Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-2-7

Fractures location on karstified limestone surfaces by Electrical Resistivity Tomography Characterization

Porres-Benito, J.A., Ibanez, S.J., Ortiz-Palacio, S., López-Ausín, V.
INGITER S.L.-University of Burgos, Burgos, Spain

ABSTRACT: The location of main surface fault zones, identified by means of the geophysical technique is nowadays being resolved successfully. The aim of this research is to develop a suitable methodology for the interpretation of Electrical Resistivity Tomography (ERT) 2D images, specifically applied to the preliminary detection of surface faults and structural characterization of active and non-active fault on limestone sites. This work compiles tests and research performed on well-known objectives and analyses the effects of the main factors that condition resistivity images, in order to help in the resistivity profile interpretation. In relation to the study, we highlight the good correlation between the laboratory test and the field works.

1 INTRODUCTION

There has been a significant increase in Geoelectrical prospecting applied in geophysical investigation to hydrological studies, mining and geotechnical research (Dahlin 2001; Griffiths and Barker 1993; Daily and Ramirez 2000, Maillol et al. 1999), as well as in environmental studies and archaeology (Griffiths and Barker 1994; Piro et al. 2000 and 2001; Chambers et al, 2002; Astin et al. 2007; Drahor et al. 2008; Cardarelli and Di Filippo 2009; Papadopoulos et al. 2006 and 2010; Tsokas et al. 2009), proving its utility as non-destructive technique for subsurface exploration. The application of Electrical Resistivity Tomography (ERT) for imaging of discontinuities and lithological contacts is well documented (Beresnev et al. 2002).

At the same time, other studies have contributed successfully in faults location (Giano et al. 2000; Storz et al. 2000; Demanet et al. 2001; Caputo et al. 2007; Rizzo et al., 2004; Fazzito et al. 2009; Terrizzano et al., 2012).

Electrical Resistivity Tomography (ERT) constitutes an important advance in the geoelectric methods because it solves automatically the data acquisition, instead the manual change of electrodes characteristic of the classic geoelectrical methods. In this way, ERT facilitates the management and fast processing of a large number of data, constituting a useful non-destructive method to detect subsurface structures.

Electrical tomography is a geoelectrical surveying method that analyzes subsoil materials according to their electrical impedance, which, in other words, allows them to be differentiated according to their resistivity (Aracil et al., 2002 and 2003; Zhou 2000). Factors that condition the presence of a greater or lesser concentration of ions depend on the nature and composition of the rocks, and their texture that may be more or less altered, or compact, or porous, in relation to their fluid content and their nature. Fault movements develop a high secondary porosity, why the water content is increased and a drop in resistivity values occurs.

Greater mobility of these ions has as a consequence, greater conductivity, or conversely less resistivity, which is the parameter used in electrical resistivity tomography (Orellana, E. 1982).

The resistivity or conductivity of the water, as the greater the conductivity of the water, the lower the resistivity of the rock formation in which it is found (Sumanovac and Weisser 2001).

According to Equation (1), Heiland's amplified equation (Heiland 1946), the resistivity in the rock will depend fundamentally on four factors:

$$[\rho] = [F/v][\rho w][1/Fs] \qquad (1)$$

Where $[\rho]$ is the resistivity of the rock, [F] is the formation factor, [v] is the porosity factor, $[\rho w]$ is the resistivity of the water contained in the rock or soil, and [Fs] is the saturation factor.

The porosity factor is defined as the proportion in volume of cavities in the rock. It takes values between 0.08-0.15 for sand, sandstone, porous limestone and compact clays. This definition of [v] coincides with that of porosity [n], for which reason reference will henceforth be made to [n]. The formation factor depends on the form and distribution of the pores. The rocks that are most affected by factor [F] are sandstones, quartzites, limestones and shales. The data for this study were collected by measuring 2D Dipole-Dipole and Wenner-Schlumberger profiles, carried out with a SYSCAL R1+ Switch 72 geo-resistivitimeter, made by Iris Instruments Company. The apparent resistivity values from field measurement are processed by means of the RES2DINV software (Loke 1999)

The results of this type of geophysical surveying are the electrical tomography profiles (Figure 1) that are simply vertical sections of the ground that are colour coded with the different resistivity measurements. The colour coding is shown in a legend at the bottom of each profile.

Consequently, once the geo-electrical prospecting research using ERT is underway different resistivity values will be determined and attributed to materials that will permit identification of lithological units of differing natures, lithologies with different textures or degrees of deterioration, structural (fractures) and geomorphologic aspects (caves and infills), etc.

The data acquisition requires the positioning of an array of, each separated at a particular distance according to the required degree of resolution (Porres 2003). Each one of these resistivity data measure, is attributed to a particular geometric point in the subsurface. The electrical images are, in fact, cross-sections of land that reflect the distribution of resistivity values at different depths corresponding to the different layers of investigation (Loke 1996-2011).

The investigation depth, therefore, will depend on the spacing between electrodes and the selected layout may easily run deeper than 100m in depth, even though shallower test boreholes into the subsurface have the definite advantages of greater resolution, as there is generally less separation between electrodes. As a rule, the resolution of the investigation decreases logarithmically in relation to the depth (Dahlin and Loke 1998).

2 LABORATORY TESTS: ELECTRICAL RESPONSE OF KNOWN MODELS

In order to meet the electrical response of different geological conditions, laboratory tests were carried out on small-scale models. Figure 1 shows the data acquisition process for an air-filled big hole in a layer of sand, trying to simulate a geology similar to a limestone place, showing an air-filled karst cavity as well as a large area fractured unfilled in a full scale test.

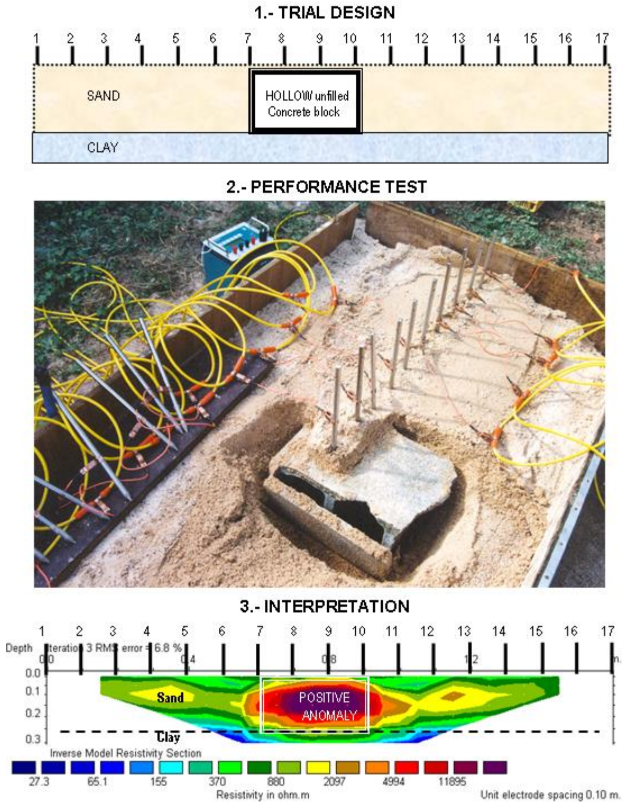

Figure 1. Electrical Resistivity Tomography laboratory test, and its corresponding 2D profile image interpretation. (Porres, J.A., 2003).

Multitude of test were conducted on a small scale, observing the influence of 5 variables in the 2D images obtained: 1- Electrode array (Schlumberger-Wenner and Dipole-Dipole), 2- Separation distance between electrodes, 3- Depth of investigation, 4- Size and shape of the discontinuities investigated, 5- Kind of filling inside the faults.

The results showed the best choice of electrode array to locate vertical fractures and high-angle faults is Dipole-Dipole array, consistent with most other works (Loke, 1996-2011; Fleta et al., 2000; Caputo et al., 2007; Rizzo et al., 2004). However, the Schlumberger-Wenner array allows higher investigation depth, and often gets good resolution images

3 FIELD WORK: LOCATION OF DISCONTINUITIES AND FAULTS ON LIMESTONE SURFACES

Electrical Resistivity Tomography profiles were taken to identify the characteristics of the subsoil, with the specific objective of identifying fractures or faults affecting the limestone massif in different places of Burgos, Spain. The geomorphology of karst in this bedrock, is clearly related with the tectonic structure (Zhou, W. et al., 2000).

The application of appropriate geophysical surveying methods to each objective provides knowledge of the subsoil materials and their layout to a greater or lesser degree of precision. Concretely, this geophysical survey method well used will allow the materials at different depths to be studied at different degrees of resolution (Martínez-Pagán et al. 2005).

The field work sections were carried out with the resistivity device SYSCAL R1 PLUS Switch72, and were processed using the software RES2DINV ver.3.42 (Locke 1999). In every section, we applied Schlumberger-Wenner and Dipole-Dipole electrode arrays. Most of the profiles present similar results using the Dipole-Dipole and Schlumberger-Wenner arrays, although in a few profiles they differ substantially, especially in those where the prospection depth is increased. In these cases, the Dipole-Dipole array showed the highest root-mean-squared errors. Also the Schlumberger-Wenner profiles provide more realistic images according to the endokarstic and geological structures observed in the "Cueva Peluda" control profile (Figure 2), what initially seems contradictory with the laboratory previous test.

In addition, the sections were drawn without vertical exaggeration, in order to facilitate georeferencing and projection of the karstic passage topography. The topography of the geophysical sections was elaborated from topographic surveys.

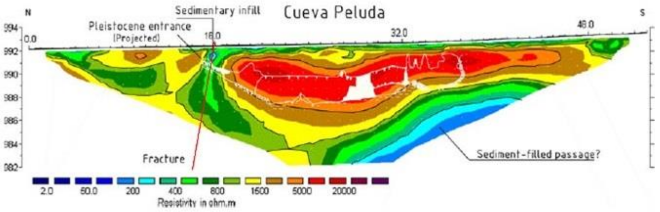

Figure 2. ERT profile recorded over "Cueva Peluda" karstic passage in Atapuerca, Spain. The whiteline shows the internal wall of the cave (Ortega, A.I. et al 2010).

The Pleistocene paleoanthropological sites of Atapuerca (Burgos, Spain), was one of the places studied on this work. The geophysical interpretation of these sections was supported by archaeological and geological field observations, 1:50.000 and 1:10.000 geological and geomorphological surface maps (Pineda, 1997; Benito, A. 2004; Benito-Calvo, A. 2008), and using the geomorphology of the known endokarst system, elaborated by detailed surveying (Ortega, 2009).

Section represented on Figure 2 was carried out along the well-known shallow main passage of the Peluda Cave and was used as a first control for the resistivity response of the fractures, cavities, sediments and limestone materials. In this section, the Dipole-Dipole and Schlumberger-Wenner arrays show similar results. Figure 2 presents a closed structure denoted by the highest resistivity values (> 1500 ohm.m, corresponding to the empty cavity of Cueva Peluda, barely a few meters (1-2 m) under the current floor. This structure is surrounded by rock, Upper Cretaceous carbonates, defined by a wide range of resistivities (> 400 ohm.m), according to its fracturation degree, local facies and stratification. In the profile, a third zone with the lowest resistivity values (< 400 ohm.m) can be distinguished. The latter correspond to non-consolidated and higher porosity material, which correspond to a sediment-filled old entrance and passage, such as was observed in several sections carried out in the site.

A similar place is the Roman City called "Colonia Clunia Sulpicia" also located in Burgos, Spain. The geology of Clunia and surrounding areas is limestone outcrops that crown the upper Miocene tertiary series. This Micritic limestone is sometimes brecciated, whose thickness ranges from 5 to 15 meters. Under the limestone in the series is a section of marls inter-bedded with lenticular sand bodies that gradually give way to carbonate crusts where Miocene limestone occur as described above. In this sense, it seems that the Roman city is located in a very favorable place for the development of karst aquifers on carbonate formations.

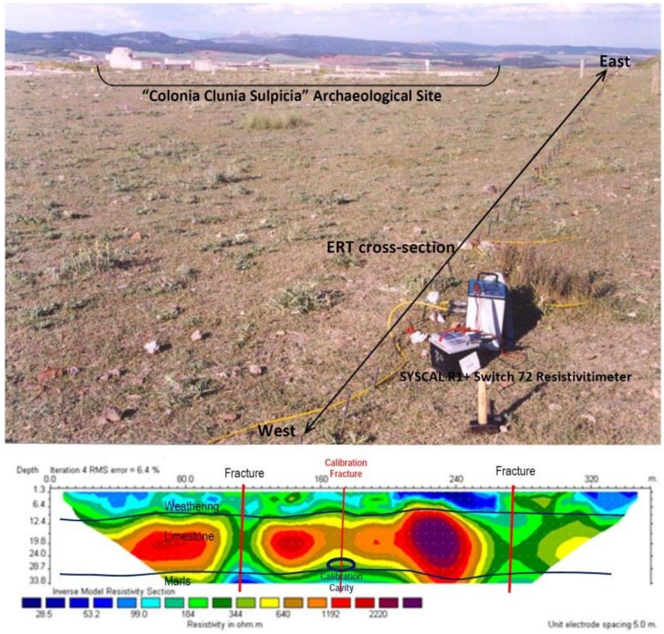

Figure 3. ERT profile recorded over a karstic passage in "Colonia Clunia Sulpicia" archaeological site, Spain. The central line shows a calibration fracture and cavity which shape and depth was well known, and the two other red lines are negative anomalies who shows Fractures or Faults. (Porres 2003).

The morphology and layout of the cavities must have been highly conditioned by the presence of fractures which would have logically been the conduits through which the water passed, which caused the formation of these caves. An effort has been made to analyze these fractures using the same type of geophysical surveying but with the profiles located on the external surface of the limestone massif. These profiles, taken with different equipment to reach greater depths, identified certain anomalies which, on account of their morphology and their resistivity values, must be fractures in which the circulation of water and the deposits of clays would give them their characteristically low resistivity values in this type of geophysical profile (Negative anomaly at figure 3).

The calibration of Profile showed in Figure 3 was possible because we know the existence of a cave and fracture under the ERT profile. The dimensions of the calibration cavity is 10 m wide and 3 m high, and is located at a depth of 25 m, following the structural discontinuities of the limestone, where the weathering is easier. The profile has 5 m as electrode spacing, so it shows 355 m lengh and 33,8 m depth. There are two clear low resistivity anomalies (<350ohm.m) in figure 3, that seems clear fracture evidence, since the normal resistivity values in the limestone itself is located, which could be around 650 ohm.m.

4 CONCLUSIONS

Electrical tomographic images show low resistivity values associated with fractures in limestone rocks, as well as significant resistivity contrast across faults in the subsurface. It has been shown an experience which permitted, through the interpretation of electrical resistivity profiles, the characterization of the geometry of fault zones, detecting the depth, size, shape and filler of surface fractures, specifically applied to karstified limestone bedrock.

To image the geometry of fault planes and tectonic structures, is essential to select the most suitable electrical arrangement and configuration, that must be used on each case to locate faults and tectonic structures. Electrical Resistivity Tomography (ERT) has been a useful non-destructive geophysical method for imaging the subsurface structures of the Sierra de Atapuerca and Clunia sites, as well as its endokarst system. The use of detailed geomorphological and geological maps of the tectonic system and the surface landscape was essential to reduce the uncertainty of the geophysical interpretation. High resolution ERT prospecting made it possible to detect and analyze structures related to the site formation and distribution, such us bedrock morphologies, fractures continuity, cavities geometries and thickness of sedimentary infills.

Deeper prospecting, related to longer length and lower resolution sections, was suitable to analyze deeper geological structures which controlled the development of the tectonic structure.

5 ACKNOWLEDGEMENTS

The writers would like to express their gratitude to A.I. Ortega, A. Benito-Calvo and A. Pérez-González, Research National Centre of Human Evolution (CENIEH) & Atapuerca Research Team.

6 REFERENCES

Aracil, E.; Maruri, U.; Porres, J.A.; Espinosa, A.B., 2002. La tomografía eléctrica: una herramienta al servicio de la obra pública. Rock Máquina, 76 (30-34).

Aracil, E.; Maruri, U.; Vallés, J.; Martínez Pagán, P.; Porres, J.A., 2003. Evaluación de problemas medioambientales mediante tomografía eléctrica. Ingeopress, 122 (34-39).

Astin, T., Eckardt, H. and Hay, S., 2007. Resistivity Imaging Survey of the Roman Barrows at Bartlow, Cambridgeshire, UK. Archeological Prospection 14: 24-37.

Benito, A., 2004. Análisis geomorfológico y reconstrucción de paleopaisajes neógenos y cuaternarios en la Sierra de Atapuerca y el valle medio del río Arlanzón. PhD Tesis, Universidad Complutense, Madrid, Spain, 381 pp, ISBN 84-669-2585-6.

Benito-Calvo, A., Pérez-González, A. and Parés, J. P., 2008. Quantitative reconstruction of late Cenozoic land-scapes: a case study in the Sierra de Atapuerca (Burgos, Spain). Earth Surface Processes and Landforms 33: 196-208.

Beresnev, I. A.; Hruby, C. and Davis, C., 2002. Exploration Geophysics. Journal of Applied Geophysics 49: 245-254.

Caputo, R., Salviulo, L., Piscitelli, S., Loperte, A., 2007. Late Quaternary activity along the Scorciabuoi fault (southern Italy) as inferred from electrical resistivity tomographies. Annals of Geophysics 50 (2), 213e223.

Cardarelli, E. and Di Filippo, G., 2009. Integrated geo-physical methods for the characterisation of an archaeological site (Massenzio Basilica – Roman forum, Rome, Italy). Journal of Applied Geophysics 68: 508-521.

Chambers, J. E., Ogilvy, R. D., Kuras, O., Cripps, J.C. and Meldrum, P. L., 2002. 3D electrical imaging of know targets a controlled environmental test site. Environmental Geology 41: 690-704.

Dahlin, T., 2001. The development of DC resistivity imaging techniques. Computer and Geosciences 27: 1019-1029.

Dahlin, T., Loke, M.H., 1998. Resolution of 2D Wenner resistivity imaging as assessed by numerical modelling. Journal of Applied Geophysics, 38. pp. 249

Daily, W. and Ramirez, A. L., 2000. Electrical imaging of engineered hydraulic barriers. Geophysics 65: 83-94.

Demanet, D., Pirard, E., Renardy, F., Jongmans, D., 2001. Application and processing of geophysical images for mapping faults. Computers and Geosciencies 27, 1031e1037.

Drahor, M. G., Berge, M. A., Kurtulmus, T. Ö., Hartmann, M. and Speidel, M. A., 2008. Magnetic and Electrical Resistivity Tomography Investigations in a Roman Legionary Camp Site (Legio IV Scythica) in Zeugma, Southeastern Anatolia, Turkey. Archaeological Prospection 15: 159-186.

Fazzito, S.Y., Rapalini, A.E., Cortés, J.M., Terrizzano, C.M., 2009. Characterization of Quaternary faults by electric resistivity tomography in the Andean Precordillera of western Argentina. Journal of South American Earth Sciences 28, 217-228.

Fleta, J., Santanach, P., Martinez, P., Goula, X., Grellet, B., Masana, E., 2000. Geologic, geomorphologic and geophysic approaches for the paleoseismological analysis of the Amer fault (NE Spain). In: Workshop Proceedings of HAN2000: Evaluation of the Potential for Large Earthquakes in Regions of Present Day Low Seismic Activity in Europe, Han-sur-Lesse, Belgium, pp. 63-66.

Giano, S.I., Lapenna, V., Piscitelli, S., Schiattarella, M., 2000. Electrical imaging and self-potential surveys to study the geological setting of the Quaternary slope deposits in the Agri High Valley (southern Italy). Annali di Geofisica 43 (2), 409e419.

Griffiths D.H.; Barker R.D., 1993. Two-dimensional resistivity imaging and modelling in areas of complex geology. Journal of Applied Geophysics, 29,211-226.

Griffiths, D.H. and Barker, R.D., 1994. Electrical Imaging in Archaeology. Journal of Archaeological Science 21:153-158.

Heiland, C.A., 1946. Geophysical Exploration. Prentice Hall Inc New York 634.

Loke, M. H., 1999. RES2DINV ver. 3.42, Geoelectrical Imaging 2D & 3D, User Manual.

Loke, M.H., 1996-2011. Tutorial: 2-D and 3-D Electrical Imaging Surveys. Geotomo Software.

Maillol, J. M., Seguin, M.-K., Gupta, O. P., Akhauri, H. M., and Sen, N. (1999). Electrical resistivity tomography survey for delineating uncharted mine galleries in West Bengal, India. Geophys Prospect 47: 103-116.

Martínez Pagán, P.; Aracil, E.; Maruri, U.; Faz, Á., 2005. Tomografía eléctrica 2D/3D sobre depósitos de estériles mineros. Ingeopress, 138 (34-36).

Orellana, E. 1982. Prospección Geoeléctrica en Corriente Continua. 2ª ed. Madrid. Paraninfo Vol.1.

Ortega, A. I. (2009). Evolución geomorfológica del Karst de la Sierra de Atapuerca (Burgos) y su relación con los yacimientos pleistocenos que contiene. Unpublished PhD Thesis, Universidad de Burgos, Burgos, Spain, 624 pp.

Ortega, A.I., Benito-Calvo, A., Porres, J., Pérez-González and Martin-Merino, M.A., 2010. Applying Electrical Resistivity Tomography to the Identification of Endokarstic Geometries in the Pleistocene Sites of the Sierra de Atapuerca (Burgos,Spain). Archaeological Prospection, Published online in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/arp.

Papadopoulos, N. G., Tsourlos, P., Tsokas, G. N. and Sarris, A., 2006. Two-dimensional and three-dimensional Electrical Imaging in Archaeological Site Investigation. Archaeological Prospection 13: 163-181.

Papadopoulos, N. G., Yi, M.-J., Kim, J.-H., Tsourlos, P. and Tsokas, G. N., 2010. Geophysical investigation of tumuli by means of surface 3D Electrical Resistivity Tomography. Journal of Applied Geophysics 70: 192-205.

Pineda, A., 1997. Mapa Geológico de España escala 1:50.000, 2ª Serie (MAGNA). Hoja de Burgos, 200 (19-10). IGME, Madrid, 93 pp.

Piro, S., Mauriello, P. and Cammarano, F., 2000. Quantitative Integration of Geophysical Methods for Archaeological Prospection. Archaeological Prospection 7: 203-213.

Piro, S., Tsourlos, P. and Tsokas, G. N., 2001. Cavity detection employing advanced geophysical techniques: a case study. European Journal of Environmental and Engineering Geophysics 6: 3-31.

Porres, J.A., 2003. Caracterización de cavidades en el subsuelo mediante la interpretación de perfiles de Tomografía Eléctrica: Aplicación al yacimiento arqueológico de Clunia. Phd. Thesis, University of Burgos, Spain. ISBN 978-84-96394-55-1.

Rizzo, E., Colella, A., Lapenna, V., Piscitelli, S., 2004. High-resolution images of the fault-controlled High Agri Valley basin (southern Italy) with deep and shallow electrical resistivity tomographies. Physics and Chemistry of the Earth 29, 321e327.

Terrizzano, C.M., Fazzito, S.Y., Cortés, J.M., Rapalini, A.E., 2012. Electrical resistivity tomography applied to the study of neotectonic structures, northwestern Precordillera Sur, Central Andes of Argentina. Journal of South American Earth Sciences 34, 47e60.

Tsokas, G. N., Tsourlos, P. I., Stampolidis, A., Katsonopoulou, D. and Soter, S. (2009): Tracing a Major Roman Road in the Area of Ancient Helike by Resistivity Tomography. Archaeological Prospection 16: 251-266.

Storz, H., Storz, W., Jacobs, F., 2000. Electrical resistivity tomography to investigate geological structures of the earth's upper crust. Geophysical Prospecting 48, 455e471.

Sumanovac, F.; Weisser, M. 2001. Evaluation of resistivity and seismic methods for hydrogeological mapping in karst terrains. Journal of Applied Geophysics, 47. 13-28

Zhou, W.; Beck, B.F.; Stephenson, J.B., 2000. Reliability of dipole-dipole electrical resistivity tomography for defining depth to bedrock in covered karst terranes. Environmental Geology, 39 (7), 760-766.