Long-term monitoring strategy to assess the inner conditions of river levees: the Colorno station

G. Tresoldi[1], A. Hojat[1,2], L. Zanzi[1]

(1) *Dipartimento di Ingegneria Civile e Ambientale, Politecnico di Milano, Milano, Italy*
(2) *Department of Mining Engineering, Shahid Bahonar University of Kerman, Kerman, Iran*

Introduction. The frequency of extreme rainfall events has dramatically increased in the last decade, causing unexpected floods which threaten human lives and properties. Long-term monitoring and proper maintenance of river embankments are key factors to reduce hydrogeological risks. In most cases, assessment of earthen embankments relies only on periodic visual inspections, and the inner conditions of the structure usually remain unknown. Earthen embankments are vulnerable to inhomogeneous seepages, long-lasting high levels of water in the river, and rapid wet-dry cycles. Geophysical techniques have shown successful in investigating the inner conditions of embankments in a non-destructive manner. Geo-electrical methods have specifically proved to be efficient in monitoring concentrated seepages and critical saturation zones within earthen slopes, dams and dikes (Dahlin et al., 2008; Kuras et al., 2009; Jomard et al., 2010; Supper et al., 2012; Perri et al., 2014; Weller et al. 2014; Loperte et al., 2016; Hojat et al., 2019a). After careful evaluation of critical sites in the territory of three managing authorities for rivers and canals in northern Italy, and numerous preliminary electrical resistivity tomography (ERT) measurements, a long-term geoelectrical monitoring system was installed on a river levee in Colorno, Parma, in November 2018 (Hojat et al., 2019b). This is the second installation of a new prototype ERT monitoring system developed by LSI Lastem s.r.l.. The first customized ERT monitoring system was installed along the embankment of an irrigation channel in San Giacomo delle Segnate in 2015 (Arosio et al. 2017; Tresoldi et al. 2018; Tresoldi et al. 2019). Thanks to these monitoring systems, the inner conditions of the study sites are assessed remotely in real time.

The study site. In this paper, we present the results from the ERT monitoring system installed in Colorno in a site named La Penza. This site was selected for long-term monitoring after receiving suggestions from three managing authorities for canals and rivers in northern Italy (Consorzio di Bonifica Terre dei Gonzaga in Destra Po, Consorzio di Bonifica Est Ticino Villoresi, and Interregional Agency for the Po River (AIPO)). The decision was mainly based on the results of reconnaissance ERT measurements along 1448m of candidate segments of Parma river embankments (Hojat et al., 2019b). Moreover, part of the selected site overlaps with the re-built part of the embankment (Fig.1a) that had experienced a concentrated seepage during Colorno flood in December 2017 (Fig. 1b). The prototype ERT system is composed of 48 electrodes and was installed along 94m of the embankment. Wenner array with a=2m was used for monitoring this site. Such a configuration ensures adequate lateral and vertical coverage of the embankment. The two 24-electrode cables are protected with anti-rodent plastic cases and were put in a 0.5m-deep trench along the embankment. To ensure permanent good contact of electrodes with the soil, plate stainless steel electrodes of 0.2m x 0.2m were used. The geo-resistivity meter, designed by LSILastem with scientific support of Politecnico di Milano, was placed in the centre of the critical levee segment and is accompanied with a meteorological station to register rainfall, air humidity and temperature (Fig. 1c). The whole system is powered by a solar panel, it is programmable and can send data through internet connection. The frequency of measurements is set by the operator through a cloud platform where data are saved and can be processed.

Fig. 1 – a) The repaired section of the monitored site in Colorno. b) Piping phenomenon observed in the levee during the flood in December 2017. c) Long-term geoelectrical and weather monitoring systems installed in La Penza site, Colorno.

Long-term monitoring results. Resistivity pseudosections were initially measured twice a day to control the capabilities of the system. The frequency of measurements was set to once a day from February 2019. Measured data are corrected to remove the influence of burial of electrodes. Moreover, since the ERT measurements are 2D, the 3D geometry effects of the levee and of the boundary conditions are also studied. Forward modelling calculations were performed in RES2DMOD (Loke 2016) and RES3DMODx64 (Loke 2014) to estimate the influence of the levee geometry. The 3D model of the embankment was built using its geometry and the available information about construction material of the levee segment. The apparent resistivity pseudosection was then calculated in RES3DMODx64 (Loke 2014) along the line corresponding to the long-term ERT profile (Fig. 2a). The 2D section of the same model was introduced in RES2DMOD (Loke 2016) and its corresponding apparent resistivity pseudosection was calculated (Fig. 2b). The amplification of measured apparent resistivity values due to 3D effects was then estimated as shown in Fig. 2c. To correct data, measured apparent resistivity pseudosections are divided by the pseudosection in Fig. 2c. It should be noted that Fig. 2c changes with the boundary conditions of the levee (air and/or water on the river side and air on the other side).

Fig. 2 – a) Apparent resistivity pseudosection calculated in Res3dmod. b) Apparent resistivity pseudosection calculated in Res2dmod. c) Pseudosection of apparent resistivity ratio.

Correcting 3D effects is an important part of processing ERT data measured along levees. The problem is challenging especially that 3D effects not only depend on the construction material of levee, but also strongly depend on external conditions on two sides of the levee. In our study site in Colorno, a wide series of levees are present, the river water rarely arrives at the monitored section and the embankment is in contact with water only during extreme events. From the time ERT system was installed, the water level has increased only after a small flood event. Therefore, 3D effects have been remained almost unchanged, and we generally skip correcting 3D effects when studying large variations in time-lapse data. However, the site-specific algorithm to correct 3D effects was developed in order to correct data when comparing seasonal datasets with changes in boundary conditions, and also when translating inverted ERT sections to water saturation maps.

Apparent resistivity pseudosections are inverted in Res2dinv (Loke, 2018), using the L2-norm option. Time changes in inverted resistivity sections are interpreted taking into account the weather datasets. The aim is to analyse the response of the levee body to rainfall events and changes in temperature. Fig. 3 shows an example of data variability with rainfall events. A rainy period during 1 April – 1 June 2019 (Fig. 3a) is considered and resistivity sections before (Fig. 3b) and after (Fig. 3c) the rainfall are shown. Fig. 3d shows the response to rainfall of the different parts of the embankment as the difference between data after and before the event. As can be seen, variations in resistivity are not constant along the levee segment: the lateral parts of the section have a sharp decrease in resistivity, due to higher permeability of the construction materials in those parts, while the central part, which is the re-built part shown in Fig. 1a, has only a moderate decrease due to higher clay content in the construction material.

Fig. 3 – a) Rainfall intensity registered by the meteorological station for the period 1 April – 1 June 2019, red arrows indicate the two selected days. b) Inverted resistivity section for 1 April 2019. c) Inverted resistivity section for1 June 2019.d) Variations in soil resistivity between 1 June 2019 and 1 April.

Conclusions. We discussed the efficiency of long-term ERT monitoring systems to study the internal conditions of river levees. ERT monitoring system would be expensive for permanent monitoring of very long sections of river embankments. Therefore, site selection studies should be performed to select the critical sections for permanent monitoring. This was done with the knowledge of the territory, thanks to the dialogues provided with managing authorities, as well as careful reconnaissance studies. Moreover, the exposure of the surrounding areas has to be considered for the final installation of a long-term monitoring system. After considering all the important issues and installing an ERT monitoring system in Colorno, real-time monitoring of the levee provides information about changes in the characteristics of the embankment. Proper data processing algorithms are developed including correcting the effect of burial of electrodes and 3D geometry effects. Time-lapse data analysis of data before and after a rainfall event showed how resistivity images can show differential infiltration in the structure. Research is now in progress to permit automatic data inversion and automatic alarm on exceeding thresholds of water content.

Acknowledgments. The research was partially funded by Ministero dell'Ambiente e della Tutela del Territorio e del Mare, grant DILEMMA. The authors want to thank Stefania Gherbi for 2D and 3D modelling; Consorzio di Bonifica Terre dei Gonzaga in Destra Po, Consorzio di Bonifica Est Ticino Villoresi and AIPO for the collaboration. The monitoring system has been developed with the technical support of LSILastem.

References.

Arosio D., Munda S., Tresoldi G., Papini M., Longoni L. and Zanzi L.; 2017: *A customized resistivity system for monitoring saturation and seepage in earthen levees: installation and validation*. Open Geosci., **9**, 457-467.

Dahlin T., Johansson S., Sjödahl P. and Loke M. H.; 2008: *Resistivity monitoring for leakage and internal erosion detection at Hällby embankment dam*. J. of Appl. Geophys., **65**(3), 155-164.

Hojat A., Arosio D., Ivanov V.I., Longoni L., Papini M., Scaioni M., Tresoldi G. and Zanzi L.; 2019a: *Geoelectrical characterization and monitoring of slopes on a rainfall-triggered landslide simulator*. J. of Appl. Geophys. https://doi.org/10.1016/j.jappgeo.2019.103844

Hojat A., Arosio D., Longoni L., Papini M., Tresoldi G. and Zanzi L.; 2019b: *Installation and validation of a customized resistivity system for permanent monitoring of a river embankment*. EAGE-GSM 2nd Asia Pacific Meeting on Near Surface Geoscience & Engineering, Kuala Lumpur, Malaysia, https://doi.org 10.3997/2214-4609.201900421.

Jomard H., Lebourg T., Guglielmi Y. and Tric E.; 2010: E*lectrical imaging of sliding geometry and fluids associated with a deep seated landslide (La Clapière, France)*. Earth Surf. Process. Landforms, **35**, 588–599.

Kuras O., Pritchard J. D., Meldrum P. I., Chambers J. E., Wilkinson P. B., Ogilvy R. D. and Wealthall G. P.; 2009: *Monitoring hydraulic processes with automated time-lapse electrical resistivity tomography (ALERT)*. Comptes Rendus Geosci., **341**, 10, 868-885.

Loke M.H.; 2014: *RES3DMODx64 ver. 3.04: 3-D resistivity and IP forward modeling using the finite-difference and finite-element methods*. Geotomosoft Solutions.

Loke M.H.; 2016: *RES2DMOD ver. 3.03: Rapid 2D resistivity and I.P. forward modeling using the finite-difference and finite-element methods*. Geotomosoft Solutions.

Loke M.H.; 2018: *Rapid 2-D Resistivity and IP inversion using the least-squares method.* www.geotomosoft.com

Loperte A., Soldovieri F., Palombo A., Santini F. and Lapenna V.; 2016: *An integrated geophysical approach for water infiltration detection and characterization at Monte Cotugno rock-fill dam (southern Italy)*. Eng. Geo., **211**, 162–170.

Morelli G., Francese R., Monteiro-Santos F., and Taylor R.; 2015: *Levee imaging using a multi-array electromagnetic induction and multi-channel radar: in GPR & EMI in Complex Environments*: *Emerging Concepts, Methods, Instruments, and Data Analysis*. Symposium on the Application of Geophysics to Engineering and Environmental Problems 2015, 344-355.

Perri M. T., Boaga J., Bersan S., Cassiani G., Cola S. and Deiana R.; 2014: *River embankment characterization: The joint use of geophysical and geothecnical techniques*. J. of Appl. Geophys., **110,** 5-22.

Supper R., Romer A., Kreuzer G., Jochum B., Ottowitz D., Ita A. and Kauer S.; 2012: *The GEOMON 4D electrical monitoring system: current state and future developments. Instrumentation and data acquisition technology*. Procedings of GELMON 2011, Berichte Geol. B.-A, 93, 23-26, ISSN 1017 – 8880.

Tresoldi G., Arosio D., Hojat A., Longoni L., Papini M. and Zanzi L.; 2018: *Tech-Levee-Watch: experimenting an integrated geophysical system for stability assessment of levees.* Rend. Online Soc. Geol. Ital., **46**, 38-43. https://doi.org/10.3301/ROL.2018.49.

Tresoldi G., Arosio D., Hojat A., Longoni L., Papini M. and Zanzi L.; 2019: *Long-term hydrogeophysical monitoring of the internal conditions of river levees.* Eng. Geo., **259,** 105139. https://doi.org/10.1016/j.enggeo.2019.05.016

Weller A., Lewis R., Tran C., Moller M. and Scholz B.; 2014: *Geotechnical and Geophysical Long-term Monitoring at a Levee of Red River in Vietnam*. J. of Environ. and Eng. Geophys., **19**(3), 183–192. DOI: 10.2113/JEEG19.3.183

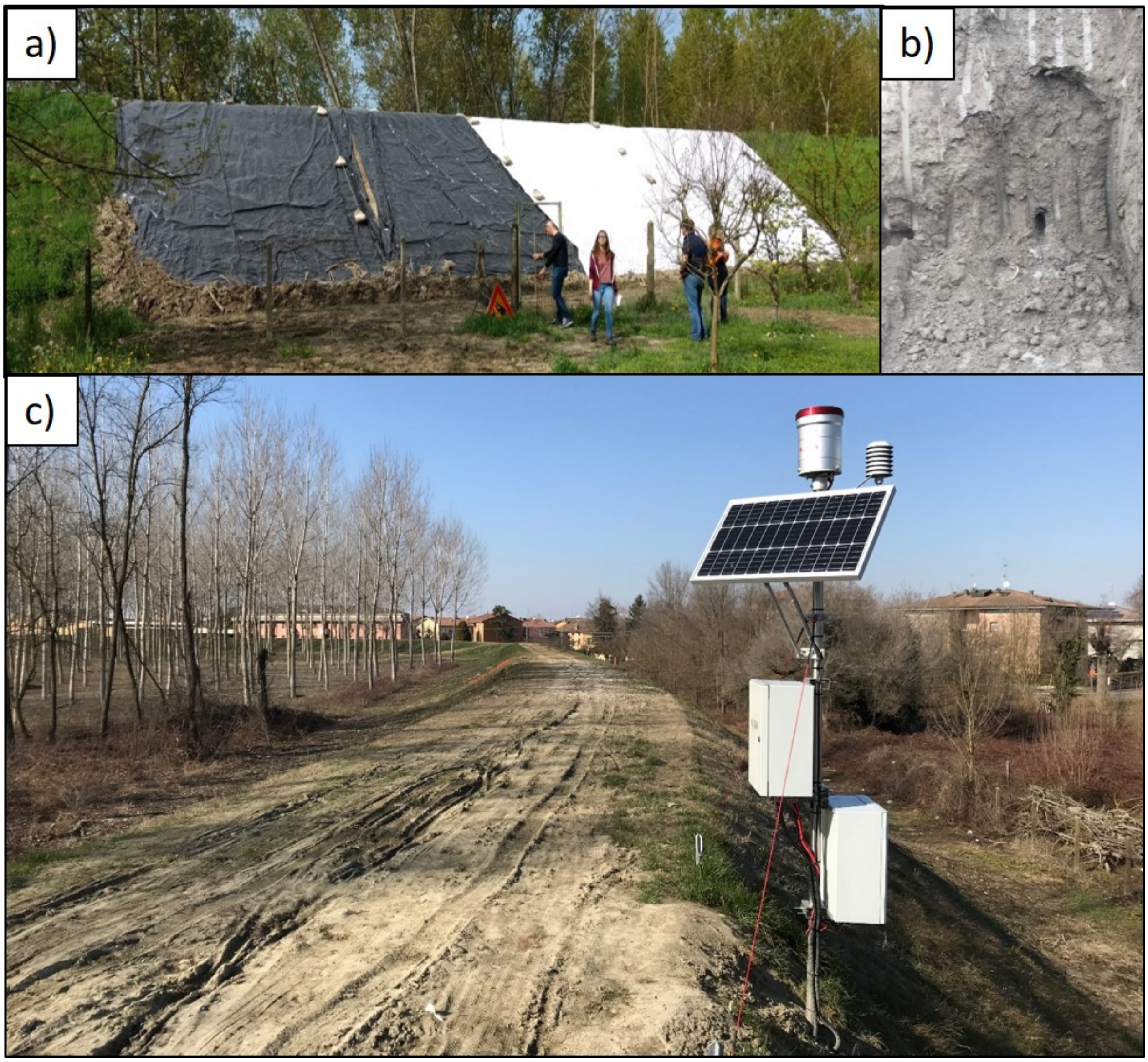

Fig. 1 – a) The repaired section of the monitored site in Colorno. b) Piping phenomenon observed in the levee during the flood in December 2017. c) Long-term geoelectrical and weather monitoring systems installed in La Penza site, Colorno.

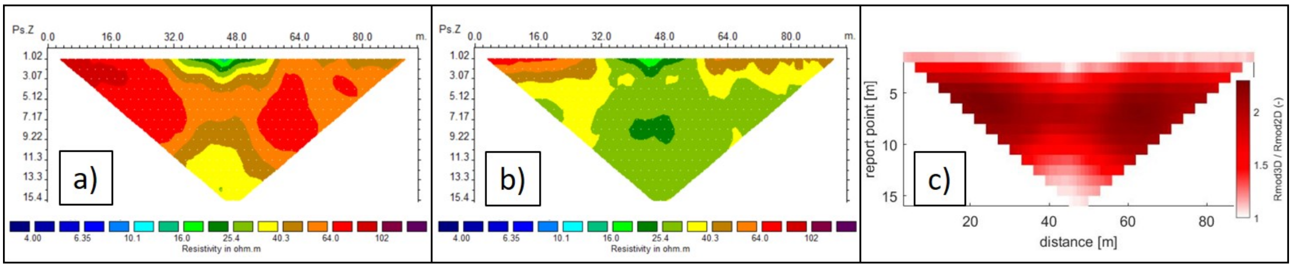

Fig. 2 – a) Apparent resistivity pseudosection calculated in Res3dmod. b) Apparent resistivity pseudosection calculated in Res2dmod. c) Pseudosection of apparent resistivity ratio.

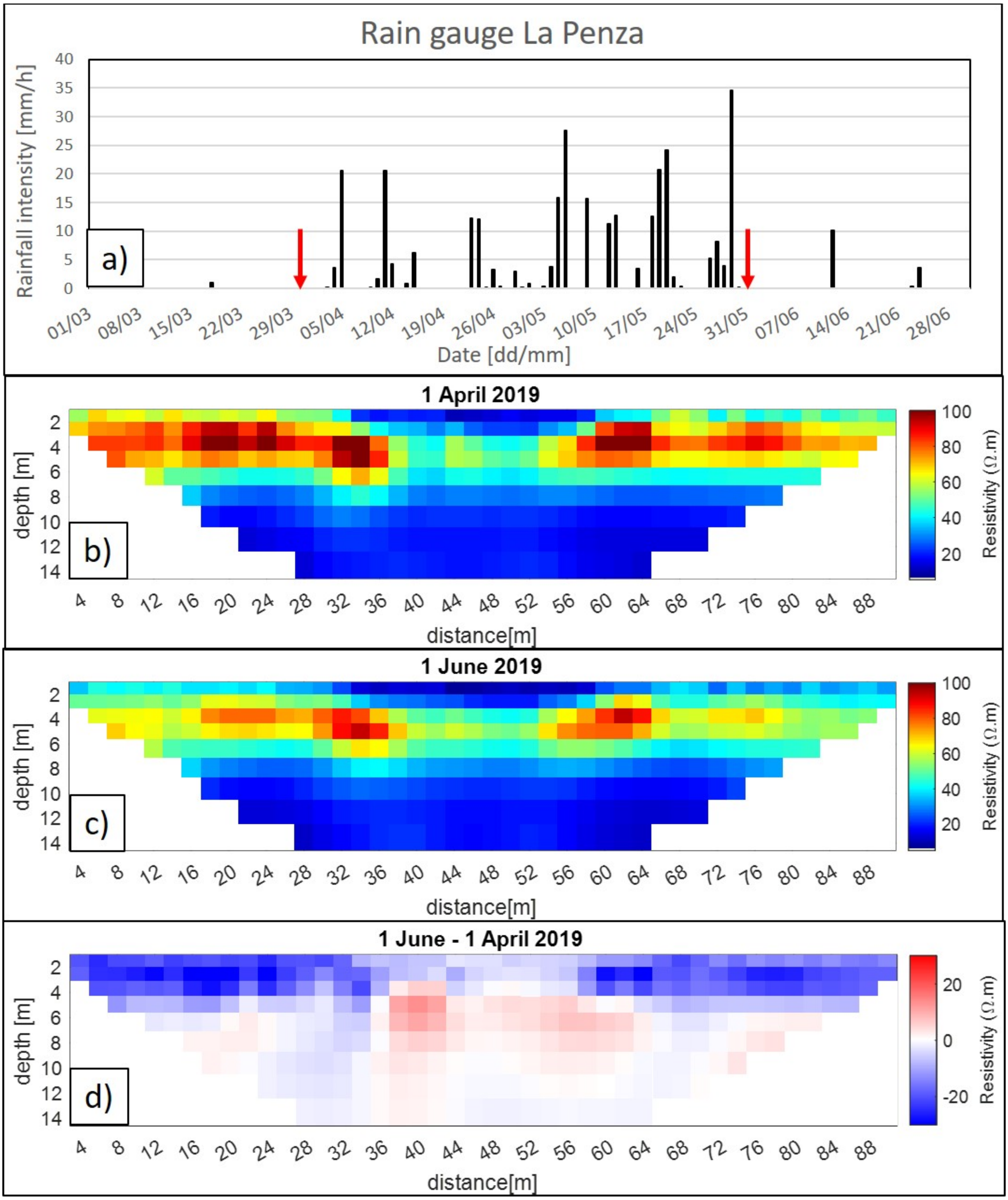

Fig. 3 – a) Rainfall intensity registered by the meteorological station for the period 1 April – 1 June 2019, red arrows indicate the two selected days. b) Inverted resistivity section for 1 April 2019. c) Inverted resistivity section for1 June 2019.d) Variations in soil resistivity between 1 June 2019 and 1 April.