Impacts of Unsaturated Zone Soil Moisture and Groundwater Table on Slope Instability

Ram L. Ray\(^1\); Jennifer M. Jacobs, M.ASCE\(^2\); and Pedro de Alba, M.ASCE\(^3\)

**Abstract:** The combined effect of soil moisture in unsaturated soil layers and pore-water pressure in saturated soil layers is critical to predict landslides. An improved infinite slope stability model, that directly includes unsaturated zone soil moisture and groundwater, is derived and used to analyze the factor of safety’s sensitivity to unsaturated zone soil moisture. This sensitivity, the change in the factor of safety with respect to variable unsaturated zone soil moisture, was studied at local and regional scales using an active landslide region as a case study. Factors of safety have the greatest sensitivity to unsaturated zone soil moisture dynamics for shallow soil layers (<2 m) and comparatively deep groundwater tables (1 m). For an identical groundwater table, the factor of safety for a 1 m thick soil mantle was four times more sensitive to soil moisture changes than a 3-m thick soil. At a regional scale, the number of unstable areas increases nonlinearly with increasing unsaturated zone soil moisture and with moderately wet slopes exhibiting the greatest sensitivity.

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**Author keywords:** Landslide; Soil moisture; Susceptibility; Slope stability; Unsaturated; Factor of safety.

**Introduction**

Based on the limit equilibrium approach, the one-dimensional infinite slope model is frequently used to study shallow landslides in which the slope length is significantly greater than its soil mantle thickness (e.g., Montgomery and Dietrich 1994; van Westen and Terlien 1996; Cho and Lee 2002; D’Odorico and Fagherazzi 2003; Onda et al. 2004; Borga et al. 2005; Muntohar and Liao 2009). Shallow landslides are common when the soil mantle thickness ranges from 1 to 3 m (Meisina and Scarabelli 2007; Au 1998). An infinite slope stability model applicable for shallow landslide studies, equates resisting and driving forces in order to estimate a factor of safety (FS). Increasing slope angle increases the driving force. The unit soil weight, dry, moist or saturated, affects the resisting force through effective normal stress ($\sigma'$) (Terzaghi 1943) applied to a potential failure surface and also the driving force along the potential failure surface on a slope. For shallow landslides, effects of soil cohesion can also be large (Sidle and Ochiai 2006).

Many authors have studied the unsaturated zone and slope instability by including matric suction or negative pore-water pressure in the infinite slope stability model (e.g., Cho and Lee 2002; Rahardjo et al. 2007; Muntohar and Liao 2009). These studies demonstrate that infiltrated rainfall water dissipates the soil suction or negative pore-water pressure in the unsaturated zone and, in turn, reduces the shear strength, triggering slope failure. Lu and Godt (2008) modified the infinite slope stability model to include a skeletal stress that depends on soil moisture in the unsaturated zone. They noted that most landslide studies that include unsaturated zone soil suction in an infinite slope stability model modify the shear strength due to soil suction, but do not account for the moist unit soil weight of the unsaturated layer or saturated layer weight in the slope stability model.

The two-layer concept, composed of distinct unsaturated and saturated soil zones, is frequently used in the infinite slope stability model to represent different unit soil weights (Ray and Jacobs 2007). Some studies use a saturated unit soil weight to represent both layers (e.g., Montgomery and Dietrich 1994; D’Odorico et al. 2005; Chiang and Chang 2009). Others, including de Vleeschauwer and De Smedt (2002) and Acharaya et al. (2006), used dry and saturated unit soil weight, respectively, for the layer above and below the saturated soil layer. Collins and Znidarcic (2004) used effective and total unit soil weight for the saturated and unsaturated soil layers, respectively. Vanacker et al. (2003) and Gabet et al. (2004) used total unit soil weight for both layers. A more physically sound representation uses a water content-dependent moist unit soil weight for the unsaturated soil layer and saturated unit soil weight for a saturated soil layer (e.g., Burton and Bathurst 1998; Sidle and Ochiai 2006). An additional advantage of this particular two-layer approach is that the emerging hillslope water dynamics also typically divide the profile into saturated and unsaturated zones. However, each of these previous two-layer slope stability analyses used static values of moist unit soil weight and saturated unit soil weight, and did not take advantage of dynamically characterized soil water states.

The influence of unsaturated zone effects is often described by the wetness index (m) which quantitatively relates the extent of the unsaturated zone to the location of the groundwater table. Traditionally the wetness index is the ratio of the saturated thick-

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ness of the soil above the failure plane to the total depth of the soil above the failure plane. However, wetness indices can also be derived in various other ways, for example, van Westen and Terlien (1996) and Acharya et al. (2006) calculated wetness indices by taking the ratio of the saturated soil layer thickness to the total soil thickness. One widely used wetness index approach is the O’Loughlin (1986) TOPOG model (e.g., Dietrich et al. 1993; Montgomery and Dietrich 1994; van Westen and Terlien 1996; Pack et al. 1998; de Vleeschauwer and De Smedt 2002; Acharya et al. 2006). The TOPOG model is based on the topographic wetness index developed by Beven and Kirkby (1979) within the runoff model TOPMODEL. These approaches are based on the assumption that all the infiltrating water in the upgradient contributing area becomes groundwater flow at the downstream convergence point. This assumption does not account for the time duration for flow accumulation or the water storage and delay in the upgradient area (Barling et al. 1994).

According to Rosso et al. (2006), wetness indices calculated by the TOPOG model neglect the presence of soil moisture in the upper soil layer above the groundwater table. This is problematic because the ground does not have to be saturated for failure (Dietrich et al. 1993). Slope failures can occur above the groundwater table in the unsaturated zone under steady infiltration conditions (Lu and Godt 2008). Thus, it is necessary to estimate a wetness index that includes the combined effects of unsaturated zone soil moisture and pore-water pressure or groundwater level in the saturated zone.

Based on these findings, the research presented herein directly includes unsaturated zone soil moisture in a slope stability model to estimate factors of safety. The approach develops a wetness index model that takes into account both saturated and unsaturated zone soil moisture in a manner that is consistent with hydrologic model state variables. Moreover, this research also presents an approach to calculate moist soil unit weight that takes into account the temporal dynamics of unsaturated soil moisture. The main objectives of this study are: (1) to modify the infinite slope stability model to dynamically include unsaturated zone soil moisture observations; (2) to develop a general equation quantifying the sensitivity of factors of safety to unsaturated zone soil moisture; and (3) to analyze the combined impacts of unsaturated zone soil moisture, groundwater table position and soil mantle thickness on instability within a case study context.

**Slope Stability Model**

This study uses the infinite slope method (Skempton and DeLory 1957) to calculate the factor of safety that expresses the ratio of resisting forces to driving forces. Fig. 1 is a schematic representation of a typical slope. The infinite slope stability model as adapted from several studies (e.g., Montgomery and Dietrich 1994; van Westen and Terlien 1996; Acharya et al. 2006; Ray and De Smedt 2009) is

$$FS = \frac{C_r + C_v}{\gamma_e H \sin \theta} + \left(1 - \frac{\gamma_m}{\gamma_e}\right) \tan \varphi \tan \theta$$

where $C_r$ and $C_v$=effective soil and root cohesion (kN/m$^2$); $\gamma_e$=effective unit soil weight (kN/m$^3$); $H$=total depth of the soil above the failure plane (m); $\theta$=slope angle (degrees); $m$ =wetness index (nondimensional) defined by ratio of saturated soil thickness to total depth of soil; $\varphi$=angle of internal friction of the soil (degrees); and $\gamma_w$=unit weight of water (kN/m$^3$). Originally, Skempton and DeLory (1957) used the saturated unit soil weight ($\gamma_s$) instead of the effective unit soil weight ($\gamma_e$). The effective unit soil weight as defined by de Vleeschauwer and De Smedt (2002) is

$$\gamma_e = \frac{q \cos \theta}{H} + (1 - m)\gamma_d + m\gamma_s$$

where $q$ is any additional load on the soil surface from the overlying vegetation or structures (kN/m$^2$) and $\gamma_d$=dry unit soil weight (kN/m$^3$) defined by

$$\gamma_d = \frac{G}{1 + e} \gamma_w$$

To include the unsaturated zone soil moisture in Eqs. (1) and (2), the wetness index and the effective unit soil weight must be modified. Sidle and Ochiai (2006) suggested using the $\gamma_m$ moist unit soil weight (kN/m$^3$) instead of the dry unit soil weight. To extend Eq. (2), the moist unit soil weight, of the unsaturated soil layer above the saturated soil layer (kN/m$^3$) is defined as

$$\gamma_m = \frac{G + S_w e}{1 + e} \gamma_w$$

where $G$=specific gravity of soil (nondimensional); $S_w$=degree of soil saturation (cm$^3$/cm$^3$) or unsaturated zone soil moisture; and $e$=void ratio (nondimensional). Here, a wetness index model is proposed that directly includes the unsaturated zone soil moisture as well as the saturated soil layer thickness as follows:

$$m_w = \frac{h + (H - h)S_w}{H}$$

where $h$=saturated thickness of the soil above the failure plane (m). This modified wetness index model assumes that the “wet” soil pores are connected, such that water pressures within the pores can be transmitted to the failure plane. This assumption essentially increases the height of the water table and the soil moisture in the unsaturated region is thereby linked to the groundwater table height through Eq. (5). Since landslides mainly occur in wet season or wet soil situation, this assumption is justified. However, this assumption may not be true when the groundwater is very low under a thick dry soil layer.
Using the wetness index estimated by Eq. (5), the Eq. (2) can be modified as follows:

$$\gamma_e = \frac{q \cos \theta}{H} + (1 - m_p)\gamma_d + m_p\gamma_t$$  \hspace{1cm} (6)$$

Eq. (1) can be modified using modified wetness index [Eq. (5)] and effective unit soil weight [Eq. (6)].

Eqs. (1), (3), (5), and (6) are combined in a factor of safety equation, which includes slope physical properties, saturated thickness, and unsaturated zone soil moisture, given as

$$FS = \frac{C_v + C_r}{\sin \theta [S_w\gamma_d(H-h) + q \cos \theta + \gamma_dH + \gamma_tH]}$$

$$+ \frac{\tan \varphi}{\tan \theta} \left[ 1 - \frac{\gamma_w}{S_w\gamma_a} \left( 1 - \frac{h}{H} \right) + \frac{h}{H} + \gamma_d + \frac{\gamma_a}{H} \right]^2$$

where $$\gamma_a = \gamma_t - \gamma_e$$. Physically, $$\gamma_a$$ represents the unit weight of available water in the soil layer.

Eq. (7) can be differentiated with respect to $$S_w$$ to develop a general relationship for the change in the factor of safety with respect to a measure of the unsaturated zone soil moisture

$$\frac{dFS}{dS_w} = -\frac{\sin \theta \gamma_a(H-h)(C_v + C_r)}{[\sin \theta (S_w\gamma_d(H-h) + q \cos \theta + \gamma_dH + \gamma_tH)]^2}$$

$$+ \frac{\gamma_a}{S_w\gamma_a} \left( 1 - \frac{h}{H} \right) \frac{\tan \varphi}{\tan \theta} \left[ \frac{\gamma_a}{S_w\gamma_a} \left( 1 - \frac{h}{H} \right) + \frac{h}{H} + \gamma_d + \frac{\gamma_a}{H} \right]^2$$

$$\times \left[ \frac{\gamma_a}{H} - S_w\gamma_a \left( 1 - \frac{h}{H} \right) + \frac{h}{H} - \gamma_d - \gamma_a + S_w\gamma_a \left( 1 - \frac{h}{H} \right) \right]$$

Thus, the factor of safety and its sensitivity to soil moisture is a function of hill-slope physical characteristics, the effective soil and root cohesion ($$C_v$$, $$C_r$$), the total depth of the soil above the failure plane ($$H$$), the slope angle ($$\theta$$), the angle of internal friction of the soil ($$\varphi$$), the soil void ratio ($$e$$) and any additional load on the soil surface ($$q$$) combined with the dynamic hydrologic conditions that are characterized by the saturated thickness of the soil above the failure plane ($$h$$), and the unsaturated zone soil moisture ($$S_w$$). For a site with defined physical characteristics, the maximum factor of safety occurs when $$h=0$$ and $$S_w=0$$ while the minimum factor of safety occurs when $$h=H$$ (effectively $$S_w=1$$). Eqs. (7) and (8) both demonstrate that the factor of safety and sensitivity to unsaturated zone moisture are nonlinear functions of $$h$$ and $$S_w$$. When it is applied using at-site hill-slope physical characteristics, these equations can be used to analyze the relative importance of unsaturated zone soil moisture and to determine if FS calculations should include unsaturated zone moisture.

**Application to a Study Area**

**Background**

To analyze the sensitivity of FS values to unsaturated zone moisture using Eqs. (7) and (8), detailed calculations were performed for a landslide-prone region in Cleveland Corral, El Dorado County, California (Fig. 2). This area is located on the western slope of the Sierra Nevada Mountains along the Highway 50 corridor, between the cities of Sacramento and South Lake Tahoe. Since 1996, slope movements and landslides have occurred regularly during the winter season with a catastrophic landslide in 1983 (Spittler and Wagner 1998; Reid et al. 2003) that temporarily dammed the South Fork of the American River and blocked Highway 50. A mapped landslide at the most active landslide zone is shown in Fig. 2.

The study focused on a 28 km by 22 km area in Cleveland Corral (Fig. 2). As derived from a 90-m digital elevation model (DEM), elevations range from about 902 to 2,379 m and slopes range from 0 to 48°. The study area has some variability in soil texture ranging from clay loam to sandy loam, although the majority is composed of sandy loam (72%). On this rugged topography, conifers (80%) and wooded grassland (14%) are the dominant land covers. Some rock outcrops are also observed along the Highway 50 corridor. Based on the observation of rock outcrops, slope failures and soil depth maps [The States Soil Geographic (STATSGO) soil database (Natural Resources Conservation Service 2008)], soil depths to the rock range from 0.6 to 1.4 m.

Since 1997, the USGS has monitored this active landslide region using real time data acquisition systems to measure rainfall, pore-water pressure, slope movements, and ground vibrations (Reid et al. 2003). Daily groundwater measurements for water years 2004 to 2006 were obtained from the USGS which uses piezometers to measure the hydraulic head at one of the active landslides in the region (Mark Reid, USGS, personal communication, April 23, 2007). Slope movements and landslides have been observed during periods with high groundwater table measurements in the winter (rainy) season (Reid et al. 2003).

To study the impact of unsaturated zone soil moisture in slope instability, a 0.7-km² area with active landslides was selected from this study area. Eq. (8) was used to estimate the factors of safety sensitivity for a time series of groundwater levels and total soil depth with varying unsaturated zone soil moisture. Finally, to obtain spatial distributions of landslide susceptibility, Eq. (7) was applied to the entire 28 km by 22 km study area with modeled unsaturated zone soil moisture and in situ groundwater measurements.

**Hydrologic Model**

The three-layer variable infiltration capacity (VIC-3L) model (Liang et al. 1994) was used to estimate soil moisture in the unsaturated zone. VIC-3L is a macroscale land surface model that simulates water and energy budgets and includes spatial variations of soil properties, soil topography, precipitation, and vegetation (Maurer et al. 2002; Huang and Liang 2006). The model’s soil column has three layers (Fig. 1). The top thin soil layer and the middle soil layer characterize the dynamic response of the soil to weather and rainfall events. The lowest layer captures the seasonal soil moisture behavior (Liang et al. 1996; Huang and Liang 2006). Based on the climatic parameter and soil and vegetation characteristics, this model can estimate soil moisture storage, evapotranspiration, runoff, and snow water equivalent at hourly to daily time steps. For this study area, the VIC-3L model was run using a daily time step from 2004 to 2006 with layers of 0.05-, 0.35-, and 1.0-m thickness at a 0.0083° resolution (latitude=longitude=0.0083°) with respect to World Geodetic System (WGS) 1984 datum. This study area has a total of 900, 0.7 km² pixels.
Table 1. List of Model Parameters and Sources by Model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sources</th>
<th>Model</th>
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<tbody>
<tr>
<td>Soil cohesion</td>
<td>Deoja et al. (1991)</td>
<td>Slope stability</td>
</tr>
<tr>
<td>Soil porosity</td>
<td>Dingman (2002)</td>
<td>Slope stability and VIC-3L</td>
</tr>
<tr>
<td>Soil texture</td>
<td>STATSGO</td>
<td>Slope stability and VIC-3L</td>
</tr>
<tr>
<td>Soil depth</td>
<td>STATSGO</td>
<td>VIC-3L</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>STATSGO</td>
<td>VIC-3L</td>
</tr>
<tr>
<td>Soil bulk density</td>
<td>Dingman (2002)</td>
<td>Slope stability and VIC-3L</td>
</tr>
<tr>
<td>Angle of internal friction</td>
<td>Deoja et al. (1991)</td>
<td>Slope stability</td>
</tr>
<tr>
<td>Land cover</td>
<td>UMD</td>
<td>Slope stability and VIC-3L</td>
</tr>
<tr>
<td>Root cohesion</td>
<td>Siddle and Ochiai (2006)</td>
<td>Slope stability</td>
</tr>
<tr>
<td>Root depth</td>
<td>LDAS</td>
<td>VIC-3L</td>
</tr>
<tr>
<td>Root fraction</td>
<td>LDAS</td>
<td>VIC-3L</td>
</tr>
<tr>
<td>Vegetation roughness</td>
<td>LDAS</td>
<td>VIC-3L</td>
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<tr>
<td>Vegetation height</td>
<td>LDAS</td>
<td>VIC-3L</td>
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<tr>
<td>Leaf area index</td>
<td>LDAS</td>
<td>VIC-3L</td>
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<tr>
<td>Rainfall</td>
<td>NCDC</td>
<td>VIC-3L</td>
</tr>
<tr>
<td>Groundwater</td>
<td>USGS</td>
<td>Slope stability</td>
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<tr>
<td>Temperature</td>
<td>NCDC</td>
<td>VIC-3L</td>
</tr>
<tr>
<td>Wind speed</td>
<td>NCDC</td>
<td>VIC-3L</td>
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</tbody>
</table>

Note: STATSGO=States Soil Geographic; LDAS=Land Data Assimilation System; USGS=U.S. Geological Survey; VIC-3L=Variable Infiltration Capacity-3 Layers; and NCDC=National Climatic Data Center.

Fig. 2. Location of the study area in El Dorado County, California
The data required for the VIC-3L hydrologic model and the slope stability model are summarized in Table 1. Rainfall, temperature, and wind speed measurements were obtained from the National Climatic Data Center (NCDC) from 2000 to 2006. Soil layers, soil thickness and soil texture information were obtained from STATSGO soil database [Soil Survey Staff, Natural Resources Conservation Service (NRCS), USDA 2008]. There are a total of 11 soil layers in STATSGO for this area. However, many layers have similar soil texture classes. To coincide with the VIC-3L model layers, the eleven soil layers were regrouped into three soil layers. The first, second to fifth, and sixth to 11th soil layers of the STATSGO soil database were regrouped into the VIC-3L first, second and third soil layers, respectively. Consequently, the first and second layers have similar soil textures. About 72 and 28% of the study area is covered with sandy loam and loam, respectively, in both layers. The third (lower) layer consists of four soil types, loam, sandy loam, clay loam, and sandy clay, and covers, respectively, 72, 16, 3, and 9%, of the study area. Each pixel was assigned a soil texture for each of the three soil layers based on majority type. For verification purposes, four soil samples were collected from the active landslide grid and tested in a laboratory using sieve analysis and Atterberg Limit tests. The tests confirmed the STATSGO soil database soil texture classification. The total soil depth ranged from 0.8 m to 1.4 m. The assumed potential failure plane underneath the soil layer is bedrock. The unit soil weight (saturated and dry) was calculated based on the soil moisture, soil porosity, and specific gravity of the soil samples using Eq. (4). Each soil type was assigned soil cohesion and friction angle values that were adapted from Deoja et al. (1991).

Advanced very high resolution radiometer land cover data (1-km spatial resolution) were obtained from University of Maryland (UMD) (Hansen et al. 2000). There are four land cover classes (types) in this study area. Each land cover class was as-

**Fig. 3.** Change in the factor of safety with varying unsaturated zone soil moisture values and depth to groundwater for total soil depths of (a) 1; (b) 1.4; (c) 2; and (d) 3.0 m; site characteristics are sandy loam, wooded grassland, and 32.5° slope.
signed a root cohesion value (Sidle and Ochiai 2006) and an additional load [Eq. (2)]. The land data assimilation system gridded vegetation database (Mitchell et al. 2004) was used to obtain the root fraction, root depth, vegetation roughness, and vegetation height required for the VIC-3L model parameterization. The shuttle radar topography mission DEM (90-m spatial resolution) was used to derive slope angle in this study.

**Coupled Slope Stability and Hydrologic Model Application**

In the following sections we consider theoretical factors of safety and their sensitivity to soil moisture using the derived Eqs. (7) and (8). First, an FS sensitivity analysis is conducted for the active landslide region for a full range of possible groundwater positions and unsaturated zone soil moisture. This analysis is then expanded to include the surrounding region. Finally, a regional application is performed using dynamic groundwater and unsaturated zone soil moisture values to determine FS values that only include feasible hydrological states. Throughout the analysis, the calculated FS values are categorized into four stability classes using the Pack et al. (1998) and Acharya et al. (2006) stability classification system of highly susceptible (FS ≤ 1), moderately susceptible (1 < FS < 1.25), slightly susceptible (1.25 < FS < 1.5) and not susceptible (FS ≥ 1.5).

**Local Soil Moisture and Groundwater Impact Analysis**

The local landslide analysis uses the physical characteristics for the most active landslide grid in the Cleveland Corral study area. This location has a 32.5° slope, a 1.4-m soil depth with sandy loam soil and wooded grassland land cover. For these characteristics and their corresponding physical parameters, the stability model is applied using Eq. (7). Then Eq. (8) is used to calculate the sensitivity of factors of safety for varying unsaturated zone

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*Fig. 3. (Continued).*
soil moisture (0–100%, using 5% increments). This analysis is repeated for a series of groundwater table positions (depth to groundwater) from 0.1 to 1 m below the surface (0.1-m increment). The 0.1-m groundwater table is the wettest scenario. The 1-m groundwater table is the driest scenario. The maximum saturation scenario is limited to 0.1-m depth to groundwater table because there is no impact of unsaturated zone soil moisture under full saturation. Soil thicknesses analyzed include the site specific 1.4-m depth as well as 1-m incremental thicknesses from 1- to 3-m depths corresponding to typical shallow landslide soils.

Regional Soil Moisture and Groundwater Impact Analysis

For the entire Cleveland Corral study area, factors of safety are calculated for a series of groundwater depths below the surface (0 to 1 m, 0.1-m increment) with a full range of unsaturated zone soil moisture values (0–100%, 10% increment). This 28 km by 22 km area has 75,988 grid cells. Each 90 x 90 m cell is assigned physical characteristics based on its slope, soil, and vegetation.

Temporal Dependent Regional Analysis

The regional application also calculates FS values in space and time for the entire study region at a 90-m spatial resolution over a 2-year period. Here the measured depth to groundwater, average unsaturated zone soil moisture values obtained from the VIC-3L model, and physical parameters are used in Eq. (7) to calculate factors of safety continuously for the region. The VIC-3L model is run at a 0.0083° approximately 1-km spatial resolution from the model, and physical parameters are used in Eq. (7) to calculate factors of safety continuously for the region. The VIC-3L model is run at a 0.0083° approximately 1-km spatial resolution from 2004 to 2006 to obtain unsaturated zone soil moisture at Cleveland Corral. Modeled moisture values’ native 1-km spatial resolution is reclassified into a 90-m spatial resolution using the nearest-neighbor resampling technique.

Results from Local and Theoretical Regional Analyses

Local Soil Moisture and Groundwater Impact Analysis

Fig. 3 shows the change in factors of safety with varying unsaturated zone soil moisture for a series of groundwater table positions, respectively, for varying soil thicknesses. For this site’s characteristics the sensitivity ranges from ~2 to ~60% where the negative relationship reflects declining factors of safety with increasing soil moisture. Overall, factors of safety are most sensitive to unsaturated zone soil moisture when the depth to groundwater is deep and the soils are thin. For all soil thicknesses, the FS sensitivity decreases when the groundwater approaches the surface. The decrease has a nearly constant rate near the surface. For example, when the depth to groundwater is 0.5 m, the observed sensitivity for factors of safety are 25, 17, 11, and 7% for soil thicknesses of 1, 1.4, 2, and 3 m, respectively. In contrast, when the groundwater table is shallow, 0.1 m (0.4-m change), factor of safety’s sensitivity declines to 5, 4, 3, and 2% for the 1-, 1.4-, 2-, and 3-m thicknesses, respectively. Thus, a 0.4 m groundwater table rise significantly decreases the FS sensitivity; by 20, 13, 8, and 5%. When the same 0.4-m groundwater table change occurs for deeper groundwater positions, 1 m rising to 0.6 m, an even larger change in the FS occurs with differences of 29, 17, 10, and 6% for the 1-, 1.4-, 2-, and 3-m soil thicknesses, respectively. For a thick soil layer (H ≥ 2 m), the FS sensitivity is constant for all soil moisture values and varies only by groundwater table position. A constant FS sensitivity is also observed for a thin soil layer (H < 2 m) when the groundwater table is shallow (depth to groundwater table ≈0.5 m). The observed FS is less sensitive with increasing unsaturated zone soil moisture (true until 70% $S_w$) for a thin soil layer with a deeper groundwater table. When the unsaturated zone soil moisture is greater than 70%, the FS values are equally sensitive to soil moisture increases even with a deep groundwater table.

Regional Soil Moisture and Groundwater Impact Analysis

In contrast to the local scale results above, at a regional scale, variations in soil moisture and groundwater differentially affect individual locations. This effect is magnified by the movement of water and is best illustrated by the contour plots of Fig. 4. The contour lines of equal percentage of highly susceptible area with 0.01% intervals becomes closer as the groundwater table approaches the ground surface and the unsaturated zone soil moisture approaches the saturation level. These results indicate that wetter unsaturated soils are more vulnerable to landslides than those with less wet unsaturated layers, even if the groundwater table is deeper for the former (i.e., unsaturated zone soil moisture can have a greater effect than the groundwater depth).

Not surprisingly, as the saturation layer thickness increases, the highly susceptible area increases. However, regardless of soil saturation, the susceptible area increases as the groundwater table nears the surface (Fig. 4). A 10% increase in soil saturation will cause more of the region to become unstable if the hillside is already wet than if the slopes were initially dry. For example, when a saturated soil zone moisture was assumed to be 60%, the estimated highly susceptible area was 0.18 and 0.14%, respec-
tively, for the comparatively wet soil (groundwater table at 0.5 m) than dry soil (groundwater table at 0.6 m). It should also be noted that the marginal increases decrease somewhat for very wet slopes, 80 to 100% saturation, as compared to more moderately wet slopes, 30 to 80%. Overall this analysis gives an indication of the relative contributions to slope instability for notably variable groundwater table depths as well as variable vadose zone saturation.

Results from the Regional Analyses

The previous section considered the factor of safety’s sensitivity for the complete range of soil moisture and groundwater table values. In reality, this complete range is not likely to be observed. In addition, the range is further limited because groundwater table and soil moisture values are somewhat correlated. Here, the potential range of hydrologic variables is narrowed through both measured and modeled results and presented within the regional susceptibility context previously introduced.

VIC-3L Model Results

Fig. 5 shows the daily average modeled unsaturated zone soil moisture, rainfall and USGS measured groundwater levels at one active landslide grid (1 km x 1 km) in this study area. Average daily soil moisture was calculated by the weighted average of daily soil moisture obtained from the VIC-3L model in the top two layers. During the wet season, groundwater was very close to the surface in this region. Although no direct measurements of soil moisture were available, the VIC-3L unsaturated zone soil moisture values and the in situ groundwater measurements have similar daily and seasonal variations throughout the year (Fig. 5).

Spring is the wettest season because relatively high amounts of rainfall (Fig. 5) and snow melt occurs during this period. This period has the highest unsaturated zone soil moisture when groundwater levels are very close to the surface. Between January and May of 2005, the highest and lowest unsaturated zone soil moisture values estimated by the model were 82 and 49%, respectively, when the shallowest and the deepest groundwater positions were 28 and 137 cm below the surface, respectively. Between January and April of 2006, the model predicted 83 and 52% unsaturated zone soil moisture when the groundwater table was 35 and 75 cm below the ground surface, respectively. The highest unsaturated zone soil moisture values predicted by the model in 2004, 2005, and 2006 were 84, 84.5, and 82.9%, respectively, when the groundwater levels were 38.5, 40.3, and 45.7 cm below the ground surface. For the dry periods, there is also good agreement between the model and the groundwater measurements. Overall, a simple linear regression analysis for depth to groundwater and average unsaturated zone soil moisture provided a good fit with a $R^2$ of 0.63.

Results therefore indicate that VIC-3L can reasonably capture the wetting and drying of the unsaturated zone. In addition, it is clear that the groundwater and the soil moisture values are strongly related. The predicted unsaturated zone soil moisture values in combination with groundwater levels can be used in the slope stability model to calculate the factors of safety.

Slope movements and landslides coincided with periods of enhanced surface soil moisture and high groundwater position (Fig. 5). In the Cleveland Corral region, 2 to 3 cm per day slope movements were frequently observed by slope movement sensors during the winter of 2005 (http://landslides.usgs.gov/monitoring/hwy50). Reported slope movements began in early April 2005 when the groundwater table was near the surface and it continued until end of the May. Except the one catastrophic landslide in

Table 2. Predicted Susceptible Area (%) for the Cleveland Corral Region during Spring 2005

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth to groundwater (m)</th>
<th>Average unsaturated zone soil moisture (%)</th>
<th>Highly susceptible</th>
<th>Moderately susceptible</th>
<th>Slightly susceptible</th>
<th>Not susceptible</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 8, 2005</td>
<td>0.28</td>
<td>72</td>
<td>0.43</td>
<td>1.39</td>
<td>2.58</td>
<td>95.60</td>
</tr>
<tr>
<td>May 23, 2005</td>
<td>0.65</td>
<td>60</td>
<td>0.26</td>
<td>0.92</td>
<td>2.02</td>
<td>96.81</td>
</tr>
<tr>
<td>May 4, 2005</td>
<td>1.12</td>
<td>52</td>
<td>0.11</td>
<td>0.44</td>
<td>1.33</td>
<td>98.13</td>
</tr>
</tbody>
</table>
1983 (Spittler and Wagner 1998), which was a deep seated landslide, all other observed landslides were shallow and transitional in nature.

Regional Slope Stability Analysis

Application of the developed slope stability model was performed for a range of hydrologic conditions. The three wet scenarios identified based on the soil saturation, very wet, wet and slightly wet, are typical of the conditions and susceptibility that might be expected for this region (Table 2). As anticipated, the area classified as “susceptible” expands as the region become wetter. In addition, the 0.84 m increase in depth to groundwater corresponds to the $S_d$ drying from 72 to 52% moisture.

These observed hydrologic conditions were used to provide a context to the factor of safety’s sensitivity results presented previously. Here, we apply the observed groundwater positions, 0.28, 0.65, and 1.12 m, to examine how the area in each susceptible class changes with varying unsaturated zone soil moisture (0–100%, 10% increment).

Influence of Unsaturated Zone Soil Moisture in Instability

Fig. 6 plots the percentage area by susceptibility class for completely dry to saturated, soil moisture, with the observed wet season groundwater tables. Under completely saturated conditions, 0.53% of the area was highly susceptible to failure. If the factor of safety calculations for the typical wet season groundwater table depth, 0.28 to 1.12 m, neglect unsaturated zone soil, then the susceptible area would be significantly reduced. The modeled average unsaturated zone soil moisture values overlain in Fig. 6 demonstrate that neither extreme, completely dry or saturated, reflects modeled field conditions. Both groundwater and vadose zone soil moisture hydrologic conditions are required to adequately characterize regional landslide susceptibility.

The transition from dry to saturated depends on the susceptibility class and the groundwater table position. Factors of safety for the highly and moderately susceptible classes have a similar dependence on groundwater table and soil moisture. In the dry conditions, when the groundwater table was deep, there is a pronounced nonlinear increase in instability with increasing unsaturated zone soil moisture. As the groundwater table approaches the ground surface, there is a more linear increase in instability with increasing unsaturated zone soil moisture. On the other hand, the slightly susceptible and the stable areas have fairly constant rates of change under all soil moisture conditions. The rate of change in the highly susceptible area is lower than the slightly susceptible area for similar saturation levels. Similarly, the rate of change in the highly susceptible area is lower for the shallowest groundwater table than for the deepest groundwater table. Thus, the unsaturated zone soil moisture has less of an impact on instability when the groundwater table is very close to the ground surface. These results are consistent for all susceptible classes (Fig. 6) that demonstrated nonlinear factor of safety’s sensitivity for the deeper groundwater tables and limited sensitivity for near surface water tables.

Influence of the Soil Thickness and Unsaturated Zone Soil Moisture in Instability

The greater sensitivity for deeper water tables was explored further to examine the relationship between a varying unsaturated zone soil moisture (90 to 50%, 10% decrements) and soil thickness (1 to 3 m, 0.5-m increments) for a groundwater table with a constant height above the failure plane. The unsaturated zone soil moisture was reduced from 90% to 50% as the groundwater tables were lowered with wetter and drier conditions, respectively, for the shallowest and the deepest groundwater tables.

Shallow soils have greater sensitivity than the thicker, drier unsaturated soil layer (Fig. 7). When the total soil thickness above the potential failure plane increased from 2 to 3 m, the estimated
change in highly, moderately and slightly susceptible areas were 0.1, 0.16 and 0.35%, respectively. In contrast, when the soil thickness increased from 1 to 2 m, the estimated change (0.51, 1.52, and 1.87%) was nearly an order of magnitude larger for highly, moderately and slightly susceptible areas, respectively.

In summary, accurate knowledge of depth to a potential failure plane, in addition to groundwater table, is necessary when accounting for dynamic unsaturated zone soil moisture. Infinite slope stability models with unsaturated zone soil moisture are best suited for shallow slope stability analysis. When soil mantles are deep, slope stability is less sensitive to anticipated unsaturated zone soil moisture variations. These observations clearly support the Sidle and Ochiai (2006) finding that for shallow soils, effects of pore-water pressure are large and for comparatively deeper soil mantles, effects of pore-water pressure are small.

Conclusions

The unsaturated zone soil moisture and pore-water pressure are important parameters for slope stability analysis because it is the combined effect of surface and subsurface saturation that is critical. This study developed infinite slope stability methods to estimate factors of safety and their sensitivity to soil moisture changes based on unsaturated zone soil moisture and saturated soil thickness as well as soil physical properties. This approach effectively divides the varying components of the total unit weight into terms that are consistently available from hydrologic models.

These general relationships demonstrate that the susceptibility to slope failure increases with an increase of unsaturated zone soil moisture as well as rising groundwater position. For shallow slope soil mantles, a thicker unsaturated soil thickness is more vulnerable to landslides in comparison to a thinner unsaturated soil thickness for the same position of the groundwater level above the potential failure plane. However, when soil mantles are deep, slope stability is less sensitive to anticipated unsaturated zone soil moisture variations. The same infinite slope stability model, applied to a regional case study using a 90 m DEM, points out the importance of soil thickness characterization as well as the need to appropriately narrow the potential range of hydrologic variables through both measured and modeled results of saturated soil thickness and unsaturated zone soil moisture. Finally, this study’s quantitative results are specific to the Cleveland Corral region and sensitive to the 90 m spatial resolution. Thus, additional studies are needed to quantify the sensitivity for a broader range of landslide-prone regions.

Although the observed slope failures along the highway were validated with predicted susceptible areas, it was not possible to ground truth the entire region. Therefore the regional study represents an example application of the methodology to predict susceptible zones, rather than a prediction of actual landslides. Additional studies that include the collection of regional ground-truth data sets are needed.

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