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Modelling dynamic drivers and uncertain soil parameters in tropical urban slopes

Modélisation des moteurs dynamiques et paramètres incertains du sol dans les pentes urbaines tropicales

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ABSTRACT: Landslide risk is increasing in tropical developing countries as rapid informal construction increases the susceptibility of slopes to rainfall-triggered landslides. These 'everyday hazards' adversely affect the livelihoods of hillside communities, hinder sustainable development, indicate a systemic lack of resilience and can be linked to the stagnation of a country's economic growth. A physically-based model of dynamic rainfall infiltration and slope hydrology coupled with limit equilibrium analysis is used to identify the progressive effects of urbanisation on slope stability over time, and the sensitivity of such analyses to variations in mechanical and hydraulic soil properties. The greatest reductions in stability are associated with slope cutting; however, planting grasses and, in some cases light-weight trees, can improve stability. For the majority of deforested slopes without cuts, mechanical soil properties have the strongest influence on stability; however, for slopes close to the point of failure, variations in saturated hydraulic conductivity become more significant.

RÉSUMÉ: Dans les pays tropicaux en voie de développement, les risques de glissement de terrain augmentent à cause de constructions inadaptées accroissant la vulnérabilité des pentes face aux glissements de terrain déclenchés par chutes d'eau. Ce risque quotidien affect les moyens de subsistance des communautés résidant à flanc de coteaux, empêche un développement durable, indique un manque systémique de résilience et peut être lié au surplace économique d'un pays. Un modèle physique des infiltrations des chutes d'eau dynamique et d'hydrologie des pentes associé à une analyse des équilibres limites est utilisés pour identifier les effets progressifs de l'urbanisation sur la stabilité des pentes dans le temps ainsi que la sensibilité de cette analyse au variations mécanique et hydraulique des propriétés des sols. La plus forte baisse de stabilité est due aux coupures de pente ; cependant la plantation d'herbes ou bien dans certain cas d'arbres légers peu améliorer la stabilité. Pour une majorité de pentes déforestées sans coupures, les propriétés mécaniques du sol ont le plus d'influence sur la stabilité ; cependant, pour les pentes proches du point de rupture, les variations dans la conductivité hydraulique saturé sont de premières importances.

KEYWORDS: slope stability; humid tropics; urbanisation; infiltration, factor of safety

1 INTRODUCTION

In the humid tropics, a large proportion of urban settlements are constructed informally on the outskirts of cities. The poorest residents often live on marginally stable hillslopes, building progressively upslope as the population increases. Slope development aggravates an inherent predisposition to instability, which was discussed by Lumb (1975) in the context of deeply-weathered residual soils. These soils have typically lower shear strength and higher permeability at depth than soils located in temperate regions (Wesley 1990). Tropical slope failures are predominantly triggered by high-intensity and high-duration rainfall events (Peel et al. 2007); however, modelling of slope urbanisation processes in Saint Lucia suggest that lower magnitude (higher frequency) events can trigger multiple local landslides (Holcombe et al. 2016). Such 'everyday' landslide hazards cause considerable damage to property and infrastructure and, in the long-term, more significant indirect costs associated with increased levels of vulnerability.

A thorough assessment of urban slope performance requires an understanding of the stability condition of the natural slope, the impact of urbanisation, and the likely response to a triggering event. In developing countries, characterising tropical slope profiles is challenging for two reasons: (1) the highly localised natural variability of soil parameters derived from the complex structure of weathered rock and seasonal cycles of wetting and drying, which is a problem compounded by (2) limited resources for obtaining geotechnical data and engineering expertise for conventional assessment and design. While urbanisation is known to increase landslide incidence, the relative impacts of informal construction methods are not well documented. Moreover, the dynamic nature of slope hydrology is prone to uncertainty associated with the interaction of patterns of precipitation and soil permeability. It may be very difficult therefore to assess the particular sensitivity of a modified urban slope to a tropical storm using traditional deterministic analysis. However, improving our current knowledge of the sensitivity of rainfall-induced instability in slopes under different conditions to the variability of key parameters may enable more targeted site investigations and guide better construction practice.

2 MODELLING TROPICAL SLOPES

The results of over 200 simulations are analysed to assess the influence of variations in mechanical and hydrological soil properties, slope geometries, vegetation, and rainfall on slope factor of safety (F). This paper extends the analysis reported in two previous studies (Holcombe et al. 2016, Shepheard et al. 2017) to present an enhanced understanding of the influence of slope hydrology on F. The model used is the Combined Hydrology And Stability Model (CHASM) – a physics-based numerical model that couples dynamic sub-surface hydrological mechanisms in unsaturated and saturated soil to limit equilibrium slope stability analysis. Rainfall infiltration and pore-water pressure responses drive changes in minimum F over time (Figure 1). CHASM can therefore be used to diagnose the dominant failure mechanisms of rainfall-triggered landslides (Holcombe et al. 2016). For example, CHASM is used within the 'Management of Slope Stability in Communities' (Mossaic) approach to guide surface water management strategies for urban landslide mitigation. Drains are then designed to intercept rainfall runoff (reducing infiltration and erosion) based on the modelled hydrological processes and on residents' observations of slope processes (Anderson and Holcombe, 2013). Further detail on CHASM can be found in various publications (e.g., Anderson 1990, Anderson et al. 1997, Wilkinson et al. 2002).

Key input parameters for CHASM are effective cohesion (c'), effective angle of friction (ϕ'), saturated hydraulic conductivity (K_{sat}), and soil moisture characteristic curves (ψ-θ). Parameters are lumped at a grid resolution of 1m^2 and allocated according to the defined slope geometry and weathering profile. Vegetation is represented in terms of mechanical and hydraulic effects (Wilkinson et al. 2002, Holcombe et al. 2016). In this study, slopes are modelled in sets as 'basic' (without vegetation or modifications), 'natural' (with 2m spacing of identical forest trees), and 'urbanised' with cycles of deforestation, cut slope excavation (excluding 40° slopes), and loading, as illustrated in Figure 2. These are specified in Table 1, each slope has a horizontal width of 90m (cases A, B, C) or 52m (all other classes) and two 4m-deep layers of residual soil and weathered material overlying bedrock. For each set of simulations, rotational and translational slip surfaces were tested using an automated circular search (Bishop's method) and fixed non-circular surface at 4m depth (Janbu), respectively (Wilkinson et al. 2002).

Table 1. Definition of slopes by angle and grade V-VI soil properties

α (°)	20			30			28			40				
c'(kPa)	10	5	2	10	5	2	0		8	10	5	2	5	2
ϕ'(°)	25			25			25	20	25	25			20	15
K_{sat}(ms^{-1})	10^{-5}								10^{-5}, 10^{-6}, 10^{-7}					
Design parameter cases:							B	C	A					

3 SENSITIVITY OF 'F' TO MODEL PARAMETERS

3.1 *Variation of mechanical soil properties*

Figure 1 shows the results of the 16 simulations where the critical failure surface is found to be translational (40° slopes with c'>2kPa). The results show that for the slopes of higher surface-strata permeability an increase of 5kPa of modelled soil cohesion increases minimum F of the basic slope by 0.12 for a particular storm magnitude. Moreover, comparing either the two basic or two natural slopes for a particular storm, shows that increasing c' increases F throughout the simulation i.e. the dynamic response of F over time is identical, but the curve is shifted up the vertical axis. Shepheard et al. (2017) also observed similar vertical transformation of F-curves in basic slopes (for circular slips) with varying soil strengths (cases A, B, C) under a different rainfall pattern (antecedent rainfall + two storms). Since each pair or set of slopes have identical geometric and hydraulic properties, this result is unsurprising: for a given pore water pressure distribution and slip surface geometry, static limit equilibrium analysis would yield a degree of variability in F proportionate to the variation in soil shear strength components. Figure 3 demonstrates that the stability of natural and urbanised slopes with similar geometry and hydrology is also sensitive to variation in c'. However, the change in stability as urbanisation progresses is dependent on the nature of the slip mechanism. Slopes prone to translational failure ($\alpha = 40°$, $c' = 5$kPa and $\alpha = 40°$, $c' = 10$kPa) show matching patterns of reduced F with each cycle of urbanisation. In contrast, rotational failures in cut slopes depend on cut location: the first cut produces identical reductions in F for slopes of the same angle (20° or 30°), which suggests that the decrease due to cutting is due to a shift in the location of the minimum F slip surface. As urbanisation progresses beyond the first cut, step-changes in F fluctuate due to the critical slip surface relocating to localised circular failures of individual cuts. Ultimately, stability appears to be influenced more by cut geometry than original slope angle or c'.

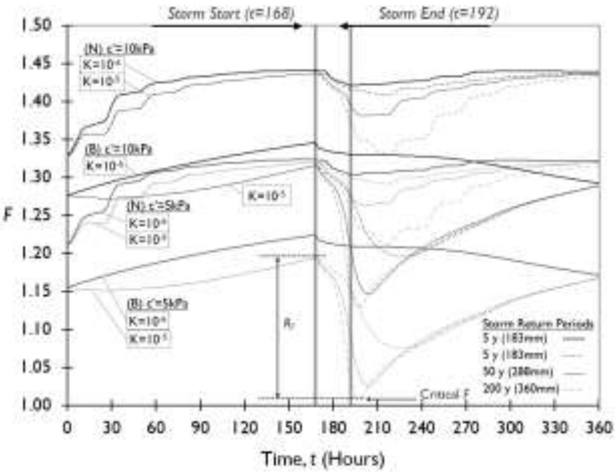

Figure 1. Response of slope factor of safety (F) over time for four slope classes *[α=40°, ϕ'=25°, c'=5 or 10kPa, K_{sat} =10^{-5} or 10^{-6} ms^{-1}, N=Natural B=Basic]* to 24-hour storms of 5, 50, and 200 year return periods, delivering a total rainfall of 183, 288, and 360mm respectively.

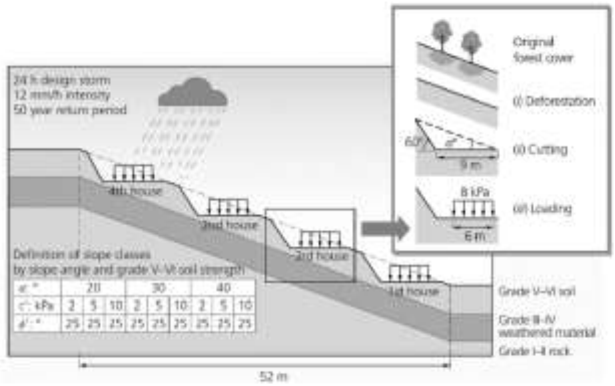

Figure 2. Representation of a typical progression of slope urbanisation using the CHASM model (adapted from Holcombe et al. 2016, © ICE Publishing, used with permission).

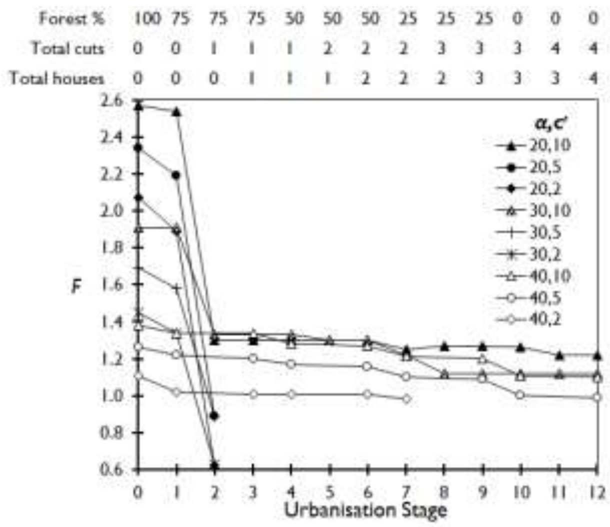

Figure 3. Factors of safety associated with each urbanisation stage for nine slope classes for a 1 in 50 year storm, delivering a total of 288mm of rainfall in 24h (ϕ' = 25° and K_{sat} = 10^{-5} ms^{-1}).

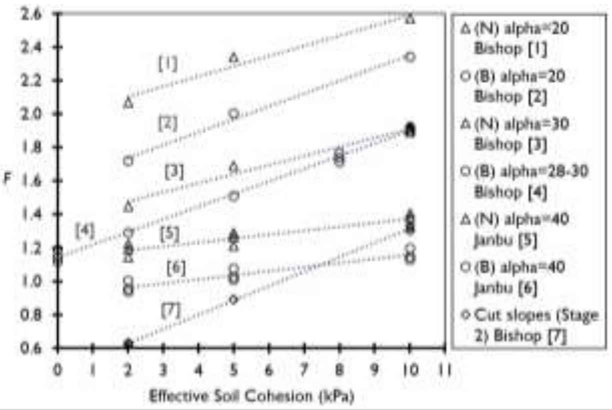

Figure 4. Sensitivity of critical F to slope geometry, forest cover, and effective cohesion of the surface soil, to 24-hour storms of 5, 50, and 200 year return periods, delivering a total rainfall of 183, 288, and 360mm respectively *[N=Natural B=Basic].*

Figure 4 identifies a greater sensitivity of F to c' where slopes fail by rotational (as opposed to translational) slip. The most significant effect on F due to reduced c' is observed in cut slopes (stage 2). Prior to cutting, the circular slip surface penetrates deeper, less weathered material over a large extent of the slope; subsequent cutting at the toe reduces the depth of the slide so that it is contained within the surface residual soil layer. Slopes with natural vegetation appear to have similar sensitivity to changes in c' as basic un-vegetated slopes of the same angle. Trees increase F of a model slope by up to 0.4. The net effect of vegetation, however, depends upon the hydrological and mechanical influences of vegetation relative to the inherent properties of the slope (Wilkinson et al. 2002, Holcombe et al. 2016). In this particular scenario, additional root-derived cohesion outweighs the impact of increased permeability, since the soil itself has sufficiently high K_{sat} for the greatest storm depth (360mm) to fully infiltrate the slope. The effectiveness of root stabilisation on different slope angles is governed by interactions of roots and tree loading with slip surface geometry (see Wilkinson et al. 2002, Holcombe et al. 2016).

3.2 *Variation of hydrological soil properties*

Fluctuations in pore pressures due to rainfall infiltration and sub-surface flows will cause changes in the effective shear strength of slope materials. The size and location of the critical slip circle will therefore change over time. In CHASM the surface infiltration capacity at each time-step depends on either K_{sat}, if a surface grid cell is saturated, or unsaturated hydraulic conductivity, if not (derived using the Millington-Quirk equation, see Wilkinson et al. 2002). The proportion of rainfall infiltrating (the 'effective rainfall') depends on the ratio between the rainfall intensity and the infiltration capacity. If rainfall intensity is greater than infiltration capacity then excess rainfall will run off the slope (i.e. be excluded from the sub-surface hydrology model). Slope instability is thus driven by effective rainfall – a function of rainfall intensity and variations in soil hydraulic conductivity with time.

If it is assumed that the ground surface becomes saturated within the first hour of rain, effective rainfall can be estimated for the rest of the 24-hour storm. For a 1 in 5-year storm (7.6 mmh^{-1}) all rainfall infiltrates into a soil with $K_{sat} = 1x10^{-5}$ ms^{-1}; whereas a lower $K_{sat} = 1x10^{-6}$ ms^{-1} gives a rainfall excess of 4 mmh^{-1} (47.5% of the rain infiltrates). Figure 1 shows that this reduction in effective rainfall for the slopes with lower K_{sat} is associated with a much less marked drop in F than for the higher K_{sat} slopes. Hydraulic conductivity also affects the rate of redistribution of initial moisture conditions within the slope. Thus, depending on the initial water table location, a higher K_{sat} can give higher pore pressures (lower F) at the critical slip surface depth, even before the rainfall starts in hour 168.

In Figure 1, the difference in the minimum F immediately after the storm is more marked in slopes without vegetation. F-curves of each pair of vegetated slopes are more closely matched in shape. Here, despite mechanically stabilising the planar slip surface throughout the slope, roots have a significant hydrological influence as they locally increase soil permeability and increase infiltration.

Shepheard et al. (2017) examined the effect of spatial variability of K_{sat} for 24-hour storms of varying magnitude on the 'case A' slope (Table 1). The slip circle corresponding to critical F remained the same for every simulation irrespective of K_{sat} value, spatial variability, and storm magnitude. With identical soil mechanical properties, F at the start of each simulation was also equal. It follows that the greatest observed sensitivity of critical F to variation in K_{sat} coincided with varying K_{sat} at the depth of the slip surface: lower values of K_{sat} reduced both the 'gain' in F during the equilibrating period and the infiltration capacity, although a greater reduction in effective rainfall appears to dominate and increases critical F.

3.3 *Variation of rainfall pattern*

To examine the influence of different types of rainfall on rainfall-induced instability, Figure 5 shows the effect of Total Effective Precipitation (P_{TE}), for each rainfall type and magnitude, on the Range in F(R_F) for a particular slope (Case A, $K_{sat} = 1x10^{-5}$ ms^{-1}, Table 1). The legend indicates total antecedent rainfall (ΣP_A) distributed between single (1h to 24h) or double (24h) storm events of increasing intensity and return period (from 1 in 5, to 1 in 500+ years). P_{TE} is calculated by estimation of infiltration capacity.

Figure 5 indicates that R_F is highly sensitive to the magnitude of the 'two-storm' scenario; with ΣP_A aggravating the impact on R_F. ΣP_A has negligible impact on the response to a single storm of specific magnitude. However, for a particular P_{TE}, increasing ΣP_A causes F to vary by up to 0.05 and 0.12 for single- and two-storm events respectively. This suggests that precipitation pattern is an important consideration, as a more adverse pore water pressure response in the slope would be expected where effective rainfall is concentrated. A general increase in P_{TE} causes the shape of the R_F response curve for each rainfall pattern to change, which identifies an increasing sensitivity of R_F to higher cumulative infiltration.

Figure 6 indicates that there is a broadly consistent correlation between effective rainfall and the hydrologic response of a variety of characteristic model slopes. The effect of varying α, in considering a region of terrain for example, causes an increased scatter of 0.12 in R_F. Varying weathered soil depth considerably affects the pore pressure response in the slope – the most detrimental effect occurs with $d = 4$m.

4 IMPLICATIONS FOR DESIGN

Slope angle and soil strength parameters must be assessed reliably to determine the slip surface geometry and stability of 'basic' slopes. Vegetation may increase stability through root-derived cohesion, depending on root-interaction with the critical failure mechanism and relative increase in soil permeability caused by root voids. Urbanisation reduces the stability of natural slopes; in particular, cutting accelerates instability and increases the sensitivity of F to variability in c'. Soil permeability determines the resilience of the slope to rainfall by controlling infiltration, although slope geometry and weathered soil depth have some influence over the hydrological system.

For informal urban communities in the humid tropics,

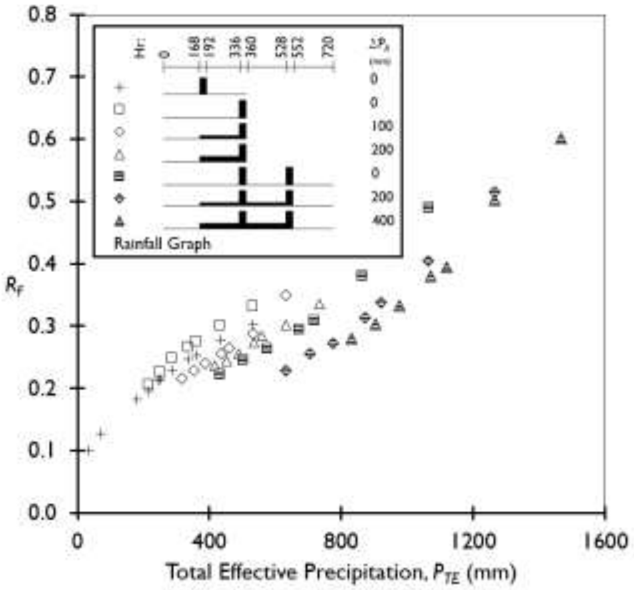

Figure 5. Rainfall response curves corresponding to simulations of one slope (Case A, $K_{sat} = 10^{-5}$ ms^{-1}) producing the lowest factor of safety under different patterns of rainfall.

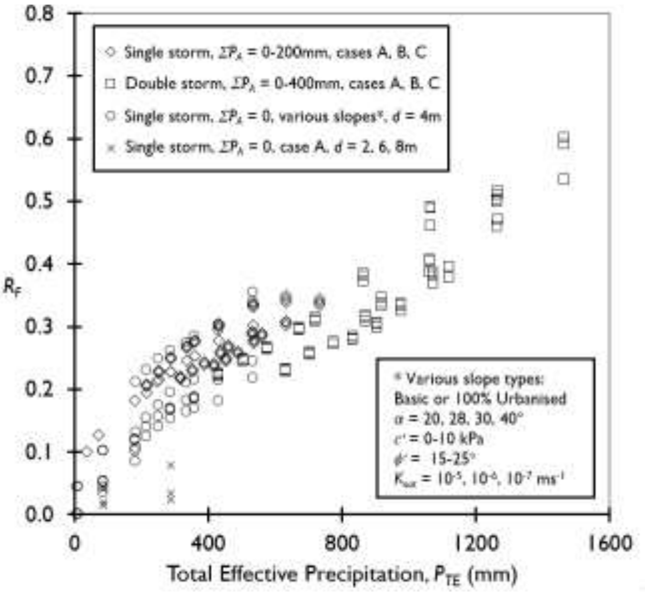

Figure 6. Rainfall response curves corresponding to simulations of various slope types producing the lowest factor of safety under different patterns of rainfall *[d=Stratum depth of Grade V-VI & III-IV soil].*

drainage and bioengineering may be considered as appropriate low-cost stabilising solutions. Figure 6 shows that if a 50% reduction in total effective rainfall can be achieved by interception, critical F will increase by about 0.15 for a variety of slope angles. Holcombe et al. (2016) showed that complete grass cover increased F by at least 0.13 in three different urbanised slopes. However, the accurate determination of the failure mechanism following rainfall infiltration is essential to making a reliable assessment of the effectiveness of root reinforcement by trees (or other means of mechanical stabilisation). Holcombe et al. (2016) demonstrated that light-weight trees with roots intersecting a considerable proportion of the slip surface (e.g., located at the crest of cuts) can reinforce the slope sufficiently to prevent rainfall from causing critical F to drop below 1.4 in response to a 1-in-200-year 24-hour storm.

The simulation results demonstrate that the stability of tropical slopes is particularly sensitive to modelled cohesion and supports the hypothesis that c' 'usually plays a significant role in maintaining the stability of slopes in residual soils' (Wesley 2010, p. 107-108). However, since effective cohesion is arguably a function of micro-structural bonding and macro-structure inherited from weathered parent rock, and can be lost rapidly with soil disturbance (Wesley 1990), it is prudent to question the validity of slope designs relying on mobilised cohesion. A conservative approach would therefore be to model slopes with zero cohesion and assess the reduction in F caused by rain infiltration. Using Figure 6 an engineer designing a slope (similar to those considered in this paper) to withstand a single storm event and up to 200mm total antecedent rainfall may use $F > 1.35$ as a conservative design rule.

5 CONCLUSIONS

Assessing the stability of tropical urban slopes for design purposes requires the determination of the failure mechanisms. The effectiveness of mechanical stabilisation schemes is influenced by slope geometry, soil strength parameters, and the pore pressure distribution triggered by rainfall. A hydrological-stability model (representing dynamic rainfall infiltration, unsaturated flows and negative pore pressures) can be used to assess the pore pressure response and critical slip mechanism for rainfall-induced landslides. The simulation of a range of slopes indicates that reducing the effective rainfall improves the critical factor of safety. By adopting a scenario-based approach to modelling parameter uncertainty, the results suggest that reducing soil infiltration with drainage or bioengineering schemes may be a viable means of improving stability. Modelling mechanical stabilisation requires many factors to be assessed which is difficult when resources are scarce. However, in this context, more reliable increases in computed factor of safety can be achieved by simply reducing infiltration.

6 ACKNOWLEDGEMENT

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