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Operating Principles of Soil-Moisture Sensors and the Role of Capacitive Soil-Moisture Sensors in Landslide Early Warning Worldwide and in Vietnam

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Abstract
Rainfall-induced landslides are among the most damaging geohazards worldwide and in Vietnam, particularly in mountainous areas characterized by steep terrain, highly weathered soil profiles, and extreme rainfall. In this context, monitoring the moisture state of soil is highly significant because soil moisture directly reflects infiltration, the degree of saturation, and the reduction of matric suction prior to slope instability. This paper reviews the operating principles of soil-moisture sensors and analyzes the role of capacitive soil-moisture sensors in landslide early-warning systems worldwide and in Vietnam. In principle, capacitive sensors estimate volumetric water content through changes in the dielectric permittivity of the soil-water medium; because water has a much higher dielectric constant than the dry soil phase, the measured capacitance signal can be converted into soil moisture after appropriate calibration. International studies show that incorporating soil-moisture data into early-warning systems that previously relied only on rainfall thresholds can improve predictive performance, with antecedent saturation and event-scale increases in saturation being highly meaningful variables for landslide risk. Capacitive sensors have received particular attention because they enable real-time measurement, are low cost, consume little power, and can be readily integrated with wireless sensor networks and IoT platforms; they are therefore suitable for wide-area monitoring systems or high-risk locations. However, the accuracy of this sensor type still depends strongly on soil-specific calibration and is affected by temperature, salinity, soil texture, and installation conditions. In Vietnam, landslide early-warning approaches have developed from rainfall-based models and susceptibility mapping toward real-time monitoring systems; selected case studies, such as Nam Dan, have integrated soil-moisture sensors with pore-water pressure, displacement, and rainfall sensors to improve warning capacity. Nevertheless, precise location-specific warning remains challenging because of limitations in geological, topographic, and real-time field observation data. The paper concludes that capacitive soil-moisture sensors are a promising component of modern landslide early-warning systems, but they should be deployed in a multi-parameter framework that combines rainfall, pore-water pressure, slope displacement, and predictive modeling to increase reliability under Vietnamese conditions.

Keywords: Soil-Moisture Sensor, Capacitive Sensor, Operating Principle, Landslide Early Warning, Volumetric Soil Water Content, Slope, Extreme Rainfall, Vietnam

1. Introduction

Against the background of increasingly severe climatic change and the unpredictable consequences recently observed in Central Vietnam, it is necessary to develop a landslide early-warning system to protect local communities from sudden landslides that cause major losses of life and property. To develop such a system, the first requirement is to identify appropriate methods for forecasting landslide events. One of the most effective approaches that has recently been validated is the direct measurement of soil moisture [1]. Historically, a wide range of methods has been used worldwide to measure soil moisture [2]. Within the scope of this paper, the focus is placed on the type of sensor most closely related to electrical and electronic engineering: the capacitive soil-moisture sensor.

2. Operating Principle of Capacitive Soil-Moisture Sensors

A capacitive soil-moisture sensor measures the capacitance of water-bearing soil, that is, moist soil, in order to determine the relative proportions of water and soil in the moist soil mass. Capacitance is defined as the amount of electric charge that a material can store under the action of an electric potential [5]. The conventional expression for capacitance is as follows:

$$C = Q / V$$

Applying Gauss's theorem and the definition of electric-field potential energy, the above expression can be equivalently written as:

$$C = (\oint_S \varepsilon E \cdot dS) / (\int E \cdot dl)$$

The above expression indicates that capacitance calculation may become very complicated when the geometry and arrangement of the plates are complex. Within the scope of this paper, only the configuration similar to the construction of a capacitive sensor, as shown in Figures 1.1, 1.2, and 1.3, is considered.

Fig 1.1

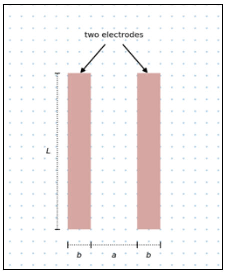

Fig 1.2

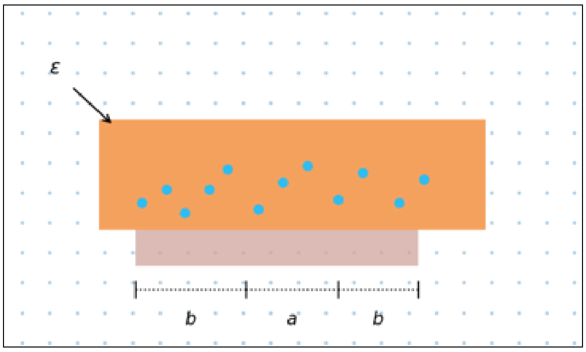

Fig 1.3

The capacitance formula for the above case is adopted from study [4]:

$$C = (\varepsilon L / \pi) \ln(1 + b / a)$$

Because L, b, a, and π are constants, the dielectric permittivity ε can be expressed as a linear function of C (1):

$$\varepsilon = f(C) \quad (1)$$

It should be noted that this relationship is valid only for the special case considered here. The ε-C relationship may become highly complex depending on the arrangement and geometry of the plates [6].

Equation (1) shows that determining the dielectric permittivity of water-bearing soil is necessary; however, in practice, this is difficult to perform directly. To address this issue, three common approaches corresponding to three types of capacitive soil-moisture sensors are currently used worldwide [2]: time-domain reflectometry (TDR), frequency-domain reflectometry (FDR), and standing-wave ratio (SWR). This paper focuses on FDR-type capacitive soil-moisture sensors because of their practical convenience. An FDR capacitive soil-moisture sensor measures the oscillation frequency of an electrical circuit and then determines its capacitance from that frequency [2]. The relationship between this frequency F and the capacitance C of soil is adopted from study [3] as follows:

$$F = 1 / (2\pi\sqrt{LC})$$

Drawing on the results of the study by T. J. Kelleners and colleagues [7], the dielectric permittivity ε can be expressed as a function of F:

$$\varepsilon = f(F)$$

Through this functional relationship, the dielectric permittivity of water-bearing soil can be determined by identifying the oscillation frequency F of the sensor circuit. This is the operating principle of an FDR-type capacitive soil-moisture sensor.

Worldwide, the moisture state of soil is commonly determined on the basis of the ratio between water volume (Vw) and soil volume (Vs), denoted by θ, or volumetric soil water content:

$$\theta = Vw / Vs$$

Adopting the result of study [8], where εs is the dielectric permittivity of soil and εw is the dielectric permittivity of water, the relationship between the dielectric permittivity ε of moist soil and θ is given as follows:

$$\varepsilon = (1 - \theta)\varepsilon s + \theta\varepsilon w$$

From this equation, θ can be expressed as a function of ε:

$$\theta = f(\varepsilon)$$

Because ε = f(F), it follows that:

$$\theta = f(F)$$

It should be emphasized that the above relationship omits many detailed theoretical calculation steps. In practice, calculating θ from F is complex and requires substantial expertise in this field. Nevertheless, within the scope of this paper, the result is sufficient to demonstrate the operating principle of capacitive soil-moisture sensors.

The above result is difficult to apply directly in practice because it is strongly affected by ionic conductivity, which changes the dielectric behavior of water, and by dielectric relaxation, which affects the response rate of water molecules in soil to the oscillation frequency of the electrical circuit [7]. In addition, F is not a basic and commonly used physical quantity, which means that its evaluation and use require complex physical equipment. Therefore, microprocessors and integrated circuits are commonly used to convert information obtained from the sensor into voltage signals through integrated conversion modules. A typical example is study [3], which used an

Arduino microcontroller to analyze data obtained from a soil-moisture sensor.

3. Role of Capacitive Soil-Moisture Sensors in Landslide Early Warning Worldwide

Earlier landslide early-warning models mainly depended on measuring rainfall-related variables over different time intervals [9]. Although these variables play a very important role in landslide early warning, they often vary considerably depending on external factors such as temperature, climatic conditions, soil and rock type, and other site-specific factors [10]. This variability can create difficulties and biases in landslide forecasting across different terrains worldwide and can indirectly lead to serious misunderstandings in landslide prevention. Recent studies have evaluated the practical value and role of hydrological, geological, and site-intrinsic variables in locations where landslides may occur; their results are promising and highlight the potential of these variables for landslide early-warning models [1]. One such variable is soil moisture, and soil-moisture sensors can be used as a simple, low-cost method to measure it. Based on the theoretical foundation outlined in the previous section, this paper discusses the application of capacitive soil-moisture sensors for identifying soil-moisture conditions in international studies of landslide early warning.

3.1 Study by the Research Group from ETH Zurich [1]

One study that has clearly influenced the integration of soil-moisture data into landslide early warning is Assessing the potential of soil moisture measurements for regional landslide early warning by Adrian Wicki, Peter Lehmann, Sonia I. Seneviratne, and colleagues, including authors affiliated with ETH Zurich in collaboration with WSL and the University of Fribourg. Published in Landslides in 2020, the study systematically evaluated the potential of using in situ soil-moisture measurements for regional landslide early warning in Switzerland.

A key contribution of the study was the construction, for the first time, of a relatively comprehensive soil-moisture database for Switzerland by synthesizing data from 35 stations and 284 soil-moisture sensors across several monitoring networks. The SwissSMEX network, established by ETH Zurich together with Agroscope and MeteoSwiss, used both TDR probes and 10HS capacitive sensors; other networks in the dataset also used capacitive sensors such as EC-5, SMT100, and PR2/6. Sensors were installed at multiple depths, mainly within the near-surface soil layer down to 100-150 cm, with measurement intervals as short as 10 minutes, thereby allowing relatively detailed monitoring of moisture dynamics during rainfall infiltration.

Methodologically, the authors did not use absolute volumetric water content directly; instead, they normalized the time series to represent relative saturation. This approach was intended to reduce the influence of differences in soil properties, installation conditions, and calibration errors among sensors. From the normalized saturation series, the study extracted "infiltration events" and described them using multiple variables, including initial saturation, saturation increase, event duration, infiltration rate, and maximum three-hour infiltration rate. Logistic regression and ROC/AUC curves were then used to evaluate landslide predictive performance. It is in this context that the study demonstrated that soil-moisture data are not merely auxiliary information but can become direct input variables for early-warning models.

The most important result was that predictive quality depended strongly on the distance between the soil-moisture measurement point and the landslide location. As the distance decreased, predictive capacity increased. In this dataset, the authors identified a prediction distance of 10-15 km as a reasonable balance between model performance and model robustness. At very short distances, the model could achieve higher AUC values; however, the number of landslide events available for calibration and validation decreased, increasing the risk of overfitting.

Further analysis showed that the two most significant variables for prediction were antecedent saturation and saturation change during the infiltration event. When these two variables were combined, model performance was nearly equivalent to the case in which the entire set of infiltration-event descriptors was used. This implies that, from a hydro-mechanical perspective, the risk of shallow landslides depends not only on current rainfall intensity but also strongly on the antecedent moisture state of the slope. In other words, for the same rainfall amount, a slope that is already close to saturation has a substantially higher probability of losing stability than a drier slope.

Another practically valuable contribution of the study was its emphasis on the need to standardize and combine sensor data from multiple depths. The authors concluded that integrating information from multiple depths and normalizing soil-moisture data is useful for landslide early warning. They also highlighted limitations related to the quality of long-term monitoring time series, errors caused by sensor-soil contact, heterogeneity among installation sites, and especially the need for calibration under local soil conditions. This observation is particularly important for capacitive sensors because they are sensitive to soil texture, temperature, salinity, and probe-soil contact conditions.

From the specific perspective of capacitive soil-moisture sensors, the ETH Zurich study is significant in three respects. First, it provides regional-scale evidence that real-time soil-moisture measurements genuinely add value to early-warning systems compared with approaches based solely on rainfall thresholds. Second, it shows that electromagnetic sensor networks, including low-cost and easily deployable capacitive sensors, can be used in early-warning applications if the data are properly normalized and processed. Third, it provides a foundation for subsequent studies on monitoring-network design, such as whether sensors installed on flat terrain can adequately represent regional landslide risk; a follow-up study in this research direction in 2023 suggested that both sloping and flat measurement sites, when evaluated in terms of relative variation, can distinguish critical from non-critical states for shallow landsliding.

3.2 Study by the Research Group from NSS College of Engineering, Palakkad, Kerala [11]

The work by Sreeja P. M. and Kala L. from the Department of Electronics and Communication Engineering, NSS College of Engineering, Palakkad, Kerala, was published in 2020 in the International Advanced Research Journal in Science, Engineering and Technology under the title A Review on Landslide Detection Methods. This is a review paper, rather than an experimental study, that systematizes published landslide detection methods. The authors emphasized three main groups of approaches: pixel-based image analysis, object-based image analysis, wireless sensor networks, and deep learning.

A notable feature of the paper is that the authors devoted a separate section to wireless sensor methods. According to the review, previous studies had used heterogeneous networks consisting of sensors, Wi-Fi, and satellite terminals combined with threshold algorithms to detect landslides. Some systems continuously monitored slope stability using sensors, processed the data with ARM microcontrollers, and transmitted data via UDP. Other configurations used Wi-SUN accelerometer sensors with the IEEE 802.15.4g standard, or MEMS sensors combined with supercapacitors to form self-powered early-warning systems transmitting data via XBee.

The review also points out that wireless sensor methods face practical limitations, including field sensor placement, sensor-node lifetime, and network operation issues. For this reason, image-processing methods remain widely used in many landslide detection contexts. At the same time, the authors note that deep learning is emerging as a highly promising direction for landslide recognition from remote-sensing imagery, although comparative evidence at that time remained limited.

Within the scope of the present paper, the value of the NSS College of Engineering study does not lie in the direct development of capacitive soil-moisture sensors, but in its provision of a systematic overview of sensor-network-based early-warning architectures. From this review, it can be inferred that capacitive soil-moisture sensors, as field measurement nodes in real-time monitoring networks, have strong potential for integration into multi-parameter landslide early-warning systems. However, effective application requires that soil-moisture sensors be embedded in a complete system consisting of data transmission, power supply, threshold algorithms or decision models, rather than operating as isolated elements.

3.3 Study by the Research Group from Indonesia [12]

In this subsection, document [12] is assumed to be the work Study of soil moisture sensor for landslide early warning system: Experiment in laboratory scale by E. Yuliza, H. Habil, M. M. Munir, M. Irsyam, M. Abdullah, and Khairurrijal, published in 2016 in Journal of Physics: Conference Series. The authors are affiliated with research institutions in Indonesia, including Institut Teknologi Bandung and the Research Center for Disaster Mitigation. The study was conducted in the context of Indonesia, a country frequently affected by rainfall-induced landslides; therefore, monitoring water changes in soil is considered an important approach for improving early-warning accuracy.

The core of the study was the development of a laboratory-scale experimental model to monitor changes in soil water using a soil-moisture sensor combined with a microcontroller. The measurement system was calibrated using the gravimetric dry-wet method, and experiments were conducted on two types of samples, soil and sand, to compare the responses of foundation materials to water infiltration. The results showed that each material type has different volumetric water content, soil matric suction, and shear strength; these differences directly affect slope stability and the likelihood of landslide initiation.

However, it should be emphasized that this Indonesian study did not use a capacitive sensor; instead, it used a low-cost resistive sensor to detect changes in soil water content. According to the principle described by the authors, as water content increases, the electrical resistance of the soil medium decreases, causing changes in the measured voltage. This signal is then amplified, digitized, and processed by a microcontroller. The study showed that as water content increases, pore-water pressure and the self-weight of the soil mass also increase, thereby making the soil more susceptible to instability.

For the purposes of the present paper, the value of this study lies in its experimental evidence that soil moisture is a hydrological variable directly linked to pre-failure slope conditions, and that continuous monitoring of soil moisture can improve the quality of early warning compared with approaches based solely on rainfall. Although the sensor used by the authors was a resistive type, the work remains an important reference for developing landslide early-warning systems based on capacitive soil-moisture sensors. Compared with resistive sensors, capacitive sensors generally offer advantages in probe durability, reduced susceptibility to corrosion, and more stable long-term field operation. Therefore, the Indonesian study can be regarded as an experimental basis supporting the argument that soil-moisture monitoring is an essential component of modern landslide early-warning systems.

4. Application to Landslide Early Warning in Vietnam

4.1 Geological, Geomorphological, and Climatic Context of the Northern Mountainous Provinces

Vietnam is a country in which mountainous terrain accounts for a large proportion of the national territory. The northern mountainous region is characterized by strongly dissected terrain, steep slopes, dense river and stream networks, and pronounced geomorphological variability over short distances. This region frequently experiences flash floods, landslides, and debris flows as a result of the combined effects of terrain, geology, and weather. According to Vietnam's disaster management authorities, more than 300 flash-flood and debris-flow events have been recorded in the northern mountainous provinces over the past two decades; during the 2001-2017 period alone, approximately 850 landslide events occurred in this region, causing substantial losses of life, housing, and infrastructure. JICA has also identified the northern mountainous region as an area with a high frequency of flash floods and landslides because of the simultaneous presence of unfavorable terrain, geological, and meteorological conditions.

Climatically, northern Vietnam is strongly influenced by the monsoon system, with the main rainy season generally lasting from approximately May to October. However, recent climate studies indicate that heavy rainfall in northern Vietnam does not occur only during the traditional rainy season but may also appear significantly during the spring transition period, around February to April, under the combined influence of cold air masses, subtropical circulation, and low-pressure troughs. This is highly significant for landslide warning because it indicates that the antecedent moisture state of slopes may accumulate earlier than assumed in the simple "dry season-rainy season" framework used by traditional warning models.

From a geological and geotechnical perspective, many studies in the northern mountainous region show that landslides and debris flows are closely associated with weathered cover layers, colluvial and proluvial deposits, tectonic fracture zones, and weak or strongly weathered bedrock on steep slopes. Field observations indicate that many slide-flow phenomena occur toward the end of the rainy season, when soil and rock materials are overly wet or close to saturation, causing shear strength to decrease and instability conditions to increase markedly. In particular, soil-rock mixtures in colluvial and residual layers have been observed to remain stable under dry or moderately moist conditions but become unstable when saturated with water or exposed to strong surface runoff.

In terms of landslide morphology, surveys in mountainous Vietnam show that rotational slides commonly occur where the weathered layer is thick and completely weathered, whereas translational slides are often associated with thin cover layers over weak to moderately weathered bedrock, together with relatively shallow colluvium. Mixed landslide types usually occur where the cover layer is thicker. This structure suggests that the hydrological mechanism governing landslides in the northern mountainous region is largely rainfall infiltration, which reduces matric suction, increases saturation, and in many cases raises pore-water pressure along weak planes in the weathered cover or at the cover-bedrock interface.

These characteristics show that, for the northern mountainous region, "rainfall" reflects only the external triggering factor, whereas the actual moisture state of the soil is the intermediate variable more closely related to the instability mechanism. In other words, under the same rainfall amount, a slope with high antecedent moisture, or a thin cover layer over fractured bedrock, will respond very differently from a drier slope. Therefore, incorporating soil-moisture information into early-warning systems in Vietnam is necessary from both mechanistic and operational perspectives.

4.2 Advantages of Capacitive Soil-Moisture Sensors over Common Soil-Moisture Determination Methods Used in Landslide Warning

Among soil-moisture determination methods, the gravimetric dry-wet method remains the classical direct measurement technique and has reference-standard value because it is based on the mass difference of soil samples before and after oven drying. However, this is an intermittent sampling method; it is destructive, depends on balances, drying ovens, and laboratory procedures, and is intrinsically unsuitable for continuous real-time monitoring on slopes. Even in recent reviews of dielectric sensor calibration, gravimetric measurement is considered impractical for large-scale studies or real-time warning requirements.

A very common approach in current landslide warning is the rainfall-threshold model. Its advantages are simplicity, ease of operation, and suitability when field data are limited. However, its core limitation is that rainfall is only an indirect proxy for hydrological conditions within the slope. The study by Wicki and colleagues showed that rainfall thresholds cannot fully reflect antecedent moisture conditions at depth, differences among soil types, or hydrological processes that directly control pore-water pressure and the loss of matric suction. This explains why adding soil-moisture information can improve predictive performance.

Compared with the gravimetric method and rainfall-only models, capacitive soil-moisture sensors have major advantages in continuous, non-destructive measurement, rapid response, and ease of automation. In principle, capacitive sensors exploit changes in the dielectric permittivity of the soil-water medium. Because water has a much higher permittivity than the solid and air phases, the electrical signal obtained can be converted into volumetric water content after calibration. Reviews of soil-moisture sensors generally regard dielectric sensor groups as fast, convenient, non-polluting, and sufficiently accurate for many field applications. Recent experimental studies also show that low-cost capacitive sensors, after calibration, can correlate strongly with reference volumetric water content and are suitable for real-time monitoring systems.

Compared with TDR, capacitive sensors generally require lower investment, consume less power, and are more convenient for constructing high-density monitoring networks. In field comparisons in Switzerland, TDR is commonly used as a high-accuracy reference tool, whereas FDR/capacitive sensors belong to a lower-cost group but require in situ calibration and may require temperature correction. In other words, TDR is more suitable for standard measurement or detailed research, whereas capacitive sensors are better suited when the objective is to deploy a wide-area, dense monitoring network with real-time data transmission for early warning.

Another practical point is that capacitive sensors are particularly suitable for IoT architectures or wireless sensor networks. In studies designing low-cost measurement systems, capacitive sensors have been connected to microcontrollers, independent power sources, and data logging or transmission devices to form continuous monitoring systems at reasonable cost. This is an important advantage in the mountainous areas of Vietnam, where terrain is fragmented, transportation is difficult, and funding for maintaining dense monitoring networks remains limited.

However, the advantages of capacitive sensors do not mean that calibration can be disregarded. Studies evaluating dielectric sensors consistently emphasize that measurement results are affected by soil texture, bulk density, temperature, electrical conductivity, and salinity. Kizito and colleagues showed that measurement frequency is a key factor controlling the sensitivity of capacitive sensors to texture, conductivity, and temperature; other studies also confirm the need for site-specific or soil-group-specific calibration to reduce the error of low-cost sensors. Therefore, in the context of landslides in Vietnam, capacitive sensors should be viewed as highly useful devices for measuring moistening trends and near-saturation states, but high reliability requires local calibration procedures, periodic repeated checks, and temperature compensation where necessary.

Compared with low-cost resistive sensors, capacitive sensors also offer advantages in long-term operational durability. Studies evaluating low-cost resistive sensors show that this type of sensor is affected by many error sources and can face serious problems in terms of accuracy and usability. In contrast, recent reviews note that capacitive sensors do not require exposed metal electrodes in direct contact with the soil in the same way, thereby providing greater field durability and broader applicability in long-duration monitoring networks. Thus, if the objective is real-time landslide early warning in mountainous regions, capacitive sensors are generally a more appropriate choice than simple resistive sensors.

4.3 Suitability of Capacitive-Sensor-Based Early Warning for Vietnamese Geological Conditions

Among the approaches discussed in Section 3, the method proposed by the ETH Zurich group is particularly relevant for Vietnam because it does not stop at merely "measuring soil moisture" but transforms soil-moisture data into hydrological indicators that have mechanical significance for landsliding. Specifically, the authors demonstrated that the two variables with outstanding predictive value are antecedent saturation and saturation change during the infiltration event. In the Swiss dataset, this pair of variables provided very good predictive performance; prediction quality increased as the distance between the measurement point and the landslide location decreased, and a distance of approximately 10-15 km represented a reasonable balance between predictive quality and model robustness.

The reason this method is suitable for Vietnam is that it corresponds well with the mechanism of rainfall-infiltration-induced sliding in shallow weathered layers. As discussed above, many landslides in the northern mountainous region occur in colluvial/proluvial cover, thick weathered layers, or thin cover layers over moderately to strongly weathered bedrock. Under these structural conditions, antecedent soil moisture and the rate of wetting during rainfall are two quantities that closely reflect the reduction of matric suction and the progression toward instability. Therefore, using multi-depth capacitive sensors to identify antecedent saturation and event-scale saturation increase is much more appropriate than relying only on total rainfall or rainfall intensity, as in conventional warning models.

Nevertheless, directly applying the ETH Zurich model to Vietnam without adjustment may lead to bias. Vietnam's geological context, especially in the northern mountainous region, is highly heterogeneous over short distances: variations occur in weathered soil type, cover-layer thickness, fracture density of bedrock, slope morphology, vegetation cover, and human impacts associated with road opening, cut slopes, and land leveling. Moreover, the Nam Dan study showed that, in some slopes, groundwater is mainly distributed in fractured weathered bedrock; rainwater can infiltrate downward along fractures and drain along the slope instead of accumulating simply in the pore space of the soil layer. It can therefore be inferred that, in Vietnam, the spatial representativeness of a single measurement point may be lower than in many temperate contexts. Sensor networks should consequently be denser and organized by slope unit or transport-corridor segment rather than assuming that a single station can represent a wide region. This is a technical inference derived from combining ETH Zurich's result on distance-dependent predictive performance with evidence on the geological and hydrological heterogeneity of Vietnamese slopes.

A suitable configuration for Vietnam would therefore be a multi-tier early-warning model that uses capacitive sensors as the hydrological core. At the first tier, at the scale of communes, small catchments, or vulnerable transport corridors, multi-depth capacitive sensor networks should be combined with rainfall measurements to calculate indicators such as antecedent saturation, event-scale saturation increase, maximum one- to three-hour infiltration rate, and seasonal saturation thresholds. At the second tier, at locations with very high risk or complex geological conditions, pore-water pressure sensors, tilt/displacement sensors, and rainfall gauges should be added, following the Nam Dan model, to elevate warnings from "increasing risk" to "imminent instability." This organization is more suitable for the reality of Vietnam than a model that measures only a single variable.

4.4 Proposed Specific Application Direction for the Northern Mountainous Region

Operationally, the most feasible method for the northern mountainous region should not be a model that measures absolute moisture and compares it against a universal threshold. Instead, it should be a model standardized by soil group, slope unit, and season. Capacitive soil-moisture data should first be calibrated against gravimetric measurements during the initial phase and then used for continuous monitoring to construct relative saturation time series. From these time series, warning thresholds can be established in terms of: (i) persistently high antecedent saturation; (ii) rapid saturation increase within 6-24 hours; and (iii) the combination of heavy rainfall and high antecedent saturation. This approach is closer to the hydro-geotechnical logic of landsliding than a purely rainfall-threshold model. Its scientific basis is provided by the ETH Zurich study, in which antecedent saturation and saturation change proved capable of distinguishing landslide from non-landslide events.

For slopes with thin cover over weak or moderately weathered bedrock, capacitive sensors should be installed at shallow and intermediate depths to capture the infiltration front within the active shallow-slide layer. For slopes with thick weathered layers or thick colluvium, more depth levels should be installed to identify moisture transfer from the surface layer to the zone near the potential slip surface. For slopes with fractured bedrock and fracture-controlled seepage, such as the Nam Dan case, capacitive sensors remain useful for monitoring wetting of the cover layer but must be combined with pore-water pressure or displacement sensors to avoid missing mechanisms of pressure increase within the fractured weathered rock mass.

Considering all mechanistic, technical, and economic criteria, capacitive soil-moisture sensors are highly suitable for landslide early warning in Vietnam. Their most notable strengths are relatively low cost, availability, ease of replacement, low power consumption, convenient integration with wireless networks, and near-real-time output. Their main weakness is that measurement error depends on soil type and the measurement environment; however, this weakness can be controlled to an acceptable level if the system is designed as a multi-sensor architecture, locally calibrated, and interpreted through trends or normalized data rather than treating individual absolute values as definitive. Given the conditions of the northern mountainous region, including steep terrain, strongly weathered geology, intense seasonal rainfall, and high spatial heterogeneity, this is a technological direction that deserves priority in the development of next-generation landslide early-warning systems.

5. Conclusions and Recommendations

5.1 Conclusions

This paper shows that soil moisture is an intermediate variable with more direct hydro-mechanical significance than rainfall in the initiation of rainfall-induced landslides. The results of Wicki and colleagues in Switzerland indicate that field soil-moisture data do contain useful information for regional landslide early warning; in particular, the two outstanding indicators are antecedent saturation and saturation change during infiltration events. This supports the argument that warning based only on rainfall thresholds is insufficient, because under the same rainfall amount, the degree of instability depends strongly on the antecedent moisture state of the slope.

From the equipment perspective, capacitive soil-moisture sensors have clear advantages for early-warning systems because they can measure continuously and non-destructively, automatically record data at short intervals, and be readily integrated into field monitoring networks. According to IAEA technical guidance, electromagnetic methods such as capacitive sensors, FDR, and TDR have the advantage that, after calibration, they disturb the soil only once during installation and can record data at short cycles to identify moisture changes during high-intensity rainfall events. However, these same methods are affected by salinity, temperature, soil texture, and calibration conditions; therefore, they cannot be used mechanically according to a single universal calibration curve for all soils.

Experimental results for low-cost capacitive sensors also indicate that this approach is highly feasible from economic and technical perspectives. The study by Okasha and colleagues showed that, after calibration, a low-cost capacitive sensor could achieve strong correlation with volumetric water content, with an average coefficient of determination of 0.967 and an RMSE of approximately 0.014 in clayey soil, while also being integrable into a real-time monitoring system. This demonstrates that, if properly calibrated, capacitive sensors not only have cost advantages but also have sufficient reliability to serve as core components in slope-moisture monitoring systems.

For Vietnam, the Nam Dan case shows that the appropriate direction is not to use a single soil-moisture sensor in isolation, but to build a multi-parameter early-warning system. That system consisted of six sensor nodes and one rain gauge, monitoring soil moisture, pore-water pressure, displacement status, and rainfall in real time; it then combined seepage and slope-stability analyses to issue three warning levels: early, intermediate, and imminent. Operation during the 2016 rainy season demonstrated the practical value of this model for landslide risk management. It can therefore be concluded that, under the conditions of strongly weathered geology, steep terrain, and concentrated heavy rainfall in mountainous Vietnam, capacitive sensors are particularly suitable when embedded in a multi-sensor warning architecture, rather than being used as a standalone indicator.

5.2 Recommendations

On the basis of the reviewed evidence and the case studies analyzed, this paper recommends that landslide early-warning systems in Vietnam, especially in the northern mountainous region, should gradually move from univariate rainfall-based warning toward warning based on hydro-geotechnical state variables. In this model, capacitive soil-moisture sensors should be used as a foundational input variable to monitor antecedent saturation, the rate of wetting, and the trend toward near-saturation of the active soil layer. At the same time, rainfall, pore-water pressure, and displacement should be integrated at critical slopes to increase warning reliability. The basis for this recommendation is the finding by Wicki and colleagues on the predictive value of antecedent saturation and saturation change, together with the multi-parameter model implemented at Nam Dan.

Technically, local calibration procedures for capacitive sensors should be developed for characteristic soil groups in Vietnam, at a minimum including sandy clay, weathered silty-clayey soil, colluvial soil, and strongly weathered residual soil. Technical documents show that the accuracy of capacitive sensors depends significantly on measurement frequency, temperature, electrical conductivity, salinity, and soil characteristics. Therefore, directly applying manufacturer coefficients without in situ calibration may generate substantial errors in warning-threshold assessment. In the initial implementation phase, gravimetric or other standard measurements should be used for comparison, after which separate calibration curves should be developed for each monitoring area.

In terms of network organization, priority should be given to installing multi-depth capacitive sensors on high-risk slopes along mountainous transport routes, slope-side residential areas, cut slopes, embankment slopes, and areas with a history of landslides. Multi-depth measurement is necessary because moisture conditions in the surface layer and near potential slip surfaces may evolve differently; moreover, electromagnetic methods provide meaningful information only when the sensor location is sufficiently representative of the soil volume being monitored. Areas with complex infiltration mechanisms or perched groundwater should be supplemented with pore-water pressure and tilt/displacement sensors, following the orientation of the EWMRIL system in Nam Dan.

Operationally, warning models in Vietnam should use normalized indices such as relative saturation, event-scale saturation increase, and rate of moisture change, rather than relying entirely on a single absolute soil-moisture threshold. This approach is more consistent with the high heterogeneity of weathered soils in Vietnam and helps reduce error arising from differences in soil structure, porosity, and installation conditions. At the same time, a long-term database linking rainfall, soil moisture, pore-water pressure, displacement, and landslide occurrence should be developed to gradually calibrate warning thresholds for each province, geological setting, and season. This direction is consistent with international evidence showing that predictive value lies more in wetting trends and antecedent saturation conditions than in a single instantaneous value.

Finally, from policy and application perspectives, capacitive sensors should be regarded as a highly feasible solution for Vietnam because they are relatively low cost, easy to replace, easily integrated with IoT, and capable of real-time data transmission. What requires investment is not only sensor hardware, but also standardized procedures for installation, calibration, periodic inspection, data governance, and decision-algorithm development. Once these components are completed in an integrated manner, capacitive soil-moisture sensors can become an important component of a new generation of landslide early-warning systems in Vietnam.

6. References

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