

Uncertainty Quantification and Sensitivity Analysis of Crosstalk in PCB Lines via the Combination of Machine Learning and Polynomial Chaos Expansion

Original

Uncertainty Quantification and Sensitivity Analysis of Crosstalk in PCB Lines via the Combination of Machine Learning and Polynomial Chaos Expansion / Manfredi, Paolo; Trincherò, Riccardo. - (2024), pp. 639-642. (Intervento presentato al convegno 2024 IEEE Joint International Symposium on Electromagnetic Compatibility, Signal & Power Integrity: EMC Japan / Asia-Pacific International Symposium on Electromagnetic Compatibility (EMC Japan/APEMC Okinawa) tenutosi a Okinawa, Giappone nel 20-24 maggio 2024) [10.23919/emcjapan/apemcokinaw58965.2024.10584863].

Availability:

This version is available at: 11583/2994782 since: 2024-11-26T08:06:30Z

Publisher:

IEEE

Published

DOI:10.23919/emcjapan/apemcokinaw58965.2024.10584863

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1 **Geotechnical screening of linear earth structures: electric and seismic streamer data for**
2 **hydraulic conductivity assessment of the Arignano earth dam.**

3

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17

18 **Keywords:** Electric streamer; Electrical Resistivity Tomography; surface waves; geotechnical
19 characterization; river embankments; earth dam; hydraulic conductivity.

20

21 **Abstract:**

22 River embankments and small earth dams are linear retaining structures commonly used to
23 protect densely populated areas from flood phenomena and to provide water reservoirs for
24 human or agricultural use. Their continuity and uniformity are fundamental to their structural
25 efficiency. Due to their significant length and the localized nature of potential weakness points,
26 their characterization cannot rely only on local geotechnical investigations: it requires the
27 application of efficient and affordable investigation methods. The need for new screening tools
28 is becoming increasingly important worldwide because most river embankments and small
29 earth dams are reaching their design life limit due to aging. This study used a new electric

30 streamer and a seismic streamer for the combined measurement of resistivity and shear wave
31 velocity to investigate the Arignano earth dam (Piedmont Region, NW Italy), a historical
32 reservoir used for agricultural purposes. A procedure is also proposed to assess hydraulic
33 conductivity from the measured geophysical parameters. The results of this assessment were
34 compared with available geotechnical investigations, also used for calibrating the proposed
35 procedure. Results are in good agreement when compared with local geotechnical
36 investigations. The proposed procedure can therefore provide engineers and local authorities
37 with information to plan maintenance or urgent measures for reducing flood risk.

38 **Introduction**

39 River embankments and small earth dams are linear earth structures commonly used to protect
40 densely populated areas from flood phenomena or as water reservoirs for human or agricultural
41 use, respectively. Both these containment structures are characterized by: relevant linear
42 extension, limited height (i.e., often less than 10 m), and recurrent material properties, as
43 usually silts and clays are used for their construction. Their potential rupture may cause
44 casualties and huge economic losses.

45 One of the main causes of ruptures is the variation of the hydraulic regime. Indeed, after
46 prolonged rainfall, the raising of water level may gradually lead to saturation of these
47 structures, reducing their stability. On the other hand, rapid lowering of the water table may
48 induce hazardous filtration forces. Where weakness points are present, the formation of
49 preferential seepage pathways or internal erosion may occur, causing instability phenomena.
50 Heterogeneity in grain size distributions and hydraulic properties, aging, design flaws or
51 invasive wildlife activities are recurrent causes of collapse.

52 The geotechnical characterization of containment structures and underlying layers (foundation
53 soils) is fundamental to prevent structural damages and to design effective countermeasures.
54 Among geotechnical parameters, hydraulic conductivity is the most relevant for evaluating
55 long-term hydraulic conditions and for detecting the presence of anomalies. Usually, hydraulic
56 conductivity is estimated with: a) in-situ tests (e.g., pumping tests in wells (Sahin 2016) and
57 falling or constant head tests in boreholes (ASTM D6391 2011)), b) laboratory tests on
58 undisturbed soil samples (constant head method (ASTM D2434 2006) and oedometer tests).
59 Both approaches require drilling a sufficient number of boreholes inside the containment
60 structure in order to be representative of the whole investigated area. These methods are both
61 time and cost-consuming and consequently limited local information is typically available.

62 Therefore, hypotheses and assumptions have to be made on the general hydraulic conductivity
63 distribution along the containment structure, increasing the possibility of wrong interpretations.
64 Geophysical surveying techniques offer an alternative approach to the geotechnical
65 characterization: seismic and geoelectrical methods allow covering wide investigation areas
66 with a good balance of costs and survey time.

67 In the last decades many researchers (Al-Saigh et al. 1994, Chen et al. 2006, Al-Fares 2014,
68 Busato et al. 2016, Arosio et al. 2017, Martínez-Moreno et al. 2018, Camarero et al. 2019,
69 Tresoldi et al. 2019, Soueid Ahmed et al. 2020a) have used geophysical surveys as non-
70 invasive techniques to detect and locate near surface anomalies in embankments and earth
71 dams.

72 Electrical Resistivity Tomography (ERT) is commonly used for embankment surveying, due
73 to the sensitivity of electric resistivity (R) to pore water presence (i.e., changes in moisture)
74 and material discontinuities (Cho and Yeom 2007, Seokhoon 2012, Fargier et al. 2014, Arato
75 et al. 2019, Jodry et al. 2019, Arato et al. 2020, Comina et al. 2020a).

76 In association with ERT, seismic shear wave velocity (V_s) based methods can be used for
77 characterizing the mechanical properties of the solid skeleton, allowing for layering
78 identification of the containment structure and foundation soil. Among the available seismic
79 methods, the multichannel analysis of surface waves (MASW), based on the Rayleigh wave
80 Dispersion Curve (DC) analysis, is widely used (Foti et al., 2018). It can be efficiently
81 implemented for the determination of shear wave velocity on multiple profiles (Socco et al.
82 2017, Socco and Comina 2017).

83 Many authors (Cardarelli et al. 2014, Arato et al. 2018, Arato et al. 2020, Comina et al. 2020a,
84 Comina et al. 2020b) have demonstrated the reliability of the simultaneous acquisition of R
85 and V_s profiles by using appropriate streamers dragged by vehicles. Several literature

86 applications of these methodologies are available along embankments, river dykes and earth
87 dams (Lane et al. 2008, Min and Kim 2006).

88 Geophysical methods need specific calibration with geotechnical data (Bièvre et al. 2017,
89 Weller et al. 2014) if geotechnical parameters (e.g., hydraulic conductivity) are the aim of the
90 characterization. Coupled R and V_S profiles may allow for a reliable estimation of geotechnical
91 parameters given the combined analysis of pore water and solid skeleton properties by the two
92 methodologies. For instance, Cosentini and Foti (2014) proposed a procedure based on R and
93 velocities measurements (both P and S waves) for the evaluation of porosity and saturation
94 degree of unsaturated coarse-grained soils. The approach is based on an electro-seismic model
95 that adopts the Archie's law (1942) to describe the electrical behaviour of soils and a
96 formulation of elastic wave propagation in unsaturated soils (Conte et al. 2009). However, this
97 approach does not allow to consider the fine content percentage for the interpretation of electric
98 data.

99 Other literature examples report the use of R and V_S data for the determination of clay content,
100 porosity and hydraulic conductivity using Hashin-Shtrikman lower bound and Glover's models
101 (Hashin and Shtrikman 1963, Glover et al. 2000, Carcione et al. 2007, Brovelli and Cassiani
102 2010, Takahashi et al. 2014). For instance, Goff et al. (2005) proposed a new relationship
103 between soil type, R and V_S to distinguish the main sediment found in deltaic environments.
104 Hayashi et al. (2013) developed a second order multivariable polynomial equation from a least
105 square regression fit of cross-plotted R and V_S data from Japan. Their model considered clays,
106 sands, and gravels, but did not distinguish silt-size clasts from clay and sand. Recently,
107 Takahashi et al. (2014) proposed a method for profiling soil permeability on a river
108 embankment with multiple geophysical data. The clay content as a control parameter of
109 mechanical property of the soil was derived from a $V_S - R$ model by implementing the
110 unconsolidated sand model and the Glover's model.

111 In this paper, the combined acquisition of electrical and seismic data on the Arignano earth
112 dam, performed with two streamers developed by the Authors (Comina et al. 2020a, Comina
113 et al. 2020b, Arato et al. 2022), was used to set up and validate a novel methodology for the
114 estimation of soil fine content, porosity and hydraulic conductivity. The results show its
115 effectiveness in comparison with local geotechnical investigations with the advantages of a
116 direct 2D profiling of interested parameters and reduced time and economic efforts for their
117 determination.

118

119 **Case study: the Arignano earth dam**

120 The Arignano earth dam (Piedmont Region, NW Italy, Fig. 1a) was built in 1838 as a water
121 supply reservoir for agricultural purposes. The dam, made of silt and clay, is founded directly
122 on the natural alluvial soil. The dam body has a trapezoidal shape, in section, with maximum
123 height of 8 m and maximum width, at the base, of about 60 m; its longitudinal extension is
124 about 380 m. The water reservoir surface extension is modest, about 0.3 km², and the maximum
125 water volume is about 10⁶ m³.

126

127 Fig. 1. a) Geographical location of the Arignano earth dam in Italy (inlet) and sketch of the
128 containment structure. b) Details of the brick channel within earth dam body

129

130 The dam has been monitored since the 1990s by the regional authorities. Apart from the usual
131 warnings due to aging, the presence of a brick channel within the dam body, used in the past
132 to power the mill located downstream of the dam (Fig. 1b), has warned the authorities on the
133 possible induced seepages and local instabilities. This channel is 2 m wide, 1.5 m tall and
134 approximately 20 m long and it is located 3.5 m below the top of the dam.

135

136 **Geotechnical investigations**

137 During 2003 and 2019, geotechnical investigations were performed for characterizing the dam
138 body and the foundation soil.

139 In 2003, three boreholes with core retrieval were drilled (S1, S2 and S3 in Fig. 2) and the
140 following in-situ and laboratory tests were performed (Table 1):

- 141 - 8 Standard Penetration Tests (SPT);
- 142 - 4 variable-head hydraulic conductivity tests (Lefranc);
- 143 - measurement of the water table depth in the boreholes;
- 144 - laboratory analyses on the undisturbed core samples: granulometry, Atterberg's limits,
145 direct shear tests, undrained unconsolidated triaxial tests and oedometer tests.

146

147 Table 1. Results from in-situ and laboratory tests for dam body and foundation soil
148 characterization.

149

150 In 2019, three seismic cone penetration tests (SCPTU) and one dilatometer test (DMT) were
151 performed from the top of the dam body (Fig. 2). SCPTU1 and SCPTU3 were performed close
152 to borehole S2 and S1 (see Fig. 2) allowing for a direct comparison with soil stratigraphy.
153 Similarly, SCPTU2 and DMT were performed close to each other for a direct comparison and
154 validation of the two methods.

155

156 Fig. 2. Locations of the boreholes (blue circles), SCPTU (red diamonds) and DMT (green
157 triangle) tests.

158

159 The results of 2003 and 2019 geotechnical characterization campaigns are resumed in Fig. 4.
160 SCPTU and DMT results are provided in terms of Soil Behaviour Type (SBT) index, I_c
161 (Robertson 2010), and material index, I_D (Marchetti 1980), respectively. The stratigraphy of

162 the dam body and foundation soil and the ground water table profile were first reconstructed
163 by analyzing the borehole logs. The dam body results mainly constituted by clayey silt and
164 silty clays. For most part of the dam, the interface with the foundation soil, formed by
165 compacted clay and local lenses of organic clay, is observed around 8 m depth. However, the
166 depth of this interface is not constant, as it becomes shallower near the S3 borehole (where the
167 foundation soil is at 3.6 m depth), mirroring the original topography of the valley. The ground
168 water level depth also slightly decreases in correspondence of S3, mirroring the topographical
169 influence of the valley. Ground water level was not constant in time: in fact, in the 2003 survey
170 the ground water table (Fig. 3) was at about 8.9 m from the top of dam. In the 2019 survey, the
171 ground water table was estimated at about 11 m below the dam top from SCPTU results.
172 From laboratory results, although there are slightly differences between hydraulic conductivity
173 values due to methodology and sample dimensions (Table 1), the dam body can be considered
174 relatively homogeneous in the few sampled points with moderate to low hydraulic
175 conductivities. The foundation soil is instead characterized by lower hydraulic conductivity
176 values reflecting the presence of compacted clays at the bottom of the dam.

177

178 Figure 3. Results of the geotechnical characterization.

179

180 Results from the 2019 campaign are in agreement with borehole logs. The I_c and I_D profiles
181 from the three SCPTU and DMT tests (Fig. 3) highlights relative homogeneity in the first 8 m
182 (dam body). Test results suggest the presence of sands in the shallow part of the dam body,
183 however, this is not particularly evident in the borehole logs. These tests also suggest some
184 spatial variability in the stratigraphic profile of the foundation soil, with presence of local sand
185 levels at depth.

186

187 **Methodology**

188 In the following sections, the methodologies used for obtaining R , V_S and hydraulic
189 conductivity (K) sections are presented. R and V_S sections along the dam were obtained by
190 using a seismic streamer and an electric streamer. These data were then used for the estimation
191 of the hydraulic conductivity distribution.

192

193 **Seismo-electric acquisitions**

194 Seismo-electric data were simultaneously acquired on the top of the dam. The two streamers
195 were dragged in parallel by a vehicle (Fig. 4a) moving along the dam at 2 m steps. The data
196 acquired at each step are then used to obtain both a R and a V_S profile referred to the respective
197 streamer mid-points. Repeating the acquisitions for each step allow therefore 2D resistivity and
198 seismic sections to be constructed.

199 The electric system is based on galvanic coupling and specifically designed electrodes that
200 guarantee an appropriate electrical coupling with the ground. An irrigation system for reducing
201 electric contact resistances was also developed. The electric streamer has a total length of 46
202 m and 12 evenly spaced electrodes (Fig. 4a), which can be used both as current and potential
203 electrodes. It is therefore possible to perform different measurement sequences. In this study,
204 the measuring sequence is based on the Wenner-Schlumberger quadrupole. It guarantees an
205 adequate data coverage from the surface to an estimated depth of about 10 meters. This depth
206 of investigation is appropriate for investigating the dam/embankment body and the first meters
207 of foundation soil where the main instability processes may occur. The electrodes were
208 connected to the acquisition system (Syscal-Pro, Iris Instruments, georesistivimeter) by means
209 of a multipolar cable. Further details on this system can be found in Comina et al. 2020a and
210 Arato et al. 2022.

211 A seismic streamer, constituted of 24, 4.5 Hz vertical geophones 1 m spaced, was deployed
212 aside to the geoelectrical one. A 40 kg accelerated mass mounted on the vehicle back was used
213 as a seismic source; a 6 m source offset was adopted in the acquisitions. Seismograms were
214 acquired by a DAQ-Link IV seismograph (Seismic Source) with a 0.5 ms sampling interval, -
215 50 ms pretrig and 1.024 s total recording length.

216

217 Figure 4. a) Scheme of the electric and seismic streamers dragged behind the vehicle. b) Detail
218 of the seismic source and acquisition equipment. c) Location of the seismic and electric
219 measurements along the dam; the location of geotechnical tests is also reported.

220

221 Data were post-processed in the office. Resistivity values were firstly filtered by using the
222 following criteria: i) measurements with an instrumental standard deviation greater than 2%;
223 ii) quadrupoles belonging to badly ground-coupled electrodes; iii) quadrupoles with
224 transmitted currents lower than 0.1 mA; iv) apparent resistivity values higher than a certain
225 threshold, established on the average of measurements. Data that did not meet the proposed
226 criteria were rejected. Filtered data were then processed and inverted with the commercial code
227 Res2DInv (Loke and Barker 1996).

228 A specific procedure for the analysis of Rayleigh wave fundamental mode dispersion curves
229 (DC) was used for the evaluation of V_S profiles for each acquisition step (Socco et al. 2017,
230 Socco and Comina 2017, Comina et al. 2020b). The procedure (W/D procedure) allows for the
231 determination of 2D V_S sections from the DCs using a direct data transform approach. A
232 relationship between the wavelength of the Rayleigh wave fundamental mode and the
233 investigation depth (W/D relationship) is estimated through a reference V_S and $V_{S,z}$ profile and
234 used to directly transform all DCs into V_S profiles.

235 Electric and seismic streamers allow for the determination of R and V_S profiles along the
236 vertical below their mid-point. Consequently, there is a gap between electric and seismic
237 measurements (Fig. 4a) at the start section of the survey, where resistivity data cannot be
238 coupled with seismic ones. Only R and V_S profiles on the same vertical were used for the
239 analysis. Further details on the electric streamer and V_S profile estimation can be found
240 respectively in Comina et al. 2020a and 2020b.

241 R and V_S data were finally interpolated by using Surfer (Golden software) with an interpolation
242 grid of 2 m in the horizontal direction (equal to the acquisition step) and of 0.25 m in the
243 vertical direction.

244

245 **Hydraulic conductivity estimation**

246 Figure 5 reports the proposed workflow for estimating hydraulic conductivity from geophysical
247 data. Takahashi et al. (2014) developed an integrated method for profiling soil permeability of
248 river embankments by coupling seismic and electric data. Following their approach, a novel
249 fully automated procedure is here proposed.

250 The intrinsic permeability of soil, k , can be estimated using the modified Kozeny-Carman
251 relation (Carman 1956):

$$252 \quad k = B \cdot \frac{\phi^3}{(1-\phi)^2 \cdot \tau^2} \cdot d^2 \quad (1)$$

253 where B is a geometric factor equal to $1/72$, ϕ is the soil porosity, τ is the tortuosity and d is
254 the average grain size. As for tortuosity, it has been demonstrated by several authors (Matyka
255 et al. 2008 and reference herein) that in porous media it can be correlated to porosity through
256 the relation:

$$257 \quad \tau = f(\phi). \quad (2)$$

258 Among the available relationships (further details will be given in Section 5.1), in this study
259 we adopted the following equation for tortuosity estimation:

260 $\tau^2 = 1 - \ln(\phi^2)$ (3)

261 Equation 1 allows for the evaluation of the intrinsic permeability of soil, which is a
 262 characteristic of the medium and has dimension of a squared length and is reported hereafter
 263 in m^2 . This term is widely used to describe multiphase flow systems (e.g., in petroleum
 264 extraction). In geotechnics and in hydraulic processes, where mainly water is involved (such
 265 as in the case of earth dams and embankments), hydraulic conductivity, K , is commonly used
 266 to describe the ability of soil to transmit fluid through pore spaces and fractures. K can be
 267 written as:

268
$$K = \frac{k \cdot \rho_w \cdot g}{\mu_w}$$
 (4)

269 where ρ_w is the water density, μ_w is the water viscosity and g is the gravity. If k is evaluated in
 270 m^2 , K can be calculated multiplying k by $9.8 \times 10^6 \text{ m}^{-1} \text{ s}^{-1}$ (Freeze and Cherry 1979).

271

272 Figure 5. Workflow for estimating soil hydraulic conductivity using multiple geophysical data.

273

274 In engineering practice, ϕ and d are usually obtained from the analysis of undisturbed core
 275 samples from boreholes. However, it has been demonstrated by many researchers (Hashin and
 276 Shtrikman 1963, Glover et al. 2000, Mavko et al. 2009) that both ϕ and d can be estimated
 277 from seismic and electric properties of soil.

278 For resistivity data, the link with porosity (and degree of saturation) can be obtained through
 279 the Glover's model (Glover et al. 2000) which represents the soil as a multiphase system
 280 according to the following equation:

281
$$\frac{1}{R} = \frac{1}{R_s} (1 - \phi)^{\frac{\log(1-\phi^m)}{\log(1-\phi)}} + \frac{1}{R_f} \phi^m S_w^q$$
 (5)

282 where R is the overall resistivity of the soil, R_s and R_f are respectively the soil grains and fluid
 283 resistivity, m is the cementation factor, q is the saturation index and S_w is the saturation degree.

284 Since the soil used for the construction of embankments and earth dams is usually a mixture of
 285 sand and clay, R_S can be expressed using the Hashin-Shtrikman model (Hashin and Shtrikman
 286 1963) as follow:

$$287 \quad \frac{1}{R_S} = \frac{1}{R_{clay}} \left[1 - \frac{3(1-C)\Delta R}{\frac{3}{R_{clay}} - C\Delta R} \right] \quad (6)$$

288 where C is the clay content, R_{clay} is the clay resistivity and ΔR is defined as:

$$289 \quad \Delta R = \frac{1}{R_{clay}} - \frac{1}{R_{sand}} \quad (7)$$

290 where R_{sand} is the resistivity of non-clay particles. A priori values of R_{clay} and R_{sand} can be
 291 assumed on the basis of the wide scientific literature on this topic.

292 In Equations 5 and 6, ϕ and C are two unknown parameters. If independent seismic data are
 293 available, the clay content, C , can be estimated from seismic properties of the soil and in
 294 particular from V_S values. Indeed, V_S can be written as a function of the shear modulus of the
 295 soil, G , and the bulk density of the soil, ρ , using the following equation:

$$296 \quad V_S = \sqrt{\frac{G}{\rho}}. \quad (8)$$

297 Moreover, combining the Hashin-Shtrikman lower bound (Hashin and Shtrikman 1963) and
 298 the Voigt-Reuss-Hill (Mavko et al. 2009) model, G is written as:

$$299 \quad G = \left(\frac{\frac{\phi}{\phi_0}}{G_{HM}+Z} + \frac{1-\frac{\phi}{\phi_0}}{G_g+Z} \right)^{-1} - Z \quad (9)$$

300 with:

$$301 \quad Z = \frac{G_{HM}}{6} \cdot \frac{9K_{HM}+8G_{HM}}{K_{HM}+2G_{HM}} \quad (10)$$

302 where:

$$303 \quad K_{HM} = \left[\frac{n^2(1-\phi_0)^2 G_g^2}{18\pi^2(1-\nu)^2} P \right]^{\frac{1}{3}} \quad (11)$$

$$304 \quad G_{HM} = \left[\frac{5-4\nu}{5(2-\nu)} \right] \left[\frac{3n^2(1-\phi_0)^2 G_g^2}{2\pi^2(1-\nu)^2} P \right]^{\frac{1}{3}} \quad (12)$$

$$G_g = \frac{\left[(1-C)G_{sand} + CG_{clay} + \left(\frac{1-C}{G_{sand}} + \frac{C}{G_{clay}} \right)^{-1} \right]}{2} \quad (13)$$

where G_{HM} and K_{HM} are respectively the shear and bulk moduli of the soil at the critical porosity, ϕ_0 , in the Hertz-Mindlin model (Mavko et al. 2009), n is the coordination number, P is the confining pressure, ν is the Poisson's ratio of the soil, G_{sand} and G_{clay} are respectively the shear moduli of sand and clay components and G_g is the shear modulus of the solid grains.

Assuming reference values for the constitutive parameters (further detailed will be given in Section 5.1), Equations 5 to 13 allow for the definition of theoretical relationships between porosity V_S and R as a function of C for a given depth of investigation, as reported in Figure 6. By combining Figures 6a and 6b, it is then possible to define a R - V_S domain (Figure 6c) as a function of constant C curves. Therefore, the clay content of the soil can be defined by superimposing the experimental R and V_S values from field measurement to the theoretical constant C curves and finding the nearest C curve to which they can be associated.

Figure 6. a) Theoretical $V_S - \phi$ and b) $R - \phi$ relationships as a function of C ; c) $V_S - R$ relationship as a function of theoretical C for a given depth and superimposed distribution field data.

Once the clay content has been calculated, the porosity, ϕ , can be obtained knowing the resistivity data and inverting Equation 5 with the additional assumption of related parameters. Then, it is possible to estimate the average grain size, d , and calculate hydraulic conductivity values (Equation 4). In this research, average grain size, d , was considered corresponding to the D_{50} . In particular, D_{50} is first estimated by assigning a reasonable D_{50} (on the basis of the Authors' experience) to a range of C values. The obtained D_{50} are then calibrated and validated on the available geotechnical data (grain size distributions).

329 **Results**

330 In the following sections, the results of the geophysical characterization are first presented and
331 compared to the available geotechnical data. Then, the obtained hydraulic conductivity
332 distribution along the dam is reported and discussed.

333

334 **Geophysical and geotechnical characterization**

335 In Fig. 7 the results of the processing of electric resistivity and seismic data along the dam are
336 reported and compared to independent geotechnical information.

337 The resistivity section is presented in Fig. 7a in log₁₀ resistivity scale, where resistivity is in
338 Ωm (Ohm m). The resistivity survey reached the depth of about 10 m. The main resistivity
339 anomaly (brick channel) is well recognized by the data elaboration with the presence of a high
340 resistivity body between the progressive distance 50 and 60 m. The depth of the top of the brick
341 channel fits with a-priori information (Fig. 1b); nevertheless, the vertical extension of the brick
342 channel anomaly appears to be overestimated with respect to the real channel dimensions. This
343 result however confirms the effectiveness of the electric streamer as a valuable alternative to
344 electric resistivity measurements for locating local anomalies along containment structures as
345 already reported by Comina et al. 2020a.

346

347 Figure 7. Comparison between seismo-electric streamer results and geotechnical surveys: a)
348 electric resistivity cross-section and b) seismic velocity cross-section.

349

350 Four main stratigraphic layers can be recognized in resistivity data, in agreement with borehole
351 logs: 1) a shallow layer of silt material with log-resistivity values larger than 1.5 up to a depth
352 of about 2.5 m; 2) a more conductive layer, 2 m thick, mainly made by silty clay; 3) between
353 5 and 8 m the presence of a relatively more resistive layer of clayey silt; 4) a clayey foundation

354 soil with log-resistivity value lower than 1.2. High resistivity values (higher than 1.8) can be
355 observed in a very shallow area up to 100 m progressive distance mirroring the presence of
356 sand and gravel used for the road pavement. The depth of the interface between the dam body
357 and the foundation soil is quite constant (at 8 m depth) up to datum 300 m, showing localized
358 discontinuities in the clay bottom layer, and then appear to slightly decrease.

359 This last observation is more evident in the seismic data (Fig. 7b) which allowed for a deeper
360 investigation depth. In seismic data, the interface between the dam body and the foundation
361 soil follows the original topography (before dam construction) of the valley. In the dam body,
362 which has an average V_S of 200 m/s, there are two local anomalies with high V_S values: one
363 roughly in correspondence of the brick channel and one at 190 m progressive distance.
364 Moreover, at 3-5 m depth, a more consistent layer, with V_S values of about 250/350 m/s is
365 identified. The V_S values from SCPTU2, partially confirm the presence of this layer which can
366 be also correlated with the clayey silt layer identified in resistivity section. In general, SCPTU
367 results are in agreement with 2D V_S images obtained with the seismic streamer. Particularly,
368 SCPTU1 reports the presence of a relevant increase of the velocity (about 450 m/s at around
369 8-10 m depth), in accordance with the V_S section from the analysis of the streamer data.

370

371 **Hydraulic conductivity estimation**

372 The procedure described in Section 3.2 was fully automated in a Matlab code. By using the
373 input parameters listed in Table 2, it was possible to define the clay content for each couple of
374 R and V_S values along the dam (Fig. 8). Once the clay content was defined, the other
375 geotechnical parameters (ϕ , D_{50} and K) were evaluated. Results are reported in Fig. 9. The dam
376 body appears relatively homogeneous with the presence of rare anomalies, already highlighted
377 by R and V_S images. The main anomaly is originated by the presence of the brick channel
378 (between 50 and 60 m progressive distance), where the proposed procedure clearly fails in

379 obtaining reliable values. This anomaly should be therefore disregarded in the geotechnical
380 interpretation. In fact it is a structural element and therefore it cannot be interpreted with the
381 approach proposed for soils. Other geotechnically interesting anomalies are related to the
382 presence of an intermediate layer at about 3 to 5 m depth showing increased porosity and
383 reduced clay content, and the presence, in the rightmost portion of the section, of a shallower
384 foundation soil.

385

386 Table 2. Input parameters used for the application of the proposed procedure.

387

388 Figure 8. Clay content evaluation for each couple of ρ and V_s value, obtained by using the
389 seismo-electric streamer data.

390

391 Figure 9. Clay content, porosity, grain size and hydraulic conductivity distribution along the
392 Arignano earth dam.

393

394 **Discussion**

395 In the following sections, a sensitivity analysis for the validation of the proposed approach for
396 hydraulic conductivity profiling is discussed.

397 The geotechnical parameters derived from the geophysical data measured using the seismo-
398 electric streamer are then compared and discussed against the available in-situ and laboratory
399 tests with the aim of benchmarking the proposed procedure.

400

401 **Sensitivity analysis of the procedure for hydraulic conductivity estimation**

402 The main limitation of the proposed methodology is related to the assessment of reference
403 parameters (Table 2). In the case history, these parameters have been inferred from independent

404 local measurements, providing the characterization along the whole investigated section. When
405 no independent local measurements are available, the proposed procedure can still produce
406 valuable information on local anomalies for planning further geotechnical investigations
407 (Vagnon et al. 2022). In this respect, a two-step sensitivity analysis has been performed to
408 check the influence of a-priori assumptions.

409 The fine content C estimation is the basis of the proposed procedure and for further estimations
410 of the other geotechnical parameters (ϕ , D_{50} and K). Possible mismatch between estimated and
411 measured fine content values were evaluated using all the possible combinations of the
412 different values of the parameters listed in Table 3, except for pore fluid resistivity (Table 2).
413 Minimum and maximum reference values were adopted for each parameter on the basis of the
414 Authors' expertise, supported by previous studies on: a) the evaluation of elastic dry properties
415 of clays and sands (Vanorio et al. 2003, Mavko et al. 2009 and references herein); b) the
416 application of Hertz-Mindlin model (Guerin et al. 2006, Takahashi et al. 2014 and references
417 herein); and c) the evaluation of soil resistivity (Archie, 2003 and reference herein). Pore fluid
418 resistivity was assumed equal to $10 \Omega\text{m}$ as a reference value for fresh water.

419 Also, the range of variability of the saturation degree was limited within 0.05 and 0.2, reflecting
420 the unsaturated conditions usually encountered within earth dams. Indeed, water saturation is
421 the main influencing parameter in the sensitivity analysis. As shown in Fig. 10, the R - V_S
422 domain in dry (Fig. 10a) and saturated conditions (Fig. 10b) exhibits large differences
423 especially for low resistivity and velocity values, mirroring difficulties in assigning the soil
424 fine content when the degree of saturation is close to 1. However, some preliminary
425 information to limit the range of variability of the saturation degree can be derived from
426 resistivity and seismic (V_P) profiles as stated by Comina et al. 2020b, even if local geotechnical
427 measurements are not available.

428

429 Figure 10. Theoretical trends of the fine content from R and V_s values in: a) dry and b) saturated
430 conditions.

431

432 Table 3. Interval parameters used for the sensitivity analysis

433

434 Murphy (1982) introduced a relationship between coordination number and critical porosity:
435 as the latter increases, the coordination number decreases. Consequently, from the original 2^{10}
436 combinations, some ineligible combinations were removed. The sensitivity analysis was
437 performed on the remaining possible combinations. Table 4 summarizes the results of the
438 sensitivity analysis and provides a comparison between estimated, calibrated and measured
439 values (and correspondent percentage differences) of fine fraction from Arignano earth dam
440 and from other two earth retaining structures (Maira and Chisola in Piedmont Region, Italy)
441 where the same procedure described in this paper was applied.

442

443 Table 4. Comparison between estimated fine fraction from sensitivity analysis and calibrated
444 theoretical model and available grain size distribution from borehole logs for three different
445 earth structures.

446

447 Results of the sensitivity analysis highlighted that the proposed methodology, if applied
448 without a-priori information, has a standard deviation of 35% and tends to underestimate the
449 fine content of about 25%, on average. Significantly better results are obtained with a specific
450 calibration of the proposed procedure based on geotechnical information (less than 5% average
451 discrepancy with boreholes information).

452 Another limitation of the proposed methodology is the evaluation of tortuosity in Equation 1.

453 Many authors have theoretically or empirically derived tortuosity as a function of porosity: in

454 Table 5, some available equations are reported. By comparing the trends of each tortuosity
455 relationships (Figure 11), it is possible to note that the formulation we propose (Equation 3) is
456 included into the domain drawn by other equations providing an average estimate.

457

458 Table 5. List of relationship between tortuosity and porosity.

459

460 Figure 11. Trend of tortuosity vs porosity for different models proposed in scientific literature.

461

462 To evaluate the influence of the choice of different formulations for the tortuosity assessment,
463 the hydraulic conductivity of a reference clay soil with an average particle diameter of 10^{-7} m
464 and porosity values ranging from 0.3 to 0.6 was estimated with the formulas reported in Table
465 5 and with Equation 3. Results of this analysis are shown in Figure 12. The limited influence
466 of the tortuosity model is confirmed by the stable order of magnitude of the hydraulic
467 conductivity in the reported calculations. Independently by the considered porosity value, the
468 hydraulic conductivity estimated by considering Equation 3 provides an average value with
469 respect to the tortuosity assumptions by other formulations with an average overestimation or
470 underestimation of 20 and 35% respectively.

471

472 Figure 12. Trend of hydraulic conductivity values as a function of porosity for different
473 tortuosity values after sensitivity analysis.

474

475 **Comparison between measured and estimated geotechnical data**

476 In Figure 13, clay content profile estimated for Arignano Dam (see Fig. 9) is converted into I_c
477 distribution by using Davies's equation (Robertson 2010) and compared to SCPTU results.

478 Similarly, I_D from DMT is also reported using the same color scale. In Fig. 13, evidences from
479 borehole logs are reported.

480

481 Figure 13. Comparison between I_c distribution derived from clay content distribution against
482 SCPTU, DMT results and borehole logs.

483

484 By comparing the distributions, the proposed procedure has generally a higher definition of the
485 layering than both SCPTU and DMT profiles. The procedure tends to partially overestimate
486 the material index with respect to invasive tests, but the results are in line with the evidence
487 from borehole logs. The main relevant anomalies are well identified. Specifically, the
488 intermediate clayey silt layer within the dam together with the reduced depth of foundation soil
489 near SCPTU1 are well identified. The proposed procedure is also capable of detecting the brick
490 channel by scoring it with a low SBT index value (<1.31).

491 The reliability of the proposed procedure was also evaluated by comparing the obtained
492 geotechnical parameters with those available from in-situ and laboratory investigations (Table
493 6 and Fig. 14).

494

495 Figure 14. Comparison between available in situ and laboratory tests and estimated porosity,
496 grain size and hydraulic conductivity distributions from geophysical data.

497

498 Table 6. Measured and estimated geotechnical values.

499

500 Only the porosity values appear to be generally overestimated with the proposed procedure
501 with respect to independent data. However, the general trends, particularly with respect to
502 hydraulic conductivity values, reflect the borehole log results and the other direct

503 measurements. Specifically, lower hydraulic conductivity values are obtained in the shallow
504 part of the dam followed by a conductivity reduction below the dam bottom.

505 With respect to local geotechnical information, the proposed procedure has the advantage of
506 estimating the parameter variations along the whole dam body and therefore possible evidence
507 of hydraulic conductivity differences which could be relevant in the overall dam stability and
508 related fluid flow. Moreover, the proposed procedure offers a quick pre-screening of the
509 geophysical and hydraulic conditions of the containment structure with clear evidence of the
510 main anomalies. In this respect, the identification of the brick channel as a very high hydraulic
511 conductivity area can be considered as an added value of the procedure with respect to local
512 direct investigations.

513 For the application of the proposed procedure, several assumptions are needed for the
514 components of the soil mixture (see Table 2 and Section 5.1 for further details). The theoretical
515 clay content curves are obtained by assuming shear moduli and resistivities of the single soil
516 components in dry conditions. Moreover, pore fluid resistivity and saturation conditions are
517 also assumed. Particularly saturation conditions are assumed constant along the whole
518 investigated sector of the embankment. This is a simplifying hypothesis because saturation
519 degree depends on many factors such as water content, porosity, soil type, depth of the ground
520 water table, suction effects and meteorological conditions.

521 However, since the ground water table is usually below the main embankment body and the
522 saturation degree is consequently low within the containment structure, this assumption can be
523 considered acceptable in most applications. In the present case study during the execution of
524 geophysical tests the ground water table was observed at about 11 m depth, deeper than the
525 investigation depth of resistivity measurements. By considering quite high (in relation to soil
526 type) electrical resistivity values, the saturation degree was considered constant and equal to

527 5% (see Table 2). Moreover, the tests were performed during summer, after a long drought,
528 justifying this hypothesis.

529 Improvements in the definition of the saturation profile along the containment structure could
530 rely on the execution of complementary geophysical tests. Resistivity images can indeed
531 provide a rough indication of the water content if calibrated with stratigraphic information.
532 However, they cannot be used to separate the bulk conductivity from the surface conductivity.
533 Other techniques, such as magneto-resistivity (Jessop et al. 2018), self-potential technique
534 (Lapenna et al. 2000, Revil et al. 2005, Bolève et al. 2009) and induced polarization (Panthulu
535 et al 2001, Abdulsamad et al. 2019, Soueid Ahmed et al. 2020b) can be adopted to separate
536 these two contributions allowing for a reliable water content to be estimated. As far as seismic
537 methods are concerned, P wave distribution could provide information not only about
538 groundwater presence, level and location, but also could allow for adopting a complete electro-
539 seismic model (e.g., Cosentini and Foti 2014) for a consistent distribution of porosity and
540 degree of saturation.

541 However, these additional tests and more complex constitutive models, would strongly
542 increase both the investigation and the data processing times, reducing the advantages for
543 which the proposed procedure is developed. Indeed, in the aim of a first screening of
544 containment structures, the survey timing is crucial. The proposed application of seismo-
545 electric streamers during field surveys, of a data transform approach (W/D procedure) for
546 seismic data elaboration and of a relatively simple hydraulic conductivity estimate were on
547 purpose adopted with the aim of reducing the acquisition and processing times. All these
548 components result in a fast-screening tool for hydraulic and geotechnical characterization to be
549 applied also during in situ measurement campaigns for a fast imaging of the geotechnical
550 properties of the containment structure.

551

552 **Summary and Conclusions**

553 In this paper, a procedure for the profiling of hydraulic conductivity distribution from
554 geophysical data was applied on an earth dam located in Arignano, Piedmont Region (Italy).

555 The procedure was validated by comparing against other geotechnical experimental data.

556 The combined use of seismic and electric streamers allowed for the simultaneous execution of
557 ERT and seismic surveys, ensuring an appropriate investigation depth for the whole structure
558 body and the first few meters of the foundation soil, in a short survey time.

559 By coupling electric and seismic data, the hydraulic conductivity distribution along the dam
560 was evaluated, together with other geotechnical parameters such as clay content, porosity and
561 grain size distribution. The estimated values are in agreement with available data from in situ
562 and laboratory tests. The approach represents a good compromise between quality of the
563 estimated data, costs and surveying time.

564 The methodology is designed for three main functions: a) profiling of wide sectors of linear
565 earth structures starting from the calibration with available punctual geotechnical
566 measurements, b) preliminary screening, starting from reference parameters, c) identification
567 of anomalies and possible instability processes, including the planning of further geotechnical
568 investigations. However, due to the speed of its execution and processing, this procedure can
569 be used for detecting hydraulic conductivity anomalies after flood events, when both
570 responsiveness and efficiency of the countermeasures are required.

571 The proposed approach has potential for universal application, with some possible limitations
572 if standard reference parameters (such as clay and sand resistivity, critical porosity, saturation
573 degree, etc.) are assumed in the absence of available a-priori information. However, when
574 calibrated against available geotechnical observations, it also allows for a detailed profiling of
575 the retaining structure.

576

577 **Data Availability Statement**

578 Data and codes that support the findings of this study are available from the corresponding
579 author upon reasonable request.

580

581 **Acknowledgements**

582 This work has been funded by FINPIEMONTE within the POR FESR 14/20 "Poli di
583 Innovazione - Agenda Strategica di Ricerca 2016 - Linea B" call for the project Mon.A.L.I.S.A.
584 (313-67). The earth dam investigated is one of the case studies of the "ReSba" (Resilienza degli
585 Sbarramenti) project supported by the European Union for regional development (Interreg-
586 ALCOTRA) for the French-Italy Alps. Authors are grateful to R. Del Vesco, D. Patrocco, G.
587 Bodrato and S. La Monica from Piedmont Region Administration for their support. Authors
588 thank Daniele Negri for helping during surveys. Authors are also thankful to the Handling
589 Editor, Prof. Catherine O'Sullivan, for her precious and constructive comments and the
590 Associate Editor and two anonymous reviewers' suggestions for helping us to improve our
591 paper.

592

593 **Notation**

594 The following symbols are used in this paper:

595 B = geometric factor equals to $1/72$;

596 C = fine content in %;

597 c' = effective cohesion in kPa;

598 c_u = undrained shear strength in kPa;

599 d = average grain size in m;

600 D_{50} = equivalent diameter in correspondence of 50% of the grain size distribution in mm;

601 DC = Dispersion Curves;

- 602 DMT = dilatometer test;
- 603 G = shear modulus of the soil in GPa;
- 604 G_{clay} = shear modulus of clay components in GPa;
- 605 G_g = shear modulus of the solid grains in GPa;
- 606 G_{HM} = shear modulus of the soil at the critical porosity in GPa;
- 607 G_{sand} = shear modulus of sand components in GPa;
- 608 I_c = Soil Behaviour Type (SBT) index;
- 609 I_D = material index;
- 610 k = permeability in m^2 ;
- 611 K = hydraulic conductivity in m/s;
- 612 K_{HM} = bulk modulus of the soil at the critical porosity in GPa;
- 613 m = cementation factor;
- 614 MASW = Multichannel Analysis of Surface Waves;
- 615 n = coordination number;
- 616 N_{SPT} = number of blows in a SPT test;
- 617 P = hydrostatic confining pressure in GPa;
- 618 q = saturation index;
- 619 R = Resistivity in Ωm ;
- 620 R_{clay} = clay resistivity in Ωm ;
- 621 R_f = fluid resistivity in Ωm ;
- 622 R_s = soil grains resistivity in Ωm ;
- 623 R_{sand} = non-clay particle resistivity in Ωm ;
- 624 SPCTU = Seismic Cone Penetration Tests;
- 625 SPT = Standard Penetration Tests;
- 626 S_w = saturation degree;

- 627 V_s = shear wave velocity in m/s;
- 628 γ = weight in the unit volume [kN/m^3]
- 629 φ = friction angle in $^\circ\text{deg}$;
- 630 ϕ = porosity;
- 631 ϕ_0 = critical porosity;
- 632 ν = Poisson's ratio of the solid grains;
- 633 μ_w = water viscosity in Pa·s;
- 634 ρ_w = water density in kg/m^3 ;
- 635 τ = tortuosity;

636

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- 808

809 **List of Tables**

810 Table 1. Results from in-situ and laboratory tests for dam body and foundation soil
 811 characterization.

Borehole	z [m]	In-situ tests			Laboratory tests					
		N _{SPT}	K [m/s]	D ₅₀ [mm]	γ [kN/m ³]	φ [°]	c' [kPa]	K [m/s]	φ [-]	c _u [kPa]
S1	3.5			0.008	18.9	29	12.5	3.37E-08	0.47	
	4	15								
	5		5.21E-09							
	6.5			0.018	20.1			1.37E-08	0.41	
	8	17								
	9		9.7E-10							
	11			0.011	19.5					10.78
	12	3								
S2	3.5			0.011	20.9	23	14.8	1.46E-09	0.38	
	4	9								
	5		3.34E-09							
	6.5			0.014	19.2					16.18
	8	18								
	9		1.46E-08							
	11			0.011	18.6			1.10E-08	0.5	
S3	3	25								
	6	18								

812

813

814 Table 2. Input parameters used for the application of the proposed procedure.

Parameter	Value	Unit measure
Coordination number, n	5	dimensionless
Critical porosity, ϕ_0	0.55	dimensionless
Shear modulus of dry clay, G_{clay}	5	GPa
Shear modulus of dry sand, G_{sand}	45	GPa
Average soil density, ρ	2000	kg/m ³
Resistivity of dry clay, R_{clay}	12	Ωm
Resistivity of dry sand, R_{sand}	10000	Ωm
Resistivity of pore fluid, R_f	10	Ωm
Saturation, S_w	0.05	dimensionless
Cementation factor, m	1.5	dimensionless
Saturation index, q	5	dimensionless

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816

817 Table 3. Interval parameters used for the sensitivity analysis

Parameter	Min value	Max value	Unit measure
Coordination number, n	4	14	dimensionless
Critical porosity, ϕ_0	0.7	0.2	dimensionless
Shear modulus of dry clay, G_{clay}	4	6	GPa
Shear modulus of dry sand, G_{sand}	40	50	Gpa
Average soil density, ρ	1800	2700	kg/m ³
Resistivity of dry clay R_{clay}	5	100	Ohmm
Resistivity of dry sand, R_{sand}	1000	50000	Ohmm
Saturation	0.05	0.2	dimensionless
Cementation factor, m	1	3	dimensionless
Sauration index, q	1	5	dimensionless

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819

820 Table 4. Comparison between estimated fine fraction from sensitivity analysis and calibrated
 821 theoretical model and available grain size distribution from borehole logs for three different
 822 earth structures.

Case study	Boreholes		Sensitivity analysis		After calibration	
	C [%]	average C [%]	C standard deviation[%]	Difference [%]	C	Difference [%]
Arignano	91.64	66.70	29.40	27.21	93.25	-1.76
	86.51	67.43	28.99	22.06	95.00	-9.81
	88.07	63.94	30.97	27.40	93.00	-5.6
	90.52	75.11	27.23	17.02	95.00	-4.95
Chisola	85.9	66.91	29.23	22.11	87.00	-1.28
	86.3	71.65	26.56	16.98	95.00	-10.08
	54.3	61.70	32.47	-13.62	57.00	-4.97
Maira	73.19	51.85	39.02	29.16	76.50	-4.52
	72.61	54.71	39.23	24.65	71.67	1.3

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824

825 Table 5. List of relationship between tortuosity and porosity.

Study	Tortuosity equation
Rayleigh 1892	$\tau = 2 - \phi$
Weissber 1963	$\tau = 1 - \frac{1}{2} \ln(\phi)$
Kim et al. 1987	$\tau = \phi^{-0.4}$
Koponen et al. 1996	$\tau = 1 + 0.8(1 - \phi)$
Koponen et al. 1997	$\tau = 1 + \frac{0.65(1 - \phi)}{(\phi - \phi_0)^m}$
Duda et al. 2011	$\tau = 1 + (1 - \phi)^{0.5}$
Pisani 2011	$\tau = \frac{1}{1 - 0.75(1 - \phi)}$
Liu and Kitanidis 2013	$\tau = \phi^{1-1.28} + 0.15$

826

827

828 Table 6. Measured and estimated geotechnical values.

Point	z [m]	ϕ [-]		D ₅₀ [mm]		K [m/s]	
		Measured	Estimated	Measured	Estimated	Measured	Estimated
1	3.5	0.47	0.53	8.00E-03	1.00E-03	3.37E-08	8.20E-08
2	6.5	0.41	0.59	1.80E-03	1.00E-03	1.37E-08	8.92E-09
3	3.5	0.38	0.41	1.10E-03	1.00E-03	1.46E-09	1.14E-09
4	6.5			1.40E-03	1.00E-03		
5	5					5.21E-09	1.93E-09
6	9					9.70E-10	8.65E-10
7	5					3.34E-09	2.30E-09
8	9					1.46E-08	2.68E-09

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