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Moisture sensing technology for assessment of rainfall-induced slope failure

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ABSTRACT: The frequency and duration of rainfall are two examples of the climatic conditions that have changed as a result of global warming. According to earlier research, slope failures are more likely to happen after a protracted period of drought followed by a strong rainfall or after a long period of light rains followed by a heavy rainfall. This occurrence demonstrates the significance of slope susceptibility or hazard maps in identifying high-risk areas during periods of excessive precipitation. The stability of high-risk slopes can then be sustained before failures by designing the proper slope preventive actions. This study reviewed various moisture sensing technologies for real-time evaluation of slope collapses brought on by rainfall. A thorough analysis of various literatures revealed that capacitance moisture sensors offer the best compromise for affordable and effective early warning systems, particularly in a tropical environment.

1 INTRODUCTION

As industry and human activity has increased, so have greenhouse gas emissions, which has significantly accelerated global warming. According to the most recent conclusions from the Intergovernmental Panel on Climate Change (IPCC, 2021), any forecasted emission scenarios will result in an inescapable rise in temperature over this century. Temperatures and humidity have risen throughout numerous regions, while rainfall patterns have altered. Numerous geotechnical structural issues involving road building, foundation design, slope stability, municipal waste storage, and nuclear waste disposal are frequently caused by climate variations, and these issues call for a fundamental understanding of unsaturated soil mechanics. Rainfall-induced slope failures are one of the most frequent physical dangers in the globe (Kristo et al., 2017; 2019; Rahardjo et al., 2007). Long and severe episodes of rainfall, which are anticipated to occur more frequently as a result of climate change, are what cause the majority of these slope failures. In example, steep and high slope with deep groundwater table frequently experience rainfall-induced slope failures (Chua et al., 2022; Rahardjo et al., 2007). According to research, shallow slip surfaces are typically involved in rainfall-induced slope failures in Asia, as seen in Kazakhstan (Satyanaga et al., 2022), Hong Kong (Brand, 1993), Singapore (Chan et al., 2020; Rahardjo et al., 2020a), Sri Lanka (Nawagamuwa and Dayarathne, 2014), and Malaysia (Saadatkha et al., 2015).

The main contributing variables to unsaturated soil mechanics have been identified as changes in soil suction and volumetric water contents. In addition, reductions in soil suction and shear strength can result in slope failures brought on by rainfall (Fredlund et al., 2012; McCartney and Khosravi, 2013). Numerous studies on landslides are carried out to promote the development of in-situ real-time monitoring employing field equipment (piezometers, tensiometers, and moisture sensors) to measure the water and suctions contents of the soil (Alonso et al., 2003; Greco et al., 2013; Rahardjo et al., 2014; Leung and Ng, 2016; Kim et al., 2017).

In order to measure soil suction in the slope, conventional water-based tensiometers are frequently employed. However, there were numerous restrictions on soil suction measurements, particularly in relation to concerns with maintenance and durability (Guan and Fredlund, 1997;

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Tarantino and Tombolato, 2005; Rahardjo and Satyanaga, 2019; Satyanaga and Rahardjo, 2020). Therefore, considerable work has been put into developing a soil moisture measurement system with increased measurement capacity and reliable performance. The goal of this work was to offer acceptable soil moisture sensors for real-time assessment of rainfall-induced slope failures by analyzing the various types of moisture sensing devices.

2 MOISTURE SENSING TECHNOLOGY

Early Warning Slope Stability Monitoring (EWSSM) systems are becoming more and more popular, but their widespread deployment has been stymied (Oguz et al., 2019) by the expensive sensors, complexity, and lack of automation of the techniques, as well as the need for regular maintenance. To predict rainfall-induced slope failures, scientists from all over the world are searching for an effective EWSSM solution (Pajali et al., 2021). Unpredictable behavior of landslides leads to serious outcomes like human casualties and financial damage. One of the key elements in keeping track of the slope instability brought on by rainfall is the soil-water dynamics. Regular measurements of the soil moisture are required for excellent simulation accuracy (Rodriguez-Iturbe, 2003).

For a variety of purposes, including agriculture, oil and gas, studies of climate change, slope stability evaluation and monitoring, numerous companies and researchers have researched soil moisture sensing systems in the recent years. The system should have appropriate response time for an early warning system built in, be low cost, simple to maintain, and suitable for real-time monitoring before a slope fails.

The many methods for detecting soil moisture that are currently available each have their own benefits and drawbacks. To choose the best one to use, some work is needed. Figure 1 depicts common methods for assessing soil moisture. Typically, two methods can be used to measure soil moisture: Soil Water Potential (SWP) and Volumetric Water Content (VWC). The most popular key parameter for assessing slope stability is SWP. SWP can be measured using tensiometers and resistance blocks (gypsum blocks), which are pricey and require extensive maintenance (WMO, 2018). Additionally, salinity has a significant impact on the readings of Gypsum blocks, and sensors have a limited lifespan in a salty environment.

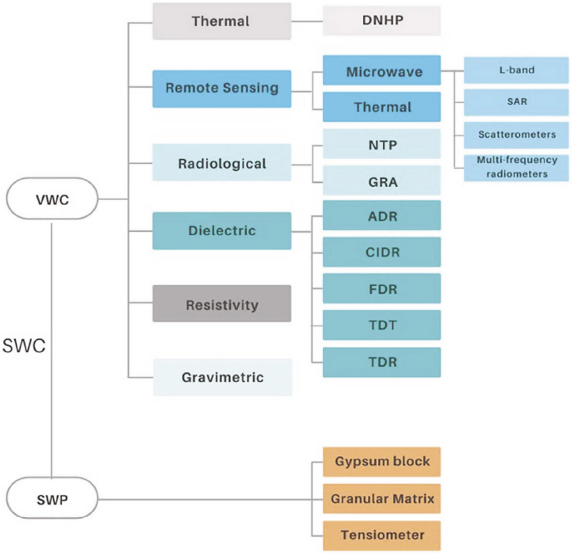

Figure 1. Prevalent soil water content (SWC) measuring techniques.

VWC is a crucial measure to quantify the effect of rainfall on the stability of the slope, according to studies by Greco et al. (2010) and Rahardjo et al. (2020a). Additionally, Greco et al. (2010) determined that VWC should be prioritized over SWP when developing a successful EWSSM system since VWC varies gradually whereas SWP may experience abrupt changes that are challenging to interpret. To increase the precision, accuracy, optimization, and cost effectiveness of moisture sensing technology, a variety of businesses and research institutes have looked at a number of approaches to measure and monitor VWC. Only a few of the widely used VWC approaches that are practical for slope stability monitoring can fulfill specific project needs when taking into account the advantages and disadvantages of each technology. Low cost, which includes the price of the sensor system, installation, and maintenance, was one of the key factors in the decision. Cost-cutting, though, shouldn't come at the expense of accuracy. At the same time, the technology must be reliable, straightforward to use, and energy-efficient. The sensor system should also be able to gather measurements from various depths in one place. This will enable the creation of a hydrological profile of slopes and improve the usability and accuracy of monitoring.

2.1 *Thermogravimetric technique*

The thermogravimetric method measures gravimetric water content (GWC) directly and uses oven drying to ascertain the real water content of soil samples. VWC can be calculated from GWC using the bulk density of the soil. The strategy is not practical for the EWSSM system due to its destructive nature and lack of logging capacity (Little et al., 1998). Before installing them on the actual slopes, it can be used to calibrate some water content sensors (such capacitors) for the soil.

A reliable methodology for carrying out automated VWC measurements with high temporal and spatial precision in the field is the Dual Needle Heat Pulse technique (DNHP) (Oschner et al., 2003). The DNHP sensor consists of two tiny (a few millimeters) needles, one of which acts as a heater and the other of which records temperature changes. Heat capacity is calculated and converted into VWC. Since the probe needles are so sensitive, any physical variation can cause measurements to be inaccurate. The technique precisely measures temperature changes just a few millimeters from the needle. To reduce the fluctuation of the DNHP sensor accuracy, Liu (2011) developed a thermo-Time Domain Reflectometry technique (TDR) sensor based on the combination of two techniques: heat-pulse and time-domain reflectometry. Thermo-TDR sensor might offer precise field estimations of VWC.

2.2 *Remote sensing*

The soil thermal characteristics measured by remote sensing can be used to estimate the moisture of the topsoil (top 5 to 10 cm) on a global scale (Mohanty et al., 2017; Lakhankar et al., 2009). To remotely monitor soil moisture over wide areas, radiometers and radars are fitted to satellites (Muoz-Carpena, 2012). The two main categories of remote sensing technologies are thermal infrared and microwave remote sensing. By analyzing interactions between the ground and electromagnetic (EM) waves, microwave techniques can estimate the soil's dielectric characteristics, allowing for the determination of the landcover's VWC (WMO, 2018). On the basis of the variations in the thermal characteristics of soil and water, thermal infrared remote sensing can be used to determine VWC (WMO, 2018). The strong contrast between the dielectric and thermal characteristics of wet and dry soil is used to determine the soil moisture (Lakhankar et al., 2009). In most cases, space-based remote sensing techniques offer measurements of moisture with time intervals of one to three days (passive radars) (WMO, 2018) or a few months (active radars) (Mohanty et al., 2017).

The Soil Moisture Near Real-Time Processor (SM-NRT-OP) was introduced in a new version of Soil Moisture and Ocean Salinity (SMOS) released by the European Space Agency in May 2021. With the fastest data retrieval possible, it promises to give soil moisture readings based on a neural network approach within three hours of sensing (European Space Agency, 2021). The spatial resolution of the measurements ranges from ten meters (synthetic aperture radar) (Moran et al., 2004) to tens of kilometers (passive radiometer) (Mohanty et al., 2017) depending on the remote sensing technique. Through the application of averaging parameters, the use of satellite-based technology to retrieve soil moisture data for vast areas appears promising. However, because of the relatively high cost, complexity of implementation, and highly fluctuating soil moisture across both time and location, this technology is not yet ready to be employed for the EWSSM system in small metropolitan islands (such as Singapore). The technique's ability to accurately predict rainfall-induced slope failures is constrained by the fact that it can only determine the soil moisture content within the top 10 cm of the surface and at a time-frequency of 3 hours at best.

2.3 *Radiological technique*

A reliable way for obtaining precise VWC profiles at any depth up to the length of the logging line is radiological technology. Currently, the soil water content (SWC) can be measured using either the neutron thermalization probe (NTP) or the gamma ray attenuation method (GRA). According to Muoz-Carpena (2012) and WMO (2018), the NTP approach is based on the interaction of high-energy (fast) neutrons with hydrogen atom nuclei. A wetter soil is represented by a slower neutron flow. Gamma ray attenuation as it travels through soil pores is measured using the GRA method (Muoz-Carpena, 2012).

2.4 *Resistivity and dielectric technique*

By measuring electrical resistivity between two electrodes, the Resistivity method (Res) is used to determine the relative moisture content. Due to its extremely low precision, the resistance probe is not appropriate for effective warning systems (Fares et al., 2011). Salinity of the soil has a considerable impact on it, necessitating frequent calibration (Tremsin, 2017). Additionally, sensors lose their effectiveness quickly. According to Muoz-Carpena (2012), the soil-probe impedance can be utilized to determine the soil water content using the amplitude domain reflectometry technique (ADR). An electro-magnetic field that is propagating between the rods is created by an oscillator. The measured impedance is a function of the soil dielectric constant. There are numerous more soil factors that affect the VWC as evaluated by the ADR approach (e.g., density, temperature, and salinity). The usefulness and viability of the ADR approach for slope stability monitoring were proven by Shimobe and Ujihira (2009). Rod contact with stones, air spaces, or water channels has a significant negative impact on the accuracy of ADR measurements. The cost of deployment is impacted by how sophisticated the system is set up. Additionally, there aren't enough field studies and publications to draw firm conclusions about its applicability for the larger EWSSM system.

Based on measured dielectric permittivity (real and apparent), the soil moisture is estimated using the Coaxial Impedance Dielectric Reflectometry technique (CIDR). The electromagnetic signal (EM) produced by an oscillator travels through the metal tines and goes into the soil (Ojo et al., 2015). The sensor determines the strength of the incident and reflected signals. After determining impedance, the raw voltage ratio is used to determine dielectric permittivity. Although the CIDR sensor's creators assert that soil-specific calibrations are not necessary, the results of an independent research revealed that doing so improves the accuracy of the sensors (Ojo et al., 2015). In order to minimize ongoing dependencies, it is not recommended to use the sensor for large-scale applications because CIDR is a patented technology.

Based on apparent dielectric permittivity, the Frequency Domain Reflectometry technique (FDR) is used to measure SWC (Ferrarezi et al., 2020). An oscillator creates an electromagnetic signal (EM signal) that travels through metal electrodes. The interference waves that are produced are then monitored at continuous frequencies (Brahma and Goswami, 2017). For reliable results, a soil-specific calibration is needed for the FDR sensor (Muoz-Carpena, 2012). Additionally, the accuracy of sensors is greatly dependent on the probes making excellent contact with the soil, and soil temperature might have an impact (Brahma and Goswami, 2017). However, this sensor is able to produce measurements at various depths at the same spot and can be used in high salinity environments. This method is also thought to be too sophisticated and expensive to be used with the EWSSM system.

The Time Domain Reflectometry (TDR) method is a well-liked method for obtaining precise measurements of VWC (Nobrio, 2001; Ferrarezi et al., 2020; Askarinejad et al., 2018). The usage of TDR technology in the field is supported by a considerable number of publications. The sensors can detect the presence of water in many types of soil, but only at a single depth and one location (Campbell, 2017). The generator transmits an EM pulse through the sensor rods, which is the fundamental idea behind TDR. The pulse moves to the rod's end and reflects there. The soil's dielectric permittivity, which can be translated into water content, determines how long it takes for the pulse to go down and then return up (Topp, 2003).

A more advanced substitute for the TDR is the Time Domain Transmissometry technique (TDT). The TDT method only calculates the length of time needed for an EM pulse to travel to the rod's end. Consequently, the transmission line must have an electrical connection at both ends (Will et al., 2012). It is possible to estimate the water content by using the relationship between the pulse's travel time and the dielectric constant. TDT, like TDR, is a sophisticated and pricey technology that does not meet the specifications of the EWSSM system.

2.5 *Capacitance technique*

The dielectric permittivity of the soil is determined using the capacitance technique (Cap), which is influenced by the soil's water content (Atkins et al., 1998). The ability of a medium to store charges is measured using two electrodes (metal probes). The charge time in the soil is measured using an oscillating voltage, which links the dielectric permittivity to the volumetric water content. Capacitance sensors have undergone a revolution in electronics recently, including their accuracy. Capacitors are out of date due to their inaccuracy and overestimation of moisture in saline environments. The effects of salinity are minimized by using the high-frequency technique (Fares et al., 2011) in the construction of contemporary sensors. Capacitance sensors are a common low-cost option for large sensing networks nowadays since they are very precise (Campbell, 2017). Additionally, this sensor's setup, upkeep, and data administration are the most straightforward of all the soil moisture measurement options. Because cap sensors use less energy and are environmentally beneficial, they could be used for many years (Campbell, 2017). Additionally, Cap sensors that have been modified with a unique circuit architecture may detect incredibly minute changes in VWC. These customized sensors have been used by NASA to investigate whether there is water on Mars (Campbell, 2017). Thus, Cap can be seen as a very alluring technology that may be used in effective and affordable EWSSM systems.

3 CONCLUSION

A thorough analysis of several moisture sensing technologies revealed that capacitance moisture sensors offer the best compromise for affordable and effective early warning systems, particularly in a tropical environment. With less expense, precision, and little maintenance requirements, capacitance sensors enable smooth water content measurement for critical slopes of interest.

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