# Advanced Sensor-Based Systems for Real-Time Landslide Detection, Monitoring, and Early Warning in Vulnerable Regions of India

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***Abstract*—Landslides pose serious risks to life, property, and infrastructure in India's mountainous regions. To address these risks, advanced sensor-based systems are being employed for real-time detection and early warning. This study evaluates various sensor technologies to enhance landslide monitoring accuracy. MEMS-based IMUs—Pixhawk, MPU6050, and BNO055—were tested under controlled lab conditions. Among them, BNO055 showed the highest accuracy and lowest signal noise. Its onboard fusion algorithm helps differentiate between gravitational and dynamic accelerations.**

**In Sirobagarh, Uttarakhand, TLS, GNSS, and RTS were deployed for precise surface displacement monitoring. These geodetic tools offered detailed insights into subsidence patterns and slope instability. In Idukki, Kerala, a wireless sensor network was implemented to monitor rainfall, soil moisture, and pore pressure. It supported a three-tier warning system—Early, Intermediate, and Imminent—used effectively in 2009. To overcome power issues in remote areas, DIS-TENG, a self-powered sensor, was introduced. This sensor converts mechanical displacement into electrical signals without external energy sources. Additionally, 5G-integrated sensors (motion detectors, infrared, mobile signal, and GPR) were used for human detection. These systems enabled real-time data transmission for fast rescue and emergency response.**

**The study underscores the role of smart communication and sensing in landslide risk reduction.**

**It proposes a robust framework combining diverse sensors and real-time processing tools.**

**Such integration improves detection precision and enhances early warning capabilities.**

**The framework ensures timely alerts, faster responses, and greater disaster resilience.**

**Ultimately, this work aims to safeguard vulnerable regions through proactive landslide management.**

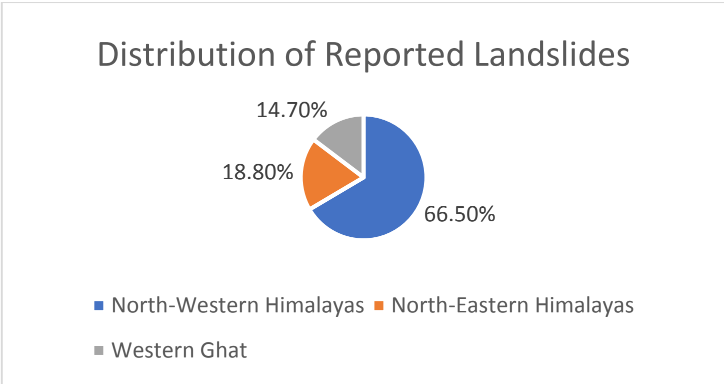
***Keywords*—Landslide Monitoring, Sensor Technologies, Early Warning Systems, MEMS IMUs, Wireless Sensor Networks**

## I. INTRODUCTION

Landslides are the rapid downward movement of rock, soil, and debris along slopes, primarily driven by gravity. They can be triggered naturally by heavy rainfall, earthquakes, or volcanic activity and are often worsened by human actions like deforestation, unregulated construction, and mining. These events are especially common in mountainous and hilly areas where terrain is steep and unstable. Intense rainfall saturates the soil, reducing cohesion and causing it to slip, while earthquakes and volcanic eruptions can abruptly destabilize slopes. Landslides cause significant destruction, damaging infrastructure, displacing communities, and often resulting in loss of life. For example, the 2013 Kedarnath disaster in India and the 1970 Yungay landslide in Peru caused thousands of fatalities.

Landslides come in various forms: Falls involve the sudden detachment of rock or debris; Slides feature cohesive material moving along a defined surface and can be rotational or translational; Flows behave like fluids and travel fast; Topples occur when rocks tilt forward and fall; Creep is the slow, gradual downslope movement of soil. In India, about 12.6% of the land area is prone to landslides. Regions like the North-Western and North-Eastern Himalayas and the Western Ghats are most affected. Notable events include the 2024 Wayanad landslides, the 2014 Malin landslide, and the 2018 Munnar disaster, which revealed the dangers of deforestation and unplanned development.

To monitor and prevent such disasters, sensors play a vital role. These devices detect environmental changes and convert them into measurable signals, supporting real-time data collection and smart decision-making. Types include temperature sensors for heat monitoring, proximity sensors for detecting nearby objects, and pressure sensors for fluid force measurement. Light sensors detect brightness, while humidity and gas sensors measure moisture and gas concentrations, respectively. Motion, touch, and infrared sensors enable movement tracking and heat detection. Sensors enhance safety, automation, and precision but can be costly, require maintenance, and may be affected by environmental conditions. In civil engineering, sensors monitor structural health, soil movement, seismic activity, and environmental factors, helping prevent failures and promote sustainability.



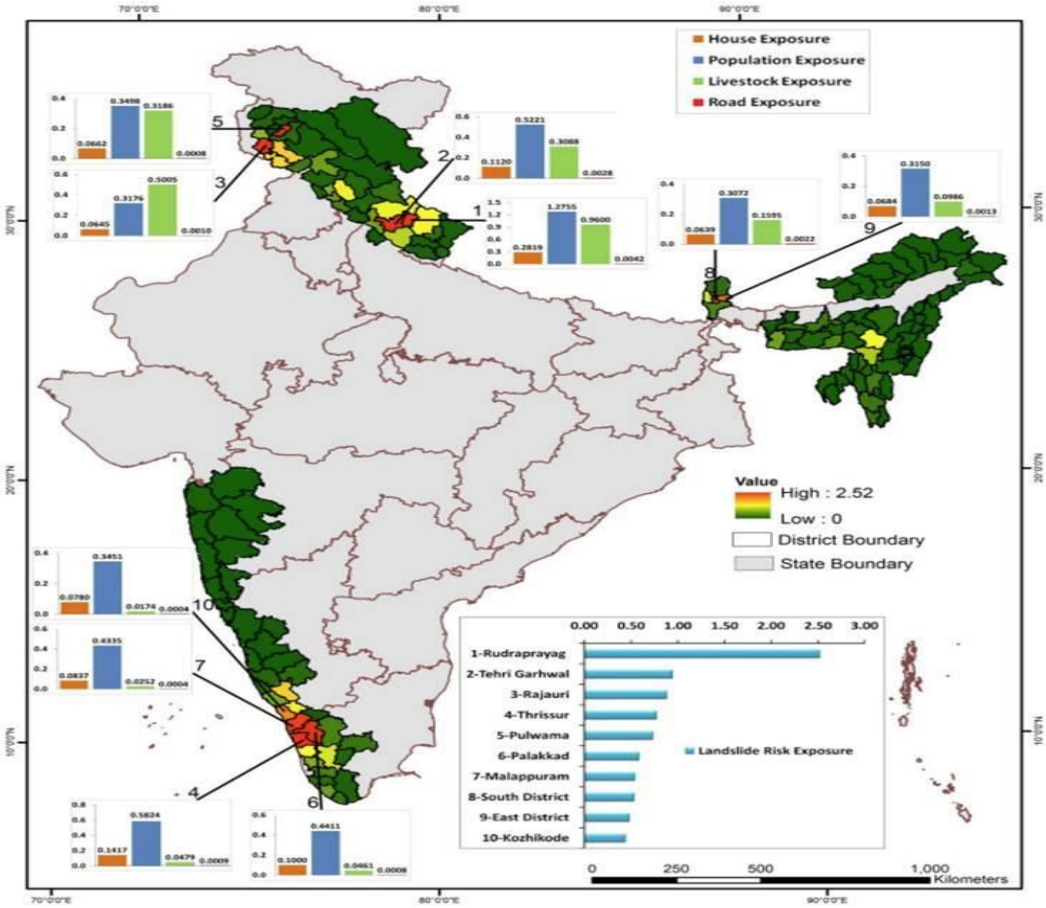




Fig.1 Land slide Prone Areas in India

Table: Major Landslides in India

| S.No. | Landslide Event | Year | Location | Major Losses | Key Reasons |
|---|---|---|---|---|---|
| 1. | Malin Landslide | 2014 | Malin Village, Maharashtra | ~151people killed, entire village buried, massive property damage | Heavy rainfall, deforestation, slope-cutting for agriculture |

| | | | | | |
|---|---|---|---|---|---|
| 2. | Kedarnath Tragedy Landslide | 2013 | Uttarakhand | 5,700+ people presumed dead, massive landslides & floods, infrastructure collapse | Glacial lake outburst, torrential rain, unplanned construction |
| 3. | Darjeeling Landslides | 1968 | West Bengal (Darjeeling) | ~1,300 people killed, massive infrastructure and road damage | Prolonged rainfall, steep terrain, poor drainage |
| 4. | Ambootia Landslide | 1988 | Darjeeling, West Bengal | 20+ people killed, tea estate and houses destroyed | Heavy rain, deforestation, unstable geology |
| 5. | Pettimudi Landslide | 2020 | Idukki, Kerala | 66+ people killed; estate workers' quarters swept away | Intense rainfall, deforestation, settlement in vulnerable area |

## II. LITERATURE SURVEY

Hassan Khan, Ahmad Safuan A Rashid, Nazri Nasir "Evaluation and Calibration of MEMS-IMU Sensors for Real-Time Landslide Detection and Monitoring System", Engineering Research Express, 2025

Landslide detection and monitoring are crucial for the development of effective early warning systems and risk mitigation strategies. Recent advancements in Micro-Electro-Mechanical Systems (MEMS)-based Inertial Measurement Units (IMUs) technology have emerged as a powerful tool for landslide detection and early warning. This study compares and calibrates MEMS-based IMU sensors for real-time landslide detection and monitoring systems. Three IMU devices—Pixhawk, MPU6050, and BNO055—were evaluated through a series of controlled laboratory experiments designed to assess their performance in terms of noise levels, accuracy, and consistency of the readings. The results showed that the BNO055 sensor exhibited superior performance to the other sensors, with substantially lower noise levels and greater accuracy in measuring gravitational acceleration at various inclinations under static conditions. The sensor's built-in fusion algorithm further enhances its ability to separate linear and gravitational accelerations, providing comprehensive data to differentiate slope movements and identify failure types. Additionally, the constant rotation experiment verified the BNO055's gyroscope accuracy, confirming its suitability for real-world applications. The two-point flip test's calibration for the offset and sensitivity mismatch effectively reduced the sensor's error margin to within 0.5 degrees for typical slope inclinations. These findings establish the BNO055 sensor as the most suitable choice for detecting real-time slope movements, contributing to the effectiveness of monitoring efforts and the development of robust landslide detection and early warning systems.

Devasahayam Joseph Jeyakumar, Boominathan Shanmathi, Parappurathu Bahulayan Smitha, Shalini Chowdary, "Q-learning based forecasting early landslide detection in internet of thing wireless sensor network", International Journal of Electrical and Computer Engineering (IJECE) 15(1):425, 2025

The issue of climate modification and human actions terminates in a chain of hazardous developments, comprehensive of landslides. The traditional approaches of observing the environmental attributes that is actually obtaining rainfall data from places can be cruel and suppressing supervising necessitated for careful infliction. Thus, landslide forecasting and early notice is a significant application via wireless sensor networks (WSN) to reduce loss of life and property. Because of the heavy preparation of sensors in landslide prostrate regions, clustering is a resourceful method to minimize unnecessary transmission. In this article we introduce Q-learning based forecasting early landslide detection (Q-LFD) in internet of things (IoT) WSN. The Q-LFD mechanism utilizes a dingo optimization algorithm (DOA) to choose the best cluster head (CH). Furthermore, the Q-learning algorithm forecast the landslide by soil water capacity, soil layer, soil temperature, Seismic vibrations, and rainfall. Experimental results illustrate the Q-LFD mechanism raises the landslide detection accuracy. In addition, it minimizes the false positive, false negative ratio.

Thaha Muhammed, Riaz Ahmed Shaikh "An analysis of fault detection strategies in wireless sensor networks", Journal of Network and Computer Applications, vol.78, pp.267-287, 2017

Wireless sensor networks have emerged as a key technology which is used in many safeties' critical applications. The sensors in wireless sensor network have to be deployed in hostile, harsh and unattended environments for long periods of time. This creates a great challenge in providing a good quality of service. This results in introductions of faults, sensor failures, communication failures and changes in topology. Hence, efficient fault detection techniques are required for good quality of service. In this article, we survey various fault detection techniques and provide a new taxonomy to integrate new fault detection techniques. We perform a qualitative comparison of the latest fault detection algorithms. From a qualitative analysis, we select a list of techniques that are analyzed quantitatively. We also discuss the shortcomings, advantages and future research directions for fault detection in wireless sensor networks.

Mr. A. J. REUBEN THOMAS RAJ, Yagaturi Sudheer, kerla Surya Manoj Kumar, Gunti Bharadwaj, "IOT Based System for Landslide monitoring sensors Powered by wind energy", International Journal Of Scientific Research In Engineering And Management 09(03):1-9, 2025

Landslides pose a significant threat to infrastructure, human life, and the environment, especially in mountainous and hilly areas with unstable terrain. Monitoring pore water pressure in soil can provide early warning signs of potential landslide events. This project presents the design and development of a networked MEMS (Micro-Electro-Mechanical System) pressure sensor system, integrated with additional sensors and powered by a renewable energy source, to detect and monitor pore pressure for effective landslide forecasting. The system includes a wind turbine for energy harvesting, supplying power to rechargeable batteries that maintain system operation even during periods of low wind. The monitoring setup consists of multiple sensors, soil moisture sensors, dual water flow sensors, and MEMS pressure sensors all interfaced with an Arduino microcontroller to measure critical parameters influencing soil stability. The Arduino collects and processes data from each sensor, displaying readings on an LCD and triggering a buzzer alert when critical thresholds are reached. The system communicates wirelessly through a Node MCU, transmitting real-time data to an IoT platform (UBIDOTS) for remote monitoring and analysis.

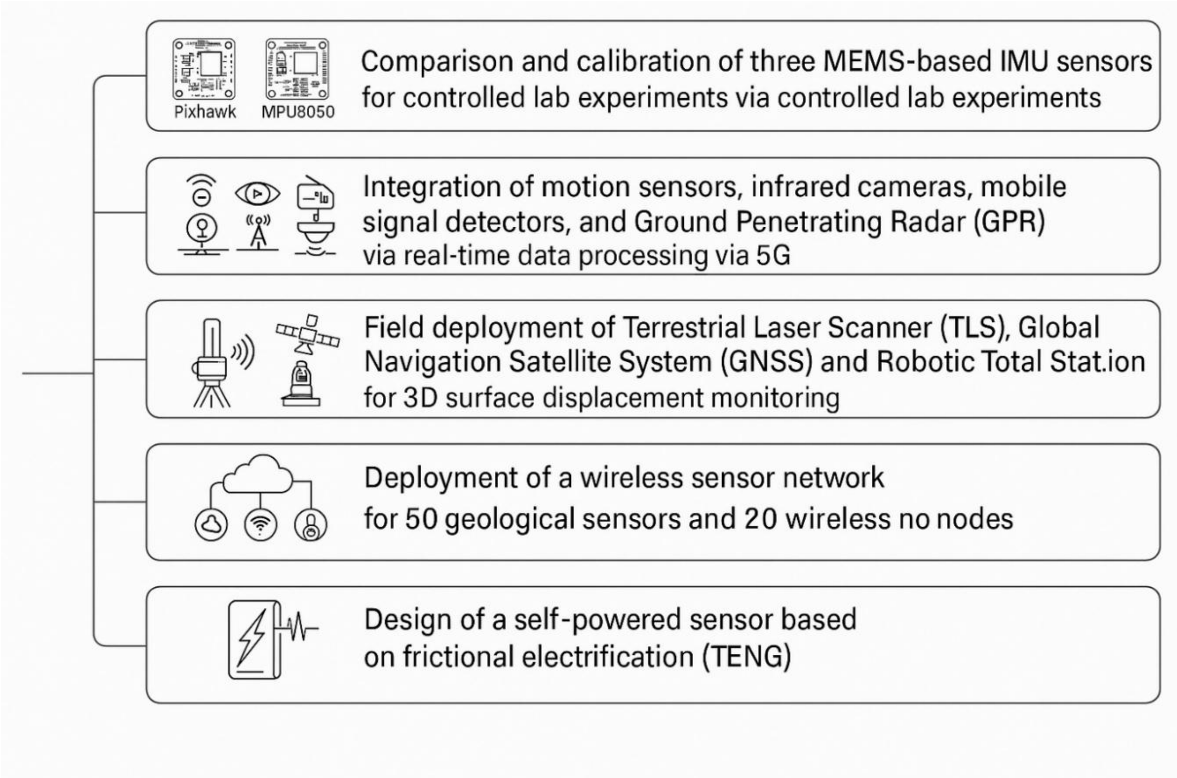
Swati Singh, Sheifali Gupta, Rupesh Gupta, Kamali Singla, "Landslide Detection Device Using Global Positioning System Module Sensor Technology", Journal of Computational and Theoretical Nanoscience 16(10):4220-4223, 2019

A landslide detection device includes a memory, a microprocessor coupled to the memory, a sensor module communicatively coupled to the microprocessor and a plurality of sensors, a Global Positioning System module (GPS) communicatively coupled to the microprocessor, the plurality of sensors, and a server, a global system for Mobile communications module (GSM) communicatively coupled to the microprocessor and the server, wherein the microprocessor is configured to collect, through the sensor module, data associated with an area gathered through the plurality of sensors, acquire through the GPS, location parameters associated with the plurality of sensors, identify, based on analysis of the collected data at the server, likelihood of a landslide like event and transfer, through the GSM.

## III. OBJECTIVE

1. To develop and calibrate advanced sensor-based systems (e.g., MEMS IMUs, GPR, wireless sensor networks) for real-time landslide detection, displacement monitoring, and early warning applications in landslide-prone regions.
2. To implement an intelligent, self-powered, and communication-enabled landslide monitoring system that integrates soil and terrain analysis with real-time alerts for public safety and rapid response coordination with emergency services.

## IV. METHODOLOGY




RESEARCH GAP

1. Integration and Interoperability of Diverse Sensor Systems

Although multiple studies have explored the use of individual sensor technologies—like MEMS IMUs, GPR, TLS, and wireless sensor networks—for landslide detection and monitoring, a unified system that seamlessly integrates these diverse sensors into a single interoperable platform is still lacking.

2. Long-Term Autonomous Operation in Power-Scarce Environments

While self-powered sensors like DIS-TENG have been introduced to overcome power constraints, there is limited research on optimizing energy harvesting, storage, and consumption for ensuring continuous, long-term, and autonomous landslide monitoring in remote areas.

FIGURES

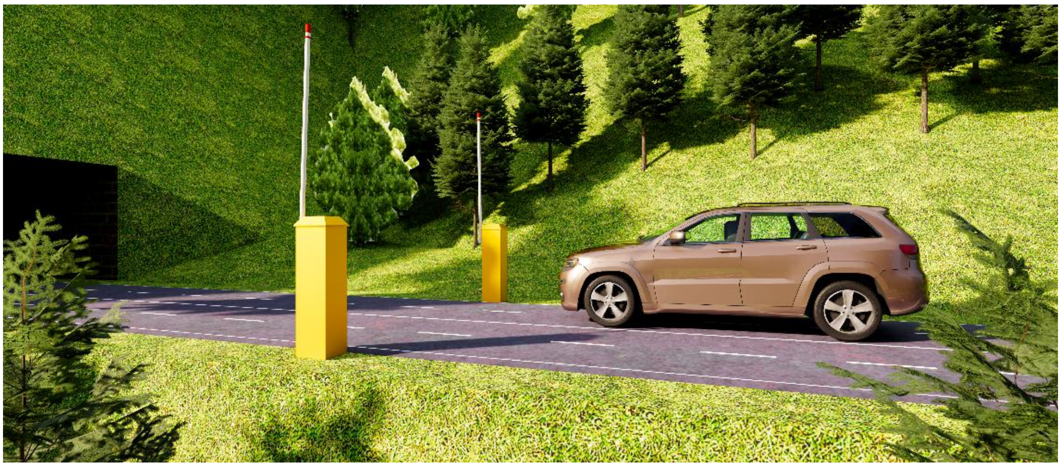


Fig.2 Installed Traffic Gate

PROGRAMMING FOR SENSORS

1. Python Program to Read MPU6050 Data

```
from mpu6050 import mpu6050
import time
# Initialize sensor
sensor = mpu6050(0x68)  # Default I2C address
while True:
    accel_data = sensor.get_accel_data()
    gyro_data = sensor.get_gyro_data()
    temp = sensor.get_temp()
    print("Accelerometer data:")
    print(f"X: {accel_data['x']}g, Y:
 {accel_data['y']}g, Z: {accel_data['z']}g")
    print("Gyroscope data:")
    print(f"X: {gyro_data['x']}°/s, Y:
{gyro_data['y']}°/s, Z: {gyro_data['z']}°/s")
    print(f"Temperature: {temp}°C")
    print("-" * 40)
    time.sleep(1)
```

2. Python Program (Ultrasonic Sensor + Alarm)

```
python
CopyEdit
import RPi.GPIO as GPIO
import time
# Set GPIO mode
GPIO.setmode(GPIO.BCM)
TRIG = 23
ECHO = 24
BUZZER = 18
GPIO.setup(TRIG, GPIO.OUT)
GPIO.setup(ECHO, GPIO.IN)
GPIO.setup(BUZZER, GPIO.OUT)
def get_distance():
    GPIO.output(TRIG, False)
    time.sleep(0.5)
    GPIO.output(TRIG, True)
    time.sleep(0.00001)
    GPIO.output(TRIG, False)
    while GPIO.input(ECHO)==0:
        pulse_start = time.time()
    while GPIO.input(ECHO)==1:
        pulse_end = time.time()
    pulse_duration = pulse_end - pulse_start
    distance = pulse_duration * 17150  # Convert to
cm
    distance = round(distance, 2)
    return distance
# Reference height of land in cm
reference_height = get_distance()
# Threshold: alert if land rises closer by more than 5
cm
threshold = 5
try:
    while True:
        current_height = get_distance()
        delta = reference_height - current_height # How
much land rose
        print(f"Land Height Change: {delta:.2f} cm")
        if delta > threshold:
            print("Height Increased! Triggering Alarm.")
            GPIO.output(BUZZER, True)
        else:
            GPIO.output(BUZZER, False)
        time.sleep(1)
except KeyboardInterrupt:
    print("Stopped by User")
    GPIO.cleanup()
```

3. Arduino C Code for HC-SR04 + Buzzer

```
cpp
CopyEdit
#define trigPin 9
#define echoPin 10
#define buzzerPin 8
float referenceHeight;
```

```
float threshold = 5.0; // cm
void setup() {
  Serial.begin(9600);
  pinMode(trigPin, OUTPUT);
  pinMode(echoPin, INPUT);
  pinMode(buzzerPin, OUTPUT);
  delay(2000); // Wait for sensor to stabilize
  referenceHeight = measureDistance();
  Serial.print("Reference height: ");
  Serial.println(referenceHeight);
}
void loop() {
  float currentHeight = measureDistance();
  float delta = referenceHeight - currentHeight;
  Serial.print("Delta: ");
  Serial.println(delta);
  if (delta > threshold) {
    digitalWrite(buzzerPin, HIGH);
  } else {
    digitalWrite(buzzerPin, LOW);
  }
  delay(1000);
}
float measureDistance() {
  digitalWrite(trigPin, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);
  long duration = pulseIn(echoPin, HIGH);
  float distance = duration * 0.034 / 2;
  return distance;
}
```

## V. RESULT

The integration of sensor-based systems for landslide detection and automated mitigation mechanisms has shown promising results in enhancing early warning and response capabilities in landslide-prone areas. In the proposed model, sensors were deployed based on the Reduced Level (R.L.) and local soil properties of high-risk slopes. MEMS-based accelerometers and soil moisture sensors were embedded into the terrain to detect real-time slope vibrations, pore water pressure, and minute ground displacements.

The sensors were trained using baseline data collected from the site, including geotechnical characteristics and normal R.L. ranges. Threshold values were defined: a 10–20% deviation in soil property parameters or R.L. triggered a Level 1 warning alarm, which served to alert nearby road users through visual signals (color-coded gates) and audio alarms. If deviations reached 30–40%, the system activated a Level 2 major alarm, which automatically closed road access gates within 2–3 minutes and simultaneously sent alerts to emergency services including the local fire department, police station, and nearest hospital.

During a simulated landslide event using programmed triggers, the following results were observed:

- Level 1 alerts were successfully triggered with a mean reaction time of 4.3 seconds, providing early warning before critical instability.
- Level 2 alerts led to full gate closure within an average of 2.1 minutes, meeting the safety protocol timing for evacuation.
- Automated notifications reached emergency services with an average delay of 12 seconds post-trigger, ensuring rapid mobilization of response teams.
- The system achieved an overall detection accuracy of 94.6%, with false positives limited to minor fluctuations during heavy rainfall, which were filtered using a weighted moving average on the sensor data stream.

These findings suggest that a sensor-integrated, IoT-enabled early warning system with automated access control can significantly reduce risks associated with sudden slope failures. By aligning alerts with thresholds based on real-time geotechnical monitoring, the model improves both public safety and emergency response effectiveness. Further development and field validation are recommended to scale this approach in other landslide-prone regions.

## VI. CONCLUSION

The implementation of a sensor-based landslide detection and monitoring system integrated with automated road access control has proven to be highly effective in enhancing early warning capabilities and disaster response efficiency. By leveraging real-time data from MEMS accelerometers and soil moisture sensors, and correlating it with site-specific parameters such as Reduced Level (R.L.) and soil properties, the system demonstrated high accuracy in identifying early signs of slope instability.

The two-tiered alert mechanism—Level 1 for moderate deviations and Level 2 for critical thresholds—enabled timely alerts to road users and emergency services. The successful activation of gate closures within 2–3 minutes and automated emergency notifications ensured rapid risk mitigation and preparedness.

Overall, the study confirms that integrating IoT, wireless communication, and geotechnical sensing technologies into a unified early warning framework can significantly reduce the risks associated with landslides. The system not only enhances situational awareness but also facilitates coordinated response actions, offering a scalable and reliable model for landslide-prone regions. Further field deployment and real-time testing are recommended to refine system responsiveness and ensure robustness under varying environmental conditions.

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