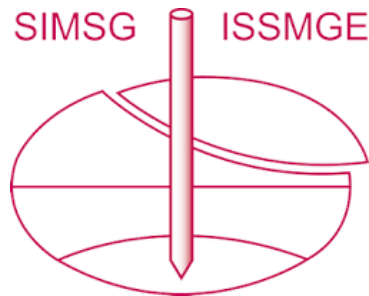


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## Tilt sensors for monitoring of unstable slopes: A case study from Kalimpong in Darjeeling Himalayas

Captors d'inclinaison pour la surveillance des pentes instables: une étude de cas de Kalimpong dans l'Himalaya de Darjeeling

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**ABSTRACT:** Rainfall induced landslides are turning into a major concern for the authorities due to their recurring occurrences in the recent past. Developing an early warning system to predict the possible occurrence of landslides and disseminate it to the public is a crucial risk reduction strategy. Darjeeling Himalayas in India is in dire need of such a Landslide Early Warning System (LEWS), being one among the highly landslide prone areas in the world. Developing rainfall thresholds is the simplest way of predicting landslide events, but it has the disadvantage of increased number of false alarms. To overcome this limitation, it is necessary to monitor the unstable slopes, in a cost effective way to get the real-time observations. This will help in making the thresholds operational, verified with real-time physical monitoring. This study gives the results of real-time field monitoring using MicroElectroMechanical Systems (MEMS) sensors in Chibo village of Darjeeling Himalayas integrated with rainfall thresholds, to develop a prototype LEWS. The study explores in detail the relationship between change in tilt angle and rainfall and the results shows the approach using MEMS sensors and rainfall thresholds is a promising one towards establishing an LEWS for the study area.

**RÉSUMÉ :** Les glissements de terrain induits par les précipitations deviennent une préoccupation majeure pour les autorités en raison de leurs occurrences récurrentes dans un passé récent. Développer un système d'alerte précoce pour prédire l'occurrence possible de glissements de terrain et le diffuser au public est une stratégie cruciale de réduction des risques. Darjeeling Himalaya en Inde a un besoin urgent d'un tel système d'alerte précoce aux glissements de terrain (LEWS), étant l'une des zones les plus sujettes aux glissements de terrain dans le monde. Le développement de seuils de précipitations est le moyen le plus simple de prédire les événements de glissement de terrain, mais il présente l'inconvénient d'augmenter le nombre de fausses alarmes. Pour surmonter cette limitation, il est nécessaire de surveiller les pentes instables, de manière rentable pour obtenir les observations en temps réel. Cela aidera à rendre les seuils opérationnels, vérifiés avec une surveillance physique en temps réel. Cette étude donne les résultats d'une surveillance sur le terrain en temps réel à l'aide de capteurs MicroElectroMechanical Systems (MEMS) dans le village de Chibo de Darjeeling Himalaya intégrés aux seuils de précipitations, pour développer un prototype de LEWS. L'étude explore en détail la relation entre le changement d'angle d'inclinaison et les précipitations et les résultats montrent que l'approche utilisant des capteurs MEMS et des seuils de précipitations est prometteuse pour établir un LEWS pour la zone d'étude.

**KEYWORDS:** early warning system; sensors; IoT; Indian Himalayas; landslides

### 1 INTRODUCTION

Landslides are morphological processes, that may lead to severe destruction, when interacted with human environment (Dowling and Santi, 2014; Petley, 2012). The increasing population and urbanisation of hilly terrains are increasing the risk due to landslides and it is high time that the authorities should focus on effective risk reduction strategies. Development of LEWS is one among the risk reduction approaches. An LEWS should forecast the probable occurrence of landslides in an area and provide enough intervention time to take necessary actions. Rainfall thresholds are the most widely followed method for forecasting landslides (Baum and Godt, 2010; Devoli et al., 2018). The threshold defines specific rainfall conditions when exceeded, may trigger slope failures in the region (Segoni et al., 2018). The thresholds can be derived using physically based approaches or statistical approaches. Physically based or process based approaches are generally preferred for site specific studies (De Vita et al., 2017; Fusco et al., 2019; Napolitano et al., 2016; Segoni et al., 2018), and statistical approaches are applied for regional and global scales (Aleotti, 2004; Bordoni et al., 2019;

Caine, 1980; Guzzetti et al., 2007). The thresholds are characterized by three rainfall parameters, the event (E), duration (D) and intensity (I). Event rainfall is the total quantity of precipitation, duration is the time period, and intensity is the ratio of event to duration. The thresholds are defined using two of these parameters, I or E on the y axis and D on x axis. Mathematically, the thresholds follow a power law and can be represented as a straight line on logarithmic scale.

The method of using rainfall thresholds is an easy way of forecasting landslides, but the conservative approach of using minimum thresholds often result in a higher number of false warnings (Abraham et al., 2020b; Bulzinetti et al., 2021; Satyam and Abraham, 2022; Segoni et al., 2021). In this study, the rainfall thresholds are coupled with field monitoring data from MEMS tilt sensors. The tilt sensors are established to be a trustworthy and low cost method for slope monitoring (Towhata et al., 2015; Uchimura et al., 2011). The sensors are installed to monitor unstable slopes in Kalimpong town of West Bengal since July 2017. The study focuses on verifying the applicability of tilt sensors in predicting slope failures and their potential use in enhancing the performance of conventional rainfall thresholds.

The two methods are combined using a decisional algorithm, which can be used for forecasting slope failures in the region.

## 2 DESCRIPTION OF THE STUDY AREA

Kalimpong is a hilly town located in the Darjeeling Himalayas (Fig. 1). The town is hemmed between two rivers, Tista and Relli. The Tista basin, on the western face of Kalimpong is very steep and are unstable. The topsoil has deposits of loose debris materials from historical slope failures. The loose topsoil often gets eroded during heavy rains. The bedrock lithology of the town mainly comprises of golden to silver coloured quartz mica schist (Mukherjee and Mitra, 2001). The rocks are highly jointed and weathered and are prone to stability issues.

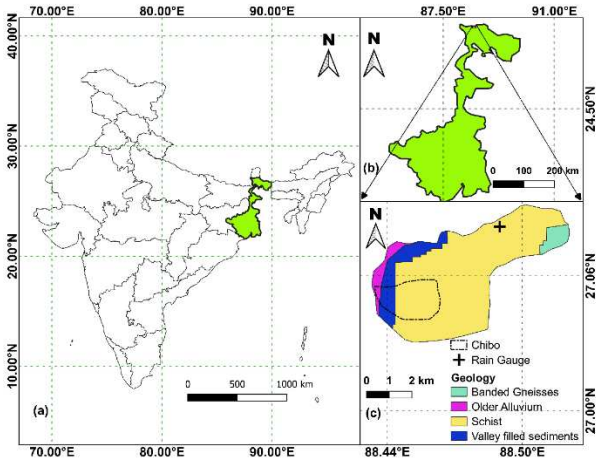


Figure 1. Details of the study area (a) India, (b) West Bengal and (c) Kalimpong town: Geological map (Abraham et al., 2020a)

The possibility of occurrence of landslides and the risk due to landslides have increased by the increase in anthropic pressure and the resulting land use changes. The landslides in the region are highly influenced by the slope cuts and untrained mountain rivulets (jhoras). The most critical landslide locations are near the jhoras. The sensors are installed in a slope near one such rivulet, called the Pyarieni jhora in the Chibo village of Kalimpong.

## 3 METHODOLOGY

### 3.1 Conventional rainfall thresholds and field monitoring system

The study assesses the performance of conventional rainfall thresholds and tilt meters when used separately and in combination. The empirical thresholds for the study area were derived in previous studies (Dikshit and Satyam, 2017; Teja et al., 2019) on both ID (Eq. 1) and ED (Eq. 2) planes as:

$$I = 3.52 D^{-0.41} \quad (1)$$

and

$$E = 4.2 D^{0.56} \quad (2)$$

In July 2017, three sensor units were employed in the unstable slopes near Pyarieni Jhora, Chibo, Kalimpong. Each sensor unit consists of a volumetric water content sensor, a tilt sensor, and a control unit (Fig. 2).

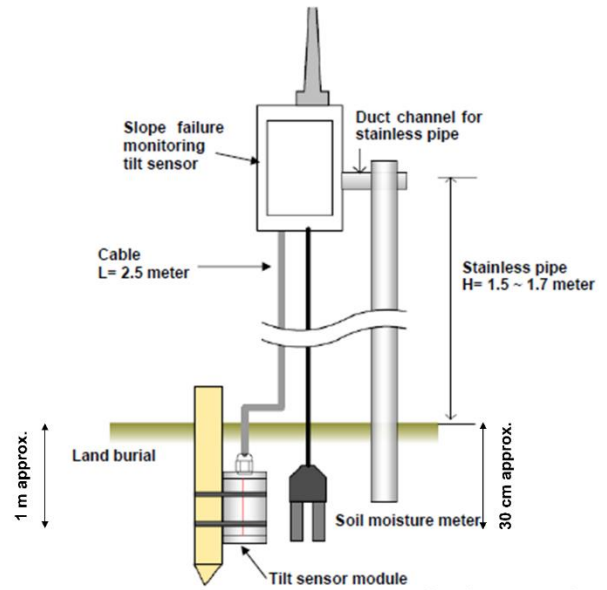


Figure 2. Schematic arrangement of sensor unit (Abraham et al., 2020c)

The positions of the sensors were carefully chosen after detailed field surveys, discussion with Geological Survey of India, and resident people of the town (Dikshit et al., 2018). The sensors S1, S2 and S3 were positioned near Pyarieni jhora as shown in Fig. 3.

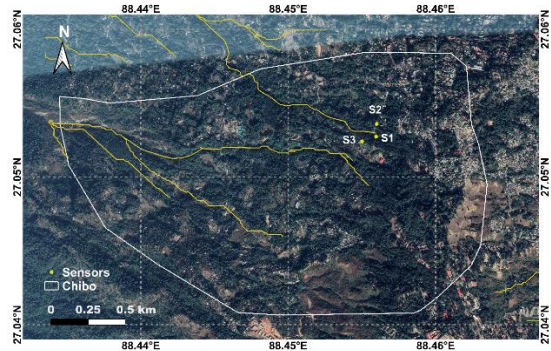


Figure 3. Location of sensors in Chibo, Kalimpong (Abraham et al., 2020a)

The sensor readings were related with observations from the field, to assess the dependability of the recorded data (Abraham et al., 2020c; Dikshit et al., 2018). The records acquired from the tilt meters for the duration of monitoring period implies that large displacements are always associated with heavy rainfall (Fig. 4).

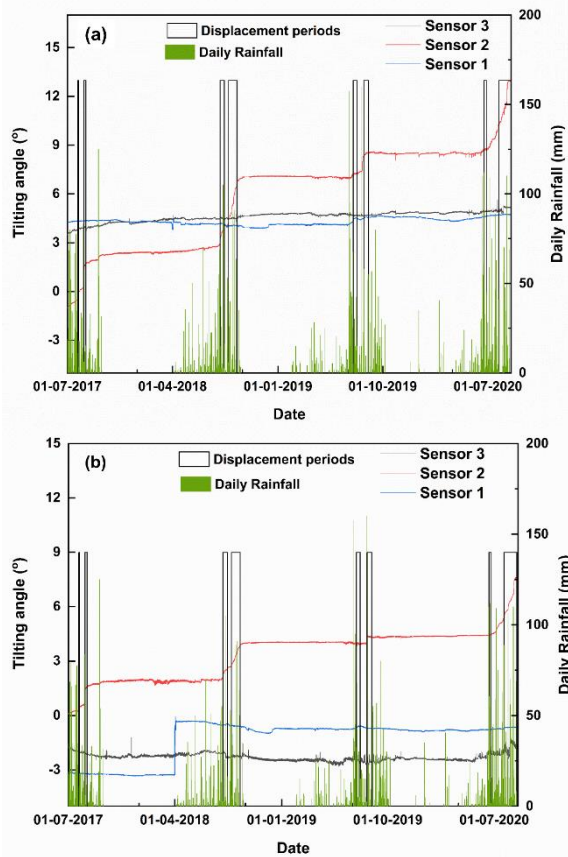


Figure 4. The tilt meter records and daily rainfall data (a) tilting angle along the slope, and (b) tilting angle perpendicular to the slope

From Fig. 4, it can be observed that sensor 2 has the most variations and the location is in a critical state. The field observations are also in accordance with the tilt meter readings. Displacement incidences were observed since the year 2017 as marked in Fig. 4. The cracks developed in roads near sensor 2 during 2020 monsoon is shown in Fig. 5. The tilt sensors have also shown variations during the displacement periods. It should also be noted that the tilt sensors have shown variations which are not associated with the displacements in field. Hence the readings are correlated with the occurrence of rainfall to forecast slope failures.



Figure 5. Cracks formed in road adjacent to Pyarienii jhora (a) on 27<sup>th</sup> July, 2020 and (b) on 6<sup>th</sup> August, 2020

Certain thresholds are defined after evaluating the field monitoring data. The peak hourly tilt rate was set to 0.03 °/h, continuously for an hour, for issuing warning. Alerts are issued if the tilting rates are crossed beyond this value. If the value goes beyond 0.1 °/h, there are high chances for slope failure and critical alert should be issued. Both these values were derived

through a trial-and-error approach. The tilt rates on the day of displacements were first checked, to determine the minimum threshold. Then the false alerts were reduced by increasing the threshold slightly, such that minimum number of true alerts are missed.

### 3.2 Combined approach: rainfall thresholds and field monitoring

The rainfall thresholds and tilt meter readings for Kalimpong are combined using the algorithm in Fig. 6.

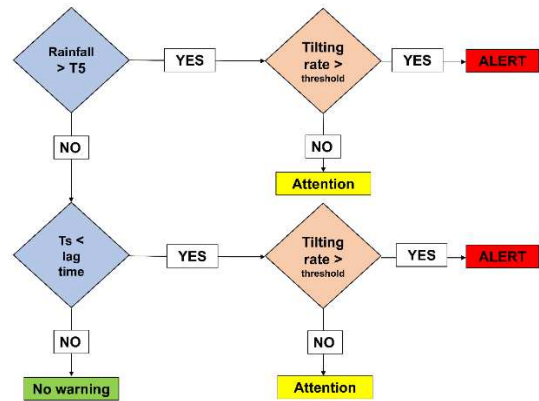


Figure 6. Prototype algorithm for warning for slope failure in Chibo area, Kalimpong

The algorithm first check for the occurrence of precursor event (Rainfall) in the study region. If a rainfall event, exceeding the threshold conditions has happened, then the tilt rates are monitored. If the tilt rates are also crossing the predefined thresholds, alert is issued. The check of tilt rates are to be done if conventional rainfall threshold with 5 % exceedance probability as mentioned in equations 1 and 2.  $T_s$  is the time at which alert is issued, after the occurrence of rainfall. a rainfall above threshold has happened within a lag time in the study area. The lag time is determined by trial and error as 72 hours for Kalimpong. The variable  $T_5$  in Fig. 6 indicates the

The performance of each model was tested using a confusion matrix. The result or forecast by the thresholds were grouped into four sets as true positives (TP), true negatives (TN), false positives (FP), false negatives (FN) for quantitative comparison. The days when the threshold forecasts the likelihood of a slope failure are positive outcomes. TPs are counted when landslide occurs on a day with positive outcome and FPs if no landslide occurs on a day with positive outcome. Negative outcome occurs on days with no landslide forecast. If no slope failures are recorded on the day, the result is a TN and if slope failure occurs, it is considered as FN. By using these four parameters, the performance of the prototypal model can be assessed. Terms like efficiency, odds ratio, sensitivity, specificity and likelihood ratio were used to evaluate the performance of different models.

## 4 RESULTS AND DISCUSSION

The rainfall, and field-based monitoring data for Kalimpong from July, 2017 to August, 2020 have been utilized for the study. The forecasted results were tested with the actual occurrence or non- occurrence of slope failures in field to understand the performance of each model. The results are tabulated in Table 1 below:

Table 1. Prediction performance of the combined approach in comparison with the conventional methods (Abraham et al., 2020a).

Statistical Attributes	ID threshold	ED threshold	Field monitor ing	ID + Tilt	ED + Tilt
TP	50	50	86	66	66
FP	134	118	273	71	63
FN	48	48	12	32	32
TN	926	942	787	989	997
Efficiency	0.84	0.86	0.75	0.91	0.92
Odds ratio	5.36	5.98	3.06	10.24	11.19
Specificity	0.87	0.89	0.74	0.93	0.94
Sensitivity	0.51	0.51	0.88	0.67	0.67
Likelihood ratio	4.04	4.58	3.41	10.05	11.33

The major drawback of the conventional methods when applied independently, is the large number of FP. The fact the conventional thresholds do not take into account a lag time will lead to many missed alarms as well. The type of landslides considered for the study includes very slow displacements as well, and hence any day on which subsidence is recorded is counted to be a day with landslide. The total number of days affected with landslides during the study period is 98. It is interesting to note that the tilt rates have crossed the threshold values in most cases, but at the same time, the number of FPs are also the highest in this case. The FPs are evident in Fig. 4 as well. This is the result of very high sensitivity of the sensors used for monitoring. The higher number of FPs also stresses the significance of data analysis and meaningful interpretation before issuing alerts.

Table 1 shows that that the forecasting ability of both ID and ED thresholds are increased substantially, by applying the combined approach proposed in this study. The major difference noticed after the usage of the new approach has occurred in the reduction of FPs issued. The count of FP has been lowered to 63, using the proposed algorithm-based approach.

The method proposed in this study should be taken as prototypal due to the high rate of faults still existing; however, the test developments could be assessed ameliorative when compared to the conventional methods applied independently. Thus the method denote a step in the correct way for a more sensible management of landslide hazard in the study area. The approach proposed in this study, can be certainly exported to other regions, to test its effectiveness in enhancing the forecasting ability of conventional thresholds in different settings.

To know the likely usage of the combined approach for various meteo-hydrological conditions, laboratory scale research can also be carried out. This can be used to confirm the likelihood of exporting the method to various regions, by the simulation of various meteorological conditions on several topographical and soil conditions (Cogan and Gratchev, 2019; Ivanov et al., 2020). The prototypal model formed in this study applicable to the test site in Kalimpong only, where slope failure happens at very gradual rates and seen as ruptures and movements in the uphill areas. By conducting a laboratory scale research, it is feasible to attempt several types of landslides and identify separate thresholds using simulations. Such findings can aid in the customization of the proposed method and critical tilt rate for different meteorological and topographical settings and can support in studies at large scale.

## 5 CONCLUSIONS

The conventional rainfall thresholds derived for Kalimpong region in West Bengal are assessed quantitatively, using the database of monsoon seasons from 2017 to 2020. The results

confirms that the large number of FPs make them inappropriate for usage in an LEWS. Even though the conventional thresholds forecast the most slope failures correctly, the FPs affect the dependability of the method and it is difficult to use the method for LEWS. To avoid this constraint, tilt angle readings obtained from MEMS based sensor data from Chibo was used to boost the forecasting ability of the conventional thresholds.

The tilt sensors were utilised to amend the empirical rainfall thresholds, by means of an algorithm-based approach, that merges lag time, rainfall thresholds, and the tilting rates. As per the algorithm, the conventional thresholds were considered as a first step and the severity of a possible slope failure was confirmed using the tilt meter readings, to issue warnings. The findings indicated that the proposed method is performing better than both the original methods, with a likelihood ratio of 11.33 and efficiency of 92 %. The algorithm overcomes the limitations of both the individual methods and can be made use of, by the concerned authorities to notify the people concerning a probable slope failure. The prototypal model is found to be a possible tool which can be developed as a part of LEWS, with further fine tunings.

## 6 ACKNOWLEDGEMENTS

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