



Application and reliability of techniques for landslide site investigation, monitoring and early warning – outcomes from a questionnaire study

I. Baroň^{1,*} and R. Supper¹

¹Geological Survey of Austria, Neulinggasse 38, 1030 Vienna, Austria

* present address: Working Group on Karst and Caves, Department of Geology and Paleontology, Museum of Natural History, Museumsplatz 1/10, 1070 Vienna, Austria

Correspondence to: I. Baroň (ivobaron@centrum.cz)

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Abstract. The presented questionnaire study summarizes an evaluation of approaches, techniques and parameters of slope-instability investigation and monitoring of their occurrence, reliability and the applicability of the monitoring techniques for early warning. The study is based on information collected from 86 monitored landslides in 14 European and Asian countries. Based on the responses, lidar ALS (airborne laser scanners), geophysical logging, aerial photographs, resistivity surveying, GB InSAR (ground-based synthetic aperture radar interferometer) and the refraction seismic were considered the most reliable methods for investigation of structure and character of landslides. Especially lidar ALS and geophysical logging were ranked high despite their application at relatively few landslides. Precipitation amount, pore-water pressure and displacement monitored by wire extensometers, dGPS and total stations, followed by air temperature and EM-emissions monitoring and displacement monitored by the TM 71 crack gauge were considered the most promising parameters for early warning.

evaluation in advance of the actual hazard and for early warning before a catastrophic event.

Such knowledge is obtainable only through a complex interdisciplinary approach consisting of investigations by variety of methods and techniques, long-time monitoring of deformation and triggering factors, and by establishing early warning centres.

Several studies attempted to review and to list the techniques applied for landslide investigation, monitoring and early warning (Angeli et al., 2000; Jaboyedoff, 2012; Jongmans and Garambois, 2007; Michoud et al., 2012, 2013; Thiebes, 2012; Turner and Schuster, 1996). As different techniques and sensors of landslide investigation, monitoring and early warning provide a different kind of information with different data reliability, we tried to provide a quantitative comparison of those methods. The evaluation was based on a questionnaire study; the “Questionnaire on National State of Landslide Site Investigation and Monitoring” had been distributed worldwide to different institutes through our cooperating partners within the frame of the SafeLand project. The forms were completed by local experts responsible for the respective sites; thus the results reflect the practical experience from the field. The main goals of the study were (i) reviewing the general state of slope-instability investigation and monitoring approaches in different European and Asian countries, (ii) assessing effectiveness/reliability of each method for slope instability investigation and monitoring, and (iii) evaluating applicability of the monitoring techniques for early warning. The study complements similar research presented

1 Introduction

Mass movements are one of the worst natural threats worldwide. Consistent information about individual unstable slopes, especially in very vulnerable areas, on their internal structure, dynamics of deformation, triggers, history and possible magnitude is an essential input for any proper

QUESTIONNAIRE ON NATIONAL MASS-MOVEMENT SITE INVESTIGATION & MONITORING

SafeLand

Study site: [REDACTED]

GENERAL INFORMATION:

Country:			
Location:	WGS coordinates: [REDACTED]		
Responsible institutions:			
Email contacts:			
Date of the answering:			
Type of slope failure: <i>(modified classification of Cruden & Varnes 1996)</i>	Topple and initial fall: in rock <input type="checkbox"/> in soil <input type="checkbox"/> Lateral spread: in rock <input type="checkbox"/> in soil <input type="checkbox"/> Slide - translational: in rock <input type="checkbox"/> in soil <input type="checkbox"/> Slide - rotational: in rock <input type="checkbox"/> in soil <input type="checkbox"/> Flow: in rock <input type="checkbox"/> in soil <input type="checkbox"/> Complex failure: <input type="checkbox"/>		
Present maximum movement rates <i>(within past 12 months)</i>	<input type="checkbox"/> < 10 mm/month <input type="checkbox"/> < 10 cm/month <input type="checkbox"/> < 100 cm/month <input type="checkbox"/> > 100 cm/month	Present activity state <i>after W9/WLJ 1993 (within past 12 months)</i>	<input type="checkbox"/> Active <input type="checkbox"/> Suspended <input type="checkbox"/> Reactivated <input type="checkbox"/> Dormant <input type="checkbox"/> Stabilized <input type="checkbox"/> Relict
Maximum estimated thickness: [REDACTED] m	Estimated volume: [REDACTED] m ³		

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QUESTIONNAIRE ON NATIONAL MASS-MOVEMENT SITE INVESTIGATION & MONITORING

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AVAILABLE INVESTIGATION:

Mapping:	<input type="checkbox"/> Geological (lithology, stratigraphy, joint and fault pattern) <input type="checkbox"/> Geomorphic (topography, geomorphic features, etc.) <input type="checkbox"/> Engineering-geological (landslide regions, strength properties, vectors of movement, infrastructure, etc.) <input type="checkbox"/> Hazard, risk, element at risk, etc. <input type="checkbox"/> Hydrogeological (drainage network, underground drainage, aquifers, etc.) Other: [REDACTED]	
Drilling:	<input type="checkbox"/> Core Max. depth: [REDACTED] m <input type="checkbox"/> Other: [REDACTED] Max. depth: [REDACTED] m	
Testing:	<input type="checkbox"/> Strength properties/ deformability Other: [REDACTED] <input type="checkbox"/> Clay mineralogy Other: [REDACTED] <input type="checkbox"/> Penetration <input type="checkbox"/> Hydrochemical tracing <input type="checkbox"/> Hydro and geochem. analysis (isotope, anion/cation balance, etc.) <input type="checkbox"/> Field dilatation tests (pressuremeter) <input type="checkbox"/> Borehole testing Please specify: [REDACTED] Other: [REDACTED] Other: [REDACTED]	
Remote sensing data:	<input type="checkbox"/> Aerial photographs and orthophotographs <input type="checkbox"/> Satellite optical very high resolution (VHR) imagery (<1 m pixel) <input type="checkbox"/> Hyperspectral satellite data <input type="checkbox"/> Airborne Geophysics <input type="checkbox"/> LIDAR ALS (Airborne Laser Scanning) <input type="checkbox"/> Radar Interferometry Other: [REDACTED] Other: [REDACTED]	Technique assessment <i>Effectiveness / Reliability of the method for landslide investigation</i>
GB Geophysical survey:	<input type="checkbox"/> Resistivity <input type="checkbox"/> Self potential (SP) <input type="checkbox"/> Induced polarization (IP) <input type="checkbox"/> Reflection seismic <input type="checkbox"/> Refraction seismic <input type="checkbox"/> Ground Penetrating Radar (GPR) <input type="checkbox"/> Frequency-domain electromagnetics <input type="checkbox"/> Time-domain electromagnetics <input type="checkbox"/> Proton (nuclear) magn. resonance (PMR) <input type="checkbox"/> Hydrophysical logging in boreholes Other: [REDACTED] Other: [REDACTED]	Technique assessment <i>Effectiveness / Reliability of the method for landslide investigation</i>

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QUESTIONNAIRE ON NATIONAL MASS-MOVEMENT SITE INVESTIGATION & MONITORING

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MONITORING OF MOVEMENT AND DEFORMATION:

Remotely sensed:	<input type="checkbox"/> Satellite optical VHR image (type: [REDACTED]) Duration: [REDACTED] years Number of scenes: [REDACTED] <input type="checkbox"/> Satellite near infrared image (type: [REDACTED]) Duration: [REDACTED] years Number of scenes: [REDACTED] <input type="checkbox"/> Orthophoto Duration: [REDACTED] years Number of scenes: [REDACTED] <input type="checkbox"/> INSAR (Radar interferometry) Duration: [REDACTED] years Number of scenes: [REDACTED] <input type="checkbox"/> LIDAR ALS (Airborne Laser Scanning) Duration: [REDACTED] years Number of scenes: [REDACTED] Other: [REDACTED] Duration: [REDACTED] years Number of scenes: [REDACTED]
Ground based:	<input type="checkbox"/> GB InSAR (Radar interferometry) <input type="checkbox"/> LIDAR TLS (Terrestrial Laser Scanning) <input type="checkbox"/> Optical image <input type="checkbox"/> Near infra-red image <input type="checkbox"/> dGPS (Global Positioning System) <input type="checkbox"/> Total station <input type="checkbox"/> Inclinator (classical) <input type="checkbox"/> Automatic inclinometer (DMS, etc.) <input type="checkbox"/> Tape extensometers <input type="checkbox"/> Wire extensometers (automatic) <input type="checkbox"/> TM 71 (opto-mechanical extensometer) <input type="checkbox"/> Optical Fibres (FBG) Other: [REDACTED] Other: [REDACTED]

Explanation:
 Active: Is the monitoring still in use? (tick = yes)
 Duration: Please write duration of monitoring (in years)
 Permanent: Is the monitoring (usually automatic) continuous and regular with periodicity shorter than 1 week?
 Regular: Is the monitoring continuous with regular periodicity >1 week and <.1 year?
 Sporadic: Is the monitoring with periodicity irregular or >.1 year?
 Potential for EW: Could be the monitoring technique used for Early Warning?

QUESTIONNAIRE ON NATIONAL MASS-MOVEMENT SITE INVESTIGATION & MONITORING

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MONITORING OF FACTORS:

Hydro-meteorological:	Precipitation amount Snow cover thickness Solar radiation Air temperature Air humidity Pore-water pressure Soil humidity Water temperature Fluid conductivity In / outflow (discharge) Other: [REDACTED] Other: [REDACTED]	Active? Duration Permanent Regular Sporadic Potential for EW?
Geophysical:	Passive seism./acoustic emission Electromagnetic emissions Self potential (SP) Induced polarization (IP) DC (Direct Current) resistivity Other: [REDACTED] Other: [REDACTED]	Active? Duration Permanent Regular Sporadic Potential for EW?

NUMERICAL MODELING:

Method 1: [REDACTED]	Code name: [REDACTED]	Studied behavior: [REDACTED]
Method 2: [REDACTED]	Code name: [REDACTED]	Studied behavior: [REDACTED]
Method 3: [REDACTED]	Code name: [REDACTED]	Studied behavior: [REDACTED]

Fig. 1. General appearance of the “Questionnaire on National State of Landslide Site Investigation and Monitoring.”

by Tofani et al. (2013), which is focused specifically on remote-sensing approaches for landslide monitoring, and by Michoud et al. (2013), focused on the operating landslide early-warning centres.

2 Methods – the questionnaire and data evaluation

The questionnaire focused on landslides that have been investigated with at least two independent methods and monitored for longer than 1 yr. A Word-doc application was prepared in a comprehensive and user-friendly way (Fig. 1). Answers were provided by ticking and filling in the active fields of the form.

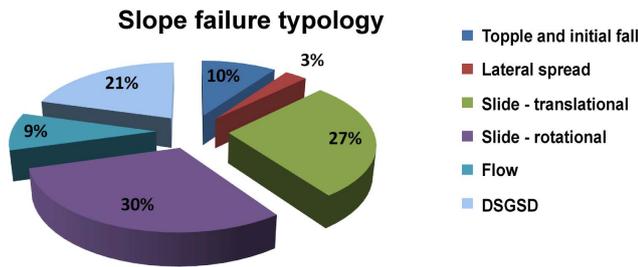


Fig. 2. Review of the total 129 monitored slope failure types from 86 sites that were included in the study. Note that 31 % of them formed complex failures (modified classification of Cruden and Varnes, 1996).

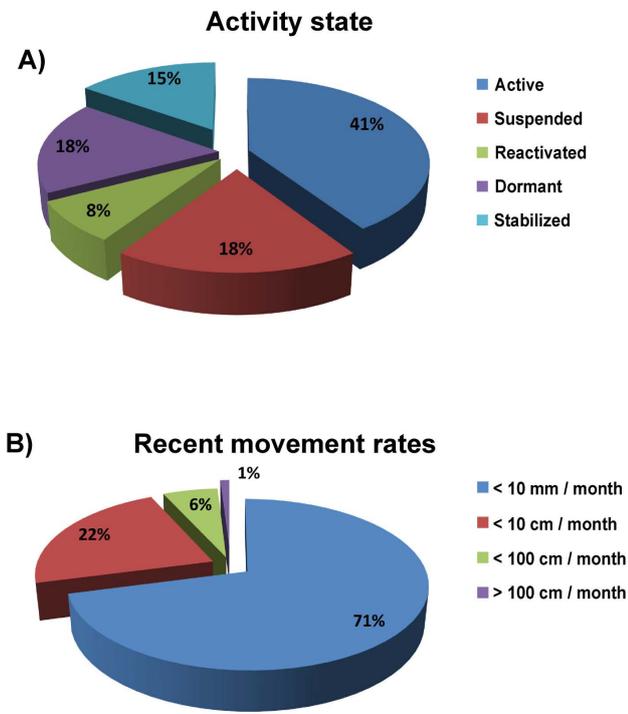


Fig. 3. Review of slope failures included in the study by (A) activity state (after WP/WLI, 1993) and (B) actual movement rates at time of response.

The general information on monitored mass movement consisted of information such as slope failure typology, activity state and recent movement rates. The classification was adopted and modified from Cruden and Varnes (1996). Different types of mass movements were then expressed relative to the total number of the particular landslide types within monitored sites, the complex failures excluded and expressed relative to the number of monitored sites.

The investigation methods, monitored parameters, and, in case of displacement, the individual monitoring techniques, were characterized by their (i) *total relative occurrence* [%], i.e. the method occurrence related to the total number of

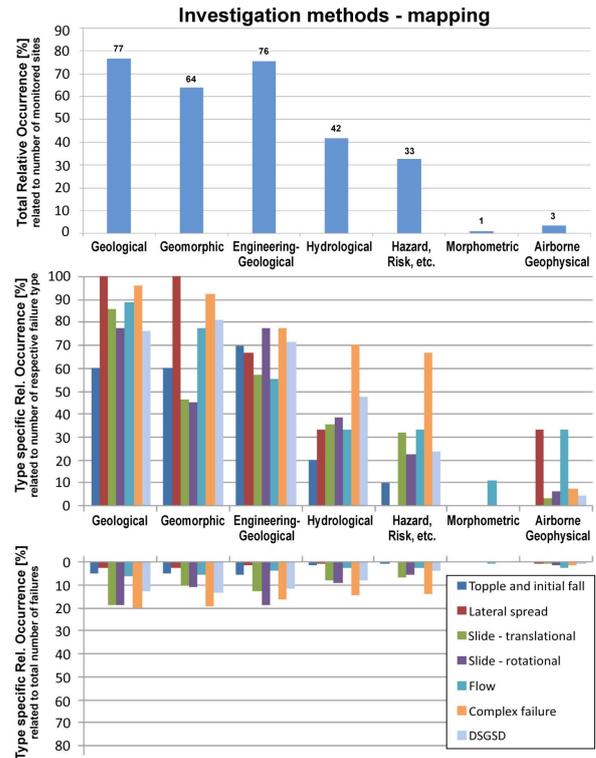


Fig. 4. Review of total relative occurrence and type-specific relative occurrence of the mapping approaches applied in the monitored landslide sites.

monitored sites included in the study, (ii) *type-specific occurrence* [%] of each method at different types of slope failures related to the number of respective failure type, and (iii) *type-specific occurrence* of each technique at different types of slope failures related to the total number of all monitored landslide types (including partial slope-failure types forming complex landslide sites). Individual techniques were then scored from 1 to 10 (1–100 %) regarding their *reliability* [%], i.e. the effectiveness of each method for slope-instability investigation and monitoring estimated subjectively by the respondents according to their practical experience. And finally, the applicability (or future potential) of the monitoring methods for early warning (i.e.; is the method suitable for early-warning purposes?) – called the *early warning potential* [%] – was evaluated subjectively by the respondents answering “yes” or “no”; positive answers have been averaged with respect to the abundance of the technique (i.e. total number of each particular method applied in all monitored sites) and normalized by the technique of total relative occurrence.

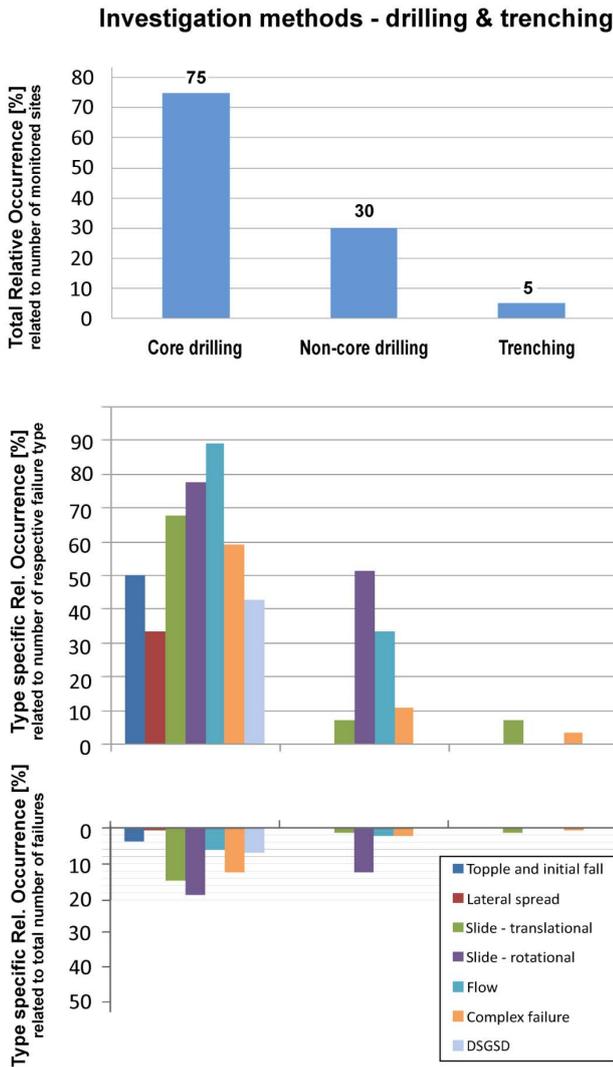


Fig. 5. Review of total relative occurrence and type-specific relative occurrence of drilling and trenching approaches applied in the monitored landslide sites.

3 Results

3.1 Review of monitored sites to be evaluated

The information has been collected from 86 monitored sites from Andorra, Austria, Switzerland, the Czech Republic, France, Great Britain, Italy, Japan, Kyrgyzstan, Norway, the Russian Federation, Slovenia, the Slovak Republic and Spain (Table 1), which included a total of 129 different slope-failure types. The most abundant slope failures that have been monitored were rotational slides (30%), translational slides (27%), and deep-seated gravitational slope deformations (DSGSD) with a total relative occurrence of 21% (Fig. 2). Topples and initial falls (10%), flows (9%) and lateral spreads (3%) were much less abundant in the responded-to monitored sites. About 31% of those particular landslide

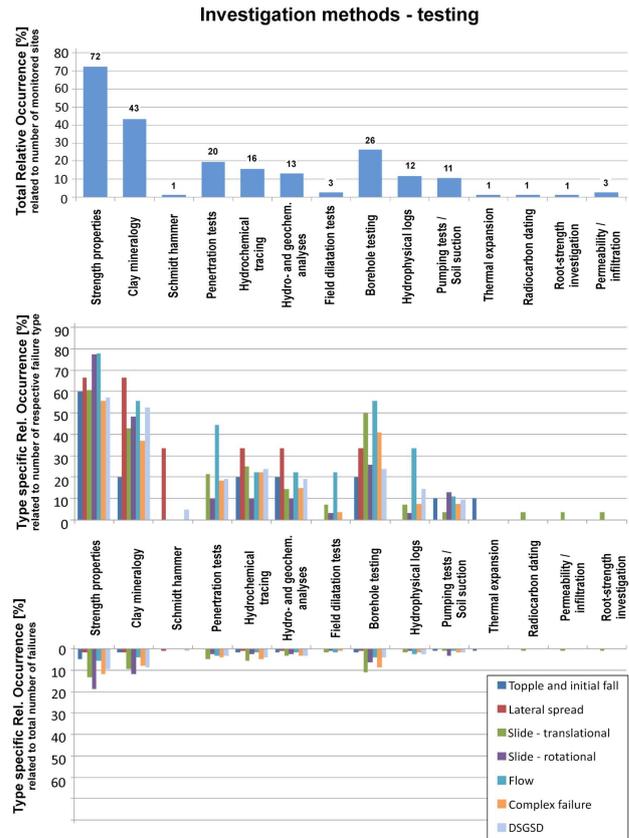


Fig. 6. Review of total relative occurrence and type-specific relative occurrence of testing approaches applied in the monitored landslide sites.

types formed complex failures. Regarding their activity state, the most abundant slope failures were the active ones (41%) with recent movement rates of less than 10 mm month^{-1} (71%) (Figs. 2, 3).

3.2 Review of the investigation methods

The most common mapping approaches applied at the monitored sites were the geological mapping (applied at 77% of the sites), engineering-geological (76% of the sites) and geomorphic (64% of the sites) (Fig. 4). Their application, however, differed at particular landslide types; for more details see type-specific relative occurrence in Fig. 4. Core drilling had been applied at 75% of the sites, mostly at rotational and translational slides (Fig. 5).

Strength properties/deformability (at 72% of the sites), clay mineralogy testing (43%) and borehole testing (26%) represented the most abundant testing surveys of the monitored sites (Fig. 6). For their application at particular landslide types see their type-specific relative occurrence in Fig. 6.

DC (direct current) resistivity (applied at 62% of the sites) and refraction seismic surveying (41%) were the most

Table 1. Review of responses: countries, monitored sites and authors.

No.	Country	Site	Author	No.	Country	Site	Author
1	Andorra	Canillo	J. Corominas	44	Italy	Tessina	A. Passuto
2	Austria	Kerschbaumsiedlung	gbl.minntal@die-wildbach.at	45	Italy	Magliatica	G. Truffelli
3	Austria	Blaubach	V. Kaufmann	46	Italy	Bosmato-Stadelte	M. Broccolato, J. Blanc
4	Austria	Murenbach	Ch. Ihnenberger	47	Italy	Vollein	M. Broccolato, J. Blanc
5	Austria	Sibratsgfäl/Rindberg	M. Wöhler-Alge	48	Italy	Letze-Bosmato	M. Broccolato, J. Blanc
6	Austria	Gschliefgraben	W. Gasperl	49	Italy	Becca di Nona	M. Broccolato, J. Blanc
7	Austria	Maesstobel	WLW	50	Italy	Pitigliano	N. Casagli
8	Austria	Wagrainer Ache	WLW	51	Italy	San Miniato	N. Casagli
9	Switzerland	Gruben	S. Springman	52	Kyrgyzstan	Gulcha-Basar	I. Torgoev
10	Switzerland	Ruedlingen	S. Springman	53	Kyrgyzstan	Kambar-Ata	I. Torgoev
11	Switzerland	Tössegg	S. Springman	54	Kyrgyzstan	Kok-Jangak, Kapitalnja	I. Torgoev
12	Czech Rep.	Pustevny	J. Klimes	55	Kyrgyzstan	Min-Kush	I. Torgoev
13	Czech Rep.	Halenkovice	M. Bil	56	Kyrgyzstan	M-Suu Izolit	I. Torgoev
14	Czech Rep.	Holstejn	V. Hanzl	57	Kyrgyzstan	M-Suu Tektonik	I. Torgoev
15	Czech Rep.	Přihrazy	J. Rybar, J. Klimes	58	Kyrgyzstan	M-Suu, Koy-Tash	I. Torgoev
16	Czech Rep.	Třebeňice	J. Rybar, J. Klimes	59	Kyrgyzstan	Taran-Basar	I. Torgoev
17	Czech Rep.	Čeřeněšřtř	J. Rybar, J. Klimes	60	Norway	Aaknes	L. H. Blikra
18	Czech Rep.	Ondřejnřk	J. Rybar, J. Klimes	61	Norway	Jettan	L. H. Blikra
19	Czech Rep.	Karolinka	P. Blaha	62	Norway	Mannen	L. H. Blikra
20	Czech Rep.	Ujala	P. Blaha	63	Russia	Zagorsk	M. M. Ilyin
21	Czech Rep.	Obri Hrad	F. Hartvich	64	Slovenia	Macesnik	M. Carman, S. Kumelj
22	Czech Rep.	Pravcicka brana	Z. Varilova	65	Slovenia	Slano Blato	M. Carman, S. Kumelj
23	Spain	Vallcebre	J. Corominas	66	Slovenia	Stože	M. Carman, S. Kumelj
24	France	Mas d'Avignonet	D. Jongmans	67	Slovakia	Banska Stiavnica	P. Wagner
25	France	Super Sauze	J.-P. Malet	68	Slovakia	SK Bojnice	P. Wagner
26	France	Villerville	J.-P. Malet	69	Slovakia	Demjata	P. Wagner
27	France	La Valette	J.-P. Malet	70	Slovakia	Dolna Micina	P. Wagner
28	France	Sřchilienne	S. Garambois, A. Helmstetter	71	Slovakia	Fintice	P. Wagner
29	Great Britain	Hollin Hill	C. Foster	72	Slovakia	Handlova 1960	P. Wagner
30	Italy	Cervinara	L. Picarelli	73	Slovakia	Handlova – Kunesov road	P. Wagner
31	Italy	Castagnola	N. Casagli	74	Slovakia	Hlohovec	P. Wagner
32	Italy	Masseria Marino	G. Urciuoli	75	Slovakia	K Klecenov	P. Wagner
33	Italy	Santo Stefano d'Aveto	N. Casagli	76	Slovakia	Liptovska Mara	P. Wagner
34	Italy	Monteforte Irpino	G. Urciuoli	77	Slovakia	Morovno Estate	P. Wagner
35	Italy	Ponti	M. Lovisolo	78	Slovakia	Okolicne	P. Wagner
36	Italy	Ruinon	M. Lovisolo	79	Slovakia	Slanec	P. Wagner
37	Italy	Idro	M. Lovisolo	80	Slovakia	Velka Izra	P. Wagner
38	Italy	Bagnaschino	M. Lovisolo	81	Slovakia	Velka Causa	P. Wagner
39	Italy	Ancona	S. Cardellini	82	Slovakia	Vistuk	P. Wagner
40	Italy	Chervaz	M. Broccolato, J. Blanc	83	Japan	Kuchisakamoto	G. Furuya
41	Italy	Comba Citrin	M. Broccolato, J. Blanc	84	Japan	Aratosawa	S. Tosa
42	Italy	Cherz	A. Passuto	85	Japan	Yui	S. Tosa
43	Italy	Passo della Morte	A. Passuto	86	Japan	Takisaka	H. Marui

abundant ground-based geophysical methods of investigation at the reported landslides. Other frequently used methods were the reflection seismic surveying (17 % total relative occurrence), self-potential survey (15 %) and ground-penetrating radar (15 %). Geophysical logging (85 % reliability), resistivity surveys (82 %) and the refraction seismic analysis (80 %) were considered as the most reliable ground-based geophysical methods. For the graphical presentation of the methods' review and for their type-specific relative occurrence at particular landslide types, see Fig. 7.

3.3 Remote-sensing approaches for landslide investigation and monitoring

The most frequently applied remote-sensing data and techniques for landslide investigation were aerial photographs

(applied at 36 % of the sites), radar interferometry (17 %) and lidar ALS (airborne laser scanners)(17 %) (see Fig. 8). Reliability of the remote-sensing methods was evaluated for both the structural investigation and for monitoring of movement. The most reliable remote-sensing methods were unequivocally evaluated to be lidar ALS (91 % reliability), then aerial photographs (83 %) and satellite optical very-high-resolution images (76 % reliability). Their application for particular landslide types, however, differed. For the graphical presentation and for the methods' review, see Fig. 8.

3.4 Monitoring parameters related to displacement and deformation

The displacement and its derivatives – the velocity and the acceleration – were considered as the most relevant

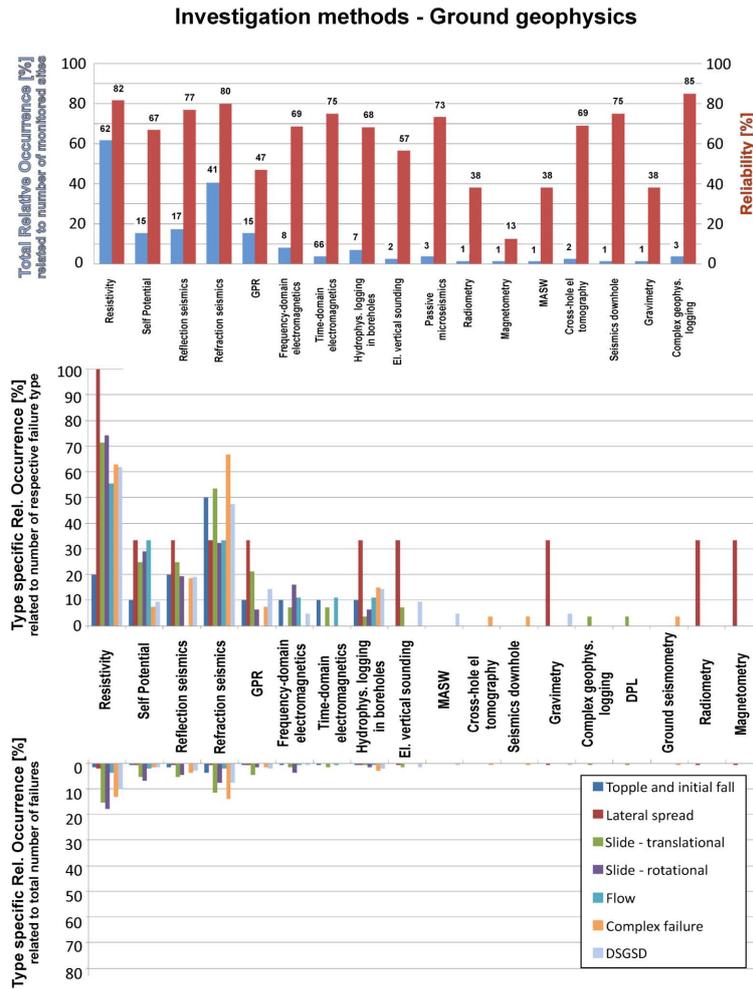


Fig. 7. Review of total relative occurrence, reliability and type-specific relative occurrence of the geophysical methods applied for the investigation of the monitored landslide sites.

monitoring parameters. The results for different ground-based sensors are presented in Fig. 9 displaying their EW (early warning) potential, total relative occurrence within all 86 monitoring sites, and type-specific relative occurrence. Classical and automated inclinometers, wire extensometers, dGPS, optical images and total stations are the most reliable sensors of displacement and deformation monitoring with the highest early warning potential.

3.5 Hydro-meteorological monitoring parameters

A total of 16 different hydro-meteorological monitoring parameters had been observed in the listed landslide sites; the precipitation amount, pore-water pressure and air temperature were the most abundant ones (Fig. 10). They were monitored at more than 55 % of the test sites. Pore-water pressure and precipitation amount had the highest EW potential. The observation of particular parameters differed within different

landslide types as documented by the type-specific relative occurrence (Fig. 10).

3.6 Geophysical monitoring parameters

The practical use of the geophysical parameters for monitoring is far from their routine application for landslide investigation; their relative abundance is generally below 20 %. Passive seismic/acoustic emissions, electromagnetic emission and DC resistivity were evaluated as the most reliable geophysical parameters for EW by the questioned experts (Fig. 11). Regarding their EW Potential, the electromagnetic emissions and DC resistivity reached relatively high values; however, all the geophysical parameters are randomly used and remain of a rather academic importance at the moment.

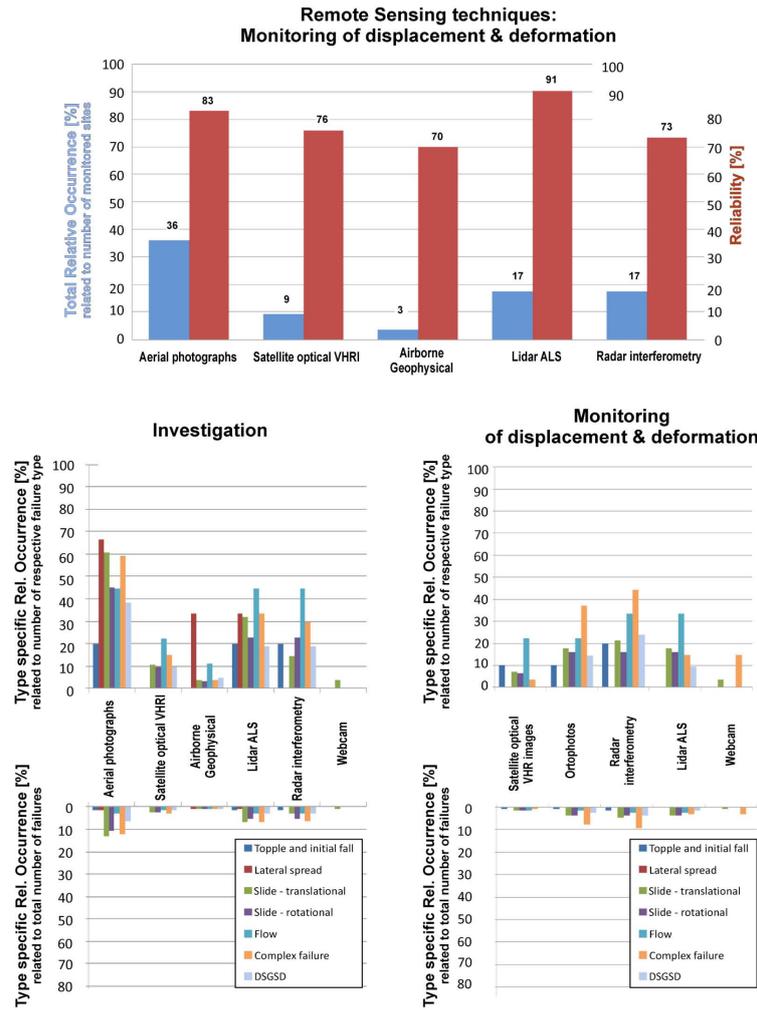


Fig. 8. Review of total relative occurrence, reliability and type-specific relative occurrence of the remote-sensing data applied for the investigation or monitoring of the case sites.

3.7 Regional aspect of the applied monitoring techniques

We observed some regional differences in the application of a particular investigation and monitoring technique within the landslide sites, especially when compared between countries of the former Western and Eastern Blocs. In general, strength testing, hydrochemical tracing, borehole testing, satellite optical VHR imagery, radar interferometry, airborne geophysics, lidar ALS and TLS (terrestrial lidar scanners), dGPS, automatic inclinometers, single lasers and superficial tiltmeters, ground-penetrating radar, hydrophysical logging in boreholes, monitoring of solar radiation, air humidity and soil/rock temperature, were distinctly more abundant approaches in the former “Western” countries in comparison to the “Eastern” ones. On the other hand, tape and wire extensometers, TM 71 optomechanical crack gauges, rod dilatometers, tools for monitoring surface residual stresses,

monitoring of discharge, and ground-based geophysical surveys of DC resistivity, self potential, reflection seismic analysis, and frequency domain electromagnetics, were more abundant in the former “Eastern” countries. Other techniques were applied almost equally in both of the regions.

4 Discussion

The presented study reviewed and attempted to evaluate the recent general state of the slope-instability investigation and monitoring, the reliability of applied remote-sensing and ground-based methods, and the occurrence and applicability of monitoring techniques for early warning. The study was based on information collected from 86 monitored landslides in 14 European and Asian countries, which have been investigated with at least two independent methods and monitored for a longer time than 1 yr. Despite a certain degree of subjectivity of the answers, as the reliability and early warning

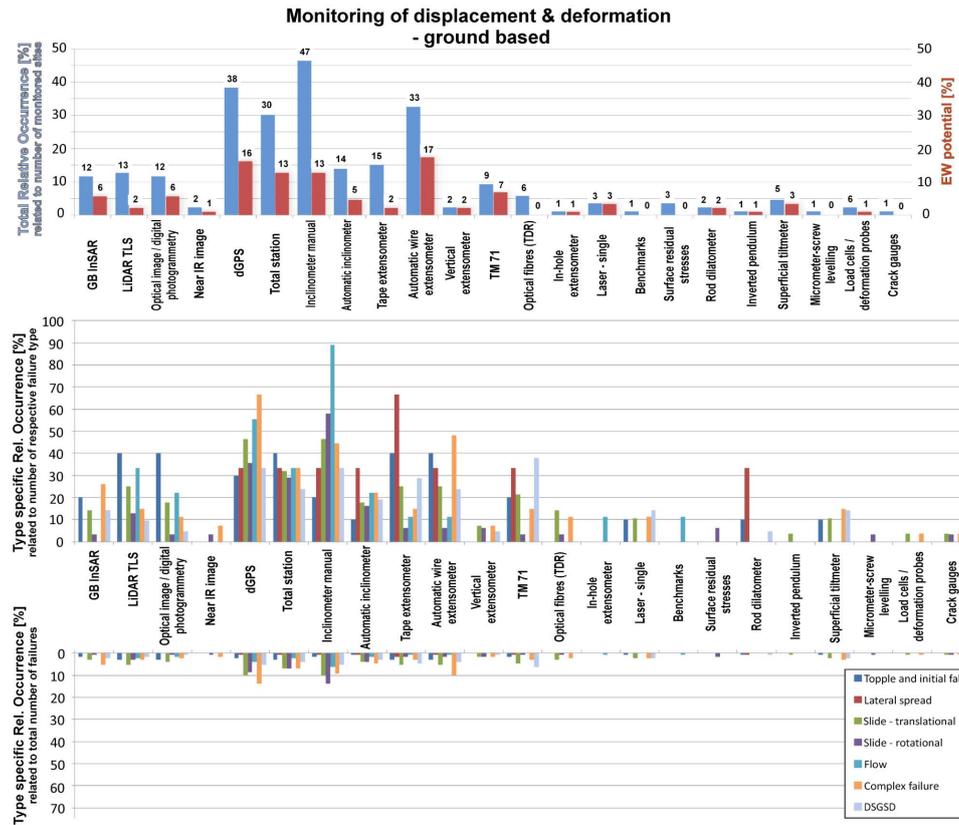


Fig. 9. Review of total relative occurrence, EW potential and type-specific relative occurrence of sensors for displacement and deformation monitoring from the 86 monitored landslide sites.

potential were assessed by the experts with different experience and profession, we believe that the study brought relatively complex and comprehensive information.

Slope instabilities comprising rotational and translational slides, topples, falls, ground flows and their complexes are being investigated and monitored by completely different methods. For example, some specific methods, applicable only for less abundant rockfalls, could appear in the evaluation less than methods applicable to a large spectra of mass movements or more abundant landslide types. Therefore any comparison of the relative occurrence of those methods is very difficult. The same restriction must be considered for monitoring methods and parameters and their early warning potential.

Based on the answered forms, Fig. 12 reviews and compares all of the methods regarding their reliability. Lidar ALS, complex geophysical logging in wells, aerial photographs, resistivity surveying, GB InSAR, and the refraction seismic analysis were considered unequivocally as the most reliable methods of the investigation of structure and character of landslides. Especially lidar ALS and TLS seem to be very challenging investigation methods for a broad spectra of slope-failure types as approved by recent literature (e.g.

Abellán et al., 2009; Jaboyedoff et al., 2012; Van Den Eckhaut, 2007; etc.); this was confirmed also by our study despite the relatively seldom application of the technique at responded-to monitored landslides. The second most reliable method – the complex geophysical logging in wells – is probably ranked so high due to its ability to render information on the landslides’ deep structure (McCann and Forster, 1990). In agreement with our observation, airborne photography is still a commonly used method for landslide investigation and mapping; the main advantage of aerial photography is, in addition to having the highest spatial resolution, the longest record of any remote-sensing data type (Stumpf et al., 2011). Electrical and seismic methods have been used in landslide practice for several decades and they are broadly applicable for investigating the landslides’ internal structure (e.g. Bogoslovsky and Ogilvy, 1977; and Turner and Schuster, 1996). This was probably one of the reasons that they occurred in our responded-to sites so frequently.

Regarding the early warning potential of the monitoring methods and parameters, the precipitation amount, pore-water pressure and displacement monitored by wire extensometers, dGPS and total stations, followed by air temperature, EM-emissions monitoring, and displacement monitored

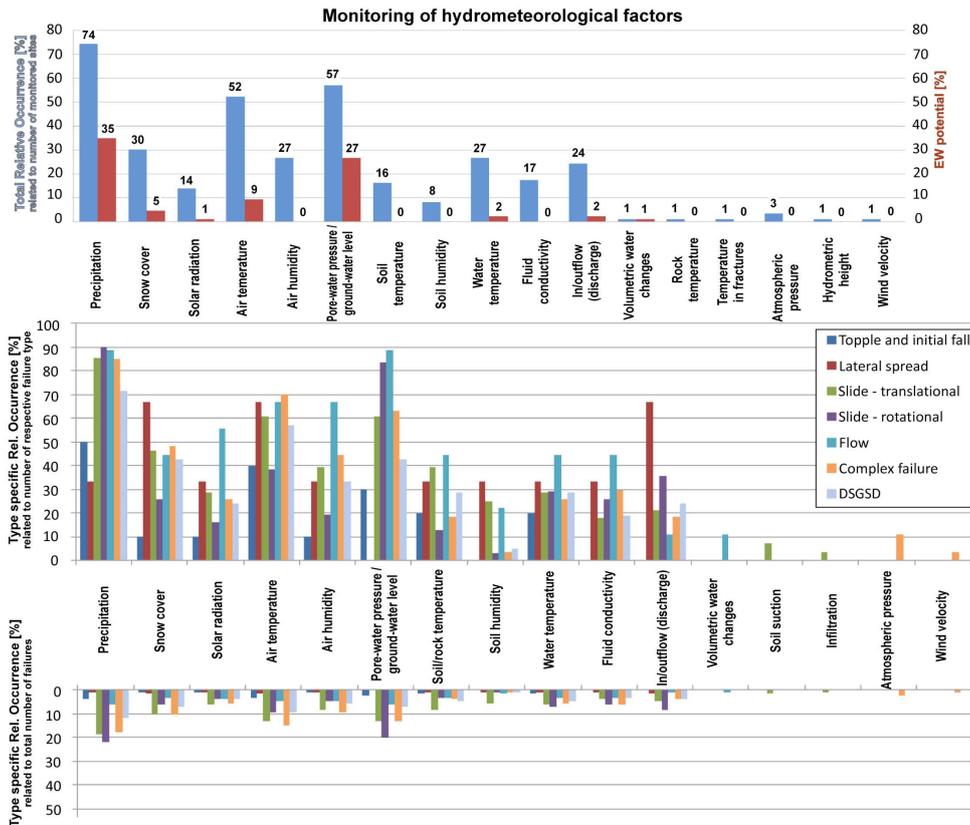


Fig. 10. Review of total relative occurrence, EW potential and type-specific relative occurrence of hydro-meteorological monitoring parameters from the 86 monitored landslide sites.

by the TM 71 crack gauge were considered the most promising parameters for early warning (Fig. 12). The precipitation amount is one of most common indirect triggering factors of landslides (Wieczorek, 1996) and it is reported in our study to be the most promising monitoring parameter for EW (Fig. 13). The warning could be based on landslide-triggering rainfall thresholds (Guzzetti et al., 2008), rainfall could be used as a dynamic variable along with the static variables of land surface factors in logistic regression approaches to landslide medelling, and the rainfall data could serve as an input for process-based hydrologic-geotechnical models (review by Apip et al., 2010); satellite real-time rainfall data are the substantial base for landslide EW systems at regional scales (e.g. Aleotti, 2004; Apip et al., 2010; Hong and Adler, 2007; and Strauch and Castellon, 2009). Real-time meteorological and geotechnical/hydrological monitoring is an essential part of any operational landslide warning system (Baum et al., 2005; Baum and Godt, 2010; Corominas et al., 2005; Keefer et al., 1987). In agreement with this statement, pore-water pressure, and displacement monitored by wire extensometers, dGPS and total stations were ranked very high also by our respondents. Air temperature is a frequently monitored parameter in the landslide monitoring networks as

well as the seasonal temperature variations are able to induce, under the central European climate regime, irregular seasonal oscillations of volume changes of rock up to 2 mm that interfere with the detection of permanent displacements (Košťák, 2006). The high EW potential of this parameter, evaluated by the respondents, corresponds also to its role, e.g. in rockfall triggering. The EM-emissions (passive/pulse electromagnetic emissions – PEE or called natural pulsed electromagnetic field of earth – NPEMFE) are reported as a new promising monitoring parameter of slope failures (e.g. Aitmanov et al., 1997; Burdakova et al., 2005; Kharkhalis 1996; Lauterbach, 2005; and Wagner et al., 2002), and within our study was also ranked by the respondents relatively high. And finally, the TM 71 crack gauge was ranked so high probably thanks to its high accuracy, ability to measure the movement of particular pairs of blocks in 3-D including rotations and resistance in harsh field conditions (Košťák, 2006), recently also profiting from its extension for automated data reading and transfer (Klimeš et al., 2012). DC resistivity, GB InSAR, optical image, automatic inclinometer and other relatively less ranked but modern methods suffered probably from their random use. They could, similarly to other even

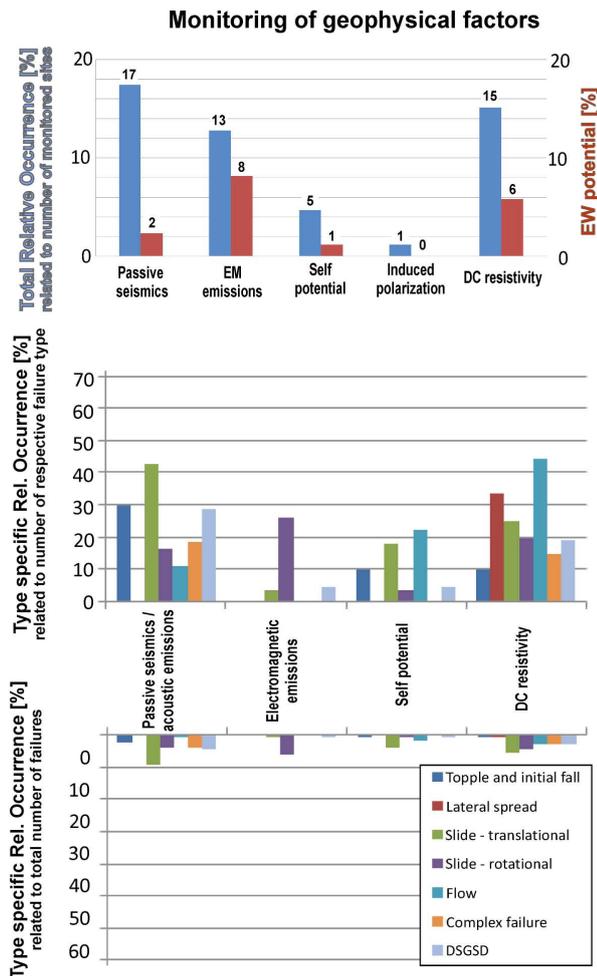


Fig. 11. Review of total relative occurrence, EW potential and type-specific relative occurrence of geophysical monitoring parameters from the 86 monitored landslide sites.

lower ranked methods, have a high EW potential if they were used more commonly in practice and were more mature.

There could be many reasons for the regional differences that we observed in the application of particular investigation and monitoring techniques at the landslide sites, especially when compared between countries of the former Western and Eastern Blocs. We suspect that those regional differences occur especially due to traditional national approaches; also the main scientific focus, education, and experience of persons in charge could have played some role; e.g. in Slovakia, much more engineering-geological and geotechnical approaches prevailed over the remote-sensing data, in contrary to, e.g. Italy, where the remote-sensing data played a substantial role. That could also be related to land use and vegetation cover of the monitored landslides making the application of remote-sensing data in densely forested Slovakia difficult. The economic situation of respective countries is a noticeable factor as well, as the modern, but still relatively

expensive methods like lidar or dGPS, have occurred more in the “Western” countries, in contrast to the traditional methods applied more in the “Eastern” countries.

5 Conclusions

The study reviewed and evaluated methods of landslide investigation and monitoring based on the information obtained from 86 real slope failures monitored in Europe and Asia.

From a total of 129 different monitored slope-failure types, the most abundant ones were rotational slides and translational active slides with recent movement rates of less than 10 mm month^{-1} , and deep-seated gravitational slope deformations. The particular landslide types, however, formed complex failures at about 31 % of the monitored sites. The most frequently used mapping and testing surveys were the geological, engineering-geological and geomorphic mappings, core drilling, strength properties/deformability tests, clay mineralogy testing, and borehole testing. The most abundant ground-based geophysical methods of investigation were DC resistivity and refraction seismic analysis, reflection seismic analysis, self-potential survey and ground-penetrating radar; the complex geophysical logging in boreholes, resistivity survey and the refraction seismic analysis were the most reliable ones.

Among the most frequently applied remote-sensing data and techniques for landslide investigation were aerial photographs, radar interferometry and lidar ALS, and as the most reliable were unequivocally evaluated to be lidar ALS, aerial photographs and satellite optical very-high resolution images.

Classical and automated inclinometers, wire extensometers, dGPS, optical images and total stations were ranked as the most reliable sensors of displacement and deformation monitoring with the highest early warning potential. The *precipitation amount*, *pore-water pressure* and *air temperature* were the most abundant hydro-meteorological monitoring parameters listed in the landslide sites; pore-water pressure and precipitation amount had the highest EW potential.

Passive seismic/acoustic emissions, electromagnetic emissions and DC resistivity were evaluated as reliable geophysical monitoring parameters for EW. However, all the geophysical parameters were randomly used for monitoring and remain of rather academic importance to date. Regional differences in the application of different methods were observed.

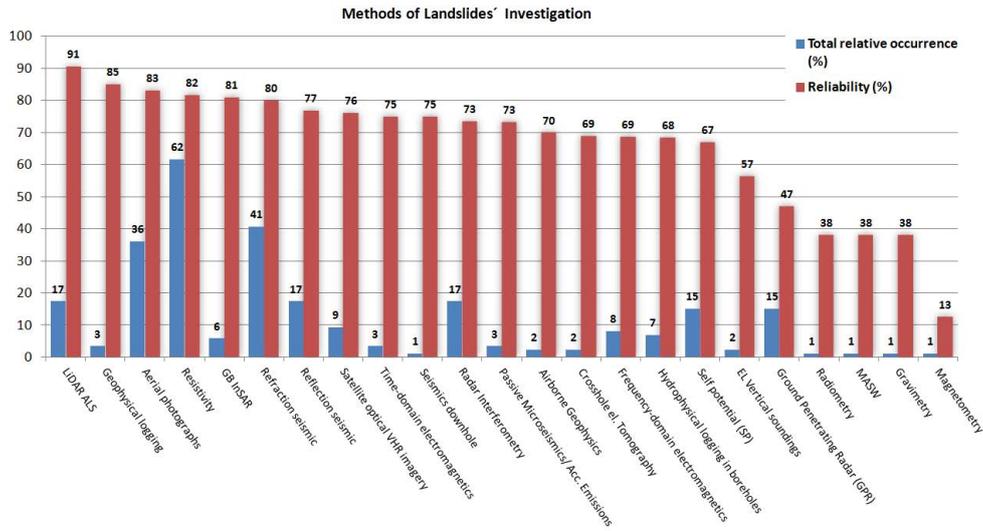


Fig. 12. Comparison of all of the evaluated methods of landslide investigation ordered by their reliability.

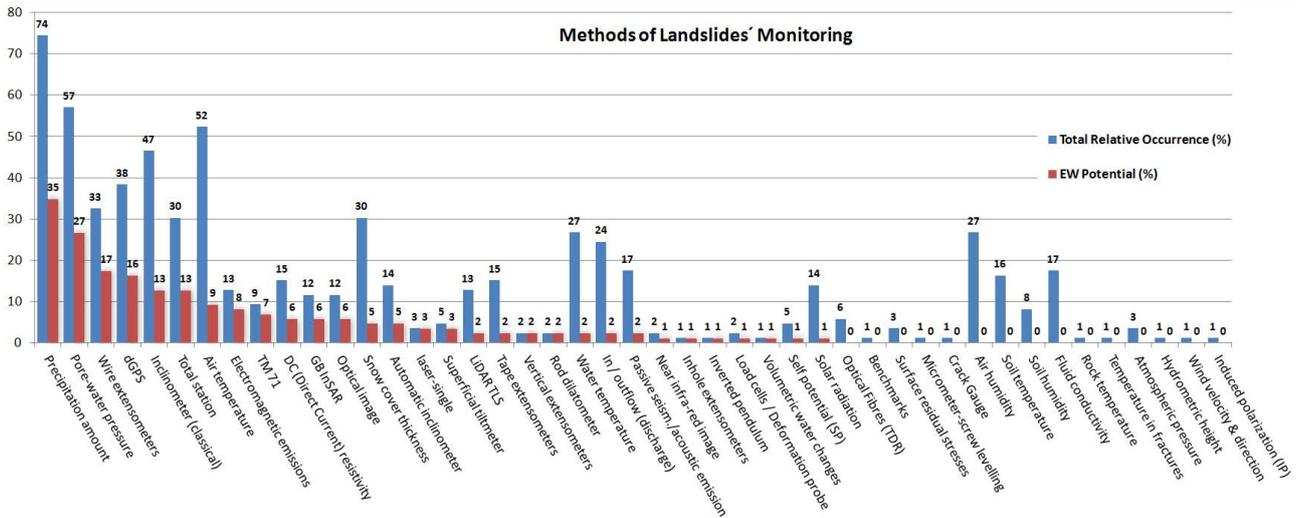


Fig. 13. Comparison of all of landslide monitoring methods included in the study ordered by their early-warning potential (red).

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