A new electric streamer for the characterization of river embankments

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ABSTRACT

River embankments are linearly extended earth structures, worldwide diffused, built for river flood protection. Their integrity and stability are fundamental prerequisites for the protection efficiency they can offer, also in relation to the increasing frequency and magnitude of extreme flood events due to climate changes. Proper characterization and monitoring of the embankments' body are essential to verify the construction requirements of newly built structures and to evaluate the durability of aged ones. Given their significant linear extension, the characterization cannot rely only on local geotechnical investigations but requires the application of efficient and economically affordable methods, able to investigate relevant lengths in a profitable way. This is even more essential when the investigations are performed after, or in foresee of, significant flood events, when embankment structures get stressed and timing of the surveys is crucial. In these conditions, new survey methodologies, eventually with the use of mobile systems, are a main research topic. In this paper the application of a new electric streamer, specifically designed for these aims, is presented. The technical solutions adopted for its construction are described and its application to the characterization of three different river embankments is presented. The case studies were chosen in accordance with the Po River Interregional Agency (AIPO), which is the authority deputed to the management of hydrographic network of Po River and to the safety of protection structures against flood risk in North-West Italy. The selected embankments are all earth type structures, constructed above the natural alluvial soils, but are characterized by different conditions and problematics. The results obtained with the new system are comparable to standard Electric Resistivity Tomography (ERT) methods. The newly developed system has however significant advantages in terms of reducing the survey time, improving the efficiency of the surveys and increasing the data coverage for a better definition of potentially dangerous anomalies.

Article Highlights:

- A new electric streamer has been developed for the characterization of river embankments;
- Application of the new electric streamer produces results comparable to those from standard geoelectrical surveys (ERT);
- Advantages in survey time and efficiency are highlighted.

Keywords: Electric streamer, ERT, river embankments.
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1. INTRODUCTION

River embankments are linearly extended earth structures constructed to serve as flood control systems during large rain events. A proper characterization of the embankment body is essential both after its construction, or partial rebuilding interventions, to verify uniformity and correspondence to design characteristics, and during its operating life, to monitor integrity losses caused by natural events or wildlife activities (e.g. animal burrows). Floods, seepages and invasive animal activities are indeed known to negatively affect the hydraulic performances of embankments, and their structural integrity. Maintenance and control of embankments integrity is specifically of fundamental importance following, or during, main flood events which could severely compromise the efficiency of specific embankment portions. In recent years, frequency and magnitude of extreme flood events have been rapidly increasing in Central America, Southern Europe and in Italy because of climate changes. Moreover, the poor maintenance of hydraulic structures, mostly reaching their design service life, makes the adoption of specific interventions of paramount international relevance.

Given the significant length of these structures, their characterization cannot rely only on local geotechnical investigations but requires the application of efficient and economically affordable methods, able to investigate the whole embankments in a profitable way. With this respect, non-invasive, rapid and cost-effective methods are desirable to identify higher potential hazard zones for planning detailed interventions and target rehabilitation efforts. The speed of the surveys is an important prerequisite when interventions must be planned in a reduced time window close to main events and when a first draft characterization of the state of life of the embankments is required.

Geophysical methods, and predominantly geoelectrical ones, are particularly suitable for these aims since they can cover long survey lengths with reduced economic and time effort. Geoelectrical measurements can investigate variations of soil composition and water saturation, detect development of weak zones and identify local anomalies potentially related to wildlife activity (e.g. burrows). In the scientific literature, several application of electrical resistivity tomography (ERT) to river embankments and earth dams have been shown in order 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. Panthulu et al., 2001; Cho and Yeom, 2007; 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), ascertain geometrical characteristics and internal properties to serve as guidance for the rehabilitation interventions (e.g. Cardarelli et al., 2014; Minsley et al., 2011; Sjödahl et al., 2006; Camarero et al., 2019) and in general for vulnerability assessment.

ERT cannot be considered as a stand-alone technique since electrical resistivity depends on both electrolytic conduction (fluid saturation and ionic composition) and interfacial/surface conduction (presence of clayey particles or organic matter). The entity of the two contribution is not easily distinguishable from survey results. Electrical resistivity is a complex quantity, composed by an in-phase component related to electrolytic conduction, and an out-of-phase component, mainly associated to Induced Polarisation (IP) mechanisms belonging to interfacial conduction from soil surface charge (Cation Exchange Capacity). These two different phenomena can be measured either in frequency domain or in time domain. Spectral Induced Polarization (SIP) implies the collection of module and phase of complex resistivity in frequency domain, spanning over a frequency range usually from 0.1 Hz up to 1 kHz (e.g., Borner et al., 1996, Binley et al., 2005). In time domain, electrical resistivity is obtained by direct current (DC) potential parameters, while the polarization mechanisms are estimated by the chargeability parameter, defined as the integral of a residual voltage decay after current switch-off.

Several applications of this IP methodology to the characterization of dams and river embankments can be found in literature (e.g. Abdulsamad et al., 2019; Soueid et al., 2020a). Nevertheless, ERT is still often adopted as a first characterization tool since the execution of ERT surveys is significantly less time consuming than IP ones. Therefore, when the time of the surveys is a requirement, ERT is the most often chosen method.

The main aim of this paper is to evaluate whether the standard ERT surveys could be further improved, mainly in terms of reducing surveying time, for increasing the investigation distance along the embankments in a single day of acquisition. Since the generation of resistivity pseudo-sections from ERT surveys is a standardized step, faster surveys could also allow for a quasi-real time processing, mapping the resistivity distribution along the investigated embankments with the advantage of directly identifying potentially dangerous anomalies and planning more extensive surveys.

Improvement of the efficiency and feasibility of ERT surveys can potentially rely on the use of mobile systems dragging the appropriate instrumentation, disposed along a streamer, behind a vehicle. This alternative survey strategy can potentially avoid the long operation of nailing electrodes in the ground and speeding the acquisition time.

Some systems based on this approach were developed in the past by using capacitive coupled methods with electromagnetic antennas, at operating frequencies in the quasi static field, carried on the surface (e.g. CCR (Capacitive Coupled Resistivity), OhmMapper from Geometrics and CRI (Capacitive Resistivity Imaging), Kuras et al., 2007). However, in low resistivity soils, such as clays or saturated silts, commonly used to build river embankments, hydraulic barriers and earth dams, capacitively coupled systems may encounter limitations in current injection within the ground. This is mainly originated by the electromagnetic interference between the antennae and the low resistivity underground that leads to a shallow distribution of the induced current flow in the subsoil. The skin depth is then limited and signal-to-noise ratio decreases, resulting in low quality data, particularly for large antennas separation (i.e. greater investigation depths) and when the contact between antennas and the ground is not properly controlled (Lee et al., 2002).

For these reasons, the most recent development of mobile geoelectric systems has been redirected towards a recovery of the galvanic coupling approach. An 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. 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). 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, Sorensen, 1996). The latter system is based on a more versatile electrode disposition, and hence the achievable survey depths can be accordingly increased.

This last system has been of inspiration for the development of a newly conceived geoelectrical streamer, also based on galvanic coupling approach but with brand new electrode design and technological details. The main research aims in developing this new streamer were related to: i) allow the execution of fast geoelectric surveys in motion along river embankments and, in general, linearly extended earth structures; ii) guarantee an investigation depth covering the whole embankment and foundation soil, overcoming current limitations of available similar instrumentation usually adopted for geoelectrical surveys in motion; iii) potentially allow for a quasi-real time imaging of the pseudo-section during surveys execution for a preliminary screening of the embankments; iv) develop a system that could be ideally combined with standard seismic streamers. An appropriate disposition of the electrodes along the streamer, and the use of different measurement combinations, allowed to set-up a measuring system for ERT in motion with similar, or even increased, resolution compared to standard ERT surveys. This innovative measuring approach is an improvement with respect to available methods for the execution of geoelectrical surveys in motion and present peculiar advantages in terms of speed of the surveys and direct imaging of potential anomalies. The newly developed instrumentation is presented in this paper, and the results obtained from test surveys in three different case studies are compared to standard ERT acquisitions to demonstrate its effectiveness.

2. CASE STUDIES

The presented case studies were defined in accordance with the River Po Interregional Agency (AIPO), which is the authority deputed to the management of hydrographic network of the Po river, the main river crossing northern Italy from West to East. Particularly, AIPO has focused its interest in three different embankment portions in the surrounding of the cities of Torino and Racconigi, in Piedmont region (Figure 1). The attention of AIPO has raised in recent years following main flood events (the most recent one in November 2019) which have affected several embankments portions and inundated the surrounding countryside and portions of some cities. The selected embankments are all earthen structures, constructed above the natural alluvial soils of the plain (mostly sand and gravels), but are characterized by different conditions and problematics.

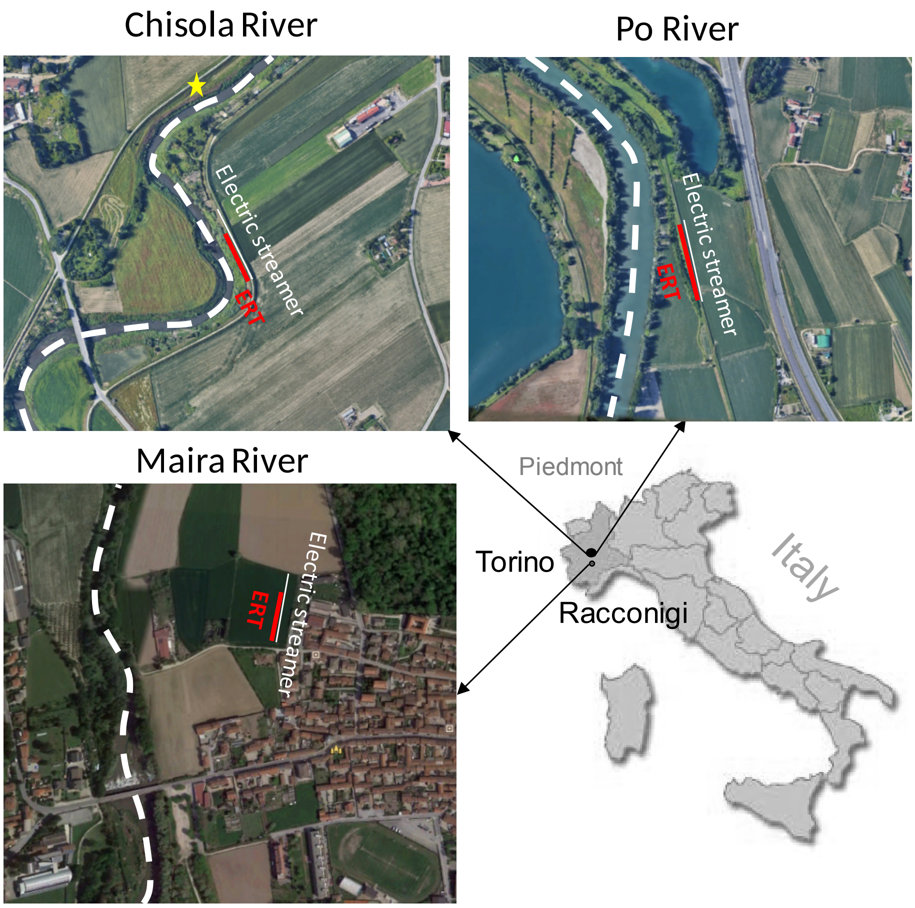

Figure 1 – Location of the case studies in the north western Italian Po plain, Piedmont region, and detail of the studied embankments and executed surveys.

The Maira river embankment is a shallow (about 1.5 m height) newly constructed embankment which protects the borders of the city of Racconigi. This embankment was constructed with selected uniform clayey material. Here, AIPO is interested in assessing the global uniformity inside the embankment and to evaluate the effectiveness of its construction, following the occurrence of some lateral landslips along the slopes, caused by the transit of heavy trucks and excavators. The Chisola river embankment is a 2.5 m high mostly silty (98.5 % passing to the 0.4 mm sieve) embankment. It is considered critical due to its peculiar location near river meanders, which significantly increase river erosion potential during flood events. Indeed, in a similar bend, north from the present survey location, a rupture of the left embankment was recently noted following the flood events of November 2016 (yellow star in Figure 1). Repair works are ongoing in the already affected portion, but attention is related to eventual extension of the interventions also to the studied embankment side. Along these two embankments a thin gravel layer was put in place to pave the road on the embankment summit. Finally, the Po river embankment is 2 m high and serves as protection to the main highway from Torino towards the south. It is the eldest among the three embankments, built in early 20th century using natural material (sands and gravels) probably exploited from surrounding caves or directly from river deposits. Along this embankment, several badger burrows were observed.

The interest of AIPO is related to the potential of the newly developed electric streamer in providing a fast and cost-effective identification of resistivity anomalies related to the different problematics evidenced in the case studies. Investigations along the three river embankments were therefore planned. The first aim of the surveys is a comparison between data obtainable with standard ERT measurements and the newly developed system; with this aim, both techniques were applied over superimposing portions along the studied embankments (Figure 1). Following this comparison, the interpretation of the evidenced anomalies is also provided to help the management authority in monitoring the integrity of the studied embankments portions.

3. ELECTRIC STREAMER AND EXECUTED SURVEYS

Electrical resistivity measurements involve the use of 4 electrodes (measurement quadrupole). Two of them (current electrodes) inject into the ground the desired current amount (I), while the other two (potential electrodes) measure the resulting potential difference (V). From these two measured values the apparent resistivity (ρ_a) of the subsoil can be obtained through:

$$\rho_a = k\frac{V}{I} \qquad (1)$$

where k is a geometric factor that, for a half-space with electrodes at the interface, depends on the electrodes arrangement within the quadrupole and is computable according to standard quadrupole dispositions (e.g. Wenner-Schlumberger and Dipole-Dipole). Generally, k depends also from topography and boundary conditions and can be computed numerically for any geometry, solving Laplace equation with finite element methods (e.g. Jougnot et al., 2010). The apparent resistivity is therefore the raw experimental result obtainable with the acquisitions. Depending on the disposition and distance of the electrodes, each measured apparent resistivity value can be related to different portions of the subsoil: increased electrode separations involve deeper current fluxes and therefore greater investigation depths; lateral resistivity variations can be detected by moving the quadrupole horizontally along the survey profile.

If the comparison of the apparent resistivity distribution obtained with different measuring approaches gives similar outcomes, this can be considered as a direct indicator of the quality and reliability of the adopted alternative measuring methods. Apparent resistivity values acquired with the new electric streamer and with standard galvanometric ERT approach will be therefore compared in this work, using standard ERT data as comparison benchmark, to prove the validity and applicability of proposed acquisition system.

Reconstructing the real resistivity distribution of the subsoil from apparent resistivity measurements involves the solution of an inverse problem. This can be performed in tomographic approach if the raw data distribution offers enough spatial coverage. Quality of the reconstructed resistivity distribution depends on quality and spatial distribution of the raw data. The two acquisition systems involve different data distributions along the survey length (see later). Inverted resistivity data from the new electric streamer and standard ERT approach will be therefore compared in this work to establish if the reconstructed resistivity distribution contain the same relevant information for the investigated embankments.

A scheme of the electric streamer designed for the execution of resistivity measurements in motion is displayed in Figure 2.

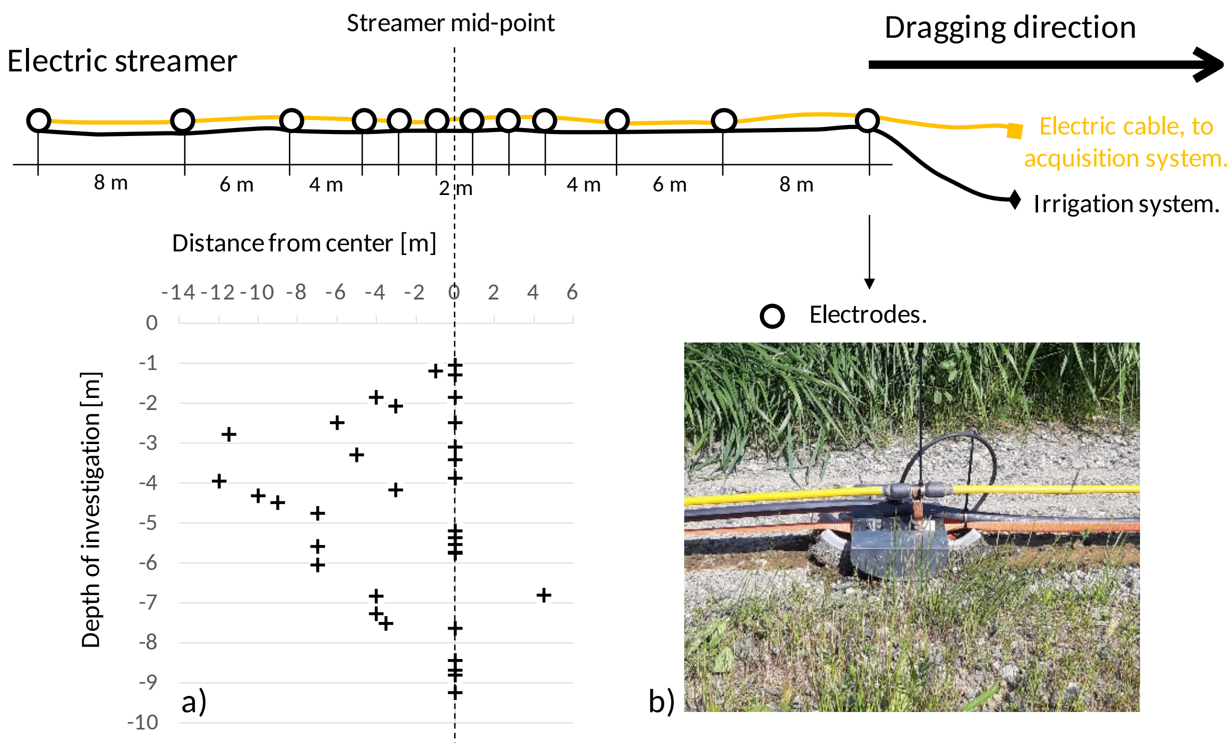

Figure 2 – Scheme of the electric streamer adopted for the surveys, in a) the depth of investigation of the different acquired measurements is reported, in b) the detail of a single electrode is depicted with evidence of the irrigation system (black) and of the multipolar cable (yellow).

The streamer foresees the use of specifically designed electrodes and an appropriate drip irrigation system (Figure 2b). Combining these two technical solutions allows to reduce contact resistances between the electrodes and the ground. Electrodes were constructed in stainless steel and have the form of brushes, i.e. containing several thin wires, in order to increase the contact surface to the ground and further reduce electric contact resistances. The shape of the brushes is similar to a sled to allow for an easy dragging of the streamer. On top of these brushes a PVC element is also present with lateral wings leaning to the ground in order to avoid overturning during dragging. Preliminary calibration tests, for single quadrupoles acquisitions, have evidenced that data acquired with this system are comparable to standard geoelectrical surveys (Arato et al., 2020). Particularly, several comparisons of dripped and dry contact resistances were performed. A strong reduction (around 75% on average) of contact resistances after dripping was observed, highlighting the importance of the irrigation system for this survey. The arrangement of the electrodes along the streamer is very versatile and can be adapted according to different investigation requirements.

In the configuration used in this study the streamer has a length of 46 m and 12 active electrodes, that can be used both as current and potential electrodes, placed at progressively increasing spacings, symmetrically centred around the streamer mid-point (Figure 2). The nearest electrodes are the ones aside the streamer mid-point (6 electrodes at 2 m separation) while the farthest ones are at the extremes of the streamer (8 m separation). The adopted disposition allows to perform different measurement combinations, with different vertical and horizontal positions. Given that survey depth is directly proportional to electrodes separation, shallow information is obtained from the measurements performed with the nearest electrodes and deeper information from measurements performed with the electrodes at the cable extremes. The measuring sequence here adopted is based both on the Wenner-Schlumberger (26 measurements) and Dipole-Dipole (8 measurements) quadrupoles and guarantees an adequate data coverage from the surface to an estimated depth of about 10 meters (Figure 2a). The depth of investigation of each quadrupole was assumed with reference to the pseudo-depth formulated by Res2DInv software (Loke and Barker, 1996) given each electrodes disposition. The pseudo-depth is the median depth of investigation, computed from the sensitivity curve and defined as the depth value at which the integral under the sensitivity curve is equally divided (e.g. Edwards, 1977, Barker, 1989).

With the adopted sequence most of the measuring points are located along the vertical below the streamer mid-point (replicating a sort of vertical electric sounding); off-vertical measurements are used to increase the lateral coverage and depth levels not covered by the quadrupoles below the streamer mid-point. Repeating the measuring sequence for different positions of the streamer mid-point (measurement step), it is therefore possible to build an apparent resistivity pseudo-section that can be subsequently elaborated with tomographic methods. A measurement step equal to 2 m was adopted in all the surveys here reported. For the different case studies the resulting survey length and number of electric streamer measurements is reported in Table 1. The survey length refers to the distance between the first streamer mid-point to the last. However, as it can be observed from Figure 2a, the effective survey length is partially increased by the presence of measurements located also before the first streamer mid-point.

The streamer is dragged, for each measurement step, by a vehicle that stores the equipment necessary for performing the resistivity measurements (acquisition system and water tank). The electrodes are connected to the acquisition system (Syscal-Pro, Iris Instruments, georesistivimeter) by means of a multipolar cable (Figure 2b).

Table 1 – Detail of the executed surveys along the studied embankments. For ERT, both the total number of measurements and the number of measurements covering the first 10 m depth are reported.

	Survey length [m]		Number of measurements	
	ERT	Electric Streamer	ERT	Electric Streamer
Maira River	94	84	565 (437 within 10 m)	1428
Chisola River	94	120	565 (437 within 10 m)	2074
Po River	142	142	1377 (802 within 10 m)	2448

For comparison and calibration purposes, standard ERT measurements were also executed along the portions of the investigated embankments (Figure 1). These latter were acquired with the same acquisition system adopted for the electric streamer and 72 (for the Po river case history) or 48 (for Maira and Chisola rivers case histories) nailed electrodes at 2 m spacing (Table 1). Standard ERT data were acquired with a the Wenner-Schlumberger array. For the different survey lengths involved in the case studies, the resulting number of ERT measurements is reported in Table 1. The resulting number of measurements levels and total measurements is in the range of commonly adopted values for ERT investigations. For both the streamer and ERT, measurements were conducted with a 3-cycle reversing square wave with a 250 ms current on time. This allowed also the determination of instrumental standard deviation.

An example of the data coverage obtainable with the two acquisition systems along the longest of the executed surveys (Po river) is reported in Figure 3.

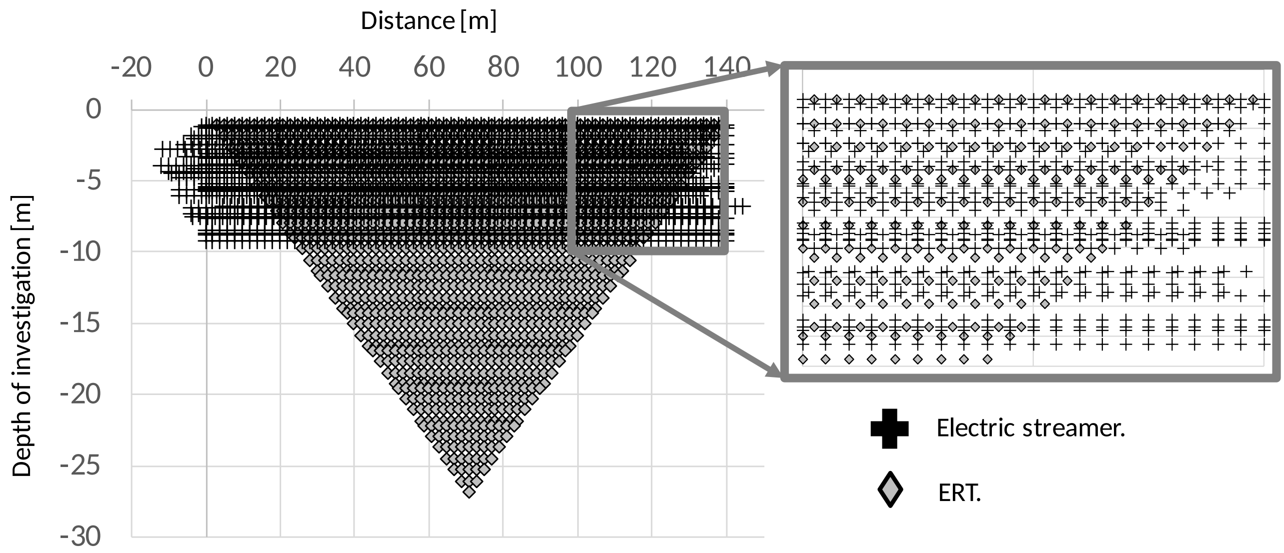

Figure 3 – Data coverage obtained with the two acquisition systems along the Po river case study.

Data distribution reported in Figure 3 highlights the greater depth of investigation offered by the standard ERT survey, given the investigated length, due to the increased electrodes separation along the whole survey line. However, within the depth range of interest in this study, and generally for the characterization of embankments body and shallow foundation soils (i.e. within the first 10 m), the streamer data coverage is improved, both laterally and vertically, in comparison to the standard ERT acquisition sequence adopted. Within this investigation depth the number of data acquired with the electric streamer is more than three times the ones of ERT (see also Table 1).

Highly noisy data acquired in the two survey modes were preliminary removed adopting several filtering 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. Following the above criteria some of the Dipole-Dipole measurements acquired with the electric streamer were removed due to their low quality. Lastly, singular outliers identified by visual analysis of the apparent resistivity profiles and pseudo-sections were also removed. Filtered data were interpolated along the studied embankments to allow for a 2D visualization of the apparent resistivity distributions from both surveys. This interpolation was performed in 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. Apparent resistivity data were then processed and inverted with the same tomographic approach by means of the Res2DInv software (Loke and Barker, 1996). Inverted resistivity data were similarly interpolated in order to allow a point by point comparison of all the resistivity maps obtained in terms of normalized differences (see later).

4. RESULTS

As far as raw data analysis is concerned, data from electric streamer measurements were, in general, slightly noisier (i.e. showing higher instrumental standard deviation and greater lateral variability) if compared to the ones obtained with traditional ERT. This was mainly due to local bad electrode-ground contacts, caused by the continuous moving of the system, and challenging initial field conditions at the moment of execution of the surveys (i.e. no rain for more than two months before the surveys and the presence of a gravel layer on the surface). Nevertheless, the high data coverage of the electric streamer allowed to perform the filtering operations avoiding no-data areas and the adopted irrigation system was effective in partially reducing the contact resistances even in very dry subsoil conditions.

Results of the acquisitions, in terms of apparent resistivity pseudo-sections, are reported in Figure 4.

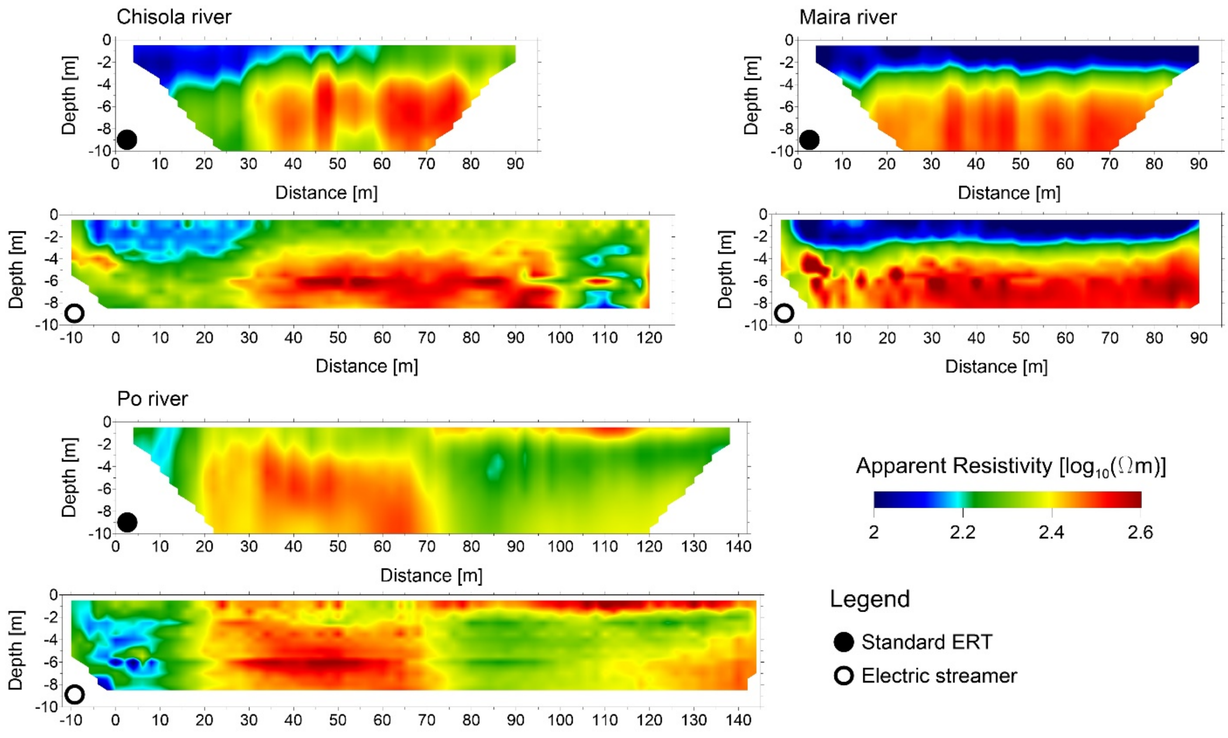

Figure 4 – Results of the ERT and electric streamer surveys in terms of apparent resistivity pseudo-sections along the studied embankments.

By analysing Figure 4 it can be noted that the results of the two different surveys are highly comparable and that the main lateral and vertical variations observed along the ERT pseudo-sections are also recognized in the electric streamer pseudo-sections. Given the different data coverage of measurements (Figure 3) the main resistivity anomalies tend to be elongated in the vertical direction for ERT measurements, which has a reduced number of levels with depth, and in the horizontal direction for electric streamer measurements, due to the presence of multiple overlapping levels with depth. Notwithstanding this different data coverage, the normalized differences between the two investigations, calculated for the superimposing portions of the surveys and reported in Figure 5, evidence that the data are in most of the situations within a ±5% difference, which is an indicator of the high comparability of acquired values. The normalized difference (*ND*) was calculated with the formula:

$$ND = \frac{\rho_{aERT} - \rho_{aES}}{\rho_{aERT}} \qquad (2)$$

were ρ_{aERT} is the apparent resistivity value obtained from ERT measurements and ρ_{aES} is the apparent resistivity value obtained from electric streamer measurements. Therefore, positive values of the normalized difference indicate zones where the electric streamer underestimate the apparent resistivity, negative values indicate the opposite.

Most of the highest difference values, mostly negative, are located either along vertical or horizontal stripes. This striping effect is related to the different data coverage of the two surveys and evidence portions in which the data comparison could be more affected by interpolation than by differences in the measured values.

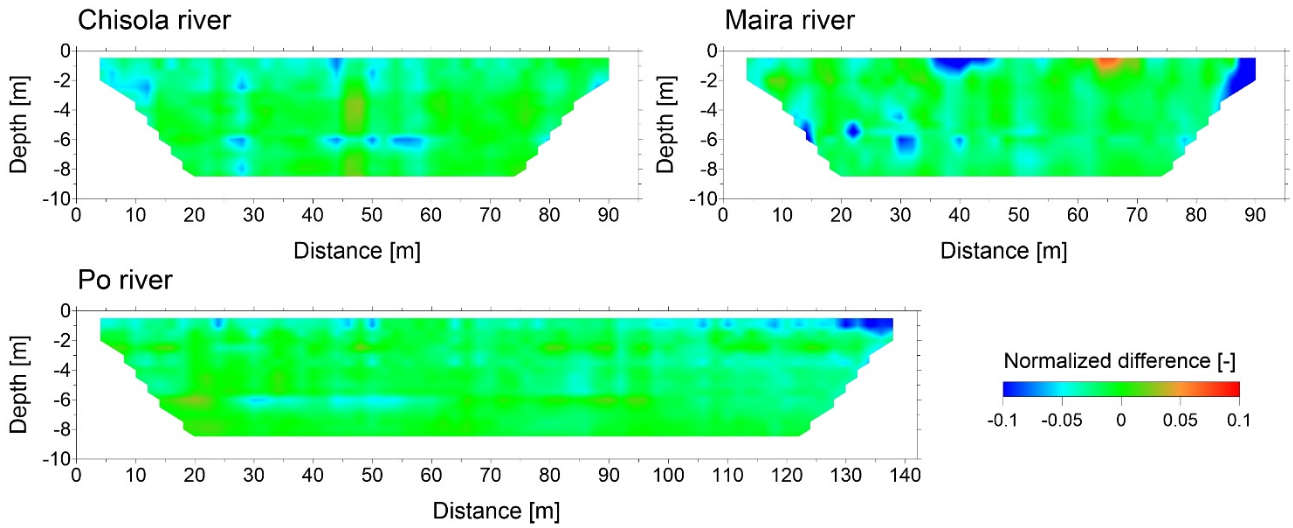

Figure 5 – Results of the ERT and electric streamer surveys in terms of normalized difference among the apparent resistivity pseudo sections of the two surveys along the studied embankments.

The experimental apparent resistivity data were processed and inverted with the same tomographic approach by means of the Res2DInv software (Loke and Barker, 1996). For most of the inversions a reliable root means square error (rms) was obtained, on average around 5%. Electric streamer data showed in general relatively higher rms; this is however not an indicator of the lower quality of the inversions but of the increased amount of data to be fitted in each survey (as mentioned, more than three times than for ERT measurements).

The inverted resistivity sections are reported in Figure 6, in terms of resistivity values, and in Figure 7 in terms of normalized differences, calculated for the superimposing portions of the surveys.

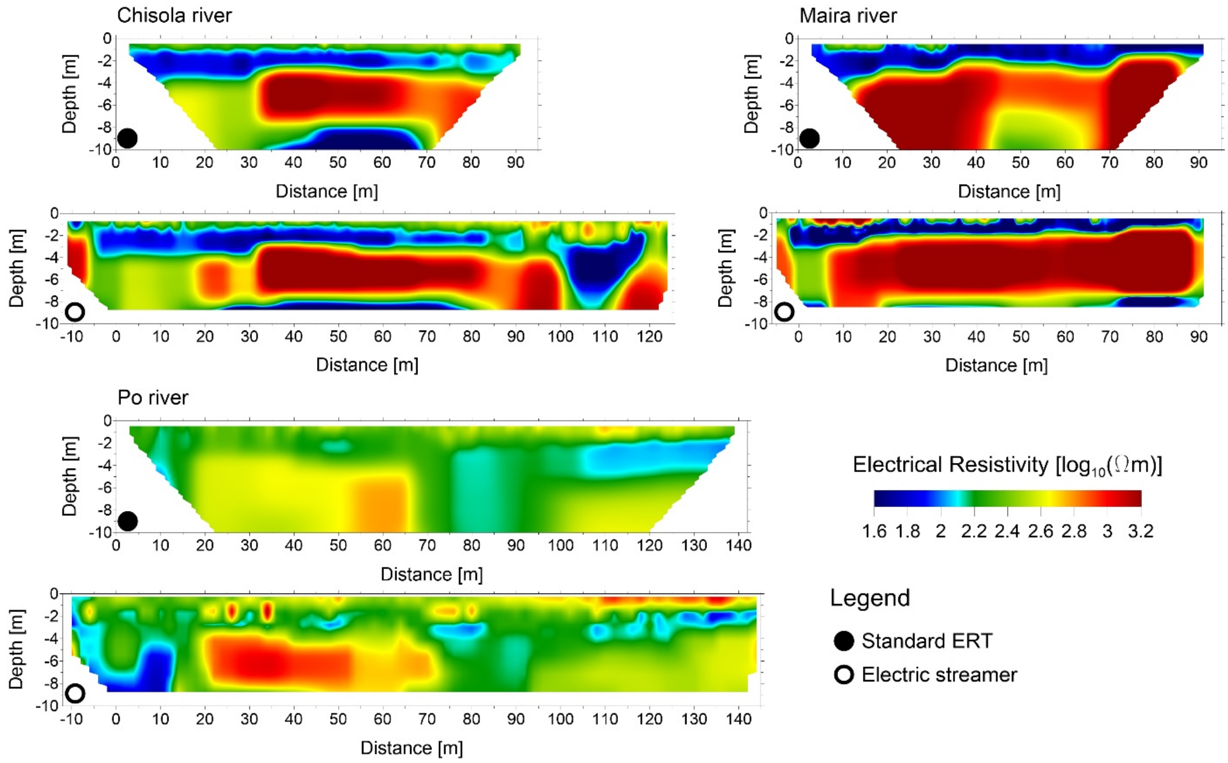

Figure 6 – Results of the ERT and electric streamer surveys in terms of inverted resistivity sections along the studied embankments.

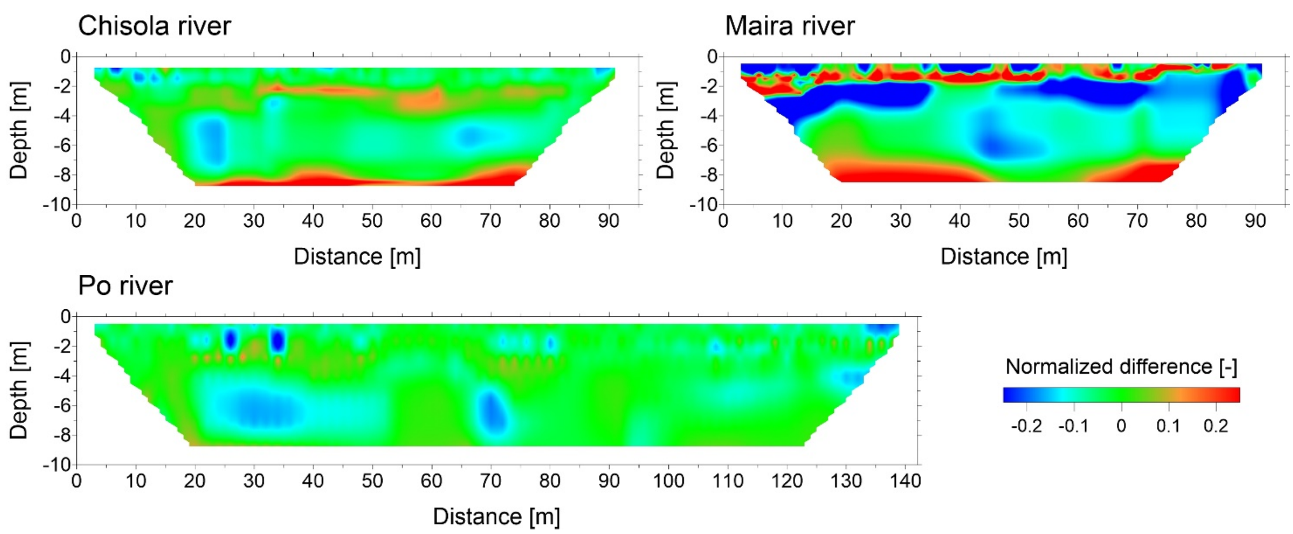

Figure 7 – Results of the ERT and electric streamer surveys in terms of normalized difference among the inverted resistivity sections of the two surveys along the studied embankments.

From these results it can be again observed that the main resistivity anomalies reported in the ERT sections are also visible in the electric streamer sections. Particularly, in the aim of characterisation and uniformity evaluation of the embankments the two data are comparable for the superimposing portions. However, an increase in the normalized difference between ERT and electric streamer results can be observed. Particularly at the Maira and Chisola river case studies, an increased difference is noted for depths near the investigation depth limit of the electric streamer. Even if ERT and electric streamer inverted models agree to indicate a decrease in resistivity values at those levels, the electric streamer results tend to underestimate the resistivity values. This difference is related to the different data coverage with depth of the ERT and electric streamer surveys (see Figure 3). When the studied embankment is characterized by a silty, clayey lower resistivity layer, as it is the case for the two mentioned cases, the current penetration of the electric streamer is reduced, given the reduced electrodes spacings adopted. Therefore, in these situations a precautionary lower limit in the investigation depth should be established. This penetration limit, as mentioned, will be even more critical for capacitive coupled systems approaches.

Notwithstanding this limitation, most of the normalized differences in the resistivity values still fall within a ±5% difference limit. Higher localized differences can be noted in the shallower portions of the sections, most significative in the Maira case study. These may be related to stronger resistivity contrasts between the embankment and the natural soil (as is the case for the Maira case study, Figure 7) or to localized anomalies evidenced by one of the two surveys only. Stronger contrasts and localized anomalies involve indeed higher nonlinearity in the inversion problem (as is the case for the Po case study, Figure 7). In these situations, inversion quality and the reconstruction of sharp resistivity contrasts can be strongly influenced by measurements distribution. As mentioned above the higher data coverage of the electric streamer potentially allow for a more accurate identification of these localized contrasts.

5. DISCUSSIONS

The presented results showed that the new electric streamer developed for the study of river embankments provided resistivity data highly comparable with the ones obtainable with standard ERT acquisitions. Not only, in all the surveys the electric streamer data, in the adopted disposition and measurement step, offered increased lateral coverage. As an example, along the Po river case study, where the survey length of the two systems is the same, it can be observed how the electric streamer is not affected by the lack of data points that characterize ERT, for the adopted electrodes spacing, at the border of the surveyed section (see Figure 4). Moreover, the data coverage is also increased within each section given that the number of electric streamer measurements is almost three time than the one of ERT surveys (see Table 1). This result is clearly dependent on the adopted streamerinfrastructure and ERT survey setup. Ideally, the same data coverage could be obtained by the two surveys, adopting similar measurements distributions and electrodes spacings. However, performing this for ERT would require significant efforts on the field while the higher data coverage can be obtained through streamer data with reduced survey time and efficiency.

The acquisition of electric streamer data is indeed a completely automatic process, once that the streamer is deployed on the embankment surface. Each measurement step involves an acquisition time of about 40 seconds, which could be eventually repeated when the contact resistances of electrodes is still insufficiently reduced by the drip irrigation system. Deployment of the streamer can be quantified around 15 to 20 minutes, depending on the number of people involved in the survey. Conversely, acquisition of ERT data involves 45 to 90 min, depending on the measuring sequence adopted, and deployment of ERT surveys is for sure more time consuming due to the necessity of nailing the electrodes, connecting all the acquisition cables and watering the electrodes for ensuring optimal galvanic contact. ERT survey time is directly proportional to the required spatial resolution, making the electric streamer significantly more advantageous for the execution of fast surveys.

The better efficiency of the electric streamer is even higher for survey lengths longer than the ones presented in the present paper, which were limited in the aim of a strict comparison of the results. For increased survey lengths the acquisition of ERT data involve indeed the use of the roll-along technique which requires to re-nail electrodes along successive portions of the line, reconnect and move the cables, and highly increase the survey time. Performing longer surveys with the electric streamer is instead only a matter of dragging the system for more time.

This increased efficiency potentially allows the streamer to be used also in situations where the speed of the surveys is essential. This is the case, for example, in situations where a specific characterization of embankments anomalies is required after, or during, large flood events. In these situations, a direct imaging of the resistivity pseudo-section during surveys execution could be also foreseen. This is a common approach adopted during the execution of resistivity surveys in water covered areas (e.g. Sysmar, Iris instruments acquisition approach, Colombero et al., 2014). Its implementation with the developed electric streamer is straightforward given that at each measurement step a new vertical portion of the embankment is investigated and can be directly visualized on the pseudo-section. This could allow a direct on site imaging of potentially dangerous anomalies. Moreover, a moving system can serve different resolution requests, and the moving steps along the embankment structures can be adjusted according to the desired target (i.e. larger moving steps for large scale characterization; smaller moving steps for highly detailed surveys).

Partial limitations in the use of the newly developed electric streamer can be foreseen in some specific conditions. The presence of a highly resistive shallow cover (i.e. presence of paved road or compacted soil) along embankment summit could strongly limit the current injection capabilities notwithstanding the used irrigation system. This situation could increase the survey time due to the necessity to increase the irrigation time. This condition was partially encountered along the Maira river embankment case study, not compromising however the overall quality of the measurements. In similar conditions standard ERT surveys can easily overlap the shallow coverage thanks to the electrode length. Also, the developed system is not designed for application along embankments with relevant curves. The dragging of the system is indeed effective only along linear embankments segments. This last limitation also affects standard ERT measurements and all problems to be solved and represented in 2-D.

Further developments in the use of the electric streamer could include different types of geoelectrical measurements rather than the only resistivity. Potentially, the streamer can be used for the execution of both Induced Polarization (IP) and Self Potential (SP) measurements. As mentioned in the introduction, IP measurements have greater potential in discriminating the effects of water content and cation exchange capacity while SP measurements can be used to monitor self-potential signals associated with seepage in embankments (e.g. Soueid et al., 2020b). However, the execution of both these types of surveys would strongly increase the acquisition time, partially reducing the advantages for which the developed electric streamer was designed.

Finally, an interesting development could be to combine the electric streamer with a seismic streamer, merging the two systems for a joint acquisition of both geoelectrical and seismic data. The streamer set-up and arrangement has been indeed designed in view of a future combination with seismic sensors, to be then combined in a seismic-electric land-streamer. Conversely than for electric data acquisitions, the technological development of seismic streamers is already well established in the geophysical community. Several examples of high-quality seismic data collected with this approach are available in literature (e.g. Van Der Veen et al., 2001; Pugin et al., 2004). From the results presented in this paper a combination of the newly developed electric streamer with a standard seismic one can be therefore foreseen. The combined use of geoelectrical and seismic data can indeed provide an even more effective geotechnical characterization of river embankments, as shown by several research groups that are working on their integration (e.g. Chen et al., 2006; Takahashi et al., 2014; Goff et al., 2015). Preliminary investigations performed with this approach (Arato et al., 2020) have shown that the combination of the two streamers can increase even more the efficiency of the surveys at strongly reduced acquisition times.

The comparison between electric streamer and ERT inverted resistivity sections has evidenced a limited increase in the normalized difference among the two surveys. This increase is partially expected given that the inversion process, due to its inherent non unicity, is highly conditioned by the number of measurements and the data distribution. Therefore, the non-perfect correspondence of the two results cannot be judged as a non-reliability of electric streamer data. Moreover, the anomalies in the electric streamer resistivity sections, which does not have a correspondence in the ERT ones, are related to good quality data (i.e. do not come from outlier data or measurement errors) and should be linked to real and more intensely detected anomalies throughout the embankments.

Apart from the higher depth portions of the electric streamer sections, where probably the electric streamer lacks in penetration and the resistivity models suffer from the different boundary assignment by the inversion software, the results of the electric streamer surveys can be therefore considered equally good as ERT surveys.

Figure 8 reports the resulting resistivity models from the electric streamer surveys, focused in the depth range between 0 to 6 m, that most properly characterizes the studied embankments. On these sections, the known heights of the different embankments from the free surface is also reported (white dashed line). Unfortunately, no data from other independent tests are available to better identify the type/origin of evidenced anomalies, so discussions on these can be only speculative. However, the focus here is more on the comparison between electric streamer and ERT results than on the origin of the anomalies. In this respect, the presented case studies can be seen as examples of the application of the newly developed measurement technique and its feasibility.

All case studies report a resistivity transition almost in correspondence of (on average about half a meter lower) the known heights of the embankments. This is coherent with embankment construction plans which included a shallow removal of topsoil. In the Maira and Chisola case studies the resistivity transition from the embankment to the natural soil is sharper. This is related to the mostly silty and clayey nature of these two embankments, having lower resistivities with respect to the natural alluvial soils of the plain, which are coarser instead. Along these embankments a shallow more resistive coverage is also evidenced, due to the presence of a thin gravel layer put in place to pave the road on the embankment summit and also to the presence of a poorly saturated layer on top of the embankments.

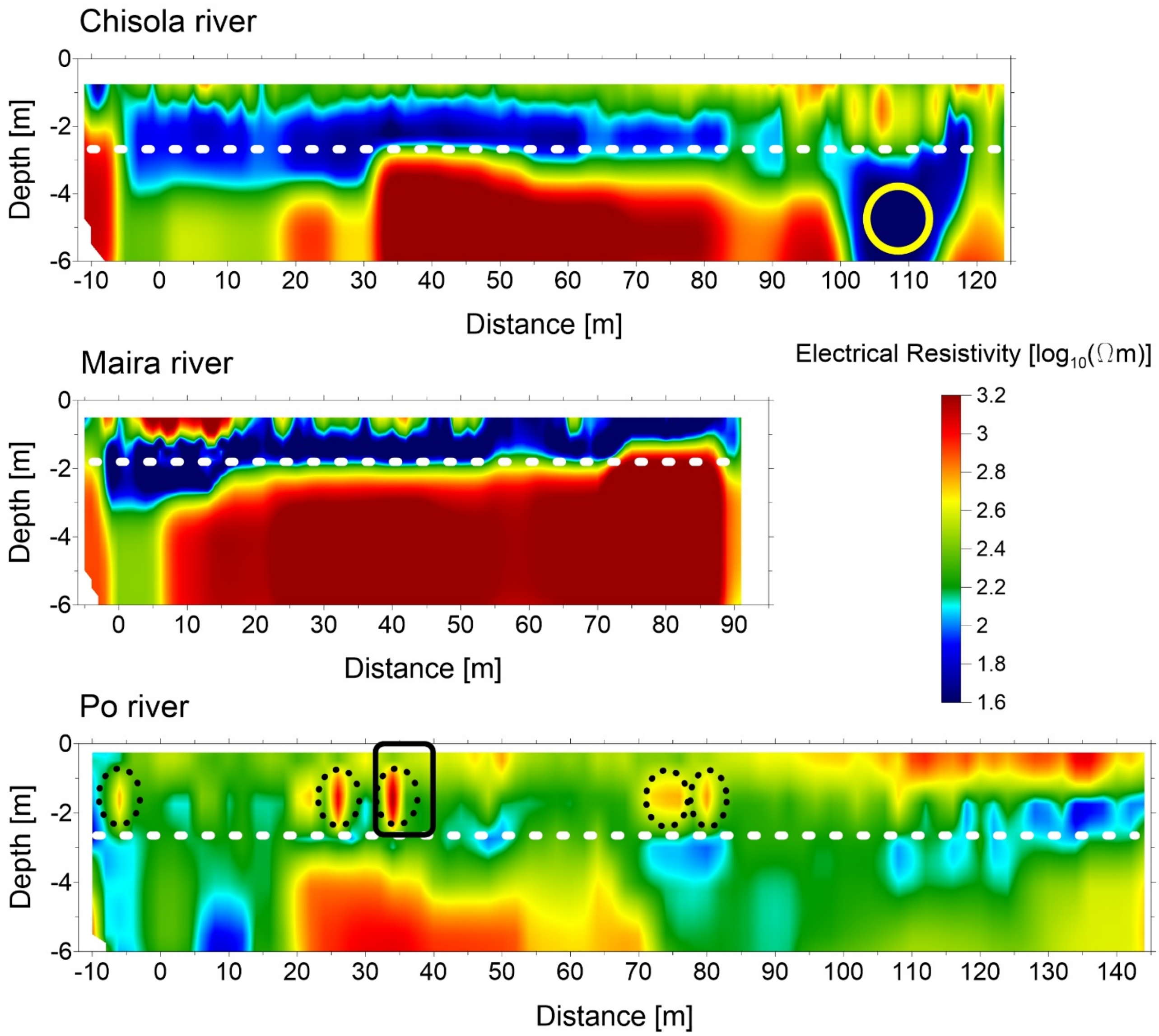

Figure 8 – Results of the electric streamer surveys in terms of inverted resistivity sections along the studied embankments with evidence of their attended depth (white dashed lines) and anomalies: low resistivity anomaly along the Chisola river embankment (yellow circle); known badger burrow portion (black square) and potentially void borrows (black dashed ellipses) along the Po river embankment.

The newly constructed Maira river embankment appears to be quite uniform, in terms of resistivity values, in the investigated length. This indicates a uniform and effective constructing procedure. Minor variations in the depth of the embankment are evidenced probably related to different soil removal in the bottom parts. A zone with a shallow high resistivity anomaly is also observable along this embankment between 0 and 20 m. A similar increase in resistivity can be also partially seen in the ERT results (Figure 6). This may be related to an increased thickness of the gravel layer on the surface. No evidences related to the lateral landslips along the slopes are however reported.

Along the Chisola river embankment a significant low resistivity anomaly (yellow circle in Figure 8) is evidenced. This could be related to a potential seepage hazard zone. The reduced resistivity of this area cannot be indeed correlated with lateral soil variations, which are quite uniform in the plain, but are most probably related to an increase in the water content of the ground.

Partially different results are obtained along the Po river case study. Here, the transition from the embankment material to the natural soil appears to be smoother, given its more dated construction, and inner resistivity heterogeneities can be related to different conferred materials, probably exploited from surrounding sand/gravel caves or directly from fine river deposits. The AIPO alerted about the presence of a known badger burrow in the portion from 32 to 40 m (black square in Figure 8). Within this area a local high resistivity anomaly, potentially correlated to the void burrow, is indeed notable (black dashed ellipse). Similar anomalies are also noted in other locations along the investigated portion (with no visual or direct external appearance) and can be suggested as probable attention zones. Their position near the embankment bottom is indeed compatible with animal activity. The effectiveness in the indication of these anomalies, which are less clear from the ERT results (see Figure 6), is a further demonstration of the increased data coverage of the developed streamer and the high resolution it can offer in the characterization.

6. CONCLUSIONS

A new electric streamer was developed within this work to allow for the execution of fast ERT (but potentially any geoelectric) surveys in motion along river embankments. The new system was developed to guarantee an investigation depth covering the whole embankment body and foundation soil, overcoming current limitations of available similar instrumentation usually adopted for geoelectrical surveys in motion. The technical solutions adopted for its construction (electrodes design and irrigation system) allowed the acquisition of reliable resistivity data, alternative to electrode nailing into the ground.

The results presented and commented in the paper shown that the newly developed electric streamer provided data which are strictly comparable to standard ERT data acquired as benchmarks. The adopted streamer arrangement and measurement step showed advantages in reducing survey time and increasing the system efficiency. Its application as a fast screening tool can be foreseen near main flood events affecting relevant portions of river embankments in different contexts. The streamer data, with the current electrode disposition, were acquired over multiple overlapping levels, offering an increased lateral and vertical coverage with respect to standard ERT surveys and entailing on a more accurate definition of localized anomalies related to animal borrows within one of the case studies.

The resulting resistivity models allowed to characterize peculiar anomalies along the studied embankments, even dough the nature and properties of these anomalies should be better studied with the use of local geotechnical investigations to have a more specific knowledge on the state of life of the embankments. With this respect, a natural development of the instrumentation can be foreseen with the implementation of rapid tools for direct in-situ mapping of apparent resistivity pseudo-sections resulting from the surveys. This implementation is straightforward, and the apparent resistivity pseudo-section can be plotted and directly visualized by adding new data at each measurement step along the streamer profile. This will allow a direct imaging of anomalous points and a fast identification of the zones of the embankment where integrative localized tests or specific intervention are necessary.

Further studies, already planned and partially executed, include the application of the new electric streamer for embankment depths greater than the ones presented in this paper and along longer survey profiles. Moreover, the combination of the present electric streamer with a standard seismic streamer will allow for joint resistivity and seismic surveys, profiting by the contemporary acquisition of electric and seismic data at each measurement step and further optimizing survey time. The combined acquisition of multiple geophysical parameters could improve the knowledge on the performance of river embankments and provide input data for specific correlations and modelling with relevant hydraulic and geotechnical parameters.

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