than that of Experiment 3, probably due to the presence of more entrapped air within the slope and the lower saturated hydraulic conductivity of the soil. Due to the high antecedent moisture content of the slope profile, the volumetric moisture content record for each sensor only shows one stage of the significant moisture content rise. Prior to Stage 1 displacement, moisture sensor TP2 responded to the development of the saturated zone in its vicinity, implying that the saturated wetting fronts had advanced to the area near the slope surface. At the beginning of Stage 1 sliding, the lower portion of the sliding soil mass attained a near-saturated value as observed by the near-surface sensor TP2; whereas moisture sensors TP3 and TP4 detected no significant volumetric moisture content increases, because the growth of the saturated zone had not yet reached the location of those sensors. The next significant increase in volumetric moisture content within the slope was almost simultaneously recorded by sensors TP3 and TP4, during which Stage 2 sliding occurred. This response may correspond to the simultaneous growth of saturated zones from the slope surface and the slope base toward those sensors. In this experiment, moisture sensors displayed no volumetric moisture content drops corresponding to shearing in Stages 1 and 2, since the sensors were located far from the slope area involved in the shearing. The lack of measurable moisture responses, in sensor TP1, may suggest that some air voids remained entrapped within the soil at the toe until the end of experiment, implying that the toe area never reached full saturation throughout the entire experiment. This permanently unsaturated condition probably inhibited the initiation of toe failures in the experiment, because the presence of entrapped air maintained soil suction, resulting in the stability of the toe area.

Discussions

Influence of Seepage Area on Failure Initiation

In each experiment, slope failures were induced in the experimental soil slope by increasing saturation and water level within the slopes. Perhaps the most significant aspect of the results of each experiment is that the process of failure initiation is always preceded by the growth of saturated seepage area. For thick, homogeneous soil slopes, the experiments indicate that the seepage area tends to be developed from the lower parts of the slopes. Results of field measurements, by Weyman (1973), indicate that saturation may also be developed first at the bottom of the slope. While others show that saturation can also be developed as a perched water table in some parts of the slope (Gasmo et al. 1999), or along the slope (Deutscher et al. 2000).

The detailed observations described above point out that the growth of the seepage area significantly contributed to the development of a highly unstable seepage area, indicated by the formation of tension cracks. This correlates with the common observation that the discharge area, where spring or seeps exist, are prone to slope failure (e.g., Lacerda 1999). Using numerical modeling studies, Iverson and Reid (1992) have demonstrated that a region of locally high failure potential tends to exist in near-surface discharge areas in a saturated hillslope. Thus, the results of the experimental study clearly show that effective drainage, at the seepage area, is needed to prevent seepage-induced instability.

The experimental results also show that the instability of the seepage area appeared to disturb the overall stability of the slope, particularly the near-surface slope region. Of course, this may not always be the case, and the hydraulic properties of the soil and the slope dimension seem to influence the development of seepage area, and hence, the initiation of overall instability. Thus, once these factors preclude the growth of seepage area, the process of instability of slopes will consequently come to an end. Other factors, such as slope morphology and hydraulic heterogeneities, will also affect the location of the seepage area and slope failures (Reneau and Dietrich 1987; Johnson and Sitar 1990; Reid and Iverson 1992).

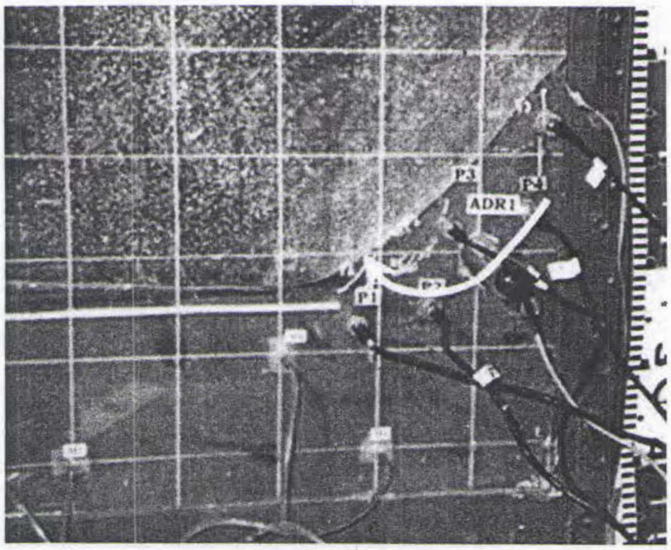

Fig. 11. Direction of water seepage outward from the slope toe as indicated by the arrow (Experiment 3)

Mechanism of Failure Initiation

The contribution of the seepage area to the initiation of failures clearly provides substantial evidence that rainfall-induced slope failures are initiated under drained conditions. This is consistent with the results of previous studies on the condition leading to the initiation of rainfall-induced debris flow failures (Sitar et al. 1992; Anderson and Sitar 1995). The mechanism of failure initiation under drained conditions involves a stress change caused by the hydrologic response of the slope to rainfall (Anderson and Sitar 1995). In the experimental study, this change in stress was concentrated in the vicinity of the toe, when the seepage area started to develop. The change in stress corresponded to the effect of groundwater seepage forces on the effective stress field of the soil at the toe. Photographic records of flow lines consistently suggest that the seepage were directed outward from the slope in this region (Fig. 11). Using numerical modeling studies, Reid and Iverson (1992) have demonstrated that the components of the seepage forces tend to develop concentrated tensile stress near the toe area. As evident in the experimental models, the development of the tension zone caused cracks above the seepage area, indicating that the saturated soil mass at the toe had reached the point of yielding, as the toe failure was initiated.

To reconcile the observation that, in some cases, the overall failures largely involved the unsaturated soil mass near the slope surface rather than just the nearly saturated soils, a mechanism of overall slope instability is needed. It must be noted that the overall failures of the near-surface soil occurred during the growth of toe tension cracks. In other words, the growth of the tension crack brought about the failure of the unsaturated near-surface region. This mechanism of progressive failure is possible only through a

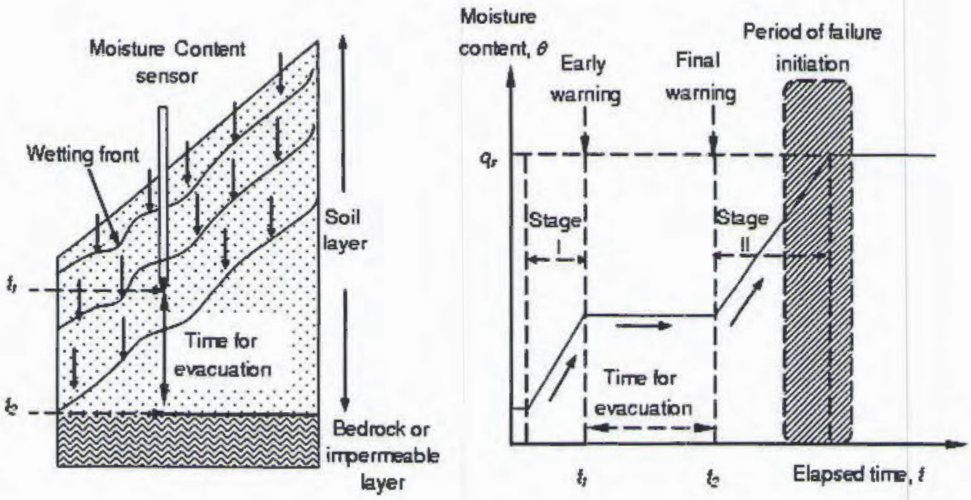

Fig. 12. The conceptual prediction methodology for rainfall-induced slope failures based on moisture content measurement

stress transfer process from the slope region that has reached failure (saturated zone near toe) to an adjacent region that has not (Anderson and Sitar 1995). Accordingly, stress concentration that developed near the base of the toe tension crack appears to have caused the unsaturated near-surface area to reach a point of failure. In other words, the loss of shear strength of the soil at the toe had reduced the lateral support to the region above the toe.

Degree of Saturation at Failure Initiation

The precise monitoring of moisture contents provides consistent indications of the likelihood of the occurrence of slope failure. The moisture content of the near surface soils reached a nearly saturated value at failure initiation. In other words, it was determined, that it is not necessary for a localized failure to initiate under a fully saturated condition; a level of soil saturation of roughly 85% appears to be sufficient to provide a hydrologic condition leading to the failure initiation of a soil slope, a conclusion similar to that drawn by Farooq et al. (2001). Despite the presence of entrapped air within the soil, this level of saturation corresponded to the effective saturation of the soil, at which point the soil lost a considerable amount of suction. This soil hydrologic condition leads to the reduction of the available shear strength at the point where failure is initiated.

Characteristics of Slope Hydrologic Response to Rainfall

According to the result of Experiments 3, the profile of the change in volumetric moisture content of dry, permeable soil slopes, observed by a moisture sensor located near the slope surface at the toe, consists of two stages of significant increase in volumetric moisture content in response to the infiltration of rainwater [see Fig. 10(c), sensor TP1]. The first stage of increase corresponds to the advancing of the unsaturated wetting front by which the soil reached about 50% degree of saturation. This unsaturated condition lasts until a groundwater table appears, and starts to rise from the slope base. The second stage of increase is associated with the rise of groundwater level to the slope surface, during which the degree of saturation of the soil increases to near 100%. In contrast, the volumetric moisture content response of a wet, less permeable soil slope (e.g., Experiment 4) to rainfall is characterized by one stage of increase in volumetric moisture content of the soil to reach saturated condition [see Fig. 10(d), Sensor TP2]. This response merely corresponds to the advancement of a saturated wetting front from the slope surface. Thus, the saturated wetting front may develop much earlier on the slope surface, than within the slope. Also, longer durations of rainfall are required to develop the hydrologic condition leading to failure initiation in the less permeable soil slopes, as indicated in Table 2. This demonstrates how the hydraulic conductivity of soil slopes control the hydrologic response of the slope and the rainfall characteristics.

Concept of Moisture Content-Based Prediction Methodology

On the basis of the experimental evidence concerning the hydrologic response of soil slopes to rainfall, it is possible to propose a concept of moisture content-based prediction methodology for rainfall-induced slope failures.

The schematic of the concept is shown in Fig. 12. The proposed prediction methodology involves determination of the monitoring locations, where the seepage area tends to develop. The use of a numerical analysis of saturated–unsaturated flow can help the most appropriate monitoring locations. Our experimental results indicate that the soil moisture content sensors should be installed close to the face of the slope to monitor the development of seepage area. Prior to installation of the sensors, it is necessary to determine the in situ soil porosity at each monitoring point in order to calculate the values of saturated volumetric moisture content, which are required to determine the degree of saturation. The monitoring also should be performed continuously to adequately assess the change of soil moisture content (or the degree of saturation) during rainfall, in order to estimate the critical time of evacuation and the warning threshold. Referring to Fig. 12(b), the critical time for evacuation can be defined as the time required for the wetting front to travel from the sensor head to the impervious layer or initial groundwater level (t_1 to t_2). The initiation of the second stage of increase in the moisture content of the near surface soil represents the hydrologic condition in which groundwater table start to rise from impermeable layer or base rock to slope surface. Thus, the corresponding time (t_2) can be designated to trigger a final warning against the slope failure hazard. The extent of the time for evacuation will depend on the depth of the sensor, with respect to the impervious layer or initial groundwater, and on the antecedent soil moisture condition. Consequently, the depth of the impermeable layer or groundwater must also be determined through adequate subsurface investigations to determine an optimum depth for installation of the sensor for the effective prediction of failure initiation.

As far as the authors are aware, no direct measurement of soil volumetric moisture content has been attempted for slope failure prediction. Thus, the application of any moisture content sensors for prediction of rainfall-induce slope failures are encouraging, and could, finally be incorporated with other monitoring instruments (e.g., tensiometers, piezometers, rainfall guage, and inclinometers) into a landslide hazard warning system.

Conclusion

The rainfall-induced slope failures simulated in the experimental program are essentially initiated under drained conditions by the loss of lateral support resulting from earlier localized seepage-induced failures, with shallow noncircular sliding being the dominant failure mode. The process leading to the failure initiation commences by the formation of the seepage area. The development of the seepage area initiates localized failure in that particular area. Stress changes concentrated in the seepage area help account for the initiation of localized instability. Thus, hydrologic conditions that create the stress concentration in a region near the slope surface tend to create localized instability in this region. This localized instability can subsequently disturb the stability of the upper portion of the slope and lead to failure of the unsaturated soil near the slope surface, most likely through a stress transfer mechanism. This points to the critical influence that the instability of the seepage area may have on the overall stability of the slope, and the importance of monitoring the formation of seepage areas, at the slope surface as a practical means for the prediction of a particular slope failure hazard.

The hydrologic properties of the slope, such as soil permeability and antecedent soil moisture conditions, clearly control the slope hydrologic response. The hydrologic response of initially dry, permeable hillslopes leading to failure initiation is characterized by two stages of significant increase in moisture content, in association with the advancement of the wetting front from the slope surface, and the development of the groundwater table at the slope surface. Meanwhile, the initially wet and less permeable hillslopes only show one stage of volumetric moisture content increase, in response to rainfall, corresponding to the advancement of saturated wetting front. The commencement of slope failures tends to occur in the stage of the increase, in which the moisture content of the near surface soil attains a near-saturated value. This observed hydrologic response forms the basis for the development of a prediction methodology for rainfall-induced slope failures. The period of the second increase in the moisture content may be used for early warning against the slope failure hazards. Therefore, precise monitoring of the change in the moisture content is likely to provide the possibility of developing a reliable and effective means for predicting failure or issuing hazard warning of slope failures, during a particular rainfall. However, further researches with the following objectives are recommended:

- Assessment and determination of the optimum depth of installation of moisture sensors for effective monitoring of the changes in moisture content during rainfall.
- Comparison of the experimental results with field measurement results to verify and modify the concept of a moisture content-based warning system.

Notation

The following symbols are used in this paper:

e = void ratio;
D_r = relative density;
k_s = saturated hydraulic conductivity;
n = porosity;
V = total volume of soil mass;
V_w = volume of water in the soil mass;
α = slope angle;
θ_i = initial volumetric moisture content; and
θ_s = saturated volumetric moisture content.

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