Wireless Sensor Networks for Early Warning of Landslides: Experiences from a Decade Long Deployment

Maneesha Vinodini Ramesh, Divya Pullarkatt, T.H. Geethu,
and P. Venkat Rangan

Abstract

Landslides are the third largest disasters worldwide. In order to save innocent lives and property damage, a system for understanding, assessment and early warning of the landslides is highly necessary. In this work, we have designed and developed an integrated wireless sensor network system for real-time monitoring and early warning of landslides. This paper will discuss the detailed requirements and design criteria considered in the design and development of the Intelligent Wireless Probe (IWP), to capture the relevant landslide triggering parameters. The network of IWPs is used to derive the local or regional contribution of geological, hydrological, and meteorological factors towards the initiation of a potentially imminent landslide. This heterogeneous sensor system provides the capability for gathering real-time context aware data to understand the dynamic variability in landslide risk. The data from these systems are continuously transmitted to our control center for real-time data analysis to derive the possibility of an imminent landslide. Based on the knowledge discovery from these analyses a three level warning system was developed to issue real-time landslide warnings. We have deployed the complete system in Western Ghats and North Eastern Himalayas in India. The system in Munnar has proven its validity by delivering real time warnings to the community in 2009, 2011, and 2013 and continues to monitor landslides even today for the tenth year in a row. The results from the experimentation shows this system has contributed in enhancing the reliability of landslide warning, reduced false alarm rate, and provides the capability to issue warnings in local, slope and regional levels. After the success of this work, Government of India has adopted the system nationally as a result of which we have carried out a second deployment in the North Eastern Himalayas.

Keywords

Rainfall induced landslides • Wireless sensor network • Early warning systems • Deployment • Real-time data analysis

Introduction

Worldwide, landslides are considered to be one of the major natural disasters causing devastation of large numbers of human beings and infrastructures every year. The lack of in-depth understanding of the complex interrelation between different triggering factors, soil properties, geological and hydrological characteristics contribute to the uncertainty in

M. Vinodini Ramesh (✉) · D. Pullarkatt · T.H. Geethu
P. Venkat Rangan
Amrita Vishwa Vidyapeetham (AMRITA University), Amrita Centre for Wireless Networks and Applications (AmritaWNA), Amrita School of Engineering, Kollam 690525India
e-mail: maneesha@amrita.edu

D. Pullarkatt
e-mail: divyap@am.amrita.edu

T.H. Geethu
e-mail: geethuth@am.amrita.edu

P. Venkat Rangan
e-mail: venkat@amrita.edu

M. Mikoš et al. (eds.), *Advancing Culture of Living with Landslides*,
DOI 10.1007/978-3-319-53487-9_4

landslide initiation. This unpredictability of when landslides are likely to occur exacerbates the death toll.

The frequency of landslide initiation is also unknown due to the lack of knowledge in the factors contributing to it and their inter-dependency. This clearly indicates the need for real-time monitoring systems to monitor the landslide triggering parameters for disseminating effective early warning of the imminent landslides.

Landslides generally impact in slope, catchment or regional scales. The research performed in Biavati et al. (2006), Marchi et al. (2002), and Hill (2002) describes the details of different sites instrumented using sensors such as rain gauges, ultrasonic sensors, seismic sensors, tensiometers, piezometers, extensometers, various meteorological sensors etc., to assess the landslide hazards based on several triggering parameters. Monitoring of these heterogeneous triggering factors for such large areas is very challenging. Though these above mentioned existing systems consists of heterogeneous sensors, they doesn't capture the integrated impact of spatial and depth-wise variability of these parameters which can help in monitoring deep seated landslides and provide timely warnings. Developing an effective early warning system will require low cost, low power sensors, effective networking systems, real-time signal processing, and extensive data analysis to learn the dynamic changes in the weather and underground environment. Wireless sensor network systems are one of the emerging technologies that could be used for solving the above mentioned research challenges. The implementations described in Kung et al. (2006), Garich (2007), and Terzis et al. (2006) have reiterated the capability of using wireless sensor network for applications that require continuous and real-time monitoring.

In India, the most prevalent type of landslide causing major devastation is rainfall-induced. For continuously monitoring one of the landslide prone areas, and for delivering early warning about the imminent landslides, we have designed and deployed a novel wireless sensor network system in Munnar, South India. To the best of our knowledge, this is one of the world's first comprehensive wireless sensor network system for real-time monitoring and early warning of landslides.

This paper describes the requirements of the system, sensor selection, spatial distribution of the sensors that can collect spatio-temporal data, geomorphic data, and variation in natural physical forces, and the wireless network system. The real time data received from the complete system from 2009 onwards is used for detailed analysis to understand the landslide phenomena and to develop an effective early warning system. The details of the results are described in the following sub sections.

Section "Design of Intelligent Wireless Probe (IWP)" elaborates the design of the Intelligent Wireless Probe (IWP). Section "Spatial Distribution of IWPs and Real-Time Monitoring Network" describes in detail the spatial distribution of the IWP's and the complete architecture of the remote monitoring system deployed in Kerala, India. Section "Field Deployment of Landslide System" illustrates the deployment experiences from two different sites in India and the validation of the complete system through the delivering of real-time warnings are briefed in Section "Delivering Real Time Warnings to the Community". Section "Data Analysis and Results" elaborates the data analysis and the results obtained. The conclusion of this research work is detailed in the Section "Conclusion and Future Work".

Design of Intelligent Wireless Probe (IWP)

Global attempts to anticipate landslides originally relied upon rainfall gauges. However, experience has taught us that this approach does not give accurate or reliable predictions. Rainfall thresholds have frequently resulted in a high degree of false positive or false landslide warnings. The actual number of landslide events in comparison with the rainfall intensity threshold using the existing methods such as Aleotti (2004), Caine (1980), Cancelli and Nova (1985), and Deganutti et al. (2000) between the years 2004–2009, has produced 30, 25, 36 and 42 false positives respectively. The discrepancy between landslide warnings and actual number of landslides can result in the inhabitants of the area becoming doubtful about the warning's veracity, and many might be less inclined to evacuate when the alarm is actually true.

To reduce the problem of a high frequency of false alarms, and to enhance the reliability of the detection system, other parameters that could trigger landslide had to be taken into consideration. As the rain falls, water infiltration will lead to increase in the water volume content of the soil. As the rain continues, volumetric moisture content of the soil gradually increases at varying rates depending upon the specific soil properties of the area being monitored and the rate of rainfall. For example, it will take less time for sandy soil to reach saturation than clay soil (Gardner 1988), and the lag time (the period of time it takes to make the soil saturated based on rainfall event) will be reduced further based upon prolonged rainfall conditions or torrential rainfall conditions. Thus, this sequence of events demonstrates that there is an interaction between the two parameters leading to a lag time for the soil to become saturated (100% volumetric water content). The two parameters differ at different layers of the soil, and also the conditions of the rainfall. To understand

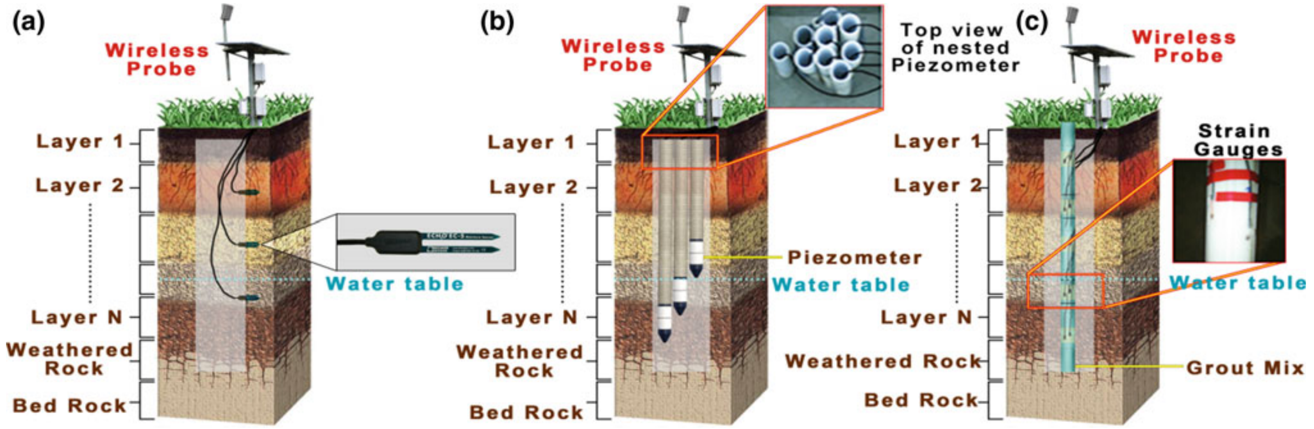

Fig. 1 **a** Nested moisture sensor. **b** Nested pore pressure transducer. **c** Nested strain gauge

this behavior occurring within the earth and to capture these important temporal changes, we require multiple dielectric moisture sensors strategically placed at different layers of the soil as shown in Fig. 1a.

When the soil reaches saturation level, only then the volumetric water content will be equal to the porosity of the soil layer. At that point in time the pore pressure value will be equal to the atmospheric pressure; the gauge pressure will be zero. As water continues to infiltrate the soil, the positive pore pressure begins to build raising the pressure levels. Even here the pore pressure value will vary at different soil layers due to the interaction between the different parameters such as rainfall, soil properties, infiltration rate, and so on. Therefore, we require multiple pore pressure sensors strategically placed at different layers of the soil as shown in Fig. 1b.

As the pore pressure increases, it stresses the soil leading to movement of vulnerable soil layers. To measure this movement, existing landslide monitoring systems have used inclinometers. These sensors capture the degree of tilt angle produced or generated by the soil movement. However, this is a very costly solution.

An alternate approach is to utilize cost-effective sensors that can be configured to capture movement. The soil layer movements will generate stress, strain or/and change in the slope angle. To capture these changes, strain gauges and tiltmeters are used. Strain gauge is the lower cost approach to consider, however because of its sensitivity it will capture "noises" along with it. Additionally, to use them efficiently it is highly necessary to know the expected direction of movement of landslide material. Based on this expected direction the strain gauges must be mounted on ABS inclinometer casings to capture the strain experienced on it due to soil layer movements. Since we expect to have movements at different depths of the soil layer, multiple strain gauges are mounted along one vertical casing at each level of the soil in a specific pattern to capture the direction and strain produced by the movement as shown in Fig. 1c.

Additionally, to increase the reliability of this movement-sensing system, tiltmeters have also been inserted in the ABS inclinometer casing at vulnerable layers to capture the soil layer movements in either of the two axes, or possible directions. This system will provide the tilt generated due to soil layer movement either in the layer in which it was placed, or in the layers below or above it.

Some landslide-prone areas fall into earthquake-prone zones as well. So to capture the seismic waves, low power geophone sensors are also installed one foot below the ground surface.

So we have multiples sensors to measure the following parameters: (1) rainfall; (2) soil moisture; (3) pore pressure; (4) movement; (5) vibration. Integrating the multiple sensors required (i.e., rain gauge, moisture sensor, pore pressure sensor, strain gauges, tilt meter, and geophone) in specific patterns at different soil layers is collectively referred to as the Deep Earth Probe (DEP).

A wireless sensor node is connected to the DEP to continuously collect data from this complex and comprehensive arrangement of heterogeneous sensors. However, this DEP requires a large amount of energy to power the sensors for long, continuous duration of data collection. Therefore, intelligent algorithms have been integrated into the system to adaptively manage the data collection, aggregation, and the determination of the likelihood of a landslide with respect to the dynamic variations in weather patterns. This entire set-up including the DEP and the intelligent algorithms is called the Intelligent Wireless Probe (IWP) as shown in Fig. 2.

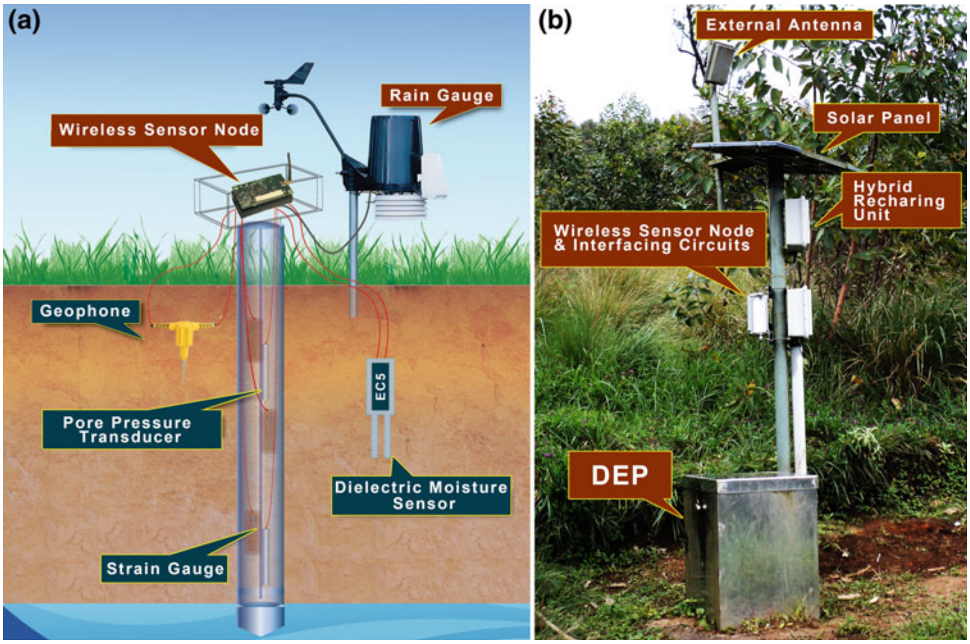

Fig. 2 **a** Intelligent wireless probe (IWP) (Ramesh 2014). **b** One of the intelligent wireless probe deployed in Munnar, Kerala, India

Spatial Distribution of IWPs and Real-Time Monitoring Network

The landslide occurrence due to slope instability usually covers very large areas of the hilly terrain. Hence, one IWP may not be adequate to cover the entire area. Additionally, the influence of landslide-triggering parameters varies at different regions of the mountain. The regions are categorized as crown, middle, and toe, descending from higher to lower.

The depths of the soil layers in different regions may vary, since the distance from the surface to the bedrock will vary with respect to the bedrock profile. Just as there are varying depths of soil layers, there are also varying levels of ground water tables at various locations across the entire slope of the hill or mountain. For example, in the crown area the water table is at a 15 m depth, whereas at the toe region it is only 2 m. These differences in the depth of soil layers, the differences in soil properties, and the differences in the ground water level will all contribute to the different responses that can be generated for the same landslide trigger.

To capture these varying responses throughout the mountain, we need to deploy spatially distributed IWPs. However, in each region we would expect to see some similarity in most of the responses. To understand the differences and commonalities in responses, it is highly required to network these IWPs to derive concrete relationships between the responses.

To continuously collect the spatio-temporal data, and to derive different conclusions specific to each region, specific to each DEP, and to derive local, regional, and global thresholds for different parameters, these IWPs have to be networked wirelessly. The design of the complete wireless network is described in detail in the research paper by Ramesh (2014) which provides the capability to capture the data from IWPs and transmit it to the university (approximately 300 km away) for further analysis to automatically disseminate warning messages.

Field Deployment of Landslide System

Extensive field investigations were performed to determine the most landslide prone area with highest risk on human life and selected The Anthonian Colony, Munnar, Kerala and Chandmari, Sikkim, India as the site for deploying our solution. In both the selected sites, extensive field investigations were conducted for identifying the possible locations for DEP deployment, for selecting the most suitable low cost, low power sensors, for choosing the right communication technology for medium and long range communication requirements, and to decide the location of management center. The borehole locations for the DEPs were chosen so as to measure the cumulative effect of geographically specific parameters that cause landslides.

Site 1: The Anthonian Colony, Munnar, Kerala

The hilly terrain of Anthoniar Colony is situated on a 7-acre land, roughly 700 m northwest of Munnar in the Idduki District of Kerala State, South India. Munnar lies in the windward slope of landslide prone Western Ghats Mountain and is characterized by rugged hills and deep valleys. The area in and around Munnar lies from 2000 to 2600 m above sea level. Geographically the area is located between north latitudes of 9° 53′ 00″ and 10° 05′ 00″ and east longitudes 76° 45′ 00″ and 76° 57′ 30″, covering an area of 420 km^2 in the Ernakulum and Idukki districts of Kerala. Munnar is characterized by two types of monsoon. The first and main monsoon of the area is Southwest Monsoon which starts at the end of May or early June and ends in September. The second one which is the north-eastern monsoon hits the area during the return of the southwest monsoon winds. These rains are in the months of October and November and sometimes last till December. The area receives maximum rainfall in July. The average annual rainfall in Munnar is between 2500 and 4500 cm and the average temperature varies between 10 and 25 °C (Ramesh and Vasudevan 2012).

Based on the detailed investigations we have deployed the pilot system in January to March, 2008 and the full scale system in January to June, 2009. Currently, the whole area consists of 20 DEPs integrated with approximately 150 geophysical sensors, connected to 20 wireless sensor nodes.

Deployment of Deep Earth Probe: One of the important activities required for deploying the landslide detection system is bore hole drilling. Bore hole location and its depth, determines the maximum amount of geological and hydrological properties that can be gathered from the field for the functioning of the landslide detection system. The decision of the bore hole depth was dependent on the location of the hole, vulnerability of the location, sensor deployment requirement, water table height, and location of weathered rock or bed rock.

Deep Earth Probe Design: The deep earth probe (DEP) design is influenced by the local geological and hydrological conditions, the terrain structure, and accessibility of that location (Ramesh and Rangan 2014). The DEPs were designed in a two-stage process. Initial DEP designs were made for the pilot deployment, which consists of two DEPs, with ten sensors, in the field along with six wireless sensor nodes. In the main deployment, the spatial granularity was increased to 20 DEPs and multiple DEPs were installed in six locations (labeled henceforth as either L1, L2, …, L6 as shown in Fig. 3a).

Site 2: Chandmari, Sikkim, India

The highly populated eastern Gangtok, Chandmari, lies at an elevation of 1650 m (27.3325°N 88.6140°E) in the lesser Himalayan region through which the Main Central Thrust passes. The area had about nine landslides between 1999 and 2015. The basement rock is of medium to high grade gneisses overlying staurolite and mica/garnet rich schist. Thirteen potential locations for deployment of DEP were identified here after detailed investigations. The pilot deployment, completed in 2015, included three pore pressure sensors, two inclinometers, three 3-axis geophones and one weather station to monitor the area.

Delivering Real Time Warnings to the Community

The complete system deployed in Munnar has been operational 24/7 since 2009. It has proven its efficacy by issuing real-time warnings in 2009, 2011, and 2013 respectively. Warnings are at three levels: (1) Early: when moisture sensor satiates above 65% (warning issued to research group), (2) Intermediate: increasing pore pressure value leading to soil saturation (warning issued to local community and government officials), (3) Imminent: changes in movement sensor values plus high pore pressure value, and factor of safety value lesser than 1 (alerts to local community and government officials).

For a more detailed description, in July 2009, high rain fall was experienced at our deployment site (Anthoniar Colony) and multiple landslides occurred throughout the state of Kerala. During the torrential rainfall our wireless sensor network system detected signals indicating landslide-vulnerability in that region. As described in Ramesh (2014), real-time data analysis revealed a saturated moisture content, high rate of change in pore pressure values, and soil movements in vulnerable locations in each of the geophysical sensors deployed at the crown, middle, and toe regions. Sensors indicated that the rainfall threshold (for intensity and duration) exceeded the limits defined by Caine (1980), secondary to antecedent rainfall conditions of continuous rainfall during the prior 2 months (June and July 2009) plus the intense rainfall experienced for a very short duration.

The rainfall data for July 2009 was at maximum value (200 mm) on July 16th, and remained almost the same (150 mm) for the next two days. This, along with the antecedent rainfall, caused the increase in pore pressure. During this period of July 18th–20th, factor of safety (FS) reading was seen as decreasing in all regions of the slope and moved to 0.806 at the toe, motivating us to issue a landslide warning based on the FS equation developed by Iverson (2000). The factor of safety clearly shows a decrease at the middle region of the slope, and later its stabilization due to eventual decreasing rainfall.

The above analysis demonstrates the vulnerability of Anthoniar Colony to landslides. In this context, we issued a preliminary warning through television channels, and the official Kerala State Government authorities were informed.

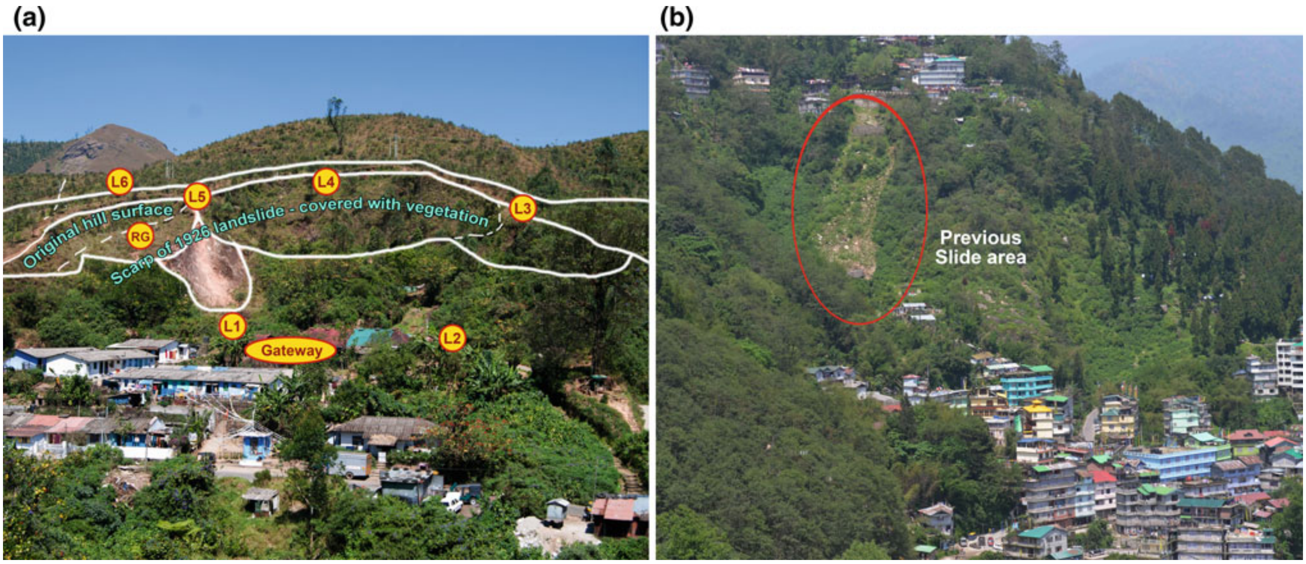

Fig. 3 **a** Deployment site—Anthoniar Colony, Munnar, Kerala, South India (Ramesh and Vasudevan 2012). **b** Front view of Chandmari, Sikkim

The government authorities took the warning seriously. Higher officials made visits to the landslide prone area and the people were asked to evacuate with the warning given below:

> We would like to inform you that in case the torrential rainfall prevails, it would be wiser to alert the people of this region and advise them to relocate to another area till the region comes back to normalcy in terms of pore pressure and underneath soil movements.

As the rainfall reduced, the real-time streaming software showed a reduction in the pore pressure and stabilization of the same. This situation helped us to validate the complete system. As a result of the successful warning issuance and system validation, the Indian government now wants to extend the network to all possible landslide areas.

Data Analysis and Results

Extensive data analysis performed on data received from the field from 2009 to 2016 demonstrated that this system is capable of providing insights into:

(a) **Spatio-Temporal Variability in Moisture Content for the Whole Slope**: The moisture sensor was deployed at multiple layers at each location in our monitoring area. Detailed analysis to learn the spatial and temporal variation of moisture content in the whole deployment was performed. Analysis revealed that increase in rainfall rate also increases moisture content. These variations in moisture content along with the soil properties of each layer can be utilized to determine the infiltration rate.

On analyzing Fig. 4, we can conclude that the moisture content is high in the toe region compared to other regions. The largest ground water table level is shown for toe-1 at 2.1 m, suggesting the possibility of the capillary rise phenomena making this region saturate faster. Additionally, the sensor is at 0.8 m below the top surface leading to quicker infiltration in the same region which might also be a factor in the toe having more moisture content.

Detailed analysis shows that the variability in moisture content (49–54%) in the toe region is less than that in the middle region (7–25%) for the summer and monsoon period. The lesser variability in the middle region may be due to (1) the absence of capillary rise since it is too far away from the ground water table level (12.8 m); and (2) the moisture sensor is deployed at 1.37 m below the top surface causing the infiltration rate to be fast in the initial periods of transition from summer to monsoon season.

(b) **Spatio-Temporal Variability in Pore Pressure for the Whole Slope**: The pore pressure in different soil layers will differ with respect to the rainfall rate, antecedent rainfall conditions, permeability of the layer, cohesion of that layer, etc. We also analyzed the variability in pore pressure behavior in the whole slope for the period of Oct to Nov 2011. The pore pressure sensors in the toe region at a depth of 5.5 m showed the maximum pressure value as shown in Fig. 5. The soil layer at about 4 m shows higher permeability (4.80E−06 cm/s) and the cohesion value is negligible. Whereas the cohesion value at 6 m is 0.21 kg/cm^2. This soil layer had the lowest bulk density (at 5 m bulk density is 18.7 kN/m^3, at 6 m the bulk density is 17.8 kN/m^3) compared to

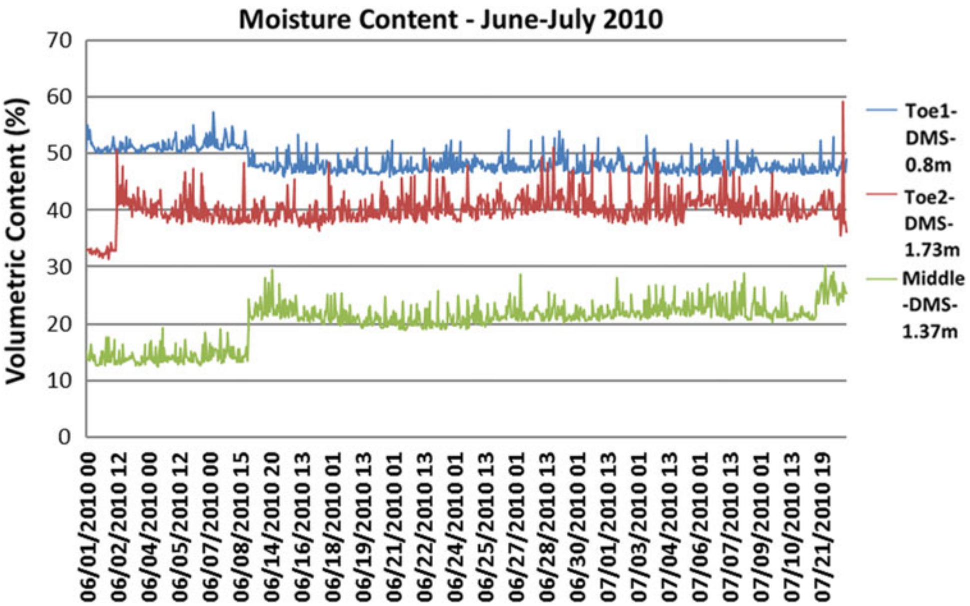

Fig. 4 Spatio-temporal variability in moisture content for the monsoon period of June–July 2010

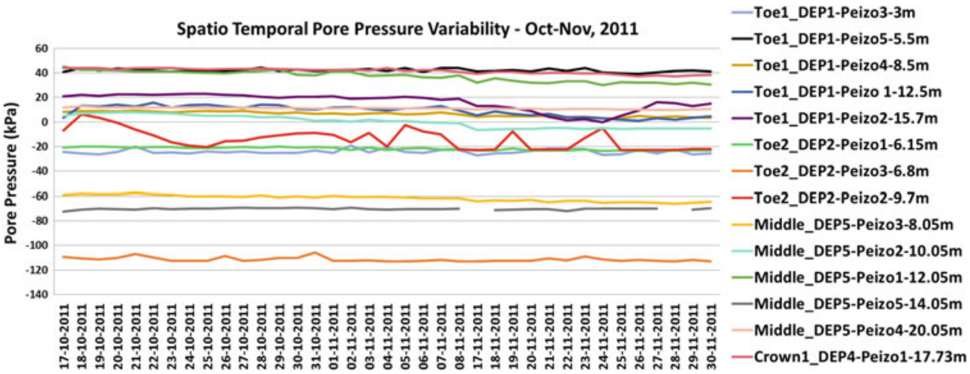

Fig. 5 Spatio-temporal variability of pore pressure values in Oct–Nov, 2011

other layers. The lowest values of pore pressure were shown by the sensor at a depth of 6.8 m in the second location of toe region. Even though the ground water table at this region is at 3.4 m, this particular layer of soil at 6.8 m shows negative pore pressure most of the time due to the presence of house debris from the houses damaged in the previous landslide event. Because of this particular composition, water is not stored in that layer due to large pore sizes. Further, the spatially separated sensors deployed at the same depth show different ranges of pore pressure values and the pore pressure variability at different depths and spatial locations follow similar trends after continuous rainfall conditions.

The spatio-temporal variability of pore pressure data for all locations has been investigated. The variability in the crown region is lowest compared to both the toe and middle region. Also the variability in the same region at different depths did not follow the rule of decrease in variability of pore pressure with respect to depth of sensor deployment.

(c) **Spatio-Temporal Variability in Factor of Safety for the Whole Slope**: The real-time data received from the system has shown that slope instability in spatially distributed areas are different, as shown in Figs. 6 and 7. This will make it challenging to understand the vulnerability due to imminent landslides.

In the same time instant, sensors deployed at different spatial locations at the same depth, showed different levels of contribution for slope instability. The factor of safety value at different locations and different depths vary based on the pore pressure response. This clearly shows that we need to develop dynamic thresholds for each of the sensor based on its terrain parameters, location, soil properties, depth of deployment, rainfall conditions, antecedent conditions etc.

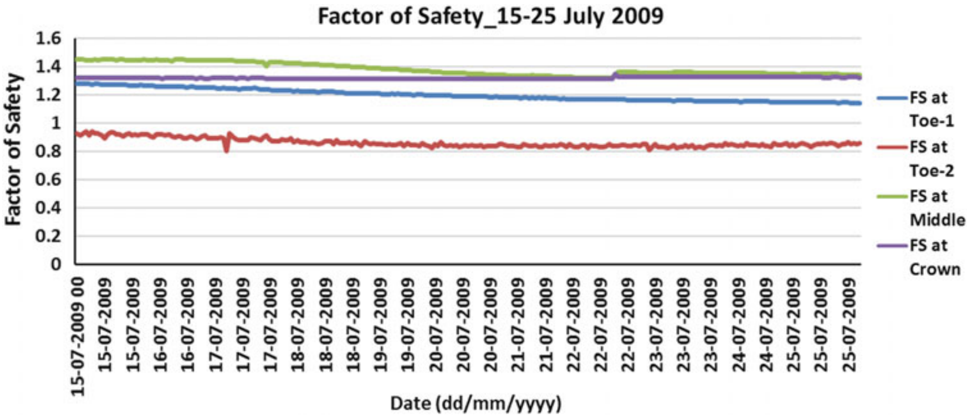

Fig. 6 Spatio-temporal variability of FoS at toe, middle and crown regions for the year 2009

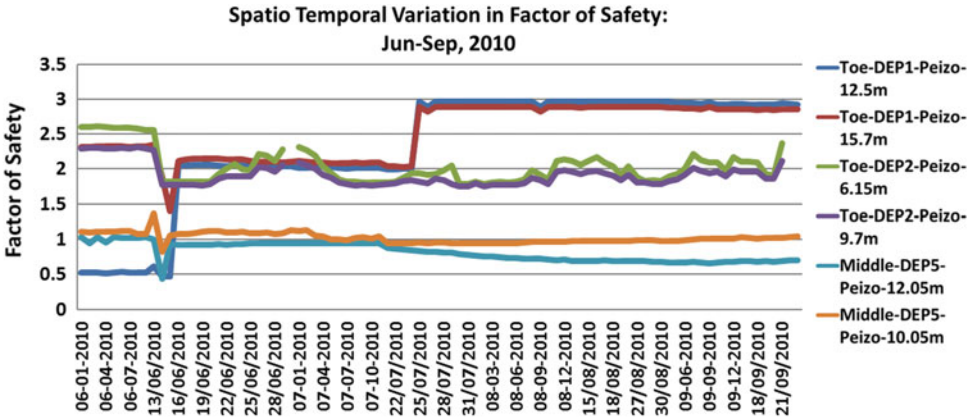

Fig. 7 Spatio-temporal variability of FoS at different depths at toe and middle regions for the year 2010

Hence it is necessary to develop a comprehensive decision support system that could provide an estimated factor of safety value for the whole slope or mountain by considering the dynamic variation in different locations and different depths. This clearly states the necessity of an automatic learning system to derive the dynamic response expected in the mountain based on the frequent changes in the environment.

(d) **Enhancing reliability of landslide warning system**: In 2013, Munnar experienced torrential rainfall in the last week of July and first week of August. Our system was 24/7 operational, and it conveyed information to activate a first level warning to us, based upon rainfall intensity-duration on a daily basis, and for 3-day, 7-day and 15-day periods, as the rain exceeded the rainfall intensity-duration thresholds during that time as shown in Fig. 8.

Second and third level thresholds, based on the remaining sensors, had not been exceeded; therefore a real-time warning to the inhabitants near our deployment site was not issued. However, local authorities were informed that real-time data showed the possibility of a landslide within a few square kilometers from our deployment site. As forecasted, a landslide did happen in a nearby area, validating our system's capability of providing multilevel warnings.

If we had only a rain gauge based warning system, we would have disseminated a false positive warning message leading to evacuation of the population in and around our deployment site. This clearly proves that the presence of heterogeneous sensors in a high landslide-prone area can contribute to effective landslide warnings with reduced number of false alarms in a regional and slope level. Further, automatic learning and real time analysis of the data from this system could provide early warnings in multiple levels. Research in this direction has already been initiated.

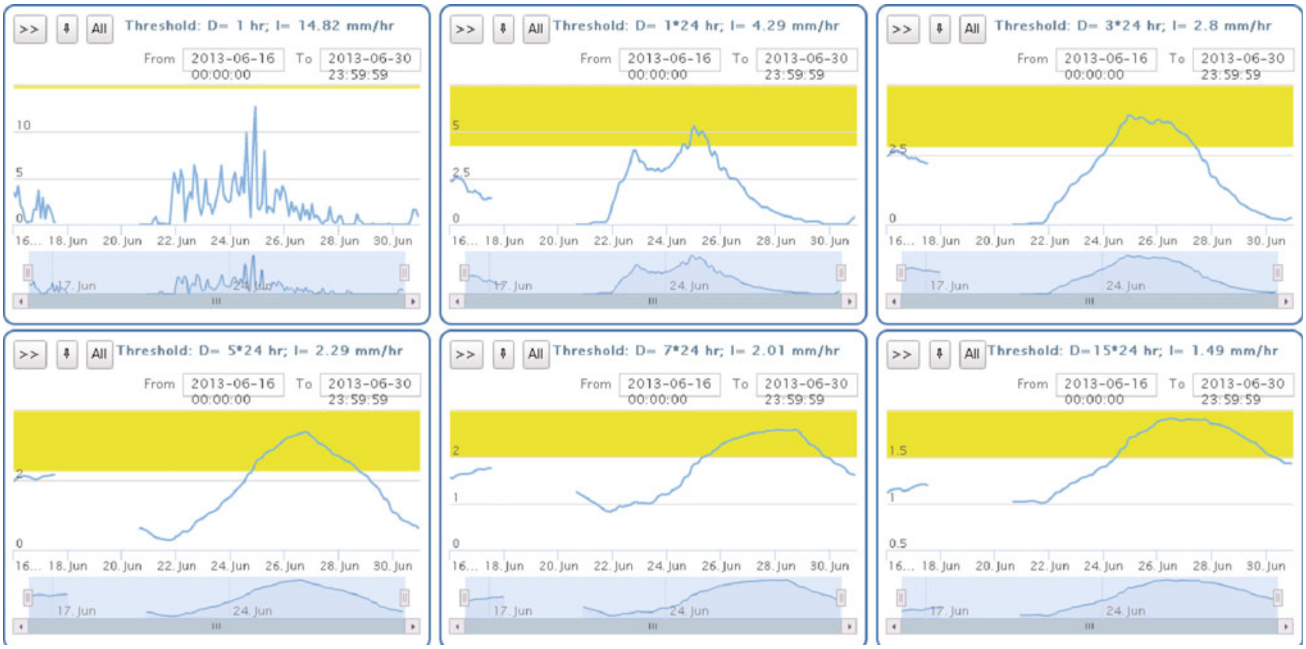

Fig. 8 First level rainfall threshold based warning in 2013

Conclusion and Future Work

Wireless sensor network system for real-time monitoring and early warning of landslides are designed and deployed at one of the landslide prone areas in Western Ghats and another area in Himalayas. This work details the design considerations and the spatio-temporal variations of each parameter and its impact on slope instability. More than 150 geophysical sensors are continuously collecting data to issue real-time warnings and save lives. After the success of this work, Government of India has adopted the system nationally, as a result of which we have carried out a second deployment in the North. This elaborate study has provided the insights and relations between dynamically changing inherent parameter on the imminent slope instability scenario. In future, the real-time data from this system has to be used for providing an optimized set of sensors and their arrangements to issue real-time warnings based on the inputs from the decision support system.

Acknowledgements We would like to express our immense gratitude to our beloved Chancellor Dr. Mata Amritanandamayi Devi (AMMA) for being the guiding light and inspiration for carrying out this work. We are extremely grateful to our colleagues Dr. L.M. Frey, Prof. Balaji H, Ms. Hemalatha T. for their immense support towards the completion of this paper. This work is part of the project titled as 'Advancing Integrated Wireless Sensor Networks for Real-time Monitoring and Detection of Disasters' which is partially funded by the Ministry of Earth Sciences (MoES), Government of India.

References

Aleotti P (2004) A warning system for rainfall-induced shallow failures. Eng Geol 73(3):247–265

Biavati G, Godt JW, McKenna JP (2006) Drainage effects on the transient, near-surface hydrologic response of a steep hillslope to rainfall: implications for slope stability, Edmonds, Washington, USA. Nat Hazards Earth Syst Sci 6(3):343–355

Caine N (1980) The rainfall intensity-duration control of shallow landslides and for debris flows. Geografiska Annaler Ser A Phys Geogr 23–27

Cancelli A, Nova R (1985, August) Landslides in soil debris cover triggered by rainstorms in Valtellina (Central Alps-Italy). In: Proceedings of the 4th international conference and field workshop on landslides, The Japan Geological Society, Tokyo, pp 267–272

Deganutti AM, Marchi L, Arattano M (2000, August) Rainfall and debris-flow occurrence in the Moscardo basin (Italian Alps). In: Proceedings, second international conference on debris-flow hazard mitigation: mechanics, prediction, and assessment. AA Balkema, Rotterdam, pp 67–72

Gardner WH (1988) Water movements in soils. Washington State University

Garich EA (2007) Wireless, automated monitoring for potential landslide hazards. Doctoral dissertation, Texas A & M University

Hill CD (2002) Modern deformation monitoring: a multi sensor approach. Retrieved from http:// http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.127.9526

Iverson RM (2000) Landslide triggering by rain infiltration. Water Resour Res 36(7):1897–1910

Kung HY, Hua JS, Chen CT (2006) Drought forecast model and framework using wireless sensor networks. J Inf Sci Eng 22 (4):751–769

Marchi L, Arattano M, Deganutti AM (2002) Ten years of debris-flow monitoring in the Moscardo Torrent (Italian Alps). Geomorphology 46(1):1–17

Ramesh MV (2014) Design, development, and deployment of a wireless sensor network for detection of landslides. Ad Hoc Netw 13:2–18

Ramesh MV, Rangan VP (2014) Data reduction and energy sustenance in multisensor networks for landslide monitoring. IEEE Sens J 14 (5):1555–1563

Ramesh MV, Vasudevan N (2012) The deployment of deep-earth sensor probes for landslide detection. Landslides 9(4):457–474

Terzis A, Anandarajah A, Moore K, Wang I (2006) Slip surface localization in wireless sensor networks for landslide prediction. In: Proceedings of the 5th international conference on Information processing in sensor networks. ACM, pp 109–116