Review of Landslide Monitoring Techniques With IoT Integration Opportunities

Hemalatha Thirugnanam, Sebastian Uhlemann, Reshma Reghunadh, Maneesha Vinodini Ramesh, and Venkat P. Rangan

***Abstract*— With the advancements of technology in the era of Big Data and artificial intelligence, Internet of Things (IoT) has a major role for the purpose of monitoring natural disasters like landslides. Landslides are a catastrophic disaster worldwide that alter from terrain to terrain. In the pursuit of saving communities that are endangered by landslides, many monitoring techniques are practiced. This article is a survey of the major landslide monitoring techniques adapted in different parts of the world to monitor unstable slopes. It provides a glance into the challenges and opportunities of integrating IoT into the major landslide monitoring techniques, which are explained briefly with emphasis on real-world case studies. Each technique is presented regarding the kind of monitoring parameters, the type of landslides that it can monitor, landslide investigating phases, advantages, disadvantages, and the possibility of IoT to integrate with each techniques. This article also aims to provide an overview of landslide monitoring in general to nonspecialist in the field. The major monitoring techniques are classified based on the type (fall, topple, slide, spread, flow, slope deformation), velocity (slow, moderate, rapid), monitoring parameters (meteorological, geological, hydro-geological, physical, geophysical), monitoring phases (spatial, temporal), and early warning systems (spatial, temporal) of landslides. This classification will serve as a guideline (but not a replacement for expert advice) for selecting appropriate landslide monitoring technique and the classifications are expressed through visual representations.**

***Index Terms*—Internet of things (IoT), landslide, landslide monitoring technique, sensing platforms.**

I. Introduction

EVERY landslides cause more than $100 million in direct damage and cause thousands of fatalities [1], [2]. The majority of these events are induced by prolonged and intensive rainfall. They are perhaps the most widespread natural hazard worldwide [3], yet they form the most undervalued hazard. In order to mitigate the landslide hazard, several landslide monitoring techniques have been developed over the last decades. Broadly, these can be categorized into remote sensing [4], [5], photogrammetric [6], geodetic [7], geotechnical [8], [9], geophysical [10], [11], wireless sensor networks (WSN) [12], [13], and most recently followed by the Internet of Things (IoT) [14], [15].

Remote sensing, photogrammetric, and geodetic techniques are commonly used to gather information about the distribution and kinematics of surface displacements [16]–[18]. These techniques make use of aircraft, spacecraft, or terrestrial-based platforms and are suitable for mapping vulnerable areas, monitoring displacements over a large area [4] even with 3-D capabilities [19], however, their applicability for real-time monitoring is limited due to the revisit period of satellites [20] and the requirement of manual processing of the collected data.

Geotechnical instruments such as inclinometers [21], extensometers [22], piezometers [23], are widely used ground-based techniques to monitor parameters such as angle, distance of displacement, pore-water pressure (PWP), and ground vibrations, respectively. These are direct monitoring techniques and give point measurements specific to an area. Geotechnical instruments are used for real-time monitoring and early warning of site-specific landslides. Even when these techniques give accurate measurements of landslide-related parameters, they are not employed for monitoring large-scale landslides, because of the cost involved in deployment.

Geophysical methods such as are electrical resistivity and seismic methods are ground-based techniques, which measure physical properties such as resistance and seismic velocities of the subsurface. These methods are used to investigate large volumes of the subsurface and real-time monitoring can be achieved by autonomous geophysical methods. However, these methods being in-direct methods [24] which only provide proxies to parameters critical for landslide initiation, which limits their usage in reliable warnings.

Satellite and airborne-based landslide monitoring techniques are bounded to use for slow or moderate type of landslides. Whereas ground-based landslide monitoring techniques are adequate to monitor slow, moderate, and rapid types of landslides.

However, the wide range in monitoring technologies with their associated measurement parameters, sensitivities, and temporal and spatial resolution poses a new question.

For any given slope vulnerable to sliding due to various factors such as geological setting, cracks, severe rainstorms, tectonic

Manuscript received 18 January 2022; revised 9 May 2022 and 24 May 2022; accepted 8 June 2022. Date of publication 17 June 2022; date of current version 13 July 2022. *(Corresponding author: Hemalatha Thirugnanam.)*

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Digital Object Identifier 10.1109/JSTARS.2022.3183684

activities, earthquakes, etc., which (combination of) techniques are the most appropriate for monitoring? This question does not have a direct answer as landslides in natural slopes are quite complex in both space and time. Unlike artificially engineered materials, geologic formations are seldom uniform in content, structure, or physical condition.

However, this question is becoming increasingly important, as with the increasing vulnerabilities and impact due to landslides, and the wide range of monitoring techniques with new developments and enhancements, practitioners and researchers face the challenge of designing an appropriate monitoring setup in order to achieve their goal of improving the understanding of landslide dynamics and reducing the landslide risk to the vulnerable communities.

The evolution of a landscape plays an important role in areas that are vulnerable to landslides. The spatial variability of landscape changes is an important phenomenon and it is largely controlled by the underlying geological settings. Most of the reported landslides are the movement of overlying weathered mass on the stable bedrock under the influence of gravity. Even if the rainfall is the same for the adjoining hills, some slopes fail and others withstand even when a certain threshold crosses. Studies have shown that this can be attributed to the differences in lithology, weathering profile, the thickness of overburden, presence of lineaments such as joints, fractures, and faults, the orientation of joint planes, relief, and slope of the hill. Engineered slope modification such as the construction of roads, toe cutting, pits construction, etc., can further increases the probability and spatio-temporal distribution of landslides. Hence, seeking expert opinion, mapping, and assessment of all these factors are essential for deployment of landslide monitoring and early warning system. In this article, we explore numerous landslide monitoring techniques as implemented in real world case studies. Each technique is explored in detail for its capabilities, advantages, and limitations through the real-world implementations. Each monitoring technique has its own capabilities, therefore it is highly recommended to perceive the choice of monitoring technique for a particular type of landslide. The comparison of each method based on their monitoring parameters, types of landslides that it can monitor, monitoring phases of landslides, movement velocity that it can monitor, advantages, and disadvantages have been done in order to identify the most relevant method for a particular type of landslide. This article is an attempt to provide a high level overview of landslide monitoring techniques, and tries to associate monitoring techniques to type of landslides that they can potentially monitor, monitoring aspects (real-time, near real-time, periodical, site-specific, and regional monitoring), and application of these techniques for providing early warning, etc. We aim to provide a single platform that defines and distinguishes different monitoring techniques. However, the geological evolution of the terrain, landslide dynamics, frequency, and failure mechanisms need to be studied in detail with the help of experts. This article is not a replacement for the expert advice that is necessary to be carried out before deploying a particular monitoring technique for any landslide application.

In the modern era, technological changes are all around us, and developing faster than ever. With the advancements of technologies like IoT, Big Data, and machine learning, data can be delivered in a simple to understand, adaptive, and smart way, driving a faster pace of adoption and generating better outcomes. This will aid in developing predictive understanding of landslide processes, thereby improving early warning and risk communication to the affected communities. Hence, a particular emphasis of this article is to identify the possibility of accommodating IoT to landslide monitoring techniques. The next section discusses the significance of IoT in landslide monitoring applications.

Abbreviations: Airborne laser scanning (ALS); terrastial laser scanning (TLS); infra red thermography (IRT); synthetic aperture radar (SAR); interferometric SAR (InSAR); ground-based SAR (GB-SAR); Internet of Things (IoT); wireless sensor networks (WSN); early warning systems (EWS); digital elevation model (DEM); structure-from-motion (SfM); global positioning system (GPS); ground penetrating radar (GPR); electromagnetic (EM); electrical resistivity tomography (ERT).

II. Significance of IoT in Landslide Monitoring

IoT is the networking of smart objects usually referred to as things that allows the interoperability and intelligent communication with services and applications in the cloud using Internet standards [25]. IoT provides inclusion of everyday objects as virtual representations, where people and objects interact with each other as peers [26]. Such an inclusiveness can provide higher penetration and understanding of the surrounding environment which helps in addressing the societal issues including disaster monitoring and early warning in a better way than before.

Several landslide monitoring techniques are implemented in various parts of the world. These landslide monitoring techniques can be part of IoT at different stages. Fig. 1 shows the IoT architecture diagram incorporating landslide monitoring techniques. Several architectures are being presented for IoT [27], [28], however, in this section, we discuss the significance of IoT for landslide monitoring and early warning in the context of Industrial IoT architecture with Edge, Fog, and Cloud [29] data processing layers.

In Fig. 1, the *Edge nodes or things* in IoT is composed of ground-based and site-specific landslide monitoring methods such as WSN [12], [13], geotechnical instrument-based methods [8], [9], geophysical [10], [11], and rainfall monitoring [30]–[32]. Apart from these, social media posts and tweets related to rainfall and landslides also act as things for the IoT. Research is being carried out for detecting precursors for events like natural hazards from the social media posts [33]–[35]. The things in IoT are usually sensors with minimal resources like energy, processing capabilities, and storage. The intelligence and data processing is done either in things itself or in the Edge layer, which is above the things layer in the IoT architecture. The edge layer can also manage the data collection from the things, make local decisions, and forward data to the Fog. The data collected from the things can be analyzed, stored, and/or processed either at the Edge layer or at the Fog layer depending upon where the intelligence and resource facility is available.

Moreover, sensors such as weather stations, rain gauges, and moisture sensors are deployed by various research organizations throughout the world [36], [37] and they can either be part of

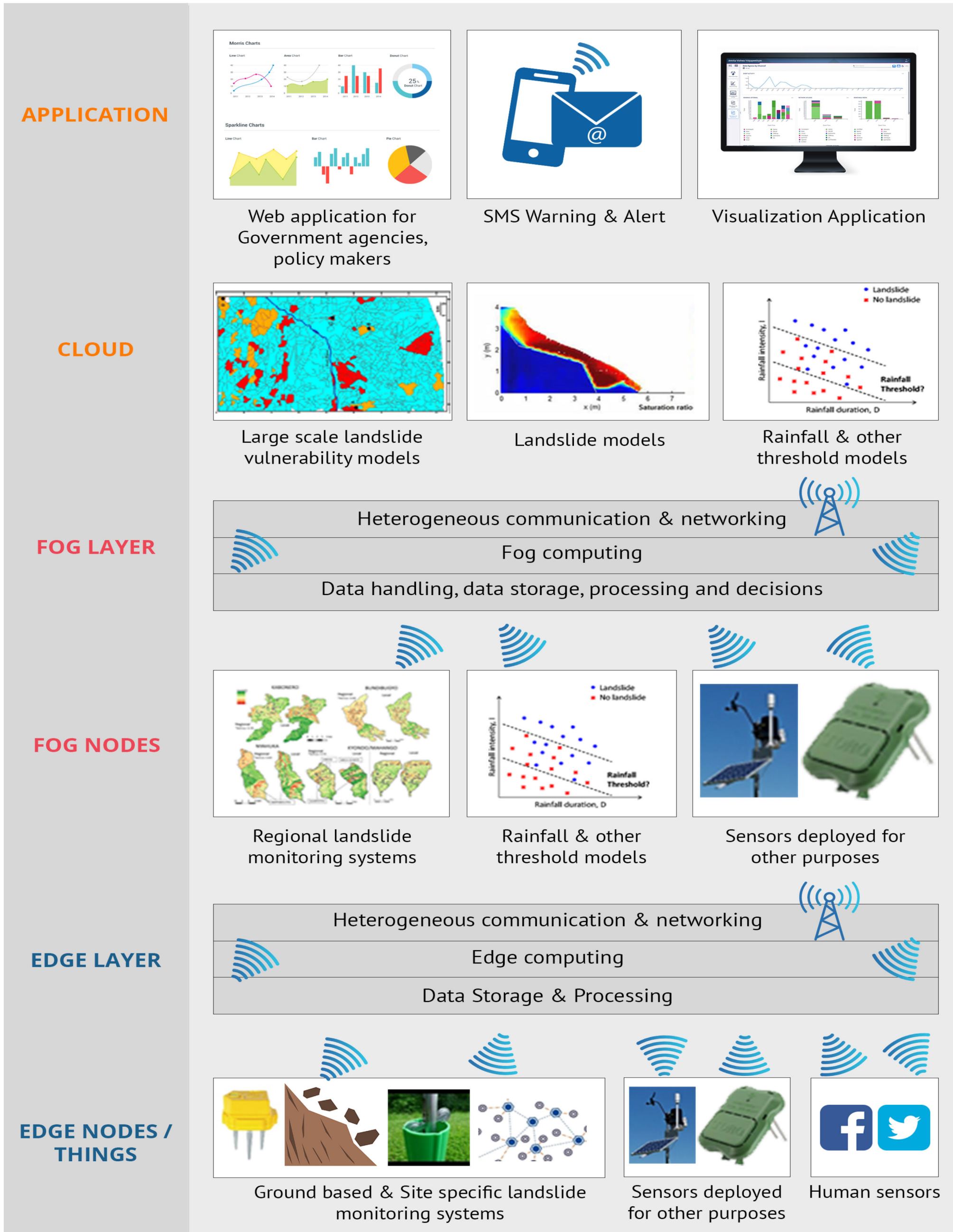

Fig. 1. Generic IoT architecture for landslide monitoring.

edge nodes or Fog nodes. Rainfall threshold models are developed on a national level and regional level in many parts of the world to provide early warnings for landslides [15], [38]– [42]. These models can be placed either in the fog or cloud depending upon how much the intelligence needs to be pushed to the Edge. Thresholds from these models can trigger automated context switching algorithms in the things [43]. The Fog layer provides heterogeneous communication, networking, data handling, data storage, and decisions between Edge and Cloud. On a global scale, landslide vulnerability maps are produced with the help of remote sensing technologies [44]. The recent global landslide model developed by NASA provides moderate to high nowcasts every 30 min on a global scale. [45]. These large scale vulnerability maps and models can be stored in the cloud which is capable of storing high volumes of data, running complex algorithms for decision-making, forecasting, and serving applications like visualization.

For a decade, researchers were talking about data integration from multiple sources and its visualization integrated in a common platform for efficient monitoring of disasters like landslides [46]–[49]. IoT is the solution for efficiently gathering data from all these techniques, introducing local intelligence, communication with other objects as peers, provide services for integrating, discovering knowledge, interpreting, and

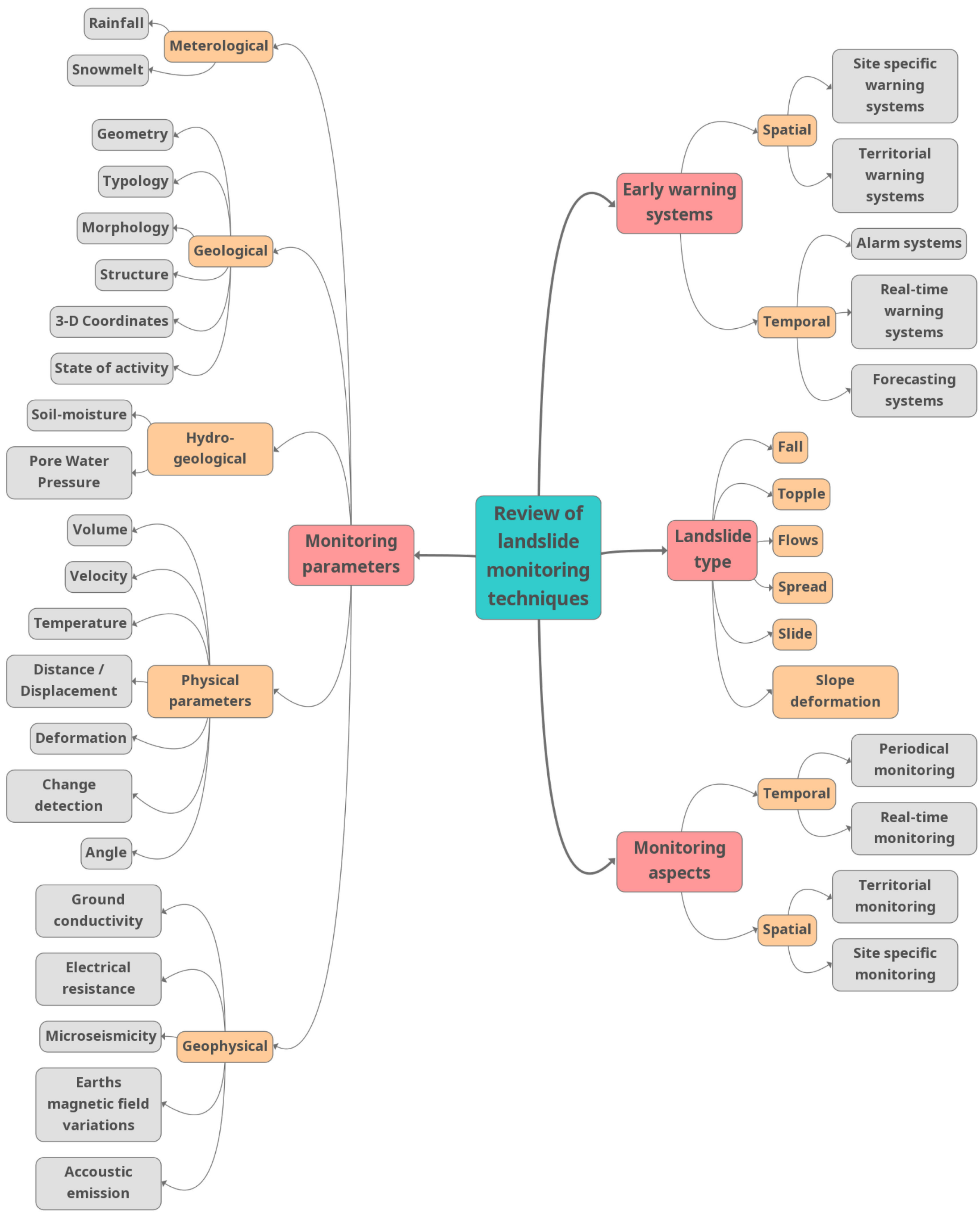

Fig. 2. Organization of the review.

visualizing. IoT can also be used for managing the crisis after a disaster [50].

III. Taxonomy

Over the last few decades, substantial developments have been made in the field of landslide monitoring techniques and there are many terminologies related to landslides used in practice today. In this section, we delineate the different terminologies that we will be using in this article to review different landslide techniques. Fig. 2 pictorially represents the four aspects with which we review the landslide monitoring techniques and the different terminologies associated with it. The four aspects are described below.

1) Landslide type: The taxonomy classification proposed by [51] is followed to identify the type of landslide movement that a technique will be more appropriate to monitor. The type of landslide movements as per [51] is fall, topple, slide, spread, flow, and slope deformation.

2) Monitoring parameters: Every landslide monitoring technique periodically collects observations related to parameters that are of interest for landslide initiation. These monitoring

techniques are explored for the type of parameter that it is monitoring and they are categorized into meteorological, geological, hydro-geological, physical, and geophysical parameters as shown in Fig. 2.

3) Monitoring aspects: In this article, we have reviewed the monitoring techniques based on spatial (territorial and site-specific) and temporal (periodical and real-time) aspects. The terminology "territorial" was adapted from [52] which includes large area, regional level, and national level monitoring systems.

4) Early warning systems (EWS): Few research and government organizations have advanced to develop EWS from landslide monitoring systems. In this article, we have reviewed the early warning systems based on spatial (territorial and site-specific) and temporal (real-time and ahead of time) aspects.

IV. Remote Sensing Techniques

Remote sensing techniques gather information about an area or an object using satellites and/or airborne and ground-based sensors. Various remote sensing techniques are used for landslide studies, however, the most commonly used techniques are based on laser, radar, and infrared sensor, such as terrestrial laser scanning (TLS), airborne laser scanning (ALS), synthetic aperture radar (SAR), interferometric SAR (InSAR) and ground-based SAR (GBSAR), and infrared thermography (IRT). Remote sensing techniques are mainly used in landslide detection, fast characterization, and mapping applications, however, in many developed countries, remote sensing techniques are used for monitoring applications also. Landslide parameters such as geometry, state of activity, velocity, typology, volume, soil moisture, morphology, structure, displacement, deformation, rainfall, and other triggers are monitored using remote sensing techniques. The scale of analysis of remote sensing techniques are in the range of 1:5000–1:25000.

TLS is an effective tool used for the characterization and monitoring of rock slope [4], [19], [53], debris flow [55], [72], [73], and slow moving landslides [54]. The major advantages of the TLS method is its 3-D capabilities, high accuracy, speed, and resolution [4], [74].

TLS combined with "structure from motion" photogrammatry technique is used for quantifying 40 years of rockfall activity in Yosemite valley [53]. This study provides an useful perspective combining historic photographs and TLS for obtaining rockfall volume estimates. The TLS system mentioned in [56] successfully monitored the deep seated landslide and prefailure deformation of an 80 m3 rockfall event. The authors mention that TLS can be an effective system for long-term high-temporal-resolution acquisition.

In [19], the authors conducted a study on Aknes rock slide in Western Norway using TLS. This study provides 3-D displacement information during the years 2006, 2007, and 2008 for a large unstable area. The authors of [19] have established a rockslide mechanism model for the uppermost part of the Aknes rockslide based on the TLS data. A detailed review about rock slope instabilities are presented in [4]. The capability of TLS to monitor slow moving landslides is assessed and compared with tachymetry and the accuracy limitations are assessed in detail by [54]. In this study, the authors have assessed the capability of TLS to monitor slow moving landslides less than 100 mm per period, and the authors claim that it is not possible to monitor landslides less than 50 mm per investigated period. However, by analyzing the point density created by TLS reliable conclusions can be made regarding slope movement patterns, erosion, and deposition of material.

TLS also has its limitations due to changing reflectively levels in slope, missing data points due to poor atmospheric conditions, existence of occlusions, acquiring data on rock slope greater than 3 km, compromise in accuracy and precision with increasing range, etc., [4], [56].

An automated monitoring of an active landslide in the French Alps using TLS system is presented in [56]. The authors mention TLS to be an effective tool in monitoring landslide and rockfall process despite its limitations during rainfall and poor atmospheric conditions. The automated TLS system discussed in this article also provides an near-real time monitoring and data processing, allowing near-real time change detection. ILRIS 3-D scanners [75] are used in this study, the software application used for automated TLS data acquisition and processing are discussed by the authors. The TLS monitoring system is connected to a on-site computer where the data are stored, processed, and the results are visualized. The hardware setup for automated TLS data collection discussed by [56], is a temporary setup for a 6-week period, to assess the efficiency of TLS for automated monitoring and near-real time processing. TLS data collected on the on-site computer can be easily transmitted through wireless transmission protocols for turning it into a IoT Edge device. An application of TLS for multimodal data capture mechanism, semiautomated processing, online archiving, and online visualization has been discussed in detail in [58]. Several TLS devices are compared with other 3-D technologies available for archaeological and heritage surveys in the age of sensing. This article provides useful information on open source softwares, 3-D visualization, and cloud services related to TLS. Another application where TLS instrument is automated to function as an Edge device is discussed in [57]. In [57], the authors have used TLS for long-term monitoring of a forest canopy. The authors have discussed the technical specifications, hardware components, software modules used for automated monitoring using a TLS instrument. The authors have also discussed the new advancements in data recording, processing, and simulation.

On the other hand, airborne laser scanning (ALS) is a technique that uses laser sensors operated form airborne platforms. ALS is an efficient method used for creating digital terrain models even in areas with high vegetation cover [76], [77]. ALS technology is majorly used for creating landslide inventory maps [77], periodical monitoring of earth flow, debris flow, and mud flow [78]–[81]. ALS can be integrated with other remote sensing techniques to monitor and map debris flow and earth flow [82], [83]. Coupling of ALS data with other remote sensing tools can aid in identifying shallow landslides. The combination of ALS and TLS has been used for the field investigation on Turtle Mountain to characterize the landslide structure and morphology [84]. It is found that ALS is extremely useful to observe features of the entire area at a large scale. The authors in [84] show a comparison of ALS with TLS and perform an investigation of mountains using the combination of ALS and TLS. ALS is used in combination with InSAR technique in Danba county, China [85] for improving the accuracy of landslide detection and identification by the following: 1) eliminating slope deformations due to nonlandslide activities; 2) identifying small landslides and landslides with unobvious deformation; and 3) accurately drawing landslide boundaries. Moreover, the authors also mention that combining high resolution LiDAR DEM's with other techniques like InSAR will be helpful to invert landslide thickness and analyze the landslide failure mechanism.

With respect to turning it into an IoT device and using the same for early warning applications, TLS instruments can be turned into an Edge device and can be used for near-real time monitoring and warning systems. However, the same is not possible using ALS devices, as they are used as and when required for investigating a field and therefore ALS device cannot act as an IoT EDGE.

Thermal IR data are used to measure relative difference of temperature in land surface. These thermal patterns are related to detecting structural discontinuities, water infiltration, saturation, cracks, and fractures within rock slope and rock cliffs [59]. High resolution ground-based and airborne infrared thermography (IRT) is a technique that uses thermal *IR* sensors for detecting irregular thermal patterns. The thermal characteristics and temporal changes of temperature in bedrock are factors for rock instability. Application of IRT for mapping open fractures in three different sites is discussed in [59]. The first study site discussed in [59], is a 500-m long and 400-m wide rockslide comprising a volume of ten million m3 bedrock and colluvium (composed of sandstone and conglomerate beds of 15–20 m thickness, alternating with sequences of weaker clay stone, shale, and thinly bedded sandstone) in Mt. Kopce, eastern Czech Republic. IRT results in Mt.Kopce showed that the deeper or longer cracks exhausted warm air. Three long and deep cracks "Naděje, Kolonie, and Slimrovka caves" are chosen and detailed results are presented in [59]. The second case study discussed in [59] is a slope failure in Mt. Kněhyně. IRT survey in this site was conducted in the afternoon, when there is direct exposure of sunlight. It is ideal to conduct IRT surveys in the absence of direct sunlight, however, due to low air temperature and technical constraints of the airplane, authors mention that the survey in Mt. Kněhyně could not be conducted during early morning and night hours. IRT results from Mt. Kněhyně show an adverse effect due to the presence of sunlight. Several group of warm objects including tree trunks showing higher thermal emissivities are detected. Only one warm object registered belong to the crack system and the six other actual crack systems were not registered as warm objects in the IRT results. Third case study discussed in [59] is a large deep-seated slope instability in Mt. Traunstein. IRT results from Mt. Traunstein correspond to relatively warm areas from different angles and distances (up to 1.3 km). The results are in accordance when mapped with open cracks, loosened rock, and rockfall detachment zones. Other observations from warmer areas and neutral areas are described in detail in [59]. The authors also mention about the constraints of the IRT method. Application of IRT for rock mass characterization in complex environments is discussed in [86]. In this article, the challenges expected, limitations, and advantages of using IRT in a complex environment is discussed in detail.

The combined use of airborne and ground-based IRT approach can be used for rapid and effective prediction of rock instability. The major limitations of using *IR* cameras is that the data interpretation is complex and used only for local applications due to the small resolution of such sensors [87]. Coupling of TLS scanner and TIR camera improves the spatial location of the thermal process which can be used for rock fall analysis.

Integration of TLS and IRT applied to an unstable sedimentary rock mass in Passodella Morte Landslide, Carnic Alps is discussed in [60]. Here, next to remote sensing, continuous monitoring of the region is carried out by means of extensometers, inclinometers, and acoustic emissions sensors. This combination of instruments provides significant information about the recognition of open joints, geometry and kinematics of the rock mass, discontinuity planes, and hence it can be used for rock fall hazard assessment. IRT is a contactless, fast, and low cost methods, however, it cannot be efficiently applied for monitoring and early warning landslide because of the following limitations [88]: 1) cold weather conditions that can mask the effect due to thermal characteristics; 2) decrease in accuracy of measurement with increase in distance; 3) underestimation and overestimation of temperature values in a heterogeneous scene; and 4) reflected temperature and sunrays have an effect on the measurement. TIR cameras with wireless transmission capabilities are already existing [61], however, TIR cameras with intelligent automation process for IoT need customisation. Potential contributions of *IR* industry in the future of IoT and AI is discussed in detail by [62] and [63], providing information on various *IR* sensors, IoT standards, application of *IR* sensors in IoT, use of AI in automation process, etc.

Synthetic aperture radar (SAR) is a radar-based technology operated from satellite and ground-based platforms used for identifying mapping and monitoring landslides. The main advantage of SAR is its capability to image during heavy rainfall and fog conditions. Interferograms are generated from two or more SAR images to quantify the amount of surface deformation. The combined use of space borne and ground-based interferometric-SAR (InSAR) are used for the detection and classification of landslides over large areas [68]. In [68], a slope instability phenomenon in San Fratello, Italy was analyzed using satellite interferometric images from 1992 to 2012. The authors have also utilized images from ground-based SAR (GB-SAR) along with satellite SAR images to monitor landslide in the same area in 2010. The authors have discussed in detail about the various satellite images used, methodology for integrating ground-based and space borne images. This allowed for the production of displacement maps with high spatial and temporal resolution. GB-SAR can be used for monitoring and recognition of both slow moving and moderate type of landslides [65]–[67]. In [89], a GB-SAR system is proposed to monitor landslide induced ground deformations in the village of Schwaz, Austria with high accuracy, continuous time coverage, and spatial resolution. GB-SAR is used for early warning of landslides

TABLE I
COMPARISON OF DIFFERENT REMOTE SENSING TECHNIQUES

Technique	Landslide types	Monitoring parameters	Monitoring phases	Early warning systems	Advantages	Disadvantages	IoT Applicability
Terrestrial Laser Scanning (TLS)	Rock fall [53], rock slides [19], slow moving landslides [54], and debris flows [55]	3D coordinates	Near realtime & periodical monitoring	No literature available	3D capabilities, high resolution, good accuracy and large coverage	Difficult to operate in rain or fog, expert staff required for data processing	Applicable by amending other devices [56], [57], [58],
Airborne Laser Scanning (ALS)	Debris flow, earth flow, mud flow	3D structure of terrain surface	Periodical monitoring, recognition, and classification of landslides	No literature available	Large coverage, Fast, Efficient, Accurate digital terrain Models	Less accuracy compared with TLS	Not Applicable as this is a airborne system
Infrared Thermography (IRT)	Cracks and fractures within rock slope [59], [60], [60]	Temperature	Periodical monitoring, recognition, and classification of landslides	No literature available	High resolution, Able to see in total darkness	Restricted to use in cold season, low resolution	Applicable by amending other devices [61], [62], [63]
Ground Based Synthetic Aperture Radar (GBSAR)	Rock slides [64], slow and moderate type landslides [65], [66], [67], complex landslides [68]	Displacements	Monitoring, Recognition, prediction, and classification	Real-time site specific warning [11], [69]	High accuracy and resolution, flexibility and versatility.	Loss of coherence, difficult in real time monitoring	Applicable by amending other devices [11], [69], [64]
Differential Interferometric SAR (DInSAR)	Translational and rotational slides, rock slides, deep seated landslides [70], creeping landslides [71] and flows [68]	Distance, deformation	Monitoring, Recognition and classification	Not possible	Possible to use at any time and atmospheric conditions.High spatial resolution	Low spatial and temporal resolution	Not Applicable due to policy restrictions

and rock slides [11], [69]. Authors of [70] have discussed the monitoring of a complex deep seated retrogressive earth slides in the little Smoky River of Northwestern Alberta using corner reflectors, InSAR and inclinometers. Results from InSAR are compared with the results from inclinometer measurements and discrepancies are found, highlighting the limitations of InSAR technique and challenges in monitoring a complex landslide. The comparison of different remote sensing techniques is shown in Table I.

Real-time monitoring of landslides is limited to ground-based systems because of the revisit time of satellites and the requirement of manpower for data collection in airborne systems. Systems employing ground-based remote sensing techniques are used for early warning applications [11], [90]. High resolution, satellite- based remote sensing imageries are usually copyrighted and governed by governmental agencies. Therefore, copyrighted satellite images and aircraft platform-based remote sensing techniques are difficult to automate and or impossible to automate because of the manpower and policy restrictions from different government agencies. Whereas free satellite images can be used alone or in combination with other ground-based techniques in the cloud layer of IoT. Ground-based remote sensing techniques have been automated and used for early warning purposes [56]–[58], [62]. In order to turn such devices into IoT Edge, intelligent, and context aware algorithms need to be incorporated to the automation software, an example of such algorithms are mentioned in [43]. Intelligent algorithms are designed based on the location of its deployment, resources such as solar power/power grid availability, frequency of data collection, transmission, feasible wireless communications, network availability, etc. Therefore, free satellite images can be incorporated in the Cloud devices of IoT and ground-based remote sensing systems can be turned into an Edge device and hence it is possible to integrate with IoT.

V. PHOTOGRAMMETRIC TECHNIQUES

Photogrammetry is a surveying and mapping technique used for determining ground movements. This technique allows to determine the movement of landslides by comparing at least two photos of the same object [98]. Two major types of photogrammetric techniques are terrestrial (close range), and aerial photogrammetry. The benefits of using this techniques are noncontact operational capability, high acquisition rate, large slope coverage, high degree of automation, and low cost. This technique can be used for displacement measurement, change detection, state of activity, deformation, etc., on the landscape by analyzing photographs.

Close range photogrammetric techniques can be used for detecting mass movements or landslides at inaccessible slope areas. Digital elevation model (DEM) derived from close range photogrammetric data act as a low cost monitoring method [99]. In this study, digital photogrammetry is used in the slope monitoring and soil volume computation under real conditions. DEMs are generated from stereo photographs taken at two different times. A block of overlapping images in close range photogrammetric techniques are acquired using calibrated digital cameras over a large area ranging from <1 to 200 m. This techniques is often suitable for stability analysis in rock faces and small glaciers.

Structure-from-motion (SfM) photogrammetric techniques and watershed models were developed to identify and map gullies and landslides in Tijuana, Mexico [95]. Photogrammetric surveys at this site were performed using a modified nonmetric

TABLE II
COMPARISON OF DIFFERENT PHOTOGRAMMETRIC TECHNIQUES

Technique	Type of movement	Monitoring parameters	Monitoring aspects	Early warning systems	Advantages	Disadvantages	IoT applicability
Aerial Photogrammetry	Slow moving landslides [91], Earth flow & slide [92], Debris flow [93]	Three dimensional coordinates	Periodical monitoring	Not applicable	It can be used in unsafe and difficult to access areas	Weather conditions could affect image quality	Not applicable as this is an airborne system
Close Range Photogrammetry	Falls [94], Translational slides [95], Debris flows, [93]	Three dimensional coordinates	Real-time monitoring	Ongoing research	Noncontact operational capability, high acquisition rate	Weather conditions could affect image quality	Images acquired from automated platforms can act as IoT Edge device [96], [97]

camera, mounted on either an unmanned aerial system or a telescoping painter's pole. From the SfM analysis two mega-gullies and one landslide was observed over a five-year monitoring period with 14 storm events. The amount of sediment mobilized due to rainfall and landslide activity is also calculated from SfM analysis.

Aerial photogrammetric techniques make use of flying airborne platforms for acquiring blocks of overlapping images with calibrated digital cameras. This technique is particularly suitable for monitoring terrain surface, vertical displacements of targets, field displacements, or deformations, etc. It is also possible to identify the morphology, vegetation cover, soil moisture, and drainage pattern by interpreting the collected data [100]. Usually the monitoring range of aerial photogrammetry is in the range of 100 m^2 to few km^2. Aerial photogrammetry techniques are combined with GPS and geophysical data to derive the landslide kinematics [6]. Photogrammatry technique provides the advantages of using archives with other techniques to understand the long term landslide kinematics. Archival aerial photogrammatry images from 1975 to 2010 are used in combination with GNSS and InSAR data to understand the 44-year long landslide kinematics in Patigno landslide, Italy [101]. Photogrammetry techniques are compared with TLS to investigate the "Cà di Malta" landslide in Italy [102]. The authors suggest that surveying and data processing using TLS is easy and less expensive compared to photogrammetry. Many studies have used photogrammetry techniques along with GPS for monitoring landslides [103], [104]. Photogrammetric techniques are a persuasive tool for tracking and modeling the slow moving landslides [91], earth flows [92], and debris flow [93], [105], [106]. Although applied in a different context, [107] have detailed the photogrammetry work and the research challenges existing in every stage of data acquisition and processing. They have also discussed the image processing algorithms, software, cloud processing, and modeling.

In [94], the authors have assessed the capability of different photogrammatric techniques for rockfall monitoring. Both aerial and terrestrial photogramatric techniques can be used for fast characterization and rapid mapping of landslides, however, terrestrial photogrammetry usually has a better temporal coverage than the aerial photogrammetry in a cost effective way and this can be used for long term periodical monitoring [98]. Accessing any area of the rock face and scree is an advantage in aerial photogrammetry. The comparison of aerial and terrestrial photogrammetric techniques is shown in Table II. In [108], limitations of photogrammetry for early warning applications and the research directions to overcome the same are discussed.

With the advancements of digital signal processing and the development of charge-coupled devices, real-time acquisition of photographs over a long period of time is possible with terrestrial photogrammetry, which can help in developing site-specific early warning systems. Automating the process of image acquisition is perhaps existing [96], [97], however, automating the image processing methods to derive accurate inferences from photogrammetry still needs expert intervention and remains a challenge. Several challenges still exists in digital photogrammetry algorithms such as point cloud generation, point cloud processing, and modeling [107]. The authors of [108] have addressed the existing challenge in digital photogrammetry and have proposed and implemented solutions to overcome "digital image correlation" challenge. Aerial photogrammetry requires manpower for the data collection and therefore aerial photogrammetric techniques cannot be converted as an EDGE device. Terrestrial photographs from automated image acquisition platforms can be converted into IoT Edge devices, however, image processing needs to be performed in the cloud.

VI. GEODETIC OR OBSERVATIONAL TECHNIQUES

Geodetic or observational techniques are used to determine the absolute value of slope movements or landslide displacements. Both ground-based and satellite-based geodetic techniques can be used for monitoring surface displacements of landslides. Many instruments and measuring methods are used for taking accurate displacement measurements in ground-based geodetic techniques [115].

Total station instruments are used to measure angle and distance between the instrument and the targeting prism. This can provide a 3-D coordinate information of the measured point. It requires line-of-sight between the instrument and the targeting prism. This instrument can be used with geotechnical and geophysical techniques in order to find the exact location at which instruments can be placed.

The global positioning system (GPS) is often used as a surveying tool in satellite-based geodetic technique. GPS measurement systems can provide 3-D coordinate time series of landslide surface displacements at discrete points. GPS offers several advantages than traditional geodetic technique as measurements can be made in a highly automatic way, requiring less labor, and there is no need for direct line of sight between the stations,

TABLE III
COMPARISON OF DIFFERENT GEODETIC TECHNIQUES

Technique	Type of movement	Monitoring parameters	Monitoring phases	Early warning systems	Advantages	Disadvantages	IoT Applicability
Ground based Geodetic Technique	Falls, Translational slides, [109] Debris flows, Mud flow [110]	Angle or distance measurements	Real-time and site specific monitoring	Site specific EWS	High acuracy	Some techniques require skilled workers	Automated GPS systems can be turned into a IoT Edge device. [111], [112]
Satellite based Geodetic Technique	Slow and moderate velocity landslides [113], [114]	Displacements	Periodical and territorial monitoring	Not applicable	Automated, direct line of sight not required	More complex receivers required for accurate measurements.	Not applicable due to policy restrictions

thus, making it more cost effective. However, vegetation cover, buildings, or other type of infrastructure can cause signal scattering, and thus, degrading GPS accuracy. In [7], GPS technology is used for monitoring the behavior of landslides at Bakthang fall landslide. Modern GPS techniques like static, rapid, and real-time kinematic were used for landslide monitoring. GPS technology provides sub centimeter accuracy for investigating ground deformations. Three-dimensional coordinates of a land surface can be obtained, but depending on satellite coverage, insufficient satellites may be available to obtain accurate data during certain times. Hence, GPS time series may be discontinuous and there applicability for EWS limited.

GPS technique is used to estimate ground deformation in Bududa, Uganda [109]. The Bududa site experiences slope deformations, which is evident from cracks in buildings after a big landslide event in 2010. Hence, the Bududa site is monitored using eleven GPS stations from June 2018 to June 2019. Six-hour sessions of different observation were conducted at various periods. The deformation measured at all the eleven stations varied largely. The results indicate that the slopes in the monitoring area are unstable, especially during wet seasons, which imposes a future landslide threat.

Ground-based geodetic technique can be used for monitoring all types of landslides [110] whereas satellite-based geodetic technique should only be used for monitoring slow and moderate type of landslides [113], [114], [116]. The comparison of ground-based and satellite-based geodetic techniques is shown in Table III. Geodetic methods are combined with other monitoring methods in early warning applications [117].

Automated GPS-based deformation monitoring systems [111], [112], [118], [119] are available and these systems can be directly converted in IoT Edge nodes. Some techniques in ground-based geodetic techniques like total station instruments need manpower to do the survey for monitoring purpose, so these devices cannot be automated. Whereas in satellite-based geodetic techniques, the data collected are not continuous and sometimes copyrighted too. Automated geodetic observation-based techniques can be used in early warning applications and geodetic techniques which require manpower cannot be used in early warning applications.

VII. GEOTECHNICAL INSTRUMENTS

Geotechnical sensors are extensively used for monitoring landslides at site-specific scale. Prolonged rainfall or torrential rainfall are one of the main triggers of rainfall induced landslides. Extended effects of antecedent rainfall conditions lead to increased volumetric water content and generation of pore pressure in different soil layers. This may lead to slope instability based on varying conditions of these multiple triggering parameters. This demands monitoring of heterogeneous parameters. The monitoring and forecasting of landslides using geotechnical sensors integrate usage of sensors such as rain gauge, moisture sensor, piezometer, extensometers, inclinometer, and tiltmeters, etc. The monitoring is achieved through deployment of these sensors in soil layers. Geotechnical sensor-based measurements are direct methods that can provide point measurements at or below the surface. This is in contrast to remote sensing and photogrammatric methods, which often only provide measurements of surface properties, and geophysical methods, which only provide indirect measurements of values critical to landslide processes. Multiple approaches are utilized in determining those hydro geological parameters at different spatial and temporal scales. Researchers have taken one step forward in deriving their interrelationship and utilized machine learning approaches to forecast pore pressure and other parameters that could provide the futuristic probability of landslides. These approaches can be seen on the research studies and deployment described in [141]. Geotechnical sensors are either connected to loggers [142], [143] or have transmitting units themselves to send the data either to a field management center or directly to the data analyst or scientific organization.

Inclinometers are geotechnical instruments usually installed at different depths in a borehole drilled within the sliding mass. They are commonly used to measure horizontal displacements along various points in a borehole. The continuous and precise monitoring over the entire length of a borehole could be possible by taking a series of readings over time. Inclinometers are often applicable in monitoring all types of landslides provided the monitoring site is not susceptible to failure due to drilling activity. Real world examples where inclinometers are used are as follows, rockslide [121], rockfall [120], topple [122], slow moving landslides [144], and deep seated complex type landslides [123]–[125]. In [21], a monitoring system consisting of in-place inclinometers are installed at Castelrotto (northern Italy), periodical measurements are gathered using a mobile probe. A local quadratic trend model is used to estimate the kinematic characteristics of deformation and a statistical approach is used for comparing the direction of displacement from in-place inclinometer data or mobile probe recordings. Some guidelines for addressing the installation factors and application of correction factors for common measurement errors are presented in [145]. This article also presented three case histories to illustrate the confusion that can develop if these installation factors and monitoring factors are not considered. The main disadvantage of using this type of instrument is that the curvature is only observed in one axis [98]. Inclinometers are used for landslide monitoring and early warning [146], [147].

Extensometers are geotechnical instruments installed within a borehole or on a landslide surface, used to measure the axial displacement between two reference points. This displacement can be continuously monitored and recorded over regular periods of time. The accuracy of measurements depends on the type of sensing device and the distance between measuring points. Borehole wire extensometers were used to detect translational landslides at Vallcebre landslides and mudslides at Alvera mudslides [133]. A borehole wire extensometer is very easy to use and cheap compared to other types of extensometers. A highly sensitive borehole wire extensometer was developed in [22] for continuous measurements of very small vertical displacements. This article describes the construction, measurement results, and practical application of the borehole extensometer on the high loess bank of the river Danube. The demonstrated application proves high resolution to study the movements and deformations of the ground due to rainfall and groundwater variations. Implementation of wire extensometers for rock slide monitoring and early warning is discussed in [148]. Extensometers can be used to monitor complex landslides [134], debris flows, deformation [149], slow moving landslides [135], [136], and to predict the time of rock falls [137]. The disadvantages of using extensometers are that they are sensitive to temperature variations, the need of expert technical staff for the installation of borehole extensometers, and the necessity to protect surface extensometers. Extensometers are widely used in early warning applications [138]–[140].

Piezometers measure PWP and/or groundwater levels. Many landslides are triggered due to elevated PWP caused by heavy rainfall. Borehole piezometers are categorized into vibrating wire, pneumatic, and standpipe type depending on the level of permeability of surrounding rocks. The advantages of using this type of instruments are simple installation, low cost, and long term reliable. The monitoring of PWP and rainfall with high temporal resolution is essential for the assessment of slope instability caused by heavy rainfall [150]. The authors in [150] used an inclinometer to identify the depth of the shear surface. Using piezometer, they analyzed the PWP at the shear surface identified by the inclinometer. The combination of inclinometer and piezometer can be used for identifying the ground displacements and predicting the rainfall triggered landslides. Piezometers are also employed in identifying the groundwater flow and process in complex landslides [128]–[131], debris flow [127], [151], deep-seated landslides [23]. Combinations of various instruments or techniques are usually employed rather than using a single technique or instrument to provide complete information about a landslide. In [125], piezometers are used along with other monitoring techniques such as GPR, time domain reflectometry, inclinometer, strain gauges for real-time monitoring and early warning of landslides in Three Georges reservoir area. In [125], the authors have used Campbell scientific data loggers [143] for automatic data acquisition and transmission. Piezometer sensors are also used in combination with rain gauges, moisture sensors, extensometers, inclinometers, etc., for heterogeneous sensing and early warning [152]. Machine learning techniques are applied to forecast PWP 24 h ahead of time from rainfall measurements and early warn potential landslides in the Munnar region, India [153].

Tilt meters are highly sensitive instruments used to measure ground tilts either on the ground or in a borehole. When combined with inclinometer and extensometer, the system is termed as integrated pit slope monitoring systems [154]. Major advantages of using tiltmeters are lightweight, simple operation, and relatively low cost. The drawback of tiltmeters is that the noise caused by temperature will affect the initial measurements. Therefore, temperature corrections are needed at the time of installation at shallow depth. An experiment has been conducted in [89] at the island of Vulcano (Aeolian archipela) using shallow borehole tiltmeters. In order to study the thermic effects on tilt recording and verify how these effects reduce with depth, three shallow borehole electronic tiltmeters were installed in the same hole at different depths. This experiment has reported the variation of thermic effects which is recorded using tiltmeters at different depths. It is found that the response of the sensor is mainly affected by variation in temperature which is relatively large at shallow depth. Tiltmeters are low cost devises used for monitoring and early warning landslides [155], [132].

Inclinometer and tiltmeters with industrial IoT capabilities, automated data logging, and visualization are readily available in the market [156]–[158]. Industrial IoT piezometer sensors are already employed for monitoring structural health in bridges. Industrial IoT geotechnical sensors [126] are already deployed in place for water monitoring systems, air quality monitoring systems, environmental monitoring, and deploying such sensors for slope monitoring applications can act as IoT EDGE device.

The comparison of different geotechnical instruments is shown in Table IV. In the case of geotechnical instruments when the data transmission part is automated, it can be directly turned into an IoT edge device. Geotechnical instruments are widely used in landslide early warning systems.

VIII. Geophysical Techniques

Earth materials are characterized by their physical properties, such as density, acoustic velocity, elastic moduli, electrical conductivity, magnetic susceptibility, and dielectric constant. These properties can vary orders of magnitude and are therefore a common target for geophysical imaging and monitoring.

Geophysical techniques are used widely for characterizing, monitoring, and providing early warning in a robust, cost-effective, and noninvasive way by providing volumetric estimates of landslide triggering factors at higher spatial resolution than many other landslide monitoring techniques.

The authors in–[174] provide comprehensive reviews of geophysical techniques applied to landslide characterization

TABLE IV
COMPARISON OF GEOTECHNICAL INSTRUMENTS

Technique	Type of movement	Monitoring parameters	Monitoring aspects	Early warning systems	Advantages	Disadvantages	IoT Applicability
Inclinometer	Rockfall [120], Rockslide [121], Topple [122], Deep seated complex landslides [123], [124], [125].	Angle	Monitoring, Slope stability investigation, and early warning	Real-time site specific monitoring and early warning	Real time monitoring is possible	High complexity	IoT geotechnical sensors are existing [126]
Piezometer	Debris flows [127], deep seated landslides [23], complex landslides [128], [129], [130], [131]	Pore pressure	Monitoring, Slope stability investigation, and early warning	Real-time site specific monitoring and early warning in combination with other sensors possible.	High accuracy and reliability	Unable to measure too small and very large pressure	IoT geotechnical sensors are existing [126]
Tilt meter	Rotational and translational slides [132].	Direction of movement	Monitoring, Slope stability investigation, and early warning	Real-time site specific monitoring and early warning in combination with other sensors possible.	Simple, and easy to use	Manual measurements, protection required for the external frames	IoT geotechnical sensors are existing [126]
Extensometer	Translational slides [133], Mud slides [133], Complex landslides [134], Debris slides [135], Slow moving landslides [136], Rock falls [137]	Distance	Monitoring, Slope stability investigation, and early warning	Real-time site specific monitoring and early warning [138], [139], [140]	Easy installation, continuous surveying, High accuracy	Sensitive to the temperature, Borehole with asing is required	IoT geotechnical sensors are existing [126]

TABLE V
COMPARISON OF GEOPHYSICAL TECHNIQUES

Technique	Type of movement	Monitoring parameters	Monitoring aspects	Early warning systems	Advantages	Disadvantages	IoT Applicability
Electromagnetic	Rock slide [159], Mud slide [160],	Ground conductivity	Real-time monitoring and site specific monitoring	Site specific EWS	Accurate, Faster than other geophysical technique	EM Noise	EM methods can be automated using dataloggers [143], wireless transmission modules and converted to IoT Edge devices by programming intelligent algorithms [43].
Ground Penetrating Radar (GPR)	Slide in clayey soils [161], Debris flow [162], Rock Fall [163]	Travel time and amplitude of reflected signal	Periodical monitoring	Not applicable	High accuracy and resolution, easy to use, works well in dry soil	Temperature sensitive, ground vibrations might adversely affects the data	Not applicable
Electrical Resistivity	Earth slide [10], [164], Debris flow [165], Complex landslide [165]	Electrical resistance	Real-time monitoring and site specific monitoring	Site specific EWS	Works well in clayey soil	Temperature sensitive, Time consuming	Automated ERT monitoring systems are existing and it can be converted to IoT Edge device by programming intelligent algorithms [43].
Seismic methods	Earth slide [166], Rock falls [167], Mud slides [167], Debris flow [168],	Travel time of compressional waves, Seismic noise	Real-time monitoring	Not applicable	Rapid, accurate and economical, Environmentally friendly	Difficult to detect low velocity layers, Time consuming, Low resolution	Can be converted to automated systems and intelligent algorithms can be programmed to identify patterns from the seismic data and transmit only the required signals [169]. Data compression algorithms can also be implemented at the Edge.

and monitoring. Table V provides a summary of the different geophysical techniques used in landslide characterization and monitoring. Some methods, like ground penetrating radar (GPR), electromagnetic (EM), and magnetic surveying require the physical movement of the recording device, and are thus, most suitable for the characterization of the subsurface, but have limited applicability for monitoring or integration into IoT. Techniques like electrical resistivity tomography (ERT), self-potential measurements, and passive seismics can also be used for long-term monitoring, as sensors can be installed across hillslopes, and data that are characteristic for spatially distributed changes in subsurface properties can be recorded over long periods of time. These techniques are automated in several real-world deployments [175]–[177], [178], and hence suitable for integration into IoT, which yet has to be developed.

While Table V provides an overview of geophysical techniques that are commonly employed in landslide investigations, more detail on electrical and seismic methods, which can readily be integrated into IoT, are given below.

A. Electrical Methods

Electrical resistivity methods measure the electrical resistivity of the subsurface, which is a characteristic property of subsurface materials. Ground resistivity is correlated to various geological parameters such as porosity, water saturation, temperature, and fluid conductivity. By imaging the subsurface electrical resistivity variations, a methodology commonly referred to as electrical resistivity tomography (ERT), geological structures, sinkholes, fractures, and ground water dynamics can be mapped and monitored. For this, usually four-point measurements are applied, where current is injected in one pair of electrodes and the resulting potential measured in another pair of electrodes. Recent instrumentation developments allow to connect numerous electrodes via multicore cables to a computer-controlled acquisition system, which acquires data at predefined measurement combinations over an entire array of electrodes [179]. The depth of the investigation mainly depends on the geometry, electrode array separation, and spacing, where sensitivity decreases with increasing distance to the electrodes, which can be deployed on the surface or in boreholes. This method has been proven to image landslide characteristics and processes in numerous studies [175], [176], [180]–[182].

In recent years, automated ERT monitoring systems have been developed. An example of this is the development of the "PRoactive Infrastructure Monitoring and Evaluation" (PRIME) system by the British Geological Survey. PRIME is an automated system that can be deployed remotely. PRIME uses solar power and battery back-up for powering and is capable of acquiring hourly to daily time-lapse images [177], [183]–[185]. These systems combine electrical resistivity imaging technique with wireless telecommunications, server-based processing, and web portal access. This can be used to monitor ground water movement, changes in the moisture content of the subsoil and surface movements in real time by measuring the resistivity of the subsurface [176], [186], [187]. The PRIME system can be readily converted into an IoT device by incorporating intelligent algorithms that can understand the context, remaining energy levels, etc., and schedule its data collection, transmission rates, take intelligent decisions, etc.

2-D and 3-D ERT techniques are used to identify the volume and geometry of the landslide bodies during the pre-event and post-event phase of the landslides [176]. Low resistivity values indicate the presence of elevated water content that could be triggering landslide processes. Although data can only be acquired at discrete time-steps, recent advances in power consumption and data transmission allow for high repetition rate, which is capable of monitoring landslide dynamics at near real-time. It is a powerful tool used during the emergency phase of the disaster cycle for mapping the water content changes in vadose zones.

Another frequently used geoelectrical technique on landslides is measuring the self (or streaming)-potential of the subsurface. These electrical potentials are caused by the movement of electrical charges, most commonly due to groundwater flow [188], [189]. On landslides, [190]–[192] show that SP mapping and monitoring are capable to image complex hydrological processes related to landslide dynamics. The associated potentials, in the order of mV, can be measured over an array of electrodes using low-cost and energy efficient instrumentation. Hence, they can easily be integrated into a IoT for long-term landslide monitoring.

B. Seismic Methods

Seismic methods are noninvasive geophysical techniques used to estimate the elastic properties of the subsurface and can be used to investigate slope instability. The seismic signals produced by the slope movement can be recorded and analyzed to get the relevant information about the dynamics of landslide [193], [194]. Seismic methods are classified into active and passive methods. While active methods are able to produce high resolution maps of subsurface elastic properties [164], the seismic signals are generated by an artificial source such as explosives and vibrators, and are thus of limited use for continuous monitoring. Passive methods, on the other hand, analyze the natural seismic noise field, e.g. from earthquakes, microseism, or anthropogenic noise, and are frequently used to estimate bulk property changes related to landslide dynamics [195], [193]. Recent instrumentation developments aim at providing low-cost sensors that can be installed at public (e.g., schools) or private properties and build an extensive, distributed network of seismic sensors [196]. The authors in [197] have shown that using these low-cost, low-power instruments landslides can be monitored continuously, despite harsh environmental conditions, and that the acquired data are indicative of rockslide occurrences.

For the application to landslides, geophones are used, these devices convert the vibration associated with the movement of ground into voltage. This instrument can be used for landslide monitoring on the basis of frequency composition, amplitude, and time duration of the vibrating signal. The main advantages of using geophones are robustness and easy to use. Geophones are used to detect the vibrations associated with debris flows in [198] and can also be used for the detection of signals associated with landslides [199] and rock falls. In [198], they presented a method to transform the complex ground vibration velocity signal into a simpler signal that helps to detect the debris flows and their main characteristics. The amplitude and frequency of the measured vibration signal depends on the meteorological changes, human actions, placement, and assembly of the sensors. The recording of geophone signals requires large storage space that leads to problems in storage capacity and power consumption. Geophones are very sensitive to seismic noise that can be reduced by using the transformation method which helps to address the problem related to the limit of power available in the monitoring stations.

Some of these geophysical techniques, like EM, GPR, magnetics, and active seismics require manpower for data collection, either because no distributed sensor system exists or because sources have to be initiated manually. Hence, these are not suitable for long-term, automated monitoring. Whereas other geophysical techniques like ERT and passive seismics can be turned into an IoT Edge device by incorporating devices like data loggers, mote, and programming intelligent algorithms in mote. Therefore, it is possible to integrate these techniques with IoT. In [200], geophones are integrated into a WSN, in order to monitor seismic precursors of landslide activation. By implementing novel data processing routines, the amount of data that needs to be transmitted through the network was reduced, thereby making it more applicable for long-term monitoring, while standard seismic recording protocols usually collected large amounts of data and thereby usually prohibit the installation of a dense network of receivers over a long time.

By combining the geophysical data with data streams of other direct sensors, and applying data mining or machine learning techniques, the acquired information can aid decision-making routines on time without taking human intervention.

IX. Wireless Sensor Network

Wireless sensor networks (WSN) was a breakthrough for the beginning of intelligent systems research with benefits to earth sciences. WSN has advantages over several other ground-based landslide monitoring techniques [201]. WSN technology integrates the advantages of sensors, embedded systems, and networking technologies to be able to monitor any parameter and effectively perform computing and communicating. WSN systems can be tailored to incorporate any external sensors for detection, prediction and early warning applications. In addition to that, as the wireless sensor nodes can communicate with each other, local processing like data aggregation, data fusion, intelligent algorithms for making decisions and adapting to the current context can be done, which can enhance the effectiveness of the monitoring system.

Design, development, and deployment of WSN for real time landslide monitoring using geotechnical instruments and sensors is discussed in [152], [170], and [202]. The authors have discussed in detail the choice of sensors for detecting landslides, sensor placement approaches and strategies, network design architecture, software architecture, power considerations, etc., from the actual real-world implementation. The WSN system for landslide monitoring and early warning described in [152], [170], and [202] consists of various heterogeneous sensors like moisture sensor, piezometer, extensometer, strain-gauge, tilt meter, and geophones; and networks such as Wi-Fi, satellite network, and broadband network for effective sensing and communication. This WSN system is upgraded to IoT-based system for landslide monitoring by the same authors and a real-time deployment is carried out in Sikkim [15]. In [152], the deployment details of the WSN system is discussed in detail and the decade long experience in developing and deploying this WSN system with data interpretations are presented in [203]. WSN techniques are combined with remote sening techniques for real-time monitoring of landslides in Thailand [204]. Data analysis [203], mathematical models [15] at both regional and site-specific levels and machine learning models for now-casting and forecasting are developed [141], [153] with high accuracy for landslide forewarning. This system offers a major contribution to the field of landslide disaster management in India. In 2009, 2011, 2013, 2018, and 2019, the system had successfully delivered real-time warnings to the government and the government evacuated people during the monsoon season in the Munnar district of Kerala.

Early warnings with regard to mass movements is discussed in [205]. They have investigated the complete process of data gathering from sensors, information processing, and analysis for early warning. An experiment for testing the robustness of WSN system to monitor and early warn landslides in critical scenarios is presented in [206]. The authors have conducted the study in a landslide prone area in Torgiovannetto (Italy). The performance of metrics, such as radio link and path statistics as well as battery levels, is analyzed and the authors reveal the high level robustness of WSN system, which makes it suitable to monitor landslides in critical scenarios.

Geotechnical instruments, ground-based remote sensing sensors, and geophysical techniques are already part of WSN technology, by incorporating intelligent algorithms and IoT protocols WSN system can readily be turned into IoT system. This can deliver a better opportunity in the field of IoT to accomplish decisions and predictions in the time of disastrous situations. Authors of [15] have already deployed a IoT-based landslide early warning system, which evolved from WSN system. Table VI shows the monitoring parameters of WSN, types of landslide at which WSN can be used and the investigation phases of landslides along with the advantages and disadvantages.

X. Discussion

The presented study reviewed and evaluated landslide monitoring techniques based on the following: 1) landslide type; 2) monitoring parameters; 3) monitoring aspects; and 4) early warning systems. The study was based on the literature gathered to identify the relevant landslide monitoring technique for a particular type of landslide catering to monitoring and early warning aspects. Fall, topple, flow, spread, slide, and slope deformation are the six categories based on the type of landslide movement.

In this section, summary of landslide monitoring techniques, based on landslide type, its failure mechanism, the vital

TABLE VI
WIRELESS SENSOR NETWORK

Technique	Type of movement	Monitoring Parameters	Monitoring aspects	Early warning systems	Advantages	Disadvantages	IoT Applicability
WSN	Debris flows, Rock fall, Rotational and Translational slides, Complex landslides [170], Deep seated landslides	Rainfall, Moisture, Pore-water pressure, Deformation angle, Distance, Inclination, Tilt, Angle, Displacement, Vibrations, Speed, Sound, Acceleration, Strain, GPS, etc.	Real-time monitoring and site specific monitoring	Site specific EWS	High speed and resolution, Continuous technical development in processor, Communication, Low-power, Usage of embedded computing	Security against hackers, Security against vandalism	Directly applicable by programming intelligent algorithms in the sensor node [43]

TABLE VII
DISCUSSION SUMMARY OF LANDSLIDE MONITORING TECHNIQUES RELATING TO LANDSLIDE TYPE AND FAILURE MECHANISM

Landslide Type	Landslide occurrence mechanism	Vital parameters to monitor	Sensors for monitoring	Monitoring technique
Fall	**Rock fall:** Detachment of rock fragments from cliffs. **Boulder/Debris/Silt fall:** Detachment of large soil fragments followed by falling, rolling and bouncing	Displacement, Cracks, Rainfall, Location, Vibration	Tiltmeters, Wire extensometers, Geophones, Rain gauge, Laser scanning, Crack meters, Radar scanning, GPS	Geotechnical instrument such as Inclinometers, Wire extensometers, Tiltmeters, Geophones based monitoring; Airborne or terrestrial laser scanning (TLS, ALS); GB-SAR; Satellite InSAR; Satellite or ground based GPS monitoring system.
Topple	**Rock block topple:** Block rotation of rock initiated by water pressure in tension cracks. Slow movement during rotation and rapid movement after failure.	Crack length	Crack meter, Wire Extensometers, Tiltmeters Radar scanning, Laser scanning	Geotechnical instrument such as Crack meter, Tiltmeter, Wire extensometer based monitoring; TLS; GBSAR.
Slide	**Rotational slide in rocks:** Occur in very weak rock masses that lie under a strong rock. Moves with slow or moderate velocity, except in few cases which could lead to rock avalanches.	Displacement, Deformation,	Inclinometer, Extensometer, Tiltmeter, Laser and Radar based sensors, High resolution cameras for image acquisition, GPS	Geotechnical instruments based monitoring; TLS and InSAR for displacement calculation & change detection; Photogrammetry; Ground or Satellite based GPS monitoring.
	Planar slide in rocks: Slide head separated from stable rock along a deep, vertical tension crack. Not self-stabilizing and the slides are extremely rapid.	Crack length	Crack meters, Inclinometer, Wire extensometers	Geotechnical instruments such as Crack meters, Inclinometers, Tiltmeters, Extensometers based monitoring
	Rock compound slide & Rock collapse: Sliding mass on irregular rupture surface with several planes and joints.	Displacement, Deformation,	Inclinometer, Extensometer, Tiltmeter, Laser and Radar sensors, High resolution cameras for image acquisition, GPS	Geotechnical instruments based monitoring; TLS and InSAR for displacement calculation & change detection; Photogrammetry; Ground or Satellite based GPS monitoring.

parameters to be monitored, sensors that could be used for monitoring, etc., are provided. Table VII gives the summary in a tabular format.

Falls are sudden and unexpected movements of rocks and boulders having velocity of > 5 m/s (extremely rapid) [207], [208] that gets detached from steep slopes or cliffs through air by free-falling, bouncing, and rolling. The vital parameters to monitor in case of falls including rock fall, boulder/debris/silt fall are displacement, cracks, rainfall, location, vibration. Sensors corresponding to monitoring these vital parameters and monitoring techniques are detailed in Table VII.

Topples are complex and composite movement usually having velocity of > 5 m/s (extremely rapid), except for rock flexural topple [209]. Crack length is the major vital parameter to be monitored and it can be monitored through geotechnical instruments such as crack meter, wire extensometers, and tiltmeters. Topples

TABLE VII
(CONTINUED)

Landslide Type	Landslide occurrence mechanism	Vital parameters to monitor	Sensors for monitoring	Monitoring technique
	Rotational slide in Clay/silt: Sliding of a mass of homogeneous cohesive soil on a rotational rupture surface. **Planar slide in Clay/silt:** Sliding of a block of cohesive soil on an planar rupture surface. **Compound slide in Clay/silt:** Sliding mass on a rupture surface with several planes and uneven curvature.	Rainfall, Moisture, Pore-water pressure, Displacement, Strain, Electrical resistance.	Rain gauges, Moisture sensor, Piezometers, Inclinometers, Tiltmeters, Strain gauges, Array of Electrodes.	Rainfall monitoring using rain gauges; Geotechnical instruments such as Moisture sensor, Piezometer, Inclinometer, Tiltmeter, Strain gauge based monitoring; Radar rainfall estimates; ERT.
	Gravel/sand/debris slide: Sliding mass composed of granular material on a shallow, planar surface parallel with the ground.	Rainfall, Moisture, Pore-water pressure, Vibration, High resolution images	Rain gauges, Moisture sensor, Piezometer, Geophones, Acceleromters. High resolution cameras	Geotechnical instruments such as Moisture sensor and Piezometer based monitoring; Network of micro seismic sensors; Photogrammetry
Spread	**Rock slope spread:** Displacement and rotation of rigid blocks of stronger rock, under a weak basal surface. Limited total displacement and slow.	Displacement, Change estimation	Inclinometers, Radar, Laser, Photographs, GPS	Geotechnical instruments based monitoring; TLS; InSAR; GPS for displacement calculation & change detection; Photogrammetry.
	Sensitive clay spread: Sensitive clay spreads result from the propagation of a quasi horizontal shear zone.	Rainfall, Moisture, Soil pressure, Displacement, Change estimation, Electrical resistance	Rainfall gauges, Moisture sensors, Piezometers, Inclinometers High resolution cameras, Array of electrodes	Geotechnical instruments based monitoring; TLS and InSAR for displacement calculation & change detection; Photogrammetry; ERT
Flow	**Dry (non-liquefied) sand/silt/ gravel/debris flow:** Slow or rapid flow-like movement of loose dry, moist material, without excess pore- pressure.	Vibration, Motion, Sound	Geophones, Accelerometer Motion sensors, Microphones, Speed sensors	Geophone or micro seismic network based monitoring, Accelerometer, Microphones Speed sensors based monitoring;
	Sand/silt/debris flowslide: Very rapid to extremely rapid flow of sorted or unsorted saturated granular material on moderate slopes, involving excess pore-pressure Sensitive clay flowslide: Rapid strength loss due to liquefaction effect.	Rainfall, Moisture, Pore-water pressure, Inclination, Vibration, Motion, Sound,	Rain gauges, Moisture sensor, Piezometers, Inclinometers, Strain gauges, Geophones, Motion sensors	Rainfall monitoring methods Geotechnical instruments such as moisture sensor, piezometer, strain gauge, inclinometer, motion sensor based monitoring; Network of geophone based monitoring.

can also be monitored through change detection from TLS and GB-SAR photographs and interferograms [210]. In the case of rapid moving landslides, the continuous monitoring of landslide prone areas is required. The movement of landslide mass in rapid moving landslides can occur within seconds or minutes. The most common landslide monitoring techniques used for identifying rapid moving landslides are based on geotechnical instrument-based measurements. Remote sensing techniques are majorly used for monitoring slow moving and creeping landslides, however, in few applications TLS, GB-SAR are used for monitoring rapid landslides too [59], [211]. The authors in [212] discussed the advantages of the combined use of GBSAR and TLS for environment monitoring by comparing the principal features of each techniques. In order to extract the absolute phase information of the entire area observed by the GBSAR it is possible to link with TLS measurements. Hence, it could be

TABLE VII
(CONTINUED)

Landslide Type	Landslide occurrence mechanism	Vital parameters to monitor	Sensors for monitoring	Monitoring technique
	Debris flow & Mud flow: It occurs periodically on established paths, usually gullies and first- or second- order drainage channels.	Rainfall, moisture, Pore-water pressure, Displacement, Vibration, Motion, Sound	Rain gauges, Moisture sensor, Piezometers, Photographs, Radar and Laser scans, Video cameras, Wire extensometers Geophones, Microphone, Speed sensors	Rainfall, Moisture and Pore-water pressure based monitoring methods. Geotechnical instruments such as Extensometers, Accelerometers, Speed sensors, Microphone based monitoring; Geophone network based monitoring; ALS; TLS; Satellite & ground based InSAR.
	Earthflow: Movement of plastic, clayey soil, facilitated by a combination of sliding along multiple discrete shear surfaces, and internal shear strains.	Rainfall, Moisture, Pore-water pressure, Change estimation, Deformation	Rain gauges, Moisture sensor, Piezometers, Photographs, Radar and Laser scans	Rainfall, Moisture and Pore-water pressure monitoring methods; TLS and InSAR for displacement calculation & change detection; Photogrammetry.
Slope deformation	**Mountain slope deformation, Rock slope deformation, Soil slope deformation, Soil creep:** Slow to extremely slow deformation rates.	Deformation	Photographs, Radar, Laser, Satellite images, GPS	Photogrammetry; InSAR; TLS; ALS; GPS; Change detection from satellite images.

possible to combine the GBSAR and TLS techniques that can be used as a powerful remote sensing technique for rapid moving landslides and environment monitoring.

A slide is a movement of soil or rock down a slope that occurs along on the surfaces of rupture, and it is moderate($>$13 m/month to $<$ 1.8 m/hour) type of landslide. This slide can be either rotational planar or compound slides. In rotational slides the mass displaces downward and outward on top of a concave upward failure surface with moderate velocity of $>$ 13 m/month. In planar slides the mass displaces downward and outward on top of an inclined planar surface with extremely rapid velocity of $>$ 5 m/s, except for the planar slide in clayey soils, which moves very slow. The movement of moderate moving landslides will be in between slow and rapid moving landslides which is usually at a rate of meter per month. This type of landslides has to be monitored frequently or continuously. The vital triggering parameter in rock slides is the displacement, deformation, and crack length. Geotechnical instruments such as inclinometers, tiltmeters, wire extensometers can be used; change detection from photogrammetry, TLS, InSAR, and GPS can also be used for monitoring rock slides. Details are given in Table VII. Rainfall and PWP are the major triggering parameters in slides comprising clay and silt. Both satellite-based and ground-based techniques can be used for monitoring slides in clay and silt. Various types of remote sensing techniques can be used for the detection of slides such as TIR, GBSAR, DInSAR, TLS, IRT, close range photogrammetry, ground-based and satellite-based geodetic techniques, extensometer, piezometer, tiltmeter, electromagnetic, GPR, ERT, and seismic.

In spread, the failure occurs due to pressure in the soil resulting from the earthquake that reduces the stiffness and strength of the soil in the case of clayey soils. Lateral spread occurs otherwise without earthquakes, when stiff rocks are lying above the plastic material and moving slowly. Displacement and change estimation are the vital parameters to monitor in the case of rock, sand and silt spread, whereas for spread in clayey soils rainfall and moisture plays a major role. Satellite-based geodetic, laser, and radar techniques, ground-based geodetic, laser and radar techniques, geotechnical instrument-based technique can be used for the detection of spread type of landslides. Velocity of spread is slow($>$ 1.6 m/year to $<$ 13 m/month).

Flow are movement of particles down a slope with tremendous force in the form of fluid or semifluid under the influence of gravity. Vibration and motion are the vital parameters to monitor in dry flows comprising sand, silt, and debris. Whereas in other flows such as mudflow, debris flow and earth flow rainfall, moisture, and pore-pressure are also required to be monitored along with vibration and motion. Flows can be detected by InSAR, TLS, ALS, aerial photogrammetry, close range photogrammetry, ground-based and satellite-based geodetic techniques, inclinometer, piezometer, geophone, GPR, magnetic, ERT, and seismic.

Slope deformations are gravitational deformations seen in steep mountainous slopes, which does not contain a proper rupture surface but contains scraps, benches, cracks, bulges, trenches all over the mountain [51], [213]. Slope deformation occurs in both rocks and soils, velocity of their movement is extremely slow, and they can be detected by change detection from satellite images and photogrammetry. Geotechnical instruments like inclinometer and crack gauge [214], [215] are used for monitoring slope deformations. Aerial photogrammetry, ALS, magnetic, and seismic methods can be used for monitoring slow moving landslides. Satellite-based techniques monitor a particular area with a specific revisit time. SAR, InSAR, DInSAR, and satellite-based geodetic techniques are satellite-based remote sensing techniques usually having a revisit period of once or twice in a month. Due to this reason, satellite-based remote sensing techniques are not applicable for rapid moving landslides. However, satellite-based techniques are applicable for both slow and moderate moving landslides where the displacements of landslide mass occur several weeks or months before the catastrophic failure. Piezometer and ground penetrating radar can also be used for monitoring both slow and moderate type of landslides.

Complex landslide is not mentioned as a separate category by [51], though it is necessary to describe a combination of two or more type of landslides. Depending upon the two or more type of landslide movements observed in a slope, monitoring techniques are chosen for a complex landslide. Terrestrial photogrammetry, ground-based geodetic, TLS, inclinometer, extensometer, tiltmeter, WSN, EM, and ERT are the techniques and instruments that can be placed at a fixed positions so that the continuous or repeated monitoring would be possible for a large area of all type of landslides.

A. IoT for Landslide Monitoring

1) Challenges: Techniques that utilize manpower (e.g., total station surveys, airborne imaging techniques) is a biggest challenge to be integrated as an IoT Edge device. However, the data from these techniques could be later made available in the Internet, which can be accessed at Fog and Cloud layers in IoT (e.g., the maps and models are part of Fog and Cloud). Copyright and policy restrictions from government and private agencies restrict the free access of data and that becomes another challenge for any device to be turned into an IoT.

2) Requirements: Each of the different techniques to efficiently identify and early warn a landslide demand the knowledge of real-time triggers and their evolution over time. In the recent decade, landslide research is moving toward knowing the futuristic conditions to forecast and provide early warnings rather than analyzing the cause for landslide after its occurrence. Researchers are changing their viewpoint in learning more about the precursors and how it can be utilized for early warnings. At this juncture, researchers are in need of a system that can continuously monitor, assess, evaluate, and map the risk levels required and this research gap is filled by IoT technology. For any landslide monitoring device to be turned into an IoT device, requires memory, processing capabilities, and a communication module. For instance, geotechnical instruments like piezometer and strain gauge are sensing devices, these devices can be turned into an IoT device by connecting them to a mote which has storage, processing, and communication capabilities. Usually these instruments are wired with appropriate signal conditioning circuitry to the motes. Some examples of mote are MicaZ, TelosB, WaspMote, emote, Shimmer, IITH-mote, EZ 430. Microcontrollers like Arduino, Raspberrypi are also used in place of motes. The motes are programmed with intelligent algorithms for adapting itself based on context and making local decisions. Intelligent algorithms need to be designed taking into consideration, the type of monitoring techniques, the amount of energy required for its operation, the kind of data that it is collecting, frequency of data transmission required for early warning, etc. These landslide monitoring systems are deployed in remote environments which are often constrained due to resources such as power. Based on the location where the monitoring system is deployed, it depends on renewable energy sources such as solar power, power from the grid, and hybrid methodologies to power the system. In adverse situations, when power levels are low but we want the system to be functional for a prolonged time, intelligence programmed in the Edge can help the system make intelligent decisions to utilize the limited power efficiently and extend the lifetime of the system. This can be accomplished by understanding the general pattern or trend in the data and then transmitting only the data of interest, so that unnecessary data transmission can be avoided and energy can be saved. Data compression algorithms can also be implemented at the Edge, so that the compressed data that consumes less energy can be transmitted instead of the original data. At times, we may need data at different sampling rates to understand the subsurface changes better. For instance, data need to be sampled at higher frequency during a disastrous context, whereas during a safe context, data sampling frequency can be kept minimal. Edge analytics can help achieve this functionality by understanding the environmental context such as amount of rain, moisture in the subsurface, etc., and make decisions to increase or decrease the sampling rate. However, computationally intensive algorithms such as inversion procedures need to run on the cloud. Even when most of the disaster monitoring applications need to be performed in a resource constrained environment, IoT system gives the opportunity to do better collection processing and transmission of the data through its intelligence. The first level of processing to understand the variability can be done in the edge through Edge analytics, and the cloud system can be used for building the deeper scale analysis to come up with the probability of an imminent landslides. Apart from these communication network also needs to be established for the IoT devices to communicate. All these together make a sensing device an IoT device.

3) Opportunities: IoT provides a platform for efficient usage of multiple resources around us in an automated and controlled manner not only for environmental monitoring and disasters but also in many other fields like health care, smart cities, etc. IoT technology is unique in providing the opportunity to continuously monitor and study the variations of the patterns, incorporate machine learning algorithms at different layers and based on that arriving at decisions. As far as landslides and disasters are considered, IoT helps in efficiently gathering data from multiple connected objects and techniques, introducing local intelligence, communication with other objects as peers, providing services for integrating, discovering knowledge, interpreting, and visualizing, managing crisis after disaster, information dissemination in real-time basis to connected objects like smartphones, smartwatches, etc. Moreover, with rapid advances in domains of IoT, artificial intelligence and Big Data analytics, the data collected from different disciplines of natural hazard science can be used for providing integrated interpretations. For instance, the rainfall data collected for landslide purpose can also be used for flood assessment and vice versa. Thereby, techniques like IoT can provide the opportunities for multihazard assessment in a more effective way than before.

XI. Conclusion

This survey article reviewed and evaluated different landslide monitoring techniques based on the following four aspects: 1) type of movement; 2) landslide monitoring parameter; 3) monitoring aspects; and 4) early warning systems. We have discussed various landslide monitoring techniques in the following: 1) remote sensing; 2) photogrammetry; 3) geodetic; 4) geotechnical; 5) geophysical; and 6) WSN. We have highlighted real deployments for each technique and various issues present in each technique. In addition, we have discussed the challenges of integrating IoT to each landslide monitoring technique. Besides, we have compared and summarized the landslide monitoring techniques based on the four reviewing aspects and IoT integration opportunities. Finally, we have discussed the suggestions to choose a particular landslide monitoring technique for a specific landslide type and failure mechanism.

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