Controls on shallow landslide size

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ABSTRACT: Most distributed slope-stability models for shallow landslide prediction neglect the forces acting on the sidewalls of landslide scars. Back-calculations and field observations, however, show that lateral root strength is a primary control on size and location of shallow landslides in soil mantled hillslopes. Here we report a theory that estimates landslide width, assuming that root strength acts primarily through a perimeter boundary. The model predicts that landslide width increases with increasing root strength and decreasing slope, as larger masses of soil are needed to overcome resisting forces. Perhaps surprisingly, the drier the soil, the larger the landslide mass (and width), whereas the water table rise reduces the size needed for failure. The comparison of the model results with field data suggests that landslide size is controlled by the local patchiness of soil thickness, root strength and topographically-driven relative saturation.

1 INTRODUCTION

Digital terrain models are becoming widely used to map the relative potential for shallow landsliding across a landscape by both process-based models and statistical analyses (e.g. review in Dietrich et al., 2001, Gritzner et al., 2001). Process-based models have been based on the infinite slope form of the Mohr-Coulomb failure law in which landslide dimensions are ignored and relative stability is performed for each individual grid cell. While the influence of spatially variable soil depth and vegetation, and temporarily variable vegetation and precipitation have been included (e.g. Hsu, 1994; Terlien et al., 1995; Wu and Sidle, 1995; Duan, 1996; Iida, 1999; Casadei et al., in press), these models nonetheless treat each grid cell independently and, therefore, depend strongly on the quality of the topographic data and the relative size of landslides compared to grid cell dimensions (e.g. Dietrich et al., 2001; Gritzner et al., 2001). Figure 1 shows the results of digital terrain based slope stability model that uses high-resolution topographic data (obtained through airborne laser swath mapping), a predicted soil depth field, a uniform field of root strength and a steady state hydrology. A calibrated threshold rainfall to transmissivity ratio is used. Mapped landslide scars generally occur in areas classified as unstable (potentially unstable areas require larger rainfall, stable areas will not fail when saturated), but there are extensive areas shown as unstable without scars and the mapped landslide scars are frequently a different size than the local unstable areas. In maps with coarser grid cells, landslides are commonly smaller than the local unstable areas (e.g. Casadei et al., in press). An improvement in grid-based models would be to predict which cluster of cells may fail together because of scale controls associated with strength effects on the boundaries and the spatially variable material and hydrologic proprieties. Prediction of landslide size would improve debris flow hazard modeling, possibly reduce the general tendency to over predict areas of instability, and be useful in landslide-driven landscape evolution models.

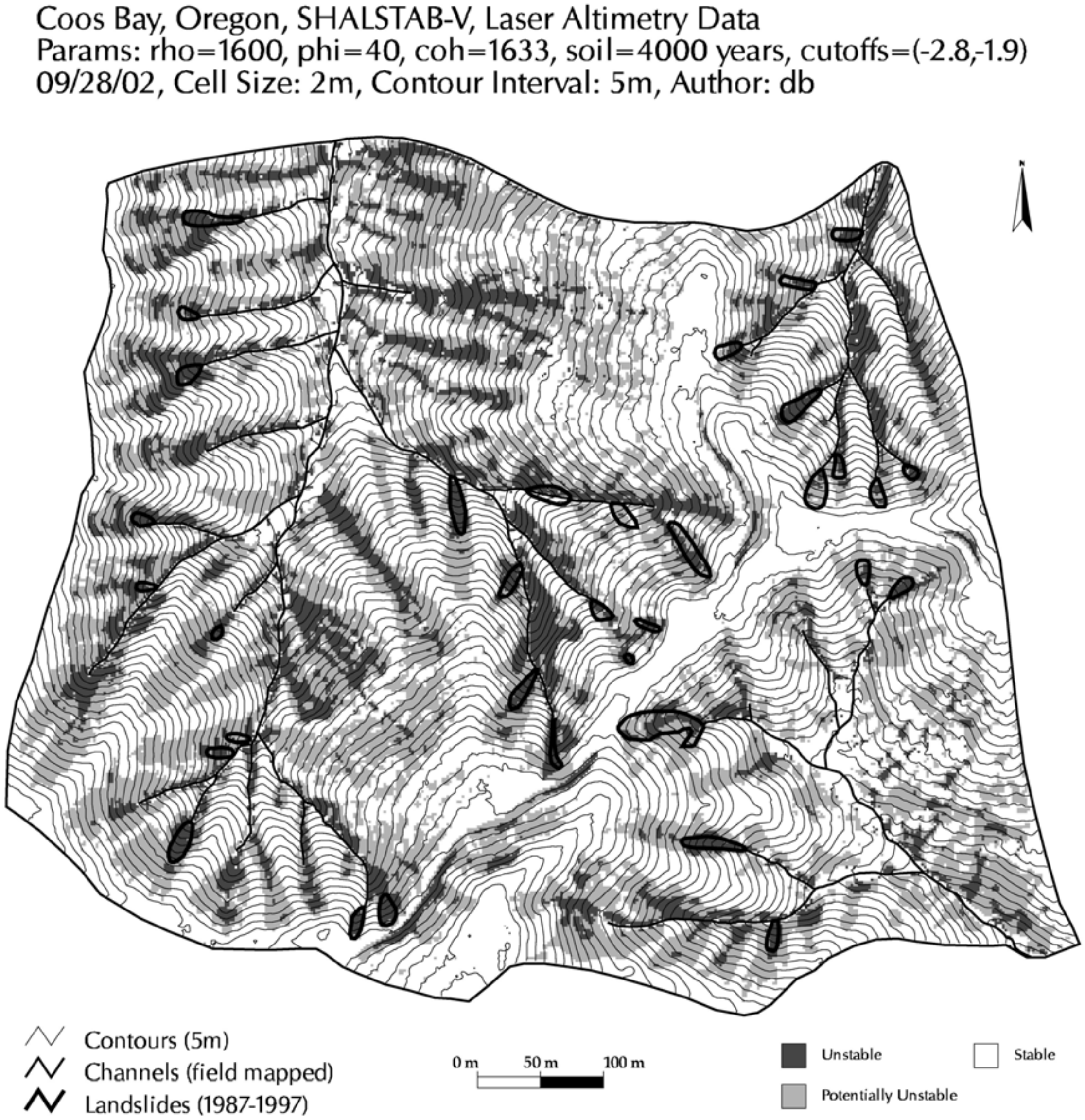

Figure 1. Delineation of landslide potential for a site in Coos Bay, Oregon, US. calculated with a version of the SHALSTAB model (Dietrich et al., 1995) which uses a calculated soil depth field The area calculated as unstable and potentially unstable is significantly larger than the actual landslides observed during the last 15 years. Potentially unstable sites are areas that could fail if greater precipitation caused sufficient pore pressure rise. This problem (overprediction of instability) is common to all current landslide hazard models.

The issue of shallow landslide size has received some previous study. Reneau and Dietrich (1987) derived an expression relating landslide width to length by assuming that the soil was saturated and that its strength was composed of a frictional term acting on a basal slide area and a root strength acting on the perimeter of the slide (a simplification of the expression proposed by Riestenberg and Sovonick-Dunford, 1983, expression). The lateral root strength imposes size constraints on landslides. The model gave reasonable estimates of root strength when calibrated with field data on landslide size and indicated that larger root strength leads to larger landslides, while steeper slopes produce smaller slides. They reasoned that shallow landslides became likely when soil thickness accumulated to sufficient depth and lateral extent that the size of the potential landslide mass could over come the local root strength. The reanalysis performed here for a very similar model reveals that landslide size also depends on relative soil saturation and this finding requires an even greater role of local topography and material properties in limiting landslide size. Just as this manuscript was being completed, Gabet and Dunne (2002) published a paper building upon the Reneau and Dietrich (1987) model, but in this case to eliminate the length dependency, they assume the landslides are infinitely long in order to eliminate the length dependency in order to model just landslide width. Here we show that the infinitely long approximation introduces an error of less than a factor of 2 in the predicted maximum landslide width.

In this paper we explore further how lateral root strength and relative soil saturation control shallow landslide size. This analysis is done in anticipation of models that will attempt to compute size from gridded surfaces of digital elevation data. The focus on root strength seems appropriate given its clear role in providing strength (and therefore influencing landslide size) and the common absence of other sources of soil cohesion in the coarse textured soils commonly found mantling steep hillslopes (Burroughs and Thomas, 1977; Riestenberg and Sovocnik-Dunford, 1983; Reneau and Dietrich, 1987; Riestenberg, 1994; Wu 1995; Montgomery et al. 2000, Schmidt et al., 2001). Most models assume that root strength acts across the basal sliding area, but field evidence shows that shallow landslides commonly occur where the soil is deeper than the rooting depth and the primary strength is provided by roots crossing the lateral boundaries (e.g. Schmidt et al., 2001). Montgomery et al. (2000) accounted for this difference by adjusting the vertical root strength to values typical of that found on the lateral boundary, which requires estimating the ratio of basal area to perimeter area of potential landslides. Okimura (1994) has developed a grid-based 3-dimensional model to predict the shape of shallow landslides. This model requires local data for soil depth, water table elevation, and the geotechnical properties of colluvium. The procedure for determining the most likely failure shape is based on the calculation of the balance of forces on a moving window along the selected hillslope. It assumes that the grid is oriented parallel to the sliding direction, a condition that is hard to reproduce as most hillslopes are oblique with respect to the main DEM axes. Nonetheless this work is an important start on the problem.

2 THEORY

Let us consider a shallow, approximately rectangular slope failure (figure 2). Here we make the standard assumptions adopted by the infinite slope theory: the slip surface is parallel to ground surface, and acts as hydraulic conductivity boundary, where a perched water table develops during wet conditions; subsurface flow lines are also assumed parallel to ground surface with a perched water table developing as described. These assumptions may fail in the case where the distortion of subsurface flow paths becomes significant (e.g. by spatial variation of hydraulic conductivity, or exfiltration from the bedrock, e.g. Montgomery et al., 1997; Iverson et al., 1997).

If we define R_b and R_l as the resistant forces acting at the base of the mass and on the sidewalls, respectively, and T = applied shear force, the balance of forces dictates that:

$$T = R_b + R_l \qquad (1)$$

The resistant forces are defined according to the Mohr-Coulomb criteria:

$$R_b = (C_b + \sigma' \tan \phi)\, A_b \qquad (2)$$
$$R_l = C_l P H \qquad (3)$$

where A_b = basal area; P = landslide scar perimeter; H = depth of slip surface and φ= angle of internal friction.

We then define σ', normal effective stress acting on the slip surface, and C_b , C_l , net effective cohesion acting at the base and along the sidewalls of the scar, respectively:

$$\sigma' = (\rho_s \ H - \ \rho_w h_w) \ g \cos^2 \beta \qquad (4)$$
$$C_b = C_{rb}+C_s \qquad (5)$$
$$C_l = C_{rl}+C_s \qquad (6)$$

where ρ_s, ρ_w= density of dry soil and water, respectively; C_s= soil cohesion; C_{rb}, C_{rl} = root cohesion acting at the base and along the sidewalls of the scar, respectively; h_w is the water table height above the failure plane and β is the local topographic slope and failure plane angle.

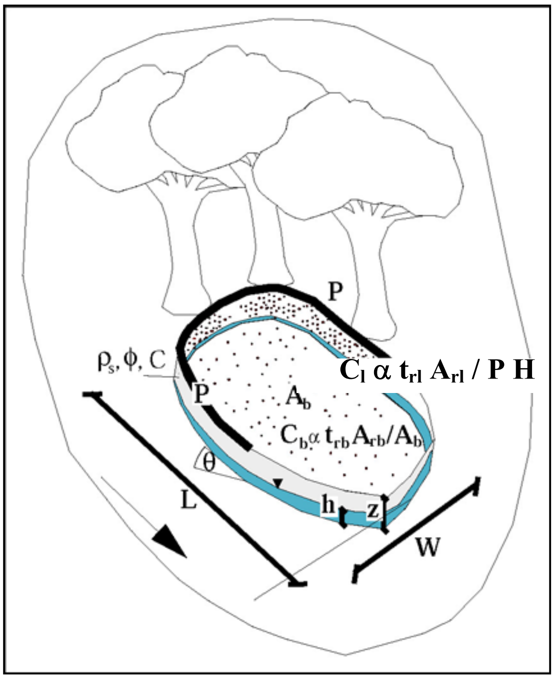

Figure 2. Assumed landslide geometry used in the model. We analyze the stability of a soil prism of width W and length L sliding along a slope-parallel slip surface. Lateral cohesion C_l acts across the perimeter boundary, P, whereas basal cohesion C_b acts on the basal area, A_b.

Schmidt et al. (2001) review the mechanics of root reinforcement and the various assumptions used to relate measurements of root strength to slope stability. They report root strength properties for a wide range of plants and document the changes in root strength associated with forest practices. We will use their data here to define reasonable values of root strength. .

Applied shear force T is defined as the product of shear stress τ over the basal area A_b:

$$T = \tau A_b \qquad (7)$$
$$\tau = \rho_s \ g \ \ H \sin \beta \ \cos \beta \qquad (8)$$

Substituting into equation (1) yields:

$$\tau A_b = (C_b + \sigma' \tan \phi) \ A_b + C_l H \ P \qquad (9)$$

Dividing by A_b and rearranging, we solve for the ratio P/A_b, which is a measure of landslide shape in plan view.

$$P/A_b = (\tau - C_b - \sigma' \tan \phi) \ / \ C_l H \qquad (10)$$

If we define m as the ratio of water table height, h_w , to the depth of the slip surface H (saturation ratio), $m = h_w / H$, then by substitution of equations (8) and (4) into equation (10) leads

$$P/A_b = (g \cos^2 \beta / C_l)\, [\rho_s \tan \beta - (\rho_s - \rho_w m) \tan \phi] - C_b/ (H C_l) \qquad (11)$$

This equation states that the plan view shape of a landslide expressed in term of perimeter/ area ratio depends upon geotechnical soil properties (density, friction angle, and cohesion), topographic conditions (slope), soil depth, hydrology (water table height), and the ratio of lateral versus basal cohesion.. When $P/A_b <= 0$, that is, g $\cos^2 \beta\, [\rho_s \tan \beta - (\rho_s - \rho_w m) \tan \phi] < C_b/H$, resistant forces exceed applied forces, and no failure can develop.

Let us assume the simple, idealized case of a rectangular failure (**fig 2**), where the lateral resistant forces act on the upper and lateral sides. Then we can solve for failure length L and width W :

$$P/A_b = (W+ 2L)/ L\, W \qquad (12)$$

Equations (12) and (11) can be solved for length L, or width W:

$$L = (B - 2/W)^{-1} \qquad (13)$$
$$W = 2(B- (1/L))^{-1} \qquad (14a)$$
$$W = (2+W/L)/B \qquad (14b)$$

where $B = (g \cos^2 \beta / C_l)\, [\rho_s \tan \beta - (\rho_s - \rho_w m) \tan \phi] - C_b/ (H C_l)$, that is, the right-hand side member of equation (11).

The form of equation (14b) has the advantage that W is expressed as a function of the non-dimensional aspect ratio of the scar, i.e. W/L. Values of W/L are often reported in the literature, and there is a tendency for this ratio to cluster around a narrow range.

Equations (13 and14) state that, all other variables being equal, there is no unique solution for the shape of failure, since width is a function of failure elongation.
Let us define a shape factor $n = (2+W/L)$, so that equation (14) becomes:

$$W = n/B \qquad (15)$$

N ranges from $n_1 = 2$, in case of a theoretically infinitely long soil slip (W/L = 0) to an upper value of $n_2 = 3.5$ (when W/L ~ 1.5), selected from literature (Reneau and Dietrich, 1987), which defines the largest expected width of a landslide given equal boundary conditions. The minimum width W_1 in the first case is:

$$W_1 = 2 / \{(g \cos^2 \beta / C_l)\, [\rho_s \tan \beta - (\rho_s - \rho_w m) \tan \phi] - C_b/ (H C_l \} \qquad (16)$$

whereas maximum width is instead:

$$W_2 = W_1\, n_2/n_1 = W_1\ 1.75 \qquad (17)$$

The variation by a factor of 1.75 is smaller than the uncertainty in the local parameterization of soil depth, cohesion, friction angle and transmissivity. Therefore, we propose that the study of the failure conditions using equation (16) (that is, assuming W/L ~ 0) is sufficiently representative of most real world slides, and it defines the critical width W_m of expected failure, or the *minimum size that will fail under homogeneous conditions*. This assumption is also equivalent to assuming $B>>1/L$ (ie. Equation 14a).

It is worth noting that if $C_b = 0$, the last term of equation 11 can be eliminated, effectively removing the effect of soil depth on critical width. This requires that basal root strength, C_{rb}, and soil cohesion, C_s, are zero. As reported in Schmidt et al. (2001), it is a common experience to find broken roots in the lateral walls of the landslide and an absence of roots in the base of the slide (either broken or pulled out) because the failure plane (normally the soil-bedrock boundary) is deeper than the rooting zone. As discussed by Reneau and Dietrich (1987), the local thickening through time of soil, due to accumulation of colluvium from upslope sources, will tend to lead to this condition. Such colluvium is typically sand and gravel rich, hence, soil cohesion, C_s, is low. In the analysis that follows, we therefore set the basal cohesion (C_b) to zero.

3 SENSITIVITY ANALYSIS

For the case of $C_b = 0$, landslide width is predicted to vary with slope, soil bulk density, relative degree of saturation, and friction angle. The model is relatively insensitive to soil bulk density. The critical width of failure W_m increases linearly as a function of lateral root cohesion (figure 3A). The variation with friction angle is not linear, since small increases of ϕ lead to higher increases of W_m at higher friction angles. Similarly, figure 3B shows that the effect of the saturation ratio m (which represents pore pressure effects) varies non-linearly, depending on the initial conditions (previous value of m) and topographic gradient. On very steep slopes, critical size is small and relatively independent of m.. On the other hand, the stability of gentler slopes is influenced by hydrology, and variations in m result in significant changes in W_m. In particular, maximum critical width is expected for failure under dry conditions (m = 0) since larger volumes are needed to trigger failure. This unexpected result has important implications for application of this model to digital terrain-based studies.

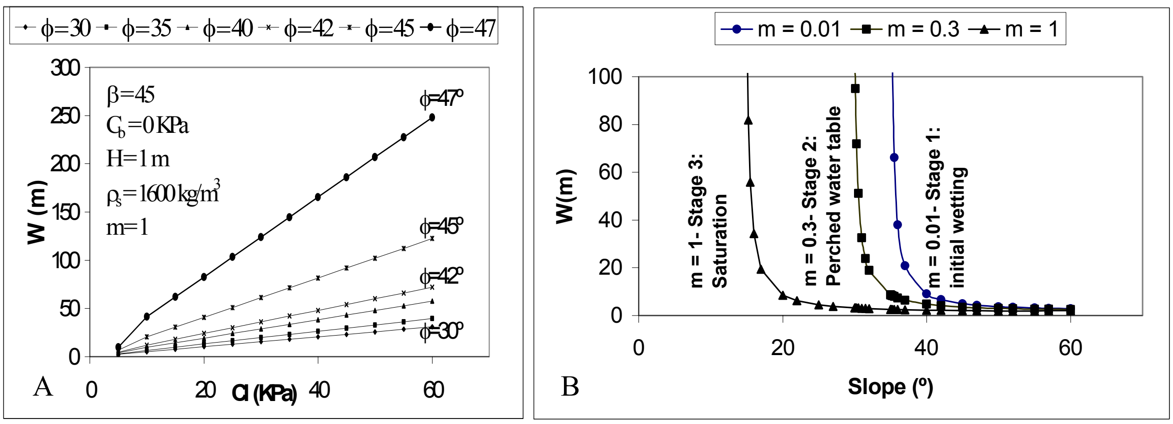

Figure 3. Sensitivity of critical width to lateral root cohesion and friction angle (A) and to saturation ratio and topographic gradient (B). Critical width of failure is proportional to lateral root cohesion and non-linearly related to friction angle. Rainstorm effect on landslide width is also described in (B): under dry conditions (low m values) the volume required for failure is higher; as the soil gets wetter, critical landslide size decreases.

Let us consider a parameter set which reflects typical conditions for the Oregon Coast Range, in the United States, reported by several authors (e.g. Dietrich et al., 2001; Montgomery et al., 2000; Schmidt et al., 2001): ρ_s = 1650 kg/m^3; ϕ = 40º ; C_l = 6 KPa; C_b = 0 KPa; and H = 1 m. Given such parameter values and m = 0.3, equation (16) predicts a failure width of 264 m on a slope slightly less steep than 30º. Failures of this size do not happen (typical shallow landslide width is about 10 m), and few landslides occur on such gentle slopes. This mismatch highlights a key finding. The model result would only apply to a hillslope on which the soil geotechnical properties, root strength and soil depth are homogeneous for an extent of at least 264 m, Not only are hillslopes cut by valleys at a spacing much finer than 264 m, but the local variation in soil depth and root strength is on the scale of meters to tens of meters.

Figure 4 illustrates how spatial heterogeneity in material properties and pore pressure evolution combine to control landslide size. Soil thickness, friction angle properties, bulk density and root strength will vary across a landscape, creating patches of varying strength and, hence, varying degrees of soil saturation needed for instability. The most susceptible sites for failure for a given soil bulk density and friction angle will be those with relatively thick soil (leading to minimal vertical root strength contribution) and low concentration of vegetation (leading to low root strength, especially lateral root strength). Figure 4 shows a gap in the canopy of the forest, which might occur due to such things as disease, fire, and clear cutting. In the pre-storm, well –drained state, the predicted failure size for the low root strength patch is much bigger than the patch size, hence no failure occurs (the root strength is much greater outside the gap and prevents instability). As rain occurs and pore pressures rise, the predicted failure size will decline (Figure 4A-C, see also Figure 3), until the size for failure matches the available low root strength patch (Figure 4D). Pore pressure development will be patchy across the landscape as well, being relatively more elevated in topographically convergent areas, where locally the underlying rock has a low permeability, where low permeability horizons develop within the soil and where water exfiltrates from the bedrock back into the soil mantle (e.g. Reneau and Dietrich, 1987; Montgomery et al., 1997, Iverson et al., 1997).

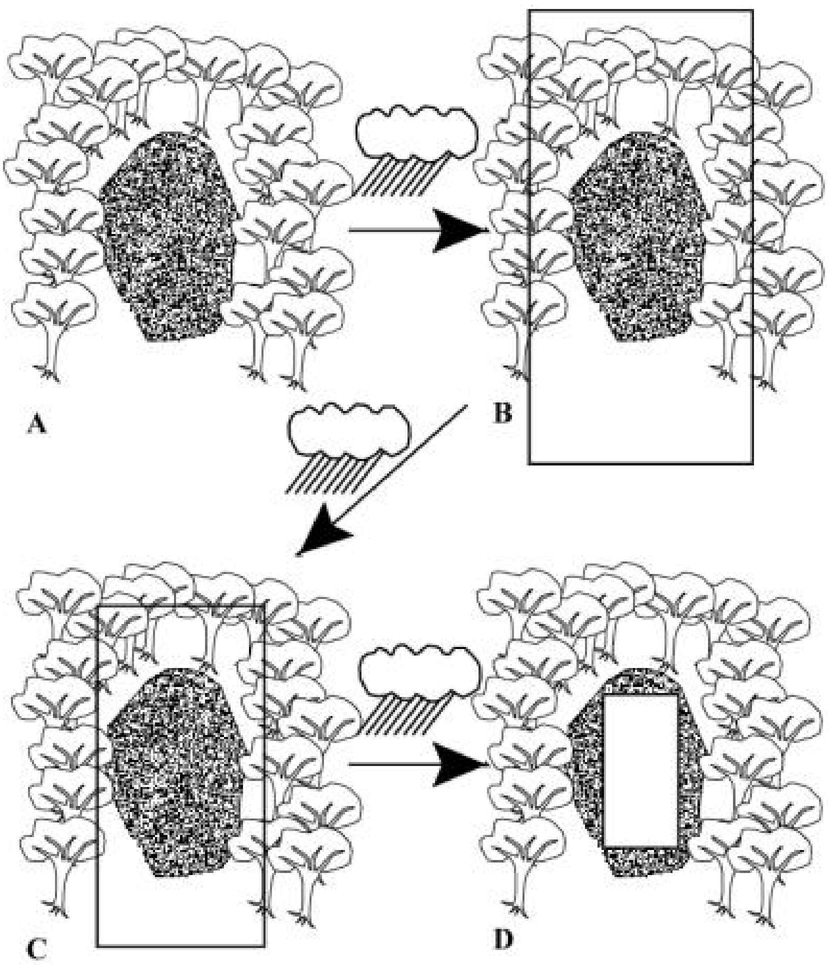

Figure 4. Suggested mechanism to explain landslide size for the case of patchy forest cover. At the onset of precipitation (A), the soil mantle is dry, and the critical landslide size (shown with a white rectangle) is greater than the homogeneous patch of soil. Under such conditions, the critical area cannot fail because it receives the contribution of root strength from the trees outside the homogeneous patch. As rainfall progresses (B and C), the perched water table rises, and the required size for failure decreases up to the point where it becomes smaller than the homogeneous soil patch (D), when failure occurs.

The linear relationship between W_m and C_l can also be used to explain landslide response to vegetation removal. Let us assume the same parameter set as before and m= 0.3, considering a decrease of C_l from 30 KPa to 5 KPa, highly representative of the changes in root strength caused by timber harvesting (Schmidt et al., 2001). Our theory predicts that such a change will cause the critical landslide width to drop from 43.4 to 8.7 m. It will be much more likely to find a patch of homogeneous soil of 8.7 m rather than 43.4 m, therefore the likelihood of occurrence of a shallow landslide should be higher in the second case.

4 APPLICATION OF THE THEORY

We compared our theory with a data set of 96 landslides provided by the Oregon Department of Forestry (ODF), documenting scar width, depth and local slope gradient (figure 5a). Our model used the same characteristic parameter set (ρ_s = 1650 kg/m^3; ϕ = 40º ; C_l = 6 KPa; C_b = 0 KPa; H = 1 m). Four landslides could not be explained by the model, which considers them as unconditionally stable (e.g. the required failure would be infinitely wide).

While the observed data points mostly lie within the conceivable m values, several points plot above the instability line for dry soils (m=0), implying these sites would fail at any time. None of the data follow the trend of the lines and none of the slides approach the large size that the theory permits. Instead the data cluster about a median width value of 15 m, a typical value for shallow slope failures, and a median hillslope gradient of 40 degrees. This cloud of data (which we also see in other data sets from California) does not support the single-valued parameterization of our proposed model.

A second example is obtained from a study by Gray and Megahan (1981), who quantified soil strength properties including root strength associated with landslides which occurred after a forest fire an area of the Idaho batholith (figure 5b). Here, following typical values reported by the authors for the Idaho batholith, we set ρ_s = 1650 kg/m^3; ϕ = 35º ; C_b = 0 KPa; H = 1 m. The residual root strength for a Douglas Fir ranges from about 10 KPa the first year, to about 5 KPa the next year, and then to 3.4 KPa, due to root decay after the tree died. Figure 5 b shows how the size of the potential slide would diminish with decreasing root strength and in this case the slides are fairly small. Still the scatter is significant.

We propose that this lack of strong agreement with theory arises from the local heterogeneity of root strength, relative soil saturation, soil depth and fine scale topography. Large slides, though theoretically possible, are prevented from occurring due to this patchiness in conditions. If this interpretation is correct, efforts to calculate landslide size in digital terrain models during precipitation events can only be meaningfully attempted using high-resolution topographic data and deterministic (e.g. Dietrich et al., 1995) or statistical procedures to estimate spatial pattern (and covariation) of controlling properties. Refinement in root strength contribution may be possible through analysis of high-resolution aerial photographs in which crown cover is converted to lateral root strength. A number of slides are predicted to occur, for example, when m is zero and these may be sites where local root strength was higher.

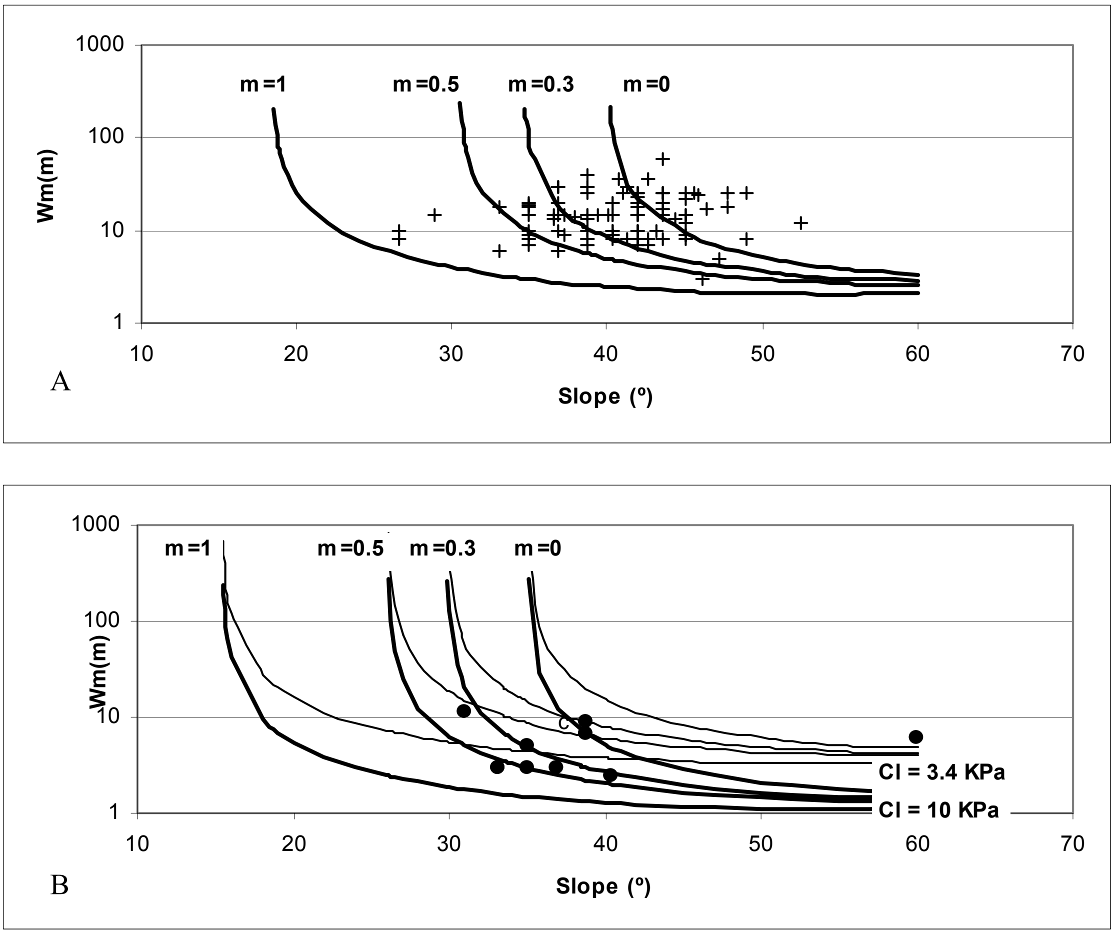

Figure 5. Field data on landslide width versus topographic gradient for 2 data sets. The upper diagram (A) refers to data from the Oregon Coast Range, provided by the Oregon Department of Forestry (ODF). The failure envelopes are drawn assuming various values of the saturation ratio m, using ρ_s = 1650 kg/m^3; ϕ = 40º ; C_l = 6 KPa; C_b = 0 KPa; H = 1 m. The lower diagram (B) shows data from Gray and Megahan (1982), and uses soil properties and root strength suggested by the authors, ρ_s = 1650 kg/m^3; ϕ = 35º ; C_b = 0 KPa; H = 1 m. The landslide distribution may be explained by vegetation removal and consequent root strength decline after a forest fire.

5 CONCLUSION

Our reanalysis of the initial model by Reneau and Dietrich (1987) supports their conclusions, but draws a somewhat different view when the effects of temporarily varying relative saturation are considered. They reasoned that areas of local thickened colluvium will develop and grow in time (such as occurs in unchanneled valleys or hollows) progressively diminishing the effectiveness of lateral root strength until the downslope pull of a critical mass of unstable soil exceeds the stabilizing strength provided by the lateral roots and frictional bottom. Here we see that this formulation of slope stability theory predicts that on steep slopes, dry soil failures would be quite large. These large failures simply don't occur. We propose that this is due to local patchiness of root strength and relative soil saturation and to limiting effects of finite scale of hillslopes (due to valley dissection). Hence, during storm events landslides are expected to occur where elevated pore pressures develop in patches of lower root strength and thicker soil. If this hypothesis is correct, digital terrain models attempting to predict landslide size must use high resolution topography, have a means of estimating the spatially explicit variation in soil and root strength properties, and have a hydrologic model for pore pressure development that includes both topographic controls and bedrock heterogeneity influences. While airborne laser swath mapping can provide high resolution topography (e.g. Montgomery et al., 2000; Dietrich et al., 2001), new methods are needed to map the spatial patterns of soil, vegetation and bedrock properties for large areas. Despite the lack of spatially explicit field data, models for shallow landslide size should be further developed for both practical application and the theoretical analysis of landscape evolution.

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