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Original
Geotechnical Screening of Linear Earth Structures: Electric and Seismic Streamer Data for Hydraulic Conductivity Assessment of the Arignano Earth Dam, Italy / Vagnon, Federico; Comina, Cesare; Arato, Alessandro; Chiappone, Antonella; Cosentini, RENATO MARIA; Foti, Sebastiano. - In: JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING. - ISSN 1090-0241. - ELETTRONICO. - 148:12(2022). [10.1061/(ASCE)GT.1943-5606.0002911]

Availability:
This version is available at: 11583/2971529 since: 2022-09-21T06:18:03Z

Publisher:
ASCE

Published
DOI:10.1061/(ASCE)GT.1943-5606.0002911

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

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

Abstract:

River embankments and small earth dams are linear retaining structures commonly used to protect densely populated areas from flood phenomena and to provide water reservoirs for human or agricultural use. Their continuity and uniformity are fundamental to their structural efficiency. Due to their significant length and the localized nature of potential weakness points, their characterization cannot rely only on local geotechnical investigations: it requires the application of efficient and affordable investigation methods. The need for new screening tools is becoming increasingly important worldwide because most river embankments and small earth dams are reaching their design life limit due to aging. This study used a new electric streamer and a seismic streamer for the combined measurement of resistivity and shear wave velocity to investigate the Arignano earth dam (Piedmont Region, NW Italy), a historical reservoir used for agricultural purposes. A procedure is also proposed to assess hydraulic conductivity from the measured geophysical parameters. The results of this assessment were compared with available geotechnical investigations, also used for calibrating the proposed procedure. Results are in good agreement when compared with local geotechnical investigations. The proposed procedure can therefore provide engineers and local authorities with information to plan maintenance or urgent measures for reducing flood risk.

Introduction

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

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

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

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

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

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

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

Many authors (Cardarelli et al. 2014, Arato et al. 2018, Arato et al. 2020, Comina et al. 2020a, Comina et al. 2020b) have demonstrated the reliability of the simultaneous acquisition of R and V_S profiles by using appropriate streamers dragged by vehicles. Several literature applications of these methodologies are available along embankments, river dykes and earth dams (Lane et al. 2008, Min and Kim 2006).

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

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

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

Case study: the Arignano earth dam

The Arignano earth dam (Piedmont Region, NW Italy, Fig. 1a) was built in 1838 as a water supply reservoir for agricultural purposes. The dam, made of silt and clay, is founded directly on the natural alluvial soil. The dam body has a trapezoidal shape, in section, with maximum height of 8 m and maximum width, at the base, of about 60 m; its longitudinal extension is about 380 m. The water reservoir surface extension is modest, about 0.3 km^2, and the maximum water volume is about 10^6 m^3.

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

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

Geotechnical investigations

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

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

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

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

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

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

The results of 2003 and 2019 geotechnical characterization campaigns are resumed in Fig. 4. SCPTU and DMT results are provided in terms of Soil Behaviour Type (SBT) index, I_c (Robertson 2010), and material index, I_D (Marchetti 1980), respectively. The stratigraphy of the dam body and foundation soil and the ground water table profile were first reconstructed by analyzing the borehole logs. The dam body results mainly constituted by clayey silt and silty clays. For most part of the dam, the interface with the foundation soil, formed by compacted clay and local lenses of organic clay, is observed around 8 m depth. However, the depth of this interface is not constant, as it becomes shallower near the S3 borehole (where the foundation soil is at 3.6 m depth), mirroring the original topography of the valley. The ground water level depth also slightly decreases in correspondence of S3, mirroring the topographical influence of the valley. Ground water level was not constant in time: in fact, in the 2003 survey the ground water table (Fig. 3) was at about 8.9 m from the top of dam. In the 2019 survey, the ground water table was estimated at about 11 m below the dam top from SCPTU results.

From laboratory results, although there are slightly differences between hydraulic conductivity values due to methodology and sample dimensions (Table 1), the dam body can be considered relatively homogeneous in the few sampled points with moderate to low hydraulic conductivities. The foundation soil is instead characterized by lower hydraulic conductivity values reflecting the presence of compacted clays at the bottom of the dam.

Figure 3. Results of the geotechnical characterization.

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

Methodology

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

Seismo-electric acquisitions

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

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

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

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

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

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

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

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

Hydraulic conductivity estimation

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

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

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

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

$$\tau = f(\phi). \tag{2}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\Delta R = \frac{1}{R_{clay}} - \frac{1}{R_{sand}} \tag{7}$$

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

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

$$V_S = \sqrt{\frac{G}{\rho}}\,. \tag{8}$$

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

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

with:

$$Z = \frac{G_{HM}}{6}\cdot\frac{9K_{HM}+8G_{HM}}{K_{HM}+2G_{HM}} \tag{10}$$

where:

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

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

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

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 - ϕ and b) R - ϕ 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).

Results

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

Geophysical and geotechnical characterization

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

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

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

Four main stratigraphic layers can be recognized in resistivity data, in agreement with borehole logs: 1) a shallow layer of silt material with log-resistivity values larger than 1.5 up to a depth of about 2.5 m; 2) a more conductive layer, 2 m thick, mainly made by silty clay; 3) between 5 and 8 m the presence of a relatively more resistive layer of clayey silt; 4) a clayey foundation soil with log-resistivity value lower than 1.2. High resistivity values (higher than 1.8) can be observed in a very shallow area up to 100 m progressive distance mirroring the presence of sand and gravel used for the road pavement. The depth of the interface between the dam body and the foundation soil is quite constant (at 8 m depth) up to datum 300 m, showing localized discontinuities in the clay bottom layer, and then appear to slightly decrease.

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

Hydraulic conductivity estimation

The procedure described in Section 3.2 was fully automated in a Matlab code. By using the input parameters listed in Table 2, it was possible to define the clay content for each couple of R and V_S values along the dam (Fig. 8). Once the clay content was defined, the other geotechnical parameters (ϕ, D_{50} and K) were evaluated. Results are reported in Fig. 9. The dam body appears relatively homogeneous with the presence of rare anomalies, already highlighted by R and V_S images. The main anomaly is originated by the presence of the brick channel (between 50 and 60 m progressive distance), where the proposed procedure clearly fails in obtaining reliable values. This anomaly should be therefore disregarded in the geotechnical interpretation. In fact it is a structural element and therefore it cannot be interpreted with the approach proposed for soils. Other geotechnically interesting anomalies are related to the presence of an intermediate layer at about 3 to 5 m depth showing increased porosity and reduced clay content, and the presence, in the rightmost portion of the section, of a shallower foundation soil.

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

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

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

Discussion

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

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

Sensitivity analysis of the procedure for hydraulic conductivity estimation

The main limitation of the proposed methodology is related to the assessment of reference parameters (Table 2). In the case history, these parameters have been inferred from independent local measurements, providing the characterization along the whole investigated section. When no independent local measurements are available, the proposed procedure can still produce valuable information on local anomalies for planning further geotechnical investigations (Vagnon et al. 2022). In this respect, a two-step sensitivity analysis has been performed to check the influence of a-priori assumptions.

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

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

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

Table 3. Interval parameters used for the sensitivity analysis

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

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

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

Another limitation of the proposed methodology is the evaluation of tortuosity in Equation 1. Many authors have theoretically or empirically derived tortuosity as a function of porosity: in

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

Table 5. List of relationship between tortuosity and porosity.

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

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

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

Comparison between measured and estimated geotechnical data

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

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

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

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

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

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

Table 6. Measured and estimated geotechnical values.

Only the porosity values appear to be generally overestimated with the proposed procedure with respect to independent data. However, the general trends, particularly with respect to hydraulic conductivity values, reflect the borehole log results and the other direct measurements. Specifically, lower hydraulic conductivity values are obtained in the shallow part of the dam followed by a conductivity reduction below the dam bottom.

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

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

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

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

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

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

Summary and Conclusions

In this paper, a procedure for the profiling of hydraulic conductivity distribution from geophysical data was applied on an earth dam located in Arignano, Piedmont Region (Italy). The procedure was validated by comparing against other geotechnical experimental data.

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

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

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

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

Data Availability Statement

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

Acknowledgements

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

Notation

The following symbols are used in this paper:

B = geometric factor equals to 1/72;

C = fine content in %;

c' = effective cohesion in kPa;

c_u = undrained shear strength in kPa;

d = average grain size in m;

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

DC = Dispersion Curves;

DMT = dilatometer test;

G = shear modulus of the soil in GPa;

G_{clay} = shear modulus of clay components in GPa;

G_g = shear modulus of the solid grains in GPa;

G_{HM} = shear modulus of the soil at the critical porosity in GPa;

G_{sand} = shear modulus of sand components in GPa;

I_c = Soil Behaviour Type (SBT) index;

I_D = material index;

k = permeability in m^2;

K = hydraulic conductivity in m/s;

K_{HM} = bulk modulus of the soil at the critical porosity in GPa;

m = cementation factor;

MASW = Multichannel Analysis of Surface Waves;

n = coordination number;

N_{SPT} = number of blows in a SPT test;

P = hydrostatic confining pressure in GPa;

q = saturation index;

R = Resistivity in Ωm;

R_{clay} = clay resistivity in Ωm;

R_f = fluid resistivity in Ωm;

R_s = soil grains resistivity in Ωm;

R_{sand} = non-clay particle resistivity in Ωm;

SPCTU = Seismic Cone Penetration Tests;

SPT = Standard Penetration Tests;

S_w = saturation degree;

V_S = shear wave velocity in m/s;

γ = weight in the unit volume [kN/m^3]

φ = friction angle in °deg;

ϕ = porosity;

ϕ_0 = critical porosity;

ν = Poisson's ratio pf the solid grains;

μ_w = water viscosity in Pa·s;

ρ_w = water density in kg/m^3;

τ = tortuosity;

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List of Tables

Table 1. Results from in-situ and laboratory tests for dam body and foundation soil 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	
	12	23								
S3	3	25								
	6	18								

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
Sauration index, q	5	dimensionless

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

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

	Boreholes	**Sensitivity analysis**			**After calibration**	
Case study	**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

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	$\tau = \phi^{1-1.28} + 0.15$

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