Improving the galvanic contact resistance for geoelectrical measurements in debris areas: a case study

Mirko Pavoni [a*], Alberto Carrera [a], Jacopo Boaga [a]
[a] Dept. of Geosciences, University of Padova, via Gradenigo 6 -35131- Padova, Italy
[*]Corresponding author: mirko.pavoni@phd.unipd.it

Abstract

This paper aims to test, in a quantitative way, the different approaches that can be applied to improve the contact resistance problem in a debris environment for the acquisition of electrical resistivity tomography. We collected various datasets on the same investigation line in a blocky ground surface of a landslide deposit, using different coupling systems: single electrodes placed between the boulders, adding extra electrodes in parallel, and drilled single electrodes inside the blocks. We performed the measurements in natural dry condition, then we added salt water nearby the electrodes hammered among the boulders and we filled the drilled holes with a conductive carbomer-based gel. The results clearly demonstrate that using salt water significantly reduces the contact resistances, but also that, if salt water is not available, we can collect a good quality dataset in dry condition by connecting more electrodes in parallel. Drilling the electrodes directly inside the boulders decrease the data quality but, if necessary, we demonstrate that the use of a commercial carbon polymer gel can provide a marked improvement in the contact resistances.

Keywords

ERT, electrical resistivity tomography, electrode, data acquisition and data processing.

1. Introduction

Gravitational mass movement such as blocky landslides and debris flows are natural hazards with great socio-economic impact in the mountain eco-system, causing infrastructures damages and casualties (Petley, 2012; Papathoma-Köhle et al. 2015). For this reason, the characterization and monitoring of these complex geological phenomena have a great importance for hazard management and stakeholders. Debris investigation usually requires a multidisciplinary approach, based on the integration of remote and in situ ground-based sensing technologies (de Bari et al., 2011; Perrone et al., 2006). In the context of in situ ground-based measurements, the geophysical methods are widely used for the characterization and monitoring of landslide areas, e.g. to delineate depth and geometry of the sliding surface. In particular, Electrical Resistivity Tomography (ERT) can provide 2D or

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/nsg.12192.

3D images of the electrical resistivity ρ (Ωm) distribution in the subsoil. This physical property of the ground is mainly influenced by the mineralogy of the particles, porosity, ground water content, water salinity and the intrinsic weathering/alteration of the material (Archie, 2003; Reynolds, 1997; Park and Kim, 2005; Bièvre et al., 2012). Since some of these factors, especially the change of water content and weathering/alteration degree, are well known rulers in the triggering mechanisms of gravitational mass movement (Gabet, 2007; Matsuura et al., 2008; Schulz et al., 2009; Sajinkumar et al., 2011; Regmi et al., 2013), ERT technique has been widely applied for landslide characterizations and monitoring studies (McCann and Forster, 1990; Hack, 2000; Jongmans and Garambois, 2007; Yilmaz, 2007; Perrone et al., 2014; Heinze et al., 2017; Boyd et al., 2019). However, direct current (DC) measurements (as ERT) can suffer from a range of sources of error that, if not correctly addressed, can have a significant impact on the interpretation of the survey results (Binley, 2015). Particularly, high galvanic contact resistance between the electrodes and the ground can be problematic, decreasing the signal-to-noise ratio and consequentially affecting the quality of the acquired dataset (Ingeman-Nielsen et al., 2016; Tomaškovičová et al., 2016). Anomalous or negative resistivity values recorded during the ERT measurements often highlight problems with contact resistances, a typical issue in high resistive environments such as rocky ground surface of debris deposits or rock glaciers (Boaga et al., 2020). In this kind of environments, the contact resistance values depend strongly on the surface conditions and can reach several hundred of kΩ (Hauck et al., 2008). Considering that usually the acceptable contact resistance is around tens of kΩ (Day-Lewis et al., 2008), this makes DC measurements particularly challenging in a mountain rocky ground surface. Usually, the coupling of electrodes in a debris terrain can be achieved in two different ways: i) by firmly placing the electrodes among the boulders or, where larger blocks are present, ii) by drilling the electrodes inside the boulders (Hauck et al., 2008). However, with a coarse-blocky terrain, even the stable coupling does not guarantee a good galvanic contact. Typically, this problem can be solved by adding salt-water in the immediate vicinity of the electrodes (Binley, 2015) or by installing extra electrodes in parallel to the main ones (Hauck et al., 2008). Recently, during ERT measurements for archaeological surveys, a carbomer-based gel has been tested with success to improve the electrical contact between ground and electrodes (Vásconez-Maza et al., 2020). This commercial product, portable and easy-to-find, is a standard electrical enhancer for magnetic resonance imaging employed in medical diagnostic. In our study case, we tested different deployments of electrodes for ERT measurements on the same investigation line in a heterogeneous rocky ground surface of a debris deposit. We compared the contact resistance and the injected current values obtained with the different deployments, and we evaluated the quality of the acquired datasets (verifying the differences of the saved quadrupoles after the reciprocal check, as in Cassiani et al. 2006). Finally, we compared the inverted resistivity sections obtained with the collected datasets, discussing the advantages and disadvantages of each acquisition mode.

Accepted Article

2. Site Description

The test site is in the Northeast of Italy, in the province of Trento, more precisely in the lower part of Sarca Valley (see Fig. 1A). The lower Sarca Valley (245 m a.s.l. - 65 m a.s.l.) is characterized by numerous post-glacial gravitational events, likely closely related to neoalpine tectonics (Ivy-Ochs et al., 2017). These landslide deposits are called “Marocche”, a local term for extensive and chaotic deposits of huge and angular blocks (Martin et al., 2014). Among the various “Marocche” landslides deposits, we selected the ‘Marocche di Dro’ site, more precisely the Kas deposit located immediately to the south of the Cavedine Lake (see Fig. 1B). The Kas landslide event took place 1080 ± 160 years ago, probably triggered by the Verona earthquake of 1117 (Guidoboni et al., 2005). The rock avalanches came from Mt. Brento (1544 m a.s.l.) and Mt. La Costa (1634 m a.s.l.), at the western side of the valley, and are mainly composed by the calcareous formations named “Calcari Grigi”. The event buried the “Marocca Principale” deposit, the older and larger landslide body of the ‘Marocche di Dro’ deposit (see Figure 1B). Kas debris area is approximately 3 km long and vary in width from 0.5 to 1.5 km, corresponding to about 3.5 km^2. The maximum thickness is estimated to be about 80 m and the deposit is composed of distinctly barren, chaotic, blocky debris almost completely devoid of vegetation (Ivy-Ochs et al., 2017) (see Fig. 2A-B). Angular boulders are abundant on the surface of the Kas deposit, while the sediment below the blocky carapace consists of angular fragments ranging from gravel to silt size (Weidinger et al., 2014).

Figure 1. *A) Location of test site selected for the measurements: the Marocche di Dro landslide; B) position of the ERT survey line performed on the Kas deposit.*

3. Methods

ERT surveys are performed with multi-electrode devices in order to retrieve the electrical properties distribution of the subsoil. An array of dozens of electrodes is coupled with the substrate in order to ensure a good galvanic contact with the ground. The apparent resistivities ρ_a (Ωm) of the subsoil are measured by injecting the current I with two of the electrodes (current electrodes dipole) and by recording the potential difference ΔV that arises at the other couples (potential electrodes dipole). The measurements are performed along the entire electrodes array, in this way a pseud-section of apparent resistivities is obtained (Day-Lewis et al., 2008). Finally, by executing the inversion process of the collected dataset we can find the real distribution of the electrical properties in the investigated subsoil. Inversion codes iteratively find the best subsoil model that minimize the misfit between the measured and the computed dataset (Binley and Kemna, 2005). At the 'Marocca di Dro' site we collected the measurements with a Syscal Pro georesistivimeter (Iris Instruments), with an investigation line of 24 stainless-steel electrodes (30 cm length), spaced 1 m apart (see Fig. 2A-B) and a Dipole-dipole skip-0 configuration (see Table 1). In the Dipole–dipole configuration, the current electrodes dipole is adjacent to the potential electrodes dipole. Both dipoles have an equal width *a* (m) and they are separated by a distance *na* (m). The skip represents the number of electrodes skipped to create a dipole: our case, skip 0 means that no electrodes have been skipped. Finally, the inversion process of the acquired datasets has been realized with the code R2, based on the Occam's inversion method (Binley, 2015).

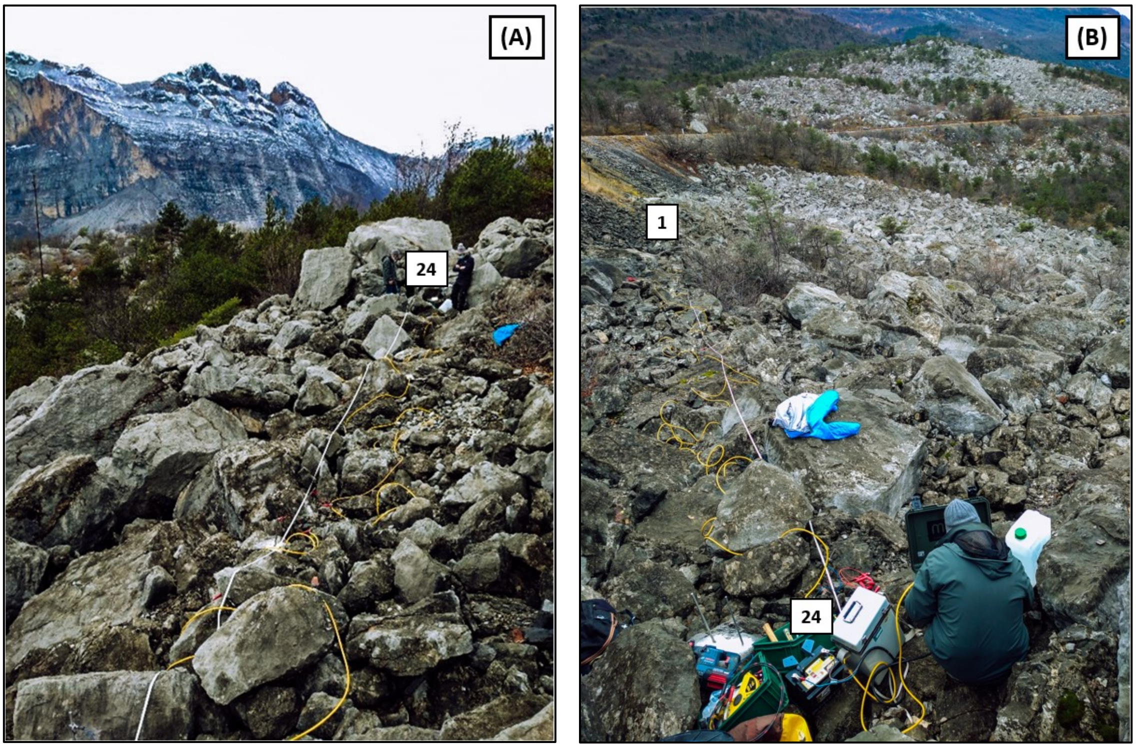

Figure 2. *Pictures taken during the ERT measurements performed on the rocky ground surface of the Kas landslide deposit; the length of the survey line is 23 m and the 24 electrodes are spaced 1 m; A) picture taken close to the first electrode ('24' is the last electrode); B) picture taken close to the last electrode ('1' is the first electrode).*

In our study case we acquired six datasets on the same investigation line, using different ways to ensure a good coupling and galvanic contact between the electrodes and the coarse-blocky terrain. Firstly, we performed the measurements by hammering the electrodes between the boulders (1 electrode in each position of the array – Fig. 3A), then we installed 2 extra electrodes connected in parallel to the main ones (3 electrodes in each position of the array for a total of 72 electrodes – Fig. 3B), and finally we drilled single electrodes inside the boulders (1 electrode in each position of the array – Fig. 3C).

Figure 3. *A) Single electrode placed between the boulders (24 electrodes - 1 per array position); B) a group of three electrodes (triplets) connected in parallel and placed between the boulders (72 electrodes - 3 per array position); C) electrode drilled inside the boulder, here the hole is filled with* the conductive *carbomer-based gel to improve the galvanic contact (24 electrodes - 1 per array position).*

Initially, the measurements were performed in dry natural condition (from now on ‘dry condition’), and afterwards by adding salt-water solution around the electrodes (a mixture of 350 g of NaCl in 15 liters of H_2O, from now on ‘wet condition’). As regards for the drilled electrodes, we firstly measured the dry condition and, subsequently, the holes were filled with a carbomer-based gel (see Fig. 3C). We tested the conductive polymer gel since it is more practical for filling the holes and it doesn’t require any physical or logistical efforts as the product is easily transportable in small jars, unlike water tanks which are very heavy and bulky. Before each survey we saved the contact resistances recorded by the georesistivimeter in order to evaluate and compare the values obtained with the different acquisition modes. Furthermore, we acquired all the datasets with reciprocal measurements

(Cassiani et al., 2006), exchanging current and potentiometric dipoles for each measured quadrupole. In this way we can assess the quality of the recorded datasets and correctly define the expected data error for the inversion processes (Day-Lewis et al., 2008). Once defined an acceptable difference threshold between the reciprocal measurements, we removed the quadrupoles exceeding that target and those with measured potential difference (ΔV) lower than 0.001 V (the instrument resolution limit).

Instrument	*Iris Instrument Syscal Pro 72*
Configuration	*Dipole-Dipole skip 0*
Injection time	*250 ms*
Stack max	*6*
V min	*0.001 V*
V max	*800 V*
Electrodes number	*24 (72 for the triplets test)*
Spacing	*1 m*
Array length	*23 m*

Table 1. *Acquisition parameters of the performed ERT surveys*

4. Results

The histograms of Figure 4 show the contact resistances recorded for each survey in dry and wet conditions. Firstly, let's consider the dry condition values. The highest contact resistances are observable with the electrodes drilled inside the boulders (Fig. 4C in blue). In this case the contact resistances are almost one order of magnitude greater than those obtained with the electrodes hammered among the blocks (Fig. 4A-B in blue). The lowest contact resistance values in dry condition (< 200 kΩ) are recorded using the triplets configuration, i.e. with three electrodes connected in parallel (Fig. 4B in blue). The values obtained with the triple electrodes are in fact more than halved if compared to those found with the common single electrode configuration (Fig. 4A). Wetting with small quantities (15 l) of saline water has a very noticeable effect on the measured contact resistances for both the configurations. In fact, the values are decreased of one order of magnitude (<20 kΩ, Fig. 4A-B in red). Finally, also adding the carbomer-based gel helps to improve the galvanic contact of the drilled electrodes, since the contact resistances are almost halved in comparison to the initial dry condition (Fig.4 C in red).

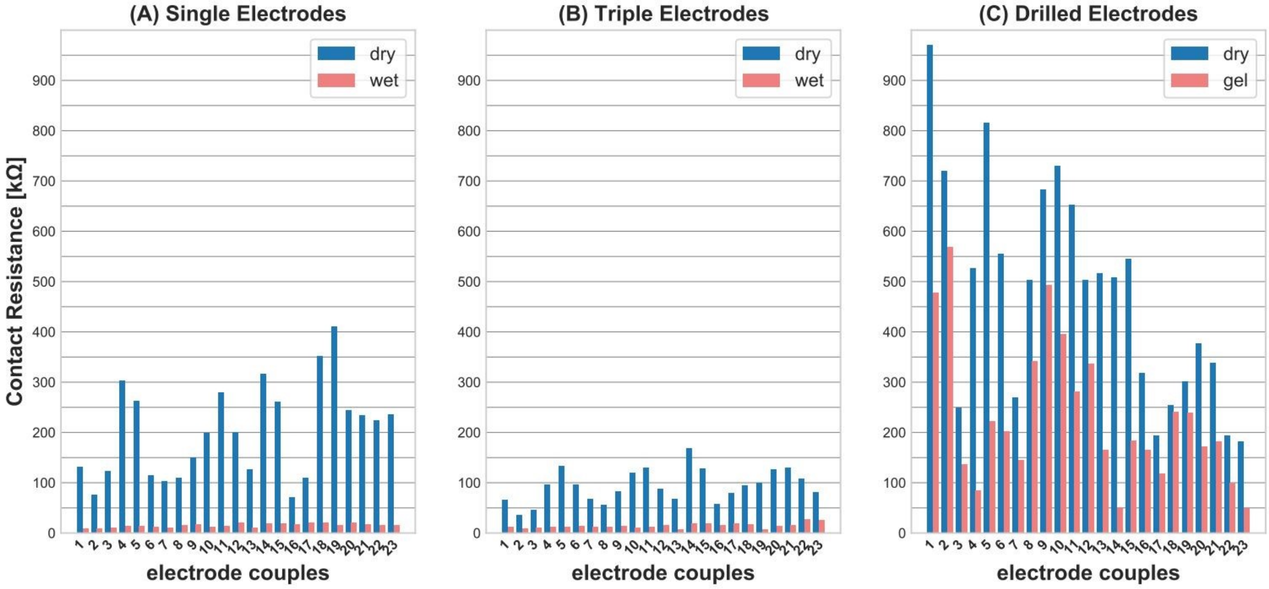

Figure 4. *A) Contact resistance values recorded with single electrodes placed between the boulders; B) contact resistance values recorded with 3 electrodes placed between the boulders and connected in parallel; C) contact resistance values recorded with the electrodes drilled inside the boulders. All the coupling modes are presented in dry condition (blue) and after adding salt-water or gel (red).*

Figure 5 represents the histograms with the values of injected current recorded in each acquired dataset. The lowest values are found in dry condition (<20 mA, Fig. 5A-C-E), particularly when the measurements were performed with the drilled electrodes (Fig 5E). In dry conditions, the higher values are obtained using the triple-electrode mode (Fig. 5C), the injected current has on average doubled if compared to that found with the single electrodes (Fig. 5A) and is almost four times that obtained with the drilled ones (Fig. 5E). Nevertheless, it is clear that in wet conditions the amount of injected current increases considerably (note the different scale of y-axes in dry and wet conditions), regardless of whether we consider the array with single (Fig. 5B) or triple electrodes (Fig. 5D) hammered between the boulders. Finally, considering the drilled mode, applying the gel (Fig. 5F) does not allow to reach the same high values found in the wet condition, but the average injected current is three times higher than in dry condition (Fig. 5E).

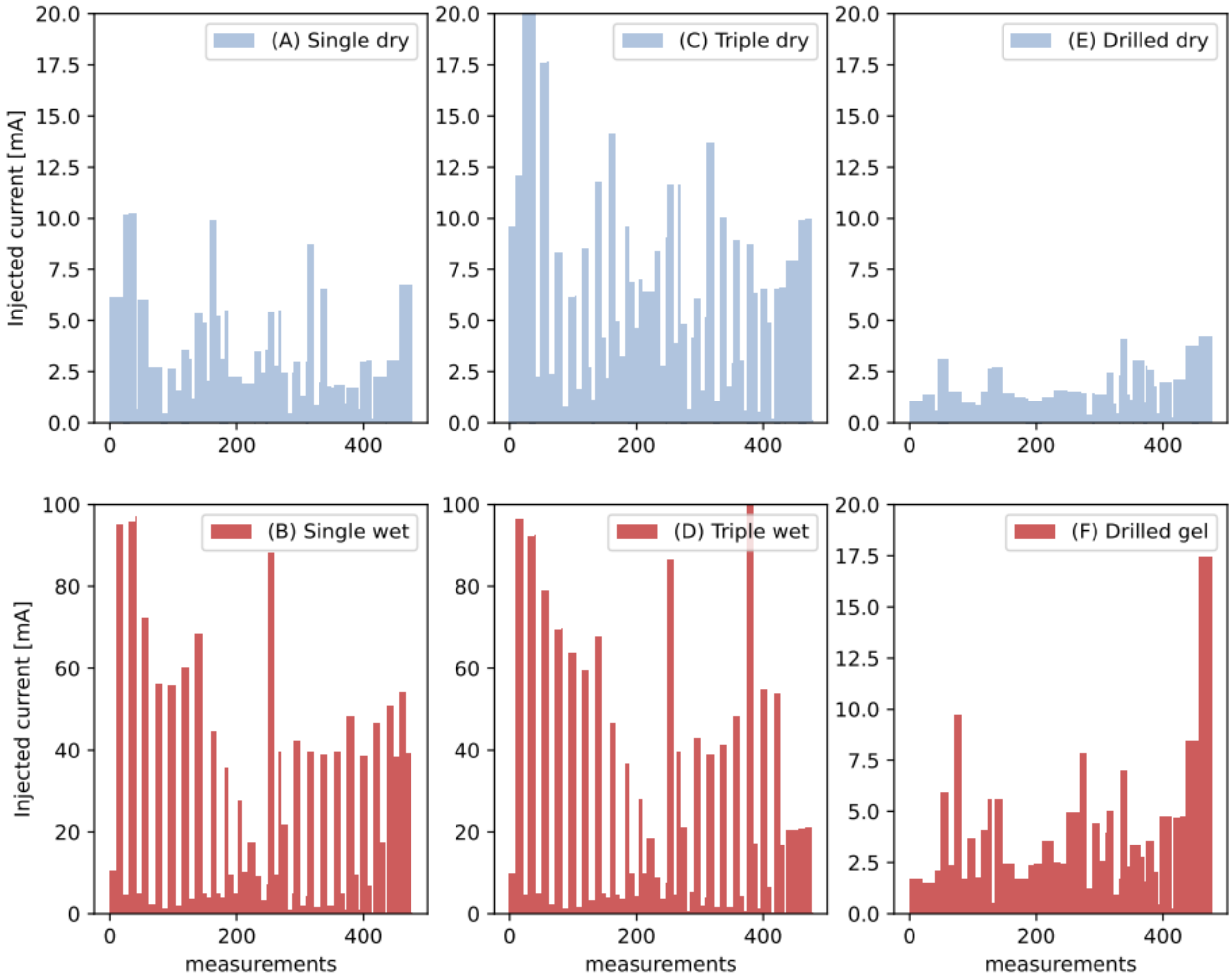

Figure 5. *Injected current values of the datasets acquired with single electrodes hammered between the boulders in A) dry and B) wet conditions; injected current values of the datasets collected with the triple-electrode mode in C) dry and D) wet conditions; injected current values of the datasets acquired with electrodes drilled inside the boulders in E) dry condition and F) after filling the holes with a conductive gel. Note the different scales of y-axes in dry and wet/gel conditions.*

Figure 6 shows the apparent resistivity pseudo-sections obtained after the reciprocity quality check (performed with 3 different error thresholds of acceptance: 5%, 10% and 20%) was applied to the datasets collected with single electrodes hammered between the boulders. As expected, regardless of the applied threshold, the number of saved quadrupoles increases considerably performing the measurements in wet condition, particularly in the deeper part of the pseudo-section. Figure 6B shows the percentages of the saved and rejected quadrupoles for each dataset. In dry condition, in order to save more than 50% of the quadrupoles, we must apply the higher reciprocity threshold error of 20%. This strongly limits our dataset confidence. On the other hand, in wet condition, the number of saved quadrupoles is nearly 90% independently of the chosen error threshold.

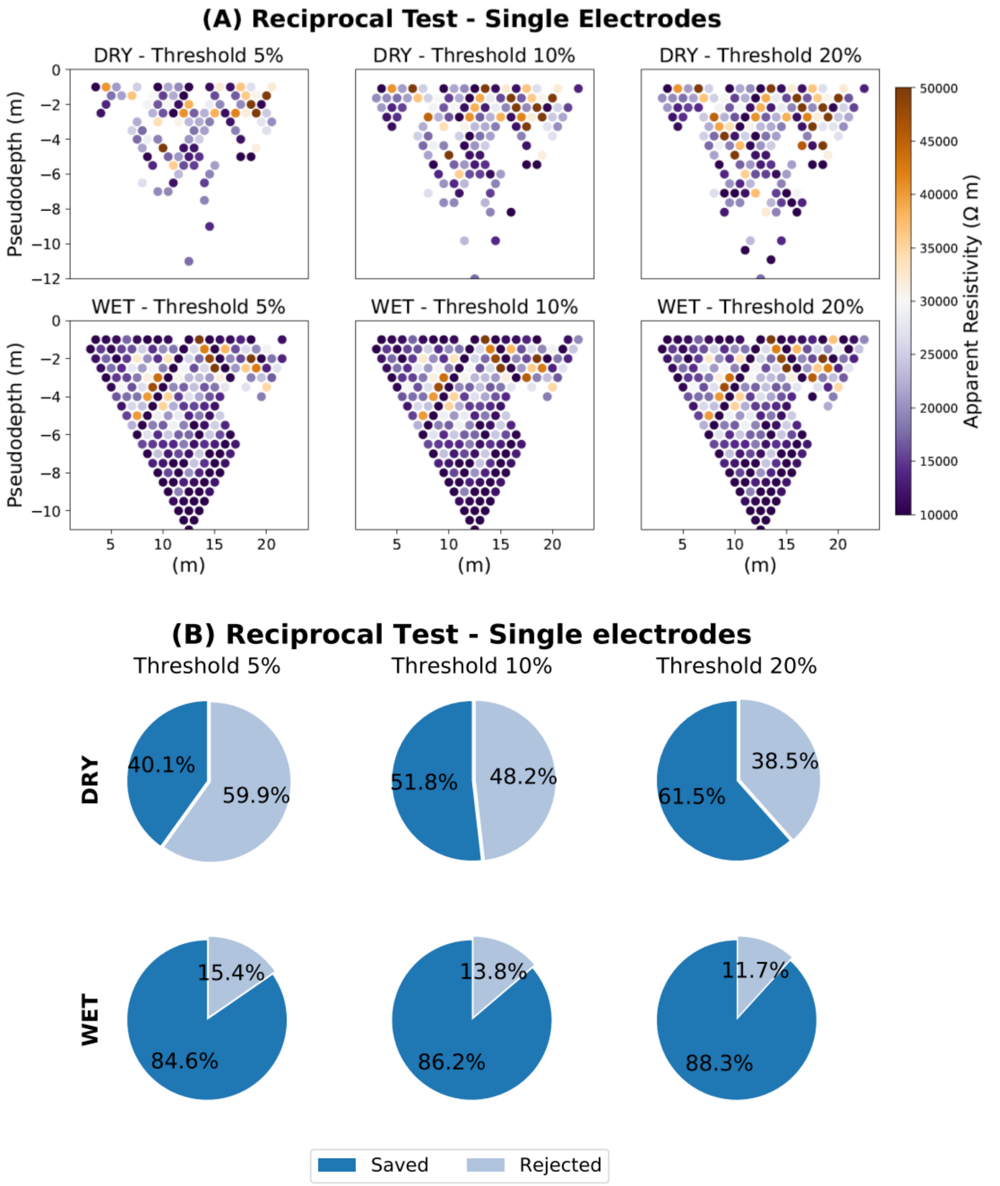

Figure 6. *A) Pseudosections obtained after we applied 3 different reciprocal error thresholds (5% - 10% - 20%) to the datasets measured with single electrodes hammered between the boulders; B) percentages of saved and rejected quadrupoles for each error threshold.*

The same procedure has been applied also to the datasets collected with three electrodes connected in parallel per array position (triplets – Fig. 7). In this case, even in dry condition, the number of saved quadrupoles is always greater than 50%, nearly 70% (Fig. 7B). This provides a large number of reliable measured points in the deeper area of the pseudo-section, respect to the dataset obtained with the single dry electrode configuration (compare Fig. 6A and Fig. 7A). As before, the percentages of saved quadrupoles increase in wet condition, regardless of the chosen reciprocal error threshold (almost 90% of measurements are always saved).

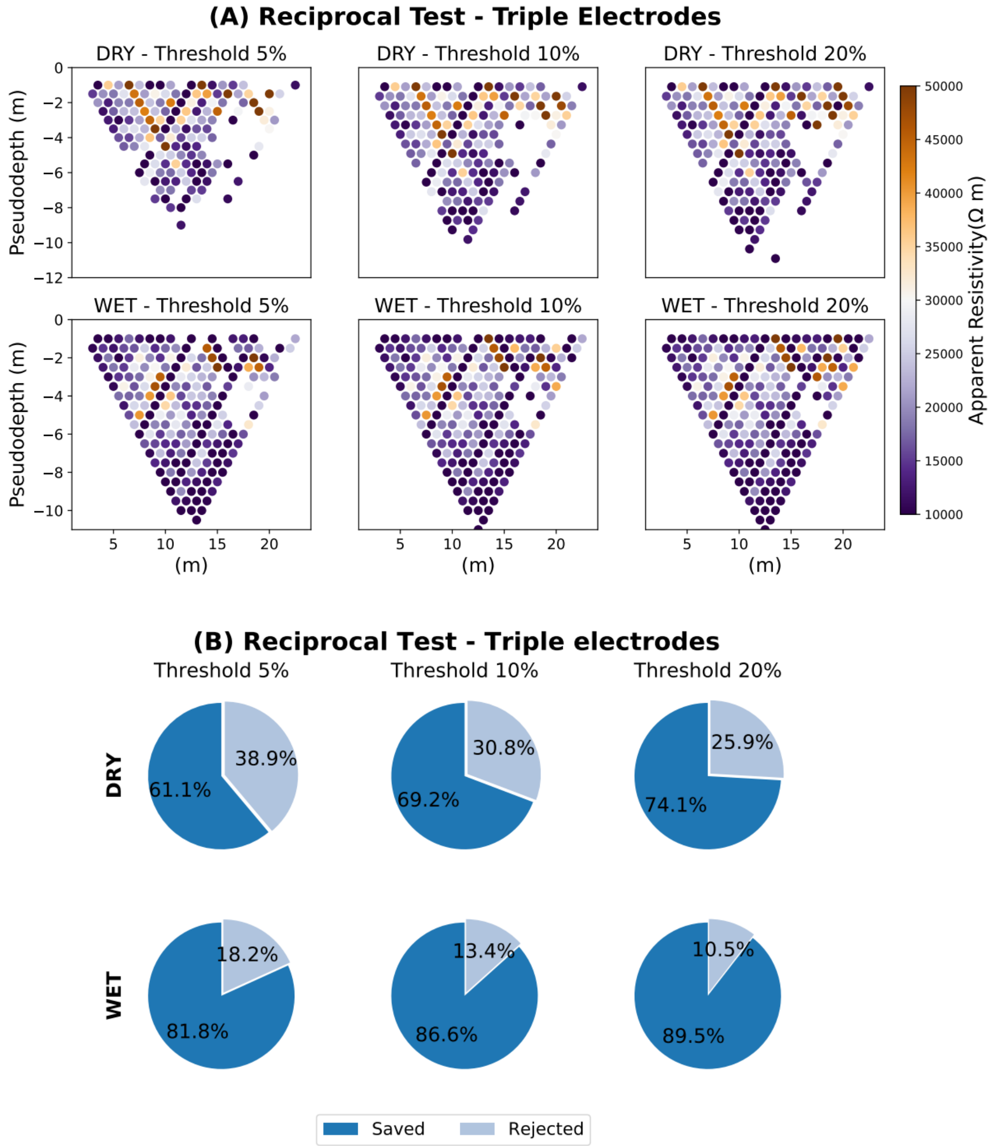

***Figure 7**. A) Pseudosections obtained after we applied 3 different reciprocal error thresholds (5% - 10% - 20%) to the datasets measured with 3 electrodes (hammered between the boulders) connected in parallel in each position of the array; B) percentages of saved and rejected quadrupoles for each error threshold.*

Finally, Figure 8 shows the output of the reciprocity check applied to the datasets measured with electrodes drilled inside the boulders. In dry natural condition the number of saved quadrupoles is clearly lower if compared with the previous cases of Figures 6 and 7, regardless of the applied error threshold. As with the salt-water previously, filling the holes with the conductive carbomer-based gel helps significantly to decrease the amount of rejected measurements, particularly at greater depths (see Fig. 8A). The number of saved quadrupoles, after gel application, becomes always greater than 50% (see Fig. 8B).

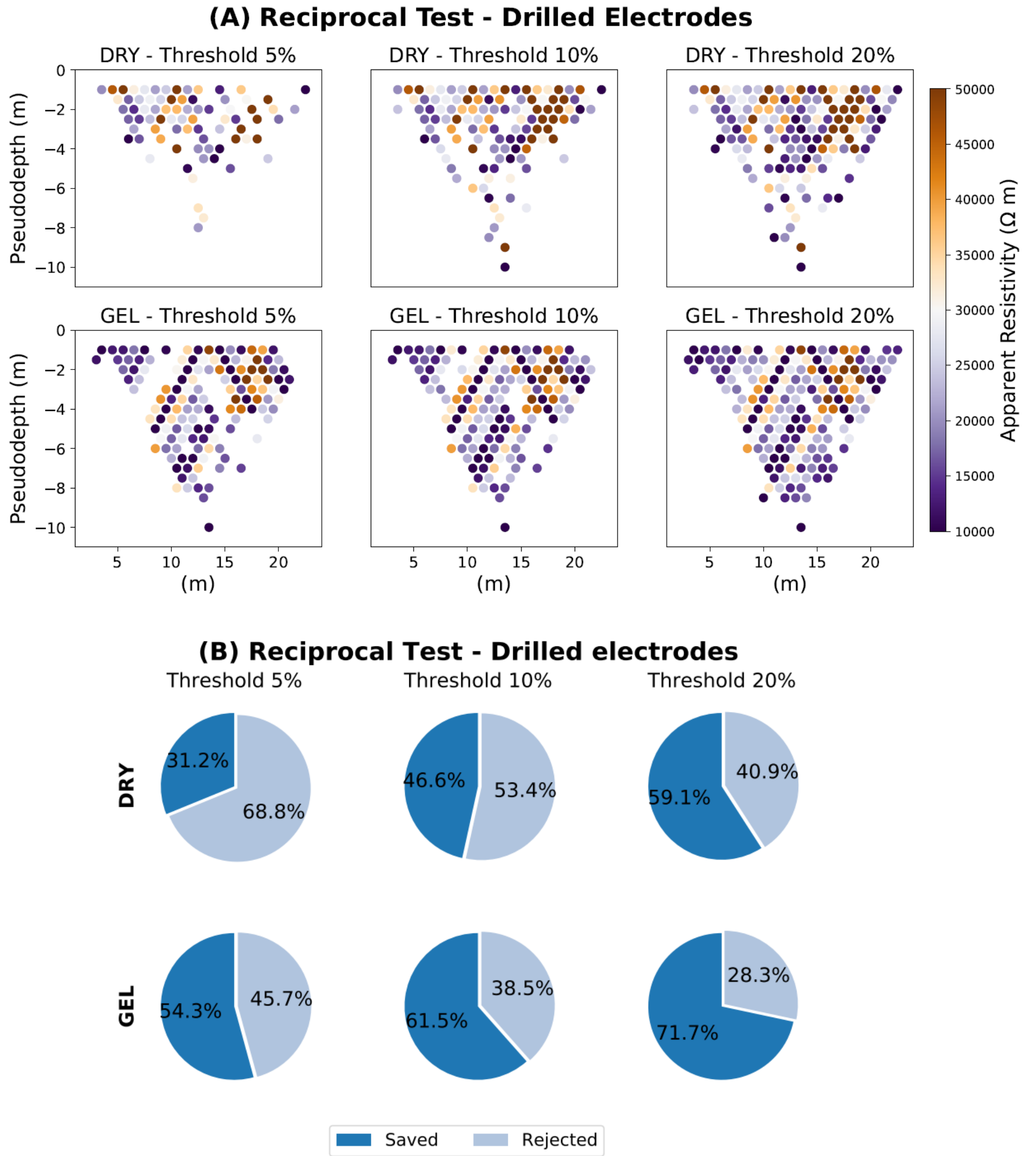

Figure 8. *A) Pseudosections obtained after we applied 3 different reciprocal thresholds (5% - 10% - 20%) to the datasets measured with the electrodes drilled in the boulders; B) percentages of saved and rejected quadrupoles for each error threshold.*

The results of the inversion process are shown in Figure 9, 10 and 11. We present only the resistivity sections obtained with an expected data error of 5% and 10%, since the 20% threshold is considered less reliable. All the inversion results have been achieved with a number of iterations always lower than 10 and with a final RMS misfit (Root Mean Square - a mean to evaluate the misfit between measured and calculated datasets) close to 1%. Figure 9 shows the results for the single electrodes hammered between the boulders. It is clear that, if we perform the measurements in dry or wet conditions, we obtain quite different results. In fact, in dry condition (Fig. 8B-D) we found much larger and deeper (> 3 m) unrealistic anomalous areas with high resistivity values (> 30000 Ωm) as compared to the resistivity sections found in wet conditions (Fig. 8A-C).

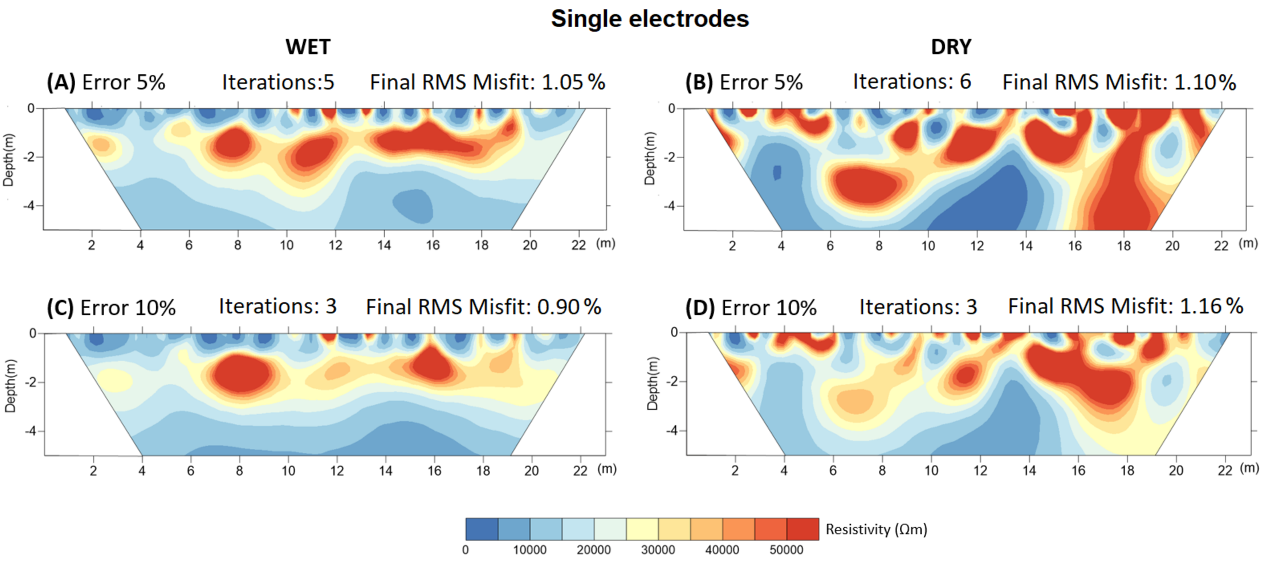

__Figure 9.__ Resistivity sections obtained from the datasets measured with single electrodes hammered between the boulders; using the dataset acquired in wet condition with A) 5% and C) 10% of expected data error; using the dataset acquired in dry condition with B) 5% and D) 10% of expected data error.

Figure 10 shows the inverted resistivity sections obtained with the triple-electrode configuration. Once again, it is clear that performing the surveys in dry (Fig- 10B-D) or wet (Fig. 10A-C) conditions change the results. However, this time the differences are almost negligible if compared to those found with the single electrode configuration (Fig. 9). In particular, the resistivity sections achieved with an expected data error of 10% (Fig. 10C-D) are very similar to each other. Practically, the triplets mode provides a reasonable image of the expected subsoil structure even in dry condition. On the other hand, considering the 'wet dataset', the results (Fig. 10A-C) are nearly the same obtained previously with single electrodes (Fig. 9A-C).

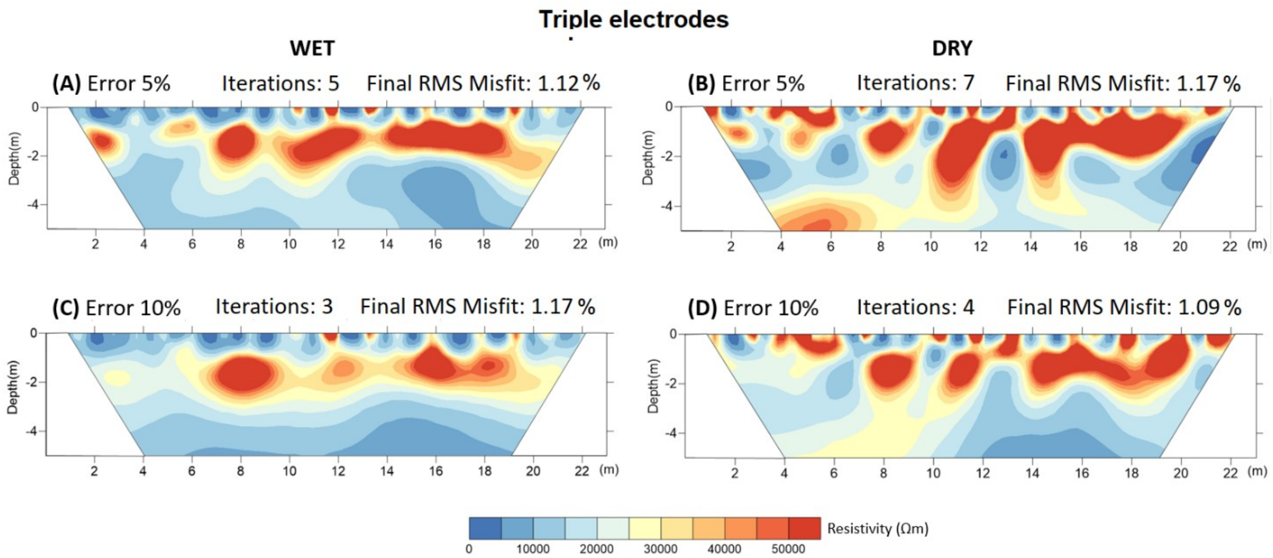

__Figure 10.__ Resistivity sections obtained from the datasets measured with the triplets electrode configuration; using the dataset acquired in wet condition with A) 5% and C) 10% of expected data error; using the dataset acquired in dry condition with B) 5% and D) 10% of expected data error.

Finally, Figure 11 represents the inverted resistivity sections achieved with the electrodes drilled inside the boulders. As in the two previous cases, once again the obtained results are different if we collect the dataset with (Fig. 11A-C) or without (Fig. 11 B-D) the conductive polymer-gel inside the holes. In fact, considering the dry condition, a lot of unrealistic high resistivity areas (> 30000 Ωm) are evident at the bottom of the sections (Fig. 11B-D).

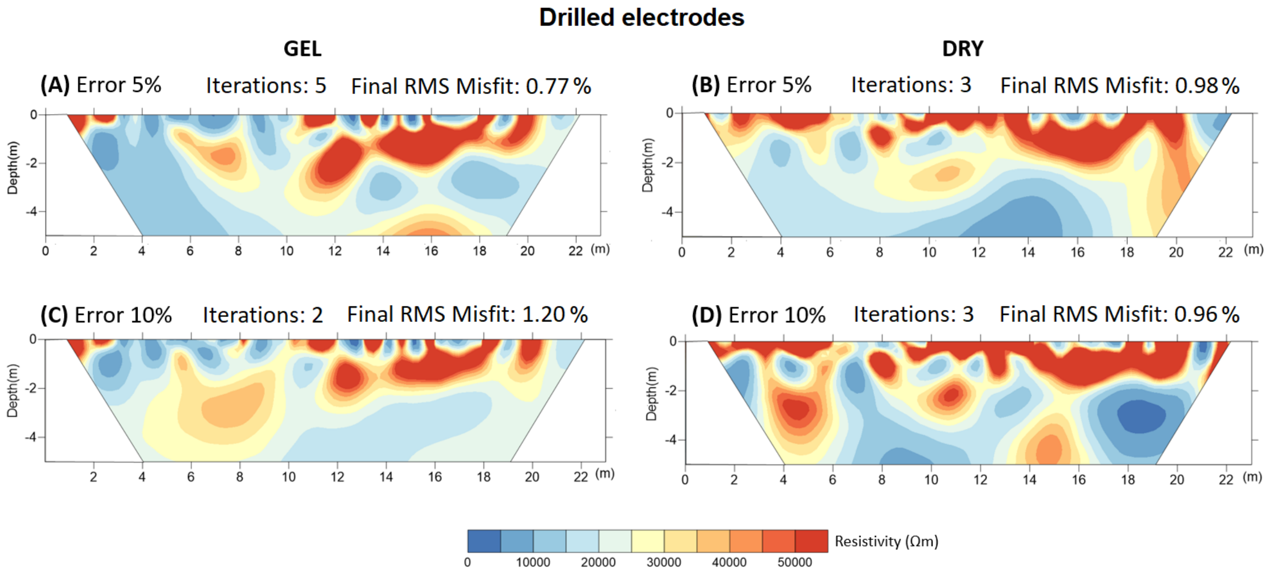

__Figure 11.__ Resistivity sections obtained from the datasets measured with electrodes partially drilled into the boulders; using the dataset acquired with polymer-gel inside the holes with A) 5% and C) 10% of expected data error; using the dataset acquired in dry condition with B) 5% and D) 10% of expected data error.

5. Discussion

Figure 4 provides a self-explanatory evaluation of the collected contact resistances. It is clear that the highest contact resistance values have been measured when the electrodes were directly drilled inside the boulders (Fig. 4C), particularly in natural dry condition. As confirmed by the histogram in Figure 5E, this implies that it is difficult to inject electrical current into the ground from the single boulder and achieve a good signal-to-noise ratio (Day-Lewis et al., 2008). Consequently, the dataset acquired with this configuration are likely to have a much lower quality than those obtained with the electrodes hammered between the boulders (Fig. 4A-B and Fig. 5A-B-C-D). This is also confirmed by direct and reciprocal measurements check (Cassiani et al., 2006). The dataset collected with the electrodes drilled inside the boulders have a number of saved quadrupoles (Fig. 8B), regardless of the reciprocal error threshold, always lower than those obtained with the other two connection modes (Fig. 6B and Fig. 7B). From Figure 4 we can also observe as, in natural dry condition, the best contact resistances are measured using the configuration of three electrodes connected in parallel (Fig. 4B). The contact resistance values reach an average of c.a. 100 kΩ, almost half of those obtained with the single electrodes (Fig. 4A) and less than ¼ of those measured with the drilled ones (Fig. 4C). This allow us to inject more electrical current into the ground, as we can clearly see comparing the histograms in Figures 5A-5C-5E. Therefore, the dataset acquired with multiple electrodes represents the one with the highest signal-to-noise ratio in dry conditions. Once again this is confirmed by the direct and reciprocal check. In fact, the number of saved quadrupoles with the triple-electrode configuration is always higher than those obtained with the single electrodes, particularly in the deeper area of the pseudo-section (see Fig. 7A). These results suggest that, if salt-water is not avaible and we want to improve the quality of our dataset, it is advisable to use more electrodes connected in parallel in each position of the array. It must be noted that this is against the assumption of punctual injection of electrical current into the ground (Everett, 2013). Nevertheless, we tested different inversion procedures considering the geometry of the triple electrodes (electrodes grouped close to each other with respect to the array spacing). Inversion results do not change, and the punctual electrodes assumption can be adopted (e.g. compare Fig. 10A and Fig. 9A). Finally, from Figures 4 and 5 we can observe as the lowest values of contact resistances (< 20 kΩ) and the highest values of injected currents are found by adding salt-water, regardless of whether we use the single or the triple electrodes mode. This implies that the datasets acquired in wet condition are those with the best signal-to-noise ratio and, consequently, have the highest quality. Both the measurements modes allow us to save more than 80% of the quadrupoles after the reciprocity check is applied, even using the lower threshold of 5% (Fig. 6B and Fig.7B). Furthermore, it must be noted that the inverted resistivity sections achieved in wet condition (Fig. 9A-C and Fig. 10A-C) are very similar to each other and, presumably, the most similar to the real subsoil condition. Among all the obtained resistivity sections, the wet condition datasets guarantee a greater confidence to reconstruct the structure of the investigated subsoil (Fig. 9A and Fig.10A). In fact, these results agree with the subsoil structure defined by Weidinger et al., 2014 for the same test site, where large blocks are abundant at the surface of the deposit (ρ > 30000 Ωm) while the underlying sediment is more heterogeneous with finer particle sizes (ρ < 30000 Ωm). Considering this as the subsoil reference model, it is clear that, among all the inversion results obtained in dry conditions, only the resistivity section achieved with the triplet electrodes and an inversion error of 10% is similar to the reference one (note the similarity between 10D and 10C). In fact, as discussed previously, the triple electrodes configuration guarantees the highest quality dataset in dry condition, as the contact resistances are the lowest, the values of injected current and the percentage of saved quadrupoles are the highest. In the other 'dry sections', high resistivity values (ρ > 30000 Ωm) can be found in deeper areas (> 3 m) and those are probably unrealistic shapes due to the lower quality of the datasets. In fact, after the reciprocity check we lost many measured points in the deeper part of the pseudo-sections (see Fig. 6A and Fig. 8A). As a consequence, the inversion code smooths the surface resistive areas in depth. Finally, considering the results obtained with the electrodes drilled inside the boulders (Fig. 11), only the resistivity sections achieved using the conductive polymer-gel (Fig. 11A and Fig.11C) defines a subsoil structure quite similar to the reference ones, even if some high resistivity values are still found at greater depths. This is expected because, as we can see in Figures 4C and 5F, filling the holes with the conductive carbomer-gel reduces the contact resistances and helps to inject more electrical current into the soil, improving the signal-to-noise ratio.

6. Conclusions

It is known that more easily the electrical current is injected into the ground through the electrodes, greater is the amount of reliable measured apparent resistivities, and consequentially more accurate will be the imaging of the subsoil. Therefore, a good galvanic contact resistance in mountain debris environments is a critical issue and some precautions must be adopted. From the results obtained with our study case, the most convenient way to perform ERT measurements in environments with rocky ground surface is to hammer the electrodes between the boulders, ensuring a good coupling, and wetting the electrodes areas with salt-water. In this way the contact resistances are minimized and more electrical current is injected into the ground. Therefore, the measurements are acquired with a good signal-to-noise ratio and consequently high-quality datasets can be collected. Accordingly, the inversion process will be performed with greater confidence, especially if the data error has been correctly evaluated with the reciprocity check of the quadrupoles (Binley and Kemna, 2005). Considering the wet condition, we have practically found the same results using the single or the multiple electrodes connected in parallel configurations. Therefore, if salt-water is available, we can simply collect the measurements using an array of single electrodes hammered between the boulders. In this way we reduce the time requested to deploy the survey line, decreasing the logistic effort because we do not need dozens of extra electrodes, and avoiding possible implications of not-punctual current injection assumption during the inversion process. On the other hand, huge amount of water is often not-available in mountain debris environments. In our study case, we used 15 litres of salt-water, meaning about 0,6 litres per electrode. This should be considered during the planning of ERT surveys in mountain environments, where the transport of the equipment can be demanding. If salt-water is not available and we have more electrodes than required to realize the array, our results suggest to collect the dataset by adding extra electrodes connected in parallel to the main ones, at least in the positions where higher contact resistances are recorded. In this way we can strongly improve the galvanic contact resistance between the electrodes and the terrain and, consequentially, the quality of the acquired dataset. Finally, if the size of the blocks is metric and placing the electrodes between them is not possible (considering that typically we want to create a straight survey line with regular spacing), or we need to place the electrodes in rock walls (Krautblatter and

Hauck, 2007; Van Schoor and Binley, 2010), the only solution remains to drill the electrodes inside the boulders/walls. Our experiment shows that contact resistances in this case are very high and it is difficult to inject the electrical current, but the problem can be limited by inserting a polymer-based gel inside the holes. The application of the carbomer-based gel does not involve any particular waste of time and does not require major physical and logistical efforts, as the product is easily available and transportable in small jars, unlike salt water tanks that are very heavy and bulky. Therefore, although our experience suggests to avoid drilled electrodes, we strongly recommend the use of a conductive gel to improve the quality of the collected dataset.

To conclude, we are aware that local conditions of different debris environments can modify the galvanic contact with the electrodes but, since the boulders of our investigated site are composed of relatively conductive carbonates, even more higher contact resistances can be expected with igneous or metamorphic debris lithologies (Keller and Frischknecht, 1966).

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

Datasets used in this research will be sent to interested researchers upon request.

Acknowledgments

We thank Editor, Associate Editor and Reviewers for the constructive comments/suggestions that
helped to improve the earlier version of this manuscript.

Author Contributions

Conceptualization, A.C., J.B. and M.P.; Methodology, A.C. and M.P.; Validation, J.B.; Formal Analysis, A.C. and M.P.; Investigation, A.C., J.B. and M.P.; Resources, J.B.; Data Curation, A.C. and M.P.; Writing – Original Draft Preparation, M.P.; Writing – Review & Editing, A.C. and J.B.; Funding Acquisition, J.B.

References

Archie, G.E., 2003. The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. SPE Reprint Series. https://doi.org/10.2118/942054-g

Bièvre, G., Jongmans, D., Winiarski, T., Zumbo, V., 2012. Application of geophysical measurements for assessing the role of fissures in water infiltration within a clay landslide (Trièves area, French Alps). Hydrological Processes 26, 2128–2142. https://doi.org/10.1002/hyp.7986

Binley, A., 2015. Tools and Techniques: Electrical Methods, Treatise on Geophysics: Second Edition. Elsevier B.V. https://doi.org/10.1016/B978-0-444-53802-4.00192-5

Binley, A., Kemna, A., 2005. DC Resistivity and Induced Polarization Methods, in: Hydrogeophysics. Springer Netherlands, pp. 129–156. https://doi.org/10.1007/1-4020-3102-5_5

Boaga, J., Phillips, M., Noetzli, J., Haberkorn, A., Kenner, R., Bast, A., 2020. A Comparison of Frequency Domain Electro-Magnetometry, Electrical Resistivity Tomography and Borehole Temperatures to Assess the Presence of Ice in a Rock Glacier. https://doi.org/10.3389/feart.2020.586430

Boyd, J., Chambers, J., Wilkinson, P., Uhlemann, S., Merritt, A., Meldrum, P., Swift, R., Kirkham, M., Jones, L., Binley, A., 2019. Linking geoelectrical monitoring to shear strength - A tool for improving understanding of slope scale stability, in: 25th European Meeting of Environmental and Engineering Geophysics, Held at Near Surface Geoscience Conference and Exhibition 2019, NSG 2019. European Association of Geoscientists and Engineers, EAGE, pp. 1–5. https://doi.org/10.3997/2214-4609.201902452

Cassiani, G., Bruno, V., Villa, A., Fusi, N., Binley, A.M., 2006. A saline trace test monitored via time-lapse surface electrical resistivity tomography. Journal of Applied Geophysics 59, 244–259. https://doi.org/10.1016/j.jappgeo.2005.10.007

Day-Lewis, F.D., Johnson, C.D., Singha, K., Lane, J.W.J., 2008. Best practices in electrical resistivity imaging: Data collection and processing, and application to data from Corinna, Maine.

De Bari, C., Lapenna, V., Perrone, A., Puglisi, C., Sdao, F., 2011. Digital photogrammetric analysis and electrical resistivity tomography for investigating the Picerno landslide (Basilicata region, southern Italy). Geomorphology, 133, 1-2, 34-36. https://doi.org/10.1016/j.geomorph.2011.06.013

Everett, M.E., 2013. Near-Surface Applied Geophysics. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781139088435

Gabet, E.J., 2007. A theoretical model coupling chemical weathering and physical erosion in landslide-dominated landscapes. Earth and Planetary Science Letters 264, 259–265. https://doi.org/10.1016/j.epsl.2007.09.028

Guidoboni, E., Comastri, A., Boschi, E., 2005. The “exceptional” earthquake of 3 January 1117 in the Verona area (northern Italy): A critical time review and detection of two lost earthquakes (lower Germany and Tuscany). Journal of Geophysical Research 110, B12309. https://doi.org/10.1029/2005JB003683

Hack, R., 2000. Geophysics for slope stability. Surveys in Geophysics 21, 423–448. https://doi.org/10.1023/A:1006797126800

Hauck, C. (Christian), 1970-, Kneisel, C., 2008. Applied geophysics in periglacial environments. Cambridge University Press.

Heinze, T., Möhring, S., Budler, J., Weigand, M., Kemna, A., 2017. Improving water content estimation on landslide-prone hillslopes using structurally-constrained inversion of electrical resistivity data, Geophysical Research Abstracts.

Ingeman-Nielsen, T., S. Tomaškovi ˇ cová, and T. Dahlin, 2016, Effect of electrode shape on grounding resistances — Part 1: The focus-one protocol: Geophysics, 80, this issue, doi: 10.1190/geo2015-0484.1.

Ivy-Ochs, S., Martin, S., Campedel, P., Hippe, K., Alfimov, V., Vockenhuber, C., Andreotti, E., Carugati, G., Pasqual, D., Rigo, M., Viganò, A., 2017. Geomorphology and age of the Marocche di Dro rock avalanches (Trentino, Italy). Quaternary Science Reviews 169, 188–205. https://doi.org/10.1016/j.quascirev.2017.05.014

Jongmans, D., Garambois, S., 2007. Geophysical investigation of landslides: A review. Bulletin de la Societe Geologique de France. https://doi.org/10.2113/gssgfbull.178.2.101

Keller, G.V., Frischknecht, F.C., 1966. Electrical methods in geophysical prospecting.

Krautblatter, M., and C. Hauck (2007), Electrical resistivity tomography monitoring of permafrost in solid rock walls, J. Geophys. Res., 112, F02S20, doi:10.1029/2006JF000546.

Martin, S., Campedel, P., Ivy-Ochs, S., Viganò, A., Alfimov, V., Vockenhuber, C., Andreotti, E., Carugati, G., Pasqual, D., Rigo, M., 2014. Lavini di Marco (Trentino, Italy): 36Cl exposure dating of a polyphase rock avalanche. Quaternary Geochronology 19, 106–116. https://doi.org/10.1016/j.quageo.2013.08.003

Matsuura, S., Asano, S., Okamoto, T., 2008. Relationship between rain and/or meltwater, pore-water pressure and displacement of a reactivated landslide. Engineering Geology 101, 49–59. https://doi.org/10.1016/j.enggeo.2008.03.007

McCann, D.M., Forster, A., 1990. Reconnaissance geophysical methods in landslide investigations. Engineering Geology 29, 59–78. https://doi.org/10.1016/0013-7952(90)90082-C

Papathoma-Köhle, M., Zischg, A., Fuchs, S., Glade, T., Keiler, M., 2015. Loss estimation for landslides in mountain areas - An integrated toolbox for vulnerability assessment and damage documentation. Environmental Modelling and Software 63, 156–169. https://doi.org/10.1016/j.envsoft.2014.10.003

Park, S.G., Kim, J.H., 2005. Geological survey by electrical resistivity prospecting in landslide area. Geosystem Engineering 8, 35–42. https://doi.org/10.1080/12269328.2005.10541234

Perrone, A., Zeni, G., Piscitelli, S., Pepe, A., Loperte, A., Lapenna, V., Lanari, R., 2006. Joint analysis of SAR interferometry and electrical resistivity tomography surveys for investigating ground deformation: the case-study of Satriano di Lucania (Potenza, Italy). Engineering Geology, 88, 3-4, 260-273. https://doi.org/10.1016/j.enggeo.2006.09.016.

Perrone, A., Lapenna, V., Piscitelli, S., 2014. Electrical resistivity tomography technique for landslide investigation: A review. Earth-Science Reviews. https://doi.org/10.1016/j.earscirev.2014.04.002

Regmi, A.D., Yoshida, K., Dhital, M.R., Devkota, K., 2013. Effect of rock weathering, clay mineralogy, and geological structures in the formation of large landslide, a case study from Dumre Besei landslide, Lesser Himalaya Nepal. Landslides 10, 1–13. https://doi.org/10.1007/s10346-011-0311-7

Petley D. 2012. Global patterns of loss of life from landslides. Geology; 40 (10): 927–930. doi: https://doi.org/10.1130/G33217.1

Reynolds, J.M., 1997. An introduction to applied and environmental geophysics, An introduction to applied and environmental geophysics. https://doi.org/10.1071/pvv2011n155other

Sajinkumar, K.S., Anbazhagan, S., Pradeepkumar, A.P., Rani, V.R., 2011. Weathering and landslide occurrences in parts of Western Ghats, Kerala. Journal of the Geological Society of India 78, 249–257. https://doi.org/10.1007/s12594-011-0089-1

Schulz, W.H., McKenna, J.P., Kibler, J.D., Biavati, G., 2009. Relations between hydrology and velocity of a continuously moving landslide-evidence of pore-pressure feedback regulating landslide motion? Landslides 6, 181–190. https://doi.org/10.1007/s10346-009-0157-4

Tomaškovičová, S., Ingeman-Nielsen, T., Christiansen, A. V., Brandt, I., Dahlin, T., and Elberling. B.: Effect of electrode shape on grounding resistances — Part 2: Experimental results and cryospheric monitoring. Geophysics, 81,1, 169-82, doi:10.1190/GEO2015-0148.1, 2016.

Vásconez-Maza, M.D., Martínez-Pagán, P., Aktarakçi, H., García-Nieto, M.C., Martínez-Segura, M.A., 2020. Enhancing Electrical Contact with a Commercial Polymer for Electrical Resistivity Tomography on Archaeological Sites: A Case Study. Materials 13, 5012. https://doi.org/10.3390/ma13215012

Van Schoor, M., and A. Binley, 2010, In-mine (tunnel-to-tunnel) electrical resistance tomography in South African platinum mines: Near Surface Geophysics, 8, 563–574, doi:10.3997/18730604.2010021.

Weidinger, J.T., Korup, O., Munack, H., Altenberger, U., Dunning, S.A., Tippelt, G., Lottermoser, W., 2014. Giant rockslides from the inside. Earth and Planetary Science Letters 389, 62–73. https://doi.org/10.1016/j.epsl.2013.12.017

Yilmaz, S., 2007. Investigation of Gürbulak landslide using 2D electrical resistivity image profiling method (Trabzon, northeastern Turkey). Journal of Environmental and Engineering Geophysics 12, 199–205. https://doi.org/10.2113/JEEG12.2.199