Combined resistivity and seismic measurements along linearly extended earth structures - acquisition and interpretation approaches

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ABSTRACT

Geotechnical parameters of linearly extended earth structures, such as embankments and earth dams, are usually obtained from localized investigations through drilling or penetration tests, commonly time and cost consuming. Non-invasive geophysical investigations may be considered an alternative approach for the geotechnical characterization of these structures, given their surveying speed and their depth and length of investigation. Particularly, new acquisition approaches with the use of appropriate streamer cables could strongly reduce the acquisition times making geophysical surveys ideal for a preliminary screening of these structures. Specifically, resistivity and seismic methods can be adopted given that these two methodologies could offer complementary information with respect to the pore fluid properties (resistivity methods) and the solid skeleton characteristics (seismic methods). Also, through specific correlations, relevant geotechnical parameters for the evaluation of the stability of these structure and its efficiency (i.e. hydraulic conductivity, porosity and others) can be obtained. In this paper a review of the methodologies developed in recent years for data acquisition along linearly extended earth structures is reported with special focus on the use of combined electric and seismic streamer cables. Suggestions with respect to interpretation approaches and data elaboration are also analysed.

Keywords: River embankments, Earth dams, Seismic and Electric methods, Geotechnical investigations.

1. Introduction

Linearly extended earth structures, such as embankments and earth dams, are engineering structures constructed for water flow control in rivers and streams. These structures are widely diffused and require constant monitoring of their integrity conditions. Worldwide about 90 million people have been affected by coastal or river floods during the last three decades (Tourment 2018). More recently, the reported number of disasters caused by floods has dramatically increased, mainly because of climate changes. Worldwide, 15% of the global population is expected to live in flood-prone areas by 2050 (Tourment 2018). Also, aging of most of the structures is worrying with respect to their stability and safety requirements. The safety assessment of linearly extended earth structures is therefore a very relevant geotechnical problem for the prevention of floods and embankments break related risks.

Conventional geotechnical methods for the characterization of these structures involve invasive techniques such as core logging (eventually with sample collection for laboratory tests) and different types of penetration tests. These methodologies provide detailed information but are affected by limitations with respect to the time and costs necessary for their execution and to the fact that the provided information is only localized in a particular position within the relevant extension of the structures. Therefore, the obtained information, even if of high quality, cannot be completely representative of the entire structure. Indeed, seepage or leaking phenomena can develop in very localized sections. The localization of potential weakness points within the structures, based on geotechnical methodologies, can therefore be time-consuming and inefficient.

Conversely, geophysical surveys are usually considered very effective in characterizing large investigation areas with reduced economic and time effort. Specifically, geophysical methods have already been applied to river embankments and earth dams in combination with localized geotechnical investigations in a variety of case studies (e.g. Inazaki et al. 2005; Perri et al. 2014; Vagnon et al. 2022a; Khalil et al. 2024). Among the available geophysical methods, the ones based on resistivity and seismic velocities (mainly shear wave velocity, Vs) have been the most adopted.

Among the resistivity methods, objectives of previous studies over linearly extended structures were mainly related to: locate fissures and desiccation cracks (e.g. Jones et al. 2014; An et al. 2020), detect animal burrows (e.g. Borgatti et al. 2017), detect seepages and leakage problems (e.g. Al-Fares 2014; Busato et al. 2016; Lee et al. 2020), monitor water saturation (e.g. Arosio et al., 2017; Tresoldi et al., 2019; Jodry et al. 2019) and generally to ascertain geometrical characteristics and internal properties serving as guidance for rehabilitation interventions.

Among the seismic methods, the multichannel analysis of surface waves (MASW), based on the Rayleigh wave dispersion curve (DC) analysis, is considered the most effective for the determination of Vs profiles (Foti et al. 2018). This methodology can be applied also for the determination of several Vs profiles along a predefined survey direction, to offer a pseudo 2D representation of the velocity field. Several literature applications of this methodology are available along embankments, river dykes and earth dams (e.g. Lutz et al. 2011; Lane et al. 2008; Min and Kim 2006; Comina et al. 2020a).

Simultaneous acquisition of both resistivity and seismic data within the same survey are also usually recommended. Indeed, the complementarity between electric and seismic data is an advantage with respect to the potential combined characterization. Electrical resistivity is very sensitive to fluid phases, while seismic wave velocity, particularly Vs, is sensitive to the mechanical properties of the soil skeleton. Integrated geophysical approaches, combining resistivity and seismic measurements can therefore be more accurate than the individual methodologies alone. Embankment and foundation soil property estimation using resistivity and MASW suveys have been already reported in some literature papers (e.g. Samyn et al. 2014; Busato et al., 2016; Bièvre et al. 2017; Rahimi et al. 2018; Arato et al. 2022).

Execution of MASW surveys can be efficiently applied to already existing seismic streamers, dragged along the earth structures. Conversely, resistivity surveys, even if commonly used, require for the tests execution the insertion of electrodes into the ground, which makes efficient surveys difficult. Particularly when long survey lines are required, which is the case for linearly extended earth structures, problems related to inefficient data acquisition become apparent. In this regard, electric streamers are not at the same technological level as seismic ones, and, therefore, research efforts are still necessary.

To summarize, when the surveys can be executed with mobile systems dragging the appropriate instrumentation, disposed along a streamer, behind a vehicle a significant increase in efficiency of the surveys is observed. In recent years there have been significant research efforts in the development of appropriate streamer systems for the characterization of linearly extended earth structures. A review of the most innovative developed methodologies, particularly with respect to the execution of resistivity measurements, will be provided in section 2.

Following data acquisition, most of the developed interpretation approaches rely on the evaluation of the geophysical parameters along longitudinal sections of the investigated structures through specific inverse problem solution. Given the aims of geophysical data as a fast characterization tool also innovative approaches to the data interpretation, providing direct data transformation strategies, have also been developed particularly for seismic data (e.g. Comina et al. 2020a; Lu et al. 2023). Also, geophysical data interpretation can be partially affected by the 3D shape of the earth structure which should be taken into account for some specific conditions (e.g. Sjödahl et al. 2006; Hojat et al. 2019; Karl et al., 2011). Synthetic discussion on these aspects will be provided in section 3.

In addition to the visualization of the variability of geophysical parameters, several researchers (e.g. Cosentini and Foti 2014; Goff et al. 2015; Hayashi et al. 2013; Takahashi et al. 2014; Vagnon et al. 2022a and b) have developed theoretical, statistical, or field-based methods for specific geotechnical parameters estimation (e.g. soil type, fine fraction content, porosity, hydraulic conductivity) from integrated resistivity and seismic surveys. A review of the most innovative methodologies for specific application to linearly extended earth structures will be also provided in section 3.

2. Acquisition Approaches

As mentioned, survey execution with mobile systems dragging the appropriate instrumentation, disposed along a streamer behind a vehicle can significantly increase efficiency of the surveys particularly over linearly extended earth structures. In the following the most innovative developed methodologies are introduced with respect to seismic streamers, electric streamers and the potential combination of the two.

2.1. Seismic streamers

From the point of view of seismic data acquisition, it must be considered that the surface of the earth structure is mostly constituted by hard compacted soil (i.e. road): it is therefore difficult and inefficient to place a geophone with associated spike on the hard road surface. Moreover, if several kilometres of seismic lines are to be acquired, the disposition operations have to be repeated many times. Conversely, seismic streamers, adopting specific geophone sliders to guarantee a coupling with the ground (e.g. Figure 1) can allow for rapid acquisition of seismic data particularly on the hardened pavement (Pugin et al. 2004; Wadas et al. 2016; Yue et al. 2020).

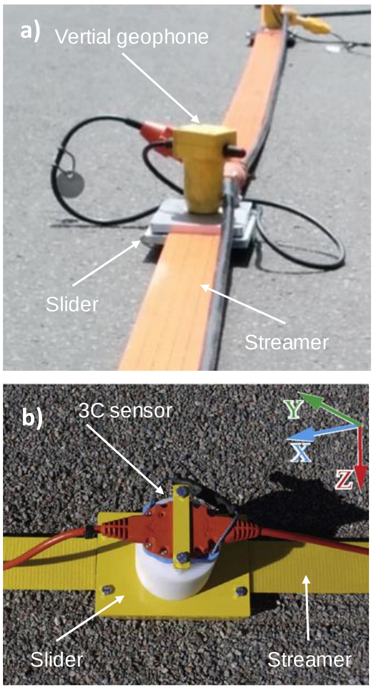

Figure 1. Examples of geophones coupling in seismic streamers: a) standard 4.5 Hz vertical geophone coupled with an appropriate slider and streamer band (courtesy of Techgea S.r.l.); b) 3C MEMS-based sensor on a sled and streamer band (modified from Brodic et al. 2015).

Seismic streamers have been used since the 1970s and numerous successful case studies have been presented during the last three decades (e.g. Van Der Veen et al. 2001; Ivanov et al. 2006; Moura and Senos Matias, 2012; Comina et al. 2020a) allowing this acquisition procedure be considered a well-established methodology. The reliability of seismic streamers in comparison with planted geophones has been demonstrated along unpaved roads (e.g., Vangkilde-Pedersen et al. 2006; Hanafy, 2022), like those usually encountered on the top of earth structures, as long as seismic streamer sliders are heavy enough to guarantee an appropriate coupling (Figure 2). For 2D MASW surveys execution usually 24 (or actually 48) 4.5 Hz vertical geophones are adopted along the streamer (Figure 1a and 2a). The use of multiple component geophones (Figure 1b) can also allow for specific applications involving the study of different types of seismic waves components. Adopted seismic sources are usually impact sources and/or wave vibrators carried by the dragging vehicle.

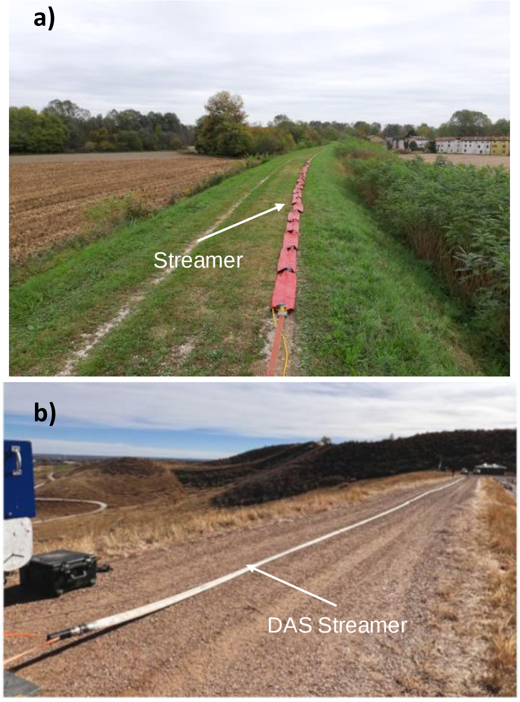

Figure 2. Examples application of seismic land streamers: a) conventional seismic streamer over an embankment structure; b) distributed acoustic sensing (DAS) land-streamer (modified from Pandey at al. 2023).

Recent developments in the seismic streamers technology foresee the use of multicomponent broadband MEMS based sensors (Brodic et al. 2015 – Figure 2b) and distributed acoustic sensing (DAS) land-streamer (Pandey at al. 2023 - Figure 2b). Particularly given the broadband nature of the sensors, the three-component recording and the close spacing of the sensors, the MEMS based land streamer enable high-resolution imaging potentially adoptable also for detailed seismic reflection or refraction surveys and/or more complete seismic analysis involving different wave components (Brodic et al. 2015). Also, the DAS land streamer is easily deployed and towed along the ground surface, allowing for very spatially dense data acquisition which is potentially not limited by the local ground contact of the geophones. However, the quality of the results is still partially dependent on favourable fiber-ground coupling conditions, and significant costs of the Interrogation Unit are to be considered.

2.2. Electric streamers

Improvement of the efficiency and feasibility of resistivity surveys can also potentially rely on the use of mobile systems. This alternative survey strategy can avoid the time-consuming operation of nailing electrodes in the ground and speed up the acquisition process.

Some systems based on this approach were developed in the past using capacitive coupled methods (e.g. Capacitive Resistivity Imaging, CRI by Kuras et al. 2007). However, in low resistivity soils, such as clays or saturated silts, commonly used to build river embankments capacitive coupled systems, and other electromagnetic systems that can be adopted for the same aim, may encounter limitations in current injection within the ground and in the maximum obtainable depth of investigation.

For these reasons, the most recent development of mobile geoelectric systems has been redirected towards the galvanic coupling approach. The ARP (Automatic Resistivity Profiling, from Geocharta) system, which involves the use of wheel-based electrodes inserted in the ground and rolled along the surface, is an example. However, this system adopts reduced electrode separation and the investigation depth is consequently limited, making it suitable for precision agricultural investigations (e.g. Dabas 2011) but not for the depths of investigation involved in the earth structures.

Recent literature works in this respect showed innovations for the execution of resistivity surveys with streamer systems. Comina et al. 2020b showed the application of a new electric streamer for the characterization of earth structures in different case histories. The electrodes of this system, specifically developed for this application, were constructed in stainless steel and have the form of brushes (Figure 3a), i.e. containing several thin wires, in order to increase the contact surface to the ground. The shape of the brushes is similar to a sled, to allow for an easy dragging of the streamer. On top of these brushes there is a PVC element with lateral wings directed to the ground in order to avoid overturning during dragging. To further reduce contact resistances a drip irrigation system is also adopted above the electrodes.

Another interesting application with a similar aim was shown in Umezawa et al. 2022 developing a system using polyvinyl alcohol (PVA) sponge roller electrodes, which are non-destructive and can be moved smoothly without damaging the ground surface. PVA sponge electrodes (Figure 3b) have a high water absorption capacity, high water retention and a large contact area with the ground. Two types of electrodes, a roller and a disc, have been developed (Jinguuji and Yokota, 2021). Because the rollertype electrodes move while rolling themselves, they have low traction resistance and can be towed smoothly.

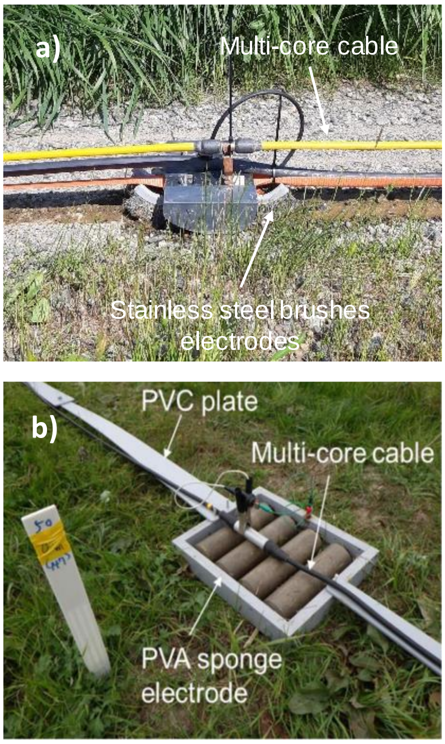

Figure 3. Recent innovations for the execution of resistivity surveys with streamer systems: a) Stainless Steel brushes electrodes (modified from Comina et al. 2020b) and b) PVA sponge electrodes (modified from Umezawa et al. 2022).

In both systems the number and spacing of available electrodes can be adjusted with respect to the investigation needs. Usually 12 to 16 electrodes are sufficient to reach the depth of investigation necessary for the characterization of linearly extended earth structures and for the execution of electric resistivity tomographies (ERT). For both proposed systems, ground coupling plays an important role with regard to the quality of obtained electrical measurements. For these reasons detailed comparisons have been performed in the aforementioned papers with standard electrodes (Figure 4) in order to ensure effective data comparison.

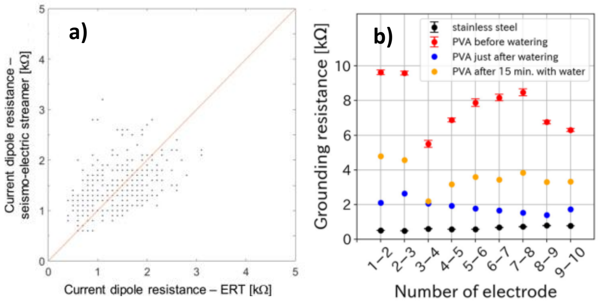

Figure 4. Example comparisons of electric contact resistances: a) between standard electrodes and Stainless Steel brushes electrodes (modified from Arato et al. 2022) and b) between standard electrodes and PVA sponge electrodes (modified from Umezawa et al. 2022).

Applications of the two above mentioned methodologies in different case studies of linearly extended earth structures (Comina et al. 2020b) have indeed shown the complementarity of the obtainable data and ERT interpretations with respect to standard surveys as can be observed in Figure 5.

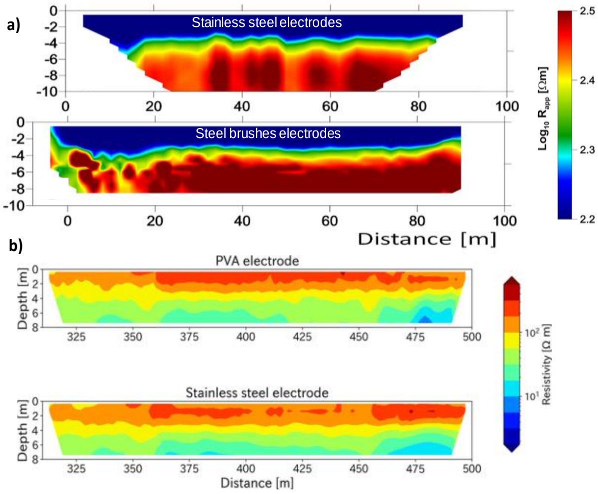

Figure 5. Example comparisons of electric surveys with dragging systems and standard electrodes: a) between standard electrodes and Stainless Steel brushes electrodes (modified from Arato et al. 2022) and b) between standard electrodes and PVA sponge electrodes (modified from Umezawa et al. 2022).

2.3. Combined seismic and electric streamer

The above mentioned streamers could be adopted in parallel along the top of the linear structures top to obtain combined information. However, the combined execution of resistivity and seismic surveys significantly increases the investigation times when the survey length becomes relevant. Moreover, different instrumentations need to be deployed, along independent arrays, within the usually reduced lateral extensions of the earth structure top, complicating the surveys execution. Furthermore, the interpretation of independent arrays, located in partially different positions with respect to the side slopes of the earth structure, can suffer from lateral/transversal variability and possible 3D effects. These effects are recognized both for resistivity methods (e.g., Sjödahl et al. 2006; Hojat et al. 2019) and for seismic methods (e.g., Karl et al. 2011) and can complicate the interpretation in the case of a non-coincident position of the resistivity and seismic profiles.

To solve some of these shortcomings Arato et al. 2022 have recently proposed the combination of a standard seismic streamer with the stainless steel brushes electric streamer in order to merge two survey systems into a unique seismo-electric streamer (Figure 6a). The resulting seismo-electric streamer allows for the simultaneous acquisition of seismic and resistivity data in a unique transect during its dragging along the investigated structure (Figure 6b).

The results obtained through the application of this streamer showed that the new seismo-electric streamer provides seismic and resistivity data highly comparable with the ones obtained by means of usual surveying methodologies. Moreover, the combination of two measurement arrays in a single streamer reduces the survey times by around 1/3 with respect of reference surveys. This increased efficiency potentially allows the seismo-electric streamer to be used in situations where the speed of the surveys is essential (e.g., after, or during, large flood events).

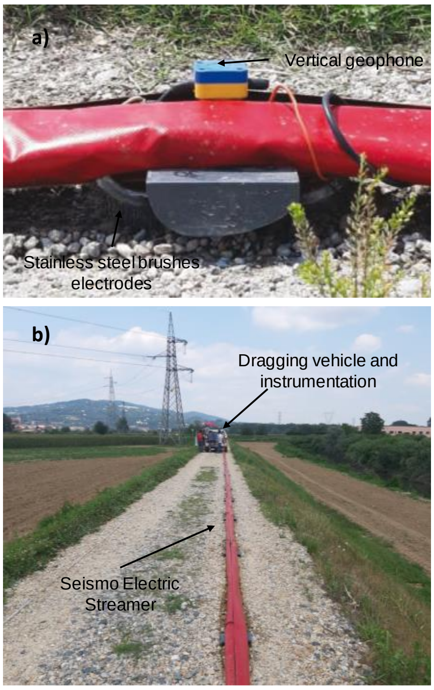

Figure 6. Example application of the Seismo-Electric streamer over an embankment structure: a) picture of a single electrode with coupled geophone (modified from Arato et al. 2022); b) Seismo Electric streamer along the embankment and Dragging vehicle and instrumentation.

3. Interpretation Approaches

Once electric and seismic data are acquired along the interested transect of the linearly extended earth structure the experimental data need to be interpreted with the aim of reconstructing 2D resistivity and seismic sections along the embankment. This part of the process is mainly related to geophysical data interpretation, and different approaches can be adopted with this aim. Following geophysical data interpretation and the availability of resistivity and seismic sections along the structure these data can be later analysed in order to estimate relevant geotechnical parameters for the charcaterization. In the following, the most innovative developed methodologies are introduced with respect to the two different interpretation steps.

3.1. Geophysical data interpretation

Geophysical interpretation approaches are mainly aimed at obtaining 2D or pseudo 2D sections of geophysical parameters along the linearly extended earth structure. For resistivity surveys the standard, and most adopted, approach is to provide an estimation of the 2D electrical resistivity distribution by merging all the experimental measurements in a unique dataset and solve the 2D inverse problem. There are several available softwares able to obtain this reconstruction (e.g. Res2DInv by Loke and Barker 1996). The imaged resistiviy distribution can then be interpreted in terms of layering properties of the different materials. Usually clay and lime layers show indeed reduced resistivity while partially saturated and sand layers show higher resistivity. An example application of this approach is reported in Figure 7a along a 300 m long transect of a linearly extended earth structure. Clear layering in the resistivity properties can be observable and potentially associated to the change in geotechnical properties of the materials (see later section 3.2).

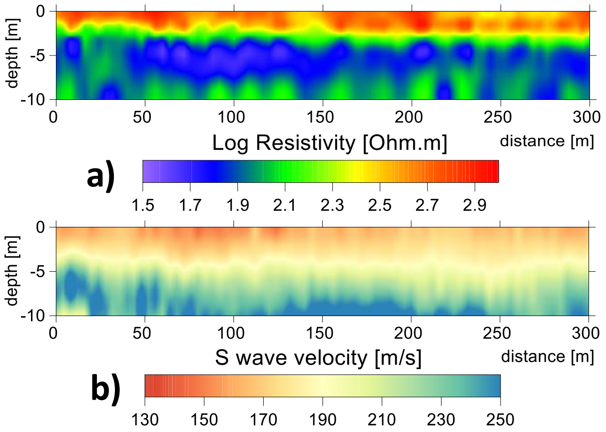

Figure 7. Example application of geophysical data interpretation for resistivity and seismic data acquired with mobile streamer systems along a linearly extended earth structure: a) 2D resistivity section and b) pseudo 2D shear wave velocity section from the interpretation of surface wave data.

For seismic data multiple interpretation approaches are instead possible depending on the types of acquired data and interested parameters to be extracted. Seismic records can indeed be interpreted in terms of first arrival traveltime tomography for the analysis of compressional wave velocities, Vp (e.g. Brodic et al. 2015; Comina et al. 2020a) or in terms of seismic reflection for layering and specific anomalies identification (e.g..Chen at al. 2006).

The most adopted approach in the interpretation of seismic data with streamer systems over linearly extended earth structures is, however, the one based on the extraction of multiple surface waves dispersion curves (DC) along the investigated profile and their following interpretation with the aim of obtaining a 2D MASW survey, i.e. pseudo 2D Vs distribution along the earth structure (e.g. Lutz et al. 2011; Lane et al. 2008; Min and Kim 2006; Comina et al. 2020a). To obtain the pseudo 2D Vs distribution several approaches can be adopted. Most of these are based on the inversion of the different DC extracted in terms of 1D layered Vs profiles. Also, Laterally Constrained Inversion approaches can be adopted to take advantage of the whole dataset in a more comprehensive manner (e.g. Comina et al. 2020a). Recent developments in DC interpretation could also rely on specific data transform procedures which could avoid the inversion step (e.g. Lu et al. 2023 or W/D procedure in Comina et al. 2020a). Particularly, the W/D procedure allows for the combined definition of 2D Vs and Vp wave velocity models and can be developed in order to be automated as a fast imaging tool. An example application of this approach for the determination of the only 2D Vs distribution is reported in Figure 7b along a 300 m long transect of a linearly extended earth structure. Clear layering in the Vs properties can be observable and potentially associated to the change in geotechnical properties of the materials (see later section 3.2).

For geophysical data interpretation, 3D effects should be taken into account, if relevant, for a proper characterization of the embankment structure. Indeed, 2D surveys and interpretation models assume that the geophysical parameters do not change in the direction perpendicular to the profile direction but this my not always be the case over the investigated earth structure. The influence of 3D effects is related to the geometrical dimensions of the structure, so can be relevant in some situations and less important in others depending on its lateral extension.

For resistivity data, Arosio et al. 2018 have underlined that resistivity measurements are not only influenced by the materials directly below the survey line, but also by lateral resistivity changes at the sides of the profile (river channel with varying water levels on one side and the air on the other side or presence of specific retaining structures on one side of the embankment). Based on the analysis of a laboratory experimental tests the authors defined a data correction strategy for the 3D effects using analytical modelling curves and forward modelling results calculated in 3D for the geometry of the experiments. Similar approaches should be adopted in real cases particularly for embankments having a high width-to-height ratio.

For seismic data, and specifically for DC curves, Karl et al. 2011 studied the influence of the earth structure topography on the test results by means of numerical analyses. Typical cross-sections are modelled using 2.5D finite and boundary elements. The results of models taking the topography into account are compared with models neglecting the topography. The differences among the results were found to be insignificant for dykes with a width-to-height ratio larger than four. In these conditions the shape of the embankment could influence the surface wave dispersive pattern and modes superposition (e.g. Karl et al., 2011). Pageot et al. 2016 have also shown that internal structure layering can emphasize geometrical effects and produce DCs very different from the theoretical 1D case, for both the fundamental and higher modes. For 3D effects evaluations also whole moving arrays consisting in different survey lines could be adopted (e.g. Lu et al. 2023).

3.2. Geotechnical parameters estimation

Following a proper geophysical data interpretation there have been significant research efforts in the development of appropriate methodologies for specific geotechnical parameters estimation (e.g. soil type, fine fraction content, porosity, hydraulic conditions) from integrated geophysical surveys.

Most of these approaches rely on combining shear wave velocity and resistivity properties to provide a more accurate description of geotechnical properties than the individual methodologies alone. With this respect cross plots of resistivity and shear wave velocity from the geophysical data analysis are often adopted either for the formulation of specific correlations with independently measured geotechnical parameters (e.g. Hayashi et al. 2013) or for comparing the experimental data to theoretical formulations as a function of different constituting parameters and back fit the experimental ones (e.g. Takahashi et al. 2014; Vagnon et al. 2022a and b). With respect to the first approach Hayashi et al. 2013 provided an extensive statistical estimation of geotechnical soil parameters of levee body and foundation using cross-plots of resistivity and Vs from a wide dataset acquired over Japanese levees. A polynomial approximation was used to estimate the soil parameters.

An example application of one of the proposed theoretical approaches is instead reported in Figure 8 where the experimental data of Figure 7 are compared to theoretical clay content curves obtained from the Glover's model (Glover et al. 2000), the Hashin-Shtrikman upper bound model (Hashin and Shtrikman 1963) and the Voigt-Reuss-Hill model (Mavko et al. 2009) as a function of apriori established parameters.

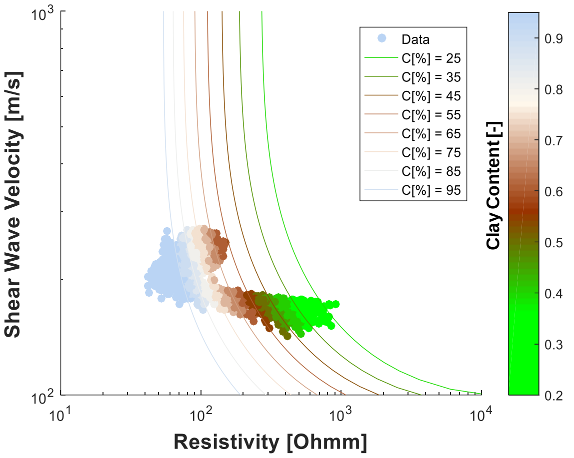

Figure 8. Cross plot of resistivity and shear wave velocity data for the experimental application reported in Figure 7 and superimposed theoretical clay content curves.

The comparison of the experimental data to the theoretical curves allows consequently for an estimation of the clay content (Figure 8). The clay content values can be then mapped along the investigated embankment or adopted to produce comparison data with local geotechnical parameters. In the example reported in Figure 9 the data obtained from this elaboration are represented in terms of material type index (Robertson 2009) and compared to the same obtained from a cone penetration test (SCPTU) and borehole investigation. From the comparison of the results it is possible to appreciate the correspondence between the direct geotechnical analyses and the geophysical data interpretation in the corresponding locations.

Moreover, the added value of the execution and interpretation of geophysical surveys, which are able to map the parameters variability along the whole embankment providing a more comprehensive analysis of the case history, is emphasized.

Also, once the clay content is calculated, the porosity can be obtained knowing the resistivity data and additional assumption of related parameters. Then, it is possible to also estimate the average grain size, d, and potentially calculate hydraulic conductivity values as reported in Vagnon et al. 2022b. Results of these elaborations showed to be in good agreement when compared with local geotechnical investigations.

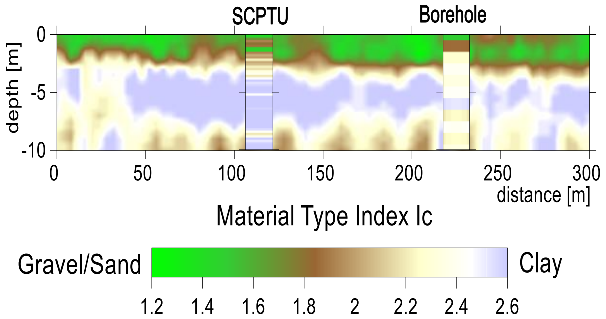

Figure 9. Example transformation of the resistivity and Vs data for the experimental application reported in Figures 7 and 8 in terms of material type index and comparison with independent borehole and SCPTU data.

4. Conclusions

Far from being exhaustive, what contained in this paper is limited by my knowledge and influenced from previous work performed by me and co-authors on the topic. Alternative approaches, both for the experimental data acquisition and for their interpretation, are possible and the wide scientific literature on the topic could contain other valuable solutions not directly mentioned in this review.

Notwithstanding the above consideration this paper aimed at underlining that several acquisition approaches with appropriate streamer that could work in movement along the investigated earth structure are nowadays available for both resistivity and seismic data. These approaches could allow for a fast, reliable and comprehensive geophysical characterization also for relevant linear extensions. The data interpretation can moreover provide important extensive information for the management of these structure.

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