HYDRAULIC CONDUCTIVITY ESTIMATION FROM GEOPHYSICAL SURVEYS: THE CASE STUDY OF ARIGNANO EARTH DAM (PIEDMONT REGION, NW ITALY)

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Sommario

River embankments and small earth dams are structures commonly used for protecting densely populated areas from floods or creating water reservoirs. Their continuity and uniformity are fundamental prerequisites for their efficiency. The need for new screening tools is becoming increasingly important given the aging of most of these structures, which are reaching their design life limit. In this study, the Arignano earth dam (Piedmont Region, NW Italy), a historical reservoir used for agricultural purpose, was investigated using a new electric streamer and a seismic streamer for the combined measurement of electrical resistivity and shear wave velocity. A procedure for the hydraulic conductivity assessment from the measured geophysical parameters is also proposed. Results of this characterization were compared with available geotechnical investigations that were also used for calibrating the proposed procedure for hydraulic conductivity estimation.

1. Introduction

River embankments and small earth dams are geotechnical structures commonly used for protecting densely populated areas from floods or as water reservoirs for human or agricultural supply. Both these containment structures are characterized by reduced heights (i.e., often less than 10÷15 m), relevant linear extension and recurrent material properties, usually silts and clays.

One of the main causes of ruptures is the variation of the hydraulic regime: after prolonged rainfalls, the raising of water level may gradually lead to saturation of the 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 seepages or internal erosion may occur, causing instability phenomena. Recurrent causes are heterogeneity in grain size distributions and hydraulic properties, aging, design flaws or invasive wildlife activity.

Consequently, their geotechnical characterization is fundamental for preventing structural damages and for designing effective countermeasures. Among geotechnical parameters, hydraulic conductivity is the

most useful for evaluating long-term hydraulic conditions and for detecting the presence of anomalies. Usually, hydraulic conductivity is estimated with in-situ tests (e.g., pumping tests in wells (Sahin 2016) and falling or constant head tests in boreholes (ASTM D6391 2011)) or with laboratory tests on undisturbed soil samples (constant head method (ASTM D2434 2006) and oedometer tests). Both approaches require drilling enough boreholes inside the containment structure to be representative of the whole investigated area. However, due to high instrumentation costs and time-consuming drilling operations, only limited local information is usually available.
An alternative approach to the characterization is offered by geophysical surveying techniques, such as seismic and geoelectrical methods, which can cover wide investigation areas with a good balance of costs and testing time. In the last decades many researchers (Hashin and Shtrikman, 1963; Glover et al., 2000; Carcione et al., 2007; Goff et al., 2005; Brovelli e Cassiani, 2010; Hayashi et al., 2013; Cosentini e Foti, 2014; Takahashi et al., 2014) have used geophysical surveys as non-invasive techniques for detecting and locating near surface anomalies in embankments and earth dams, providing new correlations for geotechnical parameter estimation.
In this paper, the first results for the hydraulic conductivity estimation by coupling seismic and electrical data are presented. The hydraulic conductivity profile along the longitudinal section of the dam was obtained following a modified approach proposed by Takahashi et al. (2014), which implements the Hashin-Shtrikman model (Hashin and Shtrikman 1963) for unconsolidated sands and the Glover's model (Glover et al. 2000). The procedure was applied to the Arignano earth dam (Piedmont, Italy) where many independent geotechnical measurements were available.

2. Case study: the Arignano earth dam

The Arignano earth dam (Piedmont Region, NW Italy, Fig.1) was built in 1838 as a water supply reservoir for agricultural purposes. The dam, mostly made of silt and clay, was 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 of 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.
Because of its age, the dam has been monitored since the 1990s by the regional authorities. Many geotechnical investigations were performed inside its main body and within shallow foundation soil: 3 boreholes, 8 Standard Penetration Tests (SPT), 4 variable-head hydraulic conductivity tests (Lefranc), laboratory analyses on the undisturbed core samples (granulometry, Atterberg's limits, direct shear tests, undrained unconsolidated triaxial tests and oedometer tests), 3 seismic cone penetration tests (SCPTU) and one dilatometer test (DMT).
Among the usual warnings with respect to the aging of the structure, the presence of a brick channel (Fig.1) within the dam body, used in the past for powering the mill located downstream of the dam, has warned the authorities on the possibility of inducing seepages and local instabilities. This channel is 2 m width, 1.5 m tall and approximately 20 m long and it is located 3.5 m below the top of the dam.

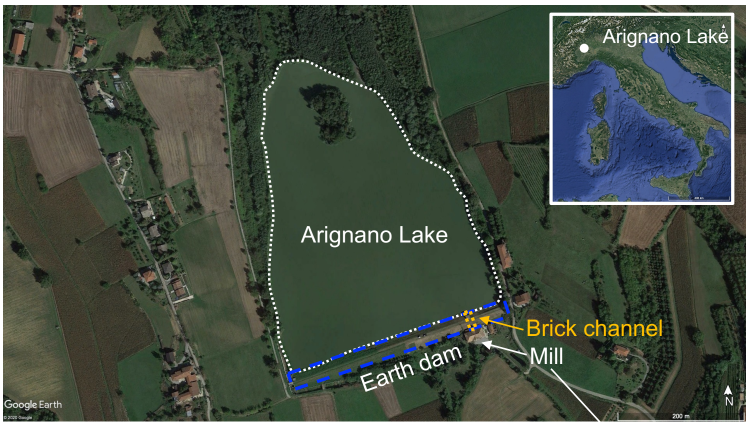

Fig 1. Geographical location of the Arignano earth dam in Italy (inlet) and sketch of the containment structure..

3. Methodology

Seismic-electric data were simultaneously acquired using two different streamers (Arato et al., 2020; Comina et al., 2020a, 2020b) on the top of the dam. The two streamers were dragged by a vehicle moving along the dam at 2 m steps: for each step, one electric sequence and a single seismic shot were acquired. The electric system is based on galvanic coupling and foresees the use of a series of specifically designed electrodes that guarantee an appropriate electrical coupling between the sensors, located along the streamer, and the ground. An irrigation system for reducing contact resistances between electrodes and ground was also developed. The electric streamer has a total length of 46 m and 12 electrodes, symmetrically spaced, that can be used both as current and potential electrodes. In this study, the measuring sequence was based on the Wenner-Schlumberger array and guaranteed an adequate data coverage from the surface to an estimated depth of about 10 meters. 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. 2020b.
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.
Data were post-processed in the office. Electrical resistivity (R) values were firstly filtered and 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). Further details on the methodology can be found in Comina et al. 2020a.
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.
Figure 2 reports the workflow for estimating hydraulic conductivity distribution within containment structures from geophysical data.

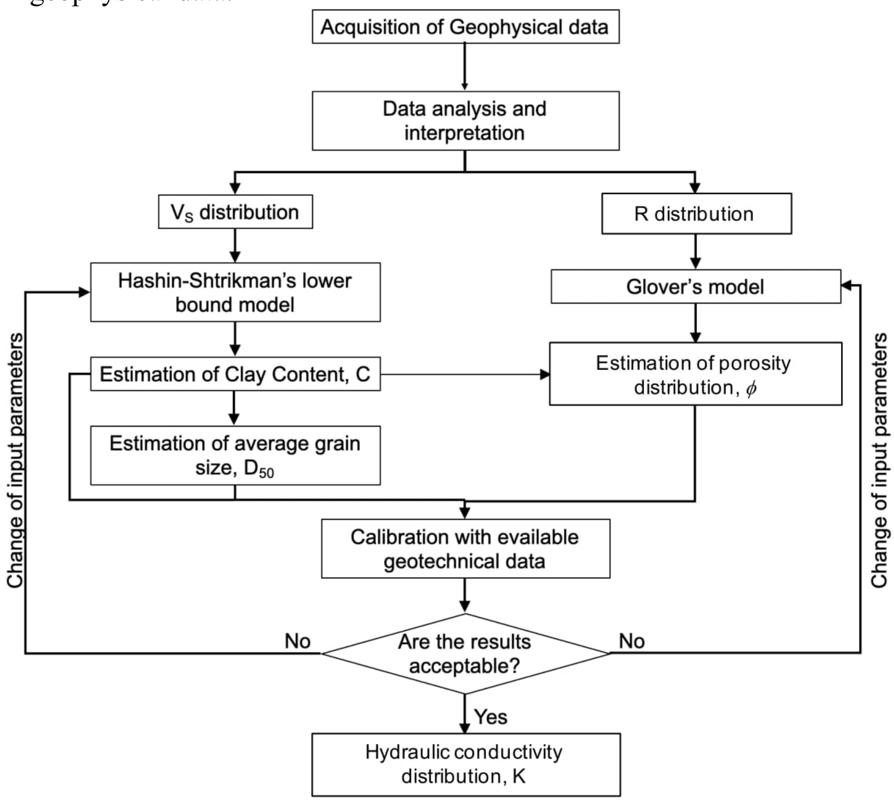

Fig 2. Workflow for estimating soil hydraulic conductivity using multiple geophysical data.

The hydraulic conductivity of soil, K, can be estimated using the common extension of Kozeny-Carman relation (Carman 1956), by knowing porosity, ϕ, and average grain size of soil, D_{50}. In engineering practice, ϕ and D_{50} are usually obtained from the analysis of undisturbed core samples from boreholes. However, it has been demonstrated by many researchers (Glover et al. 2000, Hashin and Shtrikman 1963, Mavko et al. 2009) that both these parameters can be estimated knowing both seismic and electric properties of soil. For electrical resistivity data, the link with porosity (and degree of saturation) can be obtained through the Glover's model (Glover et al. 2000). Soil electrical resistivity can be expressed using the Hashin-Shtrikman model (Hashin and Shtrikman 1963) as a function of the fine content distribution, C. If independent seismic data are available the clay content, *C*, can be estimated from V_S values. Assuming reference values for the parameters constituting the soil, theoretical relationships between porosity, V_S and R as a function of C for a given depth of investigation can be therefore defined. Consequently, 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. Once the C has been calculated, ϕ and D_{50} can be obtained from Glover's models with the additional assumption of related parameters.

4. Results

The procedure previously described allowed to define the clay content for each couple of R and V_S values along the dam (Fig. 3a). Once the clay content was defined, the other geotechnical parameters (ϕ, D_{50} and K) were evaluated. Results are reported in Fig. 3 The dam body appears relatively homogeneous with the presence of rare anomalies. 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. 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.

The reliability of the proposed procedure was also evaluated by comparing the geotechnical parameters obtained with those available from in-situ and laboratory investigations (Fig. 3b). There is a good agreement between geotechnical investigations and the corresponding values, from the proposed procedure. 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 shallower 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 parameters 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 containment structures 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.

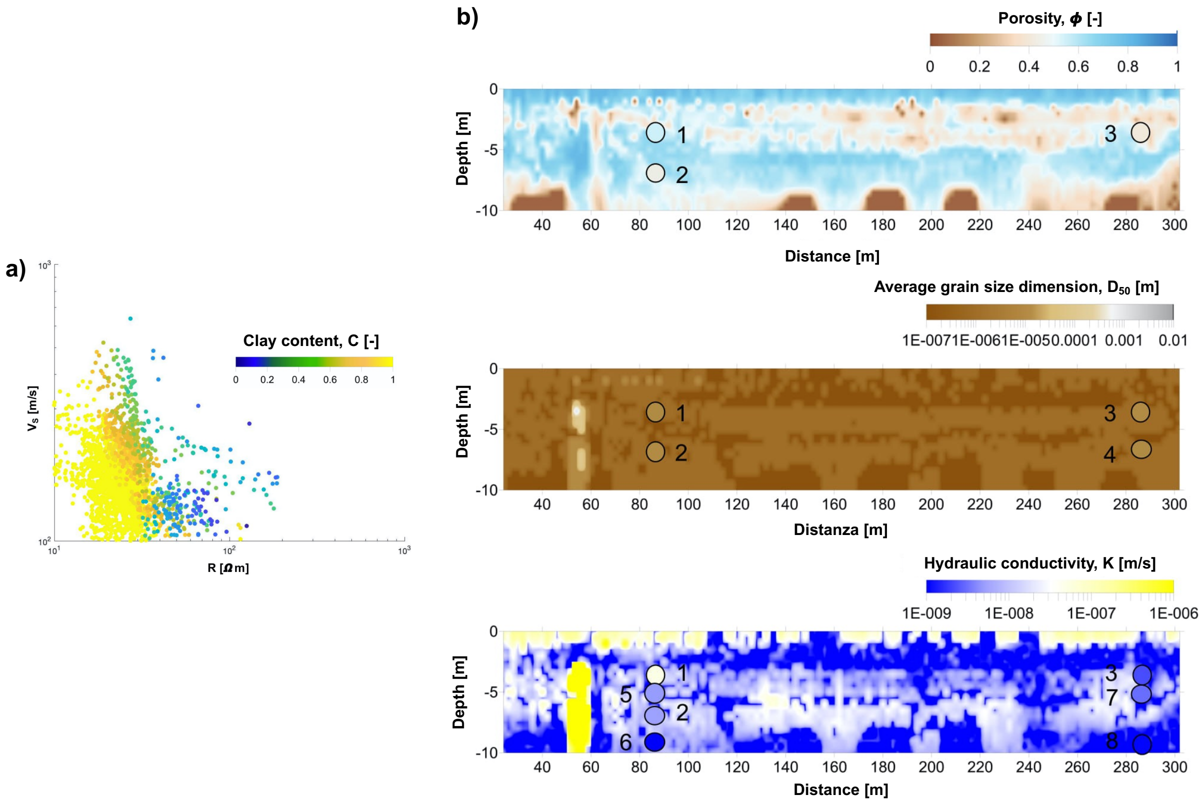

Fig 3. a) Clay content evaluation for each couple of ρ and VS value, obtained by using the seismic-electric streamer data. b) Comparison between available in situ and laboratory tests and estimated porosity, grain size and hydraulic conductivity distribution.

5. Conclusions

In this paper, a procedure for the profiling of hydraulic conductivity distribution from geophysical data was applied to an earth dam located in Arignano, Piedmont Region (Italy). The combined use of seismic and electric streamers allowed the simultaneous execution of electrical resistivity and seismic surveys, ensuring a proper investigation depth for the whole structure body and first meters of foundation soil with limited 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. Estimated values are in good agreement with previously measured data from geotechnical in situ and laboratory tests. The methodology is thought for a first screening of earth structures, for identifying anomalies and possible instability process and consequently, independent geotechnical investigations are necessary for calibrating and validating obtained results. However, due to its speed of execution and processing, this procedure can be useful for detecting hydraulic conductivity anomalies after flood events, when both responsiveness and efficiency of the countermeasures are required.

Acknowledgements

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