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Urbanisation and landslides: hazard drivers and better practices

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Rapid unplanned urbanisation is driving increasing rainfall-triggered landslide risk in low-income communities in tropical developing countries. Conventional slope stabilisation techniques are often unaffordable and most disaster-risk-reduction funding is currently spent post-disaster. However, experience in the Caribbean has changed local engineering practice and World Bank policy, demonstrating that community-based surface water drainage is affordable and effective in mitigating urban landslides. New evidence presented in this paper identifies specific informal construction practices generating further landslide hazards and bioengineering schemes most effective for landslide mitigation. A dynamic hydrology–slope stability model is used to simulate the factor of safety response of nine slope classes (angle and soil strength) to progressive vegetation removal, slope cutting and loading, for six design storms. The effectiveness of 76 bioengineering schemes for improving stability is modelled. Key recommendations are that deforestation should be limited and slope cutting avoided as cutting is most detrimental to stability. Site-specific modelling is needed to identify where deep-rooting, lightweight trees might add stability, whereas grasses are beneficial in all locations.

1. Introduction

Landslide hazards and impacts are increasing globally. Developing nations experience the highest economic losses relative to gross domestic product and the majority of fatalities – over half of which are estimated to occur in urban areas (Petley *et al.*, 2007).

High-intensity and high-duration rainfall events are the dominant landslide trigger in the humid tropics (i.e. Köppen classification: tropical rainforest and monsoonal climates; Peel *et al.*, 2007) where deeply weathered residual soils render slopes particularly susceptible to failure (Lumb, 1975). High-magnitude events, with hundreds of landslides triggered, can set back the economic growth of developing countries by several years (Peduzzi and Deichmann, 2009).

However, until recently the impact of small-scale, high-frequency landslide events on development has not been recognised. Such ‘everyday’ hazards contribute to an accumulation of risk which compromises livelihoods at community levels, erodes economic growth and indicates systemic lack of resilience (Bull-Kamanga *et al.*, 2003). Risk accumulation is part of a vicious spiral in which, ‘disasters put development at risk... [and] development choices... can generate new disaster risk’ (UNDP, 2004: p. 1).

Unfortunately current top-down disaster-risk-reduction policies struggle to address the highly localised physical and human drivers of everyday hazards such as urban landslides. Two examples of this disconnection between policy and practice are: the limited delivery of practical interventions on the ground, despite statements that disaster risk reduction is required for sustainable

development (Wamsler, 2007); and a significant lag in funding for ex-ante disaster mitigation (de la Fuente, 2010), despite evidence that it is more cost-effective than post-disaster actions (World Bank, 2010).

Effective risk reduction requires that risk drivers are identified and appropriate actions are taken to reduce hazards and/or consequences (exposure and vulnerability). The top-level drivers of the increasing landslide risk are urban migration and population growth as cities in developing nations expand rapidly.

Over 900 million people now live in overcrowded, poor-quality housing with inadequate infrastructure, making them highly vulnerable to both small- and large-scale disasters (Satterthwaite *et al.*, 2007). Often these settlements are built on hazard-prone land such as marginally stable slopes. Informal construction means that slopes and structures are not assessed or designed for safety; and high housing density increases exposure to landslides. Landslide hazard is increased further by localised changes to vegetation, topography, drainage and loading (Figures 1 and 2).

In this context controlling exposure to landslides using planning policies alone is impractical, since urbanisation often outstrips regulation and 30–50% of the population already live in informal, low-income settlements (Satterthwaite *et al.*, 2007). Vulnerability reduction thus presents a complex socioeconomic challenge; and landslide hazard drivers are not being systematically addressed.

Delivering conventional slope stabilising works is technically challenging due to the localised scale of instability drivers, widespread distribution of urban landslide hazards and high costs

Figure 1. Typical informal housing on a landslide-prone slope in Castries, Saint Lucia, Eastern Caribbean (photograph by Holcombe, 2011)

of geotechnical data, engineering expertise and construction. Furthermore, unless informal construction practices are modified, landslide hazard will continue to accumulate. Experts in the built environment are being called upon to develop innovative ‘global solutions and local actions’ to increase community resilience (IISD, 2014: p. 6).

1.1 A platform for delivering community-based landslide mitigation

Just such a community-based engineering approach to urban landslide hazard mitigation has been developed by Anderson and Holcombe (2006). Known as ‘management of slope stability in communities’ or ‘Mosaic’, it engages residents, community development practitioners and local engineers in identifying localised drivers of slope instability and implementing appropriate drainage measures.

Lack of geotechnical data and a limited budget for conventional site investigation are overcome by combining information from several sources: residents’ descriptions of slope materials, runoff, seepage and previous landslides; mapping of house plot scale slope features; elicitation of local engineering knowledge of soils; and reference to previous direct shear tests of similar local soils. This method provides detailed information on topography and surface drainage, and enables estimation of soil depths, categorisation by weathering grade and determination of relative strength with respect to other local soils (Anderson and Holcombe, 2013).

The physically based modelling software – Chasm (Combined Hydrology And Stability Model; see Section 2.2) – is then used to diagnose dominant instability processes. Where surface water infiltration is shown to drive instability, networks of open drains are designed to intercept runoff at critical locations and convey water to existing drains. Roof guttering and rainwater tanks are installed to intercept rain, supplement water supplies and attenuate peak drain flows.

Between 2004 and 2011 three Eastern Caribbean states implemented Mosaic in 12 low-income urban communities (over

Figure 2. Rainfall-triggered landslide in an informal community (photograph by Holcombe, 2004)

800 homes). There have been no subsequent landslides reported in these communities despite the exceptional rainfall associated with hurricane Tomas in 2010 (>500 mm in 24 h in Saint Lucia), whereas previously even 1 in 2 year rainfall events would trigger multiple small slope failures (Anderson and Holcombe, 2013).

By involving residents at all stages of mapping, design and construction there is evidence that both residents and local engineers have incorporated better slope drainage practices into subsequent construction (Holcombe and Anderson, 2010).

1.2 Understanding and mitigating future hazards

Mosaic addresses the hydrological drivers of rainfall-triggered landslides where urbanisation has already occurred. Its uptake by international disaster risk reduction funders, local practitioners and communities provides a unique platform to extend the analysis of urban landslide hazards and identify additional practical solutions. To this end, this paper presents numerical simulations of

- dynamic slope stability responses to progressive urbanisation, enabling identification of the most detrimental informal construction practices
- modified urbanisation scenarios to determine the effectiveness of actions by residents and engineers in offsetting accumulation of new landslide hazards.

2. Modelling urbanisation and landslide hazard drivers

Informal urbanisation of slopes typically involves removal of natural vegetation and excavation to create flatter sites for house construction (Smyth and Royle, 2000). Cut slopes are often at angles of 60° or steeper (Diaz, 1992) and may initially remain stable due to the high negative pore pressures that can develop in deep tropical residual soils, only to fail later as rainfall infiltrates (Anderson, 1983). The first houses are often built at the base of slopes adjacent to urban centres in valleys and on coastal plains. Informal settlements extend up slopes over time, and housing density increases as infilling occurs and houses are extended.

2.1 Mechanical and hydrological processes

Deforesting and cutting slopes are known to increase the incidence of landslides (Glade, 1998). Vegetation has mechanical and hydrological effects on slope stability, including root fibre reinforcement and anchoring, load transfer of self-weight and wind forces, rainfall interception, evapotranspiration and preferential flow pathways created by roots. Slope cutting alters the load distribution on potential shear surfaces within the wider slope, and can generate localised instability of the cut section.

Altered surface cover and topography also affect runoff, infiltration and drainage, leading to raised or perched water tables. Landslides become more likely to be triggered by rainfall as negative pore pressures are lost and material shear strength reduced. While the individual effects of different vegetation types, slope angles and hydrogeological conditions have previously been investigated (Anderson *et al.*, 1997), the impact on slope stability of the combination of the dynamic mechanisms that relate to progressive urbanisation and the effect of retaining or replanting vegetation in the changing urban environment have not been established.

2.2 Experiment design and data

To model dynamic slope stability processes, the physically based model Chasm was used to represent rainfall infiltration, groundwater flows, negative and positive pore pressures and slope factor of safety (F) over time. Chasm has proven reliable in predicting the safe/failed condition of tropical residual soil slopes for given rainfall events (e.g., Anderson, 1990; Holcombe, 2006) and for indicating the benefits of Mosaic drainage interventions (Holcombe *et al.*, 2012). Slopes are represented by a regular two-dimensional mesh of columns and cells with specified material parameters (Figure 3).

A forward explicit finite-difference scheme solves Richards' and Darcy's equations (Darcy, 1856; Richards, 1931) for unsaturated and saturated flows in which cell moisture contents and pore pressures are updated every time-step (usually 60s). Once the initial water table has equilibrated, a rainfall of a specified intensity and duration is imposed. Every hour pore pressures are incorporated into a limit-equilibrium analysis (Bishop's circular (Bishop, 1955) or Janbu's non-circular (Janbu, 1954)) in which the minimum F slip surface is identified using a search algorithm. The hydrological and mechanical effects of vegetation and the unit weight of houses can be included in the analysis (see Wilkinson *et al.* (2002a) for model equations).

A series of Chasm simulations was designed to represent the stability response of different slopes (classified by three angles and

Figure 3. Representation of a slope cross-section for analysis in Chasm

three soil types) to typical stages of urbanisation observed in the Eastern Caribbean and similar humid tropical locations (Smyth and Royle, 2000). Starting with a fully forested slope, urbanisation was represented as a sequence of three construction steps – vegetation removal, slope cutting and site loading – repeated at four sites on each slope, to give a total of 12 urbanisation stages (Figure 4, Table 1).

For each slope three material strata were defined using the Hong Kong weathering grade classification for tropical residual soils (GEO, 1988), and assuming no previous landslides had occurred. Strata depths and parameter values for soil cohesion c' and drained friction angle were based on direct shear tests on 25 undisturbed residual soil samples from un-failed cut slope faces in Saint Lucia (Anderson and Kemp, 1985; Holcombe, 2006).

The mean peak strength values (grade VI residual soil: $c' = 14$ kPa, $\phi' = 25^\circ$; grade V: $c' = 21$ kPa, $\phi' = 30^\circ$) were in accord with those obtained from an extensive programme of triaxial testing in Hong Kong on similar undisturbed tropical residual soils derived from volcanic bedrock (GCO, 1982). Such soils typically exhibit apparent cohesion due to the formation of high negative pore pressures, chemical bonding and the persistence of structures inherited from the parent material (c.f. Wesley, 1990).

The parameter values of $\phi' = 25^\circ$ and $c' = 2, 5$ and 10 kPa selected for modelling are thus conservative with respect to these data, reflect uncertainty surrounding apparent cohesion (negative pore pressures are represented in Chasm), and support the aim of investigating the stability response of typical slope classes.

Further studies investigating specific slopes, and with resources for additional geotechnical data, would allow revision of these values as appropriate. However, it should be recognised that, as with all such numerical models, these parameters are lumped at the grid-scale (1 m² in Chasm), effectively incorporating sub-grid mechanisms such as apparent cohesion.

Two sets of simulations were carried out. The first analysed the impact of a 12-stage 'business as usual' urbanisation scenario on each slope class to identify construction practices most detrimental to slope stability. For each simulation the minimum F and associated critical slip surface location were determined in response to Saint Lucia's 1 in 50 year, 24 h storm (based on an unpublished report from 1995 by Klohn-Crippen 'Roseau

Figure 4. Representation of a typical progression of tropical slope urbanisation used in the Chasm model (12 construction steps in total, from 100% forest cover to 100% urbanisation)

Urbanisation stage			0	1	2	3	4	5	6	7	8	9	10	11	12
	Forest %		100	75	75	75	50	50	50	25	25	25	0	0	0
	Total cuts		0	0	1	1	1	2	2	2	3	3	3	4	4
	Total houses		0	0	0	1	1	1	2	2	2	3	3	3	4
Factor of Safety for each slope class	a	Slope angle = 20° c' = 2 kPa	2.07	1.89	0.62										
	b	20° 5 kPa	2.34	2.19	0.89										
	c	20° 10 kPa	2.57	2.54	1.30	1.30	1.30	1.30	1.30	1.25	1.27	1.27	1.26	1.22	1.22
	d	Slope angle = 30° c' = 2 kPa	1.45	1.34	0.63										
	e	30° 5 kPa	1.69	1.58	0.89										
	f	30° 10 kPa	1.91	1.91	1.33	1.33	1.30	1.30	1.22	1.12	1.12	1.12	1.12	1.12	
	g	Slope angle = 40° c' = 2 kPa	1.11	1.02	–	1.01	1.01	–	1.01	0.98					
	h	40° 5 kPa	1.26 ^a	1.22	–	1.20	1.17 ^a	–	1.16 ^a	1.10 ^a	–	1.09 ^a	1.00 ^a	–	0.99 ^a
	i	40° 10 kPa	1.38 ^a	1.34 ^a	–	1.34 ^a	1.28 ^a	–	1.27 ^a	1.21 ^a	–	1.20 ^a	1.11 ^a	–	1.10 ^a
Decrease in <i>F</i> relative to previous construction step						Δ <i>F</i> ≤ 0.05			0.15 ≥ Δ <i>F</i> > 0.05			Δ <i>F</i> > 0.15			
Increase in <i>F</i> relative to previous construction step						Δ <i>F</i> ≤ 0.05			0.15 ≥ Δ <i>F</i> > 0.05			Δ <i>F</i> > 0.15			
Bold font indicates <i>F</i> > 1.4; ^a planar slip surface (Janbu) at base of top strata, otherwise failures are rotational (Bishop); – no cut geometrically possible.															

Table 1. Urbanisation stages and associated factors of safety for each slope class for a 1 in 50 year storm, delivering a total of 288 mm of rainfall in 24 h

Dam and ancillary works. Tropical storm Debbie, final report on hydrology', held by WASCO in Saint Lucia – see the online supplementary data for rainfall intensity-duration-frequency data). The second set of simulations tested the potential benefits of modified urbanisation scenarios: the impact of deforestation alone; the exclusion of the most detrimental construction practices; and bioengineering.

A series of design storms of increasing intensity and return period (from 1 in 5, to 1 in 200 years) were also simulated to identify the critical storms rendering each slope 'unsafe'. A threshold level of $F > 1.4$ was adopted 'as an acceptable number to guard against failure in a high-risk slope' (Hencher, 2012: p. 280).

3. Simulation results

Table 1 presents the lowest F for each slope class and urbanisation stage in response to the 1 in 50 year design storm. In total, 62 simulations were run; if a slope failed at a certain stage then no further urbanisation stages were imposed. Cuts were omitted from 40° slope simulations as they are not geometrically viable and houses on such slopes are often constructed on stilts.

3.1 Effect of slope cutting on stability

Table 1 aligns with observations that progressive urbanisation tends to reduce slope stability. Changes in F relate to the type of

construction activity and its location on the slope. Cutting is the dominant instability driver giving reductions in F of up to 1.30. The greatest stability decrease due to deforestation is 0.18; and housing loads have a negligible impact regardless of their position. For slope classes 'a' to 'f' the maximum impacts occur during the first construction sequence at the base of the slope.

At the start of the urbanisation process, critical failure surfaces typically encompass a large part of the slope and penetrate less-weathered material (Figure 5). Cutting at the toe of the slip surface (Figure 5, stage 2) removes a large proportion of the shear resistance and reduces the stability condition of a shallower slip surface. The first cut produces the greatest reduction in F , triggering shallow rotational failure in soils modelled with low cohesion ($c' = 2\text{--}5\text{ kPa}$).

Of the remaining stable slopes, following the second cut, the slip surface radius typically decreases further due to stress relief at its crest, and relocates to a more critical position downslope (Figure 5, stage 5). Removal of residual soil by cutting exposes less-permeable material and locally reduces rainfall infiltration. Additionally, cutting introduces an angle (60°) greater than the effective angle of friction (25°). Progressive urbanisation of slope classes c and f ultimately leads to localised circular slip surfaces on the face of each cut with critical or near-critical F values.

Slope angle and soil strength strongly influence stability of the natural slope and the impact of urbanisation. The steepest slopes

($\alpha = 40^\circ$) are inherently marginally stable and are considered unsafe for urbanisation. Here, only soils modelled with $c' = 10\text{ kPa}$ maintain $F > 1$ throughout the urbanisation process. For slopes of $\alpha = 20^\circ$ or $\alpha = 30^\circ$ the first cut produces consistent decreases in F and indicates that the landslide mechanism transformations are geometrically similar. For slopes of these angles with the highest cohesion soils (i.e. c and f) the critical surface becomes localised to one of the cut slopes and F remains relatively constant after the third cut. Here, cut slope geometry outweighs the influence of the original slope angle in determining slope stability.

None of the fully urbanised slopes meet the specified safety threshold of $F > 1.4$. Therefore, the scenario of 'urbanisation without cuts' was modelled for slope classes in which cutting led to $F < 1$ (classes a, b, d and e). The results for this scenario (Table 2) show that slopes a, b and e maintain $F > 1.4$ throughout the design storm, while d remains marginally stable ($1 < F < 1.4$).

3.2 Effect of targeted bioengineering on stability

While slope cutting dominates decreases in F , reintroducing vegetation to slopes, or limiting deforestation, is one way of mitigating the impact of urbanisation. However, despite the recognised benefits of bioengineering for reducing soil erosion, 'its ability to stabilise slopes...is less well proven, and certainly less well quantified' (Campbell *et al.*, 2007: p. 13). This is because the effect of vegetation on slope stability is strongly related to the location of roots with respect to the critical slip surface; and there is uncertainty regarding the mechanical and hydrological influences of vegetation and natural variations in plant properties (Norris and Greenwood, 2006).

The importance of the mechanical effects of vegetation, such as root-slip surface interaction and root tensile strength, was evident in simulations of the urbanisation process. Table 1 indicates a reduction in F if tree roots interact with the critical slip surface prior to deforestation. Where the sliding mechanism is translational (slopes g and h) successive stages of deforestation lower F in

Figure 5. Chasm visual output of pore water pressure, critical slip surface and F at progressive stages of simulated urbanisation at time steps corresponding to the lowest factor of safety (slope class f)

Slope definition			Business as usual		Modified urbanisation scenarios			
α , °	c' , kPa	Class	100% forest	Urbanised with cuts	100% deforested	Urbanised without cuts	Tree cover	Grass cover
20	2	a						
	5	b						
	10	c					A	A
30	2	d					B	B
	5	e						
	10	f					A	A
40	2	g					B	B
	5	h					B	B
	10	i					B	B

Dark shading: $F < 1.0$, failed; light shading: $1.0 < F < 1.4$, critical; no shading: $F > 1.4$, stable; diagonal strike through: not considered.
Modelled bioengineering schemes: A, cut slopes, one tree at crest of each cut, complete grass cover; B, uncut slopes, five trees between houses, complete grass cover

Table 2. Summary of stable, critical and failed slopes for a 1 in 50 year, 24 h design rainfall (12 mm/h)

approximately equal steps because each tree contributes an equal fraction of shear resistance. For rotational slides the critical slip surface extends up the slope as F decreases (e.g., stage 6–7, Figure 5), suggesting that trees force the critical slip surface outside the rooting zone prior to removal. Slopes with soils modelled with lower cohesion ($c' = 2\text{--}5\text{ kPa}$) are more sensitive to initial deforestation because the cohesion added by roots (taken as 6 kPa for the deforested trees (c.f. Wu *et al.* 1979)) is greater than the ‘bare-soil’ value.

To test the impact of bioengineering the three urbanised slope classes with the greatest response to vegetation removal for their soil type were selected (d, f, h). Two types of bioengineering scheme were modelled: grass (uniform distribution) and trees (at the crest and toe of cuts and downslope of houses). Vegetation effects represented in Chasm included: rainfall interception, evapotranspiration with root water uptake, increased hydraulic conductivity, root reinforcement, and surcharge (Wilkinson *et al.*, 2002b). Additionally, ranges of root area ratio, root depth, root

tensile strength and surcharge for each plant type were used to assess the sensitivity of F to variations in properties of grass and trees (see Table 3, the online supplementary data and Sorbie and Beesley (2013)). The most effective planting schemes were then applied to the remaining critical slopes (see Table 2). The design values chosen for the modelled bioengineering schemes are given in table S8 of the online supplementary data.

Table 3 shows that trees potentially produce the greatest increases in F if there is a large degree of interaction between the roots and slip surface (e.g., roots of 4 m depth located at the crest of cuts), and if the roots have a high enough root area ratio to increase cohesion significantly. However, cut slopes are particularly sensitive to surcharge due to trees (2 to 5 kPa) positioned on the crests, which reduces F by 0.89 and triggers failure during the design storm. The effectiveness of trees is thus highly dependent on their location and properties. In contrast, all three slopes (d, f, h) were found to respond positively to grass cover in every simulation, with increases in F of at least 0.13.

	Rd: m	RAR: 1×10^{-3} m^2/m^2	T_r : MPa	S: kPa	Added c' : kPa	$\alpha: 30^\circ, c': 10\text{ kPa}$		$\alpha: 40^\circ, c': 5\text{ kPa}$		$\alpha: 30^\circ, c': 2\text{ kPa}$	
						ΔF	F	ΔF	F	ΔF	F
Trees Max. $\Delta F = 0.39^*$ Mean $\Delta F = 0.14^*$ Coefficient of variation (COV)* range: 0.27–0.74 Mean COV = 0.52 *Excludes effect of variation in S	1	0.1	50	2	6	0.05	1.17	0.03	1.02	0.01	1.29
	2	0.1	50	2	6	0.09	1.21	0.03	1.02	0.03	1.31
	4	0.1	50	2	6	0.22	1.34	0.06	1.05	0.05	1.33
	Mean (SD)					0.12 (0.09)		0.04 (0.02)		0.03 (0.02)	
	4	0.1	50	2	6	0.22	1.34	0.06	1.05	0.05	1.33
	4	0.5	50	2	30	0.39	1.51	0.18	1.17	0.20	1.48
	4	1	50	2	60	0.39	1.51	0.34	1.33	0.30	1.58
	Mean (SD)					0.33 (0.10)		0.19 (0.14)		0.18 (0.10)	
	4	0.1	20	2	2.4	0.17	1.29	0.05	1.04	0.03	1.31
	4	0.1	50	2	6	0.22	1.34	0.06	1.05	0.05	1.33
	4	0.1	100	2	12	0.29	1.41	0.09	1.08	0.09	1.37
	Mean (SD)					0.23 (0.06)		0.07 (0.02)		0.06 (0.03)	
	4	0.1	50	2	6	0.22	1.34	0.06	1.05	0.05	1.33
	4	0.1	50	5	6	-0.89	0.23	0.04	1.03	0.06	1.34
	4	0.1	50	10	6	-0.92	0.2	0.01	1	0.07	1.35
	Mean (SD)					-0.53 (0.65)		0.04 (0.03)		0.06 (0.01)	
Grass Max. $\Delta F = 0.37$ Mean $\Delta F = 0.22$ COV range: 0.00–0.38 Mean COV = 0.18	1	0.1	20	0.0008	2.4	0.34	1.46	0.13	1.12	0.17	1.45
	2	0.1	20	0.0008	2.4	0.34	1.46	0.13	1.12	0.18	1.46
	4	0.1	20	0.0008	2.4	0.22	1.35	0.16	1.15	0.21	1.49
	Mean (SD)					0.30 (0.07)		0.14 (0.02)		0.19 (0.02)	
	1	0.02	20	0.0008	0.48	0.34	1.46	0.13	1.12	0.13	1.41
	1	0.1	20	0.0008	2.4	0.34	1.46	0.13	1.12	0.17	1.45
	1	0.5	20	0.0008	12	0.34	1.46	0.16	1.15	0.37	1.65
	Mean (SD)					0.34 (0.00)		0.14 (0.02)		0.22 (0.13)	
	1	0.1	4	0.0008	0.48	0.34	1.46	0.13	1.12	0.13	1.41
	1	0.1	50	0.0008	6	0.34	1.46	0.13	1.12	0.17	1.45
	1	0.1	75	0.0008	9	0.34	1.46	0.15	1.14	0.31	1.59
	Mean (SD)					0.34 (0.00)		0.14 (0.01)		0.20 (0.08)	

Table 3. Sensitivity of slope factor of safety (F) to rooting depth (Rd), root area ratio (RAR), tensile strength (T_r) and surcharge (S) (see Table 1 for colour key)

Again, high values of root area ratio increase the effectiveness of grass, particularly in soils exhibiting low cohesion. Furthermore, F is generally less sensitive to variation in grass parameters than tree parameters, and significant increases in F were observed without roots interacting with the critical slip surface. This suggests that the thatch effect, by which long grass intercepts and sheds rainfall, improves slope stability by way of a hydrological mechanism (reduced infiltration). The consistently beneficial effect of grass makes it a 'no regrets strategy' in bioengineering schemes.

Table 2 compares the selected tree and grass bioengineering schemes with current and modified urbanisation scenarios. For slopes of 20° and 30° both schemes improve slope stability to $F > 1.4$; and for the 40° slopes the 'urbanisation plus design tree cover' scenario stabilises slope i. These results rely on the design tree root area ratio of $1 \times 10^{-3} \text{ m}^2/\text{m}^2$ (see table S8 in the online supplementary data) – a parameter to which the slope shows significant sensitivity (Table 3). In comparison, complete grass cover does not increase F sufficiently for any of the 40° slopes to be considered stable, although there is less uncertainty in the effectiveness of grass schemes.

4. Discussion – urbanisation and landslide hazard

The change in landslide hazard for slopes under alternative 'business as usual' and 'modified urbanisation' scenarios is summarised in Table 4. In all cases current construction methods increase the frequency of rainfall-triggered landslides to return periods of at least 1 in 5 years, affecting multiple cut slopes. This aligns with observations of 'everyday' landslide hazards in informal urban communities in the humid tropics.

The steepest slopes are considered unsafe for urban development – again reflecting the known unsafe locations inhabited by many such communities. These results emphasise the detrimental effect of slope cutting; yet by constructing without cuts (e.g., using pier foundations as recommended by AGS (2007)), the increase in

landslide hazard could be mitigated in slopes a, b and e. To offset risk accumulation in existing urbanised slopes, both modelled bioengineering schemes are viable (classes c and f).

The value of integrating better practices is demonstrated by the response of slope class d, where a combination of informal urbanisation without cuts and with bioengineering reduces landslide hazard to below that of the original forested slope.

5. Summary and recommendations

From the simulations reported in this paper, slope cutting is shown to be the dominant instability driver; aligning with observations that high-frequency rainfall events (<1 in 5 years) often trigger multiple cut slope failures in informal urban hillside communities. The retention or reintroduction of vegetation can be effective in mitigating some of this hazard, and grass is found to be beneficial in all cases.

Site-specific bioengineering schemes can be identified for each slope class. However, given that the critical factor of safety is sensitive to the modelled cohesion of the soil and the mechanical effects (and location) of trees, a thorough ground investigation, physics-based modelling of site hydrology and stability mechanisms and selection of local tree species with beneficial characteristics (e.g., Greenwood *et al.*, 2006) is required to reduce the uncertainty in F related to tree-planting schemes. These general and site-specific actions would be suitable for application in combination with other improved construction and slope drainage practices.

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Slope definition			Business as usual		Modified urbanisation scenarios			
α : °	c : kPa	Class	100% forest	Urbanised with cuts	100% deforested	Urbanised without cuts	Tree cover	Grass cover
20	2	a	1 in 200	>1 in 5	1 in 200	1 in 200	N/C	N/C
	5	b	1 in 200	>1 in 5	1 in 200	1 in 200	N/C	N/C
	10	c	1 in 200	>1 in 5	1 in 200	N/C	1 in 200	1 in 200
30	2	d	1 in 100	>1 in 5	>1 in 5	>1 in 5	1 in 200	1 in 200
	5	e	1 in 200	>1 in 5	1 in 200	1 in 200	N/C	N/C
	10	f	1 in 200	>1 in 5	1 in 200	N/C	1 in 200	1 in 200
40	2	g	>1 in 5	N/C	>1 in 5	>1 in 5	>1 in 5	>1 in 5
	5	h	>1 in 5	N/C	>1 in 5	>1 in 5	>1 in 5	>1 in 5
	10	i	>1 in 5	N/C	>1 in 5	>1 in 5	1 in 200	>1 in 5

N/C, not considered.

Modelled tree and grass covers are defined in Tables 2 and 3.

24 h rainfalls with return periods of 1 in 5, 10, 20, 50, 100 and 200 years were simulated.

Rainfall intensity, duration, frequency data used to define the critical storms are provided in the online supplementary data.

Table 4. Return periods of 24 h storms causing $F < 1.4$ ('>1 in 5' indicates $F < 1.4$ for a storm with a return period of 1 in 5 years or lower)

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