# Chapter 2
# Rock Mass Characterization and Rockfall Monitoring: Traditional Approaches

**Ondřej Racek and Jan Blahůt**

**Abstract** Rock mass characterization and rockfall/rock slope stability monitoring methods are one of the fastest evolving research areas in the field of geosciences. Traditionally, simple mapping, geodetical or geotechnical methods are used. The ongoing rapid development of monitoring methods is conditioned by engineering challenges when new infrastructure is nowadays being constructed in complicated geological conditions. These are represented by mountainous areas, deep gorges with steep slopes, or even active landslide sites. Traditional methods can be used within these monitoring demanding sites and bring high-quality monitoring results, sometimes with higher precision than modern state-of-art methods. This chapter reviews traditional rock slope stability monitoring methods and discusses their advantages, applicability, and strong/weak sides. Traditional methods are compared against newly introduced, modern state-of-art methods.

**Keywords** Rock slope · Monitoring methods · Rockfall · Stability

## 2.1 Introduction

Rock mass characterization, together with rock slope stability monitoring methods, belongs to the fastest evolving research fields within geosciences (Fig. 2.1). Due to the expansion of civil engineering to geologically complicated sites, monitoring + of unstable rock slopes has become an irreplaceable part of engineering projects.

Since the first half of the twentieth century or even longer, traditional methods have been used. Despite the age, these are still not fully replaceable by modern methods. Even though they do not provide fast data collection or spatial resolution, traditional methods can still achieve high precision results. Often monitoring is carried out

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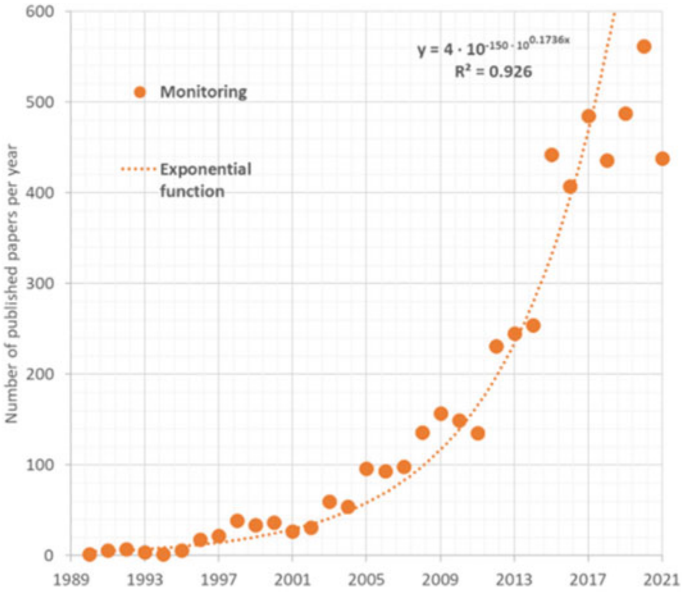


**Fig. 2.1** Slope stability monitoring domain data—published in research papers (WOS database) (Blahůt et al. 2021)

using traditional methods that are cheaper to establish and run. In comparison with modern methods (Blahůt and Racek 2023, Chapter 1) traditional methods usually demand experienced users to process and evaluate results. This paper summarizes traditional methods used for rock mass characterization and rock slope monitoring and provides a brief overview of monitored rock slope/rock mass properties. Though rockfall is a well-known process, mechanisms of rockfall triggering, or previous destabilizing processes are usually not fully described (Dorren 2003). The rockfall is a rapid process generally lasting a few seconds to minutes. Rockfall events result from long-lasting external factors (Gunzburger et al. 2005) in combination with internal site-specific properties of the rock slope (D'Amato et al. 2016). It is necessary to understand and quantify both the properties of the rock slope and the influence of exogenous processes on its stability (Fischer et al. 2012) to improve the knowledge about rock slope temporal dynamic and rockfall triggering/preparatory factors. For that, in-situ monitoring of rock slope activity is necessary (Fantini et al. 2016). Monitoring systems are used to observe natural rockfall events, rock slope temporal development (Fantini et al. 2016; Lazar et al. 2018), or for early warning infrastructure.

Traditional methods are limited by lower temporal resolution. Rock mass stability is traditionally estimated using empirical or heuristic methods based on subjective experience and knowledge of the researcher combined with empirical data (Abramson et al. 2001). This approach is applicable in well-mapped areas or known active rockfall sites. These expert methods often do not provide quantitative data;

however, in the case of risk estimation expert point of view remains irreplaceable. The ability to predict future rock slope behavior is strongly dependent on the researcher's subjective experience (Krishnan and Sommer 1994). For effective monitoring design and placement, it is crucial to cooperate with an experienced specialist/researcher to ensure solid and meaningful results (Masoumi et al. 2017). Monitoring design must reflect the main mechanisms of rock slope destabilization, the magnitude of the processes, power supply effectiveness, and data processing effectivity, together with a balanced budget (Bond et al. 2013). Each monitoring method is suitable for measuring different variables in different spatial and temporal resolutions. A monitoring system design aims to choose appropriate methods to get meaningful and easily interpretable data (Farrokh and Intrieri 2011).

Monitoring systems can use a single method (Boyd et al. 1973) or complex systems (Blahůt and Racek 2023, Chapter 1) use multiple monitoring methods (Janeras et al. 2017; Racek et al. 2021). Traditional methods are usually based on geotechnical in situ measurements. Properties of rock slopes are traditionally described by simple geological/geomorphological methods (Olona et al. 2010) or geotechnical indices (Ding et al. 2000).

## 2.2 Rock Properties and Monitored Variables

For rock slope temporal stability estimation, it is important to characterize the rock slope's initial stability and internal properties. For the rock slope, dynamic monitoring is important to track external (meteorological, seismic) factors (Gaffet et al. 2010). General stability estimation is, in most cases, done by an expert qualitative, and afterward, the appropriate quantitatively monitoring methods are selected and deployed.

### *2.2.1 Rock Slope/Rock Mass Properties*

For rock slope characterization, long-term stable descriptive variables are used. These include rock mass mechanical properties such as Young's modulus, elasticity modulus, hardness, roughness, or thermal properties (Rocha and Cording 1981). Variables are laboratory-obtained using representative rock samples or estimated in the field using geophysical methods (Blahůt and Racek 2023, Chapter 1; Klose et al. 2007). These variables determine rock mass's physical and mechanical behavior, thus rock slope stability. Rock slope stability is further affected by its structure, mainly by the discontinuities within rock mass (Einstein et al. 1983). These are crucial in rockfall development because determining unstable blocks overall weakens the rock mass (Macciotta and Derek 2015). Discontinuities are characterized by orientation (dip/dip direction), spacing, persistence, roughness, wall strength, aperture, filling, seepage, number of sets, block size, and discontinuities surface roughness or filling

(Kulatilake and Wu 1984; Barton 1974). These data are obtained in the field by direct observation or using a geological compass (dip/dip direction), a feeler gauge (aperture), roughness broom (roughness), or Schmidt hammer (hardness). Temporal stability estimation is important to know rockfall frequency, volume, and source area for rock slope. These data bring the possibility to approximately predict future rockfall dynamics of rock slope. Rockfall catch net is generally used for the direct rock slope observation to gain overall rock slope activity data (Krautblatter and Moser 2009).

### *2.2.2 External Variables/Factors Monitoring*

Rock slope temporal stability is affected by exogenous meteorological factors. Dilatation of rock mass and partial blocks, together with freeze–thaw cycles, is determined by temperature cycles (Weber et al. 2017). Rockfall events can also be triggered by severe rainfall (Maria et al. 2012) or high-velocity wind gusts (Sass 2005). These can be quantified using weather stations. Measured rock slope dynamics should be compared with the closest available meteorological data. It is possible through such a data to find correlations between rock slope dynamics and meteorological influences (Royan et al. 2015; Pratt et al. 2019). Rockfalls are often triggered by earthquake events (Marzorati et al. 2002). Therefore, seismic activity monitoring is desirable to distinguish seismically triggered events (Wieczorek and Snyder 2009).

## 2.3 Overview of Rock Slope Description and Monitoring Methods

Rockfall is a complex and fast process driven by multiple factors and variables. This makes monitoring using traditional methods (Fig. 2.2) challenging. Unlike landslide monitoring, rockfall except for slow large rockslides is a rapid movement (lasting seconds) (Stoffel and Hitz 2008; Lambert and Nicot 2013). Rock slope destabilization and consequent rockfalls are induced by the interaction of predisposing elements with external variables (Gunzburger et al. 2005; D'Amato et al. 2016). Rockfall can also be triggered artificially by human activities (Bauer et al. 2005). Conditions that destabilize rock slope affect the rock slope in the long term up to tens of thousands of years (Gunzburger et al. 2005). Changes of these or their thresholds overcoming can be recorded with traditional or modern (Blahůt and Racek 2023, Chapter 1) monitoring methods.

The purpose of the monitoring system determines the use of the specific method. Methods should be chosen according to the duration of monitoring, accessibility of the monitoring site, the safety of workers, financial resources, desirable results, and Spatio-temporal scale of the survey (Hartmeyer et al. 2012). Traditional (T) and

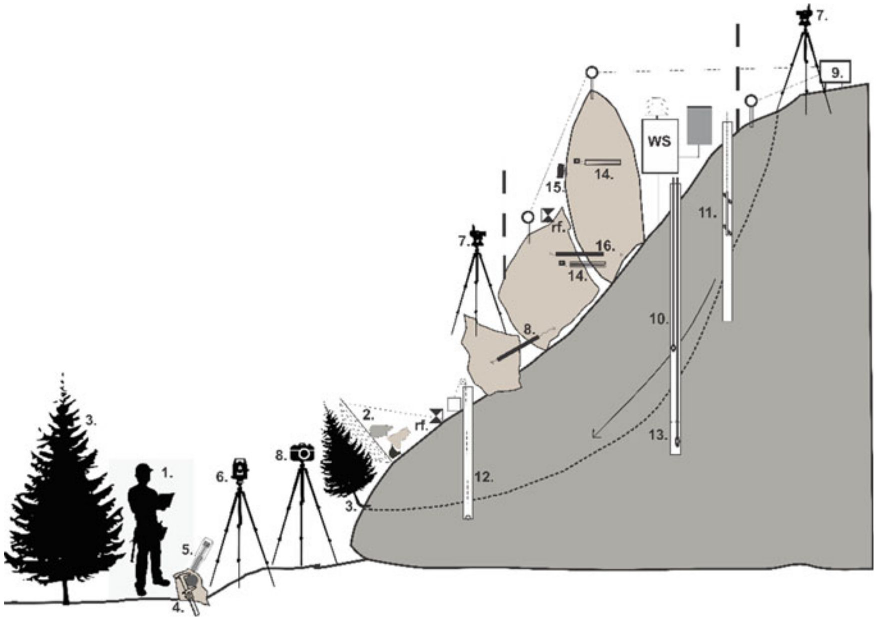


**Fig. 2.2** Overview of traditional monitoring methods. **1** Expert methods, **2** Catch net, **3** Tree ring, **4** Lichenometry, **5** DOW, **6** Tacheometry, **7** Precise levelling, **8** Photogrammetry, **9** Wire extensometer, **10** BH extensometer, **11** BH inclinometer, **12** BH wire extensometer, **13** Piezometer, **14** Strain gauge, **15** Tilt meter, **16** Crack monitoring. WS: weather station, rf: reflector

modern (M) methods of rock slope stability estimation and dynamic monitoring can be classified according to their purpose as follows:

### *2.3.1 Estimation of Rock Slope Properties Methods*

Methods are chosen based on simple expert rock slope observations or empirically defined stability indices. The expert stability estimations are nearly impossible due to their inherent subjectivity, but the results of geotechnical classifications (stability indices) can be compared between sites. Methods are used for rock slope internal properties estimation, initial stability estimation, or unstable rock slope elements identification.

- Mapping (T)
- Geotechnical classification (T)
- Electrical resistivity tomography (M)
- Seismic tomography (M)

### 2.3.2 Rockfall Events Dating Methods

Methods that analyses medium-scale Spatio-temporal patterns of rockfall activity or specific unstable rock slope past temporal activity.

- Dendrochronology (T)
- Lichenometry (T)
- Rockfall catch net (T)
- Degree of weathering (T)
- Archive review (T)
- Cosmogenic nuclides (M)
- Luminescence (M)

### 2.3.3 Spatio-Temporal Monitoring Methods for Rock Slope Activity

Methods used for direct (d) or indirect (i) measuring Spatio-temporal rock slope evolution. These methods allow the quantification of rock slope activity.

- Tachymetry (Ti)
- Precise leveling (Ti)
- Analogue (Ti)/digital (Mi) photogrammetry
- Crack monitoring (Td)
- Extenso/dilatometer (Td)
- Tiltmeter (Td)
- Strain gauges (Td)
- Piezometer (Td)
- Laser scanner terrestrial/aerial (Mi)
- GNNS (Mi)
- Ambient vibration, microseismic monitoring (Md)
- Optical fiber (Md)
- Camera monitoring (Mi)
- Aerial monitoring (Mi)
- Radar interferometry terrestrial/aerial (Mi)
- Remote vibration (Mi)
- Thermal camera (Mi)

### 2.3.4 External Variables/Factors Monitoring Methods

Monitoring of external variables/factors which contribute to rock slope temporal destabilization. It is not necessary to place sensors directly within rock slopes with these methods. But, the closer the data are gained, the more represent influence on the rock slope stability.

- Weather station monitoring
- Temperature monitoring
- Seismic station

## 2.4 Measuring Quality of Results

To evaluate the monitoring results is necessary to quantify the performance of the used sensors. This subchapter is dedicated to the description of measurement errors and uncertainties. All sensors used for monitoring bring uncertainty to monitoring outcomes (Fassò et al. 2005). Uncertainty leads to static measurement errors (Fig. 2.3). Static errors can be divided according to Menditto et al. (2007) as follows:

- **Random errors** are inconsistent and do not appear in the same magnitude or direction except by change. Random errors should be normally distributed (Viswanathan 2005).
- **Systematic errors** are caused by measuring device (system) imperfection or incorrect use. Systematic errors acquire the same value during the whole monitoring campaign and are relatively easy to remove from results. The specific type of systematic error is **Human factor error** caused by improper use of a measuring device. Human factor errors are challenging to prevent or manage (Rozsypal 2001) and can cause inaccuracies in the results. Sowers (1993) documented that human factors caused 88% of failures in geotechnical engineering problems.
- **Total error** is composed of random and systematic errors. It expresses the overall inaccuracy of measurement.

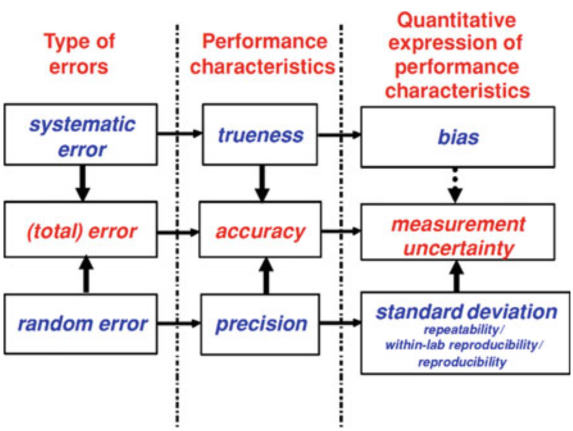


**Fig. 2.3** Relationships between type of error, qualitative performance characteristics, and their quantitative expression after (Menditto et al. 2007)

### 2.4.1 Performance Characteristics

- Knowing the sensors' performance characteristics (Fig. 2.3) is necessary to evaluate monitoring results. Errors in measuring devices can be described by performance characteristics that are obtained by testing devices in the laboratory and should be provided by the manufacturer. The performance of sensors is expressed by static (S) and dynamic (D) performance characteristics (Menditto et al. 2007; Dunnicliff 1993). Static characteristics do not vary over time. Dynamic characteristics are used in the case of high-frequency monitoring (sub-seconds).
- **Accuracy (S)** is the algebraic difference between the indicated value of the sensor (measurement) and the true value of the known measured reference value. The accuracy represents the total error of measurements, quantitatively represented by **measurement uncertainty**.
- **Precision (S)** is an instrument's ability to measure a similar value under similar circumstances repeatedly. Precision represents random errors quantitatively represented by **standard deviation**.
- **Trueness (S)** is the difference between indicated, and true values averaged from large series of tests. The Trueness represents a systematic error, which is quantitatively expressed like **bias**.
- **Sensitivity (S)** is the smallest change in input that invokes changes in the measured value.
- **Repeatability (S)** is precision determined under the same measuring conditions.
- **Reproducibility (S)** is precision determined with different operators with different measuring devices on similar specimens.
- **Resolution (S)** is the specific increment in input value that will cause a change in output from the instrument.
- **Percentage of static error (S)** is the percentage difference between the true value and the value measured by the instrument.
- **Speed of response (D)** is the response time on change in the measured input variable.
- **Lag (D)** is the delay in the response of the measuring instrument to the change in measured quantity.
- **Dynamic error (D)** is the difference between the true and measured values that vary in time.
- **Fidelity (D)** is the degree to which an instrument measures input quantity without any dynamic error.

Some errors and uncertainties can be partly reduced by using multiple sensors, different monitoring methods, or data processing (Peng et al. 2014). Every monitoring results contain uncertainties that must be considered within the resulting conclusions.

## 2.5 Traditional Methods of Rock Slope Monitoring

Traditional rock slope stability monitoring methods comprise fieldwork and raw data from the rock slope. Only a few traditional geodetical methods can measure rock face spatial changes remotely. This advantage is yet redeemed by extensive time-consuming fieldwork with slow data collection. Often these methods are dependent on the researcher's experience and knowledge of local conditions (Van Westen et al. 1999). Despite mentioned limitations, these methods can provide high precision results even for slow movements. The smallest spatial changes can be detected only by long-term monitoring, where the low temporal resolution of traditional methods is not an issue.

### *2.5.1 Expert Methods*

The use of expert methods demands an experienced researcher. Experts determine rock slope stability and temporal evolution by one visit or repeated visits to the known active area. The results of these methods are qualitative rock slope descriptions or empirically defined stability indices. By their very nature, these methods are subjective yet can produce valuable outcomes. Every thoroughly designed monitoring is based on expert site observation and evaluation of possible future dynamic scenarios.

#### 2.5.1.1 Geomorphologic Mapping (Analyses)

Mapping is usually the first step in rockfall studies or hazard estimations on chosen localities. Mapping itself can be performed on medium to large scales (Copons and Manuel Vilaplana 2008). Demek and Embleton (1978) were documented an overview of mapping methods, and geomorphological mapping (Degraaff et al. 1987) provides rockfall events volume, accumulation area, and sometimes source area spatial data (Wieczorek et al. 1992). A long-term monitoring requires repeated visits to the study area (Luckman 2008), and this method is effective in highly active localities only. The fieldwork can describe the Spatio-temporal pattern of rock slope evolution through the repeated visit to the known locality. Expert mapping of active rock faces determines the exact location of further instrumentation for meaningful data outcomes.

#### 2.5.1.2 Geotechnical Classifications

Geotechnical classifications are used to describe rock mass properties and their initial stability. Widely used methods are RQD (Deere et al. 1967), Q-Slope (Barton and Bar 2015), SMR (Romana 1993), RMR (Bienieawski 1973), or GSI index (Hoek et al. 1995). Inputs are structural elements of rock slope, properties of the rock mass, and the local hydrogeological regime. The rock slope geotechnical classifications (Q-Slope, SMR, RMR) are based on classical underground rock mass classification methods. Outcomes from the geotechnical classifications are empirically defined stability indexes which describe rock slope stability. The index values are linked to construction works recommendations. Further information about geotechnical classifications provides Yang et al. (2022) or Aksoy (2008).

#### 2.5.1.3 Rockfall Collector

Method is used for rockfall intensity or volume estimation (Krautblatter et al. 2012). It is utilised as mechanical barriers, nets, or walls to get data about rockfall temporal activity at the known active sites (Fahey and Lefebure 1988). Nets and collectors can be well equipped with warning sensors or continual camera monitoring. Usually, recorded rockfall activity or volume is correlated with meteorological data. Through this analysis, typical precipitation thresholds can be calculated, and the triggering of larger rockfalls can be determined. This type of monitoring demands repeated researcher visits or remote surveillance to estimate the changes within material accumulation. This method was documented well by Sass (2005).

### *2.5.2 Dating Methods*

The dating of rockfall events is complicated without continuous monitoring or an extensive database (Guzzetti et al. 1999). Data about past rockfall of temporal patterns can be used for rockfall hazard assessment or zonation and eventual protection. Historical data about rockfall activity should be known before the start of construction works near the rock slope.

#### 2.5.2.1 Dendrochronological/Tree Ring Methods

The method is based on detecting impact scars on trees caused by flying or bouncing boulders towards the down. Past rockfall events are dated from disturbed wood samples or tree rings from drilled cores extracted in the field (Dorren et al. 2007). Resulted Spatio-temporal rockfall distribution is implemented in hazard estimations (Stoffel and Bollschweiler 2008). Tree ring analyses potentially work with monthly temporal resolution (Ortloff et al. 1995). Dendrochronology can theoretically reach hundreds of years into the past when old trees are present near the examined slope. Stoffel (2006) reported a review of this method used for rockfall dating.

#### 2.5.2.2 Lichenometric Analyses

This method is based on the principle of measuring the diameter of particular lichen species on rockfall accumulations (André 1986). The temporal precision of lichenometry dating ranges from one-year precision for young events up to a hundred years for more than a thousand years old events (Bull 1996). A reliable calibration curve is needed to apply this method (Hartvich et al. 2017). A complex review of lichenometry was reported by Joshi et al. (2012).

#### 2.5.2.3 Degree of Weathering Dating (DOW)

The method considers that younger accumulation or recently exposed rockfall scar was less affected by the weathering process; these surfaces should be harder. The DOW is determined in the field using Schmidt hammer surface hardness testing. DOW can be used for absolute dating of accumulation age (Nesje et al. 1994) or, more often, for relative age estimation in the case of complex rockfall sites (Klapyta 2013). The DOW can also be approximately determined from the color of the surface or the absence/presence of secondary biocrust in the case of young events (Dorren et al. 2007). A review of weathering-based dating methods was elaborated by McCarroll (1985).

#### 2.5.2.4 Archive Review

A review of archive sources, such as newspapers or maintenance diaries (roads, railway, ropeway), can provide temporal rockfall information (Hungr et al. 1999). Trough the research of archive sources, it is possible to get information about mass wasting events, such as landslides or voluminous rockfalls, from mass media. Events that affected settlements or infrastructure are mentioned through archive sources. Some extensive works (Raška et al. 2015; Guzzetti et al. 1999) used newspaper articles to enrich landslide inventories.

### *2.5.3 Geodetical Methods*

Geodetical methods are used to measure both relative and absolute spatial changes in rock slope geometry (Gunzburger et al. 2005). The geodetical monitoring systems are mostly in use for landslide monitoring (Saleh and Al-Bayari 2007), glaciers monitoring (Azam et al. 2018), or monitoring of unstable open-pit mines slopes (Osasan and Afeni 2010), together with civil engineering applications (Erol et al. 2004). The possibility of remote data colection makes geodetical methods appropriate for unstable danger rock slopes monitoring.

#### 2.5.3.1 Tachymetry

This is also called tacheometry and telemetry and it is more than a century-old method used for inaccessible or dangerous rock block displacement monitoring (Cuffe 1907). Traditionally, a simple angle measuring theodolites with reflecting prisms is used. Nowadays, this method is being replaced with reflector-less total stations with a precision of approx. 1 cm per 1 km distance (Fengrui 2011). By such a method, even the spatial orientation of surfaces can be measured (Feng et al. 2001); when reflective prisms are placed within unstable features, precision rises to 1.5 mm per 1 km. The advantages of using total stations are easy transportation, simple data processing, long-range, and possible automatization of a permanently placed device (Lambrou and Pantazis 2006). In the case of multiple points are measured with the total station, a simple generalized digital model of rock slope can be created (Isioye and Jobin 2012). The permanent placement of the automatized total station can be considered a modern monitoring method. This application demands the use of reflective prisms. Total stations measuring campaigns are used within complex monitoring systems (Janeras et al. 2017; Corsini et al. 2013), and also Scherer and Lerma (2009) recorded an in-depth information of tachymetry.

#### 2.5.3.2 Precise Leveling

A precise yet straightforward all-around geodetical method is used for landslides monitoring (Savvaidis 2003). In the case of steep rock slope monitoring use of leveling is limited (Stiros et al. 2004) This method is used for slow tilting rock blocks or rock mass subsidence monitoring (Motagh et al. 2007; Košťák et al. 2006). Also, the Spatio-temporal evolution of large, slow rock slides can be determined using precise leveling campaigns (Zangerl et al. 2010) with the precision of up to tenths of millimeters. With a long enough time series, this method leveling can recognize even small movements with low magnitude.

#### 2.5.3.3 Analogue Photogrammetry

This is another traditional method in landslide monitoring. It was used for rock slopes or deep mine monitoring (Chandler and Moore 1989). This tool was used in long-range mode (landforms) and microscale close-range mapping with precision up to millimeters (Welch and Dikkers 1978). The method was also used for slope stability monitoring, where it provides Spatio-temporal information about rock slope surface dynamics in combination with tachymetry. The traditional approach uses fixed reflectors (tie points) positioned within the rock face. The spatial position of reflectors is monitored using time-lapse photos (McVey et al. 1974). The field precision of such a setup was +0.05 m. Due to complicated analog photos processing, it was a marginally used method. Nowadays, digital photogrammetry is used all around geosciences (Walstra et al. 2007).

## 2.5.4 Geotechnical Methods

Geotechnical sensors are placed within the rock face or inside the rock mass in boreholes. Direct placement brings less complicated and straighter forward, intuitive data interpretation (Dunnicliff 1993). The geotechnical methods are frequently used in the rock slope monitoring. The placement principles and measured quantities remain unchanged, yet the sensors now often work with modern technologies.

### 2.5.4.1 Crack Monitoring

Monitoring of the crack displacements is a frequently-used method. It describes rock face or unstable rock slope element Spatio-temporal behavior (Bakun-Mazor et al. 2013; Janeras et al. 2017; Collins and Stock 2016). Generally, crack displacement monitoring can be used for rockfall event prediction (Zvelebil and Moser 2001; Arosio et al. 2009). The use of sensor type is determined by the Spatio-temporal scale of the monitored feature. Simple attachable crack meters (vernier calipers) are used for measuring of fast movements or for low-frequency measuring campaigns (Boyd et al. 1973; Zvelebil et al. 2002). For first verification of the ongoing crack dynamic, glass plates are glued over the crack ("tell tale") (Price 2010). In geoengineering, mining or civil engineering used, "tell tales" are made from two overlapping plastic plates, glued or screwed over the monitored crack with an aim and cross (or moiré) pattern with submillimeter resolution (Akbari 2013; Johnson 2005). Displacement transducers (Ellis 1975) or vibrating string crack meters (Wirth and Mario 1968) are used for continuous crack monitoring. These devices can provide continuous data about crack dynamics (Ding et al. 2000; Peters and van der Vliet 2009). Data loggers should be equipped with a thermometer to distinguish thermal dilatation (Thorarinsson 2015). Continuous crack monitoring is one of the key parts of rockfall early warning systems setting on an alarm when movement accelerates (Rozsypal 2001). The precision of the mechanical (vernier) crack meter can reach 0.05 mm (Boyd et al. 1973). Modern position transducer sensitivity can be less than 0.05 mm (Fantini et al. 2016), and a typical precision reaches 0.01 mm (Klimeš et al. 2012) with 0.5% accuracy. Dilatometers are used to measure the displacements between partial blocks of rock slopes (Vařilová and Zvelebil 2005; Zvelebil et al. 2002). Dilatometers can be installed permanently, or portable dilatometers can be applied when only measuring bolts are placed within rock face (Hartvich and Mentlík 2010; Vilímek et al. 2007).

### 2.5.4.2 3D Moiré Crack Gauges

A long-term monitoring of very slow movements, an optical-mechanic TM-71 gauge (Klimeš et al. 2012) is world widely used. This device can measure relative displacements and rotations between rock blocks in 3D. The sensor is fully analog and does not require an electricity source to work. TM-71 applicable monitoring of slow movements, such as rockslides, toppling, or tectonic movements, with a precision better than 0.007 mm (Stemberk et al. 2010). In the case of rotation, precision is better than 0.00016 rad (Košťák et al. 2011). The device can be fully automated when long-term monitoring is needed. Then data can be subtracted remotely.

#### 2.5.4.3 Tape/Wire Extensometer

It is convenient to use an invar method to measure movements over greater distances in the complicated topography (Duffield and Burford 1973) by tape/wire extensometer (Lazar et al. 2018; Baroň and Supper 2013). The main advantage of this method is that the extensometer profile does not have to be straight or level. It is one of the perfect methods for large complex rockslides velocity and development monitoring or unstable block monitoring (Greif et al. 2006; Crosta and Aligardi 2002). This monitoring provides continuous data with a permanent extensometer (Lazar et al. 2018). Eventually, only the anchors are permanent, and measurement is done in campaigns (Glawe et al. 1993). The highest sub-millimetric precision is limited to approx. 60 m profile length (Osasan and Afeni 2010).When a profile is longer, outcomes can be biased by invar thermal expansion. When rockslide velocity is higher than wire thermal expansion bias, the profile can be longer (Janeras et al. 2017; Zangerl et al. 2010). Long profiles can be measured underground where the temperature is stable (Bhalla et al. 2005). The precision of wire extensometer monitoring is about 0.01 mm when accuracy decreases with profile length (Osasan and Afeni 2010).

#### 2.5.4.4 Borehole Extensometer

A borehole extensometer is used to measure slow rock mass sliding movements, like a creep (Gunatilake et al. 2002) or deep-seated slope deformations (Salvini et al. 2015). The root of the extensometer is placed in a deep stable part of the rock slope, and the borehole head is moving together with the surface. Multiple extensometers rooted in different depths to detect possible slip surface in different depths (Huang et al. 2009) must be deployed. The precision of a borehole extensometer is approximately 0.1 mm (analogue) or 0.01 mm (digital/MEMS) (Angeli et al. 2000). This method is traditionally used in civil engineering or geological application within compact rocks or soils. Burland et al. (1972) provides an overview of this method.

#### 2.5.4.5 Borehole Micrometer

A borehole micrometer is used to measure slow, predominantly vertical movements. Special borehole casings allow fixing micrometer probes in each length of the device to identify vertical movements like subsidence or heaving in the whole depth profile of the borehole (Li et al. 2012). The precision of this device is about 0.002 mm. The device can also measure changes in borehole casing inclination.

#### 2.5.4.6 Borehole Wire Extensometer

Wire borehole extensometers can monitor deep-seated rockslide velocity (Crosta et al. 2014). The wire is anchored in the stable bottom of the borehole. The head of the borehole with a reading device is moving along with sliding mass and applies tension on the wire, which transfers rockslide movement on to logger. The stable temperature inside the borehole does not affect the results by wire thermal expansion (Riley 1984). Boreholes can be drilled horizontally or inclined (Crosta et al. 2014), and the precision of the extensometer can exceed 0.001 mm (Mentes 2012).

#### 2.5.4.7 Tiltmeter

The method is applied on rock slopes (Sugawara et al. 2003; Blikra and Christiansen 2014), unstable blocks (Lambert and Nicot 2013; Janeras et al. 2017), or civil engineering monitoring (Kiremidjian et al. 1997). Monitoring can be continuous (Blikra and Christiansen 2014), or the monitored feature is instrumented with a standardized base for tiltmeter campaigns. The Tiltmeter surveys in rock slide profiles allow for decomposing partial movements within complex rockslides (Strouth et al. 2006). It provides precise data up to ±0.005° (Woschitz and Macheiner 2007).

#### 2.5.4.8 Borehole Inclinometer

A inclinometer allows for determining the velocity of the rockslide at different depths, and it is used for slow rock slide monitoring. Thus the slip surface/s depth (Crosta et al. 2014; Zangerl et al. 2010) can be determined. The inclinometer borehole casing is vulnerable, making this method suitable only for measuring small inclination changes (slow movements). Fast slope movement leads to deformation of the casing that does not allow passage of the inclinometer probe (Deschamps et al. 1998; O'Connor and Dowding 1999). This limitation can be partially overpassed by using a modern, flexible inclinometer probe (Zhang et al. 2018). The precision of the portable inclinometer is circa 1 mm/50 m of the borehole. A combined inclinometer/micrometer is used. This device measures horizontal and vertical spatial changes through the borehole profile (Frodl and Naterop 2007; Wittke 2014). The precision of this device is 0.002 to 0.003 mm in case of vertical changes and 0.0001 mm in case of lateral displacement (Frodl and Naterop 2007) and decreases with borehole depth. If continual monitoring is needed, it is possible to equip the borehole with a permanent inclinometer that provides continuous data about inclination and length change (Bell and Maud 1996).

#### 2.5.4.9 Piezometric Measurements

Monitoring groundwater pressure in landslide-prone zone areas with piezometers is an effective tool used in large, relatively slow rock slides. The first approach is underground water level monitoring is used because the rise of underground water levels often causes reactivation or acceleration of a rockslide (Crosta et al. 2014; Cloutier et al. 2015). The second approach is to measure changes in pore pressure using closed piezometers (Strauhal et al. 2016; Blikra et al. 2019).

#### 2.5.4.10 Strain Gauges

Tensiometers (strain gauges) are used for small rock mass strain changes measurement. Measurement is based on the principle of resistivity changes within a semiconductor grid (Ivor and Moxon 1965; Kanagawa et al. 1986). The Tensiometers are installed on the rock face (Fiorucci et al. 2020) or inside boreholes, perpendicular to the presumed stress directions (Lo et al. 1995). From the known changes in resistivity (strain) and Young's modulus, it is possible to compute changes in the stress field. A conical head borehole device (CCBO) is used to determining 3D tensor of the stress field inside the rock mass (Sugawara and Obara 1999), and Ljunggren et al. (2003) have been reviewed for strain measurement in rock mass.

## 2.6 Concluding Remarks

This paper enumerates the methods used for rock slope characterization, rock slope stability assessment, and rockfall monitoring. The first part of this chapter presents a short overview of rock mass properties monitored variables and rock slope stability influencing factors. After that, basic principles of functional monitoring system design are outlined. The key part of this chapter describes traditional methods for rock slope monitoring (Figs. 2.2 and 2.4). Nowadays, these methods are often replaced by their modern alternatives and are used less frequently (Fig. 2.4). Firstly, simple qualitative methods like geotechnical classifications or rockfall collector monitoring are mentioned. These methods describe rock mass characteristics, slope stability indexes, or short-term Spatio-temporal rockfall activity distribution. In contrast, the dating methods provide complex Spatio-temporal rockfall data even in the past. The enumeration and description of geodetical and geotechnical rock slope monitoring methods conclude the key part of this chapter.

All rock slope monitoring methods, traditional and modern (Blahůt and Racek 2023, Chapter 1) were primarily classified into four groups as follows:

- General properties of rock slope estimation
- Rockfall event dating
- Spatio-temporal rock slope activity

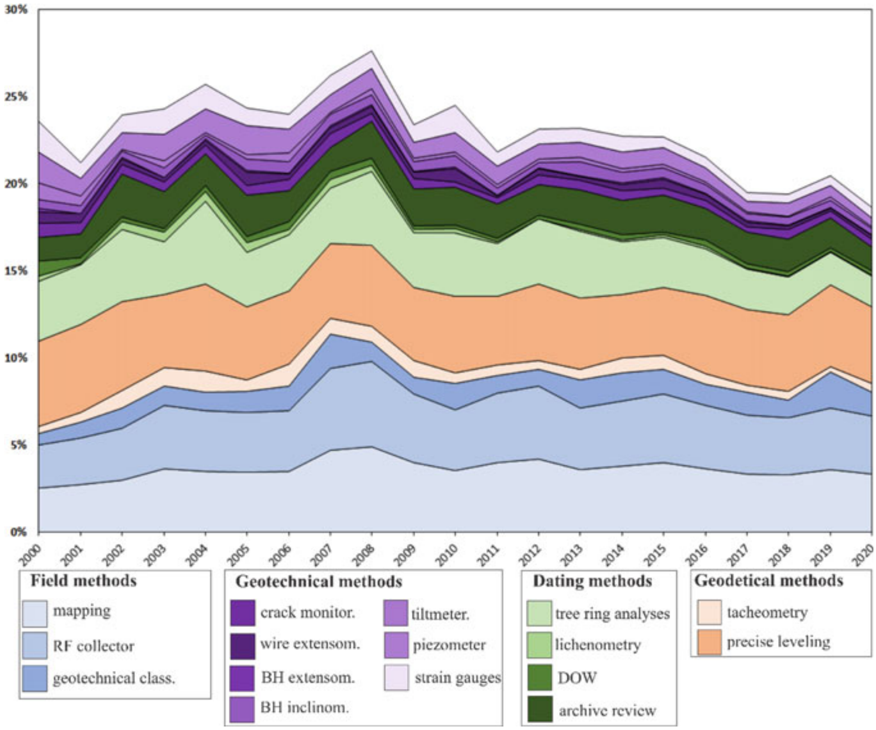


**Fig. 2.4** Traditional methods of rock slope monitoring. Percentage share of each method within published scientific papers mentioning method in the topic

- External variables/factors monitoring

The four groups listed above reflect the purpose of the methods and which variables are obtained using the listed methods. Then the traditional methods are fully described. Intelligibility these are, according to their principles, divided into four groups:

1. Expert methods should be the first step in rock slope monitoring. Complex mapping and initial stability estimation decide on future monitoring design. Quality monitoring cannot be designed without a good understanding of ongoing rock slope processes and destabilization regimes. It means expert methods will not be replaced in the future because these are still irreplaceable. The only disadvantage is low temporal resolution, as they are time-consuming and lack quantitative results.
2. Traditional geodetical methods measure Spatio-temporal rock slope surface changes. Thus these methods are selective, and the spatial change is monitored precisely with several representative points of interest. The use of traditional geodetical methods demands repeated visits to the site by the researcher.

This limitation lowers the temporal resolution of results. Some of the geodetical methods allow remote monitoring of highly active sites.

3. Dating methods include archive review, tree-ring analyses, lichenometry, and DOW are other traditional methods. These traditionally used methods provide dating possibilities up to several thousand years in the past. Their advantages over modern dating methods are the simplicity of data processing, cost-effectiveness, and ease of processing. The reach of these methods is limited, yet, their precision can overcome new, state-of-the-art dating methods.
4. Geotechnical methods measure surficial or sub-surfaced spatial changes, stress field dynamics, or underground water level changes. Traditional geotechnical approaches are still irreplaceable in rock slope monitoring. These are the key part of direct monitoring systems. These methods produce high-precision spatial data with reasonable temporal resolution. More precise sensors are still developed, but operation and sensor placement principles remain unchanged. Geotechnical methods remain unsurpassed by modern methods in terms of precision.

The fact that the methods are used traditionally does not mean that these provide low-quality data. On the contrary, traditional methods often provide results even with higher precision than modern methods (Table 2.1). There are crucial expert field methods used for monitoring design for more than a hundred years. Nowadays, traditionally used principles are transferred from analog-based sensors to new electronically-driven, state-of-the-art devices. This means traditional methods will stay in the field even in the future. Moreover, their results will be supported by newly designed, modern sensors. Table 2.1 provides an overview of all rock slope monitoring methods listed in this chapter and Blahůt and Racek (2023) in Chapter 1. It is obvious that traditionally used methods often overcome modern state-of-art methods.

Traditional methods from all groups are rarely used independently and are combined in complex systems (Racek et al. 2021) to get data about rock slope dynamics and their influencing factors. Complex monitoring systems are designed site-specifically to get the best possible results in the case of Spatio-temporal precision and capturing of mass wasting complexity. The design depends on the monitoring purpose, financial resources, and required data outcomes. The use of a particular method depends on the type and velocity of monitored movement, accessibility of the site of interest, and the overall purpose of the designed system. When these conditions are abided, good quality and meaningful data are obtained and further processed. Due to a lack of understanding of rockfall triggering and preparatory mechanisms, the design of the monitoring system requires an experienced researcher. The goal of monitoring design is to deploy as few sensors as possible but still be able to describe complex rock slope behavior. In the future, we can expect the rapid development of new sensors. This development is caused by new engineering challenges caused by infrastructure expansion to new, geologically complicated areas.

**Table 2.1** Overview of rock slope monitoring methods and their properties (Traditional and modern methods)

| Method | Primary purp. | Secondary purp. | Primary class. | Secondary class. | Measures |
|---|---|---|---|---|---|
| Field mapping | Stability estimation | Hazard estimation | General properties | Expert method | Rock slope stability |
| Geotechnical classification | Stability estimation | Hazard estimation | General properties | Expert method | Rock slope stability |
| Rockfall collector | RF properties, frequency | Hazard estimation | Event dating | Dating | Rockfall volume, frequency |
| Archive review | RF properties, frequency | Hazard estimation | Event dating | Dating | Rockfall temporal pattern |
| Tachymetry | Movement monitoring | Spatial change | Spatio-temporal activity | Geodetical | Spatial position |
| Precise levelling | Movement monitoring | Stability estimation | Spatio-temporal activity | Geodetical | Spatial position |
| TLS single | State of rock slope | Spatial change | Spatio-temporal activity | Geodetical | Rock slope geometry |
| TLS time lapse | Movement monitoring | Stability estimation | Spatio-temporal activity | Geodetical | Spatial position |
| ALS | State of rock slope | Spatial change | Spatio-temporal activity | Remote sensing | Rock slope geometry |
| Photogrametry single | State of rock slope | Spatial change | Spatio-temporal activity | Remote sensing | Spatial position |
| Photog.time-lapse | Movement monitoring | Stability estimation | Spatio-temporal activity | Remote sensing | Spatial position |
| GNSS monitoring | Movement monitoring | Stability estimation | Spatio-temporal activity | Geodetical | Spatial position |
| Dendrochronology | Rockfall properties, frequency | Hazard estimation | Event dating | Dating | Rockfall properties, frequency |
| Lichenometry | Rockfall properties, frequency | Hazard estimation | Event dating | Dating | Rockfall properties, frequency |
| Degree of weathering | Rockfall properties, frequency | Hazard estimation | Event dating | Dating | Rockfall properties, frequency |
| Cosmogenic nuclides | Rockfall properties, frequency | Hazard estimation | Event dating | Dating | Rockfall properties, frequency |

(continued)

**Table 2.1** (continued)

| | | | | | |
|---|---|---|---|---|---|
| Optical luminescence | Rockfall properties, frequency | Hazard estimation | Event dating | Dating | Rockfall properties, frequency |
| Crack meter | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Spatial position |
| TM-71 | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Spatial position |
| Wire extensometer | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Spatial position |
| BH extensometer | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Borehole spatial change |
| BH micrometer | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Borehole spatial change |
| BH inclinometer | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Borehole inclination |
| BH compound probe | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Borehole spatial change |
| Dilatometer | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Spatial position |
| Tiltmeter | Movement monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Tilt changes |
| Piezometer | Pore pressure monitoring | Hydrogeological monitoring | General properties | Geotechnical | Pore pressure, ground water |
| Strain gauge | Stress field monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Strain |
| CCBO | Stress field monitoring | Stability estimation | Spatio-temporal activity | Geotechnical | Strain |
| Optical fibre | Movement monitoring | Strain monitoring | Spatio-temporal activity | Geotechnical | Strain temperature |
| ERT single | Rock slope physical properties | Stability estimation | General properties | Geophysical | Rock slope resistivity |
| ERT time-lapse | Rock slope physical properties | Stability estimation | Spatio-temporal activity | Geophysical | Rock slope resistivity |
| Seismic tomography | Rock slope physical properties | Stability estimation | General properties | Geophysical | Seismic waves velocity |
| Ambient vibration | Rock slope physical properties | Stability estimation | General properties | Geophysical | Vibration pattern of rock slope |

(continued)

**Table 2.1** (continued)

| | | | | | |
|---|---|---|---|---|---|
| Micro seismical | Rock fall properties, frequency | Stability estimation | Spatio-temporal activity | Geophysical | In situ seismicity |
| Borehole temperature | Temporal temperature changes | Additional information | General properties | Geophysical | Temperature |
| Camera monitoring | Movement monitoring | Stability estimation | Spatio-temporal activity | Remote sensing | Rockfall properties, frequency |
| Aerial monitoring | State of rock slope | Stability estimation | Spatio-temporal activity | Remote sensing | Rock slope state, evolution |
| GB InSAR | Movement monitoring | Stability estimation | Spatio-temporal activity | Remote sensing | Spatial position |
| InSAR | Movement monitoring | Stability estimation | Spatio-temporal activity | Remote sensing | Spatial position |
| Thermal camera | Spatial temperature | Rock slope properties | Spatio-temporal activity | Remote sensing | Temperature of rock face |
| Remote vibration | Rock slope properties | Stability estimation | Spatio-temporal activity | Remote sensing | Vibration of rock slope |
| **Method** | **Measured variables** | **Precision** | **Spatial scale** | **Temporal resolution** | **Mass wasting** |
| Field mapping | Objective stability | Meters–region | 1–1000 m | Days–years | Landslide |
| Geotechnical class | Stability index | Meters–rock slope | 1–1000 m | Days–years | Rockslide |
| Rockfall collector | $\Delta$ volume, time | $cm^3$ | 1–100 m | Hours–years | Rockfall |
| Archive review | Time | Years–hours | Slope–region/state | Hours–years | Landslide |
| Tachymetry | 3D $\Delta x$, $\Delta y$, $\Delta z$ | 0.1–2 mm | 0.01–100 m | Minutes–years | Landslide |
| Precise levelling | 1D $\Delta z$ | 0.1–1 mm | 0.001–1 m | Minutes–years | Landslide |
| TLS single | 3D $\Delta x$, $\Delta y$, $\Delta z$ | 2–10 mm | 0.001–10 m | Minutes–hours | Rockfall |
| TLS time lapse | 3D $\Delta x$, $\Delta y$, $\Delta z$ | 2–10 mm | 0.001–10 m | Minutes–years | Rockfall |
| ALS | 3D $\Delta x$, $\Delta y$, $\Delta z$ | <1 m | 0.01–1000 m | Days–years | Landslide |

(continued)

**Table 2.1** (continued)

| | | | | | |
|---|---|---|---|---|---|
| Photogrametry single | 3D Δx, Δy, Δz | 1–30 mm | 0.01–100 m | Seconds–hours | Rockfall |
| Photog.time-lapse | 3D Δx, Δy, Δz | 1–30 mm | 0.01–100 m | Seconds–years | Rockfall |
| GNSS mon | 3D Δx, Δy, Δz | 5–10 mm | 0.01–100 m | Hours–years | Landslide |
| Dendrochronology | Time, 3D Δx, Δy, Δz | <1 year | 0.01–1000 m | <years | Landslide |
| Lichenometry | Time, 3D Δx, Δy, Δz | >1 year | 0.01–1000 m | years | Rockfall |
| Degree of weathering | Time, 3D Δx, Δy, Δz | >10 years | 0.1–1000 m | >years | Rockfall |
| Cosmogenic nuclides | Time, 3DΔx, Δy, Δz | >10 years | 0.1–1000 m | >years | Rockfall |
| Optical luminescence | Time, 3D Δx, Δy, Δz | >10 years | 0.1–1000 m | >years | Rockslide |
| Crack meter | 1D Δx | 0.001 mm | 0.01–1 m | Seconds–years | Rockfall |
| TM-71 | 3D Δx, Δy, Δz | 0.01–0.03 mm | 0.01–0.1 m | Minutes–years | Toppling |
| Wire extensometer | 1D Δx | 0.3 mm | 0.1–10 m | Seconds–years | Landslide |
| Borehole extensometer | 1D Δx | 0.1 mm | 0.01–1 m | Seconds–years | Landslide |
| Borehole micrometer | 1D Δx; 2D Δα, Δβ | 0.003 mm; 0.001° | 0.001–1 m | Days–years | Landslide |
| Borehole inclinometer | 2D Δα, Δβ | 0.01° | 0.01–5 m | Days–years | Landslide |
| Borehole compound probe | 2D Δα, Δβ, Δx | 0.3 mm; 0.003° | 0.01–10 m | Seconds–years | Landslide |
| Dilatometer | 1D Δx | 0.001 mm | 0.01–1 m | Seconds–years | Rockfall |
| Tiltmeter | 1D Δα | 0.004° | 0.1–100 m | Seconds–years | Toppling |
| Piezometer | 1D Δp | 0.01 kPa; 1 mm | 0.1–100 m | Seconds–years | Landslide |
| Strain gauge | 1D Δσ1 Pa | 5 µm | 0.000005–0.001 m | Seconds–months | Rockfall |
| CCBO | 3D Δx, Δy, Δz | 5 µm | 0.000005–0.001 m | Seconds–years | Rockfall |

(continued)

**Table 2.1** (continued)

| | | | | | |
|---|---|---|---|---|---|
| Optical fibre | 1D $\Delta\sigma 1$, $\Delta T$ | < 10 cm; < 1 °C | 0.1–100 m | Seconds–years | Landslide |
| ERT single | 2(3)D $\Omega$ | 0.5 $\Omega$ | 0.1–100 m | Days–years | Landslide |
| ERT time-lapse | 2(3)D $\Delta\Omega$ | 0.5 $\Omega$ | 0.1–100 m | Hours–years | Landslide |
| Seismic tomography | m/s | 0.0002 m/s | 0.1–100 m | Hours–years | Landslide |
| Ambient vibration | Hz | 0.0001 Hz | 0.001–1 m | Hours–years | Rockfall |
| Micro seismical | Hz | 0.0001 Hz | 0.001–1 m | Seconds–years | Rockfall |
| Borehole temperature | T | <0.05 °C | 1–1000 m | Seconds–years | Rockslide |
| Camera monitoring | Pixel value | Variable | 0.01–1000 m | Seconds–years | Rockfall |
| Aerial monitoring | Pixel value | Variable | 0.1–1000 m | Days–years | Landslide |
| GB InSAR | 3D $\Delta x$, $\Delta y$, $\Delta z$ | <1 mm | 0.01–100 m | Seconds–years | Rockfall |
| InSAR | 3D $\Delta x$, $\Delta y$, $\Delta z$ | 1 mm–10 cm | 0.1–100 m | Days–years | Landslide |
| Thermal camera | 3D $\Delta T$ | Variable | 0.1–10 m | Seconds–years | Rockfall |
| Remote vibration | Hz | 0.0001 Hz | 0.001–1 m | Seconds–years | Rockfall |

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