Early Warning of Water-Triggered Landslides

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Abstract. Landslides are a major societal threat, causing adverse consequences to life, economy and environment. Mitigation of the potential negative effects of landslides commonly involves deployment of challenging and costly measures. This is often the case in the development and operation of linear infrastructures such as road, pipeline, and railway networks in landslide-prone areas. One of the commonly employed measures for mitigating the adverse consequences involves monitoring of landslide triggering parameters and issuing timely warnings. Given that the landslide triggering parameters (e.g., large weather systems, local man-made triggers) and the linear infrastructures span varying spatial scales, there is a need for developing a landslide monitoring and early warning system for both regional as well as local scales. This paper presents a brief introduction of the Norwegian practice for early warning of landslides triggered by extreme weather on regional scale, which has proven to be effective. The criteria for issuing an early warning are based on the degree of saturation of soil and the supply of water to it through rainfall and snow melting. On other hand, monitoring of single slopes on local scales can be quite challenging and expensive. In order to provide landslide monitoring systems of single slopes in affordable price, Indian Institute of Technology Mandi developed a low-cost landslide monitoring and early warning system. These systems are deployed in Mandi district of Himachal Pradesh, India and monitoring fifteen plus landslide locations. A recent case study is also discussed in this paper where these systems helped in alerting people and traffic from an impending landslide.

Keywords: Landslides, Early Warning System, Landslide Monitoring.

1 Introduction

Infrastructure development including building of roads, airports and railway networks on slopes is highly challenging and expensive due to the threat of landslides i.e. down-slope movement of soil or rock along a failure plane. Landslides are triggered by combinations of natural and man-made causes such as severe rainfall, rapid snow melt, earthquake, or human activities. Moderate to steep slopes in weak soil or rock are most susceptible to landslides. Each year huge amount of property and human lives are lost due to landslides worldwide. UNISDR (2018) quotes "*nearly 87% of disaster related spending goes on response, reconstruction and rehabilitation and only 13% goes towards managing the risks, which are driving these disasters including landslides in the first place*".

Fig. 1. (Left) Water triggered Paddhar landslide in 2017 in Himachal Pradesh due to intense and persistent rainfall. The failed slope was approximately 250 m high and 150 m in width. Approximately 300 000 m^3 debris was displaced for approximately 950 meters resulting taking 46 lives. (Courtesy: Himachal Pradesh State Disaster Management Authority)

It has become quite evident that changes in the climate cause a notable increase in the frequency of landslides. Triggering factors such as extreme rainfalls, rapid snow melts, permafrost melting and abrupt temperature change are the most common climate factors leading to naturally occurred landslides (referred as water triggered landslides). Landslides cause major infrastructure damages and deaths in India. Paddhar landslide in 2017 in India exemplifies this, Ref. Figure 1 for the details. More than INR 1000 crores/year economic losses and more than 1000 deaths/year is registered in India mostly confined to the Himalayan region. Due to landslides, average losses in Himachal Pradesh alone cost more than INR 300 crores per year and cause more than 200 deaths per year (Chaturvedi et al., 2018). It is worth mentioning that majority of water triggered landslides are along transport infrastructure such as roads, railroads and pipelines, which forms the lifeline of modern society. Their reliable and secure operation is paramount to national security and economic vitality.

Similarly, a significant part of European transport infrastructures is located on or in unsafe ground and are thus subjected to risks of landslides. At least 8,000 to 20,000 km of roads and railways are highly exposed to landslide (Ko et al. 2005; Thakur et al. 2017). These risks result in high costs, with global annual losses of €18 billion caused by landslides. These losses comprise 17% of the €110 billion in global natural disaster losses each year. A majority of these costs are related to the repair and rehabilitation. In Italy, for example, total landslide-related damages in 2015 amounted to €3.9 billion (Klose et al. 2015). Germany reported an annual total loss of about €68 million in 2015 from landslide damage to the highway system alone (Klose 2015). Another example involves the collapse of the ground beneath Norway's Dovre Railway (Dovrebanen) in March 2012, for which direct repair costs exceeded €5 million. Indirect losses were significantly higher because Dovrebanen was closed for months for repair, and thus a major railroad connecting the Norwegian cities of Oslo and Trondheim was put out of commission.

The most frequent water-triggered landslides are seen in course-grained soils (sandy silty materials, tills, residual soils, debris). Sliding surface is often 1 to 2 meters deep in soil deposits as a direct result of infiltration of water in initially partially saturated soils. Shallow landslides, i.e., slides, debris slides and debris flows are the most common water-triggered landslides. Measures for mitigating of such landslide can be (a) structural solutions to reduce the frequency and severity of landslide events and (b) non-structural solutions to reduce the consequences through monitoring and prediction, improved land planning, rerouting, evacuation and early warning systems. Early Warning (EW) systems have a great flexibility and costs much lower than structural solutions, which motivated the development of a wide range of solutions that are limited to varying degrees in terms of applicability, types of measurements, fabrication costs, maintenance and accuracy. In the last decade, studies on sensor-based solutions and real-time monitoring of slopes have enabled the development of landslide mitigation strategies based on EW systems. Due to the limitation in terms of the length of the paper, our focus is limited to describe a well-functioning EW method used in Norway and an ongoing effort in India by IIT Mandi to develop low-cost EW system for water-triggered landslides.

2 Prerequisites for early warning systems

UNISDR (2009) defines an EW system as "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss. An EW system shall consist of the following components: knowledge of and means of forecasting the water-triggered landslides; information from technical monitoring and field observation; preparedness plan to act or response; dissemination of warning to population exposed to landslide risk; and public awareness and preparedness. Selection of an EW system depends on several factors. However, landslide type, and the scale of the landslide are the two major factors. Cruden and Varnes (1996) classified landslides based the movements and the material types. They suggested five movement types: fall, topple, slide, spreads and flow and three material types i.e. rock, course grained soils and fine-grained soils.

The scale of EW can be either a slope scale or regional scale. A slope scale requires a set of monitoring technologies; operated either remotely or on site. Shallow landslides are not recurrent at a given location. However, they recur within a region. Therefore, EW of shallow landslides on a regional scale has been the approach that is more popular. The reliability of EW for water-triggered shallow landslides depends on accuracy of meteorological, hydrological, hydrogeological, or geotechnical parameters. The EW of such landside is often issued using intensity–duration curves for rainfall as thresholds with varying degree of accuracy.

Another crucial aspect related to early warning is time. A successful EW shall be able to identify and measure the initiation of a landslide, and issue warnings early enough to allow sufficient time to implement actions to protect life and properties. As the forecasting of temperature, rainfall is becoming accurate, a direct link between rainfall event and landslide occurrence is becoming increasingly efficient, in a statistical way, to provide early warning at small scale.

3 Norwegian Practice of Early Warning of shallow landslides on regional scale

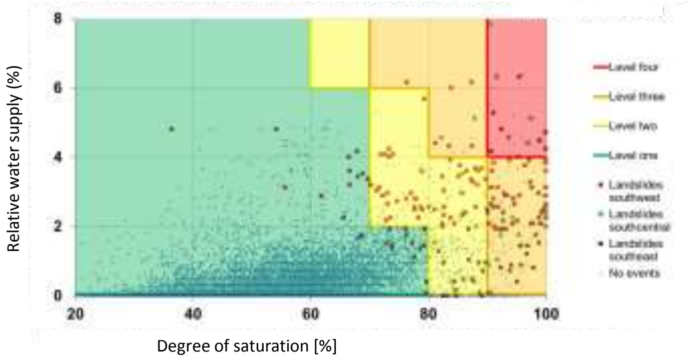


Fig. 2. National threshold for the early waning of water triggered landslide in Norway (www.nve.no). Source (www.nve.no and www.varsom.no)

Norwegian forecasting system for water-triggered landslide is developed and coordinated by Norwegian Water Resources and Energy Directorat (NVE). The EW is issued by NVE through www.varsom.no for the whole country with 1 km x 1 km resolution. The criteria for EW is based on relative water supply and the soil water saturation degree (see Figure 2) using the real-time data, climate model and simulation of hydrological data using a distributed version of the hydrological HBV model (Beldring et al., 2003).The model divides Norway into 1 km2 grid cells (total over 385 000 cells).

The relative water supply accounts for rainfall or the supply from melting of snow from the snowpack normalized with an annual average value for a 30-year period. Similarly, the relative degree of saturation (%) is the total water content normalized with annual average water content in the ground for a 30-year period. Figure 2 shows the national threshold used in Norway to issue early warning of water triggered landslide. The EW has four danger levels, see Table 1 for the description. The accuracy of this EW is above 95%. The EW is being improved further by combining it with susceptibility maps and also by developing regional thresholds to issue warning. A detailed information about the EW can be found in Devolli et al. (2018).

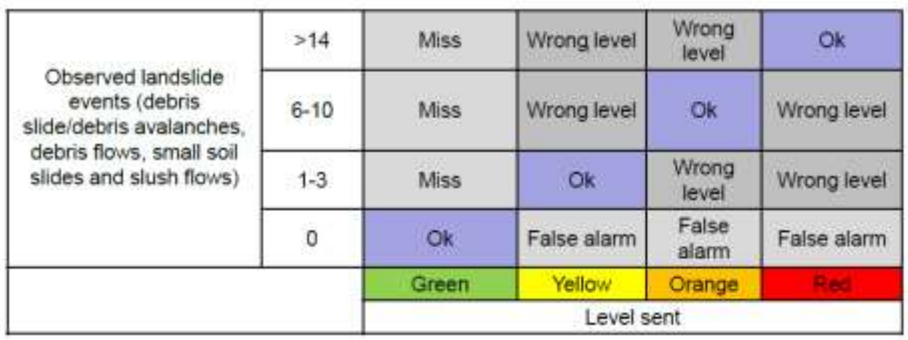
Table 1. Awareness levels for landslide hazards used in Norway (www.nve.no)

Awareness levels	Description
Green awareness level (1)	Generally safe conditions.
Yellow awareness level (2)	Situation that requires vigilance and may cause local damages. Expected some landslide events, certain large events may occur. Local flooding and/or erosional damage due to rapid increase of discharge in streams/ small rivers, ice drift, ice in streams/rivers and frozen soil.
Orange awareness level (3)	Severe situation that occurs rarely, requires contingency preparedness and may cause severe damages. Flood: Return period of more than 5 years Expected many landslide events, some with considerable consequences. Extensive flooding, erosional damage and flood damage to certain prone areas.
Red awareness level (4)	Extreme situation that occurs very rarely, requires immediate attention and may cause severe damages. Expected many landslide events, several with con-

	siderable consequences. Extensive flooding, erosional damage and flood damage to buildings and infrastructure.

There are two major demanding issues related to the designing of an EW. Firstly, the specification of appropriate threshold values for the alarms and secondly, number of false alarms and missed events. The consequences of false alarms and missed events are often so serious that every possible action must be taken to avoid them (Calvello et al. 2015). The criteria to assess the accuracy is based on how many false alarms are triggered for each danger level, ref. Table 2. The accuracy of the EW in Norway is close to 97% which can be considered quite effective (Davolli et al. 2018).

Table 2. Criteria used to evaluate the early warning system in Norway



Observed landslide events (debris slide/debris avalanches, debris flows, small soil slides and slush flows)	>14	Miss	Wrong level	Wrong level	Ok
	6-10	Miss	Wrong level	Ok	Wrong level
	1-3	Miss	Ok	Wrong level	Wrong level
	0	Ok	False alarm	False alarm	False alarm
		Green	Yellow	Orange	Red
		Level sent			

4 IoT based Early warning of landslide on a single slope scale

Recent developments in the domain of the environmental Internet of Things (IoT), however, have generated a spectrum of new opportunities for developing non-structural solutions for the prevention, detection, response and mitigation of geo-hazard risks with advanced monitoring and early warning (EW) systems. The IoT is a powerful concept of interacting with the physical world through a network of natural or manmade objects that are connected to the internet and process the collected information automatically, with or without human intervention, to gain crucial insights that support more efficient management of limited resources. The flexibility and scalability of IoT-based EW systems support significant automatization of landslide risk assessment through the implementation of advanced data analysis, statistical learning algorithms, and efficient integration of data with advanced geohazards prediction models.

IoT technology can advance existing monitoring solutions with the deployment of cost-and power-efficient, scalable and flexible IoT devices. There are several ongoing projects investigating the advantages of IoT technologies in collecting and transferring data from sensors commonly employed in MEW systems for landslides (KlimaDigital 2019; Chaturvedi 2018, Oguz et al. 2019). The Indian Institute of Technology (IIT) Mandi has developed a low-cost IoT solution for monitoring and EW of water-triggered landslides in India (Chaturvedi 2018). Figure 3 is a picture of the IoT system being developed by IIT Mandi. This IoT system is being used to monitor and issue Early Warning of landslides at 20 different locations in India. The IoT device has sensors that can be divided into several categories: soil sensors, meteorological sensors, IoT device sub-components, and programmable local outputs. A brief description of the components included with the IoT device, and their functions is provided in the following section.

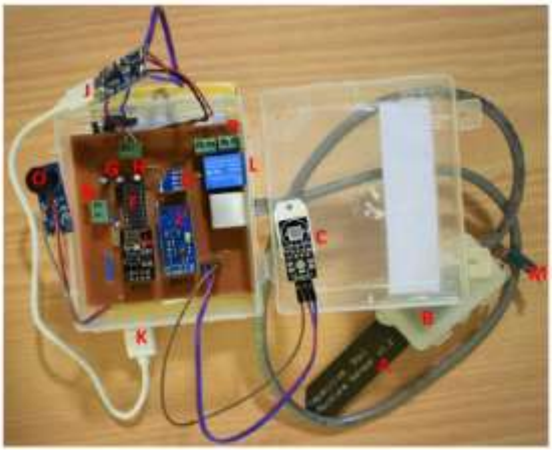


Fig. 3. IoT device developed by IIT Mandi

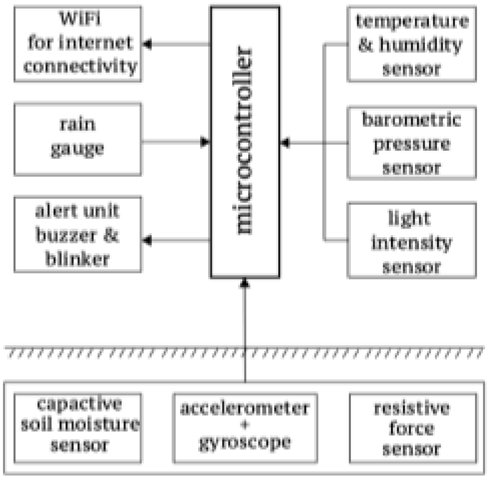


Fig. 4. The architecture of the IoT device developed by IIT Mandi.

The IoT device's main unit contains the meteorological sensors. The meteorological factors that can be monitored include temperature, humidity, light intensity, barometric pressure and rainfall.

A: Capacitive Soil Moisture Sensor: Capacitive soil moisture sensor works on the principle of change in capacitance due to changes in the dielectric properties of the soil in contact with the sensor. The sensor measures the resonant frequency of an RC circuit and this frequency value is linearly calibrated to volumetric water content of soil in percentage. The sensor's range is between 0-100% moisture by volume, its accuracy is +/-5%, and its sensitivity is +/-1%

B: Motion Processing Unit (MPU) Accelerometer: The accelerometer has both 3-Axis accelerometer and 3-Axis gyroscope integrated on a single chip. The gyroscope measures rotational velocity or rate of change of the angular position over time, along the X, Y and Z axis. It uses MEMS technology and the Coriolis Effect for measuring. The outputs of the gyroscope are in degrees per second, so in order to get the angular position we just need to integrate the angular velocity.

C: Digital Relative Humidity and Temperature Sensor: The hygrometer is used to measure the humidity in the air, using the capacitance method. Since relative humidity is the relationship between amount of moisture in the air and the moisture capacity of the air, which is dependent on air temperature, the hygrometer also measures air temperature. The air humidity can be used as a climatic indicator for precipitation and evapotranspiration potential, and can be used when computing energy balances.

D: Barometric pressure and Temperature Sensor: This sensor uses piezo-resistive technology to measure the air pressure at a certain elevation, meaning the sensor monitoring elevation must be specified in the program. Since most barometric pressures are reported as coming from sea level, the pressure is also calibrated based on the elevation of the sensor and reported back as equivalent sea level pressure. The barometric pressure can give an indication of changing weather patterns and indicate if high or low pressure zones are approaching.

E: Digital Light Intensity Sensor: The light intensity sensor measures the amount of luminance in the surroundings using a photo-diode, which converts incoming light to a current directly proportional to the amount of incoming light. The luminance is the amount of light per second per unit target area on the sensor, measured in units of lux. The luminance can give an indication of the weather and short-wave radiation entering the atmosphere, and could also be a useful measurement if solar panels are used to charge on-site batteries.

N: Rain Gauge: The device has pins for a rain gauge sensor. A rain gauge would provide a point measurement of precipitation at the slope location, instead of relying on weather stations which may not be near the site.

IoT device sub-components: These sub-components make up the hardware of the IoT device, connecting the microcontroller with the sensors, providing power and protecting the IoT device from high voltages.

F: Microcontroller: The microcontroller used in this IoT device is the same microchip used in the Arduino platform, through which the chip is programmed and connects with a computer. The microcontroller is an 8-bit, 28 pin plastic dual in-line package (PDIP), which runs the uploaded program and controls all the sensors in the IoT device. The program uploaded to the microcontroller controls the sensor reading frequency, data upload frequency and all information required to read the sensors. Any program uploaded to the microcontroller is immediately activated.

G: Linear Voltage Regulator: This voltage regulator drops incoming voltage to the IoT device to a maximum of 5V. The microcontroller and other components will not survive voltages higher than 5V without burning out, so this regulator is very important should any voltage higher than 5V be placed on the system. Since the input voltage coming from the battery and solar panel should never exceed 5V, and there were issues with voltages being too low for the device to function properly, this regulator was eventually removed from the system.

H: Fixed LDO Voltage Regulator: This voltage regulator further drops the voltage to 3.3V, which is the minimum required voltage for WiFi module. Wi-fi module is not capable of handling voltage more than 3.3V. This regulator is a Low Voltage Dropout (LDO) regulator, which can better handle small changes in voltage where other regulators require a larger voltage difference.

I: Wi-Fi module: The Wi-Fi module gives the microcontroller access to the internet. The module can be programmed as an access point, which allows other devices to connect to it via Wi-Fi, or as a station, where it searches for a Wi-Fi network with specific credentials and connects to it when found.

J: Battery Charger with Protection Module: The battery charger provides power to the IoT device from either the battery or the power source with solar panel. This module allows the battery to be charged from the power source while still powering the IoT device, and shuts off once the battery is charged.

K: Power Source: The power source is equipped with a solar panel to recharge the battery connected to the IoT device.

L: Relay module: Relay provides us the interface to switch on and off the alert unit for the local alerts.

M: Force Senstive Resisitor: A force-sensing resistor is a material whose resistance changes when a force, pressure or mechanical stress is applied. They are also known as "force-sensitive resistor" and are sometimes referred to by the initialism "FSR".

The server then reports the data via a web-based interface, at the url: http://landslidemonitoring.esy.es/index.php. Some data recorded by the IoT device is shown in Figure 5.

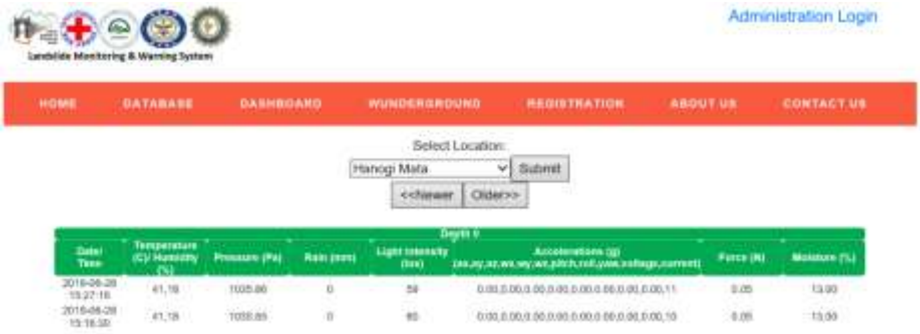


Fig. 5. Visualization of the portal for landslide monitoring and warning system by IIT Mandi

5 A case study of IoT based Early warning of Paddhar landslide on a single slope scale

Kotropi, a village located 35-kilometers from Mandi bus stand along the NH 154 in Paddhar, witnessed a massive landslide in August 2017 (ref. Figure 1) that killed more than 50-people. After the disaster, a temporary road was made through the debris for traffic flow. It is reported that Kotropi started experiencing a sewage overflow situation, which was originally a part of its old route due to substantial rainfall activity. For draining this sewage overflow, public works department (PWD) had constructed a drainage facility. However, the internal water source was still active at some places underneath the temporary road, which was not easy to identify in the massive debris. When the monsoon started in July 2018, the sewage broke the integrity of soil and allowed water to go through as water finds its path through points of lowest energy. This breakage caused the movements in soil internally, and it started sliding. This internal slide of earth began to rupture the road from the corner with a way to release internal water. This complete scenario activated movements in the soil.

At 2:30 AM, on the night of 27th July 2018, it was raining heavily at Kotropi village, and a flash flood occurred. Underground water came rushing down towards the NH 154. However, between the water source and the road, there existed a low-cost landslide monitoring and warning system (LMWS), which the Mandi district administration had just deployed a few weeks back in collaboration with IIT Mandi. The LMWS was triggered by rainwater, and the system sounded an alarm, which the police guards on the NH 154 heard in time. Figure 6 shows the movement recorded by LMWS at Kotropi between 29th June 2018 and 23rd November 2018. In the figure, one can see rapid movements in all three directions on 27th July 2018. With the signals from the installed signal posts warning the possibilities of rapid movements alerted the response team at site. Immediately, the disaster response team brought the traffic to halt which saved around 4-5 vehicles entering the sliding zone as per the report issued by district administration. This remains the one of the first positive alerts issued based on the monitoring of progressive movements observed at the site, subjected to rainfall induced landslide post a year of major incident happened in July, 2017.

Fig. 6. The movement recorded by LMWS in X, Y, and Z directions between 29th June 2018 and 23rd November 2018. The movement due to the flash flood at Paddhar on 27th July 2018 has been highlighted with a red oval.

6 Closing remarks

This paper presented a brief introduction of the Norwegian practice for early warning of ra landslide on regional scale. The criteria for issuing early warning is based on degree of saturation of soil and the supply of water to it through rainfall and snow melting. The paper also presented a promising development related to monitoring of single slopes. Indian Institute of Technology Mandi has developed a low-cost landslide monitoring and early warning system. These systems are deployed in Mandi district of Himachal Pradesh, India and monitoring more than fifteen landslide locations in India. Through a case study the usefulness of the systems was shown how it helped in alerting people and traffic from an impending landslide.

7 Acknowledgments

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