Survey of Landslide Warning Systems and their Applicability in Mauritius

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Abstract: ***Landslide is major problem in several countries causing loss of lives and major infrastructural damage. Several systems have been set-up for monitoring and predicting landslides in different countries where this problem is prevalent. These systems integrate sensing mechanism with communication systems and GPS to detect landslide conditions and alert concerned parties via sms, emails and other appropriate means. Wireless sensor networks have also been widely deployed for landslide monitoring. Mauritius which is an island nation situated in the Indian Ocean has recently faced several problems due to extreme climatic conditions such as torrential rains and flash floods that have led to major landslide problems in different parts of the island. However, to date, there is no adequate system in place to monitor landslides. This paper surveys the different landslide modelling and warning systems that have been deployed worldwide and assesses their suitability for Mauritius. Given the excellent mobile network coverage available in Mauritius, a landslide warning system based on sms notifications appears to be a viable solution for Mauritius. A potential framework for a landslide monitoring system for Mauritius is therefore proposed along with a feasibility analysis.***

Keywords: Land Slide, Warning System, Communication, Mauritius.

1. Introduction

Landslide is defined as ground displacement for example falling rocks, slope failure and flow of debris [1]. According to the United States Geological Survey, the term "landslide" describes various processes that cause the downward and outward movement of slope materials such as rocks, soil, artificial fill, or a combination of them [1]. Slope movements may originate from displacements of near-surface structures to rock masses which are deeply buried [2]. All slopes tend to degrade by weathering gradually with rock debris accumulating downslope [3].

Famous examples of landslides include the Haiyan landslides, Khait rocklide and the Vajont slide. The Haiyuan landslides (China) were triggered by an earthquake causing 675 large loess landslides to occur destroying many villages and killed more than around 100,000. The Khait (Tadzhik Rep., formerly USSR) rockslide was also triggered by an earthquake of magnitude 7.5 causing rock to slide in the form of large loess and granite debris killing some 12000-20000 people by destroying some 33 villages [1]. The Vajont Dam located in the Alps north of Venice, is a double arch dam 266 m high made up of 4-23 m thick concrete. On the 9th October 1963, 270 m^3 of rock moved 400 m and landed in the reservoir creating a huge wave 100 m high overtopping the dam to flood the downstream villages. More than 2000 people were found dead after the worst civil engineering disaster [3]. The relief of Mauritius is mountainous in nature [4] and severe structural damages have been reported in dwellings constructed on slope debris.

From the various examples described above where much loss of life and property are apparent, landslide is the natural hazard which is the most underestimated and under recognised. Mountain slopes tends to fail in a catastrophic manner without warning during earthquakes, cyclones and heavy torrential rains. Such slope failures inevitably result in the sudden and dramatic collapse of large volumes of soils and rocks which cause devastation in their passage downstream. [5]

As such, several landslide warning systems have been developed. Some of the major types of landslide movement are illustrated in Figure 1 below.

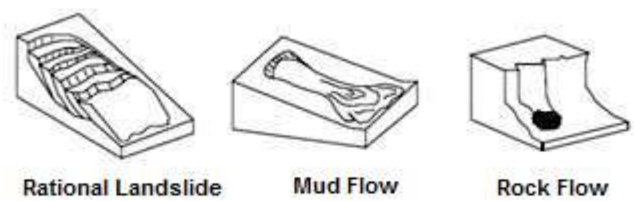

Figure1: Illustration of some of the major types of landslide movement [3]

Landslide warning systems have been developed and deployed in several countries facing this problem. In [6] a landslide alert system for the rockslide of Torgiovannetto in central Italy was proposed. The system consisted of 13 wire extensometers, one thermometer, one rain gauge and three cameras. The system monitored the velocity level by two or more sensors and whenever the velocity crossed a typical threshold, the surveillance level was raised. When a change in the characteristic of the landslide was detected which could lead to an imminent failure, an alarm was triggered and necessary action for closing the upper road was initiated. In [7] a low-cost, sustainable early warning system using SMS alerts was proposed for the areas of Ratnapura and NuwaraEliya districts in Sri Lanka. Geological factors such as distance and ground water level over a given time interval were measured by appropriate sensors. Based on the measurements taken when the probability of landslide occurrence reaches a critical value, the system sends an SMS warning message automatically to the concerned parties. A real time landslide monitoring and prediction system using wireless sensor networks (WSNs) was proposed in [8]. The system employed wireless nodes, a gateway, a base radio, a server, geosensors and a solar panel. Landslide prediction was performed using multivariate statistical analysis of measured data and using an analytical hierarchy process method. Several types of notification services were provided to concerned stakeholders based on the predicted landslide risk levels [8]. Finally in [9], an early warning system for detecting disasters such as landslide and flash floods was developed. The system used a WSN deployed on the slopes of a mountainside which susceptible to landslides and flash floods. The network was based on a Zig-Bee tree topology. A tipping rain gauge was used for the measurement of precipitation and landslides were detected using buried microphones or peizo elements to measure pressure changes. These WSN nodes report to a base station which uses a Zig Bee coordinator as a receiver and the base station communicates with a master unit using a long range RF transmitter. When rain or landslide parameters detected by the nodes exceed a given level, the master unit sounds an alarm and sends SMS warnings [9].

Many researchers have investigated the potential of various Remote Sensing (RS) techniques coupled with GIS and GPS for the detection and monitoring of landslide movements. Wagner [10] presented a new approach to geo-monitoring using a combination of point cloud and image data. In his study, data was acquired in subsequent measurement epochs wherein RGB + D images were generated and any pixel position was expressed as a polar measurement and transformed into a 3D world coordinate. Displacement vectors were then calculated for corresponding points/regions of two epochs with the help of image matching algorithms [10]. By acquiring high spatial and temporal resolution data through a combination of GPS (RTK), conventional inclinometers, Shape Acceleration Arrays, tilt meters, active waveguides and piezometers, Uhlemann et *al.* [11] successfully located areas of stability and instability across a large slope as well as captured ‘S’-shaped slope displacement-time behaviour in response to elevations in pore-water pressures. Uhlemann et *al.* [11] have also highlighted the fact that in order to fully understand failure and movement mechanisms of slopes, it is important to carefully select the correct combination of monitoring techniques that will provide high temporal and spatial resolutions on both measurement and slope scale. Stumpf et *al.* [12] found that the Multiscale Model to Model Cloud Comparison (M3C2) algorithm developed by Lague et *al.* [13] was a versatile and accurate tool for reliable change detection in active landslide zones. Moreover, M3C2 can be used to obtain volumes, erosion rates and 3D displacement in such zones [12]. Lowry et *al.* [14] investigated the potential of using the Ground-based interferometric radar (GBIR) for the monitoring of slow-moving, translational failure landslide in Colorado, USA. As such, Lowry et al. [14] monitored landslide horizontal displacements using a Gamma Portable Radar Interferometer (GPRI) and compared the results with that obtained from GPS based surveying methods to verify measured displacements. Lowry et al. [14] found that the results obtained from GBIR were in good agreement with measurements made by traditional GPS surveys. Lowry et al. [14] also concluded that landslide displacement using the GPRI platform is capable of detecting and monitoring displacement in mm-scale and useful in resolving small scale temporal variation in slip rates. Shi et *al.* [15] successfully used point-like target offset tracking with multi-mode high-resolution TerraSAR-X data for analysing the spatial–temporal pattern of landslide deformations in the Three Gorges Dam area in China. The results were then correlated with the fluctuating water level in the Three Gorges Dam for landslide warning and disaster prevention [15]. On one hand, Schlögel et al. [16] successfully used L-band ALOS/PALSAR imagery for the monitoring of active landslides covered by vegetation having substantial changes in the soil surface state. On the other hand, Zhao et *al.* [17] used multi-temporal ALOS/PALSAR images to investigate landslide activity over an area 200 km by 350 km in northern California and southern Oregon. Zhao et al. [17] claims that this method will allow identification of active landslides in broad areas of the Pacific Northwest in an efficient and systematic manner, including remote and heavily vegetated areas difficult to inventory by traditional methods. Furthermore, Zhu et al. [18] used a combination of Corner Reflector Interferometric SAR (CR-InSAR) techniques and Globe Positioning System (GPS) for high precision landslide deformation monitoring of three potential landslide fields in the Shaanxi province, China. Jeber et al. [19] concluded that a combination of satellite remote sensing (RS) data with the support of high spatial resolution aerial photography provides an excellent spatial database for the detection and monitoring of landslides. However, the availability of remote sensing data in tropical regions is made difficult by the frequent presence of thick clouds as well as dense vegetation cover [19]. According to Jeber et al. [19], the penetration capability of radar systems can overcome these restrictions. All these methods require data capture, processing and interpretation which are time consuming. Many landslides by nature do not provide reasonable warning lag time between landslide displacement and catastrophic failure. However, RS and GIS can be used for the detection and monitoring of slow soil movements in potential landslide identified zones for early warning and disaster prevention in Mauritius.

Mauritius is a volcanic island consisting of basaltic flows forming a volcanic plateau of 300-400 m formed by several late craters. The geological history of the island started approximately 10 million years ago. There were four phases of volcanic activity involved in the formation of the island and the late lava flows shaped the latter as seen at present [20]. Rainfall in Mauritius occurs mostly during the rainy and cyclonic season commencing from November up to May [4]. Most of the landslides are triggered during these periods of intense showers.

Landslide problems are frequent in island consisting of volcanic domes, especially those found in tropical regions. Mauritius unfortunately falls in this category with mountains located at altitudes ranging from 300-800 m above sea level. Most of the mountains have slopes ranging between 20^o to 60^o covering an area of more than 30,000 hectares (approximately 16 % of the total surface area). Based on land capability and land suitability indexes, it has been reported that all slopes over 30^o found along a mountain represent a hazard for most human activities and requires adequately engineered construction works [5].

Today, many areas of mountain slopes have been developed for construction of dwellings and these settlements are being erected higher beyond the zone of high risks prone to slope movement (examples of occupied mountain slopes include Tourelle du Tamarin, Chitrakoot, Quatre Soeurs, Le Bocage, Candos Hill and La Butte). This has definitely maximised the risks of landslide hazard in these areas. Mauritius being located within a cyclonic basin, it would require only a few days of heavy cyclonic rainfall to trigger landslides along mountain slopes which comprise of poorly consolidated and loose weathered materials [5].

Recently, Mauritius have witnessed several important landslides that have occurred during the heavy showers causing damage to properties, agricultural lands and several newly constructed road embankments. Examples include the appearance of progressing large cracks in dwellings of Chitrakoot Village, failure of road embankment on the Ring Road Project near Pailles village as well as soil slope failures on soil cuts along the newly constructed Terre Rouge-Verdun Link Road as given in Figure 2 below.

Figure2: Slope failures along cut mountain slopes of Terre Rouge Verdun Link Road

In this paper an analysis of different categories of landslides has been made followed by a classification as to which landslide types are found in Mauritius. An overview of different existing landslide warning systems with detailed descriptions on the types of sensors and networking configurations required is also made. Finally, a typical framework for a landslide warning system that can be deployed in Mauritius is proposed. This paper is organized as follows. Section II describes the different categories of landslides as well as the sensors and networks used in landslide warning systems. Section II gives a typical framework that can be used for landslide detection in Mauritius and Section III concludes the paper.

2. Landslide modelling and warning systems

This section describes the techniques used for modelling landslides in details as well as the warning systems that can be used.

2.1 Landslide modelling and geotechnical analysis

Weathering is a natural phenomenon that causes degradation of soil and rock strength. All slopes possess intrinsic characteristics which in the presence of other prevailing external factors give them a tendency to move. Depending on these characteristics and factors combined to a certain degree, some slopes tend to move more than others and in a catastrophic manner. Displacements of large rock or soil masses occur when the strength of the slope is exceeded by the gravity induced stresses at some critical locations within it [2].

Most landslide events may be attributed to a combination of an unstable slope structure and a trigger event [3]. Some of these triggering processes may include one or a combination of the following factors.

1. Water causing rise in groundwater pressure.
2. Removal of toe materials by natural (erosion by flowing water) or artificial (excavation) means.
3. Adding materials to the head (top part) of a slope.
4. Strength reduction due to weathering of slope materials.
5. Ground vibrations by natural (earthquake) or artificial (heavy road traffic) means

It should be highlighted that many slides have complex origins due to the combination of a number of contributory factors [3].

In order to take necessary actions, it is important to predict when and which landslides have reached a dangerous level. Based on observations, it has been found that most of the landslides in Mauritius were triggered following heavy rainfall events causing slow movement on sloppy areas.

The JICA team hired by the Government of Mauritius to study the landslide problems at Chitrakoot, proposed the following three main methods of predicting the risk of landslides [21]:

1. To install and monitor the landslide monitoring devices such as extensometers
2. To monitor the accumulated rainfall
3. To observe cracks, deformations or other abnormal phenomena on the ground surface or structures

In addition, the JICA team also proposed to establish an early warning and evacuation system, which make inhabitants know when it reach to the alert level using the following system:

1. Alert system (which is connected to the installed extensometer)
2. Simple rain gauge system (will be installed at one of the houses in the area).

The above system will be useful for inhabitants to know when landslides reach to the alert level on site, and contact relevant organizations such as police to take necessary actions.

2.2 Land slide sensing and detection mechanisms

Several techniques can be used for sensing, detecting and monitoring ground surface displacements during landslides. For landslide warning systems, geotechnical techniques are the most widely use and they provide real-time monitoring using sensors connected to communication networks. An overview of landslide detection techniques is given next with main focus on real-time monitoring [22, 23].

Geotechnical techniques use sensors permanently placed in the structure or region under consideration. They detect changes in the geometrical and/or physical characteristics of the land surface being monitored. They are often connected to a telemetric system for real-time communication of readings to a controller. Most geotechnical sensors have some memory to store the readings or they can be connected to a computer for automatic logging of the readings. An overview of the main landslide monitoting sensors is given next [22,24]:

1. Inclinometers are normally placed in boreholes drilled into the landslide area. They sense the curvature of the boreholes to detect inclination changes. When coupled with a gravity operated tilt sensor they can identify slip surfaces and moving areas. They can also reveal the depth of the planes that have failed.

2. Extensometers are capable of measuring the axial distance moved between several points of reference along a given measurement axis. They can be placed inside a borehole or on the land surface. There are also fully automatic extensometers that perform electro-optical distance measurements within fiber optic conduits. The length variations of the fiber optic sensors are detected using the electro-optical sensor and are managed by a computer [22,24,25].

3. The pore pressure of groundwater can be measured using Piezometers within a geological structure, so as to give an indication on the amount of stress and strain accumulated. Vibrating wire, pneumatic and standpipe piezometers are the most commonly used borehole piezometers. Predefined thresholds may also be set to indicate early warning of conditions that can result in landslides [22,24].

4. Geophones measure vibration associated with movement. They can detect landslides by analysing the frequency spectrum, amplitude, and duration of a signal resulting from land surface vibrations. Hence they can be easily incorporated in early warning systems.

5. Tiltmeters are based on electrolytic level sensors and can measure degrees of rotation. They can detect very slow motions associated with rotational failures. They are used to determine the direction of motion, identify areas of deformation and characterise the motion mechanism [22,24].

6. Crack meters measure the displacement between two points on the land surface undergoing distortions. They are low-cost device that can easily integrate warning systems [22,24].

7. Accelerometers are electromechanical devices used to measure acceleration forces. They are equipped with motion sensors that can detect earthquakes and landslides.

Several landslide monitoring sensors are manufactured using Micro-Electro-Mechanical Systems (MEMS) technology. MEMS technology involves miniaturized mechanical and electro-mechanical elements manufactured by microfabrication processes. The size of MEMS devices can vary from below one micron up to several millimeters [26]. Sensors used for landslide detection such as accelerometers, tiltmeters, inclinometers and piezometers are readily available from several MEMS manufacturers [27,28,29,30].

A generic block diagram for measuring landslide with real-time monitoring sensors is given in Figure 3 [31]. In this scenario a slope movement sensor for example an extensometer along with a geophone, piezometers and rain gauge have been used.

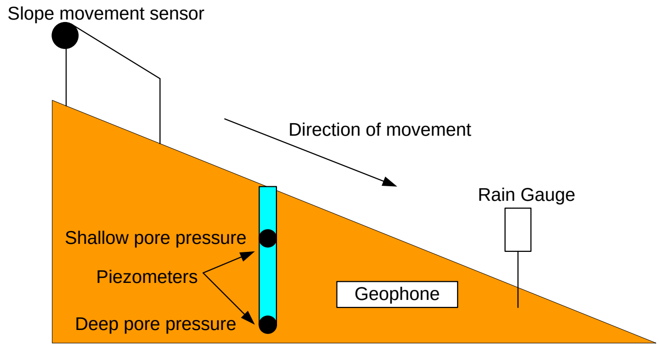

Figure3: Placement of landslide monitoring sensors [31]

Nowadays, wireless sensor networks (WSN) have become one of the major technologies that can be used for real-time monitoring of landslide. WSNs can provide large scale deployment, scalability and adaptability for different situations [32]. They can also be deployed in hostile environments, have low maintenance requirements and can still operate with limited communication facilities when the mainstream communications infrastructure has failed. Several manufacturers are now producing wireless sensor nodes with in-built capabilities to measure physical parameters such as temperature, tilt, pressure etc. [33,34]. These sensors are low-cost and low power devices which can be used in landslide detection. WSNs can be deployed either autonomously or in conjunction with conventional sensors.

When WSNs are deployed with wireless sensor nodes that do not have in-built sensors to measure physical quantities relevant for landslide detection, the geological sensors are placed inside a sensor column and they are connected to the wireless sensor node via a data acquisition board as shown in Figure 4 [32].

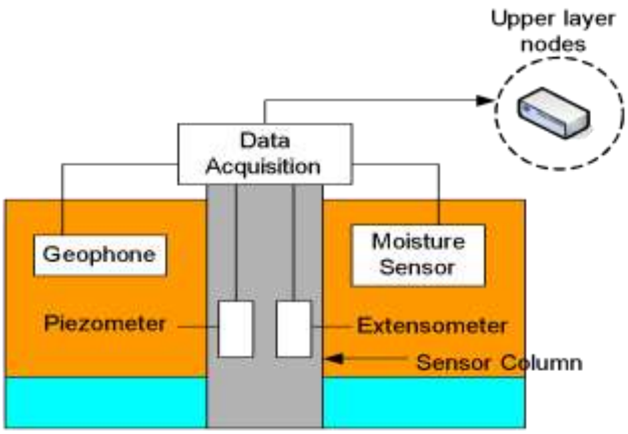

Figure4: WSN deployment with sensor column [32]

A two-layer hierarchy is used for deploying the WSN at the site. The data is first sampled and acquired from the sensor column by the lower layer nodes. Data packets are then sent to the upper layer. The upper layer forwards the data to the sink node at the deployment site. Due to differences in the geological and hydrological properties of the area being monitored, the deployment area can be divided into three regions namely crown, middle and toe regions as shown in Figure 5 [32].

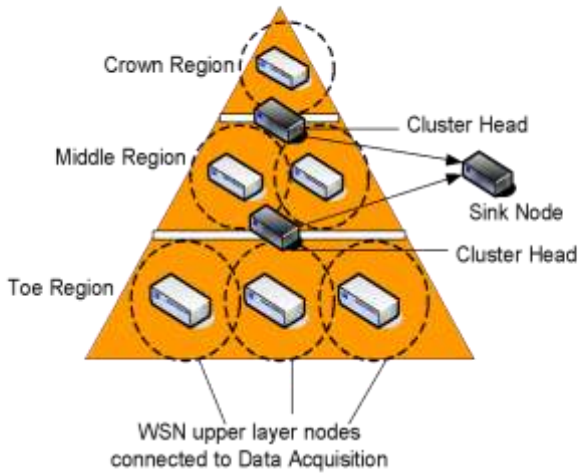

Figure5: Regionalized WSN architecture for landslides [32]

It is also possible to use wireless sensors with in-built measurement capabilities to create an autonomous WSN. The architecture of such a system is shown in Figure 6 [35]. The system consists of two subsystems, a wireless sensor network and a server system.

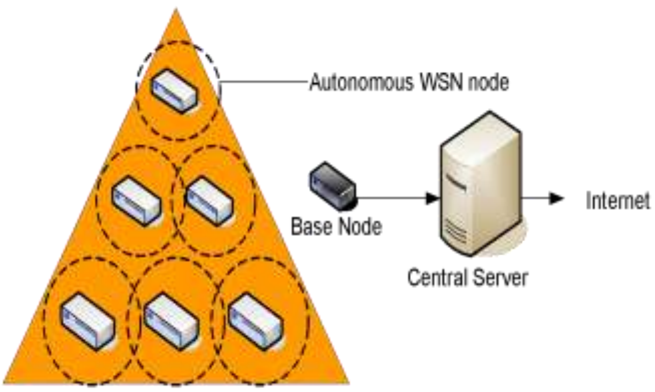

Figure6: Autonomous WNS architecture for landslides [35]

The WSN consists of sensor nodes, equipped with processors accelerometers. For data collection analysis of the monitored slope, mobile software agents are embedded into the nodes. A software agent is an autonomous program that can operate independently without human intervention [36] and can react to environmental stimuli. Communication among the sensor nodes and between sensor nodes and the server system can be achieved via several radio technologies [35]. An overview of different communication systems is given in the next section.

3. Communications systems / networks for relaying landslide warning messages

The success of any disaster warning system highly depends on how fast residents receive warning messages. Various factors such as geographical location, population density and availability of multiple warning systems affect how fast evacuation can be organized in the event of a disaster. Warning messages can be in the form of alerts (siren, radio, video or text messages) to inform the population about critical events so that people can take necessary precautions. According to several studies [37][38][39] carried out over the years, it has been observed that the public is more likely to respond to warning messages delivered over multiple channels and the response is better if people have a strong social network. With the evolution of communication networks, especially wireless networks such as cellular, mobile, wifi, wimax, satellite, messages can be transferred in a matter of seconds today. All these networks are coupled together to provide multiple channels of information and also connects the public via social networks.

3.1 Cellular Network

A cellular network is a wireless network spread over a large area and uses a different set of frequencies to avoid interference between adjacent areas. Cellular/mobile networks consist of the following [40]:

1. Network of base stations for relaying signals.
2. Circuit switched network for handling text messages and voice.
3. Packet switched network for handling mobile data.
4. Public switched telephone network (PSTN) for connecting subscribers to the network.

The cellular network is divided into several overlapping geographic areas, called cells. Each cell has a base station at the center and they are grouped to form a cluster as illustrated in Figure 7. Variations include base stations with large antenna which are supported by relays [41].

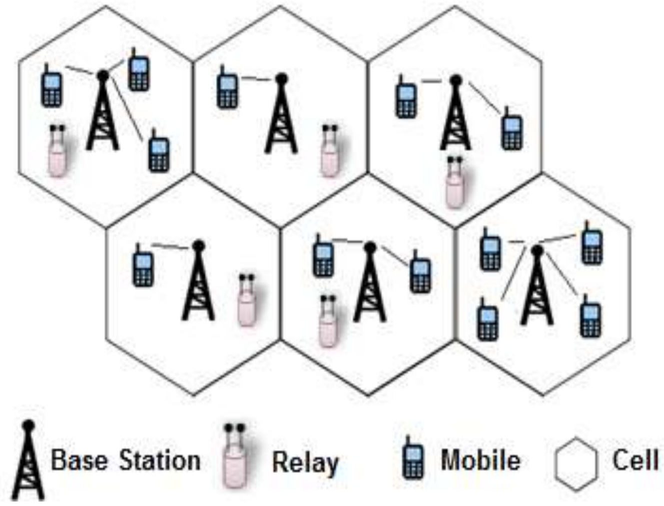

Figure7: Cells in a cellular network [41]

The cells are overlapping so that users always within the range of a base station. Base stations are connected together and they transmit signals carrying voice, text, and digital data from one device to another. The size of each cell depends on the number of subscribers; urban areas have more subscribers compared to rural areas [42]. When joined together, the cells or clusters provide coverage over a wide geographic area. Furthermore, an unlimited number of additional cells can be added to increase coverage.

With the modularity of cellular networks, telecommunication providers can now provide voice and data services over large geographical areas and target a larger population. Cellular networks allow both mobile devices and fixed telephones to communicate anywhere on the network via the base stations irrespective of the geographical location of the mobile device [40].

3.2 WIMAX Network

Wimax(Worldwide Interoperability for Microwave Access) is a wireless alternative to wired internet technology such as dial-up modem, DSL(Digital Subscriber Line), ADSL(Asymmetric Digital Subscriber Line) and fibre optic. Wimax operate similar to Wifi technology using wireless radio signals thereby allowing electronic devices to communicate over a network. However, Wifi operates using a lower signal radius to produce a wireless local area network (WLAN) that are commonly used in restaurants, hotels, coffee shops, libraries and public areas. Wimax belongs to the IEEE 802.16 family of wireless-network standards and provides a larger coverage than WLAN. Wimax aims at providing wireless broadband to both fixed and mobile devices with a signal radius of about 50 km (EEE 802.16e) and 75 Mbps (EEE 802.16a) [43].

Wimax uses transmitter stations to broadcast signals and devices equipped with a Wimax receiver can capture these signals. The base stations are connected to the ISP(Internet Service Provider) network that eventually connects to the internet [44]. Wimax can also co-exist with wifi to achieve a better coverage of wireless networks. Wimax can be used to connect Wifi hotspots while wifi improves region access [45]. A typical Wimax setup environment is illustrated in Figure 8.

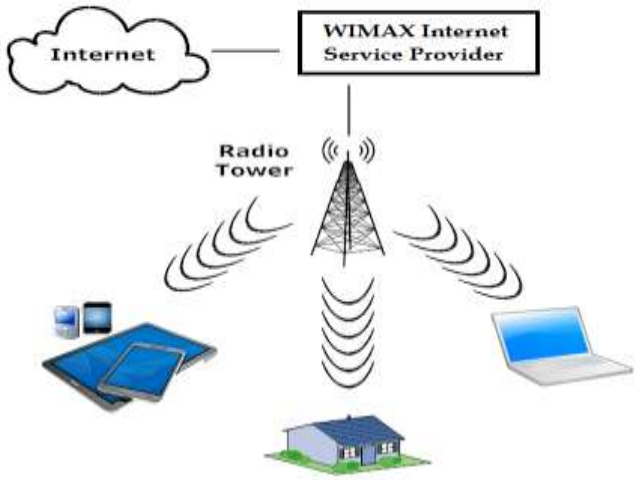

Figure8: Consumer Broadband Wimax environment [45]

The two main WiMAX Standards are the IEEE 802.16d known as Fixed WiMAX and IEEE 802.16e known as Mobile Wimax, complement each other in meeting the increasing demands for broadband wireless applications. Fixed WiMAX supports fixed and nomadic applications while mobile WiMAX encompasses mobile, portable, fixed and nomadic applications. The main difference between fixed and mobile WiMAX is that the mobile variant requires an inter base station handoff when a user who is under the coverage of one base station transits to a zone that falls under the coverage of another base station [46]. Wimax therefore aims at providing service in areas that are difficult for wired infrastructure and therefore targets a large population area. It provides connectivity to fixed wireless devices and also mobile devices that are always on the move.

3.3 Satellite Network

In addition to Cellular and Wimax networks, satellites can also be used to transfer signals over a larger geographical area. Satellites require a receptor dish to receive the wireless signals via one-way or two-way communication channel. Satellite communication can now be coupled with internet connectivity to provide a larger range of services to a wider population area. Two different frequencies are used to transmit and receive signals. Uplink frequency transmit frequency from earth station to satellite while downlink frequency transmit signal from satellite to earth station [47]. Figure 9. illustrates the components involved in a satellite network.

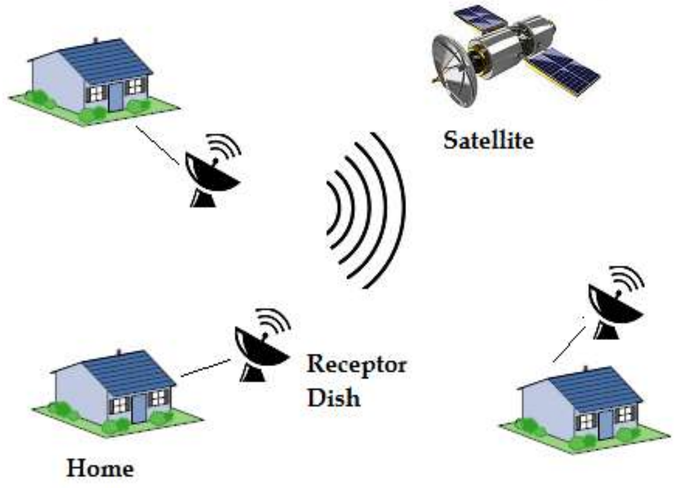

Figure9: Components of a Satellite Network [48]

The two main types of satellites are [48]:

1. GEOs (Geostationary Earth Orbit): Keep the same location with respect to earth and the receptor dish must maintain a clear line of sight to the satellite. Approximately 40% of earth can be covered by one GEO.
2. LEOs (Low Earth Orbit): Change their position relative to earth. A set of LEOs can offer entire earth surface coverage at any given time.

GEO satellite networks better support a variety of modern applications (e.g. web browsing, file downloads, video/audio conference, e-mail, etc) and they are also able to broadcast and multicast large amounts of data over a very large area [49] at high speeds (approximately 1 Gbit/s downstream and 10 Mbit/s upstream [43]).

3.4 Mobile Network

Mobile network are built over cellular network with cells and base stations. In addition to voice and text services, mobile network provide broadband internet connectivity to mobile phones or portable devices through mobile towers. These devices have an integrated modem that enables data transmission. 4G is the fourth generation of mobile communication technology that provides voice, data, multimedia and mobile broadband internet access. 4G achieves high speeds and offers transmission speeds of 100 Mbit/s with high mobility and 1GBit/s with low mobility [50]. 4G is also expected to enable simultaneous connections to high-speed networks and provide flawless change of cells over a geographical area. Table 1 shows the technologies used in 4G mobile networks.

TABLE 1: MAURITIUS INTERNET SERVICE PROVIDERS [50]

Speed in Mbits/s	Down	Up
HSPA+	21-672	5.8-168
Mobile Wimax (802.16)	37-365	17-376
LTE	100-300	50-75
LTE-Advanced: Moving at higher speeds	100 Mbits/s	
Not moving or moving at lower speeds	Up to 1000 Mbits/s	
MBWA (802.20)	80 Mbits/s	

According to Gartner, inc., 1.9 billion mobile phones have been shipped in 2014, which represents a five percent increase compared to 2013 [51]. Mobile phones represent the most used device which is always with us and can therefore be used to target a large population area via mobile networks.

4. Proposed framework for a landslide warning system for Mauritius

In the context of the Landslide Management Project commissioned by the Government of Mauritius and undertaken since May 2012 by the Japan International Cooperation Agency (JICA) expert team, 37 disaster sites were identified and classified in accordance with the types of site specific occurrences and the degree of risks. As such, Chitrakoot, Quatre Soeurs, Vallee Pitot and La Butte were selected to be those of highest priority areas because of the present landslide activity, hazard potential and the scale of the landslide as shown in Figure 10. Necessary countermeasures were implemented in these areas [52].

The La Butte area is a residential district located in the west of Port Louis at the foot of the Signal Mountain. La Butte has been suffering from repeated landslides during events of heavy rainfall. During major landslides that occurred in 1987 and 1988, several houses, roads, schools and other public facilities, were either destroyed or seriously damaged. Appropriate countermeasure construction works comprising of drainage system, steel piling, water collection boring, horizontal boring in drainage wells undertaken were completed in July 2008. According to data recorded by extensometers, no ground displacement at the sites have occurred since [53].

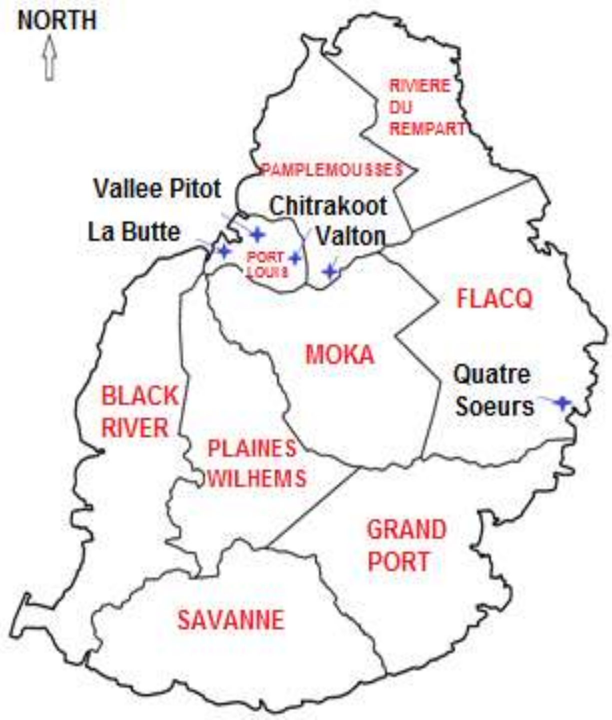

Figure10: Map showing various locations affected by soil movement in Mauritius [4]

Another important landslide site is the Chitrakoot village located in Vallee Des Pretres in the Port Louis mountain range. The village is on a dynamic upper mountain slope exceeding 35^{o}. The zone is potentially dangerous as there is a slow movement of loose soil down the slope from the mountain cliff in the direction of the village. This part requires the implementation of appropriate slope stabilization works to reduce the hazard risk [5]. Landslide occurs after continuous heavy rains as the large amount of water is accumulated on the surface and under the ground. Therefore, as countermeasures, it needs to reduce the amount of surface water and groundwater by artificial drainage system. Horizontal drainage, ditches and flood channels were planned to be undertaken in Chitrakoot [21]. And with the most recent heavy rainfall event that occurred on Tuesday 20th January 2015, the soil subsided by 3 mm in the government school while soil moved some 10 mm at other places. This increased the risk for a landslide to occur [54]. As a result, there were cracks in buildings as well as damage caused to the main underground potable water pipe supplying drinking water to the village.

Mauritius has witnessed major ICT developments in the past decade. The internet has opened a lot of opportunities for domestic and commercial use in terms of online services, better communication channels, mobile services and mobile payment among others. With a total of 186,000 fixed internet subscriptions and 549,000 mobile internet subscriptions in 2014 [55], Mauritians are now up to date with everything happening worldwide. Over the years, the arrival of new Internet Service Providers(ISP) have made all these new facilities possible. Table 2 summarises the services provided by Mauritian ISPs.

TABLE 2 : MAURITIUS INTERNET SERVICE PROVIDERS [56]

ISP	Services provided
Orange – ADSL and Dial Up	ADSL broadband services from 256 kbps, 512 kbps, 1Mbps to 2Mbps
Orange - My.T	My.T now provides ultra fast internet connection with real video talking and TV channels via fiber optic cable.
Bharat Telecom	Bees provide 2Mbs broadband connectivity via fibre optic cables
DCL	Provides ADSL services and a new 4G solution (ALICE) offering 2Gb bandwidth has recently been introduced.
NOMAD	Provides unlimited internet connection through a Rabbit modem and uses the WIMAX technology.
MTML	Also provides internet access via dial up and broadband.

Mauritius has also witnessed a significant increase in mobile cellular subscriptions which has been estimated to 1,652,000 in 2014 [55]. The number of sms sent in 2014 was estimated to be 947 million while Mobile Internet subscriptions increased from 514,100 in 2013 to 549,100 in 2014 [55]. All these figures show that mobile devices are are now increasingly being used for communication and to access web-based contents. All these facilities could not have been possible without mobile service providers. There are three main mobile cellular service providers in Mauritius: Orange, Emtel Ltd and Mahanagar Telephone Mauritius Ltd(MTML). To support the voice and data services over the island, these 3 mobile operators provide the following technologies: GSM, GPRS, 3G/UMTS, 3.5G/HSDPA, 4G/LTE, WIMAX, CdmaOne and EvDo [56].

A typical framework for a landslide early warning system modeling for Mauritius is given in Figure 11.

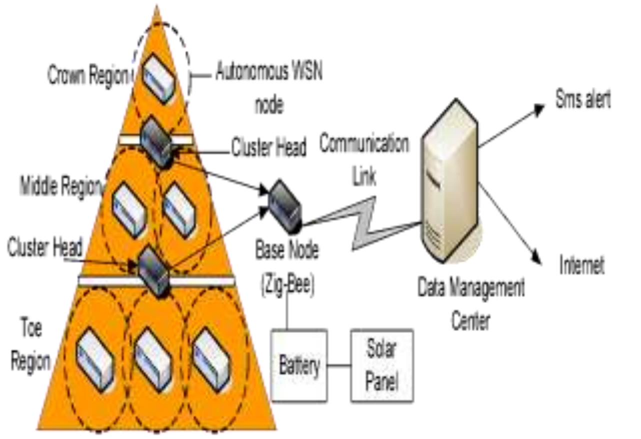

Figure11: Early Warning system for landslide in Mauritius.

The wireless sensors used are autonomous sensors capable performing the functions of accelerometers and extensometers. They are placed in three different regions starting from the toe to the crown region as in [32]. The sensors in each region report to the cluster head which will aggregate the measurements and forward them to the base node. The Base node uses a Zig-Bee coordinator receiver to establish communication with the wireless sensor nodes. Normally the wireless sensors are IEEE 802.15.4 compliant devices. The IEEE 802.15.4 standard specifies the physical and MAC layer properties for interconnecting devices. The ZigBee Alliance defines the communication layers above MAC for IEEE 802.15.4 compatible devices [57]. The Base node and the wireless sensor nodes can be powered by solar panels which are suitable for deployment in Mauritius. The Base node can use communication links based on 3G technologies or dedicated RF links to relay the measured data to a data center. At the data center, data analysis is performed and if a given threshold or condition is met to trigger an alarm, warning messages are immediately sent to concerned parties via the internet and SMS.

In the design of the WSN it is important to consider two main aspects which are the energy efficiency and routing. There are several factors associated with the MAC layer that reduces the energy efficiency and lifetime of the network. These factors include: idle listening, collisions, overhearing, protocol overhead, overmitting, packet size and traffic fluctuation [58]. Hence it is important that the MAC layer protocol minimizes energy wastes associated with these factors. Moreover, due to limitations in bandwidth, computing and battery power, routing protocols in a WSN should provide scalability, resilience and be both energy efficient and QoS aware [59]. Another important consideration for WSN is the setting up of reliable network topology that would support tolerance of gateway failure and load balancing among multiple gateways. This may be achieved using intermediate nodes using high-raised towers connected by long distance point-to-point wireless links [60].

5. Conclusion

The main objective of this paper is to propose a framework for landslide detection and warning system for Mauritius. Since the island of volcanic origin and is found in a tropical region, it is therefore affected by landslides. There have been recurrent landslides at Chitrakoot Village causing cracks in houses and more recently, the newly-built Ring Road near Pailles and the Terre Rouge-Verdun Link Road have also been severely damaged by landslides. These damages were not readily detected and road users who were passing by had reported cracks in the road infrastructure. All these damages are costing a lot of money to the Government and remedial actions undertaken are also taking time to complete, thereby affecting Mauritian citizens. Given the technological advances in mobile devices and the availability of internet and communication services in Mauritius, a landslide detection and warning system, using wireless sensors and mobile communication services, is therefore a feasible solution to monitor landslide in areas which are subject to this natural phenomena. Early detection will therefore provide a better handling of landslides and appropriate actions can be initiated earlier thereby causing less damage and prejudice to Mauritian citizens.

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