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Case Study

Landslide monitoring and prediction system using geosensors and wireless sensor network

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Abstract
Landslides in hilly regions are a frequently occurring natural phenomenon which takes a heavy toll of human lives and causes damage to different properties. Hence, prediction of landslide is essential for averting its deleterious effects by providing early warning to neighboring residents about the impending hazard of landslide. A landslide monitoring system has been designed using geosensors and high-range wireless network for on-line monitoring and prediction of landslides with the application of multivariate statistical analysis of prevailing site parameters. The system consists of various geosensors, wireless sensor network, server, and landslide monitoring and forecasting software. Crackmeter, in-place inclinometer, raingauge, tiltmeter, piezometer and other sensors are set up in the selected hill slope prone to landslide for continuous monitoring of influencing parameters. The system measures real-time landslide parameters using the said geosensors connected with wireless nodes and establishing a dynamic wireless network to overcome redundancy issue using wireless nodes of around 1200 m communication range using a high performance low power microcontroller, integrated solar panel and additional external omni-directional antenna for monitoring landslide in a large and hazardous hilly region from a distant safer location. The application software consists of different modules, namely data monitoring, analysis, storing, viewing, prediction, and generation of audio-visual, SMS and email alerts for 3 levels of landslides situations. The paper enumerates the system architecture and the application software details.

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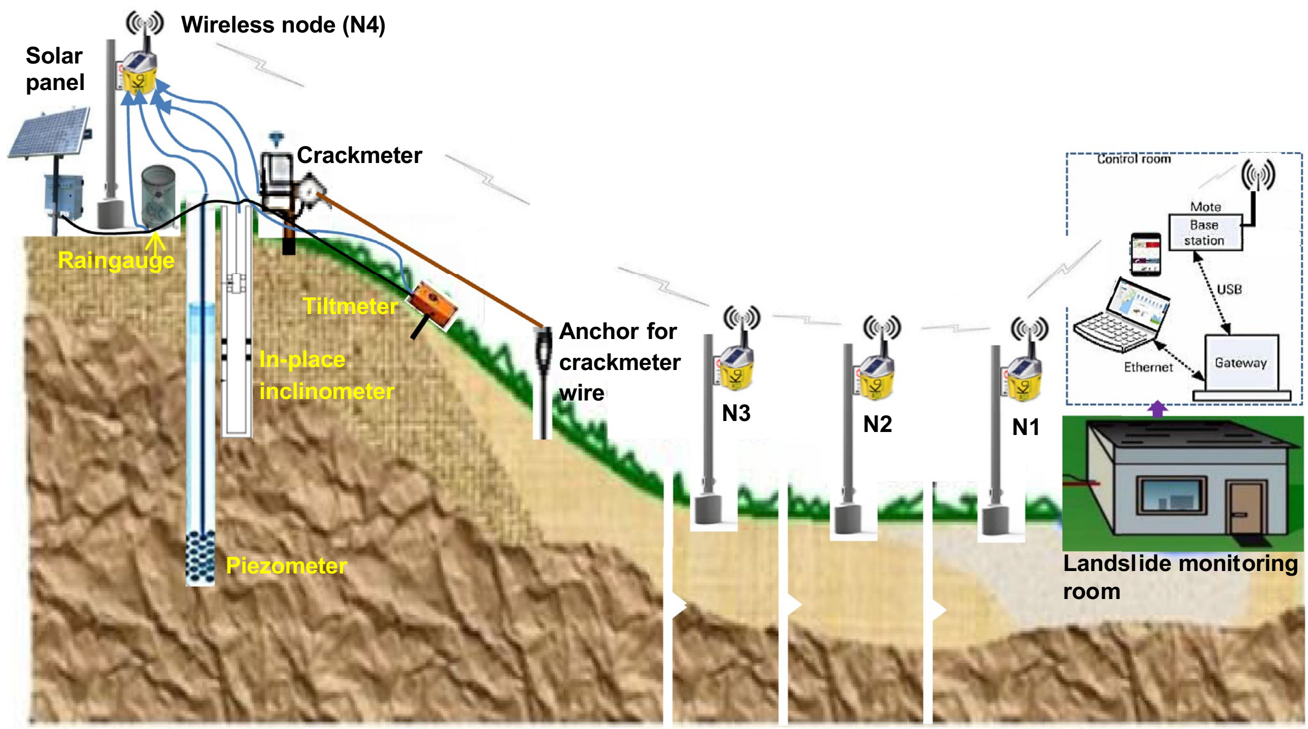
Graphical Abstract



Keywords Landslide monitoring and prediction · Geosensors · Wireless sensor network · Forecasting software

1 Introduction

Landslide in hilly regions is a frequently occurring natural phenomenon which takes heavy toll of human lives and causes damage to different properties. Hence, prediction of landslide is essential for averting its deleterious effects by providing early warning to the surrounding residents about the impending landslide danger. Parameters affecting landslide varies from place to place, which mainly depends of geology, physiography, rainfall and hill slope structure [1–3]. It is essential to measure landslide affecting parameters and predict landslide accurately before occurrence. This would help in providing warning to the surrounding people and local administration for taking appropriate measures to minimize losses.

Various technologies have been innovated for landslide monitoring and detection, namely remote sensing technique [4, 5], geographical positioning system [6, 7], geographical information system [8–10], optical fiber sensors [11], radar technology [12], wireless sensor networks [13–16], laser technology [12], displacement monitoring [17], acoustic techniques [18] etc. Each technology has its advantages, and there are limitations of the said technologies [19]. Hence, an online landslide monitoring system has been developed using geosensors and wireless sensor network, and prediction of landslides with the application of multivariate statistical analysis of prevailing site parameters to provide warning to the nearby residents so that evacuation can be done before the occurrence of landslide.

The present study has made significant contributions in the following ways:

- A system for monitoring and predicting landslides has been developed by utilizing geosensors and a wireless sensor network.
- Software for landslide prediction has been developed, which incorporates multivariate statistical analysis of various parameters and analytical hierarchy process methods for monitoring, prediction, and warning of landslides.

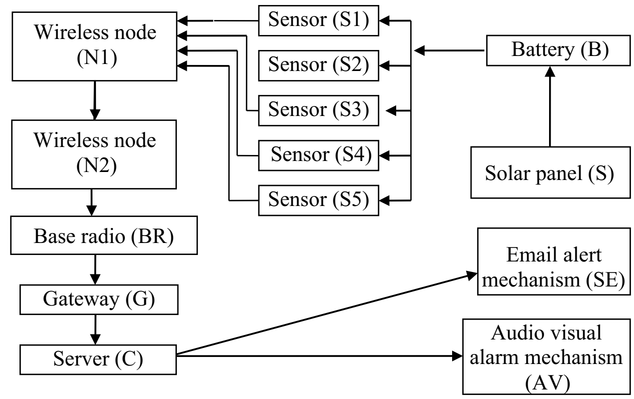


Fig. 1 Block diagram of landslide monitoring and prediction system

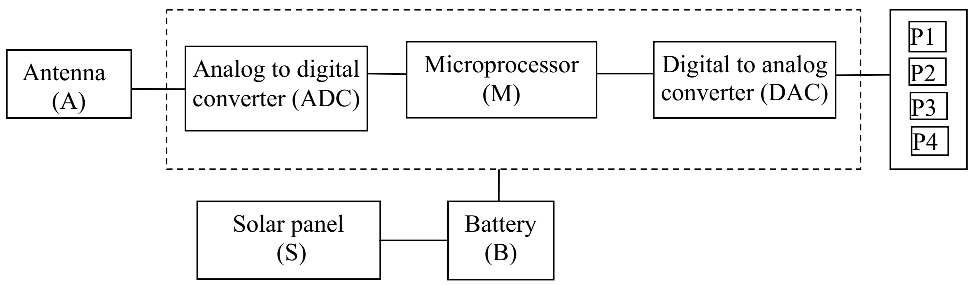


Fig. 2 Block diagram of wireless device node

- Laboratory experiments were carried out under simulated conditions to calibrate the geosensors for landslide monitoring.
- Field studies and geotechnical investigations were conducted to comprehend the factors influencing landslides in the Karshingsa hilly area near Itanagar, Arunachal Pradesh, India, prior to the installation of the developed system at the site.
- The system was successfully installed, and field trials were conducted for a duration of 8 months in the landslide-prone area of Karshingsa, Arunachal Pradesh, India, where frequent landslides have been occurring over the past three decades.

2 Landslide monitoring system

Landslide monitoring system comprises in combination of hardware and software comprises of geotechnical sensors, long range wireless nodes, interface board to connect sensors with long range wireless nodes, and application software for landslide monitoring, prediction and alert mechanism to provide audio-visual alerts of impending landslide to the surrounding people and concerned administration [20, 21]. The system constantly monitors prevailing landslide parameters using sensors connected with wireless nodes and establishing a dynamic wireless network to overcome redundancy problem using long range wireless nodes of around 1200 m range using a 8051 microcontroller, integrated solar panel and additional external omni-directional antenna for monitoring landslide in a large and hazardous hilly area where electricity is not available from a safer location away the landslide zone. The system monitors landslide parameters for hard rock strata as well as for soft strata where sudden flow slide occurs during rainy season and no sound is generated before failure. Further, the system is capable of giving three levels of warning to the local administrations and surrounding residents for evacuating the landslide area in the form audio-visual alarm, SMS and email alerts.

Figure 1 denotes block diagram of the landslide monitoring system. It consists of different geotechnical sensors (S1–S5) integrated with wireless nodes (N1 and N2), gateway and base radio (G) and server (C). The system consists of hardware and software.

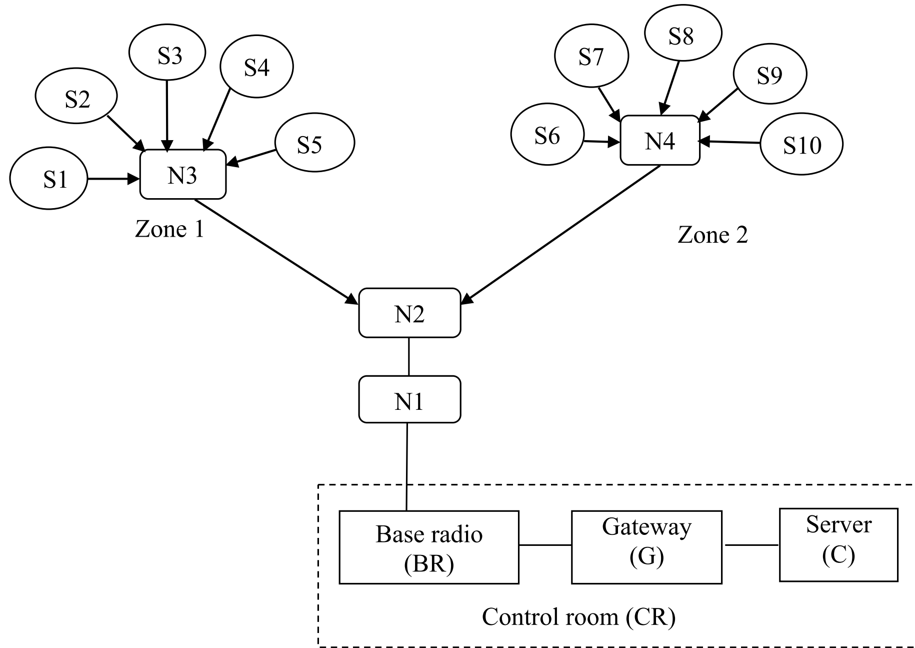


Fig. 3 System architecture diagram

Figure 2 illustrates the block diagram of wireless device consisting of microprocessor (M), antenna (A), solar panel (SP), connecting ports (P1–P4), analog to digital converter (ADC), digital to analog converter (DAC), and power supply unit (B) to supply power to the wireless device.

Figure 3 shows the system architecture diagram where sensors (S1–S5) are joined with wireless device (N3), and sensors (S6–S10) are coupled to a different wireless device (N4), and these are installed in 2 zones (Z1 and Z2), and subsequently these are sending data to the single server (C) via in-between wireless devices (N2 and N1), gateway and base radio (G).

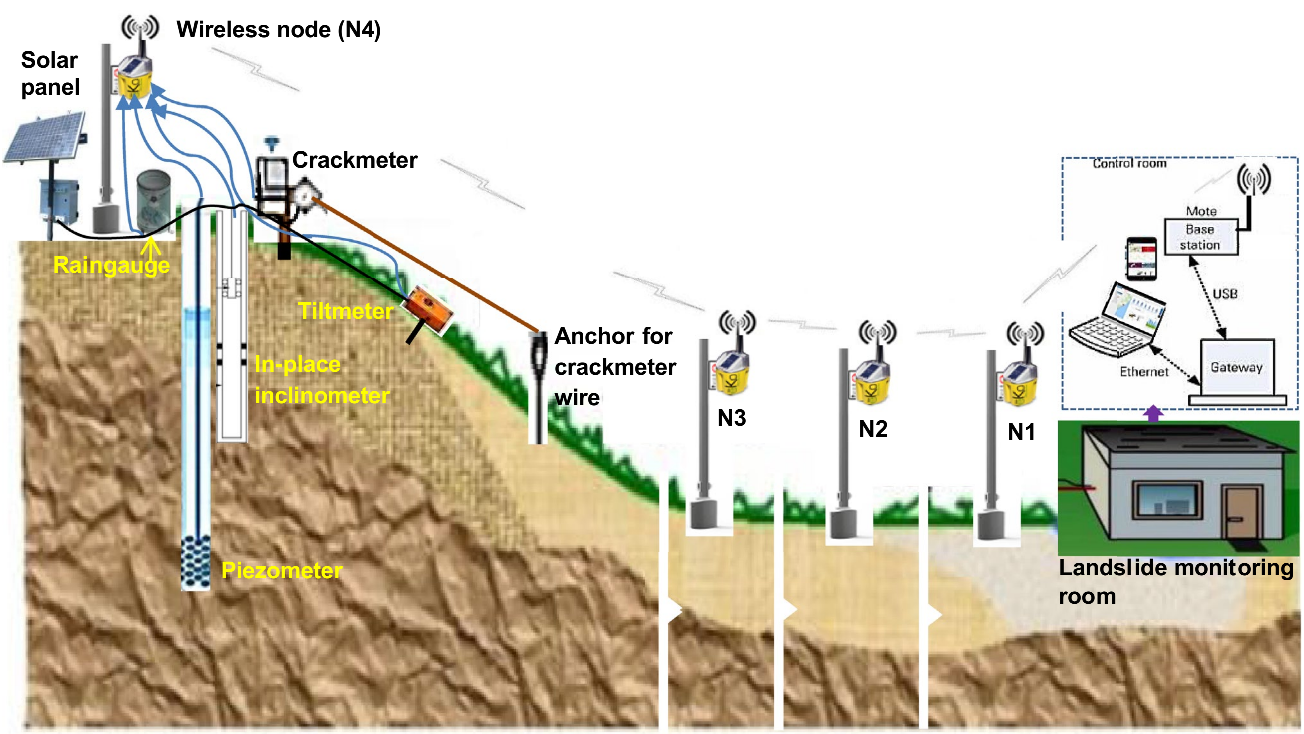


Fig. 4 Schematic diagram of system deployment at site

Table 1 Specification of geosensors used for landslide monitoring and prediction

Geosensor name	Measure parameter	Measuring range	Operating principle	Input voltage (V DC)	Output current (mA)
Tiltmeter	Vertical movement of soil mass	± 5°	micro-electro-mechanical-system (MEMS)	18–24	4–20
Crackmeter	Acceleration of soil	0–1000 mm	Vibrating wire	12–24	4–20
In-place inclinometer	Horizontal movement of soil mass	± 10°	MEMS	18–24	4–20
Raingauge	Rainfall intensity	0–999 mm	Tripping bucket mechanism	12–24	4–20
Piezometer	Underground water pressure	0–10 kg cm^{-2}	Foil strain gauge based mechanism	12–30	4–20

Fig. 5 View of test bed and geosensors utilized in the laboratory experiment for monitoring landslides: **a** test bed, **b** sensor connections in the test bed, **c** tiltmeter, **d** crackmeter, **e** in-place inclinometer, **f** raingauge, and **g** piezometer

Figure 4 illustrates the deployment architecture at site in which sensors (S1–S5) are installed in hill slope (H) and coupled with wireless device (N4) which subsequently send data through wireless devices (N3, N2 and N1), gateway and base radio (G) to computer (C) at control room (CR).

All geotechnical sensors (S1–S5) are calibrated under simulated experimental setup in the laboratory [22]. Specifications of the geosensors are given in Table 1. Figure 5 illustrates the laboratory experimental test bed and the five different types of geosensors used in the monitoring of landslides. Once the geosensors have been calibrated in the laboratory test bed, they are subsequently deployed in the real hilly regions susceptible to landslides.

The rain gauge sensor (S1) are anchored on the safe surface, wireline extensometer (S2) is anchored on a safe surface away from hill slope and its displacement measuring wire end is anchored in the hill slope and intermediate wire is supported by anchored and pulley arrangement for free movement of wire in case of slope deformation. The in-place inclinometer (S3) extension rods with coupling arrangement are inserted in a fiber pipe and placed in a bore bole and the bore hole is filled with soil, and its sensor part is fitted in the top portion of extension rod. The tiltmeter (S4) is grouted on hill slope with anchoring arrangement. The piezometer (S5) is inserted in a perforated fiber pipe and placed at the bottom of a bore hole, and the hole is filled with sand and soil. Sensors (S1–S5) are coupled with a solar panel (SP) and battery (B) having input voltage to sensors as 12–24 V DC based on the sensors' requirement. The sensors' outputs are joined with an interface circuit which is coupled with the wireless node (N4) through EPROM connector and wireless node's port (P1–P4).

Wireless node (N4) and all other intermediate wireless nodes (N1–N3) are mounted on different fixed poles at the calculated distance for forming self-healing wireless mesh network. Base radio (BR), gateway (G) and server (C) are set up in a remote control room (CR) located in a safer place. Wireless node (N4) transmits sensors data to server (C) via transitional wireless devices (N3, N2, and N1), base radio (BR) and gateway (G). All sensors (S1–S5) are set to initial zero reading. Subsequently, the sensors data are continuously monitored and data are saved in server (C) based on calibration chart. The application software monitors, analyzes, stores and views data received from wireless nodes coupled with sensors, and provides warnings (audio-visual alarm, SMS and e-mail messages) to the local administration and surrounding residents for vacating the area of imminent landslide.

3 Wireless networking technology

As mentioned earlier, the system consists of solar panel, batteries, tiltmeter, crackmeter, in-place inclinometer, raingauge, and piezometer, wireless nodes, base radio, gateway and server, audio-visual alarm mechanism, and email alert mechanism. Wireless sensor network consists of three devices connected with each other. First is the network coordinator which maintains overall network system. Second is fully functional devices (FFD), it collects the sensor's data and sends it to the network. Third is the reduced functional devices (RFD), it only acts as the transceiver in the network (Fig. 6). The power supply unit of wireless nodes and sensors are recharged with the help of solar panels. Geosensors (S1–S5) are physically connected with wireless node (N4) through an interface board. Wireless node (N4) sends data to intermediate wireless nodes (N3, N2 and N1) sequentially. Subsequently, wireless node (N1) transmits data wirelessly to the base radio (BR) as shown in (Fig. 6). Base radio (BR) is physically connected through gateway (G) to server (C). Server (C) is connected to audio-visual alarm mechanism in the control room. The application software installed in the server sends short message service (SMS) and email alerts to the pre-assigned district administrations and local residents.

3.1 Wireless node

The wireless node is utilized for both receiving and transmitting sensor data. It collects data from sensors and sends it to the base station via a wireless network that comprises multiple wireless nodes. The communication technology employed by the wireless node is ZigBee. Each wireless node is equipped with an omni-directional antenna, analog to digital converter, microprocessor, digital to analog converter, connecting ports, solar panel, and power supply unit for operational power, as illustrated in Fig. 2. ZigBee operates on the 2.4 GHz frequency band and utilizes offset quadrature phase-shift keying (OQPSK) modulation with a maximum phase transition of 90 degrees. The specifications of the wireless node include: (a) Frequency band of 2.4–2.4835 GHz industrial, scientific and medical (ISM) band; (b) High-performance low-power 8051 microcontroller core; (c) Omni-directional external antenna with a communication range of 1200 m; (d) Solar panel with a charging voltage of 3 V, rechargeable battery of 3 V, 2100 mAH; (e) Operating temperature range from − 40 to 60 °C; (f) Average current of 0.4 mA, receiver sensitivity of − 101 dBm; and (g) 4 connecting ports, each capable of connecting two sensors, allowing for a total of 8 sensors to be connected to each wireless node.

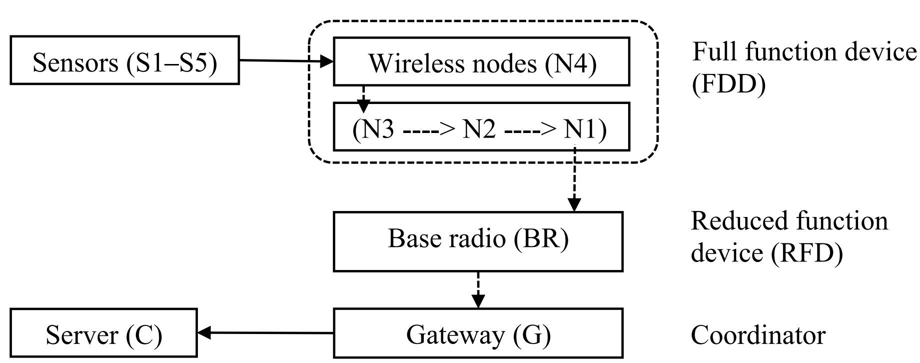
3.2 Base radio

The base radio is employed for gathering sensor data from wireless nodes. It consists of a radio board, antenna, and a universal serial bus (USB) interface board that comes preloaded with a low-power networking protocol for communicating with the deployed wireless nodes. The USB interface facilitates data transfer between the base radio and the application operating within the gateway.

3.3 Gateway

The gateway serves as a connection point between the server and base radio. It comes equipped with pre-installed network management and data visualization software. Upon powering on, these software packages initiate automatically. The gateway collects data from the base radio and sends it to the server application software.

Fig. 6 Wireless network architecture diagram



3.4 Server

A server is necessary for remote operation and monitoring functions using the application software. The server utilizes dot (.) Net software as its frontend, and structured query language (SQL) server 2005 as its backend for the collection and storage of state data. It is utilized for real-time monitoring, analysis, and prediction of landslide parameters, as well as generating audio-visual alarms, SMS, and email alerts using the specialized software developed. The minimum system requirements for this server comprise a 120 GB hard disk, 2 GB random access memory (RAM), and the application software (.)Net and SQL Server 2005.

4 Landslide monitoring and prediction software

Figures 7 and 8 depict flow chart of the application software. The developed application software conjugated with the mechanism for monitoring, prediction and information dissemination for early warning of landslides [23]. This application packaged has been focused on a multidimensional and integrated mechanism which can cater to all aspects of disaster monitoring. A novel methodology for detection, prediction and information dissemination for landslides has been developed using multivariate statistical analysis of prevailing site parameters [9, 13]. The entire application software module has been divided into three sub-modules. The first sub-module, data aggregation module calibrates the raw data with the given error constants of each sensor before sending the same to the Database Server (Data Repository). The second sub-module, data analysis module analyses the stored data and formulate a learning rule to predict the future event or the changing geotechnical condition. The final sub-module, information dissemination raises the alarms according to the value of the geosensors. The software module also nurtures the real time view of the connected geosensors readings by means of tables and graphs. The software continuously reads the data from the geosensors and predicts imminent landslide, and shows the real time data on the display board/monitor. When sensor value reaches or surpasses the threshold limit, the alarm is produced showing the pretentious area and severity of landslide in that zone with diverse colours. Consequently, with no time the information is disseminated to the target local people and concerned authorities via SMS and email.

5 Field trial site description

5.1 Location

The field installation site for landslide monitoring system is located at Karshingsa hilly region in Naharlagun Area of Papumpare district, Arunachal Pradesh, India. The NH-52A highway is the only suitable road communication to the capital complex comprising Naharlagun. This road also connects Itanagar with plains of Assam following a parallel alignment carving by a wide river valley of Dikrong River and its tributaries. When Dikrong River extends it intersects with the road alignment of (NH-52A) at Karshingsa hilly region and poses problems. Rain fed landslide, is the normal occurrence every year due to the toe erosion of hill slope by Dikrong River water (Fig. 9).

5.2 Physiography

Migration of Dikrong River towards Karshingsa hillside is occurring due to dual action of landslide and bank erosion towards hillside. The reason for occurrence of such continuous landslide was continuous rainfall. The grade of landslide was very high in the year 1988. The crest of the hillock (sliding down towards Dikrong River) flows like fluid, which deposits over the NH-52A.

Landslide occurred in the hard soil layer during March and September 2004 caused heavy destruction. The hilly region comprises of hard soil and soft soil layer at the base, and above this layer Pseudo-Conglomerate layer which causes landslide.

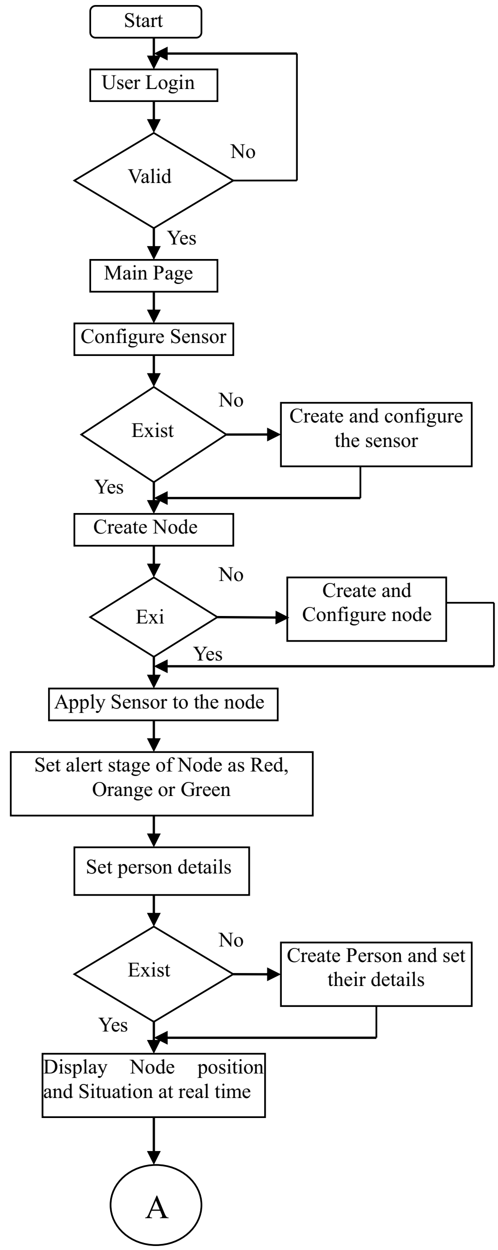


Fig. 7 Flow chart of configuration process

5.3 Geology

The study site is located beside NH-52A which is connecting Banderdewa and Itanagar, and passing through Karshingsa hilly area. The area is comprises of Upper Siwalik Formation (Fig. 10). The strata consists of Conglomerates (Pseudo-Conglomerate or Colluvium), soft and massive strata (soft rock-hard soil), and silty clay beds. The beds slightly dip towards NE and strike direction is NW–SE. There are 3 sets of joints present in bed rock. The only triggering factor causing major number of landslides is the long duration heavy rainfall that implies to flow slides only. Heavy rainfall precipitation that saturated the layer at a continuous stress developed the condition of occurrence of static liquefaction in the subsoil mass which is bedded over a more impervious layer as like the geological situation of Karshingsa area. The reason for occurrence of such phenomenon is certainly related to the long duration heavy rainfall for many days. Such phenomenon can only happen in the subsoil after attainment of saturation up to the boundary of the underlying impervious subsoil layer.

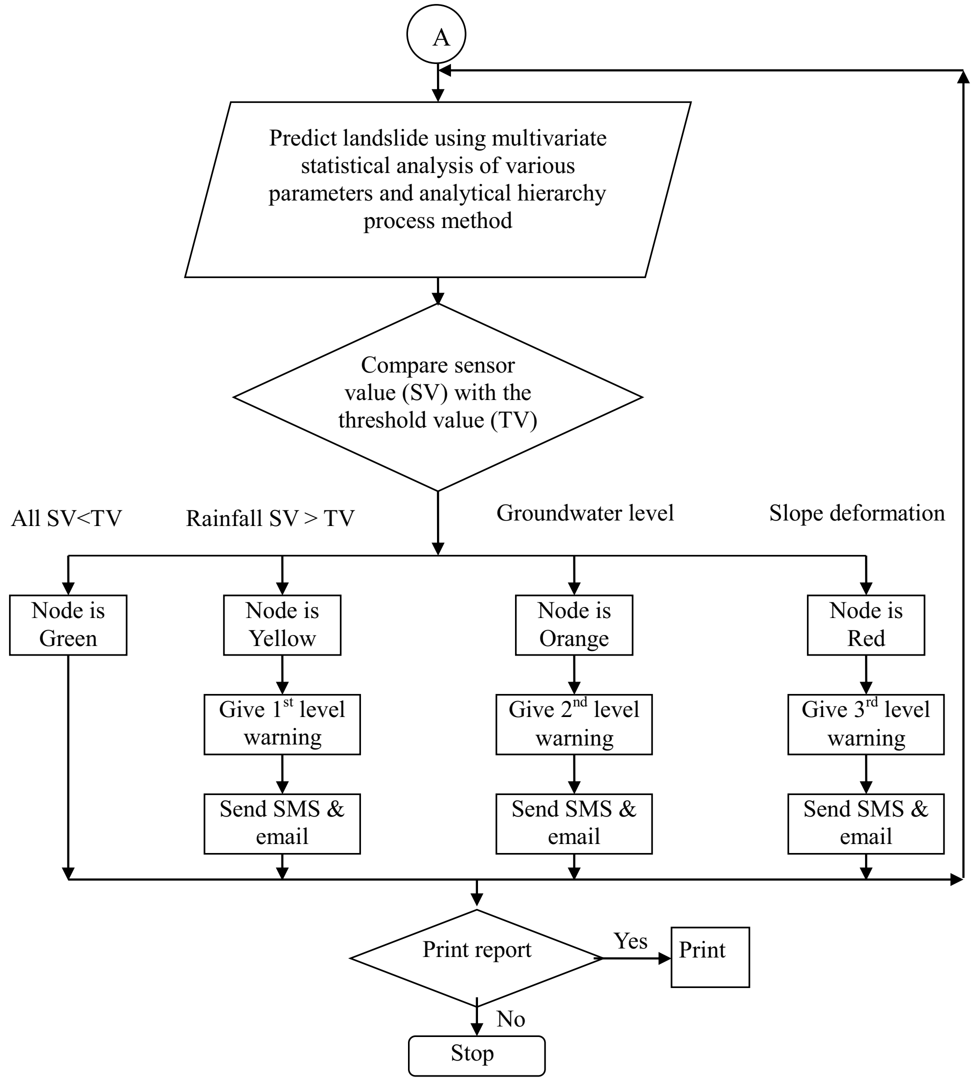


Fig. 8 Flow chart of landslide prediction procedure

5.4 Rainfall

Average annual rainfall in the study area is around 3285 mm. It varied from 2275 to 4226 mm. Maximum rainfall was occurred in 2004 which caused huge landslide in the area. Rainfall generally starts from March and continues till October. Approximately 71–85% of total annual rainfall occurs during 5 months (May to September) only. During this period major landslide occurs in the area.

6 Geotechnical study of the field trial site

Field studies were conducted to understand the factors affecting landslide in Karshingsa hilly area near Itanagar, Arunachal Pradesh, India. Various experiments were conducted in the field to analyze physiography, hydrology, geology, rainfall intensity and physico-mechanical properties of sub-surface strata. Nine bore holes were drilled in the site and core samples were analyzed for determination of physico-mechanical properties and strata profile. Standard penetration tests were also conducted in each bore hole to evaluate the strength properties. Ground water level was measured by installing two piezometers in the site. Disturbed and undisturbed core samples were tested in the laboratory for determination of physical properties and strength parameters (shear and comprehensive strengths).

Fig. 9 View of Karshingsa landslide prone area and toe erosion by Dikrong River

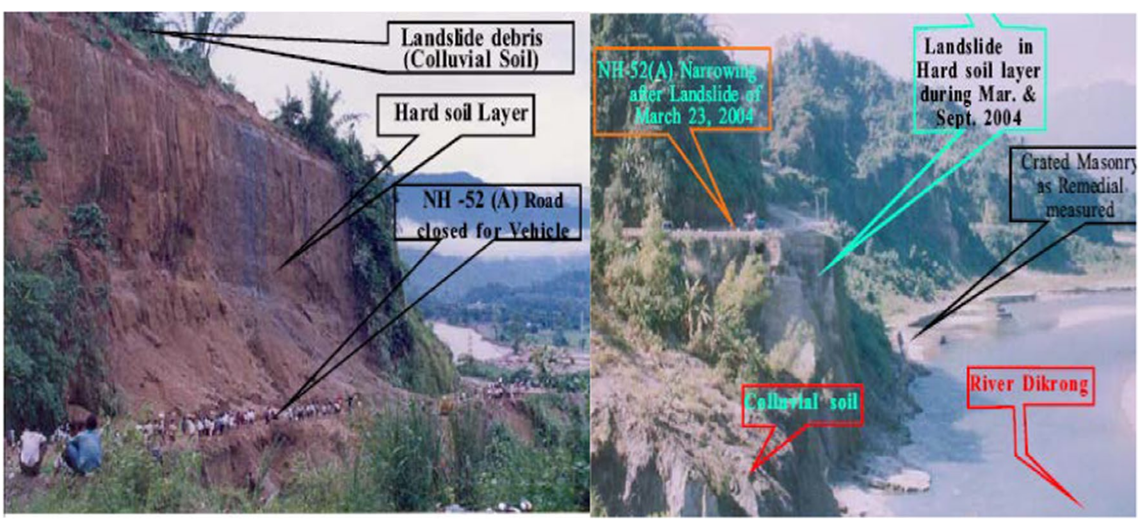


Fig. 10 Geological formation of the study site

Detail investigations were also conducted to analyze the geotechnical and hydrological properties of the particular strata (Colluvium subsoil) causing landslide in Karshingsa area.

Bore holes were required for determining the strata profile and collecting core samples to analyze physico-mechanical properties of strata. Nine boreholes (BH-1 to BH-9) of 150 mm diameter were drilled at different locations covering the study site (1000 × 500 m) up to a variable depth of 8–11 m (Fig. 11). Representative disturbed and undisturbed core samples from the bore holes at the various depths were collected for laboratory analysis. Standard Penetration Test (SPT) was conducted in each bore hole following Indian Standard (IS 2131: 1981).

The natural moisture content tests and the bulk density tests were carried out on the disturbed and undisturbed core samples collected from each bore hole. The sieve analysis tests were carried out on the samples collected from the bore holes and the results were tabulated w.r.t. their depth per bore holes. Atterberg's limit tests were carried out in the cohesive soil samples. Hydrometer tests were carried out on collected samples selected disturbed cohesive as well as cohesion less soil samples to find out the amount of silt and clay particles in the representative subsoil

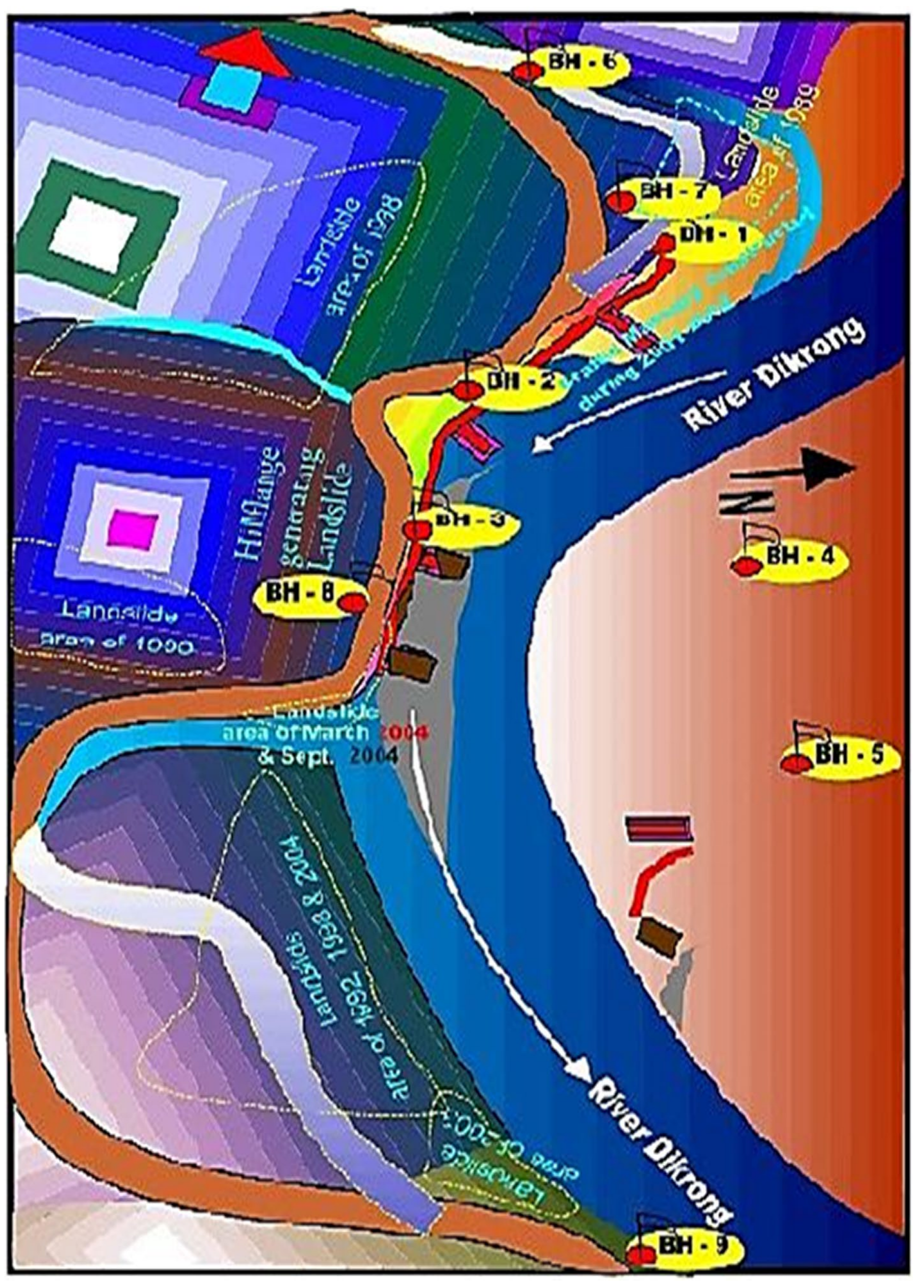


Fig. 11 Location of bore holes in the study site

and the resultants are given in the same figure. Based on the data of soil analysis and Atterberg's limits, the soil is identified and classified according to the Indian Standard (IS 1498: 1970).

To evaluate the shear parameters of the subsoil following tests were carried out in the laboratory by utilizing undisturbed soil samples collected from the field by conducting direct shear test and triaxial test as per standard procedures.

7 Geotechnical study results

7.1 Physical properties

Natural moisture content of the core samples was varied from 10 to 19%. The minimum value (10%) was determined at BH-6 and maximum value (19%) at BH-1 (Table 2). Bulk density of core samples (BH-1 to BH-9) ranged between 1.94 and 2.38 g cm^{-3}. The higest value was found for BH-3 and minimun at BH-5. Dry density of the strata core samples was found to be in the range of 1.72–2.13 g cm^{-3}. The minium and maximum values were found for BH-5 and BH-9, respectively.

7.2 Strength properties

Angle of internal friction (ϕ) and cohesion (c) of soil measured by triaxial shear test varied from 31 to 43 degree, and 0 to 0.31 kg cm^{-2}, respectively. Minimum value of cohesion measured by direct shear test found to be 0.04 kg cm^{-2} at BH-6 and maximum of 0.35 kg cm^{-2} at BH-3. Angle of internal friction (ϕ) measured by direct shear test varied between

Table 2 Physico-mechanical properties of core samples collected from Karshingsa landslide prone area

Sl. No.	Location and depth of samples from ground surface	Natural moisture (%)	Bulk density (g cm^{-3})	Dry density (g cm^{-3})	Shear test parameters				Unconfined compressive strength (kg cm^{-2})
					Direct shear test		Triaxial test		
					Cohesion 'c' (kg cm^{-2})	Φ (degree)	Cohesion 'c' (kg cm^{-2})	Φ (degree)	
1	Bore hole BH-1								
	(i) at 1.0 m	2.28	19	1.92	0.27	26.95	0.12	34	2.87
	(ii) at 3.0 m	2.35	15	2.04	0.21	31.65	0.15	36	3.98
2	Bore hole BH-2								
	(i) at 1.5 m	2.33	16	2.01	0.24	29.45	0.11	38	3.05
	(ii) at 3.0 m	2.25	14	1.97	0.34	28.75	0.29	32	4.15
3	Bore hole BH-3								
	(i) at 0.60 m	2.38	15	2.97	0.35	25.25	0.31	34	4.25
4	Bore hole BH-4								
	(i) at 1.5 m	1.98	12	1.77	0.09	30.05	0.02	38	–
5	Bore hole BH-5								
	(i) at 1.5 m	1.94	13	1.72	0.05	31.15	0.05	34	–
6	Bore hole BH-6								
	(i) at 1.5 m	2.16	11	1.95	0.04	28.50	0.00	37	–
	(ii) at 3.0 m	1.96	10	1.78	0.05	24.45	0.02	31	–
7	Bore hole BH-7								
	(i) at 1.5 m	2.36	14	2.07	0.07	35.15	0.00	42	–
8	Bore hole BH-8								
	(i) at 1.5 m	2.32	16	2.00	0.28	33.50	0.31	43	3.35
9	Bore hole BH-9								
	(i) at 1.5 m	2.34	14	2.05	0.25	30.75	0.05	39	2.45
	(ii) at 3.0 m	2.36	11	2.13	0.08	22.35	0.03	34	–

22.35 degree at BH-9 and 35.15 degree at BH-7. Comprehensive strength of soil samples varied from 2.45 kg cm^{-2} at BH-9 to 4.25 kg cm^{-2} at BH-3. Values of unconfined comprehensive strength are given in Table 2.

7.3 Physico-mechanical properties of colluvium soil

The top colluvium soil present in Karshingsa area causes frequent landslides. Detail analysis of this soil layer has been carried out to evaluate its physico-mechanical properties (Table 2). Particle size distribution of colluvium soil consists of gravel 44%, sand 19%, silt 31% and clay 6%. Chemical analysis of colluviums subsoil indicates maximum occurrence of iron as Fe_2O_3 (4.64 ppm).

Standard compaction test (Proctor's compaction) was repetitively carried out for colluvial soil. Moisture content varies from 0 to 16% and density varies from 1.990 to 2.07 g cm^{-3}. Maximum dry density observed to be 2.075 g cm^{-3} at original moisture content of 11%.

8 Field trial of landslide monitoring system

The designed system was set up at Karshingsa landslide prone hill slope having soft strata near Itanagar, Arunachal Pradesh. The monitoring site is situated on Dikrog River bank adjacent to Itanagar (Fig. 12). The monitoring site was divided in 2 zones, and 5 types of geosensors were installed in the each zone (Fig. 13). All the five types of sensors were installed in two zones of the landslide prone hill slope. The rain gauge sensor were anchored on the safe surface, wireline extensometer was anchored on a safe surface away from hill slope and its displacement measuring wire end was anchored in the hill slope and intermediate wire was supported by anchored and pulley arrangement for free moving of wire in case of slope movement. The in-place inclinometer extension rods with coupling arrangement were inserted in a fiber pipe and placed in bore bole, and the bore hole was filled with soil, and its sensor part was fitted in the top portion of extension rod. The tiltmeter was grouted on hill slope with anchoring arrangement. The piezometer was inserted in a perforated fiber pipe and placed at the bottom of a bore hole, and the hole was filled with sand and soil. All the sensors were connected with a solar panel and battery having input voltage to sensors as 12–24 V DC based on the sensors' requirement.

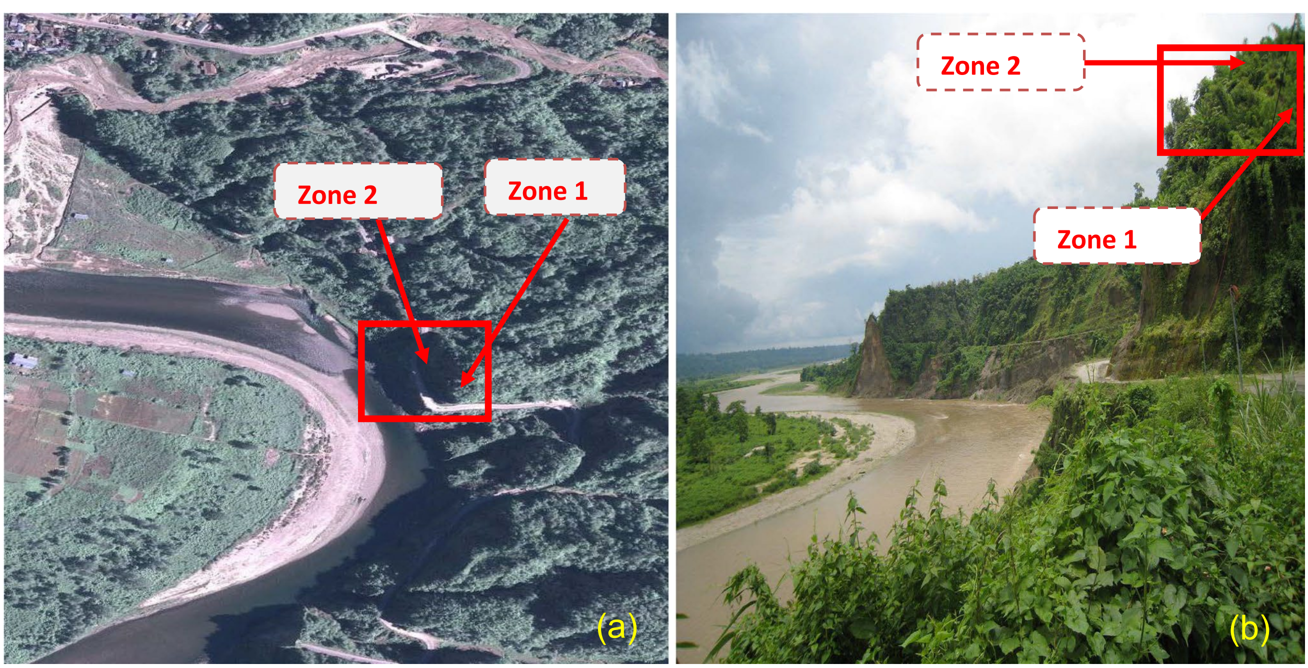


Fig. 12 View of installation site: **a** satellite view, and **b** photographic view

Fig. 13 View of geosensors and solar panel installed at Karshingsa landslide prone area: **a** raingauge, **b** tiltmeter, **c** in-place inclinometer, **d** crackmeter, **e** piezometer, and **f** solar panel

The sensors output were linked with an interface circuit, which is coupled with a wireless node. Two intermediary wireless nodes were equipped on different poles to form self-healing wireless mesh network. Further, base radio, gateway, and server were fitted in a control room built round 3000 m from the monitoring site. All sensors were fixed to initial zero reading. The wireless node connected with sensors transmitted data to server via two intermediate wireless nodes, and gateway and base radio. Subsequently, the sensors data were continuously monitored during 3 months and data were saved in server. The application software monitored, analyzed, stored and viewed data received from wireless devices coupled with sensors, and provided warnings (audio-visual alarm, SMS, and email alert) to the selected persons when particular landslide parameters crossed the respective threshold limit and online monitored data are displayed in the control room showing the condition of landslide in different colours for the respective monitoring zone on Google Map (Fig. 14).

Before installation at the site, the geosensors were calibration in the laboratory experimental setup under simulated conditions. A regression analysis was conducted to determine the optimal equation that would best fit the sensor data and the measured data. The results of the regression analysis were used to develop the most suitable equation for each sensor, as presented in Table 3. These equations were subsequently employed to convert raw data into actual sensor data for the corresponding sensor. The calibrated equations were then utilized for the uninterrupted monitoring of horizontal and vertical slope angles, rainfall, water pressure, and displacement of the landslide-prone area through the use of a wireless sensor network.

Installation was started in the month of April 2012 and completed in June 2012. Monitoring work was started from June 2012. Data were received from different installed sensors via wireless nodes and stored in server. Slope displacement, horizontal angle, vertical angle, rainfall, and pore pressure was measured using crackmeter, in-place inclinometer, tiltmeter, rainguage, and piezometer, respectively (Table 4). In the beginning data were received at 10 s interval, and consequently it was altered to 1 min to decrease the storage capability. Monitoring was continued up to November 30, 2012.

During the commencement of landslide monitoring at the said location, all sensors were initialized to zero on June 5, 2012. At that time, there was no rainfall and the groundwater was also absent at the installed depth of the piezometer sensor on the hill slope. However, as rain began to fall towards the end of June 2012, the sensor readings started to increase. The online data collected on September 24, 2012, as presented in Table 4, revealed that the recorded rainfall during the measurement period was 9.5 mm. Moreover, the corresponding piezometer value indicated approximately

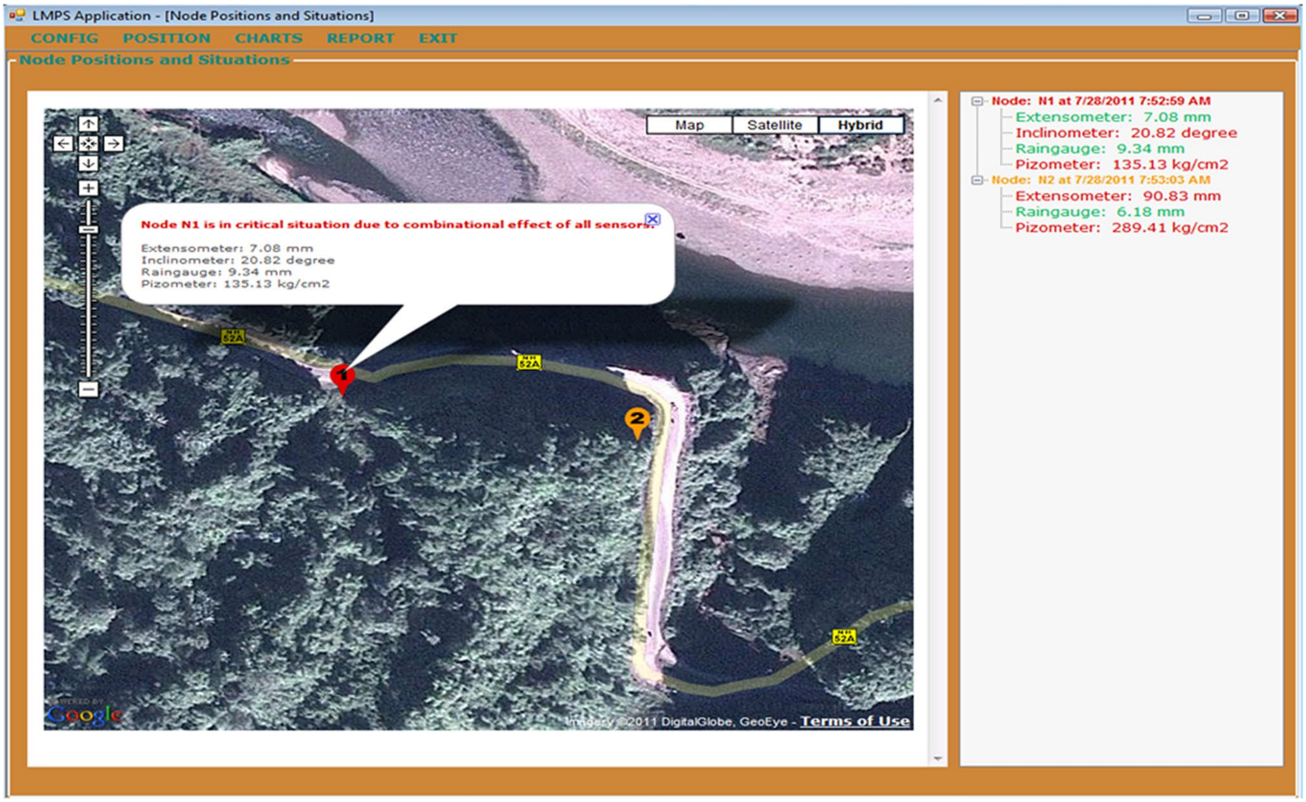


Fig. 14 Screenshot of online landslide monitoring in the control room

Table 3 Calibration equations for different geosensors

Geosensor name	Calibration equation
Piezometer	Pressure (kg cm^{-2}) = 0.009 × Measured data–1.232
Raingauge	Rainfall (mm) = 0.025 × Measured data + 3.287
Crackmeter	Displacement (mm) = 0.979 × Measured data–140.8
In-place inclinometer	Angel (degree) = 0.064 × Measured data–25.59
Tiltmeter	Angel (degree) = 0.032 × Measured data–13.10

0.275 kg cm^{-2}, and groundwater level was surpassing the installed sensor level in the hill slope. The cumulative measurements of the tiltmeter, in-place inclinometer, and crackmeter were – 0.313°, – 0.102°, and 5.47 mm, respectively. These measurements implied a slight displacement and deformation in the hill slope due to the rainfall occurring between June 5, 2012, and September 24, 2012. Furthermore, the groundwater level also increased during this period. However, it is important to note that no landslides occurred during the monitoring period at the site.

9 Conclusions

The landslide monitoring system has been developed by integrating different geotechnical sensors, interface board, wireless nodes and application software having various applications modules, namely monitoring, analyzing, storing, and viewing the prevailing parameters of landslide, and predicting landslide. Communication range of the wireless nodes has been increased to 1200 m by providing an additional external omni-directional antenna. Different types of geotechnical sensors have been integrated with one wireless node using interface board for covering large area with less numbers of wireless nodes and lower cost. Different geotechnical sensors can be installed in different zones

Table 4 Sample input sensor data saved in the server

Date	Time	Raingauge (mm)	Tiltmeter (degree)	In-place inclinometer (degree)	Crackmeter (mm)	Piezometer (kg cm^{-2})
2012/09/24	11:54:40	9.5	− 0.3136798	− 0.10124131	5.474854	0.2791276
2012/09/24	11:54:50	9.5	− 0.3136125	− 0.10180253	5.476554	0.2713908
2012/09/24	11:55:00	9.5	− 0.3135889	− 0.10226986	5.478253	0.2757597
2012/09/24	11:55:10	9.5	− 0.3137706	− 0.10198899	5.473158	0.2711799
2012/09/24	11:55:20	9.5	− 0.3137246	− 0.10273331	5.473158	0.2788651
2012/09/24	11:55:30	9.5	− 0.3137706	− 0.10255021	5.473158	0.2758118
2012/09/24	11:55:40	9.5	− 0.3138382	− 0.10282486	5.473158	0.2757597
2012/09/24	11:55:50	9.5	− 0.3136574	− 0.10320064	5.473158	0.2758118
2012/09/24	11:56:00	9.5	− 0.3137706	− 0.10329219	5.471456	0.2713371
2012/09/24	11:56:10	9.5	− 0.3138615	− 0.10338944	5.476552	0.2758118
2012/09/24	11:56:20	9.5	− 0.3139525	− 0.10366413	5.473158	0.2757597
2012/09/24	11:56:30	9.5	− 0.3138382	0.10320064	5.476552	0.2758118
2012/09/24	11:56:40	9.5	− 0.3137246	0.10255021	5.473158	0.2788651
2012/09/24	11:56:50	9.5	− 0.3135889	− 0.10226986	5.476552	0.2757597

of a large area and monitoring can be done from a remote control room by wirelessly connecting all the wireless nodes using dynamic wireless mesh network. The system displays monitoring locations and real-time landslide data on Google Map. The system predicts landslide following the multivariate statistical analysis of the measured geotechnical parameters, and subsequently analytical hierarchy process method. Further, the system gives 3 levels of warning to the district administrations and surrounding residents for evacuating the landslide area in the form audio-visual alarm, SMS and email alerts. In the future study, the system will be modified for improving accuracy of landslide prediction using artificial intelligence techniques.

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Author contributions All authors were affiliated with CSIR-Central Institute of Mining and Fuel Research, Dhanbad, India at the time of the study. All contributed to the study, design and implementation. S.C. conceptualized and designed the technical solution and manuscript writing. P.M. provided technical guidance, verification of data, and editing of manuscript. N.K. conducted laboratory studies and data analysis. VK validated the developed software with field data. V.R. generated experimental data.

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Data availability Data will be made available on request.

Declarations

Ethics approval and consent to participate Accepted principles of ethical and professional conduct have been followed.

Research involving human participants and/or animals No human participants and/or animals was involved in the research.

Competing interests The authors declare no competing interests.

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