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Co-producing data and decision support tools to reduce landslide risk in the humid tropics

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Abstract

Rainfall-triggered landslides are increasing in the humid tropics, and Small Island Developing States are disproportionately affected. Frequent shallow slides in hillside cuttings along roads and in communities hinder sustainable development. Larger, less frequent storms cause hundreds of landslides that block lifeline roads, impede disaster response and reverse economic growth. Top-down Disaster Risk Reduction (DRR) policies and approaches aiming to transfer conventional landslide assessment science and engineering practices are not always suitable in these data- and resource-limited contexts. This paper recognises the emergence of co-production approaches as part of the resilience paradigm response to DRR science-policy-practice gaps. We present a case study from Saint Lucia, Eastern Caribbean, in which government engineers and policymakers have partnered with the authors to co-produce landslide hazard assessment data and prototype decision support tools to strengthen landslide hazard management along lifeline roads.

Keywords

rainfall-triggered landslides, Small Island Developing States (SIDS), knowledge co-production, lifeline roads, geotechnical data, stochastic slope stability modelling.

Introduction

The occurrence and impact of rainfall-triggered landslides is increasing in the humid tropics due to deforestation, urbanisation and road construction (Froude and Petley, 2018). Slope failures in hillside cuttings such as those along roads and in informal communities are becoming more common (ibid). High frequency shallow soil slides in cut slopes have a localised impact on lives and livelihoods, and these ‘everyday’ (extensive) disasters can be part of a pattern of risk accumulation that hinders sustainable development (Bull-Kamanga et al., 2013). Extreme rainfall events can trigger hundreds of slope failures over wide areas causing fatalities, blocking and damaging roads, and impeding disaster response. For countries with low economic resilience these intensive disaster events can divert public expenditure, reverse economic growth and increase national debt (IMF 2016, World Bank, 2017).

The impact of disaster risks on development, and vice-versa, is recognised in the UN’s Sendai Framework for Disaster Risk Reduction, SFDRR, (UNISDR, 2015) and the Sustainable Development Goals. It is widely acknowledged that top-down development policies struggle to deliver practical hazard mitigation measures for DRR on the ground (Wamsler, 2007; Aitsi-Selmi et al., 2015). Bottom-up community-based approaches associated with the development paradigm (e.g. Wisner et al, 2012) deliver local DRR, often with an emphasis on community capacity development and vulnerability reduction. However, there is a knowledge-action gap between these two spatial and organisational scales (Gaillard and Mercer, 2013). To address this gap the SFDRR calls for “actionable knowledge” that translates new DRR science into policy and practice whilst ensuring research is informed by end-user needs (UNISDR, 2015). Knowledge production and ‘co-production’ are often cited as key components to any such endeavour (e.g. Weichselgartner and Pigeon, 2015; Scolobig and Pelling, 2016).

The interconnected human-physical causes and impacts of rainfall-triggered landslide risks provide a valuable context for exploring DRR science-policy interactions, gaps and the potential utility of co-production approaches (Scolobig and Pelling, 2016). This paper draws on our experience of longstanding partnerships with community residents, government civil engineers and policymakers to deliver landslide hazard knowledge and mitigation measures in Saint Lucia, Eastern Caribbean. We first outline typical scientific and technical challenges to landslide hazard assessment, and the science-policy interactions that may influence translation of information into actions in this context. Then, to illustrate a potential approach to addressing these challenges, we present a case study on the co-production of data on road cut slopes and prototype landslide risk management decision-support tools with our partners in Saint Lucia.

Landslide risk reduction data, knowledge and action gaps in Small Island Developing States (SIDS)

To identify typical landslide risk reduction knowledge-action gaps in the humid tropics it is helpful to consider the conventional scientific methods used for hazard assessment and how this informs policy and practice. It should be noted that the policy-practice (and funding) context can determine the scientific knowledge production process adopted. We organise this overview in terms of spatial scales (see Fig. 1).

Slope stability is determined by local topographic, geotechnical, hydrological and surface-cover factors. Constructing roads or informal communities on slopes can reduce stability where vegetation is removed, slopes cut, and drainage altered (Holcombe et al. 2016).

Top-down DRR policies typically call for wide-area Geographical Information Systems (GIS)-based hazard assessments at national or city scales to inform funding priorities and land use planning. These conventional landslide susceptibility maps cannot represent localised or dynamic landslide factors or processes, or the effects of risk mitigation and climate change. More advanced empirical-statistical and physics-based GIS hazard assessments require landslide inventories and high-resolution spatial data (van Westen at al., 2008). Yet, despite rapid progress in topographic remote sensing, it is difficult to generate detailed enough data for GIS-based cut slope stability assessment (van Westen, 2016).

Civil engineers need data from geotechnical investigations and slope surveys to analyse instability mechanisms in individual slopes and design slope stabilising measures. Practitioners typically assume a static water table in such analyses, which fails to capture the dynamic hydrological processes that often trigger landslides in soils (c.f. Anderson et al., 1997). Physics-based modelling is also too data- and time-intensive for hazard assessment at road network scales. Instead rapid field reconnaissance of slopes and qualitative scoring of hazard and vulnerability by experts, can be used to develop databases for road asset and risk management (e.g. GEO, 2013).

The thinly spread institutional capacity of small, low- to middle-income countries, such as many SIDS, means that municipal engineers have limited resources for data collection or adopting the off-the-shelf technologies often transferred under top-down programmes. Without an adequate inventory of past landslides or man-made slopes, or data on slope profiles and soil properties, many conventional landslide hazard assessment methods are not suitable. As Fig. 1 illustrates, these data gaps translate into knowledge and action gaps between top-down DRR policy and site-specific slope engineering works. Therefore, civil engineers and disaster risk management agencies in the humid tropics struggle to anticipate and mitigate rainfall-triggered landslides effectively in communities and along lifeline road networks.

Partnerships for landslide risk reduction: Saint Lucia

Community-based landslide risk reduction

Between 2004 and 2011 the Government of Saint Lucia (GoSL) partnered with Anderson and Holcombe (2013) to develop the 'Management of Slope Stability in Communities' (Mossaic) methodology and deliver landslide hazard mitigation projects in ten informal urban communities. The local actors were community residents, the social development fund, and several government ministries. Funding came from GoSL, the

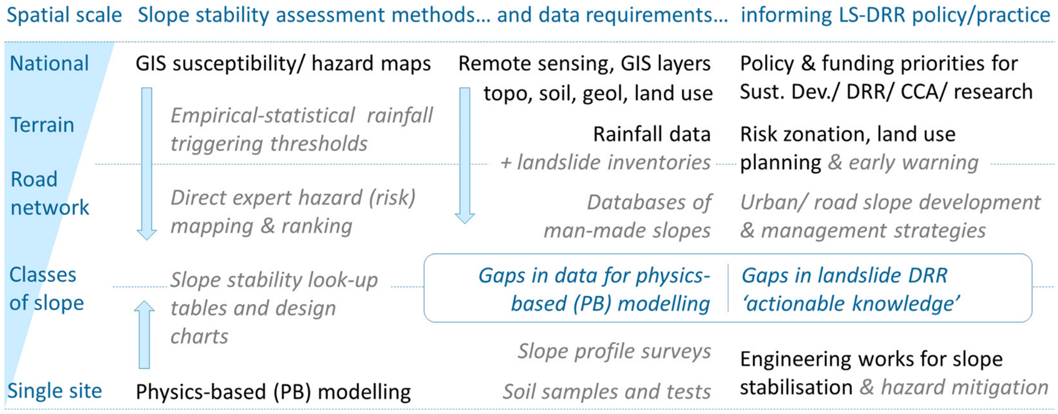

Fig. 1. Conventional landslide hazard assessment methods, data and policy/practice, and typical gaps (*italics*) in actionable knowledge for landslide hazard management in data and resource-limited countries such as SIDS

World Bank and other development banks. The Mossaic approach has three foundations that help to overcome knowledge-action gaps at community scales, and enable co-production of effective mitigation works:

1. *A community-base:* Residents of hillside communities are not just seen as those "at risk", but as people with a practical knowledge of local slope features affecting landslide hazard (e.g. drainage routes, soil depths, signs of instability), and who can actively contribute to delivering landslide mitigation works.

2. *A scientific base:* Community-based mapping and elicitation of local engineers' expert knowledge on soils allows local slope processes to be diagnosed using the Combined Hydrology And Stability Model (CHASM). If water infiltration is found to be a dominant destabilising factor, then rainwater capture and surface water drainage measures are designed and built.

3. *An evidence base:* Delivering cost-effective measures that improve slope stability can influence risk management practice and policy (World Bank, 2013).

Landslide hazards along lifeline roads at national scales

The longstanding Mossaic partnership with GoSL engineers provided the basis for a recent national scale initiative to start to address knowledge-action gaps hindering effective management of landslides along roads in Saint Lucia. Roads are important for economic development and are the primary lifeline infrastructure for disaster response and recovery (World Bank, 2017). Yet the slope cuttings along road corridors in mountainous tropical regions are many times more landslide-prone than natural slopes (Larsen and Parks, 1997), and there is often low network redundancy due to limited physical space and financial resources in SIDS. Landslides along road networks account for a large share of disaster losses. Hurricanes Tomas in St Lucia in 2010, and Maria in Dominica in 2017, caused losses exceeding 40% and 220% GDP respectively. Both events triggered hundreds of landslides in man-made cut slopes along roads, hindering disaster response, recovery and longer-term economic activity.

Between 2016 and 2018 GoSL engineers and University of Bristol researchers co-produced a prototype Platform for Road and Infrastructure Slope Management (PRISM) that builds on the three Mossaic foundations – combining *local knowledge* with landslide hazard modelling *science* to deliver an *evidence base* for LS-DRR practice and policy.

In this case the local knowledge is from GoSL civil engineers and based on their professional training and experiences (such as knowledge of Saint Lucia's soil types, past landslides, and working with governmental processes and policies, for example). To this we add data that can be collated from disparate sources, such as paper copies of geotechnical laboratory tests results; and new data from field reconnaissance of road cut slopes. The methods of data co-production, processing and curation are designed to align with existing working practice and institutional capacity, rather than being a one-off project or product. They address some of the missing data sources identified in italics in Fig. 1. and provide the basis for building up national databases of soils properties and cut slopes. They are also designed to be mapped in GIS and connected with ongoing road asset and risk management initiatives.

To increase the information obtainable from these new, but still limited, geotechnical, slope profile and rainfall data we use stochastic CHASM modelling to assess the stability of typical ranges of road cut slope geometries and soil types. Sensitivity analysis is used to identify influential slope properties and patterns of stability response to rainfall. Finally, decision-support tools are co-produced that translate the simulation results into rainfall thresholds, look-up tables for rapid slope assessment, and recommendations for targeted data acquisition. The methods for co-producing the prototype data and decision support tools are described in the remainder of this paper.

Co-producing the prototype Platform for Road and Infrastructure Slope Management (PRISM) in Saint Lucia

Prototype national cut-slope database

The primary purposes of the PRISM cut-slope database are to: (i) provide GoSL engineers with a georeferenced inventory of the slopes along roads, which can be added to over time; (ii) facilitate basic hazard assessment using a simplified and adapted version of the Priority Ranking System for Man-made Slopes (GEO, 2013); (iii) provide the slope geometry parameter ranges for stochastic modelling in CHASM; and (iv) link to slope stability look-up tables generated by the stochastic modelling methodology. After reviewing previous experiences of IT transfer with GoSL engineers, it was agreed that the prototype database should be an MS Excel workbook (to be managed by a nominated engineer) with macros for data-entry, calculating the hazard scores and reading look-up table results.

A review of available GIS data and reports from previous landslide and road mapping projects confirmed that road cut-slopes had previously been mapped on the primary road network (Mott MacDonald, 2013). However, slope characteristics were not in the GIS attribute table (just a single hazard score). Fieldwork was undertaken with GoSL engineers to check whether these slopes matched our own criteria for cut-slope identification, namely: consistent geometry and angle of cut and the surrounding topography (shape of wider slope); and consistent material type and strata along its length (see Fig. 2). Agreement was generally good, but in some cases, the Mott MacDonald (2013) slopes needed to be subdivided into two or more individual slopes. Challenges to slope identification included vegetation obscuring the slope, cut slope crests being indistinct through erosion, and GPS handsets (or mobile phone GPS) losing signal near steep hills so coordinates became inaccurate.

The next stage was to design a method for recording slope features for stability ranking and/or as inputs to CHASM (Fig. 3). Cut slope heights and angles were measured using an Abney level and a laser rangefinder (Leica DISTO S910). The instruments gave cut slope heights within 0.5 m of each other; however, slope angles were much more easily and accurately obtained with the laser rangefinder. Natural slope angles ~80m upslope and downslope of the cut and road (after Larsen and Parks, 1997) were obtained from a DEM.

The most complex aspect of the cut-slope survey design was the characterisation of the soil in enough detail to allow an appropriate statistical distribution of soil strength parameters to be assigned for stochastic modelling and for cross-referencing with the resulting stability look-up tables. We combined local engineering knowledge of soils; data from geology and soil maps and surveys; and soil test results from known locations, to define three soil 'families' that can be recognised in the field: (A) tropical residual soils formed in-situ through weathering (often clayey and red/ brown); (B) volcanic deposited soils of unsorted agglomerates and fine-grained matrix; (C) volcanic deposited soils of pumice/tuff and ash-derived lithosols (grey silty sandy soils) (Shepheard et al., 2019). The degree of weathering of the slope materials is assessed on site and assigned a weathering grade from VI – all rock material converted to soil, to I – fresh rock (Fookes, 1997).

Finally, factors are recorded for slope risk scoring:

- Facilities or features up/down-slope of cut slope
- Drainage on the slope; evidence of water ingress or seepage; presence of water-carrying services
- Surface protection or vegetation cover
- Evidence or knowledge of past instability
- Engineering judgement of stability and risk

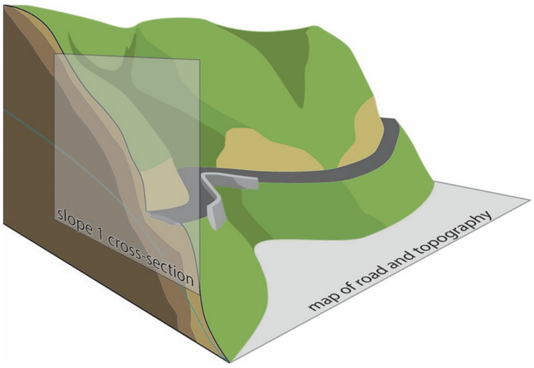

Fig. 2 Cut slopes along roads (yellow – illustrative) and an estimated profile for initial stability assessment

Prototype national soil geotechnical database

The soil data required for CHASM analysis are the effective cohesion and effective friction angle, unit weight, saturated and residual moisture contents, saturated hydraulic conductivity and soil moisture characteristic curve. Fig. 3 shows an idealised tropical residual soil profile with weathering parallel to the natural slope ('soil' 2 is unweathered volcanic bedrock).

The initial reason for compiling a soil geotechnical database for Saint Lucia was to give the basis for statistical analysis to provide parameter distributions for stochastic CHASM modelling, or for estimating distributions (such as the hydraulic parameters) from index properties such as soil texture. GoSL engineers routinely carry out basic soil tests for construction projects or after a landslide, but data from separate projects is rarely combined for use in wider analysis. Other reasons for creating the database include digitisation of paper records of soil test results; enabling verification of test results against each other or related parameters; and creation of a searchable and mappable geotechnical dataset that can be analysed with respect to geological and soil maps and used to estimate soil properties for preliminary project studies.

Shepheard et al. (2019) provides full details of the soil A, B, C classification approach, digitisation of 91 laboratory test records, benchmarking of shear box test apparatus, and the statistical analyses of soil property correlations and parameter distributions. The prototype soil database is currently in the form of an MS Excel workbook, like the prototype slope database. Over 50 additional soil test results have recently been digitised from archived records in the GoSL materials laboratory; and the database continues to be updated. A separate prototype MS Excel workbook for geotechnical test data entry was also co-designed with technical officers in the GoSL materials laboratory, so that results could be digitised during testing (with automated calculations and error-checking).

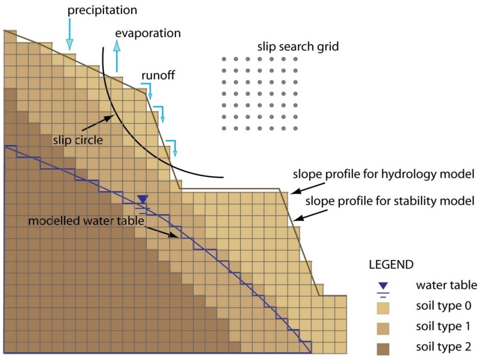

Fig. 3 Slope profile for analysis in CHASM (adapted from Anderson and Holcombe, 2013)

Prototype decision-support tools and information

The development of soil and cut slope data collection methods and prototype databases in Saint Lucia has started to address some of the data gaps at the road network and 'slope class' scales identified in our conceptual framework (Fig. 1). Translation of this data into slope hazard assessment information, knowledge and decision-support tools for LS-DRR practice and policy can also be mapped onto this framework. We provide a brief overview of these prototype outputs here (details of the methods and results are the subject of a paper in preparation):

Slope hazard (and vulnerability) ranking at road network scales is done using a macro in the cut slope database. Scores are calculated from slope geometry, instability and vulnerability factors recorded in the field (after GEO, 2013). This information will allow engineers to identify and prioritise high risk slopes for further investigation and landslide mitigation works. The scores of 36 cut slopes in the initial database, which were surveyed during development of the fieldwork methodology, show good agreement with observations of previous landslides in these locations.

Rainfall-triggering thresholds (national scale), priorities for *targeted data acquisition*, and *slope stability look-up tables* ('slope class' and site scales) are generated using a stochastic physics-based modelling approach described in detail by Almeida et al. (2017). The first step is to translate soil and slope information from the new databases, statistical analyses, local knowledge and literature review into CHASM input parameter distributions (slope geometry, strata, initial water table, geotechnical properties, and rainfall intensity and duration). CHASM simulates rainfall infiltration, groundwater seepage, negative and positive pore water pressures, and slope stability over time (see Anderson et al., 1997, and Wilkinson et al., 2002, for equations and numerical scheme). CHASM is run tens-of-thousands of times using parameter combinations generated from the Saint Lucia data. When predicted landslides are plotted with respect to the associated rainfall, we can estimate the threshold above which landslides are likely to be triggered in road cut slopes. Rainfall thresholds can be used for emergency planning and early warning at national scales. The experimental threshold in Fig. 4 was estimated using Pareto optimisation to capture 99.8% of simulated landslides (minimise area and maximise points above the line).

Classification And Regression Tree (CART) analysis of simulation input-output matrices is used to identify influential slope parameters (after Almeida et al. 2017) and provide engineers with information for prioritising data collection. To create physics-based look-up tables for rapid slope assessment a second set of simulations is run with fixed design storms. The CART analysis is constrained using six 'observable parameters' that engineers can estimate in the field to within specified ranges (cut slope height and angle, low to very high effective friction angle and cohesion, upslope angle, top strata depth). This analysis produces experimental decision-trees based on the six observable parameters which, once tested and verified, should provide look-up tables for physics-based assessment of cut slopes in the field, or as a macro in the slope database.

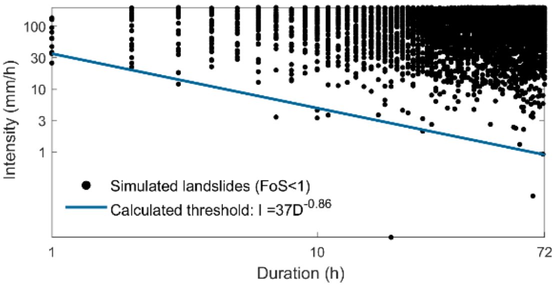

Fig. 4 Prototype landslide-triggering rainfall threshold, I = intensity (mm/h), D = duration (h), for residual soil cut slopes in Saint Lucia (>9000 simulated landslides).

Conclusions

The PRISM data and decision-support tools described here are still at a proof of concept stage. Further work on the prototype PRISM is needed to test and refine the data, methods and tools; continue to integrate with practice and policy in Saint Lucia; and define an 'adaptable blueprint' for use in similar locations. Adaptations could include road loading (negligible with respect to soil unit weight for this study's narrow, 6.5m, pavements) and, with a suitable model, seismic loading (excluded here due to the low frequency of earthquake-triggered landslides versus frequent rainfall triggering).

This case study shows a possible way of addressing some of the scale, data, knowledge and action gaps that hinder effective management of landslide hazards along lifeline roads in the tropics (i.e. creating both horizontal and vertical connections in Fig 1). Co-production has combined local knowledge with science and created appropriate tools as a basis for practice and policy. This has been a reflexive and social process involving technical and political decision-makers throughout; rather than being linear from data to knowledge to action, or science to practice and policy (Kasperson, 2010; Weichselgartner and Pigeon, 2015).

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