Towards a Seismo-Electric land streamer

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ABSTRACT: From the end of the last century several innovators have been exploring the use of seismic land streamers for the acquisition of seismic data with mobile systems. Nowadays, the technological development of these streamers is at such a point that it can be considered alternative to traditional geophones, with temporal and economic advantages in survey acquisition. Similar alternatives have also been partially developed for the acquisition of geoelectrical data with mobile systems. However, these last systems suffer from depth limitations given the difficulties in establishing proper electric contact with the ground. An appropriate streamer combining these two geophysical methodologies is currently not available. For a reliable and comprehensive soil characterization, the combined use of different geophysical parameters is suggested. In this paper, the authors therefore investigate the possibility of improving a standard seismic streamer using appropriate tools for performing combined geoelectrical acquisitions. Preliminary results with the newly developed instrumentation for geoelectrical measurements are presented. An application to a case history for the geotechnical characterization of a river embankment, combining seismic and geoelectrical surveys, is also reported. Benefits of the combination of the two survey systems in a single streamer are also briefly discussed.

Keywords: land streamers; river embankments; geoelectrical surveys; seismic surveys.

1. Introduction

Geophysical surveys are usually considered very effective in characterizing large investigation areas with reduced economic and time effort. This is particularly true when the surveys can be executed with mobile systems dragging the appropriate instrumentation, disposed along a streamer, behind a vehicle. From the end of last century several innovators (e.g. Rambøll, Tyrens, Kansas Geological Survey etc.) have been exploring the use of seismic land streamers. Nowadays, the technological development of these streamers is at such a point that it can be considered alternative to geophones for the acquisition of seismic data, with the advantage of reduced time and economic effort. Several examples of high quality seismic data collected with this approach are available in literature (e.g. [1,2]).

Similar approaches have been also partially developed for the acquisition of geoelectrical data with mobile systems. However, the efficiency and reliability of these systems cannot be compared to the seismic ones, due to limitations concerning technical equipment and survey mode. In fact, the proposed solutions are effective only for mapping the shallow resistivity distribution but are not capable to reach the same depth and vertical resolution of standard geoelectrical surveys. Motivations for this are mainly related to the more complicated coupling necessary to inject significant amounts of electric currents into the ground for reliable measurements.

Some systems were developed for overcoming these limitations, introducing a capacitive coupling approach. Particularly noteworthy are the OhmMapper from Geometrics, one of the first systems operating in this mode, and, more recently, the CRI (Capacitive Resistivity Imaging, [3]). The results obtained with these systems (e.g. [3-7]) have shown that it is possible to acquire, for different applications, data comparable with standard resistivity measurements with relatively high dragging speeds. However, in lower resistive soils (presence of clays or saturated silts) capacitive coupled systems may encounter problems related to the depth of investigation.

For these reasons, the most recent development of mobile geoelectrical systems has been directed towards a recovery of the galvanic coupling approach. Example of this is 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. This system has been particularly used for agricultural applications (e.g. [8-11]) since it is possible to map large areas in relatively short time.

All the above mentioned systems adopt reduced dipoles separation, which directly influences and limits the investigation depth, and hence are only suitable for shallow investigations. One of the older systems involving the use of electrodes with increased separation distances dragged behind a vehicle is the PACEP (Pulled Array Continuous Electrical Profiling, [12]). In this system a Wenner array configuration has been also adopted which, compared to the dipole-dipole configuration, guarantees greater potential to be measured with the same current input. Therefore, as the separation between the electrodes increases, the measurement is more reliable. The latter system is more versatile with respect to the usable separations and consequently also to the achievable survey depths. By adding other pairs of current and potential electrodes, or using different measurement combinations along the same cable, it is therefore ideally possible to perform electrical tomographies in motion. Moreover, this system is also much more similar than the previous ones to seismic land streamers and can potentially be combined with them.

In this paper, inspired from this last system, but changing the type and technological details of electrodes, the authors therefore investigate the possibility of improving a standard seismic streamer with the addition of appropriate tools for performing geoelectrical acquisitions. As part of a research project (Mon.A.L.I.S.A.) a suitable technical solution has been studied (with a patent pending request) to guarantee an appropriate electric coupling between the streamer and the ground. First results with the newly developed instrumentation for geoelectrical measurements are presented and compared to standard geoelectrical acquisitions, to demonstrate the effectiveness of the chosen approach. An application to a case history for the geotechnical characterization of a river embankment, combining seismic and electric surveys, is also reported, together with a brief discussion about the benefits of combining two different survey systems in a single streamer. The ideal application of the developed instrumentation is indeed related to surveys requiring long investigation paths like earth dams, levees or river embankments. The combined use of geoelectrical and seismic data can provide an effective geotechnical characterization of these earth structures, as shown by several research groups that are working on their integration (e.g. [13-16]).

2. Developed system

The measurement system specifically developed for the execution of geoelectrical measurements in motion is displayed, in its prototype form, in Figure 1a. This 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 (Figure 1b). The arrangement of the electrodes along the streamer is very versatile and can be adapted according to the specifications of the investigation.

The configuration shown in Figure 1a consists of a Wenner configuration with 2 current electrodes and 2 potential electrodes, 2 m spaced. The electrodes are connected to a georesistivimeter (Syscal-Pro, Iris Instruments) by means of a multipolar cable. This prototype was used for preliminary experimental and calibration measurements.

In its current configuration the streamer has instead a length of 46 m and a total of 12 electrodes, that can be used both as current and potential electrodes (Figure 2). In this way it is possible to perform different measurement combinations, centered along the vertical of investigation corresponding to the center of the streamer. The selected measurement combinations are based on the Wenner-Schlumberger configuration and guarantee an adequate coverage of the data from the surface to a depth of about 10 meters (Figure 2). Repeating the geoelectrical measurements for different positions of the cable center (measurement step), it is therefore possible to construct a pseudosection of resistivity that can be subsequently elaborated with tomographic methods. This last configuration has been adopted for the execution of the geoelectrical measurements in the case history presented in this paper.

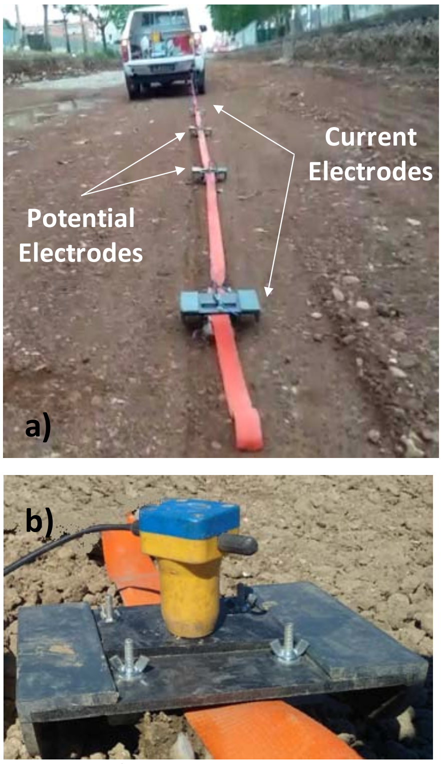

Figure 1. Prototype of mobile galvanic coupling resistivity measurement system: a) preliminary electrodes configuration and b) combination with geophones for seismic measurements.

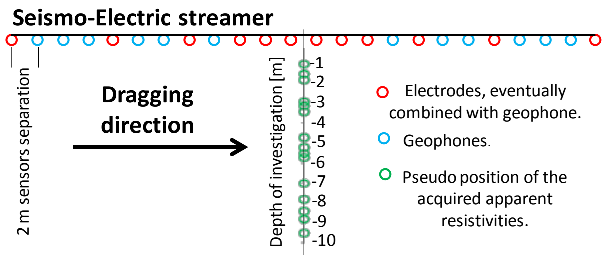

Figure 2. Seismo-Electric streamer configuration and pseudo position of the acquired apparent resistivity measurements.

The streamer is dragged by a vehicle (Figure 1a) that stores the equipment necessary for performing the geoelectrical tests (acquisition system and water tank and irrigation system for reducing contact resistances between electrodes and ground) and eventually the instruments for carrying out seismic investigations (acquisition system and seismic source device). For this purpose either a parallel seismic streamer can be deployed aside to the geoelectrical one (this configuration has been adopted in the case history presented in this paper) or potentially the two surveying approaches can be combined along the same streamer (Figure 2). Standard 4.5 Hz vertical geophones can be indeed fixed over the insulating PVC plates present above the electrodes (Figure 1b). In the actual configuration this will allow a 24 geophones streamer at 2 m spacing combined with the electric one (Figure 2). Eventually geophones number can be increased to allow for 48 geophones at 1 m spacing, in the available spaces among the sensors.

3. Preliminary experimental and calibration measurements

First measurements for evaluating the performances of the geoelectrical streamer were performed in a test site located in the CNR (National Research Council) headquarter in Turin (Italy). The test site features a known shallow anomaly, characterized by an artificial body of loose coarse sand, buried within the natural geological formation (i.e. fine sandy soil). A traditional ERT clearly shows the anomalous sand body as a more resistive volume (resistivity around 800 Ωm), due to its higher porosity and lower saturation, with respect to the surrounding natural soil (resistivity around 250 Ωm). On site measurements were performed using the first presented configuration of the electric land streamer.

The first statistical comparisons between the data acquired in the traditional way (Pk - electrodes nailed in the ground) and with the land streamer (LS) prototype are reported in Table 1. It can be observed how the system chosen for the coupling of the electrodes with the ground guarantees a correct current input (In) and acceptable contact resistances (Rs), comparable to the use of electrodes. Under different operating voltages for the instrumentation, the difference between the measured parameters is always below 5%.

Table 1. Statistical comparison between the data acquired in the traditional way (Pk) and with the land streamer prototype (LS).

	V [V]	In_m [mA]	St.dev_In [mA]	Δ In [%]	Rs_m [kΩ]	St.dev_Rs [kΩ]	Δ Rs [%]
Pk	600	70.41	14.07	4.46	11.08	2.89	0.69
LS		74.87	22.15		11.78	2.95	
Pk	100	13.37	3.88	0.6	10.7	2.72	0.56
LS		12.77	3.82		11.26	2.81	

A horizontal electrical sounding (HES) was subsequently carried out, translating the acquisition quadrupole in different acquisition modes (Figure 3): "Electrodes" refers to the acquisition performed by moving, for each measurement step, the quadrupole with 6 m steps, using stainless steel electrodes nailed in the ground; "Static Array" refers to the same acquisition mode but using the geoelectrical streamer positioned at the previous measurement points; "Mobile Array" refers to acquisitions performed by moving the geoelectrical streamer along the survey path and acquiring data at fixed time interval.

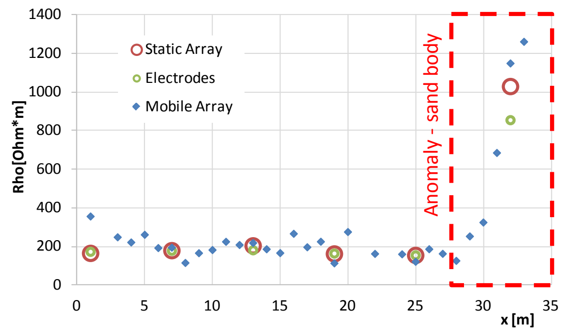

Figure 3. First results of geoelectrical streamer performance and reliability: comparison of the three acquisition methods adopted.

From the results reported in Figure 3 it can be observed that all the acquisition methods adopted are able to correctly represent the increase in resistivity related to the presence of the sand body. There is a good agreement between results obtained with the acquisition methods "Electrodes" and "Static Array", which almost perfectly overlap. The data of "Mobile Array" follow with good agreement the progress of the data obtained with the other acquisition methods, with minimal deviations in many points of the profile. The advantage in performing measurements in motion is confirmed by an increase in the number of data acquired in almost ¼ of the time necessary for other acquisition methods.

4. Bormida river embankment case history

The field scale tests on the performance of the geoelectrical streamer, in combination with seismic measurements, were performed along the right embankment of the Bormida river, in Spinetta Marengo municipality, in NW Italy (Figure 4).

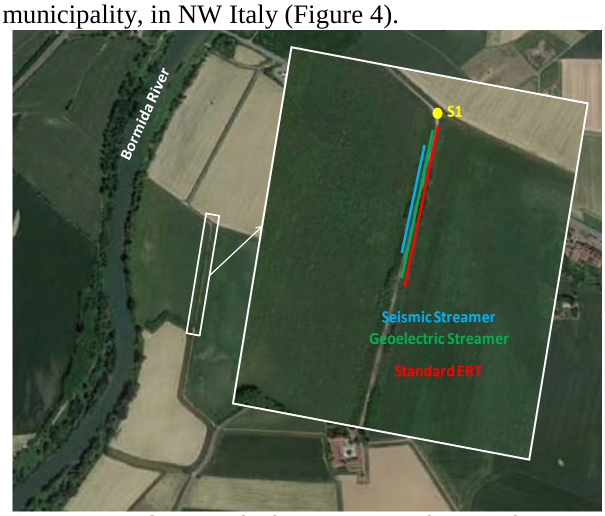

Figure 4. Bormida river embankment test site and surveys disposition.

The embankment is separated from the river by the presence of a 150 m long floodplain that serves as an expansion area during floods (Figure 4). The top of the embankment rises about 7 m from the free surface of the river, and about 3 m from the floodplain. The soil composition of the embankment (embankment body and foundation) was obtained by an available borehole (S1, Figure 4) executed on its top, and by geotechnical tests (standard penetration test, SPT, and dynamic penetration super heavy test, DPSH), interesting both embankment and foundation soil, executed in the sourroundings (Figure 5). The geotechnical setting can be sinthetized as costituted by:

- Layer 1: about 2 m thick, consisting of silts with fine sand and scattered clasts;
- Layer 2: about 3 m thick, consisting of fine to medium grained sand, moderately compacted, with sporadic clasts;
- Layer 3: about 1.5 m thick, consisting of moderately compacted gravel with medium grained sand;
- Layer 4: about 1.5 m thick, consisting of moderately compacted gravel with coarse grained sand;
- Layer 5: about 2 m thick, consisting of compact gravel with coarse grained sand:
- Layer 6: 2 m thick, consisting of sand with gravel.

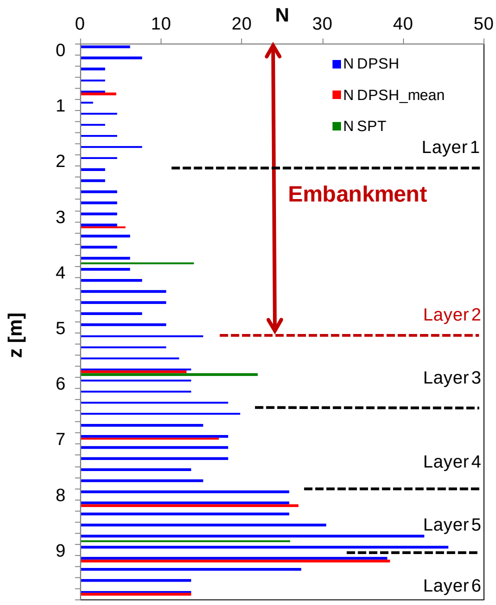

Figure 5. Results of SPT and DPSH tests and layer sequence within the embankment body and foundation soil.

Three different parallel surveys have been executed along the embankment (Figure 4):

- a standard Electric Resistivity Tomography (ERT) with 72 electrodes at 2 m spacing and a Syscal-Pro (Iris Instruments) acquisition device;
- an acquisition with the geoelectrical land streamer, in the configuration reported in Figure 2 but with only the electrodes placed along the streamer and connected to the same Syscal-Pro (Iris Instruments) acquisition device;
- a standard acquisition with a seismic streamer composed by 24, 4.5 Hz vertical geophones at 1 m spacing connected to a DAQ-link acquisition device.

In Figure 6 the results of the geoelectrical surveys, for the superposing distances from the S1 borehole, along the embankment, are reported in terms of measured apparent resistivity values. Apparent resistivity values are the input for the inversion problem therefore the correspondence of these measurements in the two acquisition modes is a reliable test on the effectiveness of the developed geoelectrical streamer.

It can be observed that the two data are highly comparable and that, apart from some isolated values, the difference between the measurements fall within a 5 % variation. Resistivity data, even in the form of pseudosection reported in Figure 6, are able to discriminate the transition from the shallow silts and sands to the bottom gravels along the embankment and to delineate the embankment bottom. Coherently with the borehole evidence this transition falls, on the left side of Figure 6, around 5 m depth. However along the embankment a variation on the depth of this interface can be evidenced. Particularly, localized anomalies suggest an increase in the depth of the shallow silts and sands at 60, 85 and 125 m progressive distance. Conversely, the depth of the interface appears to be shallower in the progressive distance range between about 90 to 120 m. A deeper increase in resistivity is also observed around 8 m depth along the whole section, were the transition to more compacted gravels is evidenced by borehole results and geotechnical tests (Figure 5). Inversion of the two resistivity data brings to very similar considerations and does not add particular details to the data interpretation.

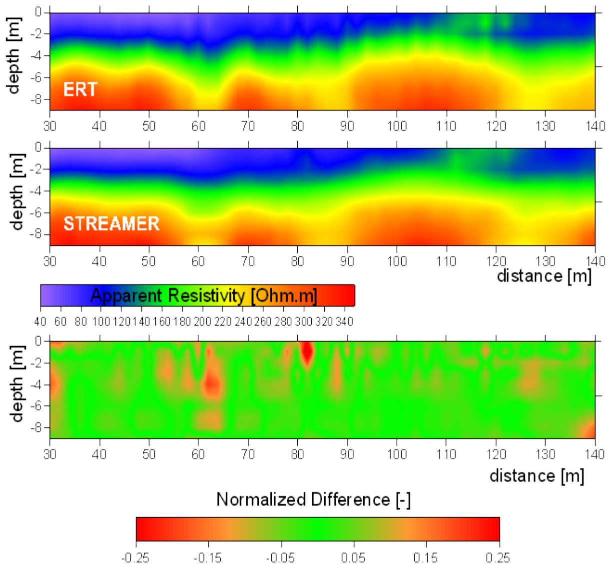

Figure 6. Results of geoelectrical acquisitions along the Bormida river embankment, comparison between standard ERT acquisition (top) and geolectrical streamer data (middle), normalized difference between the two acquisitions is also reported (bottom). Supposed embankment depth is also depicted with a maroon dashed line.

Data from the seismic streamer acquisitions have been interpreted to obtain both the shear and the compressional wave velocities (Vs and Vp respectively). A newly developed data transform approach, based on surface waves propagation properties and surface waves skin depth, was applied for this purpose. This approach has been proven to be effective and comparable to standard inversion strategies for the determination of Vs and to alternative P wave tomographic strategies for the determination of Vp (see [17-19]). In Figure 7 the results of the seismic interpretations, for the superposing distances from the S1 borehole, along the embankment, are reported in terms of both Vs and Vp.

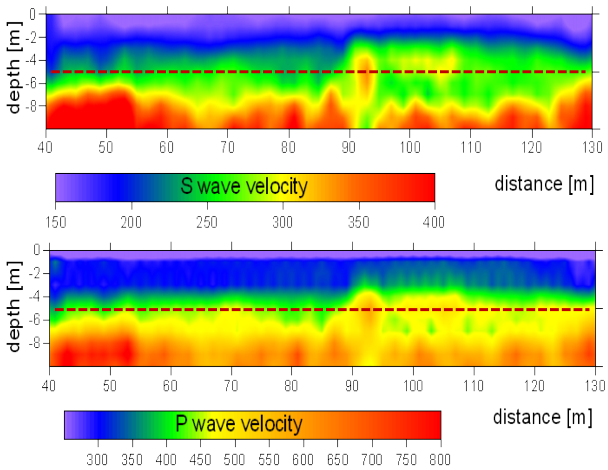

Figure 7. Results of seismic data interpretation along the Bormida river embankment in terms of both Vs (top) and Vp (bottom). Supposed embankment depth is also depicted with a maroon dashed line.

Again, seismic data along the embankment are able to discriminate the transition from the shallow silt and sand to the bottom gravel along the embankment. Depth and trend of this interface along the survey line compare well with the geoelectrical evidence (particularly for Vs data). A similar decrease in the depth of the lower embankment interface is indeed depicted from about 90 m to 120 m progressive distance, where higher Vs velocity deposits appear to be shallower. Also increased velocities are observed at the bottom of the embankment where the interface with more compacted gravels is present.

5. Discussions

The combined use of geophysical and geotechnical testing for the characterization of the studied embankment clearly represents a potential field of application for the developed streamer. With this respect local geotechnical information could be transferred to the whole embankment by establishing proper correlation between geotechnical parameters and geophysical ones.

Notwithstanding the scarcity of geotechnical tests in the studied case history, an attempt in establishing this correlation has been performed in terms of Relative Density (DR) near the position of the available sounding (S1) and geotechnical tests. Relative Density represents indeed an important parameter for defining the effectiveness of the construction stages of the embankment and its state of conservation.

With this aim Figure 8 compares the Resistivity (Figure 8a) and Vs (Figure 8b) profiles resulted from LS data in correspondence of the beginning of the surveys and average Relative Density values obtained from SPT and DPSH blow count.

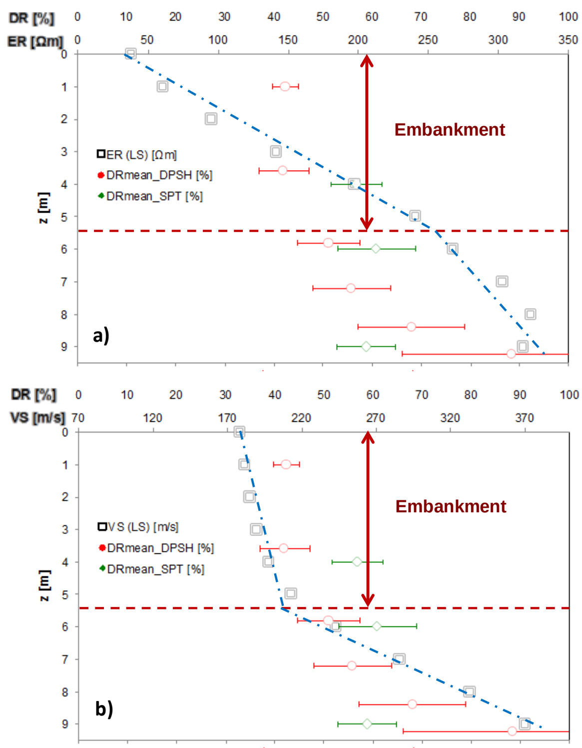

Figure 8. Comparison between average DR calculated using SPT and DPSH data and a) Resistivity profile obtained from geoelectrical survey and b) Vs profile obtained from seismic survey.

Relative Density can be calculated from these geotechnical tests using many different formulations: in this paper, Gibbs and Holtz [20] and Skempton [21] relationships were used and averaged, coupling both soil (in terms of lithology and tensional stresses) and testing mode information (in terms of equipment characteristics). Relationships between DR values and both resistivity and shear wave velocity have been also observed in literature (e.g. [22 - 24]).

From the data reported in Figure 8 a good agreement can be observed between DR and geophysical parameters as a function of depth. It is evident the change in relative density at the interface between embankment and foundation soil, which is also mirrored by a variation in the slope of the resistivity (minor) and Vs profiles. Slight differences are observable between relative density values obtained from SPT and DPSH blow count probably due to the nature of testing procedure.

The Vs profile is more promising with respect to its application with the aim of transforming the geophysical maps in terms of DR, given also established correlations in literature between Vs and geotechnical tests (e.g. [25]). Conversely resistivity data, in the apparent resistivity from reported in this paper, appears to suffer from low resolution at the embankment interface. This could be partially overcome by appropriate inversion strategies, not proposed in this paper. On the other side resistivity data appear to be more able to evidence the depth variation of the interface along the embankment body (Figure 6). This evidence stress again the importance of the combined measurement of several geophysical parameters for a more complete characterization of the studied embankment.

6. Conclusions

The first data acquired with the developed geoelectrical streamer confirmed the goodness of the technical solution adopted for establishing a satisfying electric coupling. This allowed obtaining resistivity measurement equivalent to the ones obtainable by nailing electrodes into the ground with the advantage of a reduced time effort in the surveys. Further data with increased coverage are necessary to better evaluate the performance of the proposed methodology as a substitute to standard electrical surveys.

The seismic data acquired with a combined seismic streamer were also essential for a proper characterization of the studied river embankment. The adopted seismic interpretation approach allowed the combined determination of Vs and Vp with the same measuring apparatus.

The development of a fully combined seismo-electrical land streamer is therefore foreseen given this preliminary successful application. Preliminar correlation between geotechnical and geophysical parameters have been attempted to demonstrate the potential effectiveness of the proposed surveying approach. This will result in a more comprehensive and fast characterization of surveys requiring long investigation paths like earth dams, levees or river embankments.

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