

SLOPE CONDITION MONITORING SYSTEM AND METHOD

RELATED APPLICATION

[0001] This application claims the benefit of priority to the Singapore patent application no. 10202403291W filed on October 23, 2024, the contents of which are hereby incorporated by reference in their entirety for all purposes.

TECHNICAL FIELD

[0002] The present disclosure relates to environmental monitoring and more particularly to the monitoring of slope conditions and/or early detection of slope failures.

BACKGROUND

[0003] Climate change has resulted in more erratic weather conditions. Prolonged periods of drought-like conditions may be followed by extended periods of rainfall. Rainfall conditions have become less predictable. When rainwater infiltrates the unsaturated zone (e.g., the soil forming the slope and above the groundwater table), the slope may be rendered more susceptible to slope failure. In densely populated areas, slope failure can cause significant damage to buildings and other infrastructure. Slope failure can be catastrophic, e.g., resulting in injury or even the loss of life.

[0004] Traditionally, it is believed that having vegetated slopes or growing vegetation on slopes can mitigate slope failures, e.g., theoretically, the roots of the plants should help to hold the soil of the slope together and prevent landslides. However, the erratic weather conditions resulting from climate change can also impact plant health. After a drought-like period, the plants on a slope may be so weakened that they offer inadequate support to hold the soil together in the next deluge of rainwater. There is therefore a pressing need for a better way to monitor and/or detect slope failures so that preventive measures can be taken in time.

SUMMARY

[0005] In one aspect, the present application discloses a slope condition monitoring method for monitoring a slope. The slope condition monitoring method includes acquiring a volumetric water content from a plurality of sensors disposed on the slope. The slope condition monitoring method includes using the volumetric water content to determine a factor of safety of the slope based on a linear regression model obtained from a simulated volumetric water content corresponding to wet weather conditions. The slope condition monitoring method includes generating an alert in response to the factor of safety being determined to be below a safety threshold value, the alert being indicative of a possible slope failure.

[0006] The slope condition monitoring method may include using the volumetric water content to determine a plant health indicator of one or more plants on the slope, in which the alert is generated in response to any one and/or a combination of the following: the factor of safety being determined to be below the safety threshold value, and the plant health indicator being below a health threshold value.

[0007] In another aspect, the slope condition monitoring method may further include: acquiring a plurality of the volumetric water content at a first sampling frequency in response to a presence of rainfall; and acquiring a plurality of the volumetric water content at a second sampling frequency in response to an absence of rainfall, the first sampling frequency being higher than the second sampling frequency.

[0008] In another aspect, the slope condition monitoring system, at least partially installed on a selected slope, includes a plurality of sensors disposed on the selected slope and a controller. The plurality of sensors are configured to provide a volumetric water content of the selected slope. The controller is configured to be in signal communication with the plurality of sensors. The controller is configured to perform the method of slope condition monitoring method according to any one or more of the embodiments described above. The plurality of sensors may include: a plurality of osmotic tensiometers disposed in a crest and a toe of the selected slope; and a plurality of capacitance moisture sensors distributed at various elevations of the selected slope.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] To aid understanding, various embodiments of the present disclosure will be described with reference to the following figures:

[0010] **FIG. 1** is a schematic diagram illustrating a slope condition monitoring system according to embodiments of the present disclosure.

[0011] **FIG. 2A** and **FIG. 2B** are schematic diagrams of different regions under monitoring.

[0012] **FIG. 3** is a schematic diagram of the experimental system incorporating the proposed slope condition monitoring system.

[0013] **FIG. 4A** and **FIG. 4B** are schematic diagrams of the instrumentation layout on the testbed in the field study.

[0014] **FIG. 5** is a schematic diagram of the field monitoring system structure used in the field study with advanced sensing instrumentation, including: (a) IMKO PICO 32 TDR moisture sensor; (b) Meter Group TEROS 12 capacitance moisture sensor; (c) SISGEO-P252R piezometer; and (d) osmotic tensiometer.

[0015] **FIG. 6A** and **FIG. 6B** show volumetric water content monitoring results using PICO 32 from March 2023 to July 2023. **FIG. 6A** shows the volumetric water content at 0.2m. **FIG. 6B** shows the volumetric water content at 0.75m.

[0016] **FIG. 7A** and **FIG. 7B** show volumetric water content monitoring results using TEROS 12 from March 2023 to July 2023. **FIG. 7A** shows the volumetric water content at 0.2m. **FIG. 7B** shows the volumetric water content at 0.75m.

[0017] **FIG. 8** is chart of suction monitoring results from osmotic tensiometers at 0.2m and 0.75m depth.

[0018] **FIG. 9A** and **FIG. 9B** compare the summarized volumetric water content results between PICO 32 (**FIG. 9A**) and TEROS 12 (**FIG. 9B**) measurements with monitoring depth.

[0019] **FIG. 10A** and **FIG. 10B** compare the volumetric water content results between PICO 32 (**FIG. 10A**) and TEROS 12 (**FIG. 10B**) under soil-water characteristic envelope at 0.2 m depth.

[0020] **FIG. 11A** and **FIG. 11B** compare the volumetric water content results between PICO 32 (**FIG. 11A**) and TEROS 12 (**FIG. 11B**), under soil-water characteristic envelope at 0.75m depth.

[0021] **FIG. 12** illustrates the slope model of the Rumah Tinggi testbed for the SEEP/W analysis.

[0022] **FIG. 13A** and **FIG. 13B** show soil properties used in SEEP/W analysis and more specifically, the SWCC and the permeability function, respectively.

[0023] **FIG. 14A** to **FIG. 14C** are charts showing the volumetric water content as measured (from sensor measurements) and SEEP/W analysis at 0.05 m depth, 0.2 m depth, and 0.75m depth, respectively.

[0024] **FIG. 15** shows the groundwater table variation at the crest and toe.

[0025] **FIG. 16** shows the groundwater table variation during SEEP/W analysis (ks of $2.97\text{E-}07$ m/s).

[0026] **FIG. 17** is a chart showing the actual rainfall input for the analysis between 11 June to 19 June.

[0027] **FIG. 18A** to **FIG. 18D** are charts showing factor of safety and volumetric water content results for TEROS 12 at 0.2m (middle), Slope 1, Slope 2, and Slope 3, respectively.

[0028] **FIG. 19** is a graph showing the factor of safety (FOS) determined from TEROS 12 sensor readings.

DETAILED DESCRIPTION

[0029] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0030] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments. As used herein, the singular ‘a’ and ‘an’ may be construed as including the plural “one or more” unless apparent from the context to be otherwise. In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0031] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0032] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0033] Terms such as “first” and “second” are used in the description and claims only for the sake of brevity and clarity, and do not necessarily imply a priority or order, unless required by the context.

[0034] Some methods may be described in terms of steps, stages, phases, or the like, merely to aid understanding and/or for convenient reference. The delineation between one step and another step may be merely for convenient reference in the present disclosure. It will be understood that in actual implementation there may not be a clear division or transition from one step to another subsequent step. There may be a certain amount of overlap among the steps and/or more than one step may occur or be performed concurrently in time, etc., unless the context dictates otherwise.

[0035] **FIG. 1** is a schematic diagram illustrating a slope condition monitoring system 200 according to embodiments of the present disclosure. For the avoidance of doubt, although embodiments of the present disclosure are useful for use with slopes or inclined ground (as illustrated in **FIG. 2B**), the slope condition monitoring system 200 may be used with relatively level ground (as illustrated in **FIG. 2A**). Rainfall usually infiltrates the soil which will contribute to recharging groundwater table and/or being taken up by the roots. When the rainfall exceeds the maximum

volume of water that can infiltrates the soil, it appears as runoff. Water may return to the vapor state via evaporation and/or transpiration of the plants. Other factors such as but not limited to the inclination of the slope, the type of soil, the type of plants, the density of the vegetation, the weather conditions, etc., add further complexity to the analysis of slope condition.

[0036] Referring again to **FIG. 1**, the slope condition monitoring system 200 may include a controller 240. The computing device may take the form of one or more processors or computing modules, in operable communication with one or more local or remote storage and/or memories, at least one of which is configured to store and/or execute machine-readable instructions. The controller may include or be in signal communication with a wireless communications module, in which the wireless communications module is configured to receive signals from one or more sensors 210. The controller 240 may be local, remote, or a hybrid thereof. The controller 240 may be configured to execute the machine-readable instructions to perform a method according to the present disclosure. Reference to the slope condition monitoring system 200 being configured to perform an action may also be understood to include the controller 240 being configured to execute machine-readable instructions to retrieve and/or store signal communications and/or data, and/or perform computations, acquire input(s), and/or provide output(s), etc.

[0037] The slope condition monitoring system 200 may be configured to periodically acquire signals from sensors 210 and to determine if there is currently any rainfall (e.g., step 220). Referring also to **FIG. 2A** and **FIG. 2B**, the sensors 210 may include a rain gauge 211. The sensors 210 may further include moisture sensors 212 disposed in the soil 110, including the soil on a slope 150. In some examples, the sensors 210 include selected moisture sensors 212 disposed proximal to one or more plants growing on the slope 150.

[0038] The sensors may further include moisture sensors 212 disposed on a slope 150. In one example, the moisture sensors 212 include a plurality of moisture sensors 212 that are distributed along a gradient line of the slope 150. In another example, a plurality of moisture sensors 212 may be disposed at a crest of the slope, at a mid-slope location, and at a toe of the slope. In yet another example, a

plurality of moisture sensors 212 may be distributed or spaced apart from one another between the crest of the slope and the toe of the slope.

[0039] In accordance with embodiments of the present disclosure, the slope condition monitoring system 200 is configured to responsively adjust a sampling frequency, based on first signals acquired from the rain gauge 211, in which the sampling frequency is a frequency at which second signals are acquired from the sensors 210. The sensors 210 may include the rain gauge 211 and/or moisture sensors 212.

[0040] The sampling frequency may be alternatively described in terms of how often measurements or readings are acquired or retrieved within a unit of time. Correspondingly, a sampling interval may be described in terms of a time interval between successive measurements or readings.

[0041] The slope condition monitoring system 200 is configured to adjust the sampling frequency or sampling interval in real-time and in response to a presence or an absence of rainfall. For example, in response to a presence of rainfall (e.g., it is raining at the time of acquiring the signals), the slope monitoring system 200 is configured to periodically acquire further signals (e.g., second signals from sensors 210) at a shorter sampling interval or a higher sampling frequency 223/224. This may mean a shorter loop or a faster iteration of a signal acquisition algorithm, e.g., acquiring a series of second signals at a predetermined shorter time interval. In response to an absence of rainfall (e.g., it is not raining at the time of acquiring the signals), the slope monitoring system 200 is configured to periodically acquire further signals (e.g., second signals from sensors 210) at a longer sampling interval or a lower sampling frequency 225/226. This may mean a longer loop or a slower iteration of the signal acquisition algorithm, e.g., acquiring a series of second signals at a predetermined longer time interval. Alternatively described, the controller may be configured to acquire sensor measurements at a first sampling frequency in response to a presence of rainfall and to acquire sensor measurements at a second sampling frequency in response to an absence of rainfall, the first sampling frequency being higher than the second sampling frequency.

[0042] In one example of the slope condition monitoring system 200, if a first rain gauge reading taken at time = 0 shows that it is raining (presence of rainfall), the next or second rain gauge reading may be taken at time = 10 minutes, with the subsequent or third rain gauge reading taken at time = 20 minutes. For the same slope monitoring system at the same physical or geographical location, if the first rain gauge reading taken at time = 0 shows that it is not raining (absence of rainfall), the next or second rain gauge reading may be taken at time = 3 hours or 180 minutes, with the subsequent or third rain gauge reading taken at time = 6 hours or 360 minutes.

[0043] In another example, the slope condition monitoring system 200 may be configured to operate at a default longer sampling interval in a range of hours until rainfall is detected, and in response to rainfall being detected, the sampling interval is decreased so that the sampling interval is shorter than one hour.

[0044] According to embodiments of the present disclosure, a plurality of sensors 210 are disposed in the soil on or in proximity to a slope. In the present disclosure, for the sake of brevity, a sensor 210 may be described as being disposed in a location. Reference to a sensor 210 being disposed on/along a slope can be understood to refer to the sensor 210 being deployed, installed, embedded (partially or wholly) in the soil of the slope or in the soil proximal to the slope.

[0045] In accordance with some embodiments of the present disclosure, the slope condition monitoring system 200 may be configured to transmit the measurements or readings that has been acquired from the sensors 210 (and/or results based on such measurements or readings) to a server (step 250).

[0046] In accordance with some embodiments of the present disclosure, the slope condition monitoring system 200 may be configured to check the acquired measurements or readings against a threshold value (step 260). The slope condition monitoring system 200 may be configured to generate or provide a warning signal if the measurements or readings exceed the threshold value (step 270). In some examples, the warning signal may include a message that can be sent via SMS (short message service).

[0047] The controller 240 may be configured to determine or to acquire a threshold value (step 280). The threshold value may be determined based on a volumetric water content. In some embodiments, the threshold value may be a value calculated or determined based on an expected failure line, e.g., between wetting bands that may form in the soil. In some embodiments, the threshold value may be a value calculated or determined based on a development of soil moisture over rainfall duration. The warning signal may be configured to include an early warning signal and/or a final warning signal.

[0048] Actual field experiments were conducted to verify the viability and performance of the proposed slope condition monitoring system 200.

[0049] In the field experiments, a combination of osmotic tensiometers 213 and capacitance moisture sensors were installed, e.g., the osmotic tensiometers 213 were installed at the crest of the slope and at the toe of the slope, and the capacitance moisture sensors were distributed at various elevations of the slope.

[0050] **FIG. 3** is a schematic diagram of the experimental system incorporating the proposed slope condition monitoring system 200.

[0051] To aid understanding and not to be limiting, the experimental system may be described in three parts.

[0052] Part A (also referred to as advanced sensing system development) includes development of an advanced sensing system with cloud communications for real-time data collection and analysis. Outputs were collected from a testbed over time under various weather conditions. Real-time volumetric water content (VWC) was determined based on the outputs from the testbed. Based on the real-time VWC, real-time factors of safety (FS) and real-time plant health indicators (PHI) were determined. The terms "volumetric water content", "VWC", "VWC values", and "VWC data" may be interchangeably used based on technical description in the present disclosure.

[0053] As this was an experiment, verification of the real-time FS and real-time PHI was carried out. It can be understood that in actual implementation of the proposed system, verification may be optional.

[0054] Part B (also referred to as a plant-soil study) includes monitoring plants. In the experiments, soil-water characteristic curves (SWCC) were obtained for the soil which the plants are cultivated under different water treatment regimes in a geotechnics laboratory. In the experiments, plants in a greenhouse were subjected to different water treatment regimes and monitored for VWC and for Fv/Fm ratio (ratio of variable fluorescence to maximum fluorescence). The Fv/Fm ratio reflects the efficiency of photosynthetic energy conversion of a plant. In the experiments, the Fv/Fm ratio was used as one of the plant health indicators (e.g., as a quantitative indicator of plant stress or the environmental effects on plant health). A higher Fv/Fm ratio can be taken to be indicative of better plant health, i.e., a greater capacity to photosynthesize.

[0055] In the experiments, the plants monitored for plant health indicators were plants in a laboratory or greenhouse environment. It will be understood that in actual implementation, the plants on a slope or in the outdoors environment would be the object of the plant health monitoring.

[0056] Part C (also referred to as advanced data processing or predictive analytics) includes development of a soil database including soil properties. In the example, the GEOTop, a distributed model of the mass and energy balance of the hydrological cycle (<https://geotopmodel.github.io/geotop/>), was used. Other simulation models may be used instead of GEOTop. The simulation model was used to generate outputs such as a simulated, calculated, or analytical VWC (driest weather conditions or extreme dry weather conditions) under the driest weather condition and an analytical VWC (wettest) under the wettest weather condition (or under extreme wet weather conditions), based on inputs including soil properties of the slope under monitoring.

[0057] Scoops3D (Slope Change Optimization of Probability of Stability in 3D), a three-dimensional slope stability analysis software available from the United States Geological Survey (www.usgs.gov/software/scoops3d), was used to form a second relationship between VWC with FS, and more specifically between VWC (wettest) and FS. Conventionally, Scoops3D is used for evaluating slope stability over large digital elevation models (DEMs) by searching for the most critical slip

surfaces. According to embodiments of the present disclosure, the inputs to the Scoops3D software were selected from the VWC data corresponding to the VWC (wettest).

[0058] Geographic information system (GIS) maps may be simultaneously based on both the PHI and the FS and presented as a real-time integrated output.

[0059] Field Monitoring

[0060] Field monitoring was conducted on the Rumah Tinggi slope in a residential area located in a central part of Singapore. The shallow slope with an average angle of 18° was selected because the steep slope angles would result in a high runoff which challenges the evaluation of sensor performance. The 10 m (meters) by 6m testbed on the slope had atmospheric temperature ranging between 25°C to 33°C, and the maximum daily total rainfall was 76 mm (millimeters) during the approximately four-month monitoring period between March 2023 and July 2023.

[0061] A near-surface layer (0 m – 0.5 m) of clayey soil (SC) contained mainly organic matter mixed with clayey sands and/or sand-clay mixtures. A shallow depth layer (0.5 m – 4 m) of low-plasticity clay (CL) was mainly inorganic clays of low to medium plasticity. The CL layer was taken to represent the soil composition in the transition between the unsaturated to the saturated zone where the groundwater table is located. A deep depth layer (4 m – 8 m) contained inorganic silts and (very) fine sands.

[0062] Soil sampling at the monitoring slope during borehole drilling identified three stratified soil layers based on the unified soil classification system (USCS). Table 1 below presents the indexed soil property, soil compositions, and saturated permeability from the site investigation at the shallow depth layer. These soil properties, especially in the shallow layer near the surface, were used to interpret soil-water characteristics and permeability functions that are needed to validate the sensor measurements as well as numerically calculate the soil water content in the field.

[0064]

Table 1. Residual soil properties from the testbed with depth

Depth [m]	Saturated permeability [m/s]	Bulk density [g/cm ³]	Liquid limit [%]	Plastic limit [%]	Plastic Index []	Sand [%]	Silt [%]	Clay [%]
0-0.5	2.97E-08	1.86	34	24	10	46	32	16
0.5-3		1.97	35	24	11	46	30	24
3-4	6.94E-09	2.00	33	23	10	48	26	26
4-7	5.63E-09	2.13	33	24	9	44	28	28
7-8	5.47E-10	2.05	36	25	11	11	50	39
	Soil classification							
0-0.5 m	SC, clayey sands, sand-clay mixtures							
0.5-4 m	CL, inorganic clays of low to medium plasticity							
4-8 m	ML, inorganic silts, and very fine sands							

[0065] Two piezometers were installed at the crest and the toe of the slope with a depth of 8 m below the ground surface and the reading reported a shallow groundwater table at about 2m below the ground surface.

[0066] **FIG. 4A** shows a schematic drawing of the investigated slope with geometric dimensions and the instrumentation groups deployed for the field monitoring. **FIG. 4B** shows the instrumentation layout on the testbed. Three sets of moisture sensors and osmotic tensiometers were installed at depths of 0.2 m and 0.75 m on the slope to monitor the soil water content changes, above the groundwater table.

[0067] **FIG. 5** shows the IoT (internet of things) architecture adopted for a shallow landslide monitoring system. An advanced data logging system was developed for the present purpose. The data logging system was equipped with a plurality of "slave" units that connect (in operable signal communication) to the local sensor groups, and a "master" unit that wirelessly receives the data transmitted from the "slave" units. Raw data was further transferred to cloud storage using a 4G connection. End users were able to download and plot various real-time datasets online or over the internet. The data logging system was protected in a

closure box and powered by a solar panel on top of the box. The data logger collected the real-time measurements at a resolution of ten minutes per reading and sent the data to cloud storage every hour. Subsequently, end users were able to organize and analyze the uploaded dataset from online access.

[0068] Field instrumentation

[0069] The instrumentation used included osmotic tensiometers, e.g., available from the Nanyang Technology University (NTU), and moisture sensors (e.g., IMKO PICO 32 TDR moisture sensors and Meter Group TEROS 12 sensors) connected to data acquisition devices. Table 2 summarizes the instrumentation manufacturers, models, and relevant specifications. Commercially available osmotic tensiometers may be used.

Table 2. Technical specifications of the instrumentation installed on the testbed for field monitoring

Source	Model	Sensor type	Specifications
IMKO	PICO 32	TDR moisture sensor	Measuring range: 0% - 100 %; Measuring volume > 250 ml; Fully operational up to more than 12 deciSiemens per meter (dS/m) bulk soil conductivity
Meter Group	TEROS 12	Capacitance moisture sensor	Mineral soil calibration: 0.0 m ³ /m ³ – 0.7 m ³ /m ³ Resolution: 0.0010 m ³ /m ³
NTU		Osmotic tensiometer	Operating temperature: -40 °C - 120 °C, Resolution: 0.001% FS; Pressure range: -0.1 - 2.5 megapascal (MPa)
SISGEO	P252R	Piezometer	Sensitivity: 0.01% FS; Accuracy: 0.15% FS; Measurement range: 100 kPa-1 MPa

[0070] Laboratory calibrations were carried out for all the osmotic tensiometers and moisture sensors before the field deployment. Saturated volumetric water content determined from the in-situ soil samples at the target installation depth was used to calibrate the soil moisture sensors using a linear relationship between the voltage outputs and water content readings. The osmotic tensiometers were saturated and monitored in the laboratory to identify the maximum osmotic pressure as the reference to interpret soil suction measurements. Minor pressure adjustments from soil temperature influence and pressure decay were applied to the field dataset to calculate the real-time in-situ soil suctions. These calibration procedures and data interpretation techniques effectively improved the accuracy and consistency of sensor readings.

[0071] Soil water content measurements

[0072] Two sets of moisture sensors, IMKO PICO 32 (TDR moisture sensor or time domain reflectometry moisture sensors) and Meter Group TEROS 12 (capacitance moisture sensor) were installed at the upper, middle, and lower sections of the slope as seen in **FIG. 4A** and **FIG. 4B**. Each location consists of two individually deployed sensors at 0.2 m and 0.75 m depth as the target layer to evaluate the slope stability at shallow depth. Both TDR and capacitance sensors measure the volumetric water content using dielectric permittivity in soils and have been widely applied to field monitoring on slopes. The generator inside the TDR sensor transmits an electromagnetic pulse from rods and reflects it after traveling through the rods. Precise measurements of volumetric water content may be determined by the soil dielectric permittivity calculated from the travel time. For capacitance sensors, the charge time of a medium is measured using two electrodes from the metal probes and the oscillating voltage links the dielectric permittivity to the volumetric water content. Recent developments in capacitance sensors minimized the salinity effects by using high-frequency techniques and their low cost and lower energy consumption are environmentally beneficial which allows large sensing network applications. The study conducted also evaluated the field performance between the two sensors based on the monitoring results from the testbed.

[0073] Soil suction measurements

[0074] The osmotic tensiometers were installed at the upper, middle, and lower sections of the slope followed by the distribution of the soil moisture sensors and they were strategically placed in the middle between the two sets to compare the measurements. The osmotic tensiometer includes a flat-sloped ceramic disc embedded in a steep stainless cup and connects to a piezo-resistive pressure transducer (type PT35X, Keller-Druck) with a measurement range of -0.1 to 2.5 MPa and reading accuracy of 0.01% of the full scale. The pressure transducer uses an O-ring (thickness of 0.2 mm) to seal the gap and prevent polymer leakage between the cup and the sensor.

[0075] A cross-linked sodium polyacrylate was selected as the filling polymer material to achieve high and stable swelling pressures with minimal loss and quick response time. High osmotic pressure (1 MPa $\sim$ 2 MPa depends on the polymer concentration in the mixture) was achieved with the super-absorbed sodium polyacrylate saturated with distilled water and the calibrations of osmotic tensiometers utilize the reference osmotic pressure to interpret the soil suctions. The osmotic tensiometer used did not rely on linear extrapolation into the negative pressure range and eliminates the disadvantage in sensor calibration and field applications with reliable performance reported in previous monitoring. Soil suction measurements were used to further evaluate the soil moisture sensors under the soil-water characteristics envelope.

[0076] Soil water content variations

[0077] Daily temperature variations and precipitation events directly influenced the changes in suctions and volumetric water contents of the unsaturated soils at the monitoring slope. **FIG. 6A** and **FIG. 6B** show the volumetric water content changes from 0.2 m and 0.75 m depth from March to July measured by IMKO PICO 32 TDR moisture sensors at the testbed. The overall water content ranged from 30% - 40% at 0.2 m depth and 35% - 55% at 0.75 m depth. **FIG. 7A** and **FIG. 7B** show the volumetric water content changes from 0.2 m and 0.75 m depth from March to July measured by Meter Group TEROS 12 moisture sensors at the testbed. The overall water content ranged from 35% - 55% at 0.2 m depth and 40% - 55% at

0.75 m depth. The 4-month monitoring period was the general dry period and there were not many rainfall precipitation events observed based on the weather station recordings. PICO 32 and TEROS 12 moisture sensors effectively responded to rainfall precipitation where clear spikes or one or more spike increases in volumetric water content readings were observed when the rain initiated, and the measurements gradually decreased after the end of the rainfall event. This indicated the viability of capturing immediate precipitation events with volumetric water content responses from soil moisture sensors.

[0078] Soils experienced substantial suction changes in these dry months after a sudden rainfall event. **FIG. 8** summarizes the average suction at 0.2 m and 0.75 m depth measured by the osmotic tensiometers. Significant decrease in suction at the near-surface due to rainfall events were observed from the monitoring results. Although soil suction larger than 100 kPa was not observed during the recorded period, the prevailing rising trend in field suctions due to the dry periods was identified. This indicated that suction changes at the near-surface could be used to determine the presence of rainfall events. The deployment of osmotic tensiometers can effectively pick up large suction measurements in the later monitoring.

[0079] **FIG. 9A** and **FIG. 9B** further compare a summary of the volumetric water content reported from these two sets of moisture sensors in soil profiling. PICO 32 sensors reported unexpectedly larger volumetric water content variations at 0.75 m depth compared with 0.2 m depth. In contrast, TEROS 12 sensors reported anticipated larger water content changes at 0.2 m depth near the surface owing to greater infiltration and evaporation capabilities during precipitation events. The average water contents measured by the PICO 32 moisture sensors showed a lower value of 37% at 0.2 m depth and 40% at 0.75 m depth compared with 41% at 0.2 m depth and 45% at 0.75m depth measured by TEROS 12 moisture sensors. With the development of soil-water characteristic curves constructed from the laboratory measurements, the recorded moisture contents from the TEROS 12 showed better agreement with the volumetric water contents corresponding to the measured range of field suctions on the soil-water characteristic curve. Although both the moisture sensor techniques measure the dielectric permittivity of the

surrounding medium, TEROS 12 has a shorter measurement time and high accuracy after specific soil calibrations compared with PICO 32. With the improved installation consistency and lower sensor-to-sensor variability, TEROS 12 was able to provide a more accurate field water content range with greater reliability. This comparison is not to preclude the use of other types of moisture sensors other than capacitance moisture sensors (e.g., TDR moisture sensors) but rather to experimentally verify that selected moisture sensors are capable of providing sufficiently accurate and consistent readings for use in the proposed slope condition monitoring system 200.

[0080] Soil-water characteristic analysis

[0081] The osmotic tensiometers are preferred as the field study verified their ability to capture the real-time water transfer in soils under weather variations and extended the suction measurement capacity beyond the conventional water-based tensiometers. Substantial suction drops were observed immediately after rainfall events and the negative pore-water pressure slowly built up during dry periods. In-situ soil samples from the shallow layer (0 m – 1 m) were collected and the soil-water characteristic curve (SWCC) was constructed in the laboratory. Centrifuge test (low suction range, 0 ~ 250 kPa) and WP4C potentiometer (high suction range, > 250 kPa) with the assistance of the best fitting equations helped to establish the SWCC of residual soils from the testbed. Soil volumetric water contents measured from both the TDR and capacitance moisture sensors and the suction results interpreted from the osmotic tensiometer readings were captured and plotted in the same framework of the soil water characteristic envelope for the soil, as presented in **FIG. 10A** to **FIG. 11B**.

[0082] **FIG. 10A** and **FIG. 10B** present a soil-water characteristic analysis for the combined measurements water content measurements and soil suctions at 0.2 m depth of PICO 32 and TEROS 12. The dataset at 0.2 m depth fell below the reference SWCC due to the lower volumetric water content measurements from the TDR sensors. The collected dataset from PICO 32 did not share the trend related to the SWCC as the results from TEROS 12 sensors.

[0083] **FIG. 11A** and **FIG. 11B** present the field dataset at 0.75 m depth for both PICO 32 and TEROS 12 under the SWCC envelope. Most measurements followed the SWCC despite some scattered points from the PICO 32 reported erroneously that deviated far from the reference. The groundwater table was close to 0.75 m installation depth. The field water content measurement range was much smaller compared with the collected dataset from 0.2 m as shown in the TEROS 12 results. The standard deviation between the volumetric water contents measured by PICO 32 sensors was averaged at 24%, while more consistent and accurate datasets were produced by the combination of TEROS 12 with an average standard deviation of 15%. A combination of the osmotic tensiometers and capacitance moisture sensor (e.g., Meter Group TEROS 12 moisture sensors) was found to perform well.

[0084] The proposed slope monitoring system 200 is configured provide a wider range of the field suction and volumetric water contents readings than was conventionally considered. More specifically, according to embodiments of the present disclosure, the detectable range is configured to cover both the saturated zone (before the air-entry point) and the unsaturated zone under the soil-water characteristic envelope with better accuracy.

[0085] Two-dimensional seepage analysis

[0086] Two-dimensional seepage analysis was performed with the aid of the GeoStudio SEEP/W software available from Seequent (www.seequent.com). The volumetric water content of the Rumah Tinggi slope as measured (moisture sensor measurements) and as determined analytically (by numerical analysis) was compared. A period from 11 June to 19 June was selected as it had a combination of dry and wet weather.

[0087] **FIG. 12** presents the slope model of the Rumah Tinggi testbed used in the SEEP/W analysis. The groundwater table was modeled at a depth of 8.4 m and 5.5 m at the crest and toe of the slope, respectively, following the piezometer measurements on 11 June at 00:00 am. The rainfall recorded by the nearest weather station at Alexandra Road located 0.6 km (kilometer) from the testbed was used for the numerical analysis. The rainfall was applied as a unit water flux with

potential seepage face review. Following conventionally adopted slope geometries, the side boundaries were modeled to be three times the height of the slope to reduce the influence on the seepage analysis in the slope. A zero-flux condition was applied to the side boundaries above the groundwater table while a constant total head was applied below the groundwater table. A mesh size of 0.25 m was used for the seepage analysis.

[0088] The soil properties obtained for the 0.2 m depth were used for the first soil layer which has a thickness of 0.5 m. The soil properties obtained for the 0.75 m depth were used for the second soil layer. **FIG. 13A** and **FIG. 13B** show the soil-water characteristic curve and permeability function respectively.

[0089] Soil volumetric water content comparison between numerical analysis and sensor measurements

[0090] The volumetric water content measurements from the PICO 32 and TEROS 12 sensors at 0.2 m and 0.75 m depths were plotted with the volumetric water content results from the SEEP/W analyses at 0.05 m, 0.2 m, and 0.75 m depths as seen in **FIG. 14A** to **FIG. 14C**. The SEEP/W results from the upper, middle, and lower sections were relatively similar and did not show a large variation as observed from the moisture sensor measurements. Thus, only the volumetric water content results from the middle section were plotted in **FIG. 14A** to **FIG. 14C** to allow for an easier comparison with the moisture sensor measurements.

[0091] The volumetric water content results from the SEEP/W analysis using the soil properties from laboratory testing (saturated permeability, $k_s = 2.97E-08$ m/s) did not correspond well with the rainfall for the 0.2 m and 0.75 m depths as compared to the moisture sensor measurements which showed an increase in volumetric water content during rainfall events (**FIG. 14B** and **FIG. 14C**). The SEEP/W volumetric water content at 0.2 m depth gradually increased over time as compared to the moisture sensor readings which showed a substantial increase in volumetric water content during the heavy rainfall events on 12 June and 18 June. The SEEP/W volumetric water content at near surface (0.05 m) depth responded well with the rainfall as an increase in volumetric water content could be observed during the low-intensity rainfall between 14 June and 16 June. The magnitude of

the increase in volumetric water content was smaller as compared to the moisture sensor readings.

[0092] One possible reason for the smaller change in volumetric water content observed in the SEEP/W analysis as compared to the moisture sensor measurements could be due to the saturated permeability used in the analysis. The low saturated permeability, k_s of the soil ($2.97\text{E-}08$ m/s) could have limited the rainfall infiltration and resulted in a smaller change in volumetric water content in the SEEP/W analysis. The k_s of $2.97\text{E-}08$ m/s was obtained from performing a constant head permeability test using a triaxial cell for undisturbed soil samples obtained from the testbed. There could be sample disturbance which could have altered the in-situ soil properties and led to inaccuracies in the laboratory tests, resulting in a lower saturated permeability.

[0093] An additional SEEP/W analysis was performed as a sensitivity analysis by increasing the saturated permeability by one order of magnitude to a value of $2.97\text{E-}07$ m/s to account for possible measurement inaccuracies during the laboratory testing. The additional SEEP/W analysis was also used to evaluate if the earlier SEEP/W analysis with a higher saturated permeability would produce similar results to the moisture sensor measurements in the field. The permeability function for the higher k_s is presented in **FIG. 13B**.

[0094] The SEEP/W analysis using the 1-order higher k_s of $2.97\text{E-}07$ m/s illustrates that there was a significant difference in the volumetric water content trend when the permeability of the soil was increased. With the increased permeability, the volumetric water content at 0.2 m depth was observed to increase during the heavy rainfall on 12 June and 18 June (**FIG. 14B**). Moreover, the SEEP/W results at 0.05m depth showed a greater increase in volumetric water content during all rainfall events and a faster rate of decrease in volumetric water content after the end of each rainfall event. The trend observed is similar to that in the moisture sensor measurements by the TEROS 12 sensors.

[0095] The TEROS 12 sensor at 0.2 m depth located at the lower section of the slope was the most responsive to rainfall. This could be due to the groundwater table variation at the toe of the slope (**FIG. 15**). The groundwater table at the toe

rose to the ground surface during the heavy rainfall events and varied greatly between 0 m to 5 m depths during the analysis period. However, the groundwater table at the crest only varied between 4 m to 6 m depth from the surface. Hence, significant changes in volumetric water content were observed in the sensors installed at the lower section of the slopes due to the rising groundwater table. However, this variation was not observed in the SEEP/W results as the groundwater table depth did not change much in the analysis as compared to the actual groundwater table depth measured by the piezometers on the slopes (**FIG. 16**). The differences in the groundwater depth in the analysis and field could be one important reason for the differences in volumetric water content as measured by the sensor on the slope and as determined by the seepage analysis. The measurements from the TEROS 12 sensor had a similar volumetric water content range when compared to the results from the SEEP/W analysis. The PICO 32 sensors at the 0.2 m depth had a relatively very low range of volumetric water content (e.g., between 0.27 to 0.4). Even during the heavy rainfall event, the maximum volumetric water content measured by the PICO 32 sensors was less than 0.4 whereas the TEROS 12 sensors measurements were much closer to the saturated volumetric water content of the soil. In other words, the proposed slope condition monitoring system 200 which is weather-responsive and at least partially based on real-time measurements, is able to achieve a greater accuracy in predicting imminent or possible slope failures than the conventional purely analytical approach.

[0096] Real-time slope warning system

[0097] A real-time warning system for slope instability as proposed in the present disclosure is useful for predicting slope failures, allowing engineers to take intervention measures and reduce the consequences that may arise from slope failures.

[0098] According to embodiments of the present disclosure, a linear relationship or linear regression model of the factor of safety and volumetric water content is proposed to determine a factor of safety, in which the volumetric water content is a real-time volumetric water content as measured (e.g., by moisture sensors).

[00099] In some embodiments, the linear relationship, or the linear regression model for a local area (e.g. the Rumah Tinggi slope in the experiments) is derived from best-fitting results from a regional water balance and slope stability analyses.

[00100] Regional analysis for establishing the relationship between the factor of safety and volumetric water content

[00101] Regional water balance analyses may be first performed using the GEOtop software or any three-dimensional water balance model that can analyze the groundwater flow, surface runoff, subsurface flow, and rainfall infiltration into saturated/unsaturated soil.

[00102] The soil properties used in the regional water balance analyses may be obtained from known soil databases. In the experiments which were conducted in Singapore, the soil database used was one developed and published by Li et al. (2022) (see, e.g., Li, Yangyang & Rahardjo, Harianto & Satyanaga, Alfrendo & Rangarajan, Saranya & Lee, Daryl. (2022). "Soil database development with the application of machine learning methods in soil properties prediction". Engineering Geology. 306. 106769. 10.1016/j.enggeo.2022.106769). The soil database was developed for the Singapore island, in which the island was divided into 97 zones with similar soil properties in each zone. The database includes the mean values of saturated permeability, saturated and unsaturated shear strength parameters, and SWCC in each zone.

[00103] The Rumah Tinggi slope is located within the JF20 zone of the Li et al., (2022) database. One limitation of the GEOtop model would be the choice of the SWCC equations that may not be suitable for describing conditions at the actual slope. An extreme rainfall intensity of 22.2 mm/hour was applied at a constant rate for 24 hours. Subsequently, another 24 hours of no rainfall was applied in the analysis to evaluate the recovery of the factor of safety and volumetric water content. The pore-water pressures and volumetric water content results from the water balance analysis were used as inputs for the 3D slope stability analysis for the three critical timesteps 1st hour, 24th hour, and 48th hour timesteps. The slope stability analyses were performed using Scoops3D software to calculate the factor of safety.

[00104] The average volumetric water content for 0 m to 2 m depths and factor of safety results for the three timesteps (i.e. 1st hour, 24th hour, and 48th hour) were best fitted using a linear regression model. The volumetric water content between 0m to 2m depth was used as many slope failures in Singapore were observed to have a shallow slip surface. Additional analyses were performed to verify the appropriateness of using the linear regression model to represent the relationship between the factor of safety and volumetric water content.

[00105] **Table 3** summarizes the additional analyses performed for the verification of the linear relationship. The two types of additional analyses performed are extreme rainfall analyses and actual rainfall analyses. For the extreme rainfall, additional timesteps besides the 1st, 24th, and 48th hours were analyzed to compare the actual factor of safety from the Scoops3D software with the calculated factor of safety from the linear regression line model. Secondly, actual rainfall conditions at the Rumah Tinggi slope were applied to evaluate the volumetric water content and factor of safety under actual rainfall conditions. The rainfall intensity and timesteps considered for the actual rainfall analyses are presented in **FIG. 17**.

Table 3. Additional analysis to verify the linear regression line.

Type of analysis	Timestep	Rainfall intensity at the timestep
Extreme rainfall	15 minute	Rainfall period between 0 th to 24 th hour
	30 minute	
	45 minute	
	6 hour	
	12 hour	
	18 hour	
	30 hour	No rainfall period between the 24 th to 48 th hour
	36 hour	
	42 hour	
	1 hour	1 hour after no rainfall on 11 June 0:00
	35 hour	35 hours after no rainfall on 12 June 10:00

Actual rainfall from 11 June to 19 June	36 hour	After rainfall on 12 June 11:00
	38 hour	After rainfall on 12 June 13:00
	40 hour	After rainfall on 12 June 15:00
	180 hour	After rainfall on 18 June 11:00

[00106] The linear regression line developed by best fitting the data points for the 1st, 24th, and 48th hours is presented in **FIG. 18A** to **FIG. 18D** for four different slopes within the JF20 zone. These slopes have an R^2 value of more than 0.96 indicating that the linear regression line has a good fit with the data points. Results from the additional analyses presented in **Table 3** show a slightly different trend from the linear regression line. The factor of safety before the 1st hour of extreme rainfall (i.e. 15 minutes, 30 minutes, 45 minutes) remains almost constant for all four slopes. Thus, the results show that within the first hour of rainfall, although an increase in volumetric water content was observed the factor of safety remains relatively constant. Using the linear regression line to calculate the factor of safety for a lower volumetric water content range would lead to an overestimated factor of safety. A factor of safety cutoff was imposed, e.g., the maximum factor of safety was limited to the factor of safety obtained from the 1st hour of extreme rainfall analysis. The linear regression line obtained from best fitting the 1st hour results, the 24th hour results, and the 48th hour results from extreme rainfall analyses was used to represent the relationship between the factor of safety and volumetric water content for volumetric water content ranging from the 1st hour extreme rainfall volumetric water content to the saturated volumetric water content of the soil.

[00107] Other data points from the additional analyses tend to lie above the linear regression line for volumetric water content ranging between the 1st hour and the 48th hour extreme rainfall analysis data points. Hence, the factor of safety calculated from the linear regression line would be conservative.

[00108] For the volumetric water content ranging between the 24th hour and 48th hour volumetric water content, the actual factor of safety lies very close to the linear regression line. This indicated that the calculated factor of safety was close to the actual factor of safety.

[00109] The results from the analysis show that there is some deviation from the linear regression line especially for the lower volumetric water content range. Nevertheless, the results also demonstrated that the linear regression model with a factor of safety cutoff is a viable and practical approach. The linear regression model can be developed by running the regional water balance and slope stability analyses for the three critical timesteps where the 1st hour timestep represents the initial factor of safety, the 24th hour represents the lowest factor of safety at the end of the rainfall, and the 48th hour represents the recovery of the factor of safety after the rainfall. Running additional analyses may help to improve the accuracy of predicting the factor of safety, although it is believed that additional analyses would not be necessary or computationally cost-efficient.

[00110] IoT-based real-time monitoring supported slope warning case study

[00111] Upon establishing a linear relationship between the factor of safety and volumetric water content, the factor of safety can be calculated for any volumetric water content measured by the moisture sensor placed on the slope. A real-time alert system can be implemented with the calculated factor of safety. Once the factor of safety decreases below a safety threshold value, or once the factor of safety reaches a low value (e.g., 1.5), a controller may be configured to send an alert message to indicate that the slope is close to failure, and timely slope stabilization measures may then be implemented.

[00112] The factor of safety calculation using linear regression

[00113] **FIG. 19** is a graph showing the factor of safety (FOS) predicted or determined from TEROS 12 sensor readings. In some embodiments, the volumetric water content measured by the TEROS 12 sensor may be used to calculate the real-time factor of safety of the slope given that the sensors record a larger change in volumetric water content than PICO 32. Hence, the factor of safety calculated using volumetric water content from TEROS 12 will be lower than from PICO 32. Due to differences in soil properties, such as saturated volumetric water content, the volumetric water content measured by the sensor and volumetric water content from the soil database used in the extreme rainfall analysis will be different. For example, the saturated volumetric water content from the database that was used

in the regional analysis has a value of 0.456, while some of the volumetric water content range from moisture sensor measurements spiked above 0.456 during the intense rainfall events. It follows that a volumetric water content measurement of 0.456 by the sensor does not mean the soil is fully saturated as the field-saturated volumetric water content is higher than 0.456. Therefore, substituting the raw sensor measurement into the linear regression line equation would result in an inaccurate factor of safety calculation as it would be assuming that the soil is fully saturated when in fact it is not.

[00114] According to embodiments of the present disclosure, a correlation between the soil database volumetric water content and actual soil volumetric water content is established. This addresses the inaccuracy that may arise from a simple substitution of raw sensor measurement data into the linear regression model.

[00115] A correlation factor, c_f has been introduced to calculate the degree of saturation of the actual soil for the soil properties from the database used in the regional analysis. The correlation factor is calculated by using two terms, saturated VWC_{sensor} and saturated VWC_{database} . The saturated VWC_{database} refers to the saturated volumetric water content from the database that was used to generate the linear regression line from the extreme rainfall analysis. The saturated VWC_{sensor} refers to the laboratory saturated volumetric water content (e.g., from laboratory testing). If the field saturated volumetric water content measured by the sensors disposed on the slope exceeds the laboratory saturated volumetric water content, the saturated VWC_{sensor} taken to be the value of the field saturated volumetric water content. Equation (1) below shows a method of determining the correlation factor, c_f , based on the database saturated VWC (saturated VWC_{database}) and the sensor saturated VWC (saturated VWC_{sensor}).

$$\frac{\text{Saturated } VWC_{\text{database}}}{\text{Saturated } VWC_{\text{sensor}}} \times 100\% = C_f \quad \text{Equation (1)}$$

[00116] The volumetric water content results from the TEROS 12 sensors had a maximum value exceeding the saturated volumetric water content from the lab testing. The volumetric water content readings have been capped to a maximum

value of 0.478 for 0.2 m depth and 0.520 for 1.75 m depth. The correlation factor using Equation 1 for 0.2 m and 0.75 m depth was calculated to be 95.5% and 87.8%, respectively. These correlation factors were then applied to the capped volumetric water content readings from each sensor. Subsequently, the average volumetric water content from the 0.2 m and 0.75 m sensors was calculated for the upper, middle, and lower sections of the slope, and the values were substituted in the linear regression line equation to calculate the factor of safety of the slope. **FIG. 19** shows the minimum factor of safety at the upper, middle, and lower sections of the slope. The calculated factor of safety was observed to decrease significantly during the rainfall events due to the sensors recording a significant increase in volumetric water content. The recovery of the factor of safety was much slower.

[00117] The field study at Rumah Tinggi, Singapore, conducted from March 2023 to July 2023, successfully demonstrated the feasibility and efficiency of utilizing Internet of Things (IoT)-based technologies for real-time monitoring of an unsaturated slope. By integrating advanced moisture sensors and osmotic tensiometers within a comprehensive IoT framework, a novel approach to continuously monitor the hydrological behavior of slopes under varying weather conditions has been experimentally verified. The proposed slope condition monitoring system was demonstrated to be useful for evaluating or predicting slope stability, particularly in the context of climate change and potential rainfall-induced slope failures at shallow depths, going beyond basic field monitoring and factor of safety calculations.

[00118] Based on the field performance comparison between PICO 32 and TEROS 12 moisture sensors at the Rumah Tinggi testbed, results from TEROS 12 reported more consistent measurements with an average of 41% at 0.2 m depth and 45% at 0.75 m depth during the monitoring period. By contrast, PICO 32 reported unexpectedly larger volumetric water content variations at 0.75 m depth with lower average water contents of 37% at 0.2 m depth and 40% at 0.75 m depth that deviated from the soil-water characteristic curve. The standard deviation between the volumetric water contents measured by PICO 32 sensors was averaged at 24% while TEROS 12 shared a standard deviation average of 15%

with much lower sensor-to-sensor variability. Therefore, it has been verified that the proposed slope condition monitoring system proposed herein can make a significant improvement in accurately capturing the soil-water dynamics for informing slope stability analysis.

[00119] The linear regression model proposed was able to provide a relationship between volumetric water content and factor of safety that provided practical indicators, using results from regional water balance and slope stability analyses under extreme rainfall conditions. The proposed system allows for the calculation factor of safety for slope stability analysis using field volumetric water content and provides real-time assessment of potential risky slopes with the same resolution as the moisture sensor response at 10-minute intervals. The calculated factor of safety from the Rumah Tinggi testbed spanned between 3 to 5 with two major downward spikes recorded during two intense rainfall events that took place in June 2023. Real-time recovery of the slope factor safety was also observed during the dry periods after rainfall events terminated. The ability to calculate the factor of safety in real-time through the developed linear regression model represents a pivotal step towards the implementation of proactive landslide risk management strategies.

[00120] It is envisioned that the proposed slope condition monitoring system can be applied to diverse climatic and soil conditions. It is further envisioned to expand the sensor network to cover a broader range of soil types and topographies, as well as integrating more sophisticated machine learning algorithms to enhance the predictive accuracy of slope failure events.

[00121] The proposed slope condition monitoring system integrated with IoT technologies offers a transformative tool for geotechnical engineering and slope condition monitoring practices, paving the way for more resilient infrastructure development in the face of escalating climate risks. The proposed slope condition monitoring system offers a significant improvement over conventional methods, providing higher resolution data, real-time analysis capabilities, and a more cost-effective solution for long-term slope stability assessment. The present work contributes to the advancement of slope stability analysis and realizes to some

extent the potential for IoT applications in broader geotechnical and environmental monitoring endeavors.

[00122] According to various embodiments of the present application, a slope condition monitoring method for monitoring a slope includes acquiring a volumetric water content from a plurality of sensors disposed on the slope. The slope condition monitoring method includes using the volumetric water content to determine a factor of safety of the slope based on a linear regression model obtained from a simulated volumetric water content corresponding to wet weather conditions. The slope condition monitoring method includes generating an alert in response to the factor of safety being determined to be below a safety threshold value, the alert being indicative of a possible slope failure.

[00123] The slope condition monitoring method may include using the volumetric water content to determine a plant health indicator of one or more plants on the slope, in which the alert is generated in response to any one of the following: the factor of safety being determined to be below the safety threshold value, and the plant health indicator being below a health threshold value.

[00124] The slope condition monitoring method may include: using the volumetric water content to determine a plant health indicator of one or more plants on the slope, in which the alert is generated in response to a combination of the following: the factor of safety being determined to be below the safety threshold value, and the plant health indicator being below a health threshold value.

[00125] The combination of the following may be used as an indication of the possible slope failure: (i) the factor of safety being below the safety threshold; and (ii) the plant health indicator being below the health threshold value.

[00126] The plant health indicator of the slope condition monitoring method may include a ratio of a variable fluorescence to a maximum fluorescence.

[00127] The slope condition monitoring method may include determining a relationship between the plant health indicator and the volumetric water content.

[00128] The determining of the factor of safety of the slope may include applying a correlation factor to the volumetric water content, the correlation factor being a

ratio of a database saturated volumetric water content to a sensor saturated volumetric water content.

[00129] The sensor saturated volumetric water content may be obtained from one of the following: (i) a laboratory saturated volumetric water content, and (ii) a field saturated volumetric water content measured by the sensor on the selected slope.

[00130] The sensor saturated volumetric water content may be selected from a greater of the laboratory saturated volumetric water content and the field saturated volumetric water content measured by the sensor on the selected slope

[00131] The safety threshold value in the slope condition monitoring method may be a relatively low value, e.g., preferably, 1.5.

[00132] The slope condition monitoring method may further include: acquiring a plurality of the volumetric water content at a first sampling frequency in response to a presence of rainfall; and acquiring a plurality of the volumetric water content at a second sampling frequency in response to an absence of rainfall, the first sampling frequency being higher than the second sampling frequency.

[00133] The slope condition monitoring method may further include: determining a change from the absence of rainfall to the presence of rainfall in response to sensing a spike increase in the volumetric water content over a period of time; and in response to the determining of the change from the absence of rainfall to the presence of rainfall, decreasing a sampling interval between successive measurements of the volumetric water content measurements.

[00134] The slope condition monitoring method may further include: determining a change from the presence of rainfall to the absence of rainfall in response to sensing a decrease in the volumetric water content over a later period of time; and, in response to the determining of the change from the presence of rainfall to the absence of rainfall, increasing a sampling interval between successive measurements of the volumetric water content measurements.

[00135] A slope condition monitoring system, at least partially installed on a selected slope, includes a plurality of sensors disposed on the selected slope and a controller. The plurality of sensors are configured to provide a volumetric water content of the selected slope. The controller is configured to be in signal

communication with the plurality of sensors. The controller is configured to perform the method of slope condition monitoring method according to any one or more of the embodiments described above.

[00136] The plurality of sensors may include: a plurality of osmotic tensiometers disposed in a crest and a toe of the selected slope; and a plurality of capacitance moisture sensors distributed at various elevations of the selected slope.

[00137] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding and are not intended to be limiting or exhaustive. Modifications may be made by one of ordinary skill in the art without departing from the scope of the claimed invention.

CLAIMS

1. A slope condition monitoring method for monitoring a slope comprises:
 - acquiring a volumetric water content from a plurality of sensors disposed on the slope;
 - using the volumetric water content to determine a factor of safety of the slope based on a linear regression model obtained from a simulated volumetric water content corresponding to wet weather conditions; and
 - generating an alert in response to the factor of safety being determined to be below a safety threshold value, the alert being indicative of a possible slope failure.
2. The slope condition monitoring method as recited in claim 1, comprising:
 - using the volumetric water content to determine a plant health indicator of one or more plants on the slope, wherein the alert is generated in response to any one of the following:
 - the factor of safety being determined to be below the safety threshold value;
 - and
 - the plant health indicator being below a health threshold value.
3. The slope condition monitoring method as recited in claim 1, comprising:
 - using the volumetric water content to determine a plant health indicator of one or more plants on the slope, wherein the alert is generated in response to a combination of the following:
 - the factor of safety being determined to be below the safety threshold value;
 - and
 - the plant health indicator being below a health threshold value.
4. The slope condition monitoring method as recited in claim 3, wherein a combination of the following is used as an indication of the possible slope failure:

- (i) the factor of safety being below the safety threshold; and
- (ii) the plant health indicator being below the health threshold value.

5. The slope condition monitoring method as recited in any one of claims 2 to 4, wherein the plant health indicator comprises a ratio of a variable fluorescence to a maximum fluorescence.

6. The slope condition monitoring method as recited in any one of claims 2 to 5, comprising:

- determining a relationship between the plant health indicator and the volumetric water content.

7. The slope condition monitoring method as recited in any one of claims 2 to 5, wherein the determining of the factor of safety of the slope comprises:

- applying a correlation factor to the volumetric water content, the correlation factor being a ratio of a database saturated volumetric water content to a sensor saturated volumetric water content.

8. The slope condition monitoring method as recited in claim 7, wherein the sensor saturated volumetric water content is obtained from one of the following: (i) a laboratory saturated volumetric water content; and (ii) a field saturated volumetric water content measured by the sensor on the selected slope.

9. The slope condition monitoring method as recited in claim 7, wherein the sensor saturated volumetric water content is selected from a greater of the laboratory saturated volumetric water content and the field saturated volumetric water content measured by the sensor on the selected slope

10. The slope condition monitoring method as recited in claim 1, wherein the safety threshold value is 1.5.

11. The slope condition monitoring method as recited in any one of claims 2 to 10, further comprising:

- acquiring a plurality of the volumetric water content at a first sampling frequency in response to a presence of rainfall; and
- acquiring a plurality of the volumetric water content at a second sampling frequency in response to an absence of rainfall, the first sampling frequency being higher than the second sampling frequency.

12. The slope condition monitoring method as recited in claim 11, further comprising:

- determining a change from the absence of rainfall to the presence of rainfall in response to sensing a spike increase in the volumetric water content over a period of time; and
- in response to the determining of the change from the absence of rainfall to the presence of rainfall, decreasing a sampling interval between successive measurements of the volumetric water content measurements.

13. The slope condition monitoring method as recited in claim 11, further comprising:

- determining a change from the presence of rainfall to the absence of rainfall in response to sensing a decrease in the volumetric water content over a later period of time; and
- in response to the determining of the change from the presence of rainfall to the absence of rainfall, increasing a sampling interval between successive measurements of the volumetric water content measurements.

14. A slope condition monitoring system at least partially installed on a selected slope, the slope condition monitoring system comprising:

a plurality of sensors disposed on the selected slope, the plurality of sensors being configured to provide a volumetric water content of the selected slope; and

a controller, the controller being configured to be in signal communication with the plurality of sensors, the controller being configured to perform the method of slope condition monitoring method as recited in any one of the preceding claims.

15. The slope condition monitoring system as recited in claim 14, wherein the plurality of sensors comprise:

a plurality of osmotic tensiometers disposed in a crest and a toe of the selected slope; and

a plurality of capacitance moisture sensors distributed at various elevations of the selected slope.