gravels along the
 284 embankment and delineate the embankment bottom. Coherently with the borehole results and
 285 geotechnical tests this transition falls, on the left side of the sections, where the surveys are nearer
 286 to the geotechnical tests (the DPSH Blow Count profile is also reported in Figure 8a and b), around
 287 5.3 m depth.



288

289 **Figure 8 – Results of the application of the W/D procedure to extracted DCs (section A-A’): a) V_s**
 290 **section, b) V_p section (colorbars below each figure) and c) resulting Poisson ratio. On both the sections**
 291 **the supposed depth of the embankment is also reported (dashed black line) together with coloured**
 292 **dashed lines, derived by the velocity models, indicating the transition between the shallow silts and**
 293 **sands (in red), the thickness of the embankment (in yellow) and the transition to compacted gravels**
 294 **and sands (in blue). The DPSH Blow Count profile is also reported at the beginning of the sections.**

295 However, along the embankment a variation of the depth of this interface can be evidenced.
 296 Particularly, localized anomalies appear in the V_s section suggesting an increase in the depth of the
 297 shallow silts and sands of the embankment (yellow dashed line in Figure 8) around 40 m
 298 progressive distance. Conversely, the depth of the interface appears to be shallower in the
 299 progressive distance range between about 50 to 80 m.

300 Seismic surveys are also able to depict the transition (red dashed line in [Figure 8](#)) from silts with
 301 fine sands and scattered clasts to fine to medium grained sands, as reported from the borehole and
 302 DPSH results, within the embankment. A deeper increase in velocity is also observed around 8 m
 303 depth on the left side of [Figure 8](#), where the transition to more compacted gravels (blue dashed line
 304 in [Figure 8](#)) is evidenced by borehole and DPSH results. This more compacted formation appears
 305 however to increase its depth along the section moving away from the borehole and showing on
 306 average lower velocity values. Localized velocity inversions are also partially observable below 8 m
 307 in the leftmost portions of the Vs section. This evidence again well compares with what reported by
 308 the DPSH results.

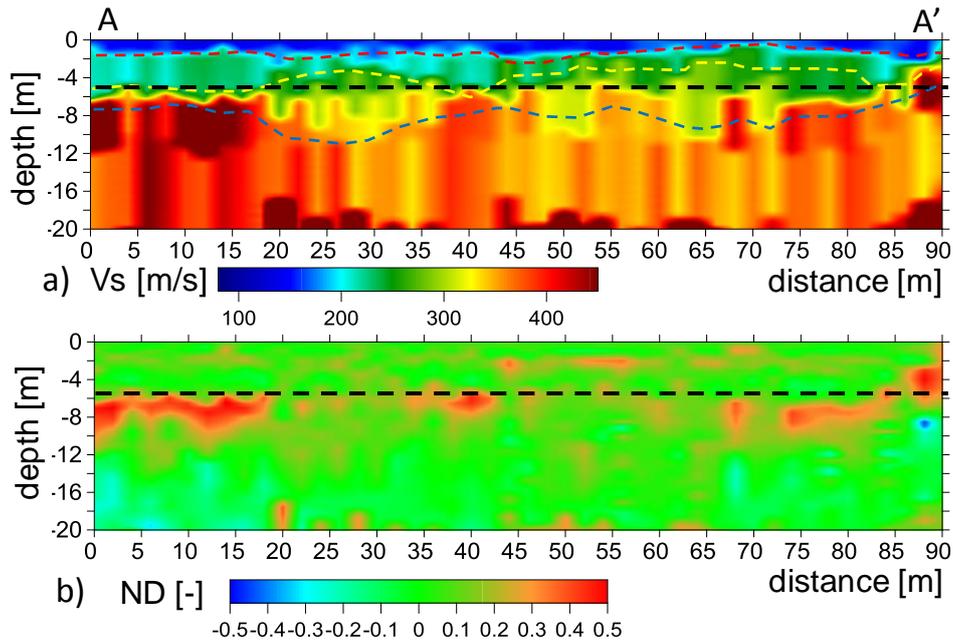
309 Notwithstanding the information on the position of the water table at the site (around 10 m) the
 310 range of Vp velocities extracted by the procedure does not report, for increasing depths, velocity
 311 ranges usually attributed to saturated materials (i.e. around 1400-1500 m/s). It must be underlined
 312 that the time span between the two surveys is relevant (from November 2007 to May 2019) so that
 313 eventual variations on the water table depth could be present. Nevertheless, the Poisson ratio profile
 314 extracted with the W/D procedure ([Figure 8c](#)) shows a marked increase nearly around 10 m
 315 exceeding the 0.4 value and tending to 0.5. Poisson ratio of saturated soils is usually reported to be
 316 in this range ([Boore, 2007](#)). It must be underlined that the Poisson ratio profile here presented is the
 317 interval Poisson ratio obtained through the Vp/Vs ratio of the resulting models. This is different
 318 from the apparent Poisson ratio that is estimated in the W/D procedure ([Figure 6](#)) for the DC
 319 transformation.

320 Results of the LCI processing of the extracted dispersion curves are reported in [Figure 9a](#). A good
 321 convergence of the inversion was obtained with LCI resulting in a final RMS error of 1.7%.

322 The comparison of the LCI result with the W/D procedure is performed in [Figure 9b](#) in term of
 323 normalized differences, taking as reference the LCI results, with the formula:

$$324 \quad ND = \frac{V_{i,LCI} - V_{i,W/D}}{V_{i,LCI}} \quad (1)$$

325
 326 were $V_{i,W/D}$ is the velocity value obtained from the W/D procedure and $V_{i,LCI}$ is the velocity value
 327 obtained from the LCI in each location within the models. Therefore, positive values of the
 328 normalized difference indicate zones where the W/D procedure underestimate the velocity, negative
 329 values indicate the opposite. To allow computing the normalized differences in each point of the
 330 models also layered LCI results were gridded with the same interpolation scheme of the W/D
 331 procedure results.



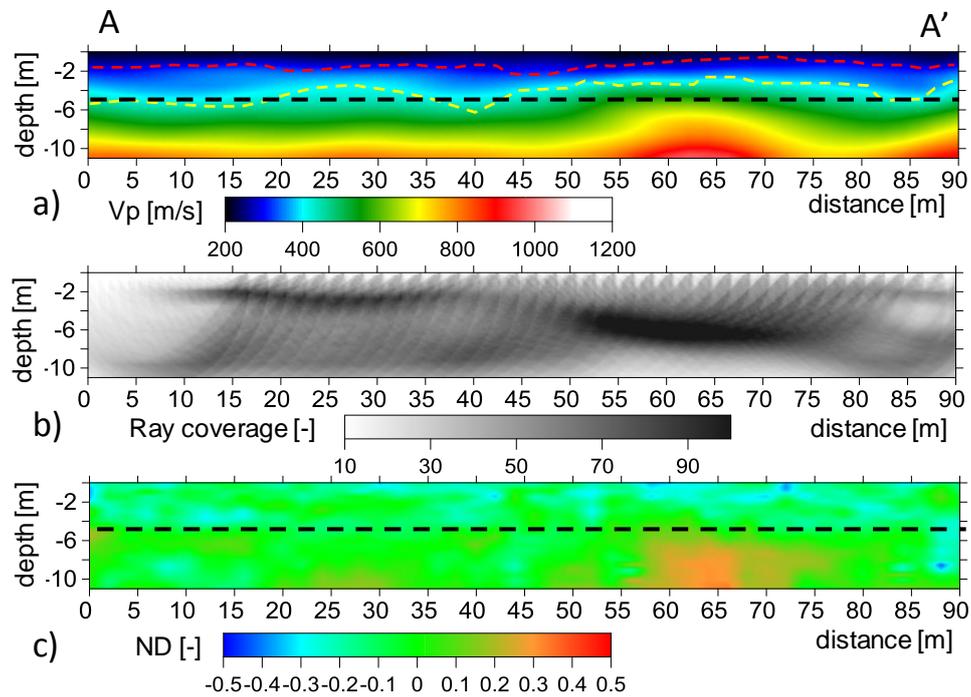
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333 **Figure 9 – Results of the LCI of the extracted DCs (section A-A’): a) Vs section and b) Normalized**
 334 **differences with the Vs results of the W/D procedure (colorbars below each figure). On both the**
 335 **sections the supposed depth of the embankment is also reported (dashed black line). Over the LCI**
 336 **section, the interfaces evidenced by the W/D procedure indicating the transition between the shallow**
 337 **silts and sands (in red), the thickness of the embankment (in yellow) and the transition to compacted**
 338 **gravels and sands (in blue), are superimposed.**

339 Figure 9 shows that the Vs velocity range obtained using LCI inversion is comparable with that
 340 from the W/D procedure. The interfaces evidenced by the W/D procedure are reported for
 341 comparison over the resulting Vs image. Similar variability in the depth of the interfaces is noted.
 342 As an example, both the increased depth of shallower silts and sands around progressive 40 m and
 343 the shallower depth of the embankment in the progressive distance range between about 50 to 80 m
 344 are confirmed. Most of the normalized differences among the W/D and LCI models fall within a
 345 $\pm 10\%$ range indicating the good correspondence of the two results. The only portions of the section
 346 affected by higher positive normalized differences cannot be attributed to errors in the W/D
 347 procedure, but to the layering assumption in the LCI. The layered discretization adopted in the LCI
 348 can indeed result in an overestimation of the velocity near the layer boundaries (see also Figure 7
 349 for comparison). Most of the higher difference values fall indeed near the embankment/foundation
 350 soil interface where the layered profile results from LCI tend to give a sharper transition than the
 351 W/D result.

352 Results of the tomographic inversion of picked first arrivals are reported in Figure 10 and
 353 compared, in term of normalized differences, with the Vp results obtained with the W/D procedure.
 354 The same equation 1 was adopted for the computation of normalized differences with Vp values

355 from W/D procedure and first arrivals tomography (these last substituting the LCI values in
356 equation 1).



357

358 **Figure 10 – Results of the first break tomography (section A-A’): a) Vp section, b) Ray coverage along**
359 **the section and c) Normalized differences with the Vp results of the W/D procedure** colorbars below
360 each figure. **On both the sections the supposed depth of the embankment is also reported (dashed**
361 **black line). Over the tomography the first two interfaces evidenced by the W/D procedure, indicating**
362 **the transition between the shallow silts and sands (in red), the thickness of the embankment (in**
363 **yellow), are superimposed.**

364 From Figure 10 it can be observed that, given the reduced length of the streamer adopted, the depth
365 of investigation of the tomography is limited to about 10 m, or even less in some portions.
366 Nevertheless, within this depth, a high ray coverage is obtained in most of the section by the
367 combined elaboration of all the shots. A good convergence of the inversion was obtained with a
368 resulting RMS error of 2.7% after the final iteration.

369 Again, from Figure 10 it can be observed that the tomographic inversion depicts the same velocity
370 range compared to the one obtained with the W/D procedure. Given the reduced investigation depth
371 of the tomography only the first two interfaces evidenced by the W/D procedure are reported for
372 comparison over the resulting Vp image. Similar variability in the depth of these two interfaces is
373 noted. As an example, both the increased depth of shallower silts and sands around progressive 40
374 m and the shallower depth of the embankment in the progressive distance range between about 50
375 to 80 m are confirmed. Being based on relatively long-path raytracing, the tomographic result

376 shows generally a reduced lateral resolution in the identification of the velocity variations within the
377 section.

378 Most of the normalized differences, also for V_p , fall within a $\pm 10\%$ range indicating the good
379 correspondence of the two results. The only portion of the section showing higher normalized
380 differences can be attributed to a lower ray coverage zone (see [Figure 10b](#) below 7 m at about 55 to
381 70 progressive distances) making the assumed V_p values less reliable in the tomography. Given its
382 shallower investigation depth, also the tomography does not highlight a marked increase of V_p
383 values, at the bottom of the model, attributable to the presence of the water table.

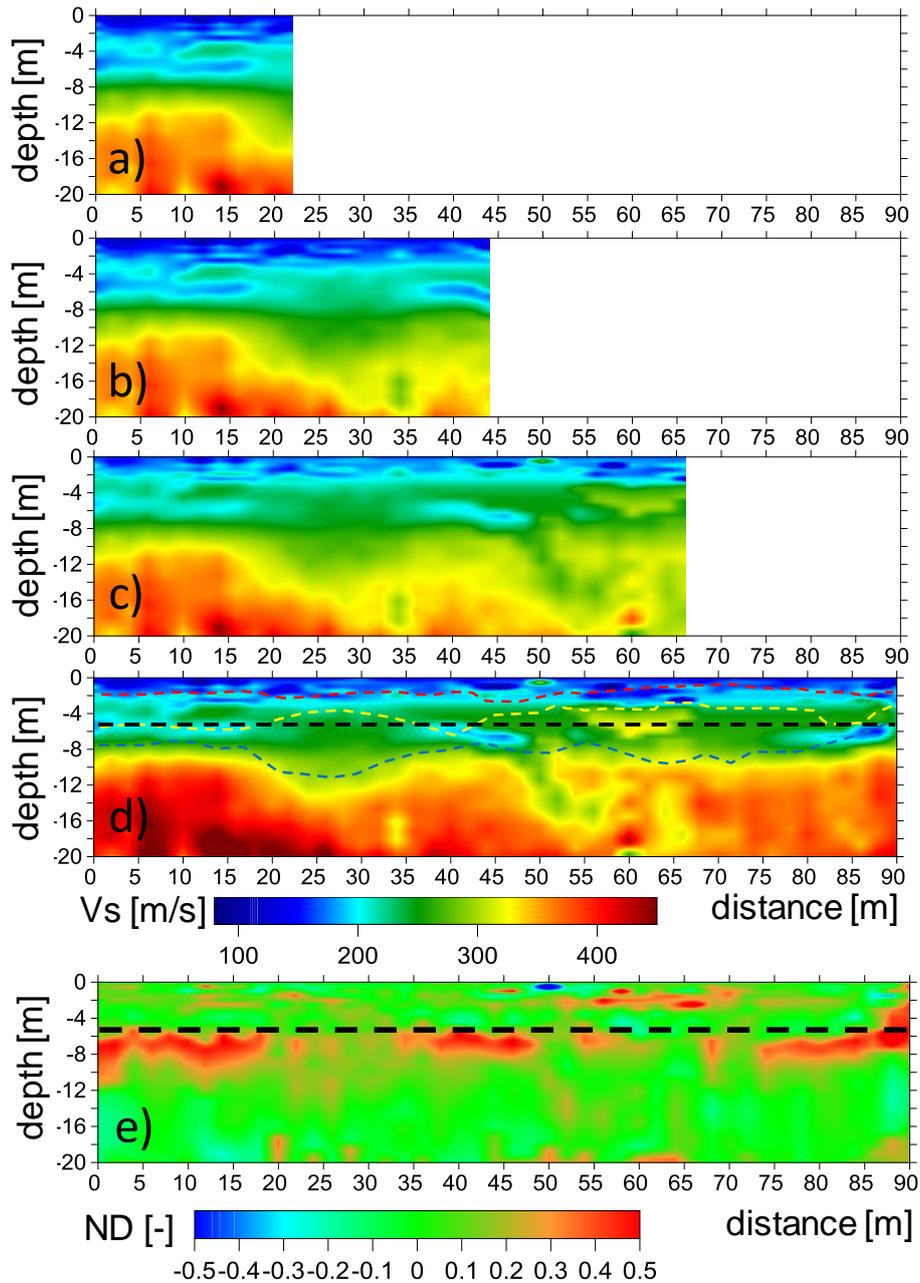
384

385 **5. DISCUSSION**

386 It was shown in the paper that the results obtainable with the W/D procedure are comparable both in
387 terms of V_s and V_p to standard seismic processing approaches. This comparison validates therefore
388 the application of the W/D procedure. It was observed, in the presented case study, that most of the
389 normalized differences between the W/D procedure and both LCI and first arrivals tomography fall
390 within a $\pm 10\%$ range, indicating the good correspondence of the two results. Higher normalized
391 differences along the sections can be attributed to different resolution or underlying
392 methodological assumptions among the methods and cannot be considered as an error in the W/D
393 procedure. A most rigorous validation of the W/D procedure could be obtained through waveform
394 matching from elastic waveform modelling and dispersion comparison. These comparisons were
395 already performed, showing very reliable results, in Khosro Anjom et al. (2019) and Teodor et al.
396 (2020). The V_s and V_p models, from LCI and first arrivals tomography, to which the W/D
397 procedure is here compared are considered standard practice for the seismic characterization.
398 Therefore, the W/D procedure can be established as a reliable alternative to the methods here
399 compared for the characterization of embankments and overall linear earth structures.

400 The W/D procedure has also main advantages with respect to usually seismic processing
401 approaches applied to the data obtained from similar surveys: i) being a data transform approach it
402 does not requires relevant processing and time consuming interpretations; ii) it does not make any
403 assumption with respect to the number of layers present along the investigated embankment and iii)
404 allow the combined estimation of V_s and V_p for increased depths given the same acquisition setup.
405 Particularly the first advantage is important if the speed of the surveys is considered, for example in
406 situations in which a fast and preliminary evaluation of the state of health of an embankment is
407 required. This can be the case of surveys conducted after, or in foresee of, significant rain and/or
408 flood events. In these conditions the W/D procedure, applied to the fully automated extracted DCs
409 ([Figure 4a](#)), can allow for a first, almost immediate, on site evaluation of the V_s and V_p velocity

410 field. Both the automated DC extraction step and the conversion of DC data to Vs and Vp profiles is
 411 indeed a very fast process (few tens of seconds on a notebook), that outputs direct velocity models
 412 while the acquisition is in progress and the streamer is dragged along the embankment.
 413 An example application of this direct visualization of the Vs section during data acquisition is
 414 reported in Figure 11. It can be particularly observed that the final Vs section determined from the
 415 fully automated extracted DCs (Figure 11d) is roughly comparable with the one determined with the
 416 semi-automatic procedure (Figure 8a) with very similar depiction of the main interfaces.



417
 418 **Figure 11 – Example application of the direct visualization of the Vs section during data acquisition:**
 419 **a), b) and c) Vs sections while dragging the streamer along the embankment; d) final Vs section and c)**
 420 **Normalized differences with the LCI (colorbars below each figure). In d) and e) the supposed depth of**
 421 **the embankment is also reported (dashed black line). In d) the interfaces evidenced by the semi-**

422 **automated W/D procedure, indicating the transition between the shallow silts and sands (in red), the**
423 **thickness of the embankment (in yellow) and the transition to compacted gravels and sands (in blue),**
424 **are superimposed.**

425

426 The presence of some artefacts can be however noted within the section and can be related to the
427 reduced precision of the automatic picking of the DCs. A general increase in the normalized
428 differences with the LCI (Figure 11d) is also observed, with the presence of localized anomalous
429 local velocity values (e.g. see the shallow portion of the embankment around progressive 50 m).
430 Nevertheless, the general imaging of the Vs structure can be considered accurate enough for a first
431 estimation of the geotechnical variability at the site and a useful tool for a preliminary identification
432 of anomalous portions of the examined embankments. Given the use of the same Poisson ratio
433 profile (Figure 8c), uniform through the section, very similar considerations can be performed for
434 what concerns the resulting Vp image.

435 This direct visualization requires the knowledge of reference Vs and Vs,z profiles over which
436 calibrate the W/D relationship and the following Poisson ratio computation. In the present paper
437 these reference profiles were obtained through MCI of a reference DC. The same approach can be
438 adopted on site at the beginning of the surveys by selecting one of the clearer DCs during the first
439 shots. Nevertheless, the MCI step can be significantly time consuming and not always applied with
440 reliability on site. Possible alternative approaches would therefore require the execution of initial
441 detailed tests and interpretations through which determine with accuracy the reference profiles and
442 only later proceed with the execution of the streamer surveys. Alternatively, the reference profiles
443 can be extracted from already available geotechnical and/or geophysical surveys along the
444 embankment. With this respect the W/D procedure already showed comparable results also with
445 respect to Down Hole surveys (Socco et al., 2017).

446 In both the automatic and semi-automatic procedures, the DCs uncertainties in the maxima
447 identifications were not considered (Figure 4). This is in-line with the aim of obtaining a fast
448 imaging tool for the seismic properties of the studied embankment. A rigorous experimental
449 uncertainties evaluation requires indeed a statistical population of test repetitions (i.e., multiple
450 shots at different locations) which could compromise the speed of the surveys. Alternative
451 uncertainties estimations can be attempted with a single seismic shot by considering, for each
452 frequency, the phase velocities whose energy maxima fall within a certain range of the of picked
453 one. These last uncertainties are a partial estimation of the true ones, since reflect the intrinsic
454 resolution of the geometrical arrangement adopted in acquisition, but could be worth considered in
455 future developments of the methodology. If experimental uncertainties are correctly estimated their

456 [propagation to the final velocity models can be obtained as performed by Khosro Anjom et al.](#)
457 [\(2019\).](#)

458 Limitations of the proposed W/D procedure can be related to: i) its application to only fundamental
459 mode DC; ii) the assumption of a laterally invariable W/D relationship and Poisson ratio along the
460 embankment. With respect to the first one, the W/D procedure has been mainly developed and
461 applied to fundamental mode DC, but some attempts have been already made to include also higher
462 propagation modes (e.g. [Bamarouf et al., 2017](#)). Including higher modes showed to give advantages
463 mainly with respect to the investigation depth, even though it is a more time-consuming process.

464 However, this could be a necessary step along embankments with peculiar shape dimensions, since
465 it is well known that the shape of the embankment could influence the surface wave dispersive
466 pattern and modes superposition (e.g. [Karl et al., 2011](#)). [Pageot et al. \(2016\)](#) have also shown that
467 internal structure layering can emphasize geometrical effects and produce DCs very different from
468 the theoretical 1D case, for both the fundamental and higher modes. In these conditions even a
469 multi-modal inversion approach could encounter some limitations to infer accurate Vs and Vp
470 models.

471 These effects have not been particularly noted at the site. As it can be observed in [Figure 3b](#), higher
472 modes are indeed present in the higher frequency range, but the fundamental mode propagation is
473 still easily recognizable as local energy maxima. This may be related to the reduced contrast
474 between the embankment body and the underlying subsoil ([Figure 2](#)) which limits the layering
475 effect and to the relevant width of the embankment (width to height ratio of about 5.5) which limits
476 the presence of 3D effects.

477 Conversely the laterally invariant assumption could be easily overcome using appropriate clustering
478 techniques on the extracted DCs that can be analysed for grouping them into subsets with
479 homogeneous properties. The W/D procedure has then to be applied to each of the identified
480 subsets. The application of this further processing step however increases again the computation
481 times and prevent a direct in situ application of the procedure but has been shown to provide
482 increased resolution in the identification of sharp lateral variations with the W/D procedure ([Khosro](#)
483 [Anjom et al., 2019](#); [Teodor et al., 2020](#)).

484 The clustering approach was judged to be unnecessary in the presented case study given the
485 uniformity of the extracted DCs (see [Figure 4](#)) which suggest the presence of smooth depth
486 variations along the embankment but the absence of particularly sharp variations. When sharp
487 lateral variations along the embankment are the main survey target alternative identification
488 methods based on the surface waves spectral properties (e.g. [Colombero et al., 2019](#)) could also be
489 applied to the acquired streamer data.

490 To allow for a more complete characterization of the state of health of embankments, seismic data
491 are usually combined with electric resistivity data. These last can indeed give important information
492 on the variations of soil composition and water saturation, detect development of weak zones and
493 identify local anomalies potentially related to seepage. The combined use of seismic and electrical
494 data can indeed provide an effective geotechnical characterization of these earth structures, as
495 shown by several research groups that are working on their integration (e.g. [Takahashi et al., 2014](#);
496 [Goff et al. 2015](#); [Lorenzo et al., 2016](#)). In this respect the W/D procedure has its natural
497 development in combination with mobile electric systems allowing also a fast and effective
498 evaluation of resistivity properties (e.g. [Kuras et al., 2007](#); [Comina et al., 2020](#)).

499 **6. CONCLUSION**

500 This paper presents the application of a novel processing approach (W/D procedure) to surface
501 wave streamer data. This approach is based on the definition a wavelength/depth (W/D) relationship
502 for surface waves and allows the combined definition of shear (V_s) and compressional (V_p) wave
503 velocities. The results obtained within the paper with the W/D procedure are comparable to
504 standard seismic processing approaches with the advantage of reduced survey time and increased
505 efficiency. It was shown in the paper as the W/D procedure can be developed in order to be
506 completely automated and used as a fast in situ imaging tool along embankments for preliminary
507 evaluations on their state of life.

508 Processing of the seismic streamer data yielded to an effective characterization of the V_s and V_p
509 velocity field along the studied embankment. The origin and properties of the anomalies
510 encountered could be better studied with the use of local geotechnical investigations to provide a
511 more specific knowledge on the state of life of the embankment. The produced seismic sections, if
512 properly calibrated with the few independent geotechnical tests available, can be nevertheless used
513 for preliminary stability evaluations also in portion of the embankment non directly covered by
514 geotechnical tests.

515 Further studies, already planned and partially executed, include the application of the W/D
516 procedure to different embankments shapes with the eventual inclusion of higher modes in the
517 interpretation. Moreover, the combined acquisition of electrical resistivity data, even with
518 innovative acquisition approaches, will allow the contemporary execution of resistivity and seismic
519 surveys with even more reduced survey time and increased knowledge on the state of health of the
520 embankments due to the acquisition of the different complementary parameters.

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526 **REFERENCES**

- 527 1. Arato A., Naldi M., Vai L., Chiappone A., Vagnon F. and Comina C. (2020) Towards a Seismo-Electric
528 land streamer, submitted for the 6th International Conference on Geotechnical and Geophysical Site
529 Characterization, 7-11 September 2020, Budapest.
- 530 2. Auken, E., and A. V. Christiansen, 2004, Layered and laterally constrained 2D inversion of resistivity
531 data: *Geophysics*, 69, 752–761.
- 532 3. Bamarouf, T., Socco, L.V. & Comina, C., 2017. Direct Statics estimation from ground roll data—the
533 role of higher modes, in 79th EAGE Conference and Exhibition.
- 534 4. Bergamo P, Dashwood B, Uhlemann S, Swift Chambers JE, Gunn DA, Donohue S (2016) Time-lapse
535 monitoring of fluid-induced geophysical property variations within an unstable earthwork using P-wave
536 refraction. *Geophysics* 81(4):17–27
- 537 5. Bièvre, G., Lacroix, P., Oxarango, L., Goutaland, D., Monnot, G., Fargier, Y., 2017. Integration of
538 geotechnical and geophysical techniques for the characterization of a small earth-filled canal dyke and
539 the localization of water leakage. *J. Appl. Geophys.* 139, 1–15.
- 540 6. Boore, D., 2007, Dave Boore's notes on Poisson's ratio (the relation between VP and VS),
541 http://www.daveboore.com/daves_notes.html, accessed 03 March 2017.
- 542 7. Busato, L., Boaga, J., Peruzzo, L., Himi, M., Cola, S., Bersan, S., Cassiani, G., 2016. Combined
543 geophysical surveys for the characterization of a reconstructed river embankment. *Eng. Geol.* 211, 74–
544 84.
- 545 8. Chao C et al (2006) Integrated geophysical techniques in detecting hidden dangers in river
546 embankments. *J Environ Eng Geophys* 11:83–94.
- 547 9. Colombero, C., Comina, C., Socco, L.V. (2019) Imaging near-surface sharp lateral variations with
548 surface-wave methods - Part 1: Detection and location, *Geophysics*, 84 (6), pp. EN93-EN111.
- 549 10. Comina C., Vagnon F., Arato A., Fantini F. and Naldi M., Application of a new electric streamer to the
550 characterization of river embankments, submitted to *Journal of Geotechnical and Geoenvironmental*
551 *engineering*.
- 552 11. Dal Moro G., M. Pipan, E. Forte and I. Finetti, 2005, Determination of Rayleigh wave dispersion curves
553 for near surface applications in unconsolidated sediments, SEG Technical Program Expanded Abstracts
554 2003, pages 1247-1250.
- 555 12. Foti, S., Lai, C.G., Rix, G.J., Strobbia, C., 2014. *Surface Wave Methods for Near-Surface Site*
556 *Characterization*. CRC Press.
- 557 13. Goff, D.S., Lorenzo, J.M., Hayashi, K. "Resistivity and shear wave velocity as a predictive tool of
558 sediment type in coastal levee foundation soils, 28th Symposium on the Application of Geophysics to
559 Engineering and environmental Problems 2015, SAGEEP 2015, pp. 145-154.
- 560 14. Hu Hao, Mustafa Senkaya, Yingcai Zheng, A novel measurement of the surface wave dispersion with
561 high and adjustable resolution: Multi-channel nonlinear signal comparison, *Journal of Applied*
562 *Geophysics*, Volume 160, 2019, Pages 236-241.
- 563 15. Karl, L., Fechner, T., Schevenels, M., François, S., Degrande, G., 2011. Geotechnical characterization
564 of a river dyke by surface waves. *Surf. Geophys.* 9, 515–527.
- 565 16. Khosro Anjom, F., D. Teodor, C. Comina, R. Brossier, J. Virieux, and L. V. Socco, 2019, Full
566 waveform matching of Vp and Vs models from surface waves, *Geophysical Journal International*, 218,
567 1873-1891.
- 568 17. Kramer S.L. 1996. *Geotechnical Earthquake Engineering*. Prentice Hall.
- 569 18. Kuras, O., Meldrum, P.I., Beamish, D., Ogilvy, R.D., Lala, D. "Capacitive resistivity imaging with
570 towed arrays", 2007, *Journal of Environmental and Engineering Geophysics*, 12 (3), pp. 267-279.

- 571 19. Lane Jr. J.W., Ivanov J., Day-Lewis F.D., Clemens D., Patev R. and Miller R.D. 2008. Levee evaluation
572 using MASW: Preliminary findings from the Citrus Lakefront Levee, New Orleans, Louisiana. 21st
573 Symposium on the Application of Geophysics to Engineering and Environmental Problems,
574 Philadelphia, USA, Expanded Abstracts, 703–712.
- 575 20. Li Jing, Zongcai Feng, Gerard Schuster, Wave-equation dispersion inversion, *Geophysical Journal*
576 *International*, Volume 208, Issue 3, 1 March 2017, Pages 1567–1578.
- 577 21. Lorenzo, J.M., Goff, D.S., Hayashi, K. "Soil-Type estimation beneath a coastal protection levee, using
578 resistivity and shear wave velocity" 22nd European Meeting of Environmental and Engineering
579 Geophysics, Near Surface Geoscience 2016.
- 580 22. Lutz K., Fechner T., Schevenels M., Stijn F. and Degrande G., 2011, Geotechnical characterization of a
581 river dyke by surface waves, *Near Surface Geophysics*, Volume9, Issue6, Pages 515-527.
- 582 23. Min D.-J. and Kim H.-S. 2006. Feasibility of the surface-wave method for the assessment of physical
583 properties of a dam using numerical analysis. *Journal of Applied Geophysics* 59, 236–243.
- 584 24. Pageot, D., Le Feuvre, M., Donatienne, L., Philippe, C., Yann, C., 2016. Importance of a 3D forward
585 modeling tool for surface wave analysis methods, in: EGU General Assembly Conference Abstracts. p.
586 11812.
- 587 25. Pan Yudi, Lingli Gao, Renat Shigapov, Multi-objective waveform inversion of shallow seismic
588 wavefields, *Geophysical Journal International*, Volume 220, Issue 3, March 2020, Pages 1619–1631.
- 589 26. Park, C. B., Xia, J., and Miller, R. D., 1998, Imaging dispersion curves of surface waves on
590 multichannel record: 68th Ann. Internat. Mtg., Soc. Explor. Geophys., Expanded Abstracts, 1377-1380.
- 591 27. Rahimi S., Clinton M. Wood, Folaseye Coker, Timothy Moody, Michelle Bernhardt-Barry, Behdad
592 Mofarraj Kouchaki, 2018, The combined use of MASW and resistivity surveys for levee assessment: A
593 case study of the Melvin Price Reach of the Wood River Levee, *Engineering Geology*, Volume 241,
594 Pages 11-24.
- 595 28. Samui, P., Sitharam, T.G. Correlation between SPT, CPT and MASW (2010) *International Journal of*
596 *Geotechnical Engineering*, 4 (2), pp. 279-288.
- 597 29. Samyn, K., Mathieu, F., Bitri, A., Nachbaur, A., Closset, L., 2014. Integrated geophysical approach in
598 assessing karst presence and sinkhole susceptibility along flood-protection dykes of the Loire River,
599 Orléans, France. *Eng. Geol.* 183, 170–184.
- 600 30. Sentenac P, Benes V, Keenan H (2018) Reservoir assessment using non-invasive geophysical
601 techniques. *Environmental Earth Sciences* 77(293):1-14
- 602 31. Socco, L.V. and Boiero, D., 2008. Improved Monte Carlo inversion of surface wave data, *Geophys.*
603 *Prospect.*, 56, 357–371.
- 604 32. Socco, L. V., D. Boiero, S. Foti, and R. Wisén, 2009, Laterally constrained inversion of ground roll
605 from seismic reflection records: *Geophysics*, 74, no. 6, G35–G45.
- 606 33. Socco, L. V., and C. Comina, 2015, Approximate direct estimate of S-wave velocity model from surface
607 wave dispersion curves: 21st Annual International Conference and Exhibition, EAGE, Extended
608 Abstracts, A09.
- 609 34. Socco, L.V., Comina, C. and Khosro Anjom, F., 2017. Time-average velocity estimation through
610 surface-wave analysis: Part 1—S-wave velocity, *Geophysics*, 82(3), U49–U59.
- 611 35. Socco, L.V. and Comina, C., 2017. Time-average velocity estimation through surface-wave analysis:
612 Part 2—P-wave velocity, *Geophysics*, 82(3), U61–U73.
- 613 36. Takahashi T, Yamamoto T (2010) An attempt at soil profiling on a river embankment using geophysical
614 data. *Explor Geophys* 41(1):102–108
- 615 37. Takahashi, T., Aizawa, T., Murata, K., Nishio, H., Mat-suoka, T. "Soil permeability profiling on a river
616 embankment using integrated geophysical data", 2014, SEG Technical Program Expanded Abstracts,
617 33, pp. 4534-4538.
- 618 38. Teodor D., Comina C., Khosro Anjom F., Socco L.V., Brossier R. and Virieux J., 2020, Challenges in
619 shallow targets reconstruction by 3D elastic full-waveform inversion – Which initial model?, submitted
620 to *Geophysics*.