Earth-Science Reviews 135 (2014) 65–82

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Electrical resistivity tomography technique for landslide investigation: A review

A. Perrone *, V. Lapenna, S. Piscitelli

Institute of Methodologies for Environmental Analysis, CNR, Italy

ARTICLE INFO

Article history:
Received 18 September 2013
Accepted 8 April 2014
Available online 18 April 2014

Keywords:
Review
Electrical resistivity tomography
2D
3D
Time-lapse
Landslides

ABSTRACT

In the context of in-situ geophysical methods the Electrical Resistivity Tomography (ERT) is widely used for the near-surface exploration of landslide areas characterized by a complex geological setting. Over the last decade the technological improvements in field-data acquisition systems and the development of novel algorithms for tomographic inversion have made this technique more suitable for studying landslide areas, with a particular attention to the rotational, translational and earth-flow slides. This paper aims to present a review of the main results obtained by applying ERT for the investigation of a wide spectrum of landslide phenomena which affected various geological formations and occurred in different geographic areas. In particular, significant and representative results obtained by applying 2D and 3D ERT are analyzed highlighting the advantages and drawbacks of this geophysical technique. Finally, recent applications of the time-lapse ERT (tl-ERT) for landslide investigation and the future scientific challenges to be faced are presented and discussed.

Contents

1. Introduction

Landslides are complex geological phenomena with a high socio-economical impact also in terms of loss of lives and damage. Their investigation usually requires a multidisciplinary approach, based on the integration of satellite, airborne and ground-based sensing technologies. Each technique allows the study of specific triggering factors and/or particular physical features, characterizing the landslide body compared with the material not affected by the movement.

Airborne and satellite methods (i.e. digital aerophotogrammetry, GPS, differential interferometric SAR, etc.) can provide information on the surface characteristics of the investigated slope, such as geomorphological features, the areal extension of the landslide body, superficial displacement and velocity (Catani et al., 2005; Squarzoni et al., 2005; Glenn et al., 2006; Lanari et al., 2007; Baldi et al., 2008; Roering et al., 2009; Cascini et al., 2010; Strozzi et al., 2010; Ventura et al., 2011; Guzzetti et al., 2012), without giving any information on subsoil characteristics.

Direct ground-based techniques (i.e. piezometer, inclinometer, laboratory tests, etc.) give true information on the mechanical and hydraulic characteristics of the terrains affected by the landslide but in a specific point of the subsoil (Petley et al., 2005; Marcato et al., 2012).

* Corresponding author at: CNR-IMAA, c.da S. Loja, 85050 Tito Scalo PZ. Tel.: +39 0971 427282.
E-mail address: angela.perrone@imaa.cnr.it (A. Perrone).

http://dx.doi.org/10.1016/j.earscirev.2014.04.002
0012-8252/

In-situ geophysical techniques are able to measure physical parameters directly or indirectly linked with the lithological, hydrological and geotechnical characteristics of the terrains related to the movement (McCann and Foster, 1990; Hack, 2000; Jongmans and Garambois, 2007). These techniques, less invasive than the previous ones, provide information integrated on a greater volume of the soil thus overcoming the point-scale feature of classic geotechnical measurements. Among the in-situ geophysical techniques, the Electrical Resistivity Tomography (ERT) has been increasingly applied for landslide investigation (McCann and Foster, 1990; Hack, 2000; Jongmans and Garambois, 2007; references in Table 1, 3 and 5). This technique is based on the measure of the electrical resistivity and can provide 2D and 3D images of its distribution in the subsoil.

The frequent use of this method in the study of landslide areas is mainly due to the factors that can affect resistivity and its extreme variability in space and time domains. Indeed, this parameter is mostly influenced by the mineralogy of the particles, the ground water content, the nature of electrolyte, the porosity and the intrinsic matrix resistivity with weathering and alteration (Archie, 1942; Reynolds, 1997; Park and Kim, 2005; Bievre et al., 2012). Some of these factors, especially the change of water content and the consequent increase in pore water pressures, can play an important role in the triggering mechanisms of a landslide (Bishop, 1960; Morgenstern and Price, 1965).

This paper aims at presenting the current state of-the-art on the application of ERT for landslide investigation, mainly considering the technological and methodological improvements of this technique. The work is focused on the scientific papers published in international journals since 2000 and available online. In particular, this study presents the results of field geophysical surveys based on 2D, 3D and time-lapse ERT carried out for the investigation of different typologies of landslide, also considering the acquisition systems and the inversion algorithms. The main advantages and drawbacks related to the application of the ERT method are identified and discussed. Finally, the future challenges for a better use of the ERT in the landslide investigation and monitoring are presented.

2. The ERT method for landslide investigation

The Electrical Resistivity Tomography is an active geophysical method that can provide 2D or 3D images of the distribution of the electrical resistivity in the subsoil. The analysis and interpretation of these electrical images allow the identification of resistivity contrasts that can be mainly due to the lithological nature of the terrains and the water content variation.

The in-field procedure includes the use of a multi-electrode cable, laid out on the ground, to which a number of steel electrodes are connected at a fixed distance according to a specific electrode configuration. The electrodes are used both for the injection of the current (I) in the subsoil and the measurement of the voltage (V). Knowing the I and V values and the geometrical coefficient depending on the electrode configuration used, the apparent resistivity values characterizing the subsoil investigated can be calculated. These values are positioned at pseudo-depths according to a geometrical reconstruction (Edwards, 1977), which results in a pseudo-section representing an approximate picture of the true subsurface resistivity distribution (Hack, 2000).

To obtain an electrical resistivity tomography, the apparent resistivity values must be inverted by using inversion routines. The best known and most applied algorithm is Res2Dinv (Loke and Barker, 1996; Loke et al., 2003) based on a smoothness-constrained least-squares method which allows to obtain two-dimensional sections through finite differences or finite elements computations, taking into account the topographic corrections. To evaluate the fit of the resistivity model obtained, the root mean square error (RMS) can be considered. This error provides the percentage difference between the measured values and those calculated; so, the correspondence between the field data and the ones of the model is higher when the error is lower. Although Res2Dinv is the most widely applied software, many other methods are currently available for the electrical resistivity data inversion (see Section 2.1 and Table 1).

The first applications of ERT in the study of landslides (Gallipoli et al., 2000; Lapenna et al., 2003) involved the use of manual systems characterized by separated energization and measurement devices and single cables. Due to the absence of multi-core cables, the operators used four separate insulated cables connected to four metal electrodes, two of steel for the injection of current and the other two non-polarizable for the measurement of the voltage. The use of manual equipment resulted in rather slow data acquisition; moreover, the possibility or the necessity to keep the energization and the measurement systems separate mainly favored the use of dipole–dipole configuration which is more suitable for the investigation of vertical boundaries (landslide lateral boundaries, source area, fault) than for the identification of the horizontal ones (sliding surface, lithological contact).

Technological improvements, which produced more compact and portable equipments and faster acquisition systems, as well as the development of novel software for data processing and the creation of 2D and 3D tomographic images of the resistivity distribution in the subsoil have greatly increased the applicability of this technique for the study of landslide areas.

Over the last 15 years the number of systems for the resistivity imaging survey has considerably grown. Two categories of systems are now available, the static and the dynamic. In the static one many electrodes are connected to a multi-electrode cable and planted into the ground during the survey. The dynamic systems use a small number of nodes but move the entire equipment to obtain a wide coverage (Loke, 2013). The static systems are usually used for the investigation of landslides. In particular, the introduction of static multi-electrode systems (Barker, 1981; Griffiths and Turnbull, 1985; Griffiths et al., 1990; Li and Oldenburg., 1992; Dahlin, 1993, 1996; Dahlin and Bernstone, 1997; Stummer, 2002), mainly using single channel data acquisition, has greatly reduced the acquisition time and also improved some logistic aspects. These systems allow the use of a large number of electrodes with an increase in the profile length and the automatic change of spatial resolution and investigation depth. They have made it easier to carry out 2D ERT on landslides and obtain a 3D geoelectrical model of the subsoil, particularly where the logistic conditions are advantageous (small-sized landslides and slightly steep slopes).

The development of algorithms for the inversion of apparent resistivity data (Dey and Morrison, 1979; Barker, 1992; Oldenburg et al., 1993; Oldenburg and Li, 1994; Tsourlos, 1995; LaBrecque et al., 1996; Loke and Barker, 1996; Dahlin, 2001 and reference therein; Loke et al., 2003) made it easier to analyze the data and generate 2D and 3D images useful for the characterization of the slope investigated so as to obtain information on the geometry of a landslide body (i.e. the slide material thickness, the location of areas characterized by a higher water content, the presence of potentially unstable areas, etc.). From a temporal point of view, the information obtained can be considered static being related only to the day of acquisition. Resistivity data are usually acquired after the occurrence of an event and give an image of that moment, without providing any indications on the dynamic evolution affecting the slope investigated. Very recently, the development of static multi-channel measuring systems, able to simultaneously acquire a number of potential measurements for a single pair of current electrodes, have significantly reduced the acquisition time. These systems can be set up to provide ERT at specific times during the day, and they can also repeat the measurement in order to give ERT images at very close time intervals called time-lapse ERT (tl-ERT). This is extremely important as it allows the exploitation of ERT not only to define the geometrical characteristics of the landslide body or the slope investigated but also to monitor a potentially unstable area. The literature reports some examples of tl-ERT applications in landslide areas with the main aim to obtain information on the water content change (see Section 2.3). Obviously, although some software for the processing of data continuously acquired has already been developed, there is still a need to improve this aspect and especially to quantify the relationship between the variations of the electrical resistivity as a function of changes in hydrological parameters.

2.1. The 2D ERT imaging

Since 2000 a lot of papers dealing with the application of 2D ERT for landslide investigation have been published. For each paper Table 1 specifies the year of publication, the name of the authors and the journal, the typology of landslide investigated, the lithological nature of the material involved in the movement and the country affected by the event.

The majority of the case histories considered (73%) are located in Europe, a lower percentage (24%) in Asia and a very low percentage (3%) in America (Fig. 1). No example has been found for Oceania, while only few examples of the Vertical Electrical Sounding (VES) application for the investigation of unstable areas (Ayenew and Barbieri, 2005; Epada et al., 2012) are available for Africa.

The 65 papers analyzed deal with different landslide typologies. Two of the papers are reviews (Hack, 2000; Jongmans and Garambois, 2007) and other three do not include information on the type of landslide (Otto and Sass, 2006; Yilmaz, 2007; Mondal et al., 2008), therefore, only 60 papers have been considered for the classification of the phenomenon typology.

In particular, as also shown in Table 2, twelve (20%) papers concern complex landslides (slides evolving in earth-flow; or retrogressive landslides, etc.) (Gallipoli et al., 2000; Lapenna et al., 2003; Bichler et al., 2004; Perrone et al., 2004; Lapenna et al., 2005; Park and Kim, 2005; Colangelo et al., 2008; Naudet et al., 2008; Panek et al., 2008; Sass et al., 2008; Jongmans et al., 2009; Ogusnsuyi, 2010), nineteen (32%) study translational or rotational slides (Godio and Bottino, 2001; Meric et al., 2005; Drahor et al., 2006; Friedel et al., 2006; Perrone et al., 2006; Göktürkler et al., 2008; Lee et al., 2008; Marescot et al., 2008; Schrott and Sass, 2008; Erginal et al., 2009; Bekler et al., 2011; de Bari et al., 2011; Grandjean et al., 2011; Le Roux et al., 2011; Bièvre et al., 2012; Hibert et al., 2012; Ravindran and Ramanujam, 2012; Sastry and Mondal, 2013; Shan et al., 2013), six (10%) analyze rockfalls and rockslides (Batayneh et al., 2002; Godio et al., 2006; Ganerød et al., 2008; Heincke et al., 2010; Socco et al., 2010; Oppikofer et al., 2011), eight (13%) investigate deep seated landslides (Lebourg et al., 2005; Jomard et al., 2007a, b; Van Den Eeckhaut et al., 2007; Jomard et al., 2010; Migoń et al., 2010; Tric et al., 2010; Zerathe and Lebourg, 2012), twelve (20%) consider debris, earth flows or shallow landslides (Havenith et al., 2000; Jongmans et al., 2000; Demoulin et al., 2003; Grandjean et al., 2006; Perrone et al., 2008; Piegari et al., 2009; Schmutz et al., 2009; Chambers et al., 2011; Carpentier et al., 2012; Chang et al., 2012; Mainsant et al., 2012; Ravindran and Prabhu, 2012), and three (5%) focus on quick clay slides (Lundstrom et al., 2009; Donohue et al., 2012; Solberg et al., 2012). No examples of topples and lateral spread have been found.

To define the resistive characteristics of the material involved in the landslides, 63 papers, excluding the reviews, have been analyzed. In particular, in 41 case studies (65%) the slide material is conductive, in 14 case studies (22%) it is resistive and in the remaining 8 (13%) it is not well defined (Table 2). This percentage distribution is mainly due both to the clayey and flyschoid nature of the material involved in the landslides and the high content of water that usually characterize landslide areas.

Table 1 also reports the information related to the acquisition systems, the electrode configuration and inversion software used by each team of authors. As for the acquisition systems, the different models of the IRIS-Instruments (http://www.iris-instruments.com) are found to be the most widely used among the available commercial tools, in addition to: i) ABEM Lund Imaging System (http://www.abem.se), ii) GeoTomo of Geolog (http://www.geolog2000.de), iii) AGI-SuperSting (http://www.agiusa.com), iv) OYO McOHM Profiler-4 System (http://www.oyo.co.jp/english.html), v) Campus Tigre (http://www.allied-associates.co.uk/files/index.html), vi) Multi Function Digital DC Resistivity IP/Meter (http://www.tradeindia.com/fp745352/Multi-Funciton-Digital-DC-Resistivity-IP-Meter.html). They are static acquisition systems usually working by using a multi-electrode cable and measuring a voltage only on a single pair of electrodes.

As regards the arrays, dipole–dipole (DD) is the most used electrode configuration, followed by Wenner (W) and Wenner–Schlumberger (WS); only few examples using pole–pole (PP), pole–dipole (PD), multi-gradient (MG) and Wenner-alpha (W-α) electrode configuration can be found. In most cases, the authors use PP and PD array to study complex deep seated landslides (Lebourg et al., 2005; Jomard et al., 2007a,b, 2010; Tric et al., 2010; Zerathe and Lebourg, 2012) so as to reach deeper investigation depths.

In order to highlight vertical structures some authors prefer to use the DD configuration (Godio and Bottino, 2001; Lebourg et al., 2005; Godio et al., 2006; Perrone et al., 2006; Colangelo et al., 2008; Naudet et al., 2008; Perrone et al., 2008) also in combination with other configurations to study deep and complex landslides (Lebourg et al., 2005; Jomard et al., 2007a, 2010; Tric et al., 2010). The W and WS arrays are used to characterize horizontal discontinuities (Colangelo et al., 2008; Perrone et al., 2008; de Bari et al., 2011) and, in the last examples (since 2012), especially to investigate shallow and non-complex landslides.

Sometimes, different array configurations are used to measure resistivity data along the same profile in order to compare the resistivity images obtained and overcome the intrinsic limitations of each configuration (Godio and Bottino, 2001; Lebourg et al., 2005; Friedel et al., 2006; Godio et al., 2006; Perrone et al., 2006; Jomard et al., 2007a; Van Den Eeckhaut et al., 2007; Colangelo et al., 2008; Ganerod et al., 2008; Naudet et al., 2008; Perrone et al., 2008; Heincke et al., 2010; Jomard et al., 2010; Tric et al., 2010; de Bari et al., 2011; Grandjean et al., 2011). The resistivity distribution obtained with the different configurations is often proved to be comparable and the one showing the lowest RMS is generally reported (Van Den Eeckhaut et al., 2007). Friedel et al. (2006) show a quantitative comparison between the results obtained using W, WS and DD configurations along the same profile. The authors point out the difference of resolution and sensitivity of each single array. All the models obtained have the same basic features, which indicates a high data quality and a stable inversion procedure. The authors conclude that in their specific case study, the best compromise between resolution and measurement time is represented by the joint inversion of WS + DD data set.

Generally, to invert the data the authors mainly apply the RES2Dinv algorithm proposed by Loke and Barker (1996). For the same aim, Park and Kim (2005) use the DIPRO algorithm (Hee Song Geotek, 2002), Meric et al. (2005) the DCIP2D (UBC-GIF2001), based on subspace methods (Oldenburg et al., 1993); Yilmaz (2007) the IP2DI (Wannamaker, 1992); Gokturkler et al. (2008) the DC2DInvRes (Günther, 2007); Heincke et al. (2010) the BERT algorithm (Günther et al., 2006) and Chang et al. (2012) the Earth Imager ™ 2D (AGI, 2009).

The main information obtained by applying the 2D ERT technique helped the authors to define the geological setting of the investigated subsoil, to reconstruct the geometry of landslide body, to estimate the thickness of sliding material, to locate the possible sliding surface and lateral boundaries of the landslide, to characterize fractures or tectonic elements that could bring about an event, etc. (Fig. 2). In some cases, ERT was also applied with the aim to evaluate the groundwater conditions, to locate areas with a high water content, to verify the network of water drainage, to study the groundwater circulation and storage within an unstable area (Perrone et al., 2004; Lapenna et al., 2005; Grandjean et al., 2006; Jomard et al., 2007a, b; Yilmaz, 2007; Colangelo et al., 2008; Gokturkler et al., 2008; Marescot et al., 2008; Heickne et al., 2010; McClymont et al., 2010; Langston et al., 2011).

In many of the case studies reported, ERT are compared with other geophysical methods, such as seismics and Ground Penetrating Radar

Table 1
Scientific papers related to the application of 2D ERT for landslide investigation, published on international journal since 2000 or available online. All the information about the kind of landslide, the lithological nature of material involved in the movement, the technical information on the equipments used to carry out electrical resistivity measurements and software applied for data inversion and the comparison with direct data or other indirect geophysical data, are also reported. Legend: *n.a.i.* = not available information; M = Manual; A = Automatic; A-Mu = Automatic and multi-electrode; SA = Semi-automatic; DD = Dipole–dipole; W = Wenner; W(α) = Wenner-alpha; PP = Pole–pole; S = Schlumberger; WS = Wenner–Schlumberger; PD = Pole–Dipole; MG = Multi-gradient.

Publication year	Authors	Journal	Landslide typology	Geological context	Country	Acquisition system	Instrument	Electrode configuration	Inversion algorithm	Direct data	Other geophysical data
2000	Gallipoli, M.R., Lapenna, V., Lorenzo, P., Mucciarelli, M., Perrone, A., Piscitelli, S., Sdao, F.	Europ. J. of Envir. and Eng. Geophys.	Trans-rotational earthflow slide	Intensively tectonized, fissured clay shales, clay and mudstones	Italy	M	Syscal Junior	DD	RES2Dinv	Stratigraphical data	Seismic noise measurements
	Hack, R.	Survey in Geophysics	Review	Review	Review	Review	Review	Review	Review	Review	Review
	Havenith, H.-B., Jongmans, D., Abdrakhmatov, K., Trefois, P.,Delvaux, D., Torgoev, I.A.	Surveys in Geophysics	Debris slide	Arenite and clay	Kyrgyzstan	A-Mu	ABEM Lund Imaging System	W	RES2Dinv	n.a.i	Seismic refraction profiles
	Jongmans, D., Hemroulle, P., Demanet, D., Renardy, F., Vanbrabant, Y.	Europ. J. of Envir. and Eng. Geophys.	Shallow instantaneous landslide	Carboniferous shale and coal debris	Belgium	A-Mu	ABEM Lund Imaging System	W	RES2Dinv	n.a.i	Seismic refraction soundings
2001	Godio, A., Bottino, G.	Phys. Chem. Earth	Slide	Terrigenous deposits and stiff marl sequences	Italy	A	Sting-AGI	DD-W	RES2Dinv	Stratigraphical data	Vertical electrical sounding (VES) and electromagnetic soundings (TDEM)
2002	Batayneh, A.T., Abdullah, A., Al-Diabat, A.	Environmental Geology	Rock slide	Shale, marl and marly limestone	Jordan	A-Mu	Syscal R2	W	RES2Dinv	n.a.i.	n.a.i.
2003	Demoulin, A., Pissart, A., Schroeder, C.	Int. J. Earth Sci.	Multiple earth slide	Clay and sand	Belgium	n.a.i.	n.a.i.	n.a.i.	n.a.i.	Trenches - 14C dating - Borehole data - Cone penetration tests	Sesimic refraction profiles
	Lapenna, V., Lorenzo. P., Perrone, A., Piscitelli, S., Sdao, F., Rizzo, E.	Bull. of Eng. Geol. and the Envir.	Trans-rotational earthflow slide	Intensively tectonized, fissured clay shales, clay and mudstones	Italy	M	Syscal Junior	DD	RES2Dinv	Stratigraphical data	Self potential map and tomography
2004	Bichler, A., Bobrowsky, P., Best, M., Douma, M., Hunter, J., Calvert, T., Burns, R.	Landslides	Retrogr., dry earth slide – debris flow	Sand to clay sediments	Canada	A-Mu	Syscal R1-Plus Switch 48 DC	W	RES2Dinv	Stratigraphical data	Ground penetrating radar (GPR), seismic reflection and refraction profiles
	Perrone, A., Iannuzzi, A., Lapenna, V., Lorenzo, P., Piscitelli, S., Rizzo, E., Sdao, F.	J. of App. Geophys.	Roto-translational and earthflow	Structurally complex clayey-marly terrains	Italy	A-Mu	Syscal R2	DD	RES2Dinv	Stratigraphical data	Self potential map and tomography
2005	Lapenna, V., Lorenzo, P., Perrone,A., Piscitelli, S., Rizzo, E., Sdao,F.	Geophysics	Trans-rotational earthflow slides	Sedimentary rocks	Italy	A-Mu	Syscal R2	DD	RES2Dinv	Stratigraphical data	Self potential survey
	Lebourg, T., Binet, S., Tric, E., Jomard, H., El Bedoui, S.	Terra Nova	Complex deep seated landslide	Basement rocks composed mainly of migmatitic gneiss	France	A-Mu	Syscal R1 Plus	DD - PP	RES2Dinv	Hydrogeological data	n.a.i.
	Meric, O., Garambois, S., Jongmans, D., Wathelet, M., Chatelain, J.L., Vengeon, J.M.	Can. Geotech. J.	Large gravitational mass movement	Mica schists with interbedded quartz-feldspar-rich layers	France	n.a.i.	n.a.i.	n.a.i.	RES2Dinv and DCIP2D (UBC-GIF2001)	n.a.i.	Electromagnetic profiles, sesimic tomography, self potential survey, seismic noise measuremts
	Park, S-G., Kim, J-H.	Geosystem Engineering	Complex landslide	Sedimentary soft rocks (mudstone and sandstone)	Japan	n.a.i.	n.a.i.	DD	DIPRO algorithm	Stratigraphical data	n.a.i.
2006	Drahor, M.G., Gokturkler, G., Berge, M.A., Kurtulmus, T.O.	Environm. Geology	Slide	Sandstone, siltstone and mudstone	Turkey	A-Mu	n.a.i.	W	RES2Dinv	Stratigraphical data	n.a.i.
	Friedel, S., Thielen, A., Springman, S.M.	J. of App. Geophys.	Slide	Sedimentary rocks (sandstones)	Switzerland	A-Mu	Geotom of Geolog	W-S-DD	RES2Dinv and RES3Dinv	Stratigraphical data, penetration tests (DPT) and laboratory analysis	n.a.i.
	Godio, A., Strobbia, C., De Bacco, G.	Engineering Geology	Rockslide	Metamorphic rocks	Italy	A-Mu	n.a.i.	WS-DD	No information available	Stratigraphical and inclinometric data	Seismic refraction tomography and spectral analysis of surface waves (SWM)
		C. R. Geoscience	Earth-flow	Balck marls	France	A-Mu	n.a.i.	n.a.i.	RES2Dinv		Seismic profiles

	Grandjean, G., Pennetier, C., Bitri, A., Meric, O., Malet, J.-P.									No information available	
	Otto, J.C., Sass, O.	Geomorphology	n.a.i.	Talus cones, moraine ridges and rock glaciers	Switzerland	A-Mu	ABEM Lund Imaging System	W	RES2Dinv	n.a.i.	Ground Penatrating Radar (GPR) and Seismic refraction survey
	Perrone, A., Zeni, G., Piscitelli, S., Pepe, A., Loperte, A., Lapenna, V., Lanari, R.	Engineering Geology	Translational slide	Terrigenous deposits and calcareous member	Italy	A-Mu	Syscal R2	DD-WS	RES2Dinv	Stratigrapghical data	n.a.i.
2007	Jomard, H., Lebourg, T., Tric, E.	J. of App. Geophys.	Complex deep seated landslide	Basement rocks composed mainly of migmatitic gneiss	France	A-Mu	Syscal	PP-DD	RES2Dinv	n.a.i.	Seismic measurements
	Jomard, H., Lebourg, T., Binet, S., Tric, E., Hernandez, M.	Terra Nova	Complex deep seated landslide	Basement rocks composed mainly of migmatitic gneiss	France	A-Mu	Syscal R1 Plus	PD	RES2Dinv	Hydrogeological data	n.a.i.
	Jongmans, D., Garambois, S.	Bull. Soc. Géol. Fr.	Review	Review	Review	n.a.	Review	Review	Review	Review	Review
	Van Den Eeckhaut, M., Verstraeten, G., Poesen, J.	Geomorphology	Deep seated landslide	Clayey sand/silt	Belgium	A-Mu	n.a.i.	W-WS	RES2Dinv	AMS radiocarbon dating	n.a.i.
	Yilmaz, S.	J. of Envir. and Engin. Geophys.	n.a.i.	volcanic and sedimentary (clayey and marls) sequences	Turkey	A-Mu	SAS 1000 - ABEM	DD	IP2DI	n.a.i.	n.a.i.
2008	Colangelo, G., Lapenna, V., Loperte, A., Perrone, A., Telesca, L.	Annals of Geophysics	Roto-translational slides – earthflow	Clay and mudstones	Italy	A-Mu	Syscal R2	DD-WS	RES2Dinv	n.a.i.	n.a.i.
	Ganerød, G.V., Grøneng, G., Rønning, J.S., Dalsegg, E., Elvebakk, H., Tønnesen, J.F., Kveldsvik, V., Eiken, T., Blikra, L.H., Braathen, A.	Engineering Geology	Rockslide	Gneisses with lenses of mafic material	Norway	A-Mu	ABEM Lund Imaging System	W-DD	RES2Dinv	Drill cores and borehole	Ground Penetrating Radar and refraction seismic
	Göktürkler, G., Balkaya, C., Erhan, Z.	J. of App. Geophys.	Slide	Quaternary alluvium and sedimentary rocks consisting of marl, limestone,conglomerate and flysch formations	Turkey	SA	n.a.i.	WS	DC2InvRes	n.a.i.	Seismic refraction tomography
	Lee, C-C., Yang, C-H., Liu, H-C., Wen, K-L., Wang, Z-B., Chen, Y-J.	Engineering Geology	Slide	Slate of Miocene Lushan Formation	Taiwan	A-Mu	Sting R1/IP	PP	RES2Dinv	Stratigraphical, piezometers, inclinometers and tiltmeters data	n.a.i.
	Marescot, L., Monnet, R., Chapellier, D.	Engineering Geology	Translational slide	Gray schistes (with graphite) and quartzitic sandstones	Switzerland	A-Mu	Syscal R1	WS	RES2Dinv	n.a.i.	Induced polarization tomography
	Mondal, S.K., Sastry, R.G., Pachauri, A.K., Gautam, P.K.	Current Science	n.a.i.	Gray chlorite mica schist	India	A-Mu	Syscal Junior	WS	RES2Dinv	n.a.i.	n.a.i.
	Naudet, V., Lazzari, M., Perrone, A., Loperte, A., Piscitelli, S., Lapenna, V.	Engineering Geology	Complex landslide (rotational and mudflow)	Clayey–marly–arenaceous deposits and marly limestones	Italy	A-Mu	Syscal R2	DD-WS	RES2Dinv	Stratigraphical data	Self potential survey
	Panek, T., Hradecky, J., Šilhan, K.	Studia Geomor. Carpatho-Balcanica	Different slope deformations	Anisotropic bedrock of the Flysch Carpathains	Czech Republic	A-Mu	n.a.i.	S	RES2Dinv	n.a.i.	n.a.i.
	Perrone, A., Vassallo, R., Lapenna, V., Di Maio, C.	J. Geophys. Eng.	Superficial ground deformation	Clayey silty material	Italy	A-Mu	Syscal R2	DD-WS	RES2Dinv	Stratigraphical, inclinometric and piezometric data	n.a.i.
	Sass, O., Bell, R., Glade, T.	Geomorphology	Complex landslide	Jurassic sedimentary rocks involving clays, marls and limestones	Germany	A-Mu	GeoTom Unit (GeoLog2000)	W	RES2Dinv	Stratigraphical and inclinometric data, penetration tests	Ground penetrating radar (GPR)
	Schrott, L., Sass, O.	Geomorphology	Rotational slide	Flysch and Ultrahelvetikum rock series (sandstone and claystone)	Germany	A-Mu	GeoTom Unit (GeoLog2000)	n.a.i.	RES2Dinv	n.a.i.	n.a.i.
2009	Erginal, A.E., Ozturk, B., Ekinci, Y.L:, Demirci, A.	Environ. Geol.	Rotational slide	Claystone and mudstone with brown reddish color	Turkey	A-Mu	Syscal R1 Plus	WS	RES2Dinv	Geochemical data	n.a.i.
	Jongmans, D., Bièvre, G., Renalier, F., Schwartz, S., Beaurez, N., Orengo, Y.	Engineering Geology	Complex deformation process	Saturated laminated clays	France	A-Mu	n.a.i.	W	RES2Dinv	Stratigraphical, inclinometric and piezometric data	Seismic refraction profiles, seismic noise measurements, surface wave inversion
	Lundstrom, K., Larsson, R., Dahlin, T.	Landslides	Quick clay slide	Quick clay	Sweden	A-Mu	ABEM- Lund System	MG	RES2Dinv	Geotechnical soundings	n.a.i.
				Pyroclastic covers	Italy	A-Mu	Syscal Pro	n.a.i.	RES2Dinv	Geochemical data	n.a.i.

(continued on next page)

Table 1 (*continued*)

Publication year	Authors	Journal	Landslide typology	Geological context	Country	Acquisition system	Instrument	Electrode configuration	Inversion algorithm	Direct data	Other geophysical data
	Piegari, E., Cataudella, V., Di Maio, R., Milano, L., Nicodemi, M., Soldovieri, M.G.	J. of App. Geophys.	Shallow landslide								
	Schmutz, M., Guérin, R., Andrieux, P., Maquaire, O.	J. of App. Geophys.	Earthflow	Black marls	France	A-Mu	n.a.i.	PP	n.a.i.	Drill holes, penetometer and pressiometer geotechnical tests	TDEM survey
2010	Heincke, B., Günther, T., Dalsegg, E., Rønning, J.S., Ganerød, G.V., Elvebakk, H.	J. of App. Geophys.	Rockslide	Gneissic rocks	Norway	A-Mu	ABEM Terrameter SAS400	W-DD	BERT algorithm	Stratigraphical data	Seismic tomography
	Jomard, H., Lebourg, T., Guglielmi, Y., Tric, E.	Earth Surf. Process. and Landforms	Complex deep seated landslide	Basement rocks composed mainly of migmatitic gneiss	France	A-Mu	Syscal R1 Plus	PP-DD	RES2Dinv	n.a.i.	n.a.i.
	Migoń, P., Pánek, T., Malik, I., Hrádecký, J., Owczarek, P., Šilhán, K.	Geomorphology	Complex deep seated landslide	Volcanic and sedimentary rocks	Poland	A-Mu	ARES System	WS	RES2Dinv	n.a.i.	n.a.i.
	Ogunsuyi, O.	M.S. Thesis, University of Alberta	Retrogressive translational earth slide	Overconsolidated glaciolacustrine sediments	Canada	A-Mu	ABEM Terrameter SAS1000 and ABEM Lund	W	RES2Dinv	n.a.i.	Sesimic reflection and refraction
	Socco, L. V., Jongmans, D., Boiero, D., Stocco, S., Maraschini, M., Tokeshi, K., Hantz, D.	J. of App. Geophys.	Rock avalanches	Gray limestone layers interbedded with withe and green calcareous marl layers	Switzerland	A-Mu	Syscal Junior	WS	RES2Dinv	n.a.i.	P-wave tomography, active and passive surface wave
	Tric, E., Lebourg, T., Jomard, H., Le Cossec, J.	J. of App. Geophys.	Complex deep seated landslide	Basement rocks composed mainly of migmatitic gneiss	France	A-Mu	Syscal R1 Plus	PP-DD	RES2Dinv	n.a.i.	n.a.i.
2011	Bekler, T., Ekinci, Y.L., Demirci, A., Erginal, A.E., Ertekin, C.	J. of Envir. and Engin. Geophys.	Rotational slide	sequence of sandstone, coarse-grained sandstone and siltstone, mudstone, marn and shelly limestone	Turkey	A-Mu	Syscal R1 Plus	WS	RES2Dinv	Samples for hydrometer analysis	Seismic refraction
	Chambers, J.E., Wilkinson, P.B., Kuras, O., Ford, J.R., Gunn, D.A., Meldrum, P.I., Pennington, C.V.L., Weller, A.L., Hobbs, P.R.N., Ogilvy, R.D.	Geomorphology	Slow moving earth slide–earth flow	Lower Jurassic Lias Group rocks	United Kingdom	A-Mu	AGI SuperSting R8 IP System	DD	RES2Dinv	Boreholes and auger holes	Self potential survey
	de Bari, C., Lapenna, V., Perrone, A., Puglisi, C., Sdao, F.	Geomorphology	Roto-translational slide	Corleto Perticara, Red Flysch and Galestrino Flysch formations	Italy	A-Mu	Syscal R2 and Syscal Pro	DD-WS	RES2Dinv	Stratigraphical data	n.a.i.
	Grandjean, G., Gourry, J.C., Sanchez, O., Bitri, A., Garambois, S.	J. of App. Geophys.	Slide	Quartzitic and gypseous	France	A-Mu	Syscal PRO	MG-PD	RES2Dinv	Inclinometric data	Electromagnetic map, seismic tomography, spatial analysis of surface waves, H/V

	Le Roux, O., Jongmans, D., Kasperski, J., Schwartz, S., Potherat, P., Lebrouc, V., Lagabrielle, R., Meric, O.	Eng. Geology	Large landslide	Complex of different metamorphic rocks	France	A-Mu	n.a.i.	WS	RES2Dinv	Gallery and borehole data	Seismic profiles
	Oppikofer, T., Jaboyedoff, M., Pedrazzini, A., Derron, M-H., Blikra, L.H.	J. of Geophys. Res.	Rockslide	Gneisses with lenses of mafic material	Norway	n.a.i.	n.a.i.	n.a.i.	n.a.i.	stratigraphical data	n.a.i.
2012	Bievre, G., Jongmans, D., Winiarski, T., Zumbo, V.	Hydrological Processes	Slide	Clay materials	France	A-Mu	n.a.i.	W	RES2Dinv	Stratigraphical and hydrogeological data	S-wave refraction tomography, seismic down-hole tests
	Carpentier, S., Konz, M., Fischer, R., Anagnostopoulos, G., Meusburger, K., Schoeck, K.,	J. of App. Geophys.	Shallow landslide	Permian Schist and Jurassic calcareous shales	Switzerland	A-Mu	Syscal Kid	n.a.i.	RES2Dinv	n.a.i.	Ground Penetrating Radar
	Chang, P.-Y., Chen, C.-c., Chang, S.-K., Wang, T.-B., Wang, C.-Y., Hsu, S.-K.	Geophys. J. Intern.	Debris flow	Thick shale with thin sandstone lens	Taiwan	A-Mu	OYO McOHM Profiler-4 system	PP	EarthImagerTM 2-D	n.a.i.	Seismic refraction survey
	Donohue, S., Long, M., O'Connor, P., Helle T.E., Pfaffhuber, A.A., Romoen, M.	Near Surface Geophysics	Quick clay slide	Quick clay	Norway	A-Mu	Campus Tigre	W(a)	RES2Dinv	Straigraphical data	Sesimic refaction, MASW and EM
	Hibert, C., Grandjean, G., Bitri, A., Travelletti, J., Malet, J.-P.	Eng. Geology	Slide	Clay material	France	n.a.i.	n.a.i.	WS	RES2Dinv	n.a.i.	Seismic P-wave tomogrpahy, spectral analysis of surface wave (SASW)
	Mainsant, G., Larose, E., Brönnimann, C., Jongmans, D., Michoud, C., Jaboyedoff, M.	J. of Geophys. Res.	Earthslide-earthflow	Moraine material and clayey material	Switzerland	A-Mu	n.a.i.	WS	RES2Dinv	Piezometer and inclinometer data	Seismic profiles and seismic ambient noise measurements
	Ravindran, A. A., Prabhu, H.M.A.K.	ARPN J. of Earth Science	Creep, flow and slump	Archean metamorphic rocks including charnockite, biotite gneiss, laterite and lithomorgic clay.	India	A-Mu	Multi Function Digital DC Resistivity IP/ Meter	W	RES2Dinv	n.a.i.	n.a.i.
	Ravindran, A.A., Ramanujam, N.	Int. J. of Physic. Sciences	Soil slides	Archean metamorphic rocks including charnockite, biotite gneiss, laterite and lithomorgic clay.	India	A-Mu	n.a.i.	W	RES2Dinv	n.a.i.	Seismic refraction
	Solberg, I.-L., Hansen, L., Ronning, J.S., Haugen, E.D., Dalsegg, E., Tonnesen, J.F.	Bull. Eng. Geol. Environ.	Quick clay slide	Quick clay	Norway	A-Mu	ABEM Terrameter SAS400	MG-W(a)	RES2Dinv	Geotechnical soundings	Sesimic refraction
	Zerathe, S., Lebourg, T.	Geomorphology	Deep seated landslide	Triassic layers of mudstone with gypsum overlain by highly faulted Jurassic limestone	France	A-Mu	Syscal PRO	PP	RES2Dinv	n.a.i.	n.a.i.
2013	Sastry, R.G., Mondal, S.K.	Survey in Geophysics	Slide	Quartzite, phyllite, schists, gneisses, and metavolcanics of various genres	India	A-Mu	SYSCAL Jr Switch—72	WS	RES2Dinv	n.a.i.	IP and gravimetric measurements
	Shan, W., Hu, Z., Jiang, H., Guo, Y., Wang, C.	Progr. of Geo-Disas. Mitig. Techn. in Asia	Translational slide	Silty clay	China	A-Mu	n.a.i.	W	RES2Dinv	Stratigraphical data	n.a.i.

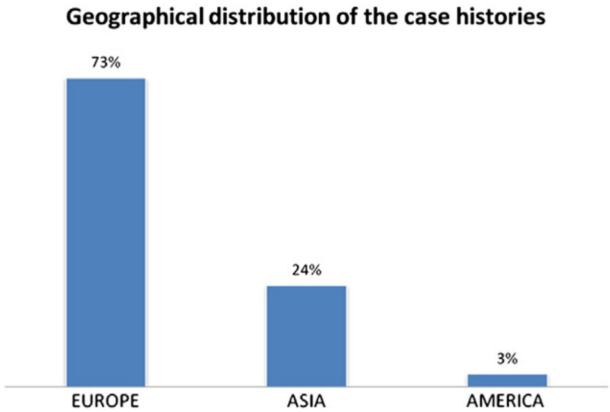

Fig. 1. Geographical distribution of the case histories considered for the review. The graph shows that most of the examples considered are related to landslides located in Europe.

GPR, or stratigraphical and hydrological data (Table 1 last 2 columns) in order to validate and calibrate the resistivity results.

Among the geophysical methods, the ERT and seismic tomography combination proves to be the most successful (Fig. 3). The joint application of GPR, ERT and seismic tomography seems to solve and overcome the resolution problems of each single method. Indeed, the GPR provides more useful information on the shallowest layers (Sass et al., 2008), ERT on the intermediate layers and the seismic on the deepest ones (Bichler et al., 2004). If the investigated material is very wet, the seismic method can work better than ERT, providing information on the displacement material (Jongmans et al., 2009; Le Roux et al., 2011). Literature reports very few examples of ERT combined with Induced Polarization (IP) used for the discrimination of clayey material from the matrix or for a better interpretation of ERT (Marescot et al., 2008; Sastry et al., 2013).

2.2. The 3D ERT imaging

Landslides are volumetric targets and their reconstruction and characterization should be carried out by means of 3D imaging and visualization procedures. Although the introduction of multi-electrode and multi-channel systems has strongly increased the speed of data acquisition, literature reports only very few cases of 3D ERT application in landslide areas (Table 3).

Very often, logistic conditions in these areas are not so conducive giving rise to problems in transporting and installing the instruments and equipment. The planning and the carrying out of a 3D geoelectrical campaign on landslides can be very tiring, exhausting and costly. Indeed, the slide material is usually strongly reworked, and, although the measurement equipment is now very compact and easy to carry, it still remains extremely difficult to be moved on the slope. Depending on the type of landslide and material involved, the slope can be very steep making it very difficult to install the cable network necessary to perform a 3D survey. Generally, landslides can present a large superficial extension and, therefore, a very long multi-core cable could be necessary to cover the entire area investigated. A possible solution could be to use more instruments connected to each other and many multi-core cables. This would probably reduce the efficiency of the method and increase the electrical power required by the system.

Table 2
Percentage distribution of landslide typologies studied by applying 2D ERT and of resistivity values related to the material involved in these landslides.

Landslide typology	%	Resistivity values	%
Slides	32	Conductive	65
Debris and earth flows	20	Resistive	22
Complex landslides	20	Mixed	13
Deep seated landslides	13		
Rock slides	10		
Quick clay slides	5		

Despite all these problems, some authors have tried to perform a 3D investigation of a landslide (Bichler et al., 2004; Lebourg et al., 2005; Drahor et al., 2006; Friedel et al., 2006; Yilmaz, 2007; Chambers et al., 2009; Heincke et al., 2010; Chambers et al., 2011; Grandjean et al., 2011; Di Maio and Piegari, 2011; Udphuay et al., 2011; Di Maio and Piegari, 2012). In all the cases reported, the acquisition has been carried out in a 2D way along parallel profiles whose direction is generally transversal to the dip of the slope and, sometimes, additional perpendicular profiles are also used.

The acquisition systems of the IRIS-Instruments (http://www.iris-instruments.com) and the DD electrode configuration prove to be the most used also for the 3D applications. In one case, the authors apply a system (ALERT system of the British Geological Survey) that they themselves designed. Only few authors carry out a 3D inversion of the acquired data by applying some dedicated software (Fig. 4), the others have used the 2D profiles in a graphical way to get a 3D fence diagram (Bichler et al., 2004; Drahor et al., 2006; Grandjean et al., 2011) (Fig. 5).

As reported in Table 4, the slides (63%) are the most studied type of landslide and, as in the case of 2D ERT applications, the material involved in the movement is essentially conductive (67%).

The information obtained through 3D ERT, very similar to that obtained for the 2D ERT applications, allowed the definition of a 3D geoelectrical model useful for the reconstruction of the subsoil geological setting and the identification of areas characterized by a high water content.

2.3. The time-lapse ERT monitoring

Despite the ERT technological and methodological development over the past 15 years, 2D and 3D ERT surveys have provided only static information. Generally, these investigations have been carried out after the occurrence of an event or in old landslide areas potentially subject to new activations. The information gathered is always related to the acquisition time without providing any indications on the possible evolution of physical parameters in the slope investigated. Considering the influence that the water content change could have on the electrical resistivity and taking into account the role played by the water content in the triggering of some landslides, a continuous monitoring of the resistivity could give information on the dynamic behavior of the slope investigated. This has led to the use of a new acquisition procedure known as time-lapse ERT (tl-ERT). These are usually acquire through multi-channel systems which allow the simultaneous potential measurement on many channels by means of a single pair of current electrodes. The Syscal PRO of IRIS Instruments proves to be the most popular. Systems like the GEOMON^{4D} (Supper et al., 2008), ALERT (Kuras et al., 2009; Wilkinson et al., 2010) and A-ERT (Hilbich et al., 2011) have also been developed in order to obtain tl-ERT. These systems can use local power generated by wind, solar and fuel cell technology, and can incorporate telemetric control and data transfer (Loke et al., 2013).

To accommodate time-lapse resistivity in inverse models, different approaches such as the ratio method, the cascaded time-lapse inversion, the difference inversion and the differencing in dependent inversions have been proposed (Hayley et al., 2011; Loke et al., 2014). In the most common, the measured data, acquired at each monitoring phase, are independently inverted (Loke et al., 1999; Tsourlos, 2003). This kind of approach mainly assumed that the time-lapse images are calculated under the time-invariant static condition and that the changes of the ground properties during the acquisition can be ignored. However, the images obtained from this approach may be strongly contaminated with inversion artefacts due to both the presence of noise in the measurements and independent inversion errors. This generates false anomalies of ground condition changes. Furthermore, the time-

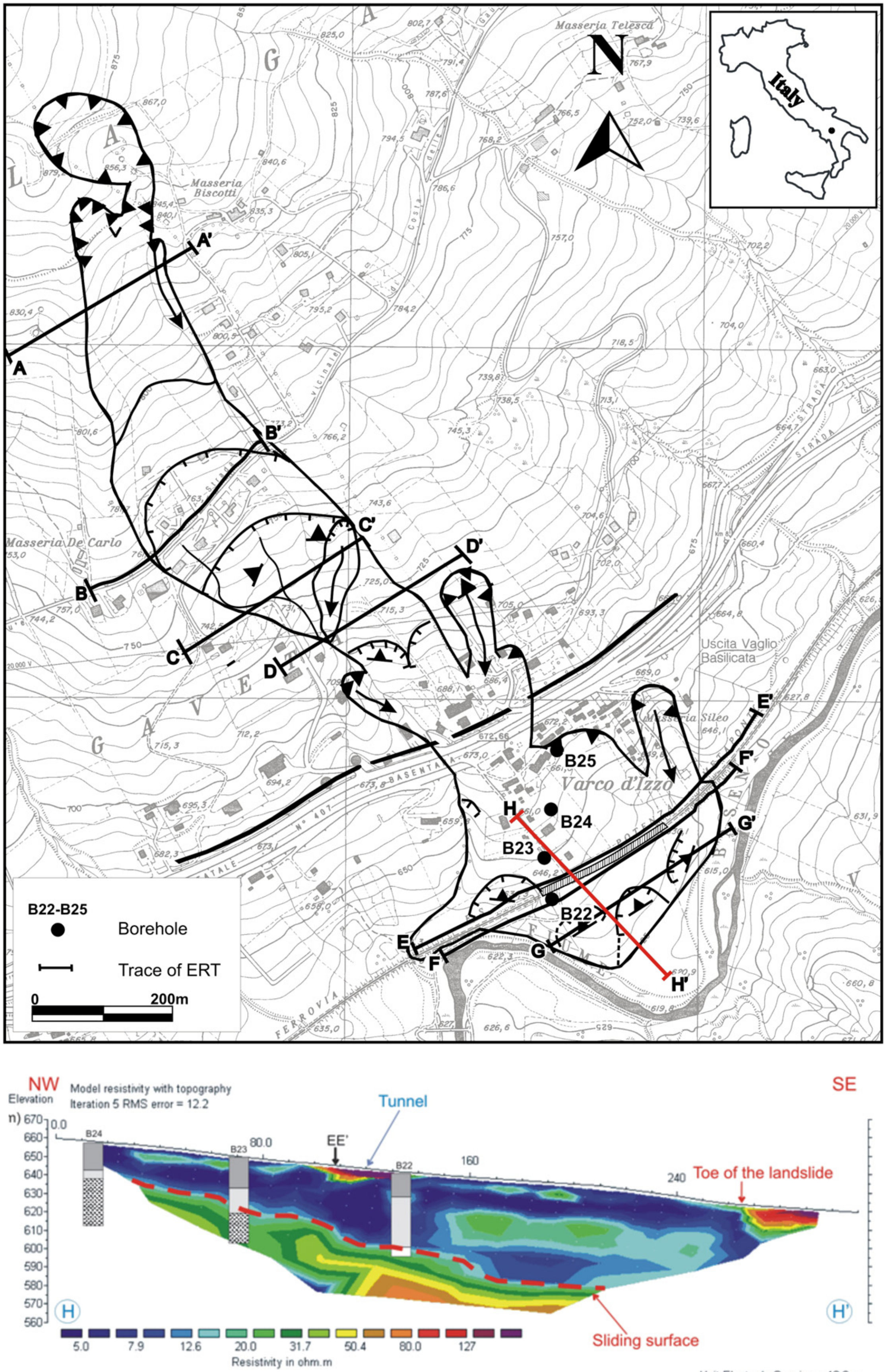

Fig. 2. Varco d'Izzo landslide (Basilicata region, southern Italy): identification of the sliding surface and definition of landslide shape by the comparison between the HH′ 2D ERT and the stratigraphic data inferred from boreholes B22, B23 and B24 (redrawn from Lapenna et al., (2005)).

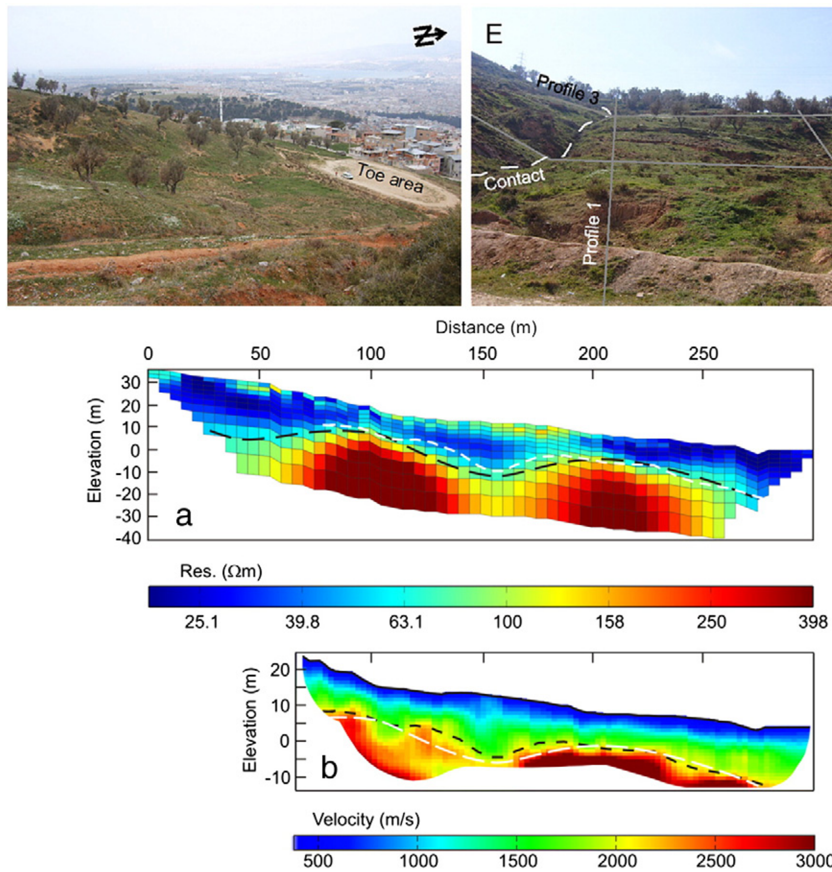

Fig. 3. (Top) A general view of the Altındağ landslide site, İzmir (western Turkey) with location of measurement profiles; (bottom) identification of the sliding surface by the comparison between 2D ERT and the seismic refraction tomography carried out along the profile 1 (redrawn from Göktürkler et al., (2008)).

invariant static condition becomes invalid if the material property changes significantly during the acquisition.

With the aim to minimize the artefacts, LaBrecque and Yang (2001) have proposed the difference inversion algorithm. In particular, they seek to reduce the misfit between the difference in two datasets and the difference between two model responses. Daily et al. (2004) have proposed a similar approach based on the ratio inversion of the initial and subsequent datasets.

Kim et al. (2009) have developed a four dimensional (4D) inversion algorithm, where time dimension is included directly into the inversion procedure. The regularization in space-time domain effectively reduces inversion artefacts.

Karaoulis et al. (2011) have noted that the time regularization sometimes makes the inverted results too smooth in the time domain and proposed the 4D Active Time Constrained (4D-ATC) inversion, where the time regularization is allowed to vary depending on the degree of resistivity changes in the space–time domain. Hayley et al. (2011) have proposed two additional methods in which both time-lapse data sets are inverted simultaneously.

Recently, Loke et al. (2014) have modified the 4D inversion method (Kim et al., 2009) to obtain 3D space models incorporating the L-curve method (Farquharson and Oldenburg, 2004) to determine optimum spatial and temporal factors.

To date, there have still been very few examples of tl-ERT in landslide areas (Table 5) and, very often, they refer to short acquisition periods. In most cases, the authors have installed a system of permanent electrodes leaving the main data acquisition equipment behind. They prefer to return periodically to the area investigated in order to carry out measurements.

Lebourg et al. (2005), in the site of La Clapiere landslide (South East French Alps), have repeated resistivity measurements along the same profile for five times and compared the results with hydrogeological rate of flow evaluated by considering the concentration of chemical contents during the spring and summer period. They haven't used a remotely controlled multi-channel system, but they periodically returned to the site to carry out measurements. On the same landslide, Jomard et al. (2007b) have used the Syscal R1 Plus resistivimeter to obtain continuous electrical resistivity measurements (288 min) along one profile. They have used the difference inversion approach between a reference ERT, obtained by applying RES2Dinv software before the injection of water, and the subsequent resistivity models. The comparison with hydrological results has allowed the estimation of the surface water drainage in space and time within the slipping mass.

Chambers et al. (2009) have developed and used an automatic time-lapse electrical resistivity tomography (ALERT) system to investigate an active landslide at a site near Malton (North Yorkshire, UK). They prepared a grid of five profiles with permanently installed electrodes and obtained time-lapse ERT by applying the time-lapse routine of the RES2Dinv software (Loke and Barker, 1996; Loke et al., 2003) (Fig. 6). The tl-ERT has been used to reveal the hydraulic precursors to movement. In the same test site, Wilkinson et al. (2010) have used the ALERT system to study the effects of electrode movements on the tl-ERT. In particular, they considered and tried to eliminate possible artifacts due to the movement of electrodes which could obscure the genuine time-lapse resistivity changes in the subsurface. The same authors (Wilkinson et al., 2011) have used the tl-ERT obtained by the ALERT system with the aim of revealing the hydrogeological precursors to movements.

Lebourg et al. (2010) performed a permanent time-lapse ERT survey on Vence landslide (South-eastern France) for three months. They coupled tl-ERT with water level acquisitions (piezometric levels) and rainfall events. The data comparison allowed the validation of the existence of two different subsoil hydrogeological answers to rainfall events.

Table 3
Scientific papers related to the application of 3D ERT for landslide investigation, published on international journal since 2000 or available online. All the information about the kind of landslide, the lithological nature of material involved in the movement, the technical information on the equipments used to carry out electrical resistivity measurements and software applied for data inversion and the comparison with direct data or other indirect geophysical data, are also reported. Legend: *n.a.i.* = not available information; M = Manual; A = Automatic; A-Mu = Automatic and multi-electrode; SA = Semi-automatic; DD = Dipole–dipole; W = Wenner; PP = Pole–pole; S = Schlumberger; WS = Wenner–Schlumberger; PD = Pole–Dipole; MG = Multi-gradient.

Publication year	Authors	Journal	Landslide typology	Geological context	Country	Acquisition system	Instrument	Electrode configuration	Inversion algorithm	Direct data	Other geophysical data
2004	Bichler, A., Bobrowsky, P., Best, M., Douma, M., Hunter, J., Calvert, T., Burns, R.	Landslides	Retrogr., dry earth slide – debris flow	Sand to clay sediments	Canada	A-Mu	Syscal R1- Plus Switch 48 DC	W	RES2Dinv	Stratigraphical data	Ground penetrating radar (GPR), seismic reflection and refraction profiles
2005	Lebourg, T., Binet, S., Tric, E., Jomard, H., El Bedoui, S.	Terra Nova	Complex deep seated landslide	Basement rocks composed mainly of migmatitic gneiss	France	A-Mu	Syscal R1 Plus	DD-PP	RES3Dinv	Hydrogeological data	n.a.i.
2006	Drahor, M.G., Gokturkler, G., Berge, M.A., Kurtulmus, T.O.	Environm. Geology	Slide	Sandstone, siltstone and mudstone	Turkey	A-Mu	n.a.i.	W	RES2Dinv	Stratigraphical data	n.a.i.
	Friedel, S., Thielen, A., Springman, S.M.	J. of App. Geophys.	Slide	Sedimentary rocks (sandstones)	Switzerland	A-Mu	Geotom of Geolog	W-S-DD	RES3Dinv	Stratigraphical data, penetration tests (DPT) and laboratory analysis	n.a.i.
2007	Yilmaz, S.	J. of Envir. and Engin. Geophys.	n.a.i.	Volcanic and sedimentary (clayey and marls) sequences	Turkey	A-Mu	SAS 1000 - ABEM	DD	Damped leastsquares inversion algorithm (Wannamaker, 1992)	n.a.i.	n.a.i.
2009	Chambers, J.E., Meldrum, P.I., Gunn, D.A., Wilkinson, P.B., Kuras, O., Weller, A.L., Ogilvy, R.D.	Near Surface	Rotational slide	Lower Jurassic Lias Group rocks	United Kingdom	A-Mu	ALERT system	DD	n.a.i.	n.a.i.	n.a.i.
2010	Heincke, B., Günther, T., Dalsegg, E., Rønning, J.S., Ganerød, G.V., Elvebakk, H.	J. of App. Geophys.	Rockslide	Gneissic rocks	Norway	A-Mu	ABEM Terrameter SAS400	W-DD	BERT algorithm	Stratigraphical data	Seismic tomography
2011	Chambers, J.E., Wilkinson, P.B., Kuras, O., Ford, J.R., Gunn, D.A., Meldrum, P.I., Pennington, C.V.L., Weller, A.L., Hobbs, P.R.N., Ogilvy, R.D.	Geomorphology	Slow moving earth slide–earth flow	Lower Jurassic Lias Group rocks	United Kingdom	A-Mu	AGI SuperSting R8 IP Sys-tem	DD	RES3Dinv	Boreholes and auger holes	Self potential survey
	Grandjean, G., Gourry, J.C., Sanchez, O., Bitri, A., Garambois, S.	J. of App. Geophys.	Slide	Quartzitic and gypseous	France	A-Mu	Syscal PRO	MG-PD	RES2Dinv	Inclinometric data	Electromagnetic map, seismic tomography, spatial analysis of surface waves, H/V
	Di Maio, R., Piegari, E.	J. of App. Geophys.	Shallow landslide	Pyroclastic covers	Italy	A-Mu	Syscal PRO	WS	RES3Dinv	Laboratory analysis	n.a.i.
	Udphuay, S., Gunther, T., Everett, M.E., Warden, R.R., Briaud, J.L.	Geophys. J. Intern.	Cliff collapse	Silty-clay and siliciclastic/ carbonate rocks	France	A-Mu	AGI SuperSting R8/IP System	Hybrid DD/S	BERT algorithm	Stratigraphical data	n.a.i.
2012	Di Maio, R., Piegari, E.	J. of Geoph. and Engin.	Shallow landslide	Pyroclastic covers	Italy	A-Mu	Syscal PRO	WS	RES3Dinv	n.a.i.	n.a.i.

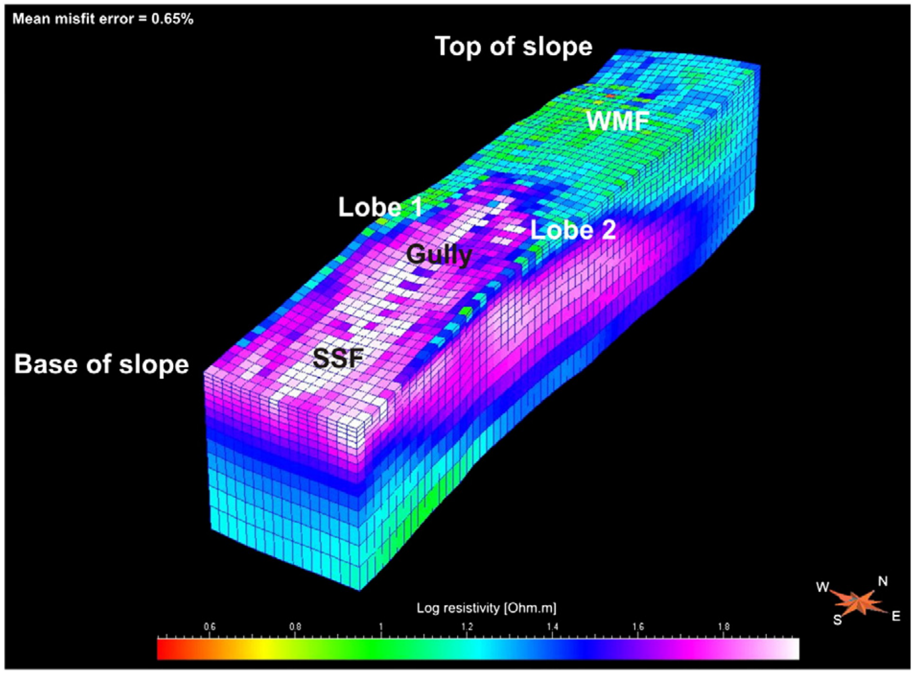

Fig. 4. Landslide in Malton site (North Yorkshire, UK): 3D geoelectrical model of the landslide obtained by applying a 3D data inversion (after Chambers et al., 2009).

Bievre et al. (2012) have used tl-ERT to detect water content variations within the unsaturated media along the unstable clay slopes of the Trieves area (French Alpes). They carried out electrical resistivity measurements along the same profile for two years. They have chosen a reference starting model acquired in a dry period to calculate the resistivity changes occurred after. tl-ERT showed significant resistivity variations in time, especially below a particular tension fissure, resulting from water content changes and suggesting that this fissure constitutes a preferential path for water.

Luongo et al. (2012) have planned and installed a prototype system for the acquisition of tl-ERT and time domain reflectometry (TDR) measurements in a landslide area of the Lucanian Apennine (Southern Italy). The aim of the experiment, that lasted two years, was to monitor the rainwater infiltration and the variation of water content in the first layers of the subsoil. The system was also equipped with a rain gauge to measure the precipitation frequency and intensity. The data analysis has proved the stability of the measured signals and the good correlation between resistivity and soil moisture measurements.

Supper et al. (2012b) have installed the GEOMON 4D system to investigate the structure of an earth flow in Gschliefgraben site (Austria) in order to evaluate maximum hazard scenarios as a basis for the planning of further measures.

Travelletti et al. (2012) have tried to monitor water infiltration and subsurface flow within the clay-shale material of Laval landslide (ORE Draix, South French Alps). The experiment lasted 67 h and was aimed to characterize the spatial and temporal development of water circulation in the soil and to identify when the steady-state flow conditions were reached. Measurements were repeated every 1–3 h. The data acquired have been inverted by using the RES2Dinv time-lapse routine.

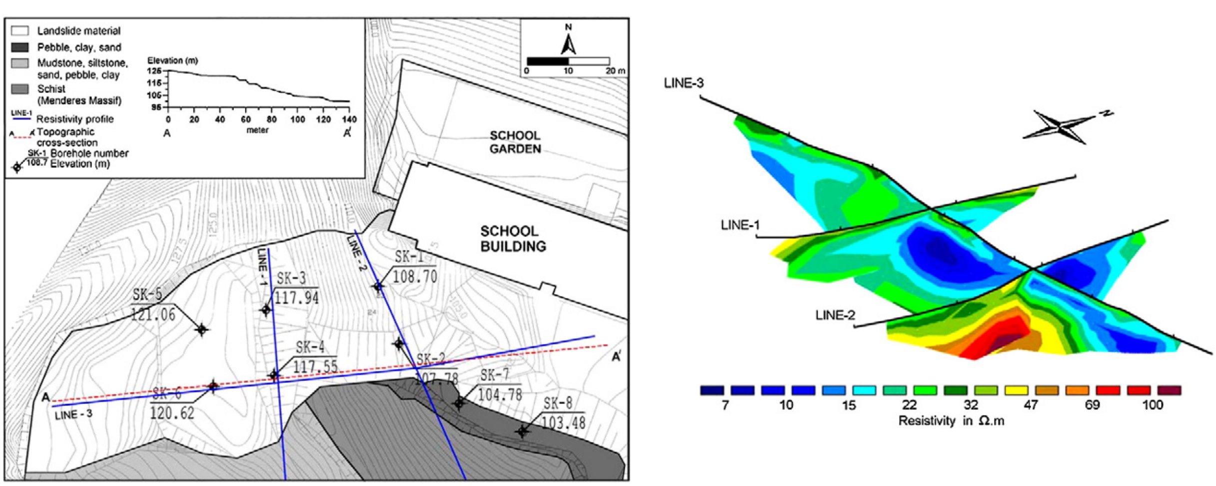

Fig. 5. Geological map of the Soke landslide area in the district of Aydin (Turkey) with location of measurement profiles. 3D fence diagram of the resistivity sections carried out on the landslide (redrawn from Drahor et al., (2006)).

Table 4
Percentage distribution of landslide typologies studied by applying 3D ERT and of resistivity values related to the material involved in these landslides.

Landslide typology	%	Resistivity values	%
Slides	64	Conductive	67
Debris and earth flows	9	Resistive	25
Complex landslides	9	Mixed	8
Deep seated landslides	9		
Cliff collapse	9		

Lehmann et al. (2013) have applied the tl-ERT, TDR and tensiometer sensors to monitor the hydrological state of a hillslope, located near Rudlingen in Northern Switzerland, prior the occurrence of a sprinkling-induced shallow landslide. They have carried out the experiments considering both a stable and an unstable portion of the slope. In unstable conditions, they have shown that tl-ERT is able to delineate the spatial and temporal evolution of the subsurface wetting in response to hydrological perturbations.

3. Discussion on the ERT advantages and drawbacks for landslide investigation

The examples reported in this review have helped us to highlight the main advantages and drawbacks encountered by using the ERT technique in landslide areas. Obviously, all the limitations that usually characterize this method, regardless of the application field, must to be considered also in the case of landslides. Loke et al. (2013) have highlighted and discussed the major ERT limitations among which, as also pointed out in the papers analyzed, the most important in landslide application are: the non-uniqueness of solution, the investigation depth and resolution, the calibration of data, the three-dimensional structures, the survey design and the electrode position.

As already discussed before, the ERT technique is mainly applied in landslide areas with the aim to reconstruct the geometry of slope and body, to locate the possible sliding surface, to identify vulnerability surfaces, to estimate the slide material thickness and to detect areas with a high water content. Where the resistivity contrasts between slide material and bedrock are well-rendered, ERT proved to be very useful for the retrieval of this kind of information. In these cases, for example, the sliding surface, the lateral boundaries and the vulnerability surfaces are located at the transition between the conductive and resistive material or vice versa. In subsoil with a high water or clayey material content, resistivity contrasts can be reduced making it difficult to interpret the tomographic images correctly. In these cases, the application of seismic tomography or induced polarization methods can provide useful information to discriminate both different kinds of lithologies and the changes of physical parameters (e.g. different water content) in the same lithology. In the absence of clayey material, the areas with a higher water content can correspond to very low resistive values. This can also be verified by applying the IP method. Of course, in all the cases, the authors' assumptions must be validated by comparing other geophysical data or direct data.

Although in some cases the ERT method has been individually applied and the results have been compared only with the superficial geological, geomorphological and structural information (Batayneh and Al-Diabat, 2002; Yilmaz, 2007; Colangelo et al., 2008; Panek et al., 2008; Chambers et al., 2009; Lundstrom et al., 2009; Jomard et al., 2010; Migon et al., 2010; Tric et al., 2010; Di Maio and Piegari, 2012; Zerathe and Lebourg, 2012; Shan et al., 2013), the need to calibrate and validate geophysical data is still required (Jongmans and Garambois, 2007), which is a disadvantage not fully overcome. This is the reason why the ERT method, as well as other geophysical methods, should not be seen as an isolated technique and it should be used in conjunction with other methods. In the examples considered, ERT has generally been integrated with seismic methods, which proved to be particularly interesting and useful especially for the analysis of terrain with a high water content (Jongmans et al., 2009; Le Roux et al., 2011). Only a few examples of joint application with GPR (Bichler et al., 2004; Otto and Sass, 2006; Ganerod et al., 2008; Sass et al., 2008; Carpentier et al., 2012), self-potential (Lapenna et al., 2003; Perrone et al., 2004; Lapenna et al., 2005; Meric et al., 2005; Naudet et al., 2008; Chambers et al., 2011) and IP (Marescot et al., 2008; Sastry and Mondal, 2013) methods have been reported. Due to the insufficient investigation depth, the GPR method has usually been applied to characterize the first subsoil layers. The self-potential method has been used to discriminate high water content areas possibly affected by sliding, while IP to discriminate clayey material from water. Generally speaking, the integration with other geophysical techniques allows the detection of different sub-surface structure features, thus making it possible both to confirm the existence of vague features that may be

Table 5
Scientific papers related to the application of tl-ERT for landslide investigation, published on international journal since 2000 or available online.

Publication year	Authors	Journal	Landslide typology	Geological context	Country
2005	Lebourg, T., Binet, S., Tric, E., Jomard, H., El Bedoui, S.	Terra Nova	Complex deep seated landslide	Basement rocks composed mainly of migmatitic gneiss	France
2007	Jomard, H., Lebourg, T., Binet, S., Tric, E., Hernandez, M.	Terra Nova	Complex deep seated landslide	Basement rocks composed mainly of migmatitic gneiss	France
2009	Chambers, J.E., Meldrum, P.I., Gunn, D.A., Wilkinson, P.B., Kuras, O., Weller, A.L., Ogilvy, R.D.	Near Surface	Rotational slide	Lower Jurassic Lias Group rocks	United Kingdom
2010	Lebourg, T., Hernandez, M., Zerathe, S., El Bedoui, S., Jomard, H., Fresia, B.	Engineering Geology	Translational landslide	Sandy-clay sliding mass	France
	Wilkinson, P.B., Chambers, J.E., Meldrum, P.I., Gunn, D.A., Ogilvy, R.D., Kuras, O.	Geophysical Journal International	Rotational slide	Lower Jurassic Lias Group rocks	United Kingdom
2011	Wilkinson, P., Chambers, J., Kuras, O., Meldrum, P., Gunn, D.	First break	Rotational slide	Lower Jurassic Lias Group rocks	United Kingdom
2012	Bievre, G., Jongmans, D., Winiarski, T., Zumbo, V.	Hydrological Processes	Slide	Clay materials	France
	Luongo, R., Perrone, A., Piscitelli, S., Lapenna, V.	Int. J. Of Geophys.	Complex retrograssive roto-translational slide	Flyschoide material	Italy
	Supper, R., Jochum, B., Kim, J.-H., Ottowitz, D., Pfeiller, S., Baron, I., Romer, A., Lovisolo, M., Moser, G.,	Berichte Geol. B.-A., 93	Earth flow	Colluvial mass	Austria
	Travelletti, J., Sailhac, P., Malet, J-P., Grandjean, G., Ponton, J.	Hydrological Processes	Slide	Weathered Callovo-Oxfordian black marls	France
2013	Lehmann, P., Gambazzi, F., Suski, B., Baron, L., Askarinejad, A., Springman, S.M., Holliger, K., Or, D.	Water Resources Research	Shallow landslide	Silty sand	Switzerland

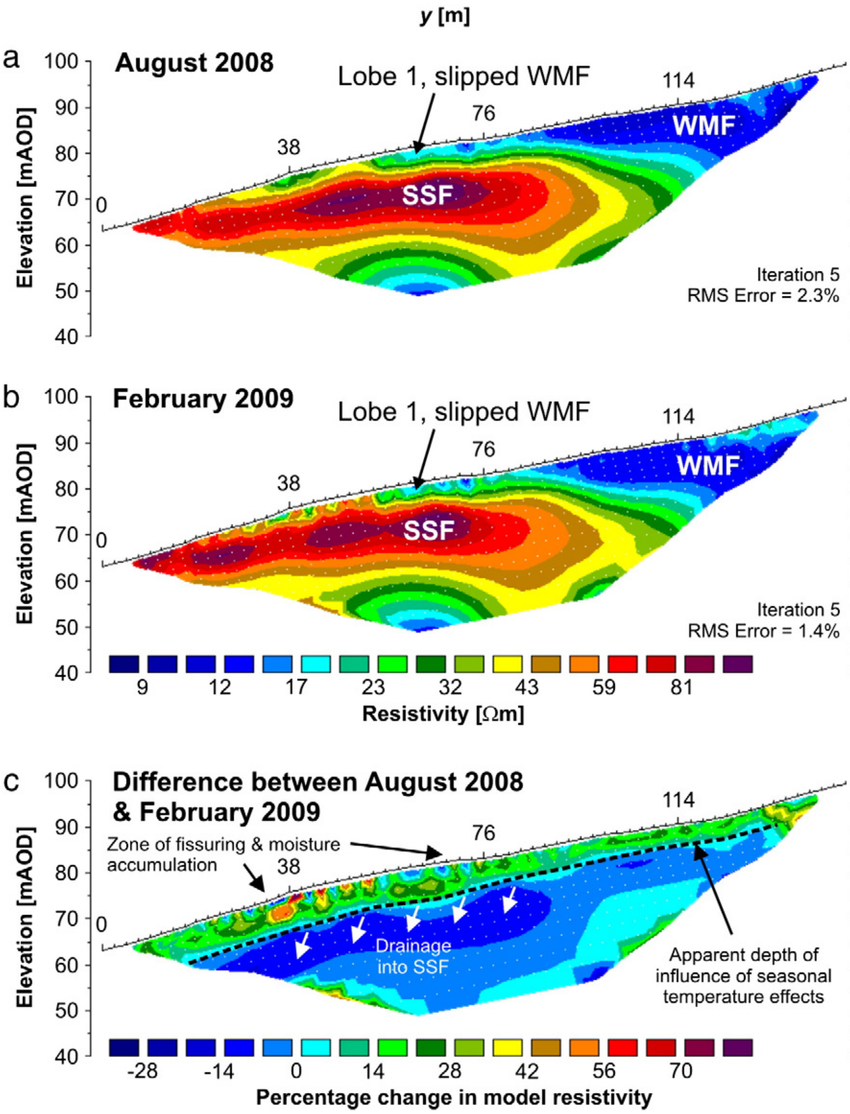

Fig. 6. Landslide in Malton site (North Yorkshire, UK): Tl-ERT obtained by the ALERT (Kuras et al., 2009) data. (a) 2D ERT carried out on August 2008; (b) 2D ERT carried out on February 2009; (c) resulting differential resistivity image (after Chambers et al., (2009)).

missed because of the use of one single method (Hack, 2000) and increase the investigation resolution (Bichler et al., 2004; Meric et al., 2005; Ganerod et al., 2008). Furthermore, the additional integration with geological and borehole information is useful for the improvement of the geophysical data interpretation, overcoming the non-uniqueness typical of the geophysical model obtained (McCann and Forster, 1990; Loke et al., 2013).

To date, in landslide areas, the comparison between ERT and other geophysical data or direct data has been simply qualitative. The scientific community agrees on the necessity to obtain combined information from multiple images acquired through different techniques for more accurate interpretations (Gallardo and Meju, 2011). There are generally two common 2D joint different data inversion approaches: one involves the use of petrophysical or hydrological characteristics to relate two different geophysical properties (Gallardo and Meju, 2004; Abubakar et al., 2012; Hamdan and Vafidis, 2012); the other makes use of structural attributes (e.g., geological boundaries) as a common factor between two geophysical models (Gallardo and Meju, 2004; de Nardis et al., 2005; Gallardo and Meju, 2011; Abubakar et al., 2012; Hamdan and Vafidis, 2012). Research is still being carried out to find the best solution to this problem. The joint inversion is usually implemented using synthetic data, and after that the same procedure is applied to study in-field data. de Nardis et al. (2005), for example, have applied a hybrid joint inversion approach to analyze VES and seismic refraction data in order to study a landslide located close to Rome (Italy).

The joint inversion of different data can be considered a key challenge for the future to get the best geological model of the investigated subsoil. When more efficient and performing joint inversion approaches are tested, it will be possible to use less expensive and faster geophysical methods. In this case, no comparison between geophysical results and the ones obtained by applying more expensive direct and invasive techniques would be required. One of the most promising approach is based on the resistivity and self-potential data joint inversion. Seminal papers have already been published (Jardani et al., 2008) and interesting results have been obtained in the study of volcanic and geothermal areas. Self-potential data are of particular interest for their correlation with groundwater patterns, and impressive results have been achieved during laboratory controlled experiments (Jardani et al., 2012).

This review also highlights that only few examples of 3D applications in landslide areas are available. As already explained, this could be mainly due to the logistical problems normally encountered during the data acquisition stage (survey design limitation). Indeed, in order to cover large areas it may be necessary to use multiple instruments connected to many multi-core cables. This, of course, reduces the method efficiency and increases the survey cost. Therefore, it would be necessary to plan systems that allow the measurement of data using separate current injection and voltage measuring systems. This, also means experimenting with technologies that minimize the number of cables by automatically switching the functionality of the electrodes. In this context new technologies for smart sensors and web-based services for wireless sensor network (Kerkez et al., 2012), new unmanned or drone systems for geophysical surveys in extreme environment could make a more widespread use of the 3D ERT mapping of landslide areas.

Regarding tl-ERT, there are different critical aspects to be considered such as the engineering of the current acquisition system, the equipment maintenance, the inversion software and the data analysis.

The most popular systems used to acquire tl-ERT are the multichannel systems which allow the simultaneous potential measurement on several channels by using a single pair of current electrodes, which increases the data acquisition speed significantly. The systems make it possible both to adjust the current intensity injected into the ground and check all the factors affecting the measurements to be automatically carried out. At first, the main problems of the systems used to obtain tl-ERT were both to ensure a continuous power supply to the instrument where a power line was not available and control the system remotely especially in hardly accessible areas. Recently, the new monitoring systems have incorporated telemetric control, data transfer and make use of wind, solar, fuel cell technology as local power generation (Supper et al., 2008; Wilkinson et al., 2010; Hilbich et al., 2011; Supper et al., 2012a).

The installation of permanent systems can cause a lot of problems (e.g. thefts, damage by animals, cable break, electrode oxidation, etc.) which have nothing to do with the instrument used.

During the soil excavation and equipment installation, a great attention should be paid to the possibility to check the instruments in the future, in order to examine the electrode/cable and electrode/terrain contacts and, eventually, to improve the resistivity check. Moreover, the movement of electrodes in landslide areas can bring about a systematic data error. Although the analysis of the results obtained by using different electrode configurations along the same profile has not revealed the most appropriate device for the investigation of specific landslides and material, the choice of measurement array geometries less sensitive to the positional errors (Wilkinson et al., 2008, 2013) as well as the use of position inversion routine (Wilkinson et al., 2010) can reduce these errors. Generally speaking, the use of optimized resistivity tomography configurations can introduce additional constraints on the design strategy that allow the maximization of the tomographic image quality (Wilkinson et al., 2012).

The papers considered also highlighted the difficulty in analyzing the resistivity data acquired in time-lapse procedure. As discussed in Section 2.3, different software for the processing of these data have already been developed; the real problem is to test these algorithms not only on synthetic data but also on the experimental ones. Moreover, it is important to quantify the relationship between the electrical resistivity variations as a function of changes in hydrological parameters. This result can be achieved by increasing the case studies and the time of monitoring also taking into account, for example, the seasonal variability.

4. Conclusions

The critical overview of the papers considered highlights the potential applications of the ERT method in the study of a wide spectrum of landslide phenomena. The electrical images obtained by applying the ERT method in landslide areas provide effective and useful information on the distribution of resistivity contrasts that often correspond to the boundaries between the sliding material and bedrock. In particular, the ERT method can be considered suitable for the geometrical characterization of a landslide body, the identification of potentially unstable areas and, also, the definition of the geological setting in areas affected by instability phenomena. Resistivity images can also help to locate areas with a high water content where the planning and the installation of drainage systems could be necessary to stabilize the slope. On the other hand, the examples shown have also highlighted the main drawbacks of this method that still requires the calibration of the results using other geophysical or geological data, especially when a very wet material is investigated. The reliability and the exploitation of this method does not seem to depend either on the type of landslide or on the material involved in the movement. Thus, the method seems to work well in all the types of landslide considered and, as for all the other geophysical methods, provides ambiguous results where the resistivity contrasts are scarce or masked. In this case, it is necessary to integrate ERT results with direct or indirect data. The quality of ERT results does not seem to be affected either by the measuring instrument used or the type of electrode configuration chosen. Although in the past there was a tendency to use different arrays along the same profile, very recently W and WS configurations have been favored especially in the study of shallow and non-complex landslides (Table 1).

As concerns the operative and technological aspects during the monitoring phase, the introduction of automatic multi-channel systems has significantly improved the data acquisition stage, making it much faster and reliable. However, there are still very few examples on the application of time-lapse ERT in the frame of state-of-the-art landslide early-warning systems. Furthermore, the interpretation of continuous resistivity data is still too qualitative to provide a quantitative estimate of hydrological or geotechnical parameters (e.g. water content, pore water pressure, etc.) which play a key role in the triggering of landslides.

In the frame of methodological studies, much more attention should be devoted to the integration with other geophysical methods, and the key challenge will be the joint inversion of field resistivity data with other electromagnetic and hydrogeological parameters.

Finally, the overall discussion carried out in this review paper allows us to consider the ERT method as a well-consolidated tool that can be applied in all the phases concerning the mitigation and the prevention of hydrogeological risks. In the near future, the ERT method role in developing advanced integrated systems for landslide monitoring could be more relevant especially during the early-warning stage.

Acknowledgments

We would like to thank two anonymous reviewers for their constructive comments and suggestions that have helped to greatly improve our paper.

References

Abubakar, A., Gao, G., Habashy, T.M., Liu, J., 2012. Joint inversion approaches for geophysical electromagnetic and elastic full-waveform data. Inverse Probl. 28. http://dx.doi.org/10.1088/0266-5611/28/5/055016.

AGI, 2009. Instruction Manual for EarthImagerTM 2D Version 2.4.0. Advanced Geosciences, Inc, Austin, Texas.

Archie, G.E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. Am. Inst. Min. Metall. Pet. Eng. 146, 54–62.

Ayenew, T., Barbieri, G., 2005. Inventory of landslides and susceptibility mapping in the Dessie area, Northern Ethiopia. Eng. Geol. 77, 1–15.

Baldi, P., Cenni, N., Fabris, M., Zanutta, A., 2008. Kinematics of a landslide derived from archival photogrammetry and GPS data. Geomorphology 102, 435–444.

Barker, R., 1981. The offset system of electrical resistivity sounding and its use with a multi-core cable. Geophys. Prospect. 29, 128–143.

Barker, R., 1992. A simple algorithm for electrical imaging of the subsurface. First Break 10, 53–62.

Batayneh, A.T., Al-Diabat, A.A., 2002. Application of a two-dimensional electrical tomography technique for investigating landslides along the Amman-Dead Sea highway, Jordan. Environ. Geol. 42, 399–403.

Bekler, T., Ekinci, Y.L., Demirci, A., Erginal, A.E., Ertekin, C., 2011. Characterization of a landslide using seismic refraction, electrical resistivity and hydrometer methods, Adatepe – Canakkale, NW Turkey. J. Environ. Eng. Geophys. 16 (3), 115–126.

Bichler, A., Bobrowsky, P., Best, M., Douma, M., Hunter, J., Calvert, T., Burns, R., 2004. Three-dimensional mapping of a landslide using a multi-geophysical approach: the Quesnel Forks landslide. Landslides 1 (1), 29–40.

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 (Trieves area, French Alps). Hydrol. Process. 26, 2128–2142.
Bishop, A.W., 1960. The principle of effective stress. Norw. Geotech. Inst. Publ. 32, 1–5.
Carpentier, S., Konz, M., Fischer, R., Anagnostopoulos, G., Meusburger, K., Schoeck, K., 2012. Geophysical imaging of shallow subsurface topography and its implication for shallow landslide susceptibility in the Urseren Valley, Switzerland. J. Appl. Geophys. 83, 46–56.
Cascini, L., Fornaro, G., Peduto, D., 2010. Advanced low- and full-resolution DInSAR map generation for slow-moving landslide analysis at different scales. Eng. Geol. 112, 29–42.
Catani, F., Farina, P., Moretti, S., Nico, G., Strozzi, T., 2005. On the application of SAR interferometry to geomorphological studies: estimation of landform attributes and mass movements. Geomorphology 66, 119–131.
Chambers, J.E., Meldrum, P.I., Gunn, D.A., Wilkinson, P.B., Kuras, O., Weller, A.L., Ogilvy, R.D., 2009. Hydrogeophysical Monitoring of Landslide Processes Using Automated Time-Lapse Electrical Resistivity Tomography (ALERT). Near Surface 2009 – 15th European Meeting of Environmental and Engineering Geophysics. Dublin, Ireland.
Chambers, J.E., Wilkinson, P.B., Kuras, O., Ford, J.R., Gunn, D.A., Meldrum, P.I., Pennington, C.V.L., Weller, A.L., Hobbs, P.R.N., Ogilvy, R.D., 2011. Three-dimensional geophysical anatomy of an active landslide in Lias Group mudrocks, Cleveland Basin, UK. Geomorphology 125, 472–484.
Chang, P.-Y., Chen, C.-c, Chang, S.-K., Wang, T.-B., Wang, C.-Y., Hsu, S.-K., 2012. An investigation into debris flow induced by Typhoon Morakot in the Siaolin Area, Southern Taiwan, using electrical resistivity imaging method. Geophys. J. Int. 188, 1012–1024.
Colangelo, G., Lapenna, V., Loperte, A., Perrone, A., Telesca, L., 2008. 2D electrical resistivity tomographies for investigating recent activation landslides in Basilicata Region (Southern Italy). Ann. Geophys. 51 (1), 275–285.
Dahlin, T., 1993. On the automation of 2D resistivity surveying for engineering and environmental applications. Lund University 91-628-1032-4 p. 187 (Ph.D. Thesis, ISRN LUTVDG/TVDG-1007-SE).
Dahlin, T., 1996. 2D resistivity surveying for environmental and engineering applications. First Break 14 (7), 275–283.
Dahlin, T., 2001. The development of DC resistivity imaging techniques. Comput. Geosci. 27, 1019–1029.
Dahlin, T., Bernstone, C., 1997. A roll-along technique for 3D resistivity data acquisition with multi-electrode arrays. Proceedings SAGEEP'97, Reno, Nevada, 2 pp. 927–935.
Daily, W., Ramirez, A., Binley, A., 2004. Remote monitoring of leaks in storage tanks using electrical resistance tomography: application at the Hanford site. J. Environ. Eng. 9 (1), 11–24.
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, 34–46.
de Nardis, R., Cardarelli, E., Dobroka, M., 2005. Quasi-2D hybrid joint inversion of seismic and geoelectric data. Geophys. Prospect. 53, 705–716.
Demoulin, A., Pissart, A., Schroeder, C., 2003. On the origin of late Quaternary palaeolandslides in the Liège (E Belgium) area. Int. J. Earth Sci. 92, 795–805.
Dey, A., Morrison, H.F., 1979. Resistivity modeling for arbitrary shaped two-dimensional structures. Geophys. Prospect. 27, 106–136.
Di Maio, R., Piegari, E., 2011. Water storage mapping of pyroclastic covers through electrical resistivity measurements. J. Appl. Geophys. 75, 196–202.
Di Maio, R., Piegari, E., 2012. A study of the stability analysis of pyroclastic covers based on electrical resistivity measurements. J. Geophys. Eng. 9, 191–200.
Donohue, S., Long, M., O'Connor, P., Helle, T.E., Pfaffhuber, A.A., Romoen, M., 2012. Multi-method geophysical mapping of quick clay. Near Surf. Geophys. 10, 207–219.
Drahor, M.G., Gokturkler, G., Berge, M.A., Kurtulmus, T.O., 2006. Application of electrical resistivity tomography technique for investigation of landslides: a case from Turkey. Environ. Geol. 50, 147–155.
Edwards, L.S., 1977. A modified pseudosection for resistivity and IP. Geophysics 42, 1020–1036.
Epada, P.D., Sylvestre, G., Tabod, T.C., 2012. Geophysical and geotechnical investigations of a landslide in Kekem area, western Cameroon. Int. J. Geosci. 3, 780–789.
Erginal, A.E., Ozturk, B., Ekinci, Y.L., Demirci, A., 2009. Investigation of the nature of slip surface using geochemical analyses and 2-D electrical resistivity tomography: a case study from Lapseki area, NW Turkey. Environ. Geol. 58, 1167–1175.
Farquharson, C.G., Oldenburg, D.W., 2004. A comparison of automatic techniques for estimating the regularization parameter in non-linear inverse problem. Geophys. J. Int. 156, 411–425.
Friedel, S., Thielen, A., Springman, S.M., 2006. Investigation of a slope endangered by rainfall-induced landslides using 3D resistivity tomography and geotechnical testing. J. Appl. Geophys. 60, 100–114.
Gallardo, L.A., Meju, M.A., 2004. Joint two-dimensional DC resistivity and seismic travel time inversion with cross-gradients constraints. J. Geophys. Res. 109 B03311.
Gallardo, L.A., Meju, M.A., 2011. Structure-coupled multiphysics imaging in geophysical sciences. Rev. Geophys. 49 RG1003.
Gallipoli, M.R., Lapenna, V., Lorenzo, P., Mucciarelli, M., Perrone, A., Piscitelli, S., Sdao, F., 2000. Comparison of geological and geophysical prospecting techniques in the study of a landslide in southern Italy. Eur. J. Environ. Eng. Geophys. 4, 117–128.
Ganerød, G.V., Grøneng, G., Rønning, J.S., Dalsegg, E., Elvebakk, H., Tønnesen, J.F., Kveldsvik, V., Eiken, T., Blikra, L.H., Braathen, A., 2008. Geological model of the Åknes rockslide, western Norway. Eng. Geol. 102, 1–18.
Glenn, N.F., Streutker, D.R., Chadwick, D.J., Thackray, G.D., Dorsch, S.J., 2006. Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. Geomorphology 73, 131–148.
Godio, A., Bottino, G., 2001. Electrical and electromagnetic investigation for landslide characterisation. Phys. Chem. Earth C 26 (9), 705–710.
Godio, A., Strobbia, C., De Bacco, G., 2006. Geophysical characterisation of a rockslide in alpine region. Eng. Geol. 83, 273–286.
Göktürkler, G., Balkaya, C., Erhan, Z., 2008. Geophysical investigation of a landslide: the Altındağ landslide site, İzmir (western Turkey). J. Appl. Geophys. 65, 84–96.
Grandjean, G., Pennetier, C., Bitri, A., Meric, O., Malet, J.-P., 2006. Caractérisation de la structure interne et de l'état hydrique de glissements argilo-marneux par tomographie géophysique: l'exemple du glissement-coulée de Super-Sauze (Alpes du Sud, France). Compt. Rendus Geosci. 338, 587–595.
Grandjean, G., Gourry, J.C., Sanchez, O., Bitri, A., Garambois, S., 2011. Structural study of the Ballandaz landslide (French Alps) using geophysical imagery. J. Appl. Geophys. 75, 531–542.
Griffiths, D.H., Turnbull, J., 1985. A multi-electrode array for resistivity surveying. First Break 3, 16–20.
Griffiths, D.H., Turnbull, J., Olayinka, A.I., 1990. Two dimensional resistivity mapping with a computer-controlled array. First Break 8 (4), 121–129.
Günther, T., 2007. DC2DInvRes-Direct current 2D inversion and resolution, online documentation. http://dc2dinvres.resistivity.net.
Günther, T., Rücker, C., Spitzer, K., 2006. Three-dimensional modelling and inversion of DC resistivity data incorporating topography — II. Inversion. Geophys. J. Int. 166, 506–517.
Guzzetti, F., Mondini, A.C., Cardinali, M., Fiorucci, F., Santangelo, M., Chang, K.-T., 2012. Landslide inventory maps: new tools for an old problem. Earth Sci. Rev. 112, 42–66.
Hack, R., 2000. Geophysics for slope stability. Surv. Geophys. 21, 423–448.
Hamdan, H.A., Vafidis, A., 2012. Joint inversion of 2D resistivity and seismic travel time data to image saltwater intrusion over karstic areas. Environ. Earth Sci. http://dx.doi.org/10.1007/s12665-012-1875-9.
Havenith, H.B., Jongmans, D., Abdrakmatov, K., Trefois, P., Delvaux, D., Torgoev, A., 2000. Geophysical investigations on seismically induced surface effects, case study of a landslide in the Suusamyr valley, Kyrgyzstan. Surv. Geophys. 21, 349–369.
Hayley, K., Pidlisecky, A., Bentley, L.R., 2011. Simultaneous time-lapse electrical resistivity inversion. J. Appl. Geophys. 75, 401–411.
Hee Song Geotek, 2002. DIPRO for Windows User's Guide.
Heincke, B., Günther, T., Dalsegg, E., Rønning, J.S., Ganerød, G.V., Elvebakk, H., 2010. Combined three-dimensional electric and seismic tomography study on the Åknes rockslide in western Norway. J. Appl. Geophys. 70, 292–306.
Hibert, C., Grandjean, G., Bitri, A., Travelletti, J., Malet, J.-P., 2012. Characterizing landslides through geophysical data fusion: example of the La Valette landslide (France). Eng. Geol. 128, 23–29.
Hilbich, C., Fuss, C., Hauck, C., 2011. Automated Time-lapse ERT for Improved Process Analysis and Monitoring of Frozen Ground. Permafr. Periglac. Process. 22, 306–319.
Jardani, A., Revil, A., Bolève, A., Dupont, J.P., 2008. Pattern of groundwater flow inferred from the three-dimensional inversion of self potential data and application to geothermal fields. J. Geophys. Res. 113 B09204.
Jardani, A., Revil, A., Dupont, J.P., 2012. Stochastic joint inversion of hydrogeophysical data for salt tracer test monitoring and hydraulic conductivity imaging. Adv. Water Resour. http://dx.doi.org/10.1016/j.advwatres.2012.08.005.
Jomard, H., Lebourg, T., Tric, E., 2007a. Identification of the gravitational boundary in weathered gneiss by geophysical survey: La Clapière landslide (France). J. Appl. Geophys. 62, 47–57.
Jomard, H., Lebourg, T., Binet, S., Tric, E., Hernandez, M., 2007b. Characterization of an internal slope movement structure by hydrogeophysical surveying. Terra Nova 19, 48–57.
Jomard, H., Lebourg, T., Guglielmi, Y., Tric, E., 2010. Electrical imaging of sliding geometry and fluids associated with a deep seated landslide (La Clapière, France). Earth Surf. Process. Landf. 35, 588–599.
Jongmans, D., Hemroulle, P., Demanet, D., Renardy, F., Vanbrabant, Y., 2000. Application of 2D electrical and seismic tomography techniques for investigating landslides. Eur. J. Environ. Eng. Geophys. 5, 75–89.
Jongmans, D., Garambois, S., 2007. Geophysical investigation of landslides: a review. Bull. Soc. Geol. Fr. 178 (2), 101–112.
Jongmans, D., Bièvre, G., Renalier, F., Schwartz, S., Beaurez, N., Orengo, Y., 2009. Geophysical investigation of a large landslide in glaciolacustrine clays in the Trièves area (French Alps). Eng. Geol. 109, 45–56.
Karaoulis, M.C., Kim, J.H., Tsourlos, P.I., 2011. 4D active time constrained resistivity inversion. J. Appl. Geophys. 73, 25–34.
Kerkez, B., Glaser, S.D., Bales, R.C., Meadows, M.W., 2012. Design and performance of a wireless sensor network for catchment-scale snow and soil moisture measurements. Water Resour. Res. 48 (9) W09515.
Kim, J.-H., Yi, M.-J., Park, S.-G., Kim, J.G., 2009. 4-D inversion of DC resistivity monitoring data acquired over a dynamically changing earth model. J. Appl. Geophys. 68, 522–532.
Kuras, O., Pritchard, J., Meldrum, P.I., Chambers, J.E., Wilkinson, P.B., Ogilvy, R.D., Wealthall, G.P., 2009. Monitoring hydraulic processes with Automated time-Lapse Electrical Resistivity Tomography (ALERT). C. R. Geosci. 341, 868–885 Special Issue on Hydrogeophysics.
LaBrecque, D.J., Milleto, M., Daily, W., Ramirez, A., Owen, E., 1996. The effect of noise on OCCAM's inversion of resistivity tomography data. Geophysics 61, 538–548.
LaBrecque, D.J., Yang, X., 2001. Difference inversion of ERT dat. A fast inversion method for 3-D in situ monitoring. J. Environ. Eng. Geophys. 6, 83–89.
Lanari, R., Casu, F., Manzo, M., Zeni, G., Berardino, P., Manunta, M., Pepe, A., 2007. An overview of the small baseline subset algorithm: a DInSAR technique for surface deformation analysis. Pure Appl. Geophys. 164, 637–661.
Langston, G., Bentley, L.R., Hayashi, M., McClymont, A., Pidlisecky, A., 2011. Internal structure and hydrological functions of an alpine proglacial moraine. Hydrol. Process. 25, 2967–2982.

Lapenna, V., Lorenzo, P., Perrone, A., Piscitelli, S., Rizzo, E., Sdao, F., 2003. High-resolution geoelectrical tomographies in the study of the Giarrossa landslide (Potenza, Basilicata). Bull. Eng. Geol. Environ. 62, 259–268.

Lapenna, V., Lorenzo, P., Perrone, A., Piscitelli, S., Rizzo, E., Sdao, F., 2005. 2D electrical resistivity imaging of some complex landslides in Lucanian Apennine chain, southern Italy. Geophysics 70, B11–B18.

Le Roux, O., Jongmans, D., Kasperski, J., Schwartz, S., Potherat, P., Lebrouc, V., Lagabrielle, R., Meric, O., 2011. Deep geophysical investigation of the large Séchilienne landslide (Western Alps, France) and calibration with geological data. Eng. Geol. 120, 18–31.

Lebourg, T., Binet, S., Tric, E., Jomard, H., El Bedoui, S., 2005. Geophysical survey to estimate the 3D sliding surface and the 4D evolution of the water pressure on part of a deep-seated landslide. Terra Nova 17, 399–406.

Lebourg, T., Hernandez, M., Zerathe, S., El Bedoui, S., Jomard, H., Fresia, B., 2010. Landslides triggered factors analysed by time lapse electrical survey and multidimensional statistical approach. Eng. Geol. 114, 238–250.

Lee, C.-C., Yang, C.-H., Liu, H.-C., Wen, K.-L., Wang, Z.-B., Chen, Y.-J., 2008. A Study of the hydrogeological environment of the Lishan landslide area using resistivity image profiling and borehole data. Eng. Geol. 98, 115–125.

Lehmann, P., Gambazzi, F., Suski, B., Baron, L., Askarinejad, A., Springman, S.M., Holliger, K., Or, D., 2013. Evolution of soil wetting patterns preceding a hydrologically induced landslide inferred from electrical resistivity survey and point measurements of volumetric water content and pore water pressure. Water Resour. Res. 49, 1–13.

Li, Y., Oldenburg, D.W., 1992. Approximate inverse mappings in DC resistivity problems. Geophys. J. Int. 109, 343–362.

Loke, M.H., 1999. Time lapse resistivity imaging inversion. Proceedings of the 5th Meeting of the Environmental and Engineering European, Em 1, Budapest, Hungary.

Loke, M.H., 2013. Tutorial: 2-D and 3-D electrical imaging surveys. www.geotomosoft.com.

Loke, M.H., Barker, R.D., 1996. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophys. Prospect. 44 (1), 131–152.

Loke, M.H., Acworth, I., Dahlin, T., 2003. A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. Explor. Geophys. 34, 182–187.

Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O., Wilkinson, P.B., 2013. Recent developments in the direct-current geoelectrical imaging method. J. Appl. Geophys. 95, 135–156.

Loke, M.H., Dahlin, T., Rucker, D.F., 2014. Smoothness-constrained time-lapse inversion of data from 3D resistivity surveys. Near Surf. Geophys. 12, 5–24.

Lundstrom, K., Larsson, R., Dahlin, T., 2009. Mapping of quick clay formations using geotechnical and geophysical methods. Landslides 6, 1–15.

Luongo, R., Perrone, A., Piscitelli, S., Lapenna, V., 2012. A prototype system for time-lapse electrical resistivity tomographies. Int. J. Geophys. http://dx.doi.org/10.1155/2012/176895.

Mainsant, G., Larose, E., Brönnimann, C., Jongmans, D., Michoud, C., Jaboyedoff, M., 2012. Ambient seismic noise monitoring of a clay landslide: Toward failure prediction. J. Geophys. Res. 117 F01030.

Marcato, G., Mantovani, M., Pasuto, A., Zabuski, L., Borgatti, L., 2012. Monitoring, numerical modelling and hazard mitigation of the Moscardo landslide (Eastern Italian Alps). Eng. Geol. 128, 95–107.

Marescot, L., Monnet, R., Chapellier, D., 2008. Resistivity and induced polarization surveys for slope instability studies in the Swiss Alps. Eng. Geol. 98, 18–28.

McCann, D.M., Forster, A., 1990. Reconnaissance geophysical methods in landslide investigations. Eng. Geol. 29, 59–78.

McClymont, A.F., Hayashi, M., Bentley, L.R., Muir, D., Ernst, E., 2010. Groundwater flow and storage within an alpine meadow-talus complex. Hydrol. Earth Syst. Sci. 14, 859–872.

Meric, O., Garambois, S., Jongmans, D., Wathelet, M., Chatelain, J.-L., Vengeon, J.-M., 2005. Application of geophysical methods for the investigation of the large gravitational mass movement of Séchilienne, France. Can. Geotech. J. 42, 1105–1115.

Migoń, P., Pánek, T., Malik, I., Hrádecký, J., Owczarek, P., Šilhán, K., 2010. Complex landslide terrain in the Kamienne Mountains, Middle Sudetes, SW Poland. Geomorphology 124, 200–214.

Mondal, S.K., Sastry, R.G., Pachauri, A.K., Gautam, P.K., 2008. High resolution 2D electrical resistivity tomography to characterize active Naitwar Bazar landslide, Garhwal Himalaya, India. Curr. Sci. 94 (7), 871–875.

Morgenstern, N.R., Price, V.E., 1965. The analysis of the stability of general slip surfaces. Geotechnique 15 (1), 79–93.

Naudet, V., Lazzari, M., Perrone, A., Loperte, A., Piscitelli, S., Lapenna, V., 2008. Integrated geophysical and geomorphological approach to investigate the snowmelt-triggered landslide of Bosco Piccolo village (Basilicata, southern Italy). Eng. Geol. 98, 156–167.

Ogusnsuyi, O., 2010. Geophysical characterization of Peace River landslide. University of Alberta, Canada. M.S. Thesis,.

Oldenburg, D.W., McGillivray, P.R., Ellis, R.G., 1993. Generalized subspace methods for large-scale inverse problems. Geophys. J. Int. 114, 12–20.

Oldenburg, D.W., Li, Y., 1994. Inversion of induced polarization data. Geophysics 59, 1327–1341.

Oppikofer, T., Jaboyedoff, M., Pedrazzini, A., Derron, M.-H., Blikra, L.H., 2011. Detailed DEM analysis of a rockslide scar to characterize the basal sliding surface of active rockslides. J. Geophys. Res. 116 F02016.

Otto, J.C., Sass, O., 2006. Comparing geophysical methods for talus slope investigations in the Turtmann valley (Swiss Alps). Geomorphology 76, 257–272.

Panek, T., Hradecky, J., Šilhan, K., 2008. Application of electrical resistivity tomography (ERT) in the study of various types of slope deformations in anisotropic bedrock: case studies from the Flysch Carpathians. Stud. Geomorphol. Carpatho Balc. XLII, 57–73.

Park, S.-G., Kim, J.-H., 2005. Geological survey by electrical resistivity prospecting in landslide area. Geosyst. Eng. 8 (2), 35–42.

Perrone, A., Iannuzzi, A., Lapenna, V., Lorenzo, P., Piscitelli, S., Rizzo, E., Sdao, F., 2004. High-resolution electrical imaging of the Varco d'Izzo earthflow (southern Italy). J. Appl. Geophys. 56, 17–29.

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). Eng. Geol. 88, 260–273.

Perrone, A., Vassallo, R., Lapenna, V., Di Maio, C., 2008. Pore water pressures and slope stability: a joint geophysical and geotechnical analysis. J. Geophys. Eng. 5, 323–337.

Petley, D.N., Mantovani, F., Bulmer, M.H., Zannoni, A., 2005. The use of surface monitoring data for the interpretation of landslide movement patterns. Geomorphology 66, 133–147.

Piegari, E., Cataudella, V., Di Maio, R., Milano, L., Nicodemi, M., Soldovieri, M.G., 2009. Electrical resistivity tomography and statistical analysis in landslide modelling: a conceptual approach. J. Appl. Geophys. 68, 151–158.

Ravindran, A.A., Prabhu, H.M.A.K., 2012. Prediction and control of landslide using W-4 system -2D electrical resistivity imaging technique in Padukadu, Ooty, Nilgiri district, Tamilnadu, India. ARPN J. Earth Sci. 1 (2), 42–47.

Ravindran, A.A., Ramanujam, N., 2012. Landslide investigation study using seismic refraction and 2D electrical resistivity imaging (ERI) technique in Ooty, Nilgiri District, Tamilnadu. Int. J. Phys. Sci. 7 (49), 6263–6269.

Reynolds, J.M., 1997. An Introduction to Applied and Environmental Geophysics. J. Wiley and Sons, Chichester, UK.

Roering, J.J., Stimely, L.L., Mackey, B.H., Schmidt, D.A., 2009. Using DInSAR, airborne, LiDAR, and archival air photos to quantify landsliding and sediment transport. Geophys. Res. Lett. 36 L19402.

Sass, O., Bell, R., Glade, T., 2008. Comparison of GPR, 2D-resistivity and traditional techniques for the subsurface exploration of the Öschingen landslide, Swabian Alb (Germany). Geomorphology 93, 89–103.

Sastry, R.G., Mondal, S.K., 2013. Geophysical Characterization of the Salna Sinking Zone, Garhwal Himalaya, India. Surv. Geophys. 34, 89–119.

Schmutz, M., Guérin, R., Andrieux, P., Maquaire, O., 2009. Determination of the 3D structure of an earthflow by geophysical methods The case of Super Sauze, in the French southern Alps. J. Appl. Geophys. 68, 500–507.

Schrott, L., Sass, O., 2008. Application of field geophysics in geomorphology: advances and limitations exemplified by case studies. Geomorphology 93, 55–73.

Shan, W., Hu, Z., Jiang, H., Guo, Y., Wang, C., 2013. Mechanism of permafrost landslide based on GPS and Resistivity Surveying. Progress of Geo-Disaster Mitigation Technology in Asia, Environmental Science and Engineering. Springer-Verlag, Berlin Heidelberg, pp. 349–361.

Socco, L.V., Jongmans, D., Boiero, D., Stocco, S., Maraschini, M., Tokeschi, K., Hantz, D., 2010. Geophysical investigation of the Sandalp rock avalanche deposits. J. Appl. Geophys. 70, 277–291.

Solberg, I.-L., Hensen, L., Ronning, J.S., Haugen, E.D., Dalsegg, E., Tonnesen, J.F., 2012. Combined geophysical and geotechnical approach to ground investigations and hazard zonation of a quick clay area, mid Norway. Bull. Eng. Geol. Environ. 71, 119–133.

Squarzoni, C., Delacourt, T.C., Allemand, P., 2005. Differential single-frequency GPS monitoring of the La Valette landslide (French Alps). Eng. Geol. 79, 215–229.

Strozzi, T., Delaloye, R., Kääb, A., Ambrosi, C., Perruchoud, E., Wegmüller, U., 2010. Combined observations of rock mass movements using satellite SAR interferometry, differential GPS, airborne digital photogrammetry, and airborne photography interpretation. J. Geophys. Res. Earth Surf. 115 F01014.

Stummer, P., 2002. Optimization of DC resistivity data acquisition: real-time experimental design and a new multielectrode system. IEEE Trans. Geosci. Remote Sens. 40, 2727–2735.

Supper, R., Romer, A., Jochum, B., Bieber, G., Jaritz, W., 2008. A complex geo-scientific strategy for landslide hazard mitigation-from airborne mapping to ground monitoring. Adv. Geosci. 14, 195–200.

Supper, R., Romer, A., Kreuzer, G., Jochum, B., Ottowitz, D., Ita, A., Kauer, S., 2012a. The GEOMON 4D electrical monitoring system: current state and future developments. Instrumentation and Data Acquisition Technology. Proceedings of GELMON 2011, Berichte Geol. B.-A., 93, pp. 23–26. ISSN 1017 – 8880 –.

Supper, R., Jochum, B., Kim, J.-H., Ottowitz, D., Pfeiller, S., Baron, I., Romer, A., Lovisolo, M., Moser, G., 2012b. The TEMPEL geoelectrical monitoring network for landslides: highlights of recent monitoring result. Application in landslide monitoring. Proceedings of GELMON 2011, Berichte Geol. B.-A., 93, pp. 144–151 (ISSN 1017 – 8880).

Travelletti, J., Sailhac, P., Malet, J.-P., Grandjean, G., Ponton, J., 2012. Hydrological response of weathered clay-shale slopes: water infiltration monitoring with time-lapse electrical resistivity. Hydrol. Process. 26, 2106–2119.

Tric, E., Lebourg, T., Jomard, H., Le Cossec, J., 2010. Study of large-scale deformation induced by gravity on the La Clapière landslide (Saint-Etienne de Tinée, France) using numerical and geophysical approaches. J. Appl. Geophys. 70, 206–215.

Tsourlos, P., 1995. Modelling, interpretation and inversion of multielectrode resistivity survey data. Ph.D. dissertation Dept. of Electronics, University of York, York, U.K, p. 315pp.

Tsourlos, P., Ogilvy, R.D., Meldrum, P.I., Williams, G.M., 2003. Time-lapse monitoring in single boreholes using electrical resistivity tomography. J. Environ. Eng. Geophys. 8 (1), 1–14.

Udphuay, S., Gunther, T., Everett, M.E., Warden, R.R., Briaud, J.-L., 2011. Three-dimensional resistivity tomography in extreme coastal terrain amidst dense cultural signals: application to cliff stability assessment at the historic D-Day site. Geophys. J. Int. 185, 201–220.

Van Den Eeckhaut, M., Verstraeten, G., Poesen, J., 2007. Morphology and internal structure of a dormant landslide in a hilly area: the Collinabos landslide (Belgium). Geomorphology 89, 258–273.

Ventura, G., Vilardo, G., Terranova, C., Bellucci Sessa, E., 2011. Tracking and evolution of complex active landslides by multi-temporal airborne LiDAR data: the Montaguto landslide (Southern Italy). Remote Sens. Environ. 115, 3237–3248.

Wannamaker, P.E., 1992. IP2DI-v1.00 finite element program for dipole–dipole resistivity/IP forward modeling and parameterized inversion of two-dimensional earth resistivity structure. User Documentation. University of Utah, Salt Lake City.

Wilkinson, P.B., Chambers, J.E., Lelliott, M., Wealthall, G.P., Ogilvy, R.D., 2008. Extreme sensitivity of crosshole electrical resistivity tomography measurements to geometric errors. Geophys. J. Int. 173 (1), 49–62.

Wilkinson, P.B., Chambers, J.E., Meldrum, P.I., Gunn, D.A., Ogilvy, R.D., Kuras, O., 2010. Predicting the movements of permanently installed electrodes on an active landslide using time-lapse geoelectrical resistivity data only. Geophys. J. Int. 183, 543–556.

Wilkinson, P., Chambers, J., Kuras, O., Meldrum, P., Gunn, D., 2011. Long-term time-lapse geoelectrical monitoring. First Break 29, 77–84.

Wilkinson, P.B., Loke, M.H., Meldrum, P.I., Chambers, J.E., Kuras, O., Gunn, D.A., Ogilvy, R.D., 2012. Practical aspects of applied optimized survey design for electrical resistivity tomography. Geophys. J. Int. 189, 428–440.

Wilkinson, P.B., Uhlemann, S.S., Chambers, J.E., Meldrum, P.I., Oxby, L.S., Kuras, O., 2013. Optimised Sequential Experimental Design for Geoelectrical Resistivity Monitoring Surveys. Near Surface Geoscience – 19th European Meeting of Environmental and Engineering Geophysics, Bochum, Germany, 9–11 September 2011.

Yilmaz, S., 2007. Investigation of Gu¨rbulak Landslide Using 2D Electrical Resistivity Image Profiling Method (Trabzon, Northeastern Turkey). J. Environ. Eng. Geophys. 12 (2), 199–205.

Zerathe, S., Lebourg, T., 2012. Evolution stages of large deep-seated landslides at the front of a subalpine meridional chain (Maritime-Alps, France). Geomorphology 138, 390–403.