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► **To cite this version:**

Yannick Fargier, Sergio Palma-Lopes, Cyrille Fauchard, Daniel Francois, Philippe Cote. DC-Electrical Resistivity Imaging for embankment dike investigation: A 3D extended normalisation approach. Journal of Applied Geophysics, 2014, 103, pp. 245-256. 10.1016/j.jappgeo.2014.02.007 . hal-01951865

HAL Id: hal-01951865

<https://hal.science/hal-01951865v1>

Submitted on 11 Dec 2018

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1 DC-Electrical Resistivity Imaging for embankment dike
2 investigation: A 3D extended normalisation approach

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9 **Abstract**

10 Levee, dike and earth embankment dam structures are difficult to assess
11 because of their length and complexity. Managers often include geophysical
12 investigations in the overall dike condition assessment and the DC-Electrical
13 Resistivity Imaging (ERI) method is particularly applicable owing to its cost-
14 effectiveness and its potential sensitivity to internal erosion. However, due to
15 the truly 3D nature of embankment dikes, implementing inline longitudinal
16 tomographies along with conventional 2D inversion is likely to yield image
17 artifacts. 3D effects from external causes (geometry, water reservoir) can be
18 predicted and therefore we present a new approach based on redefining the
19 normalisation principle to derive apparent resistivities from the measured
20 data. The aim is to provide a set of pre-processed apparent resistivities that
21 are not contaminated by external 3D effects and that yield more reliable
22 results when processed within a 2D conventional inversion scheme. The
23 presented approach is successfully applied to synthetic and real data sets,
24 proving superior to the conventional 2D approach, although data acquisition

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Preprint submitted to Elsevier

25 approach is the same thus keeping the same cost-effectiveness.

26 *Keywords:* Embankment hydraulic structures, Electrical Resistivity
27 Imaging, Apparent resistivity concept, Normalisation

28 **1. Introduction**

29 Hydraulic earthfill structures such as the embankment dams, dikes and
30 levees are essential infrastructures. A variety of functions are performed by
31 hydraulic embankments in interest of populations such as energy produc-
32 tion, waterway freight transport, water retention and storage and protection
33 against flood events (Fauchard and Mériaux, 2007; Royet, 2006). However,
34 embankment dikes and dams are subject to several phenomena such as water
35 infiltration and internal erosion, which may lead to mechanical weakness and
36 even breaching (Foster et al., 2000a; Fell and Fry, 2007).

37 Stability assessment methodologies more often include geophysical inves-
38 tigation for the identification of weak segments and for the optimization of
39 geotechnical testing (Carlsten et al., 1995; Mériaux et al., 2006). More pre-
40 cisely, the common geophysical practice includes high output investigation
41 methods for fast zoning purposes, and DC-electrical resistivity imaging (ERI)
42 for a higher resolution locating and characterizing of defaults (Fauchard and
43 Mériaux, 2007; Royet et al., 2012). Thanks to recent improvements in data
44 acquisition, ERI is now widely used for dike survey and monitoring (Hennig
45 et al., 2005; Sjö Dahl et al., 2006, 2008; Tsourlos et al., 1999). Advantages
46 of ERI based techniques are numerous. They are moderately fast to imple-
47 ment, cost-effective and highly sensitive to DC-electrical conductivity con-
48 trasts commonly found in dikes due to state and variability of encountered

49 materials (clay content, moisture content in vadose zone, temperature, poros-
50 ity or compaction level) (Johansson and Dahlin, 1996). For cost-effectiveness
51 reasons (dikes being long linear structures), ERI is usually applied in a con-
52 ventional way, based on a line of equidistant electrodes parallel to the longi-
53 tudinal direction (e.g. on the crest axis). When the layout includes two or
54 more parallel lines, these are usually obtained or processed separately and
55 inverted within two-dimensional ($2D$) type inversion schemes (except in few
56 cases e.g.(Cho and Yeom, 2007), but still with a $2D$ type of inversion).

57 However, dike geometry and internal property distribution clearly violates
58 such a simple $2D$ assumption leading to potential artifacts in resulting $2D$
59 images (Hennig et al., 2005; Tsourlos et al., 1999). The development of data
60 processing techniques for improving ERI relevance for dike investigation is
61 clearly essential. Although fully $3D$ approaches would address the problem
62 in a more rigorous manner, they do not benefit from the cost-effectiveness of
63 $2D$ data acquisition procedures for dike assessment.

64 In this context, we propose to still carry out a classical $2D$ ERI acquisition
65 technique and then to insert external $3D$ information in the data before per-
66 forming the conventional $2D$ data inversion, similarly to previously published
67 work for other applications (Fox et al., 1980; Vickery and Hobbs, 2002). This
68 information is included through a new data normalisation scheme that leads
69 to apparent resistivities corrected for external $3D$ effects. In this paper, the
70 common $2D$ ERI practice and related potential pitfalls are presented. Then,
71 the conventional normalisation technique is i) redefined and ii) developed to
72 address the specific limitations of dike longitudinal survey. The new normal-
73 isation approach takes into account the known neighbouring media (external

74 causes of $3D$ effects). Finally, this new development is applied to both syn-
75 thetic and real case data sets and results are compared with conventional $2D$
76 inversion results.

77 **2. Application of $2D$ ERI investigation to embankment dikes: back-** 78 **ground and limitations**

79 *2.1. Common methodology*

80 DC-ERI method is usually used to image rapidly and efficiently variations
81 along the longitudinal or transverse directions of the surveyed dike (Sjödahl
82 et al., 2006, 2008). A $2D$ longitudinal survey implies the positioning of a line
83 of electrodes along the structure whether it is on the crest, the slopes or at
84 the toe of the dike (Figure 1(a)). But, in this case, the $2D$ assumption implies
85 that the resistivity does not vary in the transverse direction perpendicular
86 to the electrode line. From this point of view, a simple scheme representing
87 a cross section of a hydraulic structure (Figure 1(b)) clearly shows that $2D$
88 inversion schemes cannot be used theoretically to process geo-electrical data
89 from a longitudinal ERI survey. Obviously, the stronger the $3D$ in-situ fea-
90 tures, the less rigorous the use of $2D$ inversion. Thus, it is important in a
91 first approach to identify and quantify the effects related to the $3D$ behaviour
92 of the surveyed structure and surroundings.

93 *2.2. Potential pitfalls*

94 Dikes and earth embankment dams are structures of which the $3D$ ge-
95 ometry and resistivity distribution have a disturbing effect on $2D$ inversion
96 results. However, it is important to determine what $3D$ effects can be con-
97 sidered as disturbing or not. This study leads us to separate media having

98 an effect on the measurements in two categories: i) the media that we need
99 to be assessed (usually the dike body and foundation) ii) neighbouring media
100 that are not to be assessed (e.g. the water reservoir).

101 Consequently, the effects of the dike topography and water reservoir can
102 be considered as disturbing. The dike topography, the geometry of the reser-
103 voir and its resistivity distribution are all information that can be measured
104 directly. Some national regulations regarding the safety of hydraulic struc-
105 tures require a monitoring of the topography of the structure and the water
106 level in the reservoir (ex: by LiDAR techniques (Mallet and Bretar, 2009)).
107 This information can be directly supplied by the asset manager. Moreover,
108 the electrical resistivity distribution in the water reservoir can also be mea-
109 sured with adequate equipment during the geophysical campaign without
110 adding a significant cost.

111 We performed a parametric study to quantify the effects on the measure-
112 ments caused by the dike geometry and the water reservoir. A Finite Element
113 Method (Comsol Multiphysics software (COMSOL Multiphysics, 2009)) was
114 used to solve the forward problem and simulate geo-electrical survey data.
115 Main principle and results are shown Figures 2 and 3. The principle of this
116 study was to simulate 4-electrodes (quadrupole) Wenner measurements on
117 a dike surface, as shown in the Figure 2(a), in varying the inter-electrode
118 spacing a and the distance d between the quadrupole and the water reser-
119 voir. The resistivity of the dike is 1000 Ohm-m whereas water resistivity
120 is 100 Ohm-m. Then, the simulated transfer resistance (R_t) is obtained by
121 numerically computing the potential difference between two potential elec-
122 trodes divided by the injected current intensity (I). Then, the simulated R_t

123 is multiplied by the Geometrical Factor (GF) computed analytically (Wenner
124 protocol for a flat homogenous half space) to obtain the apparent resistivity
125 (ρ_a). The result of this numerical modelling is illustrated in the form of a ma-
126 trix (Figure 2(b)). For this particular case (geometry, resistivity contrast),
127 the effects of the water volume and the topography are clearly visible because
128 the simulated apparent resistivities do not equal the resistivity of the dike
129 body (1000 Ohm-m). A maximum negative effect (about -35 % relative to
130 the dike resistivity) is found for an inter-electrode spacing of about 20 m and
131 when the distance between the quadrupole and the reservoir is the lowest.
132 Two maximum positive effects (about +20 % relative to the dike resistiv-
133 ity) are observed for a minimum inter electrode spacing ($a=1$ m) and for
134 measurements performed on topography edges. It can be noted that when
135 the inter-electrode spacing is greater than 40 m the apparent resistivities in-
136 crease again due to the limited width of the water reservoir in the model. It
137 is confirmed that topography artificially increases conventionnaly calculated
138 apparent resistivities (near the convex areas) whereas it can be seen that the
139 water has an opposite effect. However, such results cannot cover all situa-
140 tions and serve as master curves on the field although they give useful and
141 qualitative information and show that 3D effects are significant.

142 *2.3. Principle, contribution and limitation of the normalisation technique*

143 According to Kunetz (1966) the normalisation is an operation transform-
144 ing the measure of R_t into an observable that does not depend on the po-
145 sition of the electrodes and on the geometry of the investigated medium.
146 This method is widely used to compare measurements and qualitatively de-
147 tect anomalies (Loke, 2011). This operation is performed by means of the

148 following expression:

$$\rho_a = R_t^{meas} \times GF = R_t^{meas} \times \frac{\rho_h}{R_t^{mod\rho_h}} \quad (1)$$

149 Where ρ_a represents the generalized apparent resistivity, R_t^{meas} the mea-
150 sured transfer resistance, GF the generalized Geometrical Factor and $R_t^{mod\rho_h}$
151 the simulated transfer resistance on a homogeneous medium of resistivity ρ_h
152 (the electrode positions and the medium geometry being identical in both
153 real and synthetic models).

154 In consequence, Equation 1 defines the apparent resistivity as the resis-
155 tivity that would be observed after the inversion of one measure alone, and
156 assuming that the auscultated medium is homogeneous.

157 This principle is applied to the previous parametric study to normalize the
158 effect of the topography. This implies to set all resistivities of the model to 1
159 Ohm-m by considering the reservoir and the dike as part of this homogeneous
160 block (Marescot et al., 2006) and then apply Equation 1. Figure 3(a) presents
161 the result of normalising the topography effect. According to this new graph
162 Figure 3(a)(as compared to Figure 2(b)), the procedure nearly completely
163 cancels the effect of the topography.

164 Indeed, apparent resistivities do not show a dependency on the geome-
165 try as they do not exceed the true dike resistivity anymore and no effects
166 are observed near edges (convex or concave areas). The apparent resistivity
167 decrease zone in the graph only relates to the presence of the water reser-
168 voir. Consequently, this normalisation reveals the effect of the water reservoir
169 alone on the measurements (conductive zone, figure 3(a)). To reveal the to-
170 pography effect alone, the relative variations $((\rho_{a1} - \rho_{a2})/\rho_{a2})$ between the

171 plots Figure 2 and 3(a) are presented Figure 3(b). This result shows again
172 that the maximum (positive and negative) topography effects stand near the
173 changes in slope (geometry edges).

174 We perform complementary numerical to study the effect on the measure-
175 ment of the resistivity contrast between the water reservoir and the dike body
176 and foundation. Figure 4 shows the effects of varying the resistivity contrast
177 between the dike body and the water reservoir on simulated measurements
178 respectively located at (a) 4 m (b) 12 m (c) 20 m from the reservoir. Ac-
179 cording to this result, the knowledge of the resistivity contrast between the
180 reservoir and the dike body plays a key role on the measurements.

181 In summary, this study shows that three parameters have significant influ-
182 ences on DC-resistivity measurements: i) the geometry of the overall model
183 (dike body and reservoir), ii) the location of the electrodes (which includes
184 electrode spacing) and iii) the resistivity contrast between the water reservoir
185 and the dike body. Depending on the apparent resistivity definition (normal-
186 isation) used, it was shown that the apparent resistivities can account for the
187 electrode positions (analytical GF based on a flat homogeneous half space)
188 or for the electrode positions and the medium topography (numerical GF
189 based on a homogeneous medium of given geometry).

190 *2.4. Normalisation of the effect of the water reservoir*

191 Figures 2, 3 and 4 have shown that the effect of the water reservoir can
192 be predominant. This study also shows that it is possible to compute the
193 theoretical effect of the water reservoir on the measurement and to normalise
194 the topography effect. The objective of this section is to present an ap-
195 proach that allows to additionally normalise the water reservoir effect on the

196 DC-resistivity measurements. The principle of this Extended Normalisation
197 (EN) technique is summarized in the Figure 5. As opposed to the previous
198 normalisation technique, we numerically simulate a model composed of two
199 blocs, the dike and the water reservoir, in an attempt to delete the effect of
200 the water volume on the measurements by a more complete normalisation.
201 The resistivity of the dike is set to 1 Ohm-m while the resistivity of the water
202 reservoir is set to the reciprocal value of the resistivity ratio between the dike
203 and the water reservoir. Similarly to the previous techniques, the new GF
204 are simply the reciprocal of the simulated transfer resistances.

205 This normalisation assumes that i) the dike body and foundation bloc
206 is homogeneous, ii) the resistivity contrast between the disturbing medium
207 (the water reservoir) and the investigated medium (the dike) is known and
208 iii) the geometries of both media are known.

209 However, even if it exists theoretical limitations, we admit here that the
210 inversion of (even approximately) normalised apparent resistivities always
211 leads to more reliable results than the inversion of raw data not accounting
212 for geometry and water volume effects.

213 *2.5. Impact of 3D effects and normalisation on inversion results*

214 We think that is interesting to study the impact of the 3D effects on the
215 imaging result. For this purpose, we present a numerical test of the grad-
216 ually more complete normalisations (1: with a conventional GF, 2: with a
217 generalized GF, 3: with the EN technique). The test is based on a model
218 presenting a more complex geometry (varying cross-section) and six cylindri-
219 cal heterogeneities crossing the dike body in the transverse direction (Figure
220 6). In this numerical study, a 2D longitudinal ERI survey was simulated

221 on the dike under load condition. The width of crest is 6 m. A Wenner-
222 Schlumberger acquisition protocol was used (690 quadripole measurements)
223 and the inter-electrode spacing is 4 m. The resistivity of the dike body was
224 2000 Ohm-m and its height varies from 0 to 6 m. The six transverse hetero-
225 geneities are located in the dike body at different depths. Their resistivity is
226 set to 80 Ohm-m equal to that of the water reservoir. The transfer resistances
227 simulated are then processed with the 2D inversion software Res2Dinv (Loke
228 and Barker, 1996a) yielding 2D resistivity sections shown in the Figures 7(a)
229 to 7(c) using the default inversion parameters. Figure 7(a) is obtained with
230 the raw data (ρ_a) for which only the electrodes positions is accounted for
231 and the other effects (topography and water reservoir) are not normalised.
232 Figures 7(b) and 7(c) show respectively the inversion results after removing
233 the effect of the dike topography and after removing the combined effects of
234 the topography and water reservoir. This result clearly shows that the more
235 conductive layer (Figure 7(a) and 7(b)) is in fact an artifact due to the effect
236 of the water reservoir on the simulated measurements and that the highly
237 resistive zone on the right hand side of the upper layer Figure 7(a) is partly
238 influenced by the dike topography. Figure 7(c) shows that the locating of
239 the six anomalies (due to the modeled heterogeneities) is clearly improved
240 by applying the EN technique.

241 This normalisation technique supposes that a single resistivity ratio (con-
242 trast) is selected to compute all measured apparent resistivities over the whole
243 dike surface. However, a real embankment dike is never homogeneous and
244 its resistivity distribution remains unknown. Consequently, in real cases, the
245 resistivity ratio between the dike and the water reservoir cannot be consid-

246 ered as unique for a whole set of DC-resistivity measurements. Thus, the
247 natural variability in embankment dikes and dams restricts the applicability
248 of the suggested "EN" technique.

249 In order to demonstrate this limitation an additional synthetic test was
250 performed. This study is similar to that used in the previous test (figure
251 6) except that the dike body is now composed of two contrasting stretches
252 (Figure 8(a)): A resistive stretch on the left hand side (2000 Ohm-m) and a
253 more conductive stretch on the right hand side (1000 Ohm-m).

254 Figures 8(b) to 8(d) present the results at the 4th iteration of the 2D-
255 inversion process (also based on the Res2dinv software). Figure 8(b) shows
256 the resistivity section obtained when inverting data without normalisation
257 approach. Figure 8(c) presents the case where the resistivity ratio is selected
258 at its maximum value (2000/80=25) and shows a resistive layer artifact on
259 the right hand side of the model due to the over-estimation for the resistivity
260 contrast for this area. Figure 8(d) presents the opposite case with a conduc-
261 tive layer artifact on the left hand side due to an under-estimated resistivity
262 contrast (1000/80=12.5). This result clearly shows that neglecting the spatial
263 variability of the dike body when normalising the data inevitably underesti-
264 mates (or inversely, overestimates) the resistivity contrast between the water
265 reservoir and the investigated embankment. This leads to an unsuitable nor-
266 malisation level (too strong or too weak) of the 3D external effects which in
267 turn causes artifacts in the resulting image.

268 **3. An Enhanced Extended Normalisation approach**

269 *3.1. Concept*

270 The previous section discusses two main limitations restricting the use
271 of the EN technique : i) the resistivity contrast between the water reservoir
272 and the dike has to be known to a certain accuracy level ii) The resistiv-
273 ity distribution of the dike body has to be sufficiently constant (homoge-
274 neous medium). In order to overcome these restrictions, we present a new
275 approach that Enhances the Extended Normalisation (EEN) technique and
276 better matches the original apparent resistivity definition (Kunetz, 1966).

277 As a consequence of Kunetz (1966) apparent resistivity definition (as de-
278 rived in Equation 1), one can say that in the trivial case of a homogeneous
279 medium (of arbitrary geometry) the apparent resistivity equals the true re-
280 sistivity, irrespective of the medium geometry. Conversely, one can postulate
281 that the inversion of a single measurement to adjust a single model parame-
282 ter (the "true" resistivity of the investigated medium assumed to be homo-
283 geneous) would lead this true resistivity to tend to the measured apparent
284 resistivity. Therefore, we suggest in this paper that an apparent resistivity
285 can be considered as the result of a basic inversion process for which the
286 particular electrode positions are considered and the model is assumed to be
287 homogeneous. Although in real cases the medium can rarely be considered
288 homogeneous, one can still carry out such a straightforward inversion for
289 each individual measured apparent resistivity. This concept is the basis of
290 the procedure presented in the following sections.

291 *3.2. Methodology*

292 The method presented within the framework of this article takes the form
 293 of a pre-processing function. This method modifies the measured data into
 294 apparent resistivities corrected for the effects of the topography and the
 295 water reservoir and partly accounting for the inhomogeneity of the dike body.
 296 This methodology, schematized Figure 9, introduces three kinds of input
 297 parameters:

$$\mathbf{DEM} = [\mathbf{X}_{topo}, \mathbf{Y}_{topo}, \mathbf{Z}_{topo}]; \quad (2)$$

$$\rho_{water}^{mes}; \quad (3)$$

$$\mathbf{d}^{mes} = \left[\rho_{a_1}^{mes} \quad \rho_{a_2}^{mes} \quad \dots \quad \rho_{a_N}^{mes} \right]^T; \quad (4)$$

298 **DEM** is a matrix containing elevation data used for building the numer-
 299 ical model (dike and reservoir). ρ_{water}^{mes} is the DC-electrical resistivity of the
 300 water reservoir. \mathbf{d}^{mes} represents the vector of the measured data (apparent
 301 resistivities), N is the number of quadrupole measurements. The procedure
 302 consists in two steps as follows.

303 *3.2.1. Step 1*

304 The objective of *Step1* is to provide the "mean" resistivity of the dike
 305 needed as an input to *Step2*. A basic inverse problem is used for which the
 306 inverse model is only composed of two inversion "cells" (dike body and water
 307 reservoir). Within these cells of known geometry, the model is considered to
 308 be homogeneous. Therefore, only two model parameters are needed.

$$\mathbf{m}_{step1} = \begin{bmatrix} \rho_{dike} & \rho_{water} \end{bmatrix}^T ; \quad (5)$$

309 Where ρ_{water} is the resistivity of the water reservoir medium and ρ_{dike}
 310 that of the dike body medium. In order to perform the inversion, the ma-
 311 trix of Fréchet derivatives is built by calculating the pole-pole sensitivities
 312 by means of the adjoint state method (Park and Van, 1991) and then by
 313 recombining the pole-pole to get the sensitivities associated to the electrode
 314 arrays (quadrupoles) in the acquisition protocol. The finite element method
 315 (see section 2.2) is used, with mesh deformation to simulate the topography,
 316 to solve the forward problem and compute the sensitivity matrix \mathbf{G}_{step1} :

$$\mathbf{G}_{step1} = \begin{bmatrix} \frac{\delta \rho_{a_1}^{mes}}{\delta \rho_{dike}} & \frac{\delta \rho_{a_1}^{mes}}{\delta \rho_{water}} \\ \frac{\delta \rho_{a_2}^{mes}}{\delta \rho_{dike}} & \frac{\delta \rho_{a_2}^{mes}}{\delta \rho_{water}} \\ \vdots & \vdots \\ \frac{\delta \rho_{a_N}^{mes}}{\delta \rho_{dike}} & \frac{\delta \rho_{a_N}^{mes}}{\delta \rho_{water}} \end{bmatrix} ; \quad (6)$$

317 As shown in Equation 6, the dimension of this sensitivity matrix is only
 318 $[N,2]$ (which is quite different from most sensitivity matrices usually appear-
 319 ing in discrete geophysical inversion). The "effective" mean model \mathbf{m}_{step2} is
 320 then adjusted by solving the basic inverse problem as follows (7) :

$$(\mathbf{G}_{step1}^T \mathbf{W}_d^T \mathbf{W}_d \mathbf{G}_{step1} + \lambda_{step1} \mathbf{I}_{step1}) \mathbf{m}_{step2} = \mathbf{G}_{step1}^T \mathbf{W}_d^T \mathbf{W}_d (\mathbf{d}^{mes}) \quad (7)$$

321 where the diagonal of the matrix \mathbf{W}_d contains estimated measurements
 322 uncertainties and \mathbf{I}_{step1} is the $[2 \times 2]$ identity matrix and $\lambda_{step1} = [\lambda_{dike}, \lambda_{water}]^T$
 323 is the damping factor which can be different for the water and the dike

324 terms. Depending on the reliability of the *a priori* information on the water
 325 resistivity, a more or less high damping factor is selected for adjusting the
 326 resistivity of the water part of the model. However, the inverse problem
 327 is well-determined. so, the choice of these parameters does not modify the
 328 result radically. Finally, this step supplies resistivities for both the dike body
 329 and the water reservoir considered as homogeneous and that best explains
 330 the measured data in the sense of a least squares criterion.

$$\mathbf{m}_{step2} = \left[\begin{array}{cc} \rho_{dike}^{step2} & \rho_{water}^{step2} \end{array} \right]^T ; \quad (8)$$

331 However, this could have been performed, more simply but less accurately,
 332 by selecting the mean of the shallowest apparent resistivity measurements
 333 (lowest inter electrode spacing) to limit the topography and reservoir effects
 334 (Figure 4).

335 3.2.2. Step 2

336 The only objective of the previous step is to provide an initial model for
 337 the main step presented here. The role of this main step is to yield apparent
 338 resistivities corrected for the effect of the water reservoir and the topography
 339 and accounting for the medium inhomogeneities.

340 Following the concept introduced in section 3.1, the idea is to estimate a
 341 resistivity for the dike body seen as homogeneous that best fits each measure-
 342 ment considered alone. Thus, by inverting individually each measurement
 343 gets one dike resistivity per measured datum and ends up with N resistivi-
 344 ties. As previously stated, it can be inferred from the apparent resistivity
 345 definition (Kunetz, 1966) that each resistivity estimated alone should then

346 be regarded as an apparent resistivity that accounts for the medium geom-
 347 etry. In addition here, we propose that this apparent resistivity correction
 348 accounts for the presence of a water reservoir and supports dike body in-
 349 homogeneity. Therefore, we extend the concept saying that each apparent
 350 resistivity corrected for topography and water reservoir effects should be seen
 351 as a corresponding resistivity for the dike body considered as homogeneous.
 352 To achieve this step a new inverse problem is developed (Equation 9) :

$$(\mathbf{G}_{step2}^T \mathbf{W}_d^T \mathbf{W}_d \mathbf{G}_{step2} + \lambda \mathbf{I}_{step2}) \delta \mathbf{m}_{pert} = \mathbf{G}_{step2}^T \mathbf{W}_d^T \mathbf{W}_d (\mathbf{d}^{mes} - \mathbf{d}^{calc}) \quad (9)$$

353 Two new variables must be computed to solve this equation:

354 1. The modeled apparent resistivities (\mathbf{d}^{calc});

$$\mathbf{d}^{calc} = \left[\begin{array}{cccc} \rho_{a_1}^{calc} & \rho_{a_2}^{calc} & \dots & \rho_{a_N}^{calc} \end{array} \right]^T; \quad (10)$$

355 2. The matrix of the Fréchet derivatives (\mathbf{G}_{step2}).

$$\mathbf{G}_{step2} = \left[\begin{array}{ccccc} \frac{\delta d_1^{calc}}{\delta \rho_{dike}} & 0 & \dots & 0 & \frac{\delta d_1^{calc}}{\delta \rho_{water}} \\ 0 & \frac{\delta d_2^{calc}}{\delta \rho_{dike}} & \dots & 0 & \frac{\delta d_2^{calc}}{\delta \rho_{water}} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & \frac{\delta d_N^{calc}}{\delta \rho_{dike}} & \frac{\delta d_N^{calc}}{\delta \rho_{water}} \end{array} \right]; \quad (11)$$

356 These two parameters are obtained by solving a complete forward problem
 357 with the determined resistivities of water reservoir and dike body from *Step1*.
 358 In the sensitivity matrix (Equation 11), the left-hand side $[N \times N]$ diagonal
 359 block expresses the concept of each measurement being inverted individually.

360 This is obviously different from usual sensitivity matrices where all data
361 may be sensitive to all model parameters. Even though all N inversion
362 parameters m_1 to m_N represent the same physical parameter (the resistivity
363 of the dike body when assumed homogeneous), they have different values for
364 each measurement and have to be considered separately. Thus, they are N
365 distinct parameters. In cases where the water resistivity and the reservoir
366 geometry are well known (reliable a priori information), this diagonal block
367 can be considered alone. This leads to a trivial scheme (equivalent to N
368 independent processes individually applied to each measured datum). In
369 the sensitivity matrix (Equation 11), we propose to add the right-hand side
370 column to simultaneously estimate the water resistivity.

371 In the framework of this study, we prefer keeping the resistivity of the wa-
372 ter reservoir as a free parameter of which range can be controlled by adjusting
373 a damping factor (for example : $\lambda_{reservoir} = 1000 \times \lambda_{dike}$). This leads to the
374 more general case where the water resistivity may be known inaccurately or
375 may slightly vary in space and time.

376 The solution of Equation 9 is a perturbation vector $\delta\mathbf{m}_{pert}$ that allows to
377 update the inversion "model" containing the corrected apparent resistivities
378 ρ_a^{corr} following Equation 12 :

$$\rho_a^{corr} = [\rho_{dike}^{step2} + \delta\mathbf{m}_{pert}(1 : N), \rho_{water}^{step2} + \delta\mathbf{m}_{pert}(N + 1)] \quad (12)$$

379 Thus, the corrected ρ_a^{corr} are the output of the presented pre-processing
380 method, supplying the apparent resistivities that can be processed with $2D$
381 type of inversion software.

382 3.3. Synthetic results

383 The EEN technique is applied to the numerical study presented Figure
384 8 and presented in the section 2.5 (same model, same acquisition protocol)
385 with 6 anomalies buried in a double-compartment dike. The objective is
386 to demonstrate the added value of the new normalisation procedure. Fig-
387 ure 10 shows the inversion result obtained with data normalized with the
388 new method (EEN) and using the Res2Dinv commercial software. in order
389 to obtain the corrected apparent resistivities we impose $\lambda_{dike} = 0.01$ and
390 $\lambda_{water} = 10$ during *Step1* and *Step2* and a measurement noise of 0.5%. The
391 mean resistivities resulting from *Step1* are 1324 ohm-m and 80.1 ohm-m for
392 the dike and reservoir respectively.

393 The presented imaging result corresponds to the 4th iteration with a RMS
394 value lower than 1 %. This result shows the superiority of the new technique
395 in this case as very few artifacts are present in the inversion result com-
396 pared to Figures 8(a) to 8(c) where false layers could be denoted. Moreover,
397 a better assessment of the anomalies is performed allowing a more robust
398 interpretation of the imaging result.

399 4. Case study

400 A survey in high output conditions ("roll-along" longitudinal survey) was
401 performed in situ on a dike owned and managed by EDF (Electricité De
402 France) in the Southern France (Figure 11) in the framework of a more gen-
403 eral assessment campaign. For this purpose, 96 electrodes were aligned with
404 a 5 m electrode spacing on the central axis of the crest. The investigated dike
405 is a water retaining structure leading water to a very close hydro-electricity

406 production plant and was in full load condition at the time of the DC-ERI
407 survey. The dike is 6 to 7 m high. The sealing is ensured by a concrete facing
408 on the upstream side. We measured the resistivity of water on the surface of
409 the reservoir with various locations and found a constant value of 80.2 ohm-m
410 ± 0.5 ohm-m. A Wenner-Schlumberger acquisition procedure including 1502
411 quadrupole measurements was performed. Figure 11 shows the electrode ca-
412 ble layout near the location of the water reservoir. Available information on
413 the construction phase and the geological context of the area indicate that
414 the dike body is composed of recent coarse alluvial deposits exploited in the
415 vicinity and corresponding to the foundation of the structure.

416 Figure 12 presents the imaging results obtained with the Res2Dinv soft-
417 ware for various normalisation levels applied to the same measured data set.
418 Concerning the inversion parameter λ , we imposed the same parameters as
419 for the synthetic case (ratio=1000) and an equivalent noise measurement.
420 The mean resistivities resulting from *Step1* are 1429 ohm-m and 79.9 ohm-m
421 for the dike and reservoir respectively. The first global conclusion that would
422 arise from the upper resistivity sections 12(a) with no normalisation of the
423 reservoir or topography is that the dike is composed of two layers horizontal
424 layers of varying thicknesses. The upper layer (5 to 8 m thick) appears to be
425 more resistive (about 1000 to 2000 ohm-m) and shows some resistivity vari-
426 ations. The lower layer seems significantly less resistive (100 to 500 ohm-m)
427 and could be interpreted as the alluvial substratum of varying upper limit
428 (between 8 and 12 m deep below the crest). These results show that the
429 normalisation of the topography effect alone (Figure 12(b)) lowers the over-
430 all resistivity of the dike body and leaves room for what could be seen as

431 an intermediate layer (upper limit between 3 and 6 m deep below the crest).
432 The third result (Figure 12(c)) indicates that adding the normalisation of
433 the water reservoir effect tends to push away the presumed conductive layer
434 that could be seen at the bottom of the resistivity section (12(a) and (b))
435 and therefore increases the interpreted thickness of the dike body up to 13 m.
436 Consequently, it can be concluded that this previous conductive layer in sec-
437 tions 12(a) and (b) is partly an artifact due to the effect of the water reservoir
438 on the measured data. Moreover, the inversion result presented on Figure
439 12(c) (based on the normalisation extended to the water reservoir effect)
440 shows some new heterogeneities between the dike body and the foundation
441 ($x=200$ m) which may be critical for the safety assessment of the structure
442 (internal erosion below the foundation). The last inversion result (Figure
443 12(d)) shows a very similar result to the previous one (12(c)) although it
444 tends to limit significantly more the presence of the lower conductive layer,
445 which will be discussed in the following section.

446 Concerning the four inversion results (figure 12) we do not prefer to say
447 that a result is better than another, each one bringing of additional details.
448 We think that the better interpretation consists in comparing the results
449 between them in order to see the possible 3D pitfalls. In this manner a more
450 robust interpretation can be performed.

451 *4.1. Discussion*

452 In the previous result (Figure 12(d)) presenting a 2D-inversion of real
453 data corrected for the combined topography and water reservoir effects, the
454 bottom conductive layer was not fully removed. Consequently, two interper-
455 tations can be proposed.

456 From an optimistic point of view, one can say that this layer actually
457 exists and that the correction procedure performed well providing a reliable
458 image of the resistivity section.

459 From an opposite point of view, one could conclude that the subsisting
460 conductive layer is an artefact due to an incomplete correction of the com-
461 bined topography and water reservoir effects. This incomplete normalisation
462 can come from resistivity variations in the water reservoir not taken into ac-
463 count. Those variations can have an effect on the measurements, especially
464 for high resistivity contrast between the dike body and the water reservoir.
465 A solution would be to accurately measure the resistivity variations in the
466 water reservoir and to impose this distribution during the inversion process.

467 Finally, a more realistic point of view is to conclude that the presented
468 correction approach has proved some efficiency although some 3D combined
469 effects (due to the water reservoir and other external media, the topogra-
470 phy and the internal resistivity distribution of the dike body) still remain.
471 It can be noted that such combined 3D effects cannot be supported by a
472 data normalisation or correction procedure and can only be delineated by
473 means of a fully 3D acquisition and inversion process. It could be noted that
474 the study focuses on quite homogenous structures. Structures such as earth
475 embankment dams often have strong heterogeneities (concrete or clay core)
476 that could reinforce this phenomenon.

477 Moreover, this study presents a successful outcome for the new normal-
478 isation because the dike body presents a strong contrast between the dike
479 body and the water reservoir. In less contrasting cases, one can anticipate
480 that the added value of the EEN technique would be lower.

481 The EEN procedure does not add a cost to the survey except for the
482 water resistivity measurement. Concerning the computational cost, as we
483 can see in Figure 9, in addition to the stage of inversion, this technique
484 requires the calculation of 1 to 2 additional 3D forward problems as well as
485 the calculation of two matrices of Fréchet derivatives of size $N \times 4$. In general,
486 for a common longitudinal DC-ERI survey based on 96 inline electrodes, this
487 correction approach needs 10 minutes for the processing of 1500 quadrupole
488 measurements with an E5405 Intel Xeon @2 GHz CPU and requires less than
489 4 Gb of RAM.

490 5. Conclusion

491 Nowadays, $2D$ -ERI is a commonly employed method within the overall
492 condition assessment methodology hydraulic embankment structures. How-
493 ever, the use of a $2D$ inversion scheme leads to artifacts due to combined $3D$
494 effects. Those artifacts are often interpreted as real layers (alluvial founda-
495 tion for the water reservoir effect) or anomalies and limit the robustness of
496 the interpretation and the assessment of real anomalies. Numerical studies
497 are used to demonstrate and quantify some $3D$ effects specific to dike inves-
498 tigation and their impact on the reconstructed models for $2D$ longitudinal
499 surveys. Then a classical technique, the normalisation, is redefined and used
500 to suppress the topography effects on the data. This technique is extended
501 to the normalisation of the effect of the water reservoir in the case of dike
502 in load condition. First, we simply assume that the embankment dike is
503 homogeneous and second, we enhance this concept to arbitrary resistivity
504 distributions. Results show that the EEN technique is able to support the

505 non-homogeneity of the dike body and to satisfactorily suppress the effect of
506 the water reservoir. When applied to real data, this new approach leads to
507 an improved interpretation of the survey. Consequently, the technique proves
508 usefull when data are contaminated by "external" 3D effects of which causes
509 (topography, external neighbouring media such as a water reservoir) are well
510 documented or directly identifiable on site without adding a real cost to the
511 survey campaign. In this context, this technique could also be employed to
512 normalise the effect of sheet piles, concrete facing and internal networks on
513 measurements. It can be noted, that the effect of an internal core (rockfill
514 dams for example) on the EEN procedure has not been studied in this paper.
515 Authors think that these hydraulic structures deserve specific attention (due
516 to internal erosion) and further research. Our approach cannot account for
517 all 3D effects, particularly those due to the actual dike resistivity distribu-
518 tion ("internal" causes). In conclusion, further studies are needed to build
519 cost-effective inversion strategies well-adapted to long dike investigation at
520 reasonable speed.

521 **Acknowledgment**

522 The authors wish to thank EDF-CIH as well as the research projects
523 ERINOH and DOFEAS for the funding and access to the site, and more
524 particularly Jean Robert Courivaud and Julien Cintract for the assistance
525 on site. We also thank Dr Mathieu Le Feuvre and the reviewers for the
526 discussions and their impact on the article.

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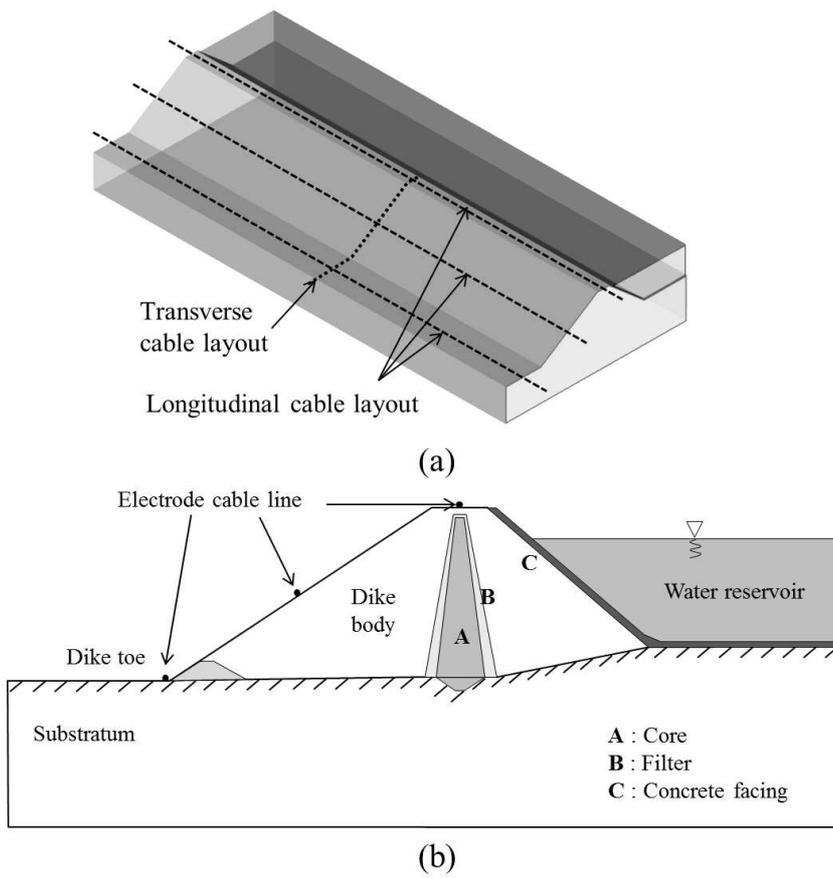


Figure 1: 1(a) Perspective view of a schematic dike with various electrode cable layouts
 1(b) schematic section of a dike in load condition presenting some barriers to infiltrations
 and three longitudinal cable layouts.

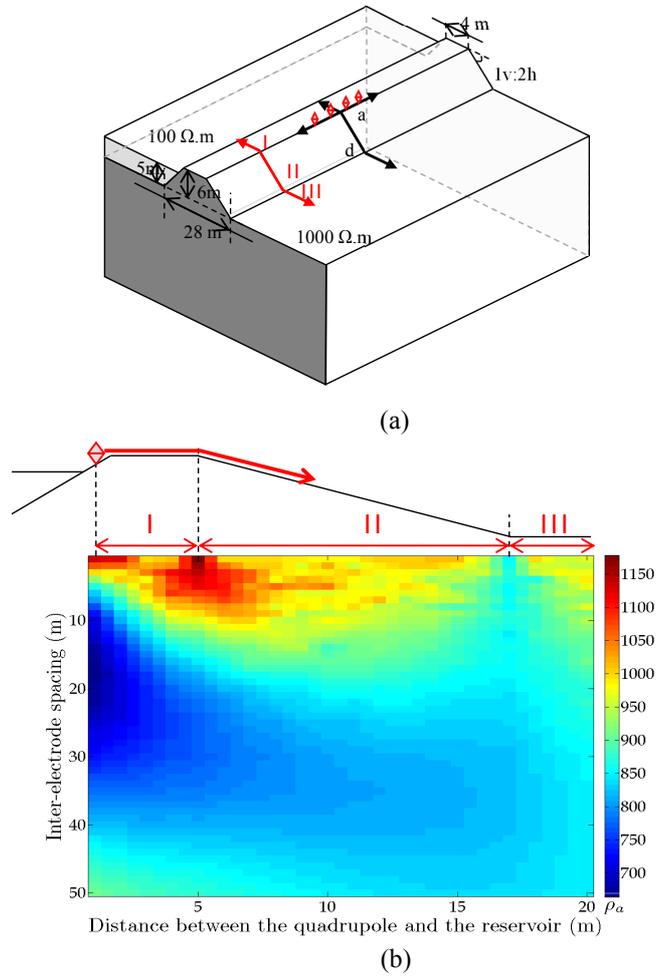


Figure 2: Parametric study of dike geometry and water reservoir effects, 2(a) Simplified dike model showing electrode positions (red diamonds) and 2(b) apparent resistivity plot against interelectrode spacing and distance between electrode quadrupole and water reservoir. Analytic geometric factors are used for apparent resistivity calculation.

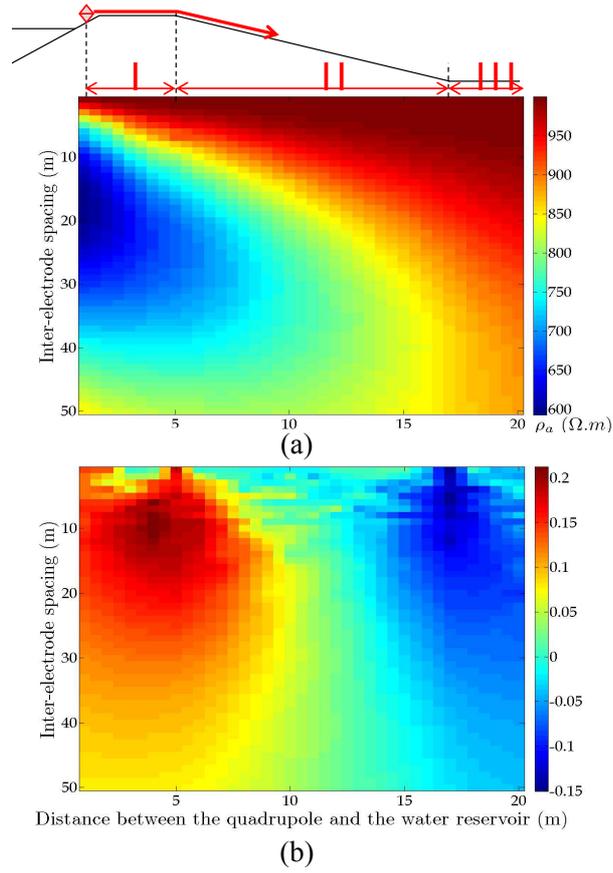


Figure 3: Normalisation effects: 3(a) Apparent resistivities calculated with a generalized geometrical factor obtained by numerical modeling and 3(b) relative variation between the conventional and generalized apparent resistivities.

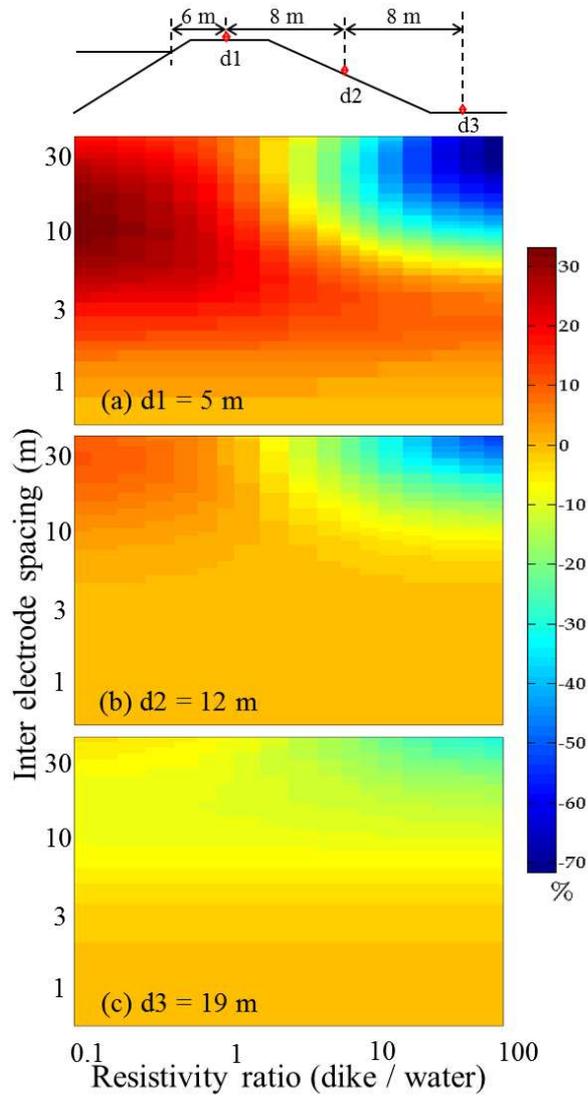


Figure 4: Relative changes in apparent resistivities against inter-electrode spacing and resistivity contrast between water reservoir and dike body (ρ_{water}/ρ_{dike}) for an electrode quadrupole at a distance of (a) 4 m (b) 12 m and (c) 20 m respectively from the water reservoir.

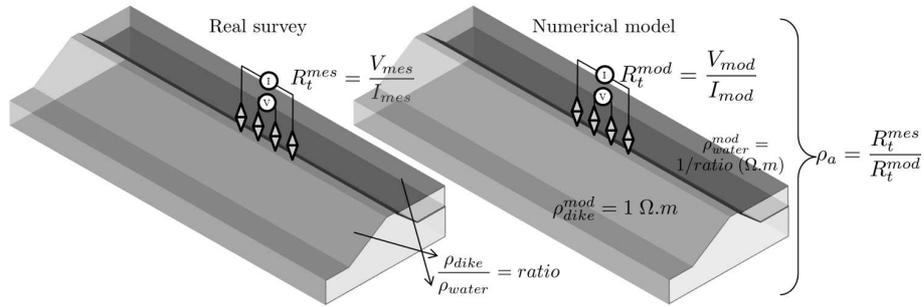


Figure 5: Schematic principle of the Extended Normalisation Technique additionally accounting for the water reservoir effect.

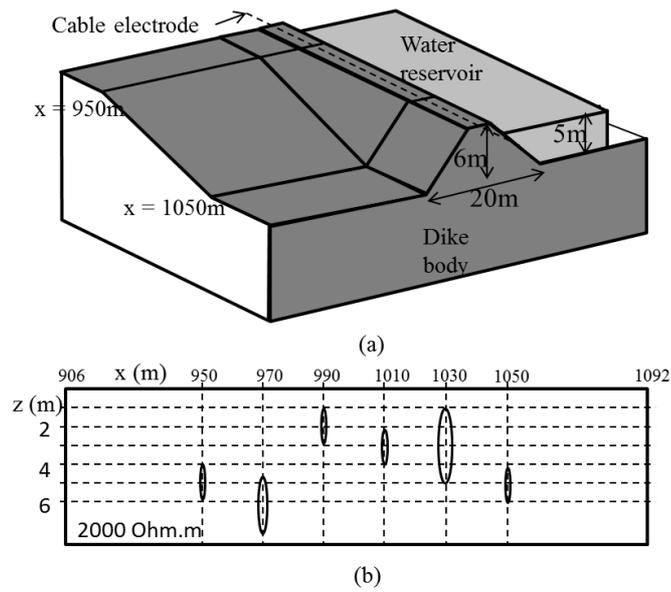


Figure 6: Bloc figure presenting (a) a perspective view of the dike model used for the numerical test exhibiting a varying topography and containing six heterogeneities and (b) a schematic longitudinal section of this model showing the location of the 6 conductive cross-sectional "pipes".

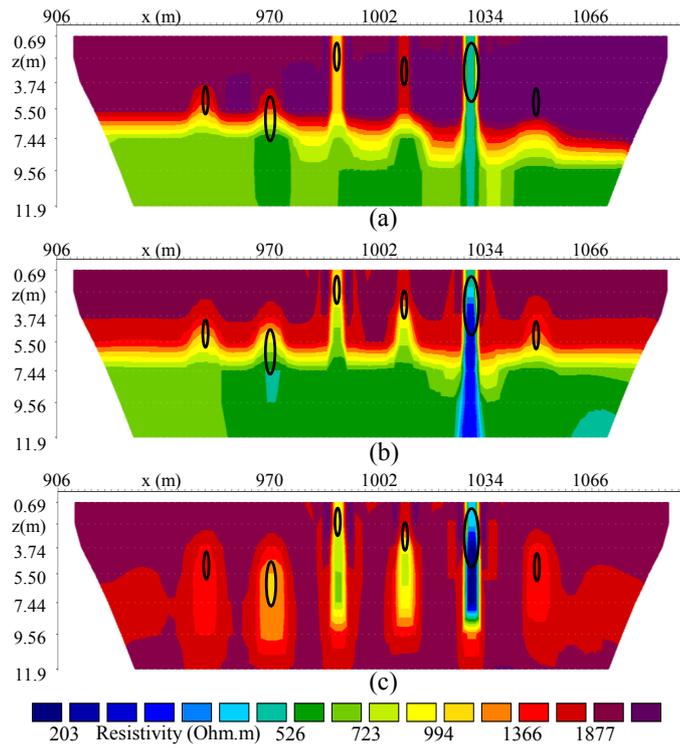


Figure 7: Numerical test 2D-inversion results for (a) simulated ρ_a (without any normalisation) (b) data normalised for the effect of the topography (c) data normalised for the combined effect of the water reservoir and the topography.

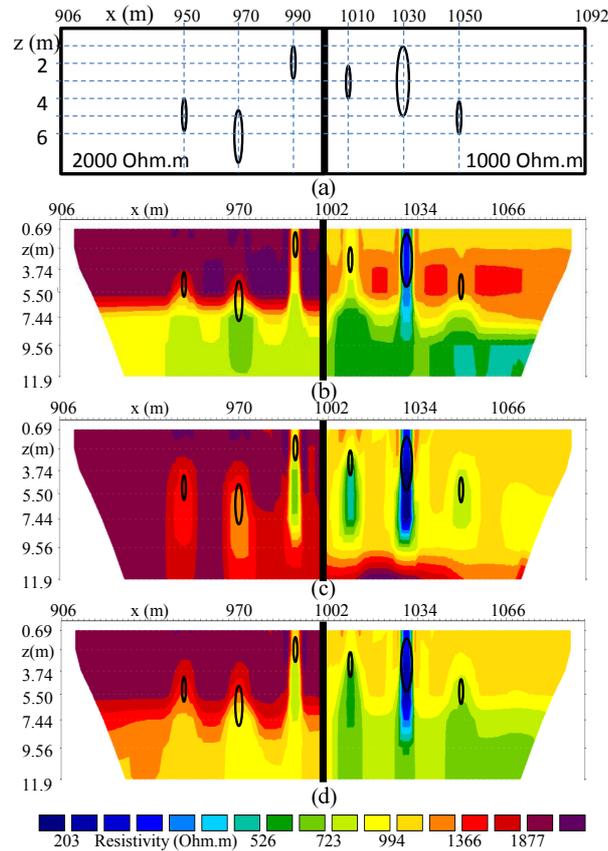


Figure 8: Numerical test demonstrating the limitations due to dike inhomogeneity: (a) a longitudinal section of the dike model composed of two contrasting stretches and the six conductive anomalies and the 2D-inversion results based on (b) raw data (no normalisation applied), (c) with an underestimated and (d) an overestimated resistivity contrast when normalising the data for the combined effect of the water reservoir and the topography.

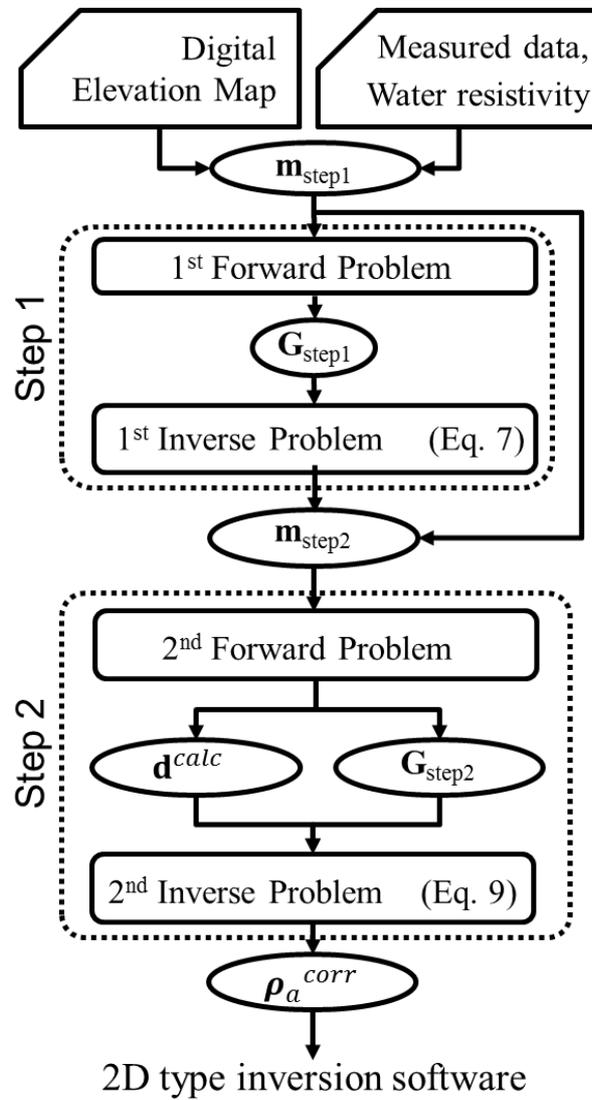


Figure 9: Scheme illustrating the steps of the EEN technique.

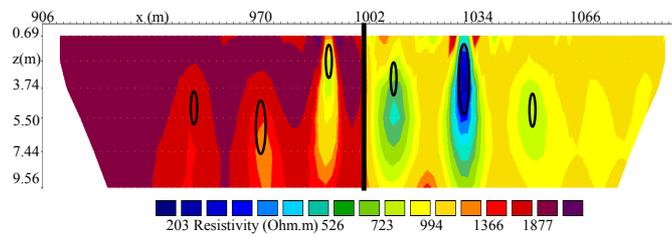


Figure 10: Figure shows the inversion result obtained with apparent resistivity data set normalized with the EEN technique. The true location of the six anomalies and the limit between the stretches are also illustrated.

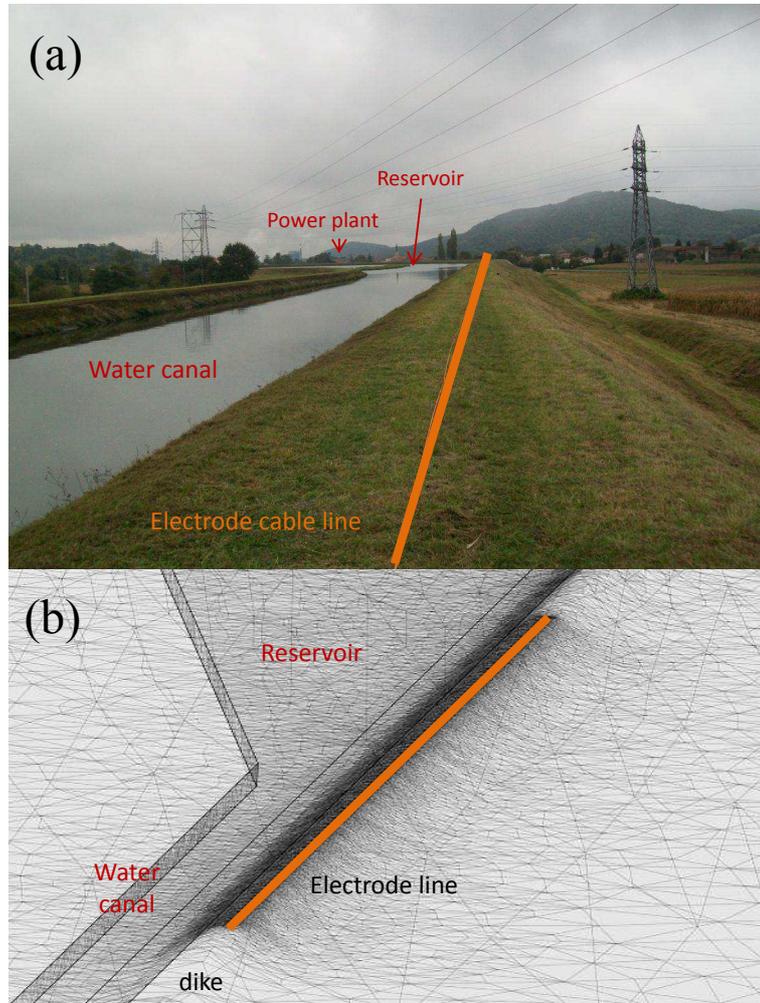


Figure 11: In situ investigation site with 11(a) a view of the survey area and 11(b) the finite element meshing of the numerical model performed by mesh deformation based on the digital elevation map.

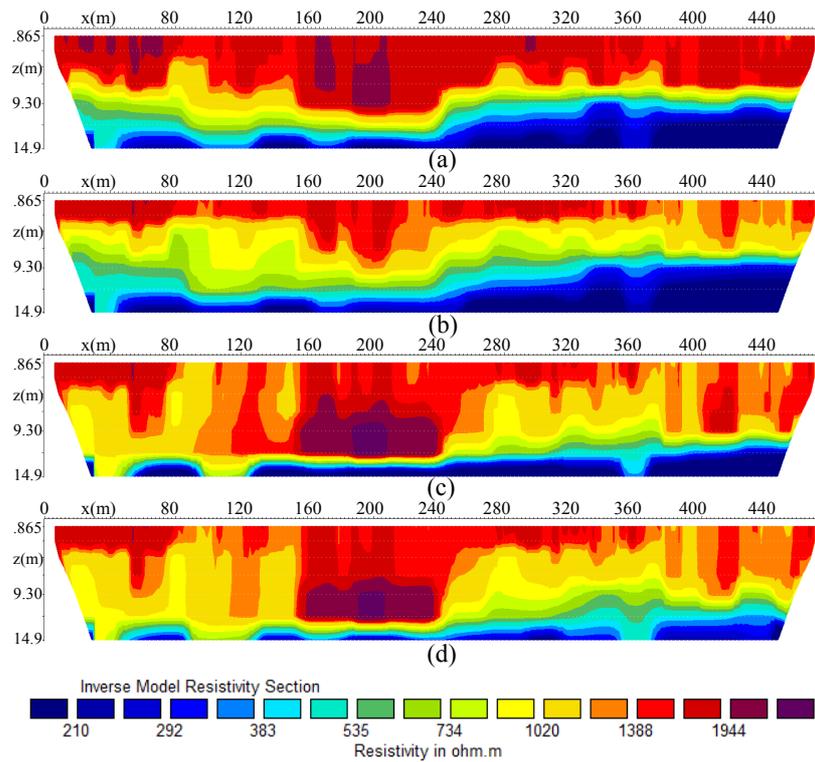


Figure 12: Imaging results obtained with the Res2dinv software for the same set of raw data (a) without any correction (b) normalised for the effect of the topography (c) normalised for the combined effects of the topography and the water reservoir and (d) corrected with the EEN procedure.