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Review Article

A Review of the Advantages and Limitations of Geophysical Investigations in Landslide Studies

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Landslide deformations involve approximately all geological materials (natural rocks, soil, artificial fill, or combinations of these materials) and can occur and develop in a large variety of volumes and shapes. The characterization of the material inhomogeneities and their properties, the study of the deformation processes, and the delimitation of boundaries and potential slip surfaces are not simple goals. Since the '70s, the international community (mainly geophysicists and lower geologists and geological engineers) has begun to employ, together with other techniques, geophysical methods to characterize and monitor landslides. Both the associated advantages and limitations have been highlighted over the years, and some drawbacks are still open. This review is focused on works of the last twelve years (2007-2018), and the main goal is to analyse the geophysical community efforts toward overcoming the geophysical technique limitations highlighted in the 2007 geophysics and landslide review. To achieve this aim, contrary to previous reviews that analysed the advantages and limitations of each technique using a "technique approach," the analysis was carried out using a "material landslide approach" on the basis of the more recent landslides classification.

1. Introduction

Large landslides and smaller-scale mass movements are natural widespread processes that result in the downward and outward movement of slope-forming materials, significantly sculpting the landscape and redistributing sediment and debris to gentler terrain. The rapid population growth and the pressure from human activities have strongly influenced their extension and occurrence so that they have become disasters causing vast direct and indirect socioeconomic consequences [1]. These deformations involve approximately all geological materials (natural rocks, soil, artificial fill, or combinations of these materials) and can occur and develop in a large variety of volumes and shapes [2]. Artificial fills are usually composed of excavated, transported, and placed soil or rock, but they can also contain demolition debris, ash, slag, and solid trash. The term rock refers to hard or firm bedrock that was intact and in place prior to slope movement. Soil, either residual or transported material, is used for unconsolidated particles or poorly cemented rock or aggregates. Soil is usually further distinguished on the basis of texture as debris (coarse fragments) or earth (fine fragments) according to the well-established Varnes Classification [3]. Following the recent updating of [4], more reasonable use of geotechnical material terminology (clay, silt, sand, gravel, and boulders) is starting to spread, although some classical terminologies (mud, debris, earthflow, peat, and ice) are maintained after a recalibration of their definitions, because they have acquired a recognized status in landslide science by now. The Hungr classification includes aggregations of different materials that have been mixed by geomorphic processes such as weathering, mass wasting, glacier transport, explosive volcanism, or human activity. The use of geotechnical terminology is indeed most useful, as it relates best to the mechanical behaviour of the landslide as stated by [4] and even to most common investigation methods. In any case, the distinction between different materials is usually based on interpretation of the main geomorphic characteristics within landslide deposits but can also be inferred from the geological attributes of the involved parent material. The type of material is one of the most important factors influencing the movement of landslides, which can be categorized as falls, topples, spreads, slides, or flows according to their behaviour from the source area to the final deposit through distinctive kinematics [2, 3, 5]. Actually, the most common criterion used in landslides classification is based on the combination of the materials with the type of movement, but it is possible to find many other classification criteria, including velocities, volumes, water content, geotechnical parameters, and processes related to the formation of the mobilized material, among others. This is because, as stated by [5], engineering geology literature on landslides is affected by inconsistent terminology and ambiguous definitions from older classifications and current key terms for both specialists and the public. Currently, the most widely accepted and used classification is that of [2], which enhances the previous system devised by D.J. Varnes [3, 6]. Since then, only small improvements for specific categories have occurred, such as that for flow-like landslides by [5]. In 2014 Hungr et al. [4], by maintaining the consolidated concepts introduced by [2], redefined some basic elements (basically typology and material) that still refer to the original characterization of [3] and, consequently, updated the total amount of categories (from 29 to 32), along with revisiting some of their descriptions. This new landslides classification version (Table 1), which was proposed to simplify landslides studies, is increasingly circulating in the academic world, and for this reason, it is used as the reference in the present paper.

Characterizing landslide material inhomogeneities and their properties, studying the deformation processes, and delimiting boundaries and potential slip surfaces are not simple goals. They require the availability of a wide range of data, observations, and measurements (e.g., kinematic, geomorphologic, geological, geotechnical, and petro-physical data [7]) and the evaluation of geologic and hydrologic conditions related to phenomena occurrences [8]. To obtain the needed information, many techniques including both traditional methods (detailed geomorphological surveys, geotechnical investigations, local instrumentation, and meteorological parameters analyses) and more recent methods (remote-sensing satellite data, aerial techniques, and synthetic aperture radar interferometry) can be employed [[9, 10] and references within]. Among the latter, geophysical techniques are also included, since they are very useful in detecting the petro-physical properties of the subsoil (e.g., seismic wave velocity, electrical resistivity, dielectric permittivity, and gravitational acceleration [7]). Even though linking geophysical parameters and geological/geotechnical properties should always be supported with direct information (e.g., data from drillings), geophysical methods can provide the layered structure of the soil and certain mechanical parameters [11]. Therefore, because almost all of the advantages of geophysical methods correspond to disadvantages of geotechnical techniques and vice versa, the two investigation techniques can be considered complementary. Finally, the geophysical inversion data, and, therefore, the creation of a reliable subsoil model, is a complex and nonlinear problem that must be evaluated by taking into account all the available data on the site [11].

It is to be noted that the success of geophysical methods is mostly dependent on the presence of a significant and detectable contrast in the physical properties of different lithological units. However, in landslide characterization, geophysical contrast (i.e., differences in mechanical and physical properties) cannot be associated only with a boundary in mechanical properties (i.e., landslide boundaries) and therefore be of interest relative to the slope stability. These measured variations, in fact, could be local anomalies within the landslide or caused by the rough topography, and as a result, they could be of no or little interest [12]. This is why according to [11], the references for landslide investigation purposes are relatively few, and according to [13], there have been few landslides in which geophysical techniques were very useful. Nevertheless, the application of these techniques has changed over the years thanks to technological progress, the availability of cheaper computer electronic parts, and the development of more portable and faster equipment and new software for data processing [12], allowing the adequate investigation of 3D structures, which addresses one of the most ancient geophysical method limitations according to [11].

This review work, which starts from [11], is focused on the last twelve years of works (2007-2018) published in international journals and available online. The main goal was to analyse the geophysical community efforts in overcoming the geophysical technique limitations highlighted in the conclusion section of [11]. The drawbacks pointed out were as follows: (i) geophysicists have to make an effort in the presentation of their results; (ii) the resolution and penetration depth of each method are not systematically discussed in an understandable way; (iii) the geological interpretation of geophysical data should be more clearly and critically explained; (iv) the challenge for geophysicists is to convince geologists and engineers that 3D and 4D geophysical imaging techniques can be valuable tools for investigating and monitoring landslides; and finally, (v) efforts should also be made towards achieving quantitative information from geophysics in terms of geotechnical parameters and hydrological properties. To reach the aim, contrary to the four geophysics and landslide reviews discussed in section number 2 [8, 11, 12, 14] that analysed the advantages and limitations of each technique using a "technique approach," the analysis in this paper was carried out on the basis of a "material landslide approach" according to the recent landslide classification discussed above [4]. Finally, since it is beyond the aim of the work, we do not discuss the theoretical principles of the different geophysical techniques nor how to perform field surveys in this paper.

2. Geophysical Techniques and Landslides: The State of the Art of Review Papers

One of the first papers related to the application of geophysical techniques for the investigation of landslides, defined as a pioneering work by [11], is [8]. Herein, "landslides" are defined as a sudden or gradual rupture of rocks and their movement downslope by the force of gravity. In this paper, the main advantages of applying geophysical methods are as follows: (a) the rapid investigation of vast areas, collecting a larger number of sample points than those acquired by geologic engineering techniques; (b) the determination of the mechanical properties of wet and dry soils based on the measurements of large rock volumes directly involved in the processes; (c) the measured parameters reflect the combined geological and hydrological characteristics, which sometimes cannot be identified separately; and (d) the measurements

Table 1: Nomenclature of the newly proposed landslide classification version according to [4] based on the Varnes classification system. Words divided by / (slash symbol) have to be used alternatively. In italic movement types that usually reach extremely rapid velocities as defined by [2], while for the others, the velocity varies between extremely slow to very rapid (for details, refer to [4]).

TYPE OF MOVEMENT	ROCK	SOIL
Fall	*Rock/ice fall*	*Boulder/debris/silt fall*
Topple	*Rock block topple* Rock flexural topple	*Gravel/sand/silt topple*
Slide	Rock rotational slide *Rock planar slide* *Rock wedge slide* Rock compound slide *Rock irregular slide*	Clay/silt rotational slide Clay/silt planar slide *Gravel/sand/debris slide* *Clay/silt compound slide*
Spread	Rock slope spread	*Sand/silt liquefaction spread* *Sensitive clay spread*
Flow	*Rock/ice avalanche*	Sand/silt/debris dry flow *Sand/silt/debris flowslide* *Sensitive clay flowslide* *Debris flow* *Mud flow* Debris flood *Debris avalanche* Earthflow Peat flow
Slope Deformation	Mountain slope deformation Rock slope deformation	Soil slope deformation Soil creep Solifluction

can be repeated any number of times without disturbing the environment. Four main goals can be reached by applying vertical electric sounding (VES), seismic refraction (SR), self-potential (SP), and electromagnetic measurements (EM), listed as follows: (i) the investigation of the landslide geologic configuration, (ii) the investigation of the groundwater (determining the level and its fluctuation with time) as a landslide formation factor, (iii) the study of the physical properties and status of the landslide deposits and their changes with time, and (iv) the investigation of the landslide displacement process. Reference [8] also showed how electrical resistivity values and seismic waves velocities decrease between the bedrock and the rocks in the landslide body. Finally, in the conclusion section of [8], microseismic noise (SN) analysis is mentioned as a valuable method by which to characterize the slope soil strata.

Reference [14] conducted a review of the geophysical methods employed in landslide investigations. They highlighted that the selection of the method/s to be applied depends on its/their suitability for solving the problem. To estimate this adequacy, there are four main control factors: (i) the definition/understanding of the geophysical contrasts that have to be investigated, (ii) the evaluation of the characteristics (penetration depth and resolution) of the geophysical methods, (iii) the calibration of the acquired data by means of geological/geotechnical data, and finally, (iv) the signal-to-noise ratio. In the paper, several case studies are shown wherein the SR was successfully employed to determine the lower landslide boundary.

Ten years later, the SR, seismic reflection (SRe), electrical resistivity (ER), SP, EM, and gravimetry were discussed by [12] as the most frequently used methods in landslide characterization. For each method, the author gives (i) the theoretical principles, (ii) how to perform the measurements, (iii) the sources for those which are active techniques, and, finally, (iv) some expected results. Moreover, he presents some summary tables with the physical property ranges (e.g., those of the P-wave velocity, density, and electrical resistivity) of the most common soil and rock masses in their crude form (without taking into account variations caused by different clay contents, weathering, saturation, etc.). Finally, for each discussed method, [12] synthesizes in one table its suitability for use in landslide characterization, human artefact (like pipes and foundations) identification, and physical properties determination for geotechnical purposes. Overall, the SP method results are not or only marginally suitable in all fields. Nevertheless, in the same year, [15] and, later, [16–18] showed how the SP method could be helpfully employed. From the table in [12], the seismic tomography and 2D and 3D geo-electric results correspond to the best methods for use in landslide characterization.

Reference [11] presents the state of the art of the geophysical techniques applied in landslide characterization based on papers after 1990. According to this review, the methods could be divided into seldom, widely, and increasingly used categories. Among the first methods they enumerate are SRe, ground penetrating radar (GPR), and gravimetry, while among the second group are SR, ER VES, or tomographies (ERT), and SP, and, finally, among the third group are SN, surface waves (SW), and EM. Moreover, they indicate seismic tomography (ST) as method useful only for limited site conditions (rock slides). They synthetize in a table (a) the main geophysical methods used, (b) the measured geophysical parameters and information type, (c) the geological context, (d) the landslide classification following [2], (e) the geomorphology, and (f) the applications (targets). According to the review in [11], there are three main advantages and three main limitations in employing geophysics for the subsurface mapping of landslides. As benefits of the geophysical methods, the author enumerates (i) the flexibility and the relative efficiency on slopes; (ii) the noninvasiveness and the generation of information on the internal structures of soil or rock masses; and (iii) the allowance of examining large volumes of soil. As drawbacks, he highlights that (i) the resolution, which is dependent on the signal-to-noise ratio, decreases with depth; (ii) the solution for a set of data is nonunique, and the results must be calibrated; and (iii) these methods yield indirect information on the subsoil, such as physical parameters rather than geological or geotechnical properties. One of the main conclusions of the review is that in landslide characterization, the geophysical survey design is still a much-debated question, and no unique strategy has arisen from the literature.

Reference [11] is the last review published in an international journal and available online that focused on the advantages and limitations of the geophysical methods applied in landslides characterization. Reference [19], in fact, discusses, by means of case studies, benefits and drawbacks of the most common geophysical techniques (GPR, ER, and SR) in geomorphological applications. Therefore, in this paper landslides are just one of the possible fields of application. Two more recent reviews about geophysics and landslides are [20, 21]. The first is focused only on the ERT technique applied in landslide investigations and analyses the advantages and limitations of 2D-, 3D-, and 4D-ERT (or time-lapse ERT: tl-ERT) surveys based on papers of the period from 2000 to 2013. The second is a review of the current state of the art and the future prospects of the near surface geophysical characterization of areas prone to natural hazards (e.g., landslides, rockfalls, avalanches and rock glaciers, floods, sinkholes and subsidences, earthquakes, and volcanos) published in a book series (and, therefore, not freely available online for download), wherein the analysis of the geophysical techniques applied in landslides characterization is limited to subsections of the case study section.

3. Geophysical Techniques and Landslides: A "Landslide Approach" Analysis

As mentioned in Introduction, this review work is based on a "material landslide approach" analysis on the basis of the more recent landslide classification presented by [4] and discussed in Introduction. Even though this classification is not widely employed (only 20% of the analysed papers from the years 2015-2018 adopted it, and these papers are marked with # in Tables 2 and 3), we decided to use it considering that the same landslide could assume different names from paper to paper, though the authors could be more or less the same. Among the analysed papers, examples are the Super Sauze landslide and the La Vallette landslides (marked in Table 2 with (°) and (°°), respectively) or the Randa landslide (marked with (°) in Table 3). This means that the analysed works are clustered and discussed in two groups, "soil" and "rock," respectively, on the basis of the material landslide type (columns 2 and 3 of Table 1).

Moreover, we decided to analyse the works starting from 2007 because the review in [20] is focused only on the ERT technique application; nevertheless, we do not analyse in detail all references already discussed therein, but we synthetize the results. The results of the review analysis are summarized in Tables 2 and 3, where for each work, we specify: (a) the landslide typology according the authors of the paper (i.e., how they refer to the landslide in the text) and (b) according to the classification from [4] (where possible, since sometimes it is not easy to identify the landslide classes from [4] on the basis of only the text); (c) the materials involved in the landslides; (d) which geophysical methods and (e) which other traditional techniques were employed; and (f)-(l) how many efforts were performed to overcome the five drawbacks highlighted by [11] and listed in Introduction. To quantify these efforts, a three-level scale was employed, where +, -, and n.d. mean, respectively, that many/some, insufficient, and nondiscussed efforts were made to overcome the limitations. Unfortunately, we know that the evaluation of how many efforts were performed could seem subjective. Therefore, in Table 4, for each drawback, we summarize how we evaluated the efforts.

3.1. "Soil" Landslides. "Soil" landslides, with respect to "rock" landslides, are the typology most studied with geophysical techniques. Among the 120 analysed papers, more than half (e.g., 66 papers, which means 75 landslides analysed without considering those reported in [20]) were about "soil" landslides, and among them, more than half were on the flow type. As summarized in Table 5, in fact, no one was focused on falls, topples, or spreads, while 28 landslides (the 37.3%) were analysed focused on the slide (6 clay/silt rotational slides, 8 clay/silt planar slides, 11 rotational and planar slides, 1 debris slide, and 2 clay/silt compound slides), 41 (the 54.6%) on the flows (5 sensitive clay flowslides, 9 debris flows, 5 mud flows, and 22 earthflows), and 6 (the 8.1%) on the slope deformations (soil slope deformation). Only two of the analysed landslides were marine landslides [33, 35], indicating that it is not easy to conduct geophysical surveys to characterize landslides that dive into the sea. It is also

Table 2: This table summarizes the analysed scientific papers from the last twelve years (2007-2018) focused on "soil landslide". The landslide typology and materials are defined as in the papers themselves. Moreover, where possible, we added the landslide classification according to [4]. Papers marked with # already adopted this classification. Papers marked with (°) and (°°) focus on the Super Sauze and La Vallette landslides, respectively. Drawbacks 1 to 5 are the limitations of the geophysical techniques applied to landslide characterizations pointed out by [11]. They are, respectively, as follows: *Drawback 1*: geophysicists have to make an effort in the presentation of their results; *Drawback 2*: the resolution and the penetration depth of each method are not systematically discussed in an understandable way; *Drawback 3*: the geological interpretation of geophysical data should be more clearly and critically explained; *Drawback 4*: the challenge for geophysicists is to convince geologists and engineers that 3D and 4D geophysical imaging techniques can be valuable tools for investigating and monitoring landslides; and *Drawback 5*: efforts should also be made towards obtaining quantitative information from geophysics in terms of geotechnical parameters and hydrological properties. +, -, and n.d. mean, respectively, that many/some, insufficient, and non-discussed efforts were made to overcome the limitations (see Table 4), while +* means that the interpretation is linked to a numerical model or landslide feature identification. VES: vertical electrical sounding, ERT: electrical resistivity tomography, IP/SIP: induced polarization/spectral induced polarization, SP: self-potential, SPT: self-potential tomography, F/TDEM: frequency/time domain electro magnetism, VLF-EM: very low-frequency electro magnetism, EM: electro magnetism, RMT: radio magnetotelluric, AE: acoustic emission, SN: seismic noise, SR: seismic refraction, SRe: seismic reflection, SW: surface waves, DH: downhole, CH: crosshole, GPR: ground penetrating radar, MG: micro gravity, DTM: digital terrain model, SAR: synthetic aperture radar, GB-InSAR: ground based interferometric SAR, GPS: global position system, TS: total station, TLS: terrestrial laser scanners, CPT: cone penetration test, TDR: time domain reflectometry.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2007	[22] (°)	mudslide	earthflow	clay formation	SN (local)	GPS, geodetic and strain instrument, piezometer	-	n.d.	n.d.	n.d.	n.d.
2007	[23]	earthflow (the oldest movement), clay planar slide (reactivations)	earthflow	clay body over mudstone-shale basement	ERT, SR, SW, SN (local), DH	SAR data, inclinometers, stratigraphy	+	+	-	n.d.	n.d.
2007	[24]	/	/	mudstone, colluvium, limestone and carbonate breccia	SN (regional)	/	-	n.d.	-	n.d.	+
2007	[25] (°)	intra-material mudslide	earthflow	clay formation	SR, ERT, SW, SN (local)	boreholes	+	-	+	n.d.	+
2007	[26]	rock and debris flows	rock avalanche and debris flows	/	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2007	[27] (°)	(a) soft-rock (mudslide or clayey flow-like landslide) (b) translational landslide	(a) earthflow (b) clay planar landslide	clay formation	SN (local), ERT	(a) geology, geomorphology, geotechnics and hydrology (b) geomorphology and geotechnics	+	+	-	-	n.d.
2008	[28]	earthflow	earthflow	loess	ERT, SR, SN (local)	DEM	-	n.d.	+	n.d.	+

Table 2: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2008	[29]	/	/	mudstone, colluvium, limestone and carbonate breccia	SN (local)	/	-	n.d.	-	n.d.	+
2009	[30]	debris flow	debris flow	metasediments, gneisses, quartzites	SN (local)	meteorological data	+	n.d.	+*	n.d.	n.d.
2009	[31]	earthflow	earthflow	flysch, calcareous Alps	SRe	boreholes, DEM	-	n.d.	+	n.d.	n.d.
2009	[32]	earthflow	earthflow	coarse components in silty-clayey matrix	SR, SRe	boreholes	-	n.d.	n.d.	n.d.	n.d.
2009	[33]	/	clay rotational and planar slide	/	SRe	/	-	-	-	n.d	n.d.
2010	[34]	sandy-clay translational landslide	clay planar slide	marly limestone	ERT	piezometer, field observations, boreholes	-	n.d.	+	n.d./+	+
2010	[35]	translational slope landslide	clay rotational slide, sensitive clay flowslide	marine and glaciomarine clay (Fjord-deltaic sediments)	seismic sub-bottom profile	boreholes, CPT, geotechnical test, trenches, bathymetric data	+	n.d.	+	n.d.	n.d.
2010	[36]	deep landslide	clay/silt rotational slide, mud flow	glaciolacustrine clays	SN (local)	inclinometers, boreholes, GPS	+	n.d.	+	+/n.d.	n.d.
2010	[37]	debris slide	debris slide	schist and gneiss	VLF-EM, VES	boreholes, TS	-	n.d.	-	n.d.	n.d.
2010	[38]	composite multiple earth slide – earth flow	earth flow	mudstone, sandstone	ERT	GPS	+	+	-	n.d./+	n.d.
2011	[39]	deep-seated landslide	soil slope deformation	coarse colluvium over mudstone	SN (local)	/	-	n.d.	+	n.d.	+

Table 2: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2011	[40]	/	clay compound slide	sandy, silty clay	SN (local)	meteorological data, extensometers, SR, robotic TS	-	n.d.	+	n.d.	-
2012	[41]	clayey landslide	earthflow	black marls	SR	geometrical model, DEM	+	-	+	n.d.	n.d.
2012	[42]	many	/	black marl	ERT, SR, SW	/	-	n.d.	+	n.d.	+
2012	[43] (°°)	intra-material landslide	rotational and planar slide, mud flow	clay-shale deposits	ERT, SR, SW	/	-	-	+	n.d.	+
2012	[44]	debris flow	debris flow	/	SN (regional)	/	-	n.d.	+*	n.d./-	n.d.
2012	[45]	complex retrogressive rot-translational slide	rotational and planar slide	schist, flysch	ERT	TDR, weather station	+	n.d.	-	n.d./+	-
2012	[46] (°°)	flow-like landslide	rotational and planar slide, mud flow	black marls	3D-SR	boreholes, SR, ERT	+	n.d.	+	+/n.d.	n.d.
2012	[7] (°)	flow-like landslides (mudslides)	earthflow	/	SR, ERT, GPR, EM, MG	many	+	+	+	n.d	n.d.
2012	[47]	deep-seated landslide	soil slope deformation	/	SN (regional)	/	-	n.d.	+*	n.d.	n.d.
2013	[48]	quick clay landslide	sensitive clay flow-like	clay	ERT, IP	resistivity CPT, geotechnical test	-	n.d.	+	n.d	n.d.
2013	[49]	deep-seated landslide	soil slope deformation	clay-rich formation and colluvial deposits	SN (local)	/	-	-	+	n.d.	n.d.
2013	[50]	shallow landslide	planar slide-earthflow	silty sand, marlstone, sandstone	ERT	TRD, tensiometer	-	-	+	n.d./+	+

Table 2: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2013	[51]	earth flow (quick clay landslide)	sensitive clay flowslide	quick clay	2D and 3D SR, SRe, SN (local), 2D and 3D ERT, EM, GPR, RMT, MG	boreholes, CPT, LiDAR, geotechnical test	-	n.d.	+	-/n.d.	n.d.
2013	[52]	earth flow (quick clay landslide)	sensitive clay flowslide	quick clay	SRe	boreholes, CPT, LiDAR, geotechnical test, ERT, IP	-	n.d.	+	-/n.d.	n.d.
2013	[53]	/	clay/silt rotational slide	gravel, sand, and plastic and non-plastic fines from quartzite, phyllite, slate, and limestone	ERT, IP, MG	geotechnical analysis	-	n.d.	-	n.d.	n.d.
2013	[54]	surficial failures along a planar soil/rock interface	clay/silt planar slide	clayey sand, silty sand, sandstone	ERT	boreholes, geotechnical analysis, meteorological station, TDR. piezometer	-	n.d.	-	n.d./-	+
2013	[55]	muddy landslide	debris flow, rock fall	(a) black marls, (b) flysch and clay-shale	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2013	[9]	mudslide and rotational/planar slide (°°)	planar slide	black marls, flysch	SR	LiDAR, TLS, field investigations, GPS, DEM	+	n.d.	+	n.d.	n.d.
2013	[56]	deep-seated landslide	soil slope deformation	/	SN (local)	LiDAR	-	n.d.	+*	n.d.	n.d.
2014	[57]	transitional slide	clay planar slide	clay sandy calcarenitic succession	2D and 3D ERT, SR, SN (local), SW	boreholes	+	n.d.	+	+/n.d.	n.d.
2014	[58]	/	/	/	SN (local)	/	-	n.d.	n.d.	n.d.	+
2014	[59]	composite rotational landslide (complex landslide)	clay rotational landslide	marls, chalks	ERT, SR	field investigation, aerial orthophotographs, LiDAR, boreholes, DEM	+	n.d.	+	n.d.	n.d.

Table 2: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2014	[60]	complex, composite, successive earth-slide earth flow	clay/silt rotational slide, earthflow	mudstone	ERT	boreholes, LiDAR, aerial photos, DEM, GPS, inclinometer	-	n.d.	+	+/n.d.	-
2014	[20]	many	/	many	ERT (ERT technique review paper)	many	+	-	-	+/+	n.d.
2014	[61]	deep-seated gravitational deformation dismantled into slides and flows	clay/silt rotational and planar slide, earthflow, creep	boulders, gravel and coarse sand over argillites and limestone	SRe, ERT	inclinometers, boreholes, SR	+	n.d.	-	n.d.	n.d.
2014	[62]	(a) and (b) rotational-translational landslide	(a) and (b) clay rotational/planar slide	(a) colluvium, (b) colluvium and amphibolite	ERT	inclinometer, 3D displacement measures, piezometric water level, soil temperature	+	+	+	n.d./+	n.d.
2015	[63] (#)	debris flow	debris flow	glacial till, outwash sediments	SN (regional)	LiDAR, GIS, numerical modelling	+	n.d.	+*	n.d.	n.d.
2015	[64]	debris flow	debris flow		SN (regional)	/	-	n.d.	+*	n.d.	n.d.
2015	[65]	earth-flow	earthflow	sandstone and limestone	ERT	GPS	+	n.d.	n.d.	+	n.d.
2015	[66]	earthflow	earthflow	marl, claystone, mudstone, alluvium, limestone	ERT, SP,	/	-	n.d.	+	n.d.	n.d.
2016	[67] (#)	shallow clay planar slide	clay planar slide	plastic blue marls, limestone, blue clays	ERT	GPS, aerial photo, boreholes, auger and penetration, geotechnical analysis, rainfall and groundwater level data	+	-	+	n.d.	n.d.
2016	[68] (°)	clayey landslide	earthflow	black marls	ERT	/	+	+	+	n.d./+	-

Table 2: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2016	[69]	shallow creeping landslide	soil slope deformation	clayey silt, mild clay and gravelly sand, covered by grass peat and turf. (bedrock: mudstone, sandstone)	ERT, GPR	boreholes	-	n.d.	-	n.d.	n.d.
2016	[70] (#)	debris flow	debris flow	sandstone, claystone, siltstone, volcanic rocks, Quaternary sediments	ERT, EM, SP, MG	gamma-ray, soil Radon, boreholes, GPS	-	n.d.	-	n.d.	n.d.
2016	[71]	translational landslide	clay/silt planar slide	silty clay with gravels over sandstone and mudstone	ERT	boreholes, inclinometers, piezometers, pluviometer, osmometer	+	n.d.	+	n.d./-	n.d.
2016	[72]	quick-clay landslide	sensitive clay flowslide	quick clay	FDEM, ERT, SR, SW	LiDAR, geotechnical test, resistivity-CPT, boreholes	+	n.d.	+	n.d.	n.d.
2016	[73]	loess landslide	clay/silt rotational slide	sandy and clayey loess	ERT	/	-	-	+	n.d.	+
2016	[74] (#)	multiple earth slide-earth flow	earth flow	mudstone, sandstone	SR	3D-ERT, geotechnical analysis	+	-	+	n.d.	-
2016	[75]	complex landslide	clay compound slide	clays, sands, gravels	SW, SN (local), VES	borehole	+	-	+	n.d.	n.d.
2017	[10]	(a), (b) complex roto-translational landslide	(a) clay/silt rotational and planar slide (b) clay/silt rotational and planar slide, earthflow	limestone	SN (local)	boreholes, inclinometers,	+	n.d.	-	+/n.d.	n.d.
2017	[76]	debris flow	debris flow	schists, dolobreccias, quartzites	SN (local)	flow stage sensors	-	n.d.	+*	n.d.	n.d.
2018	[77]	Sackung-like movement	soil slope deformation	sandstone, colluvium Quaternary deposits	ERT, SR, SN (local)	boreholes, geotechnical analysis, DEM, remote images, GPS	+	n.d.	+	n.d.	n.d.

Table 2: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2018	[78]	flow-like landslide	rotational and planar slide, mud flow	sandstone, limestone	IP, SIP	LiDAR, GPS, boreholes geotechnical analysis, ERT, SR	+	-	+	n.d.	n.d.
2018	[79]	roto-translational slide, earth slide and flows	clay/silt rotational and planar slide, earthflow	flysch, metamorphic rocks	SN (local), ERT	DTM, aerial images	-	n.d.	+	n.d.	n.d.
2018	[80]	/	earth flow (?)	sandstone, shale, coal shale, marl, clay, silt	ERT	boreholes, geotechnical analysis, SPT, field investigations	+	-	+	n.d./+	+
2018	[81]	(a) mudflow, (b) debris flow	(a) mud flow, (b) debris flow	/	SN (local), AE	ultrasonic gauge, video cameras	+	n.d.	+*	n.d./-	n.d.
2018	[82]	loess landslide	clay/silt rotational slide	clayey and sandy loess	ERT	pressure pore	-	n.d.	+	n.d.	n.d.
2018	[83] (#)	(a), (b) clay-rich debris slide (clayey landslide)	(a), (b) earthflow	clay-rich matrix, marls and limestone	SN (local)	/	+	n.d.	+*	n.d.	n.d.

Table 3: This table summarizes the analysed scientific papers from the last twelve years (2007-2018) focused on "rock landslide". Landslide typology and materials are defined as in the papers themselves. Moreover, where possible, we added the landslide classification according to [4]. Papers marked with # already adopted this classification. Papers marked with (°) focus on the Randa landslides. Drawbacks 1 to 5 are the limitations of the geophysical techniques applied to landslide characterizations pointed out by [11]. They are, respectively, as follows *Drawback 1*: geophysicists have to make an effort in the presentation of their results; *Drawback 2*: the resolution and penetration depth of each method are not systematically discussed in an understandable way; *Drawback 3*: the geological interpretation of geophysical data should be more clearly and critically explained; *Drawback 4*: the challenge for geophysicists is to convince geologists and engineers that 3D and 4D geophysical imaging techniques can be valuable tools for investigating and monitoring landslides; and *Drawback 5*: efforts should also be made towards obtaining quantitative information from geophysics in terms of geotechnical parameters and hydrological properties. +, -, and n.d. mean, respectively, that many/some, insufficient, and non-discussed efforts were made to overcome the limitations (see Table 4), while +* means that the interpretation is linked to a numerical model or landslide feature identification. VES: vertical electrical sounding, ERT: electrical resistivity tomography, IP/SIP: induced polarization/spectral induced polarization, SP: self-potential, SPT: self-potential tomography, F/TDEM: frequency/time domain electro magnetism, VLF-EM: very low-frequency electro magnetism, EM: electro magnetism, RMT: radio magnetotelluric, AE: acoustic emission, SN: seismic noise, SR: seismic refraction, SRe: seismic reflection, SW: surface waves, DH: downhole, CH: crosshole, GPR: ground penetrating radar, MG: micro gravity, DTM: digital terrain model, SAR: synthetic aperture radar, GB-InSAR: ground based interferometric SAR, GPS: global position system, TS: total station, TLS: terrestrial laser scanners, CPT: cone penetration test, TDR: time domain reflectometry.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2007	[84]	Rockfall/debris flows	rock fall, debris flow	basaltic	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2007	[85]	rock fall	rock fall	limestone	GPR	boreholes, mining	-	-	+	n.d.	n.d.
2007	[26]	rock and debris flows	rock avalanche and debris flows	/	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2007	[86] (°)	rock fall	rock fall	heterogeneous gneisses	SN (local), 3D-SRT	boreholes, GPR, geodetic, geotechnical, meteorological monitoring system	+	n.d.	-	+/n.d.	n.d.
2008	[87]	rock fall	rock fall	limestone	ERT, GPR	TLS, photogrammetry	+	-	+*	n.d.	n.d.
2008	[88]	rock fall and rock-fall avalanches	rock fall and rock avalanche	limestone, amphibolite, granite	SN (regional)	/	-	n.d.	+*	n.d.	n.d.
2008	[89]	rockfall	rock fall	lava dome	SN (regional)	/	-	n.d.	+*	n.d	n.d.
2008	[90]	rotational sliding	rockslide (any specific typology emerged)	marl and schist	airborne EM, ERT, geophysical logs, SP	boreholes, geotechnical test, hydrophysical logs, DEM, gamma ray spectrometer, inclinometers	-	-	+	n.d/-	n.d.

Table 3: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2008	[91]	rockfall (artificial)	rock fall	/	SN (local)	videos, photos	+	n.d.	+*	n.d.	-
2008	[92] (°)	rockslide	rock wedge slide	heterogeneous gneisses	SR, GPR,	boreholes, field mapping	+	-	+	-/n.d.	n.d.
2009	[93]	rockfall	rock fall	metalliferous limestone	SN (local)	TS, TLS	+	+	-*	n.d.	n.d.
2009	[94]	rock-fall	rock fall	chalk	SN (local)		+	n.d.	-*	n.d.	n.d.
2010	[95]	rockfall	rock fall	othogneisses	SN (local)	thermometer	-	n.d.	-*	n.d.	n.d.
2010	[96]	rockslide	rock block toppling	heterogeneous gneisses	SN (local)	GPS	+	n.d.	+*	n.d.	n.d.
2010	[97]	rockslide	rock compound slide	meta-granodiorite and two-mica gneiss	SN (local)	GPS, meteorological data	-	n.d.	+	n.d.	n.d.
2010	[98]	rock slice collapse	rock rotational slide	limestone	SN (local)	extensometer	-	n.d.	+*	n.d.	n.d.
2010	[99]	rockslide	rock fall	micaschists	SN (local)	meteorological station, GPS	+	n.d.	+*	n.d.	n.d.
2010	[100]	rock fall	rock fall	limestone and marly limestone	SN (local), SR	extensometer	+	n.d.	+*	n.d.	n.d.
2010	[101]	rock-ice avalanche	rock/ice avalanche	plutonic rocks	SN (regional)	DEM	-	n.d.	+*	n.d.	n.d.
2010	[102]	deep-seated with several debris flow	rock slope deformation	flysh and evaporites	SR, SRe	/	+	n.d	+	n.d.	n.d.
2011	[103]	rockslide	many	many	SN (regional)	/	-	n.d.	+*	n.d.	n.d.
2011	[104]	rockfall	rock fall	volcanos	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2011	[105]	rockslide	rock fall	micaschists	SN (local)	GPS, boreholes	+	+	+*	n.d.	n.d.
2011	[106]	rockfall	rock fall	limestone	SN (local), SR		-	n.d.	+*	n.d	n.d.

Table 3: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2011	[107]	rock slope	rock block toppling	paragneiss and schists	SN (local)	regional earthquakes, fibre optic strain sensors	+	n.d.	+*	n.d.	n.d.
2011	[108]	rockslide (long-runout)	rock planar slide	flysch (clay-stone/mudstone sequence)	ERT	radiocarbon and dendrogeomorphological analysis, geomorphic mapping, GPS, geotechnical analysis	+	n.d.	+	n.d.	n.d.
2011	[109]	deep-seated gravitational slope deformation	mountain slope deformation	flysch	ERT	field survey, kinematic analysis, trenches	+	-	+	n.d.	n.d.
2012	[110]	rock fall (precondition for)	rock fall	granitic gneiss	AE	meteorological data	-	-	+*	n.d.	n.d.
2012	[111]	/	rock fall/rock block topple (?)	orthogneiss	SN (local)	/	+	n.d.	+*	n.d.	n.d.
2012	[112]	rock-fall	rock fall	gneiss and gabbro	SN (local)	thermometers, GPS	-	n.d.	+*	n.d./-	n.d.
2012	[113]	rockfall and lateral spreading	rock fall	limestone, clay formation	SN (local)		+	n.d.	+	n.d.	n.d.
2012	[114]	rockfall in the source area of a mudslide	rock fall	black marls	SN (regional)	extensometers, DEM	+	n.d.	+*	n.d.	n.d.
2012	[115]	rockfall	rock fall	flysch, marls and limestone	SN (local)	meteorological and hydrological data, local seismicity	+	n.d.	+*	n.d./-	n.d.

Table 3: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2013	[116]	rockslide-debris flow	rock irregular slide, debris flow	rhyodacite breccias, tuff	SN (regional)	/	-	n.d.	+*	n.d.	-
2013	[117]	(a), (b), and (d) toppling/basal sliding, (c) rock compound slide	(a), (b), and (d) rock block topple, (c) rock compound slide	(a) argillites (b) and (d) limestone (c) shale- sandstone series	SN (local) (a) SR, (c) ST	meteorological station (a) displacement measures, (b) and (c) extensometers,	-	n.d.	+	n.d.	n.d.
2013	[118]	many: rockfall, debris avalanche, slides	many: rock fall, debris avalanche (any specific soil or rock emerged)	many (not specified)	SN (regional/catchment)	meteorological data, satellite images, aerial photos	+	n.d.	+*	n.d.	n.d.
2013	[119]	plan and toppling failures	/	mainly claystone and siltstone	VES	DEM	-	n.d.	-	n.d.	n.d.
2013	[55]	muddy landslide	debris flow, rock fall	(a) black marls, (b) flysch and clay-shale	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2014	[120]	rockfall	/	limestone	SN (local)	LiDAR, photogrammetry, video cameras, extensometer, tiltmeter	+	n.d.	+*	n.d.	n.d.
2014	[121]	rockfall	rock fall	volcanos	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2014	[122]	deep-seated landslide	mountain slope deformation	flysch, sandstone	ERT	field survey	+	n.d.	+	n.d.	n.d.
2015	[123]	rockslide	/	argillaceous materials intercalated with mudstone/limestone	ERT, VES, SR		-	n.d.	+	n.d.	n.d.
2015	[124] (#)	tilting and rock fall	rock slope spread	dolomite	ERT	TLS, GPS	+	n.d.	+	+/n.d	n.d.

Table 3: Continued.

Year	Reference	Landslide typology (as defined by the author/s)	Landslide typology (according [4])	Material	Geophysical Technique/s	Other available data	Drawback 1	Drawback 2	Drawback 3	Drawback 4	Drawback 5
2016	[125]	rockfall	rock fall	granite	CH, SR	geotechnical analysis, crackmeters, temperature probes, inclinometers, SN	-	n.d.	+	n.d.	+
2016	[126] (#)	21 landslides: 12 rock falls, 8 rock slides and 1 rock avalanche	21 landslides: 12 rock falls, 8 rock slides (any specific typology emerged) and 1 rock	many	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2016	[127]	rockslide	planar rockslide, rock fall, debris avalanche	dolomite	SN (regional)	/	-	n.d.	+*	n.d./-	n.d.
2017	[128]	rockfall	rock fall	limestone	SN (local)	TLS	+	+	+*	n.d.	n.d.
2017	[129]	rockfall	rock fall	limestone	SN (local)	GPS, photo camera	+	n.d.	+*	n.d.	n.d.
2017	[130]	rock slide	rockslide (any specific typology emerged)	paragneiss	SW, SN	/	-	n.d.	+	n.d.	n.d.
2017	[131]	rockfall	rock fall	black marls	SN (local)	/	-	n.d.	+*	n.d.	n.d.
2017	[132]	deep-seated landslide	mountain slope deformation	sedimentary rocks and flysch	ERT, GPR, SR, MG	field survey, GPS	+	-	+	n.d.	n.d.
2018	[133]	rockfall	rock fall	limestone	SN (local)	weather station, DEM	-	n.d.	+*	n.d.	n.d.
2018	[134]	rock slide	rock compound slide, rock fall, debris avalanche	amphibolitic and augen gneiss	SN (local)	extensometers, meteorological station, GPS	+	n.d.	+*	n.d.	n.d.
2018	[135]	rockfall	rock fall	limestone	SN (local)	extensometer, meteorological data	+	n.d.	-	n.d./-	n.d.

Table 4: For each drawback, this table explains how the three-level scale (+, -, and n.d., which mean that many/some, insufficient, and non-discussed efforts were made to overcome the limitations) was applied.

	+	-	n.d.
Drawback 1	(i) Coloured figures (ii) 3D figures (iii) Figures with interpretations	(i) B&W figures (ii) Non-interpreted figures (iii) Figures too small (iv) Only raw data	/
Drawback 2	There is wide discussion about the technique/s penetration depth and/or resolution	There are only some mentions of the technique/s penetration depth and/or resolution	There are no mentions of the technique/s penetration depth and/or resolution
Drawback 3	There is wide discussion about the geological interpretation of the geophysical data	There are only some mentions of the geological interpretation of the geophysical data	There are no mentions of the geological interpretation of the geophysical data
Drawback 4	3D/4D data are presented and discussed	3D/4D data are presented but they are not discussed in depth	No 3D/4D data are presented or discussed
Drawback 5	There is wide discussion on how to link geophysical data with geotechnical and/or hydrological properties	There are only some mentions of how to link geophysical data with geotechnical and/or hydrological properties	There are no mentions of how to link geophysical data with geotechnical and/or hydrological properties

Table 5: For each type of movement and "soil" landslide typology, the table summarizes how many papers are focused on it. In italic movement types that usually reach extremely rapid velocities as defined by [2], while for the others, the velocity varies between extremely slow to very rapid (for details, refer to [4]).

TYPE OF MOVEMENT	Number of papers	SOIL	Number of papers	
Fall	/	*Boulder/debris/silt fall*	/	
Topple	/	*Gravel/sand/silt topple*	/	
Slide	28	Clay/silt rotational slide	6	11
		Clay/silt planar slide	8	
		Gravel/sand/debris slide	1	
		Clay/silt compound slide	2	
Spread	/	*Sand/silt liquefaction spread*	/	
		Sensitive clay spread	/	
Flow	41	Sand/silt/debris dry flow	/	
		Sand/silt/debris flowslide	/	
		Sensitive clay flowslide	5	
		Debris flow	9	
		Mud flow	5	
		Debris flood	/	
		Debris avalanche	/	
		Earthflow	22	
		Peat flow	/	
Slope Deformation	6	Soil slope deformation	6	
		Soil creep	/	
		Solifluction	/	

important to point out that in our analysis, we do not consider papers focused on the geophysical characterization of quick-clay that could evolve into a sensitive clay flowslide but only papers focused on those that already occurred [35, 51, 52, 72].

In only 8 works (12.1% of the analysed "soil" landslide works), it is possible to find a detailed discussion of the theory applied to landslides, concerning either how to formulate the inversion problem [41, 46, 52, 55, 68, 83] or how to combine data from different surveys [7, 42]. All the other papers deal with the discussion of a case study.

A detailed analysis of the applied techniques is discussed in Section 4. Below, we present only the main considerations from some papers. ERT is an active geophysical method that can provide both 2D and 3D images of the subsoil. A wide review of this technique applied to landslides is provided in [20]. Therefore, here, we limit discussion to saying that in most papers (29 of 33 that present ERT applications, i.e., 88.0%), 2D ERTs are shown, while only in 6.0% (2 papers of 33), 3D ERTs are shown, and in the remaining 6.0% (2 papers of 33), both 3D and 2D applications are presented.

Since the '60s, passive seismic techniques have been developed to monitor and characterize signals triggered by landslide dynamics and related changes in the material mechanical properties (i.e., (i) material bending, shearing, or compression; (ii) fissure opening; (iii) slipping at the bedrock interface; and (iv) debris flows or mudslides) [22, 55]. They are of great interest in (a) detecting debris flows [30], (b) assessing site effects [24, 29], (c) detecting landslide slip surfaces [10], and (d) estimating the thickness of a material that could be mobilized by a landslide [136]. Another advantage of this method is its ability to detect remote events that might otherwise go unnoticed for weeks or months. The main difficulties arise from two issues: (i) the seismic signatures of landslides and mud/debris flows are very complex and cannot be effectively identified without a detailed waveform analysis and (ii) the epicentres of landslides and mud/debris flows cannot be confidently determined by conventional earthquake-locating methods, mainly due to the lack of clear arrivals of P and S phases [44].

3.2. "Rock" Landslides. Among the 120 analysed papers, less than half (e.g., 54) were about "rock" landslides, and the majority discussed were of the rock fall type. As summarized in Table 6 the landslide typology is divided as follows: 41 (the 54.6%) falls, 5 (the 6.7%) topples (5 block topples), 18 (the 24.0%) slides (1 rotational, 2 planar, 1 wedge, 3 compound, 1 irregular), 1 (the 1.3%) spread (rock slope spread), 6 (the 8.0%) flows (avalanches), and 4 (the 5.4%) slope deformations (3 mountain slope deformations and 1 rock slope deformation). In all the works that discuss the application of seismic techniques [26, 55, 84, 86, 87, 89, 91, 93–101, 103–107, 111–118, 120, 121, 126–128, 130, 131, 133, 134], it is possible to find a more- or less-detailed discussion on the theory of the seismic wave analysis carried out to find the "rock" landslide features.

"Rock" landslides are well-known phenomena but are poorly understood. Contrary to other landslide types, rockfalls are usually sudden phenomena with few apparent precursory patterns observed prior to the collapse. A key point in the prediction of rock slope failure is better knowledge of the internal structure (e.g., the persistence of joints), which requires an interdisciplinary research field among rock mechanics, rock engineering, and mining [98]. This is why in 64.8% of the analysed papers, the geophysical technique is carried out along with more traditional methods (i.e., boreholes, mining, extensometers, and inclinometers). Moreover, there are at least two limitations in applying geophysical methods for rock deposits: (a) the difficulty of deploying sensors (i.e., ER electrodes, geophones, or GPR antennas) on sharp and blocky ground with a high void ratio and (b) the low geophysical contrast between the rock deposit and the underlying layers with comparable properties [[137], not listed in Table 3 because it was already analysed by [20]]. In [137], there is another limitation in applying geophysics for rock deposits: the presence of a shallow geophysical contrast caused by the subsoil water table that could mask deeper interfaces. Nevertheless, this limitation also has to be considered for "soil" landslides.

More recently, to overcome these limitations, rock slope stability characterization and monitoring has been carried out using passive seismic techniques (see also the discussion session), implemented initially in open-mine monitoring [98]. These techniques, in fact, could help in (i) understanding the seismic responses of rock to slope deformation (e.g., the release of stored elastic energy under particular conditions) [135, 138], (ii) detecting and locating microearthquakes generated by fracturing within unstable rock masses (major effort is required for classifying seismic signals and extracting those related to landslides [86, 99, 129]), and (iii) identifying remote events that could otherwise go unnoticed for weeks or months. Therefore, these methods are applied to avalanches [26, 84, 101, 126], rock topplings [107, 111, 117, 134], rockslides [55, 96–99, 103, 116, 126, 127, 130], and rock falls or cliff failures [86, 88, 89, 91, 93–95, 100, 104–106, 112–115, 118, 120, 121, 126, 128, 131, 133]. Finally, some works are focused on finding the relation among "rock" landslides, displacement rate measurements, and meteorological (i.e., rain and temperature) parameters [95, 99, 100].

4. Discussion

Most studies focused on geophysical surveys are applied (a) to explore the subsoil for mineral deposits or fossil fuels, (b) to find underground water supplies, (c) for engineering purposes, and (d) for archaeological investigations [19]. Technological progress and the availability of cheaper computer electronic parts has allowed the improvement of more portable equipment and the development of 2D and 3D geophysical techniques [11, 12]. Therefore, the applicability of geophysical methods in landslide characterization has grown over the years. Starting from the state of the art of the geophysical techniques applied in landslide characterizations pointed out in [12], this review focused on the papers from the last twelve (2007-2018) years and tried to understand how many efforts have been made by the international scientific community to overcome the drawbacks. These geophysical techniques limitations are listed in Introduction. To reach the goal of this paper, contrary to the four reviews discussed in Section 2 [8, 11, 12, 14], the analyses of the geophysical method advantages and limitation were carried out on the basis of the latest landslide classification, which is mainly based on the involved materials and geotechnical properties [4]. Therefore, the 120 analysed papers were divided into two classes: "soil" (in red in the following figures) and "rock" (in green in the following figures), which account for 66 and 54 works, respectively.

Even though it is well known that it is better to integrate more than one geophysical technique because of the intrinsic limitations of each approach, in 68.3% of the analysed papers (Figure 1), only one geophysical method is presented and discussed. However, in 64.6% of these works (which

Table 6: For each movement type and "rock" landslide typology, the table summarizes how many papers are focused on it. In italic movement types that usually reach extremely rapid velocities as defined by [2], while for the others, the velocity varies between extremely slow to very rapid (for details, refer to [4]).

TYPE OF MOVEMENT	Number of papers	ROCK	Number of papers
Fall	41	*Rock/ice fall*	40
Topple	5	*Rock block topple*	5
		Rock flexural topple	/
Slide	18	Rock rotational slide	1
		Rock planar slide	2
		Rock wedge slide	1
		Rock compound slide	3
		Rock irregular slide	1
Spread	1	Rock slope spread	1
Flow	6	*Rock/ice avalanche*	6
Slope Deformation	4	Mountain slope deformation	3
		Rock slope deformation	1

correspond to 44.1% of the total analysed papers, as indicated by the bottom/darker part of the blue bar in Figure 1), the geophysical results are interpreted on the basis of other techniques. This means that only in 24.2% of the analysed works (the top/lighter part of the blue bar in Figure 1) is just one technique presented, and in 80% of these 24.2% (which means four works out of five), the employed method is a passive seismic technique. This is probably because these techniques (a) require quite light equipment, (b) can be employed to both monitor and characterize seismic signals triggered by landslide dynamics [55, 133, 134], and (c) can be useful for overcoming the unpredictable occurrence of rockfalls [128], even though it is not easy to correlate seismic signal features with landslide geological properties [120, 134].

In general, active and passive seismic methods are the most employed in landslide characterization and monitoring (Figure 2). In "soil" landslides, the three most employed techniques are ERT, SN (at local and regional scales), and SR. The last, together with SRe and SW, is largely used in this kind of landslide typology, and in general, it is easier to find papers focused on "soil" landslides that integrate the abovementioned seismic techniques with other less-common techniques (e.g., MG, IP, SP, and EM). Our analysis of "soil" landslides confirms the conclusions of [20]; i.e., (a) ERT and SR integration proves to be the most effective, (b) the joint application of ERT, SR, and GPR seems to solve and overcome the resolution problems of each single method, and (c) in the literature, there are very few examples of ERT combined with IP to distinguish clayey material or to better interpret ERT. In "rock" landslides, the three most employed techniques are SN (at local and regional scales), ERT, and SR, indicating that passive seismic techniques are preferred over electrical ones. As mentioned above, this is probably because they can be employed to both monitor and characterize seismic signals triggered by landslide dynamics [55, 133, 134]. At the fourth position is GPR, although the authors highlight both the difficulty of deployment on cliffs and the limitation of its applicability to only highly resistive rock slopes [87, 88, 92, 132].

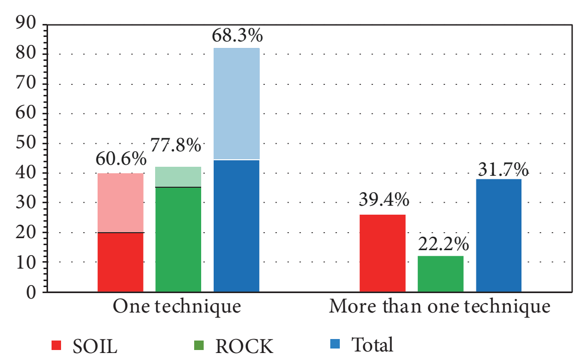

Figure 1: For each landslide typology ("soil" in red, "rock" in green, and total in blue), the bar graph shows the number of papers focused on just one technique or on more than one. Numbers on the top of the bars are the percentage values with respect to the total number of analysed papers. The darker colours of the "soil" and "rock" bars of the "one-technique" group indicate in how many works the passive seismic technique was employed alone. The dark blue portion of the "one-technique total bar" indicates in how many works other nongeophysical techniques were employed.

In Figure 3, for each drawback, the percentages and the numbers of papers (numbers on the top of the bars) that fall into each level of the three-level scale (+, -, and n.d., which mean that many/some, insufficient, and nondiscussed efforts were made to overcome the limitations, as shown in Table 4) are summarized. In general, it is possible to observe that great efforts were made (95 papers out of the 120 analysed, which is 79.1%, are on the + level of the scale) to improve the geological interpretation of the geophysical data and to explain it more clearly and critically (drawback 3). In contrast, very few efforts were made to (a) systematically discuss, in an understandable way, the resolution and penetration depth of each method (drawback 2: 91 papers out of the 120 analysed, which are 75.8%, are on the n.d. level of the scale), (b) to convince geologists and engineers that 3D and 4D geophysical imaging techniques can be valuable tools for investigating and monitoring landslides (drawback

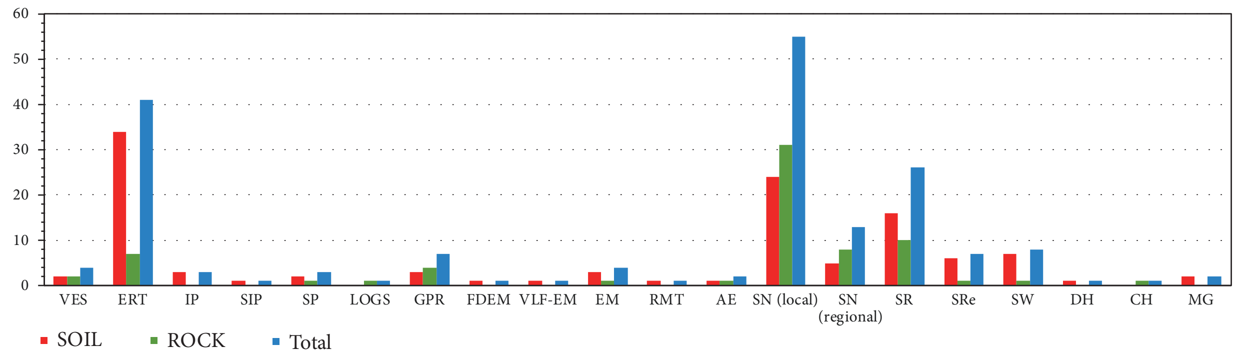

FIGURE 2: For each landslide typology ("soil" in red, "rock" in green, and total in blue), the bar graph shows the number of papers focused on each geophysical method.

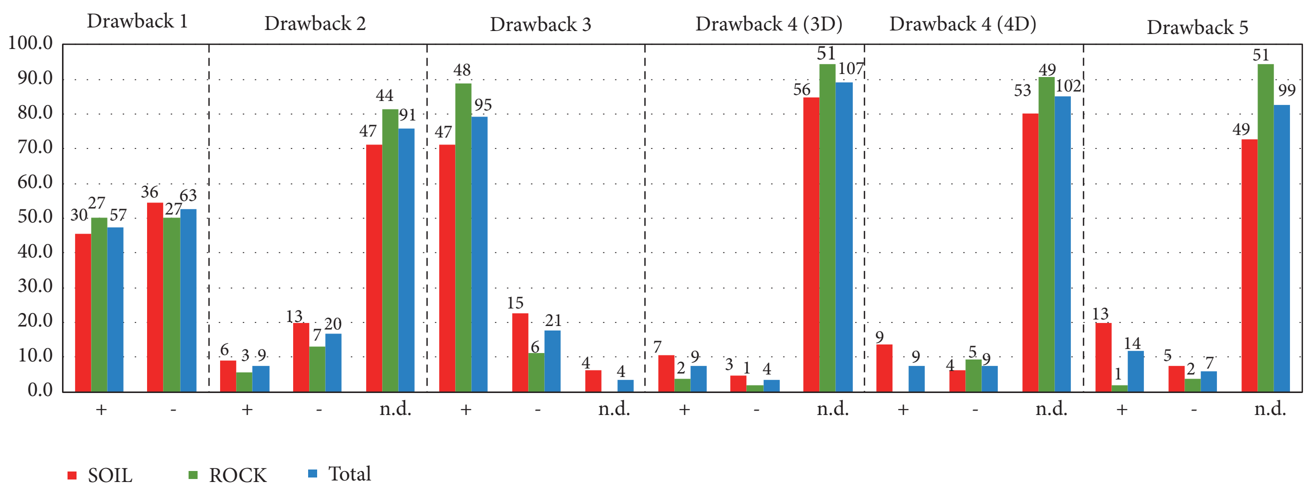

FIGURE 3: The bar graph indicates the percentage of efforts made (+ means many/some, - means insufficient, and n.d. means nondiscussed) to overcome each drawback. The percentages of papers focused on "soil" landslides are in red, those of papers focused on "rock" landslides are in green, while in blue are the total percentages. The numbers on the top of each bar indicate the numbers of papers.

4: 107 papers for 3D applications and 102 papers for 4D applications out of the 120 analysed, which are 89.2% and 85.0%, respectively, are on the + level of the scale), and (c) to obtain quantitative information in terms of geotechnical parameters and hydrological properties from geophysical data (drawback 5: 99 papers out of the 120 analysed, which are 82.5%, are on the n.d. level of the scale). Finally, thanks to the development of new 2D and 3D imaging software, some efforts, but still not enough (57 papers out of the 120 analysed, which is 47.5%, are on the + level of the scale), were made to show the geophysical results more clearly (drawback 1).

In the following discussion, we analyse point-by-point the efforts made to overcome each drawback highlighted by [11].

Drawback 1: Geophysicists Have to Make an Effort in the Presentation of Their Results. According to our analysis (Figure 3), the efforts to overcome this drawback were performed more or less in the same way for both "soil" and "rock" landslides. This means that a tendency to show and present the results more objectively is beginning to emerge. This could be possible thanks to the development of new 2D and 3D software that allow the integration of data from different sources and surveys (e.g., geophysical, geotechnical, and borehole data). Nevertheless, the presentation of seismic data is sometimes still hard, since authors often show the rough traces or spectra (e.g., [22, 24, 26, 29, 39, 40, 44, 47, 49, 55, 56, 58, 64, 76, 84, 89, 95, 97, 98, 101, 103, 104, 106, 112, 116, 117, 121, 126, 127, 131, 133]) that could be difficult to read for a nonexpert audience.

Drawback 2: The Spatial Resolution and Penetration Depth of Each Method Are Not Systematically Discussed in an Understandable Way. Each technique has a different resolution and penetration depth that contribute to the final quality of a geometrical model. According to [7], several preprocessing steps are needed to carefully check the data quality and, therefore, the resolution and penetration depth before incorporation into a 3D model. In total, 75.8% of the analysed papers (47 of those on "soil" landslides and 44 of those on the "rock" type) do not discuss either the resolution or the penetration depth of the presented methodology (Figure 3). Additionally, in the review in [20], none of the cited papers within the year range (2007-2013) examine these two points. In contrast, in the remaining 24.2% (Figure 3) of the examined works, these two points are discussed more in depth in nine papers [7, 23, 27, 38, 62, 68, 93, 105, 128], and only few words are presented in the other twenty [25, 33, 41, 43, 49, 50, 67, 73–75, 78, 80, 85, 87, 90, 92, 108, 110, 132]. Therefore, most of the authors who present the results of an integrated survey do not discuss how to consider and combine these data. It is possible to conclude that this drawback has still not been overcome since 2007 and the review in [11].

Drawback 3: The Geological Interpretation of Geophysical Data Should Be More Clearly and Critically Explained. The 3D internal structural characterization of a slope/cliff is essential to any landslide stability analysis and to hydro-mechanical modelling [7]. Nevertheless, interdisciplinary aspects between geomorphological and geophysical data/results are poorly addressed [19]. According to our review (Figure 3), in 79.2% of the analysed papers (47 of those on "soil" landslides and 48 of those on the "rock" type), many efforts have been made to interpret, show, and explain the geophysical data in a more clear and critical way. However, almost 50.0% of these works (those marked with +∗ in Tables 2 and 3, which total 11 of 47 for "soil" landslides and 36 of 48 for the "rock" type) involve passive seismic monitoring and data analysis and interpretation to (a) provide information on slope dynamics and (b) identify landslide features. Moreover, it is worthwhile to note that the geophysical data interpretations are still not indisputable. In many papers, in fact, the discussion of the results is accompanied by words such as "suspect," "suppose," "speculate," "probably/probable," "potential," "our preferred interpretation," and "provide important information on possible" [9, 22, 25–27, 35, 38–40, 42–44, 46, 48–53, 57, 58, 63, 68, 72, 74, 75, 77, 85, 86, 96, 99, 101, 102, 104, 106, 108–110, 112, 114, 115, 118, 122, 126, 134]. Without close collaboration between geophysicists and geomorphologists, the accurate and effective use of geophysical techniques, as well as the corresponding data interpretation, is often very limited [19].

Drawback 4: The Challenge for Geophysicists Is to Convince Geologists and Engineers That 3D and 4D Geophysical Imaging Techniques Can Be Valuable Tools for Investigating and Monitoring Landslides. In the hydrocarbon industry, the best strategy for reconstructing a high-resolution model is acquiring a 3D data set [31]. On the other hand, there are interesting results from the noninvasive time-lapse monitoring of the hydrological behaviour of a mountain slope [139]. However, in 89.2% of the analysed works (Figure 3) 3D geophysical imaging is not discussed. Even though the 3D volumetric reconstruction of a landslide is a suitable target with new technologies [46, 60, 65, 92], a 3D survey could be very tiring, exhausting, and time-consuming, since it is still difficult to carry and move the equipment over the slope [18, 20]. To overcome this limitation, the acquisition is usually performed by means of 2D parallel profiles, and the results are shown in a 3D fence diagram [[20] and references within, [27, 51, 52, 57, 86, 92, 124]]. Thus, this drawback highlighted by [11] has not been overcome and is still a challenge for geophysicists.

Passive seismic monitoring could be considered a 4D technique, but none of the authors refer to this method in this way. Therefore, in our analysis, we also have not considered it as a 4D technique, and the results show that in 85% of the works (Figure 3), 4D geophysical imaging is not discussed. In general, 4D ERT has been more frequently employed thanks to the development of ER multichannel measuring systems that significantly reduced the acquisition time [20, 140]. These systems [such as those employed in [141, 142]], in fact, (i) are able to simultaneously acquire a number of potential measurements for a single pair of current electrodes and (ii) can be set up to provide ERT at specific times during the day. Nevertheless, even though tl-ERTs could be helpfully employed in landslide monitoring, since they could provide information about the water content changes (i.e., the data could be related to pore water pressure variations and, therefore, to landslide triggering mechanisms), there are still few examples of 4D ERTs in landslide areas [60, 65, 92]. Moreover, it is still needed to improve software such that it is able to (i) continuously (or very frequently) process acquired data (e.g., ErtLab by Geostudy Astier, [140]), (ii) to link ER variations with hydrological parameter changes, and (ii) to take into account that the positions of the electrodes could change over the time because of the landslide movement [38, 65].

Drawback 5: Efforts Should Also Be Made towards Obtaining Quantitative Information from Geophysics in Terms of Geotechnical Parameters and Hydrological Properties. Authors agree that seismic wave velocities and soil ER could be useful in identifying anomalies related to structural (faults, fissures, and stability), lithological (sand to clay or calcareous variations) and hydrological (moisture, water flow) conditions [42, 123, 143]. However, drillings and inclinometer measurements are still crucial to providing a reliable idea of landslide structures and slip surfaces and to validate any geophysical measurements. This is probably because the geophysical property ranges cover several orders of magnitude, and a measured parameter cannot be directly assigned to a sure substrate. Currently, the major difficulty of applying geophysical techniques to landslides, as also highlighted by [11], is still the complex relationship between the measured geophysical parameters and the desired geotechnical and hydrogeological properties, which prevents the provision, in terms of engineering properties, of a straightforward interpretation. Moreover, a very accurate and high-resolution survey can still only be done on a small landslide portion [23, 24, 27, 28, 38, 40, 46, 60, 78, 86, 92], as it is costly and time-consuming. As also pointed out by [143], this complexity in obtaining quantitative information from geophysical data is probably also caused by (a) the lack of knowledge about geophysics techniques in the geotechnical engineering/geological community and (b) engineers inclination to believe in soil and rock that they can see visually (borehole log), rather than in what they cannot see (geophysical signal).

These abovementioned limitations are confirmed by our analysis. In total, 82.5% of the works (99 of 120, Figure 3), in fact, do not discuss how to obtain quantitative information on geotechnical and hydrogeological properties from geophysical data. In the remaining 17.5% (21 works, 14 of those on "soil" landslides and 7 of those on the "rock" type), both seismic and electrical methods are used in the same percentage (9 works focused on seismic methods, 8 on ER, and 4 on both seismic and ER methods). Thus, this drawback has still not been overcome, and laboratory surveys to establish a link between rock properties and geophysical data, as well as interdisciplinary communication and discussion, are the primary keys [90].

5. Conclusion

This review work analysed the papers published in open-access journals from 2007 until today, focusing on the application of geophysical techniques to landslides. It was based on a "material landslide approach" analysis and evaluated how many efforts were performed to overcome the five drawbacks highlighted by the last review, which dates to 2007, concerning geophysical techniques applied to landslide monitoring and characterization. To quantify these efforts, a three-level scale was employed (from many/some efforts to nondiscussed). In general, it is possible to observe that (i) many efforts were made to improve the geological interpretation of geophysical data and to explain the interpretations more clearly and critically (drawback 3); (ii) some efforts, but still not enough, were made to show geophysical results more clearly (drawback 1); and (iii) very few efforts were made to (a) systematically discuss, in an understandable way, the resolution and penetration depth of each method (drawback 2), (b) to convince geologists and engineers that 3D and 4D geophysical imaging techniques can be valuable tools for investigating and monitoring landslides (drawback 4), and (c) to obtain quantitative information in terms of geotechnical parameters and hydrological properties from geophysical data (drawback 5).

The most studied landslides are those of the flow type for "soil" landslide typology and those of the fall type for the "rock" category. From the "employed method" point of view, active and passive seismic methods are the most employed in landslide characterization and monitoring. The latest method is also able to remotely detect events that might otherwise go unnoticed for weeks or months, and therefore, it is widely employed. The three more frequently applied techniques, regardless the typology ("soil" or "rock"), are ERT, SN and SR, which are to both characterize and monitor the slope deformation. Finally, independently of the applied technique/s, a very accurate and high-resolution survey could be performed only on a small landslide portion, as it is costly and time-consuming.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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