Reducing Landslide Risk Using Cut Slope Stability Maps:

Excavating for Safe Development in the British Virgin Islands

R3i Regional Risk Reduction Initiative

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Contents

Introduction

The Caribbean region is highly vulnerable to climate change impacts and various natural hazards, including earthquakes, hurricanes, floods, landslides, tsunamis and volcanic eruptions. The increasing incidence of such disasters, coupled with the small size of the islands and fragile ecosystems compound their vulnerabilities. Additionally, the location of businesses, settlements and livelihoods in low-lying coastal areas and the sensitivity of the main economic sector, tourism, exacerbate these vulnerabilities.

Geological and seismic hazards are among these risks to which many islands are exposed, such as landslides, rockslides, earthquake and secondary hazards such as liquefaction.

The Regional Risk Reduction Initiative (R3I)

Like the other small island developing states (SIDS) in the region, the English and Dutch overseas countries and territories (OCTs) in the wider Caribbean region are highly vulnerable to various natural hazards and climate change impacts, and have fragile ecosystems. Settlements are often concentrated in low-lying coastal areas and other hazard-prone locations.

The R3I was a 4-year project (2009-2012) funded by the European Commission (€4.932m) and implemented by UNDP's sub-regional office for Barbados and the OECS with the objective of developing the local capacities for disaster risk management of the beneficiary territories, namely Anguilla, Aruba, Bonaire, British Virgin Islands, Cayman Islands, Curaçao, Montserrat, Saba, Sint Eustatius, Sint Maarten, and Turks and Caicos Islands by:

- Increasing capacity in hazard mapping and associated vulnerability assessments, to further be incorporated into spatial information systems to inform planning and development processes
- Developing a regional early warning system (EWS) pilot for the OCTs, based on the International Telecommunication Union (ITU) automated alert protocol for warnings
- Building capacities in response, rescue and recovery through the use of risk assessment and mitigation practice in order to shorten recovery periods
- Strengthening local disaster management structures and capacities in terms of tools and best practices to support comprehensive disaster risk management schemes
- Enhancing cooperation and coordination between the OCTs, with documentation and dissemination of best practices

By emphasizing intra-regional learning and sharing of tools, knowledge and best practices, the R3I has enhanced the territories' individual and collective capacities to predict and prepare for disasters, thus improving resilience and reducing risk and subsequent loss.

Geological History

The British Virgin Islands hill slopes are underlain by nearly vertical metamorphic and volcanic rock layers or massive igneous intrusive rocks. Because of their limited degree of weathering, these rocks are able to maintain strength and support steep hill slopes. Their overall strength and ability to resist slope failure is controlled by the thickness of layering and intensity of jointing or fracturing of the rock mass.

Joints are fractures in solid bedrock that open up due to extensional forces caused by tectonic plate interaction and the removal of the overlying rock mass by uplift and erosion. Slopes that are directly underlain by bedrock evolve to stable angles in equilibrium with the bedrock structure and composition.

Rock Slope Failures

A common cause of landslides is destabilization by over-steepening of slopes. Over-steepened slopes are created naturally in areas of active uplift by down-cutting rivers and wave erosion along emerging shorelines. Over-steepened slopes are also the common consequences of development on hill slopes. In more humid climates slope destabilization also occurs because of decomposition and weakening of the rock mass by intense weathering.

Rock slope failures are largely controlled by the conditions of the constituent layers and joints. The joints and layers are continually degraded overtime by the interaction with water. Joints also open over time as a consequence of extensional forces on the cut face caused by the removal of the adjacent rock mass. Rock slope failures commonly occur during rain events because water pressure in the open joints reduces the frictional forces acting on the joint planes

Joint Control over Natural and Rock Cut Slope Stability

The cuts in the Coastal Road in Cox Heath, Tortola are plagued by rock falls and slides during major rain events. Photo 1 shows that the rocks are broken up and loosened into blocks by near vertical joints that form parallel and perpendicular to the metamorphosed sedimentary layers. The blocks of rock slide out on to the roadway along joint planes that are inclined out of the cut slope face at 35°. Note that the natural slope in the background has equilibrated to an angle a little less than the outward inclined joint set.

Photo 1: Road cut slopes and natural slopes on the west end of Tortola

This is a clear indication of joint control natural slope evolution. Coastal erosion and road cut excavation have undercut the slope and created the unstable and hazardous conditions. Blasting of the hard rock during the excavation worsened the problem by opening the joints and further fracturing the rocks.

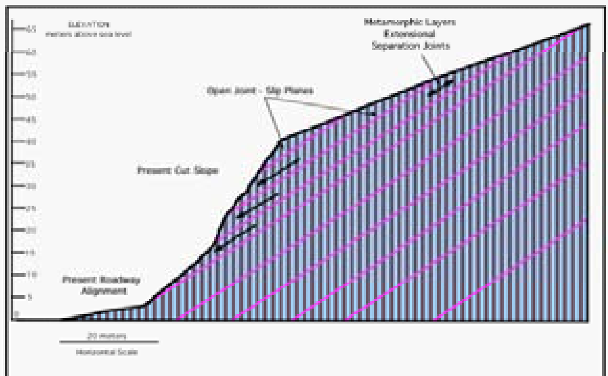

FIGURE 1 GEOLOGIC PROFILE ALONG COASTAL ROAD, COX HEATH, SECTION 4+890

Coastal erosion and cut slope excavation created slopes steeper than the joint inclination. The overlying rock mass is unsupported and subject to sliding on the joint planes (Figure 1).

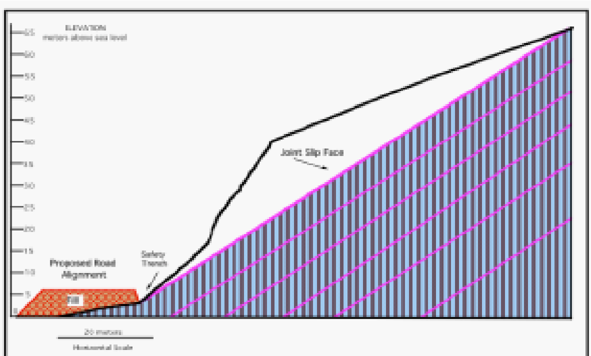

FIGURE 2 STABLE CUT SLOPE ALONG JOINT SLIP PLANES STA. 4+890, COX HEATH

The concept of a stable cut slope is simple. If the cut slope can be reduced to the angle of the joint set that is inclined out of the slope then the overlying rock mass will be supported at depth and the slope will remain stable (Figure 2). In cases where there is limited land availability and the stable cut slope angle is low, steeper unstable cuts will be necessary to optimize land use (Figures 3 and 4). Cuts steeper than the stable cut slope will require cut slope support and/or terracing to maintain the safety of the adjoining properties and infrastructure.

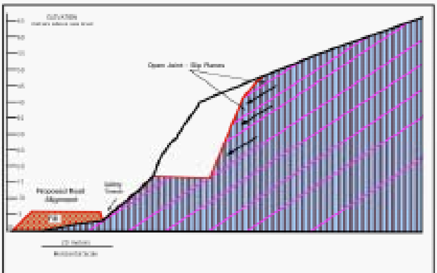

FIGURE 3 ALTERNATIVE CUT SLOPE AT STA. 4+890, COASTAL ROAD, COX HEATH

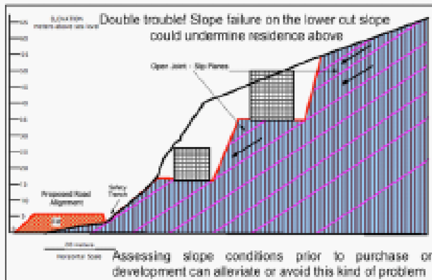

FIGURE 4 ALTERNATIVE CUT SLOPE AT STA. 4+890, COASTAL ROAD, COX HEATH

Slope Failures in Jointed and Fractured Rock

These occur in two modes:

Planar rockslide

The slope failure occurs by slip or sliding directly along the joint set planes. The size of the resultant landslide is dependent on the continuity and spacing of the set of joint planes. If the rock above the slide plane is disaggregated by weathering and intense fracturing the resulting failure will be a debris slide or avalanche.

The landslide that occurred at Katiche Point is an excellent example of a planar rockslide, which was caused by undercutting steeply inclined joint planes in massive igneous rock (Photos 2 and 3). The slope cut was required to provide sufficient set back from the shoreline to permit the construction of the restaurant at that location.

Obviously, the owner and the permitting authorities were unaware of the dire consequences of the required slope excavation.

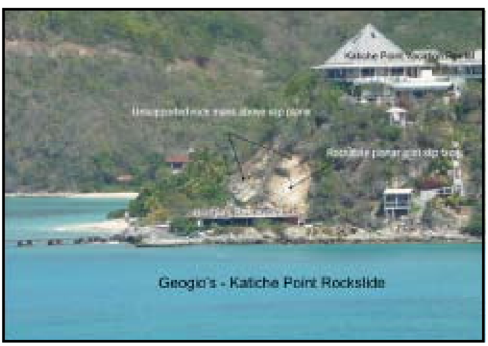

Photo 2: Katiche Point rockslide on Savannah Bay Virgin Gorda BVI

Photo 3: Planar joint slide surface of the Katiche Point rockslide above Giorgio's Restaurant

Numerous boulder size blocks created by intersecting joint planes slid down the outward inclined joint planes and into the restaurant (Photo 4). Fortunately it was unoccupied at that time and there were no casualties.

Photo 4: Boulders that crashed through the back of Georgio's Restaurant

Photo 5: Subsequent enlargement of the Katiche Point rockslide

Enlargement and retreat of the rockslide towards the residence above occurred when the unsupported rock mass above the original slip plane failed during the attempt to reconstruct the restaurant.

Joint wedge failure

The slope failure occurs by slip along the planes two intersecting joint sets with different orientations. This creates a triangular wedge rockslide that slides in the direction of their line of intersection. The size of the resultant landslide is determined by the spacing and the continuity of the intersecting joint planes. If the rocks above the joint planes are disaggregated then a narrow, linear debris avalanche is formed. Where there is sufficient soil development above the jointed rock and infiltration of water the failure will be converted into a debris flow.

The Jean's Hill landslide occurred during a period of heavy rain in 2010 and is an example of a joint intersection wedge failure road cut slope. Disaggregated rock, colluvial soils and vegetation above the road cut were incorporated into the wedge failure to create a debris avalanche-flow. The rock, soil and debris covered over the roadway and continued down slope toppling a retaining wall and crushing and removing the outer portion of a residence on the slope below (Photos 6 and 7).

Photo 6: Debris Avalanche at Jean's Hill, Tortola in 2010

Photo 7: Residence damaged by the Jean's Hill debris avalanche

Photo 8: Jean's Hill debris avalanche scar

The Jean's Hill debris avalanche scar shows the 2 intersecting joint planes that created the joint wedge failure. The rock and debris slid along both planes in the direction of their intersection shown by the red arrow (Photo 8).

Systematic Joint Sets

Systematic joint sets are characterized by joint planes that are parallel and exhibit consistent spacing between adjacent joint planes (Photo 9). All the BVI geologic formations were recognized to have orthogonal systematic joint sets. The orientation of the orthogonal systematic joints in layered volcanic and metamorphic rocks is largely controlled by the consistent, nearly east-west trending, steeply inclined layering that characterizes most of the islands.

The joint sets form parallel to layers, and perpendicular to them with one set being steeply inclined to vertical and the other with only moderate to shallow inclinations. Orthogonal joint sets also occur in the massive coarse-grained igneous rock.

Orientation of the igneous rock joints may be related to the shape and size of the intrusive body. Non-orthogonal conjugate joint sets have been observed and their orientations are consequence of ancient directed forces induced by convergent plate boundary deformation. The orthogonal systematic joint sets are the consequence of unloading caused by uplift and erosion of the ancient rock masses. Representative orientations for each joint set from each measurement site were used for the regional distribution analysis.

Photo 9: Two oppositely inclined systematic joint sets with consistent spacing shown with double arrows

Shark Bay Member of the Tortola Formation is composed of thick massive volcanic breccia interlayered with thin-bedded finer grained tuffs and showed the most consistent systematic joint data of all the geologic units. Stereographic analysis of joint data from this member showed that systematic joint sets were dominantly steeply inclined >60° to the North and West.

Subordinate joint sets were inclined moderately east-northeast to east-southeast and west to northwest and steeply inclined to the south. The joint set intersection directions were similar (Figure 5).

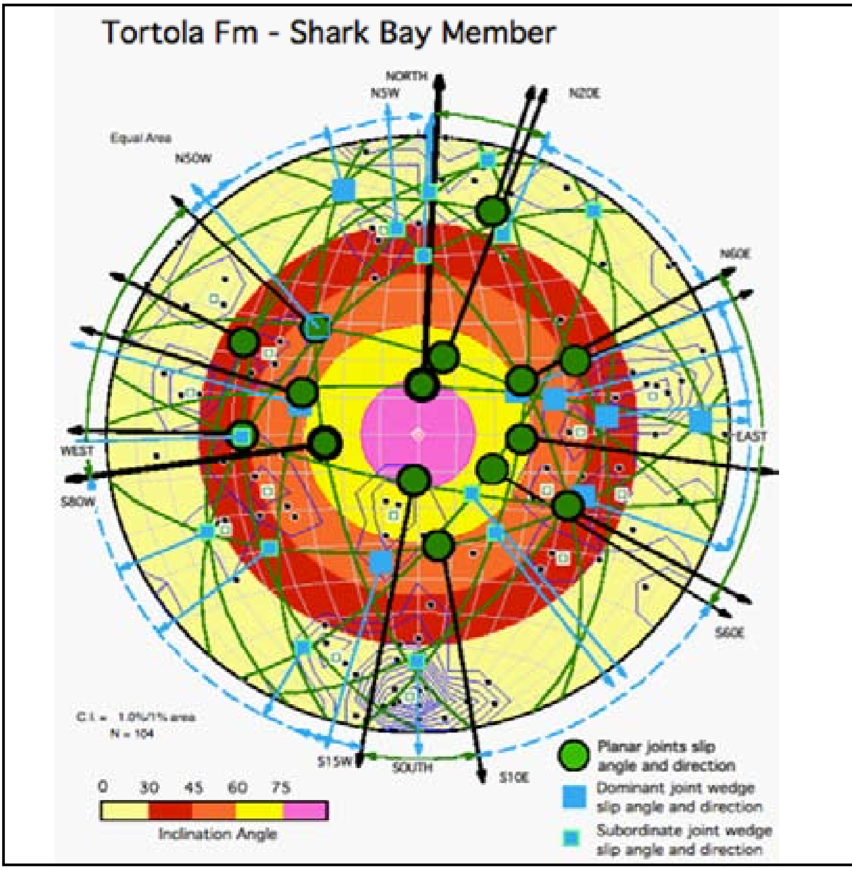

Figure 5: Stereographic projection of systematic joint set data and vulnerability table

Stereographic analysis of the systematic joint data indicated a generally regular distribution of the systematic joint sets. Natural slope vulnerability was established based on topographic slope orientation and angle relative to the orientation and angle of systematic joint set planes show as green circles with black arrows and intersection wedges shown as blue boxes with arrows. The data interpretation was used to create the GIS based landslide susceptibility maps.

Revision of QRAP Landslide Data for Cut Slope Stability GIS Maps

The original Quantitative Risk Assessment Project (QRAP) landslide susceptibility maps pertained only to natural slopes and did not address the more serious problem of cut slope failures in the BVI. All of the slope failures observed during field inspections of past rain storm impacts, were joint controlled cut slope failures. No natural slope failures occurred during these rainstorms other than wash outs induced by excess runoff from roadways. Although cut slope recommendations formed part of the landslide study the data was limited to tables and not readily accessible. In order to address the more serious problem of cut slope failures joint orientation and inclination data collected for the QRAP landslide vulnerability analysis and subsequent field studies were utilized in the cut slope map analyses. Stable cut slope and vulnerability were analyzed for directional segments of 45° in order to be incorporated into the BVI GIS program (Figure 6).

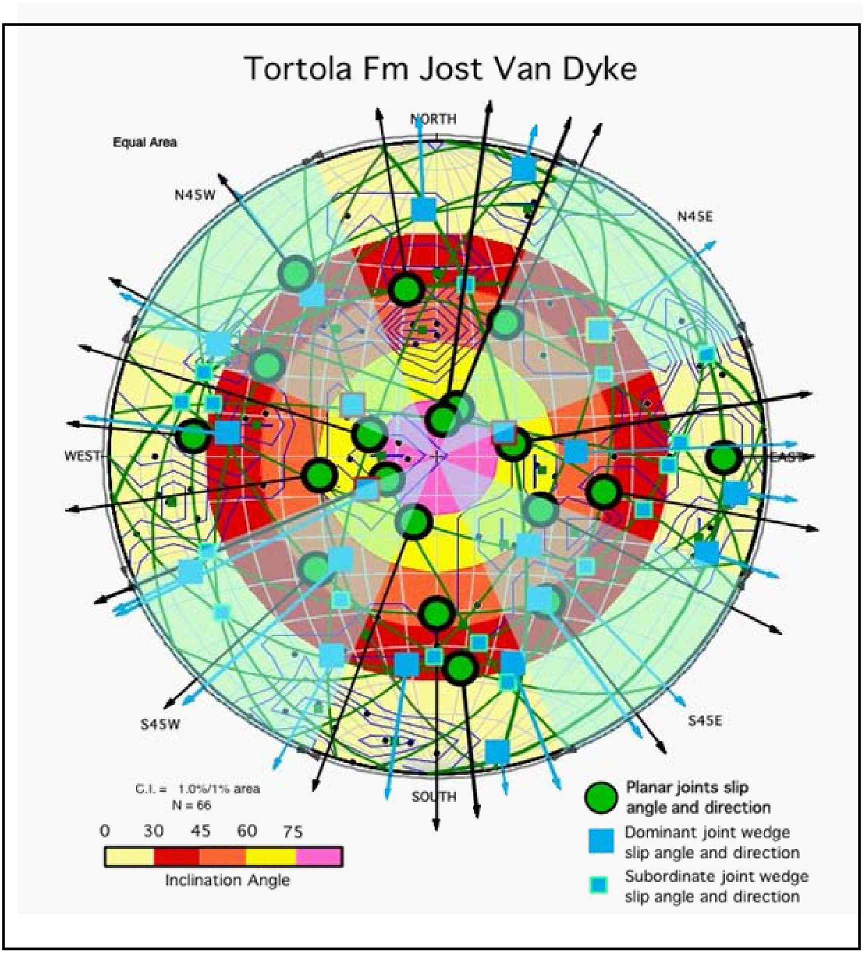

Figure 6: Stereographic projection of systematic joint set data for the cut slope analysis

Cut Slope Vulnerability and Stable Angles Based on Structural Data

Stable recommended cut slope angle was based on the inclination angle of planar joints, shown as green circles with black arrows, and joint wedge intersections, shown as blue boxes with arrows, in the cut slope directional segment of Figure 6. Cut slope vulnerability was based on the number of joint measurements, shown as black dots and quantity contoured with blue lines, which are inclined in any given directional segment. The vulnerability and stable recommended cut slope angles were separated by formations, rock type and location and tabulated for easy incorporation into the established BVI GIS system (Figure 7 and Table 1). Vulnerability and cut slope stability maps were created through the GIS program for the major islands of the BVI.

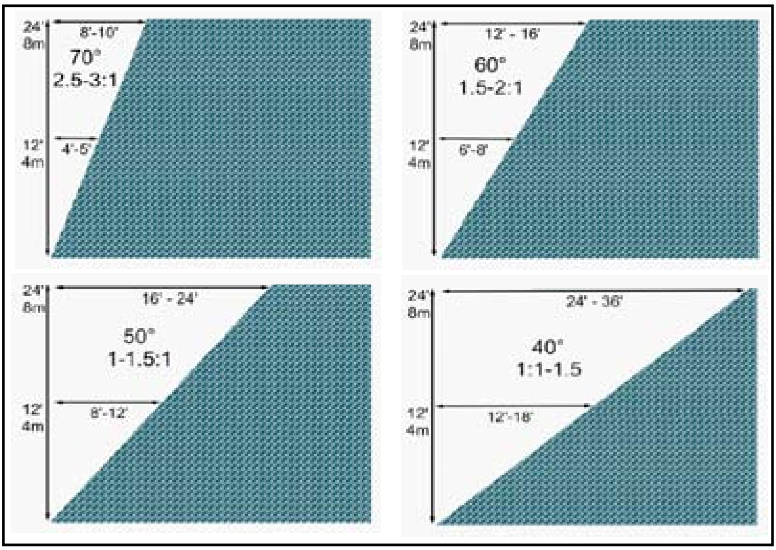

Figure 7: Recommended cut slope angles and vertical to horizontal ratios

Table 1: Tabulated cut slope vulnerability and stability data

Tortola Formation	Slope Facing Azimuth	Angle	Vulnerability	
Hans Lollik and Sage Mt Members	000-022.5	60	High	N
	022.5-066.5	50	High	NE
	066.5-112.5	50	High	E
	112.5-157.5	70	Lower	SE
	157.5-202.5	50	High	S
	202.5-247.5	60	Moderate	SW
	247.5-292.5	40	High	W
	292.5-337.5	50	Moderate	NW
	337.5-360	60	High	N
Tortola Formation Shark Bay Member	000-022.5	60	High	N
	022.5-066.5	40	High	NE
	066.5-112.5	40	High	E
	112.5-157.5	70	Lower	SE
	157.5-202.5	60	Moderate	S
	202.5-247.5	70	Lower	SW
	247.5-292.5	40	High	W
	292.5-337.5	40	High	NW
	337.5-360	60	High	N
Tutu Formation Metamorphic Rocks	000-022.5	40	Moderate	N
	022.5-066.5	60	Moderate	NE
	066.5-112.5	60	Moderate	E
	112.5-157.5	70	Lower	SE
	157.5-202.5	40	High	S
	202.5-247.5	70	Lower	SW
	247.5-292.5	40	Moderate	W
	292.5-337.5	70	Lower	NW
	337.5-360	40	Moderate	N
Igneous Intrusions	000-022.5	40	High	N
Tortola East End	022.5-066.5	40	High	NE
Beef Island	066.5-112.5	60	Moderate	E
Virgin Gorda	112.5-157.5	60	Moderate	SE
	157.5-202.5	40	High	S
	202.5-247.5	50	Moderate	SW
	247.5-292.5	40	High	W
	292.5-337.5	50	Moderate	NW
	337.5-360	40	High	N
Tortola Formation	Slope Facing Azimuth	Angle	Vulnerability	
Jost Van Dyke	000-022.5	50	High	N
	022.5-066.5	40	Moderate	NE
	066.5-112.5	50	High	E
	112.5-157.5	50	High	SE
	157.5-202.5	40	High	S
	202.5-247.5	50	Moderate	SW
	247.5-292.5	40	Moderate	W
	292.5-337.5	40	Moderate	NW
	337.5-360	50	High	N

Cut Slope Vulnerability and Stability Maps

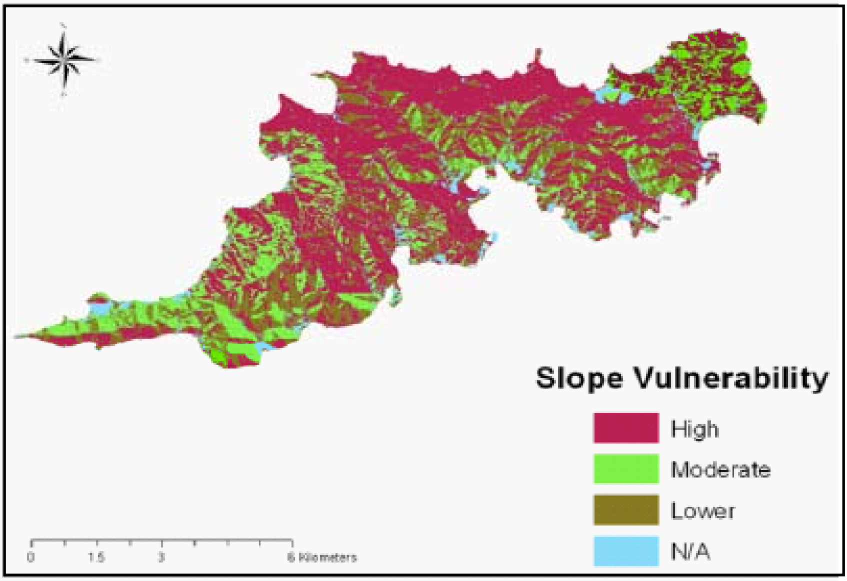

Figure 8: Tortola Cut Slope Vulnerability Map

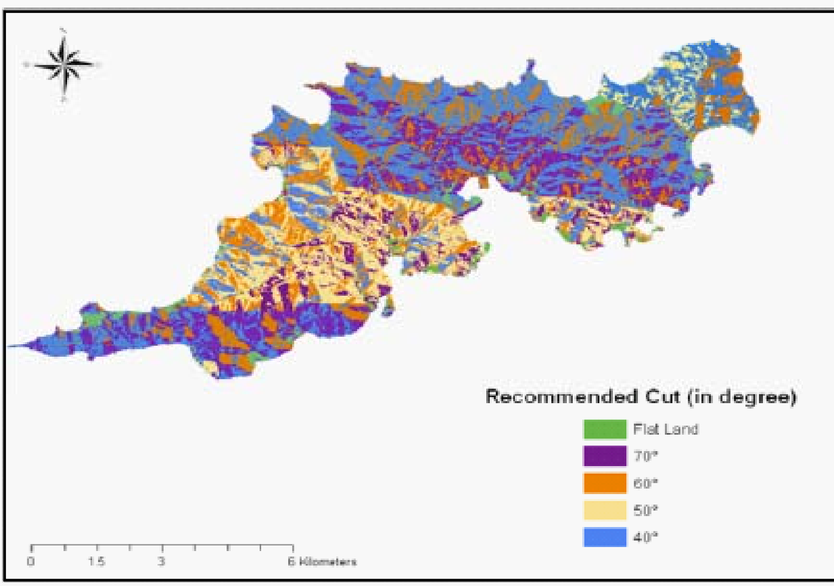

Figure 9: Tortola Cut Slope Stability Map

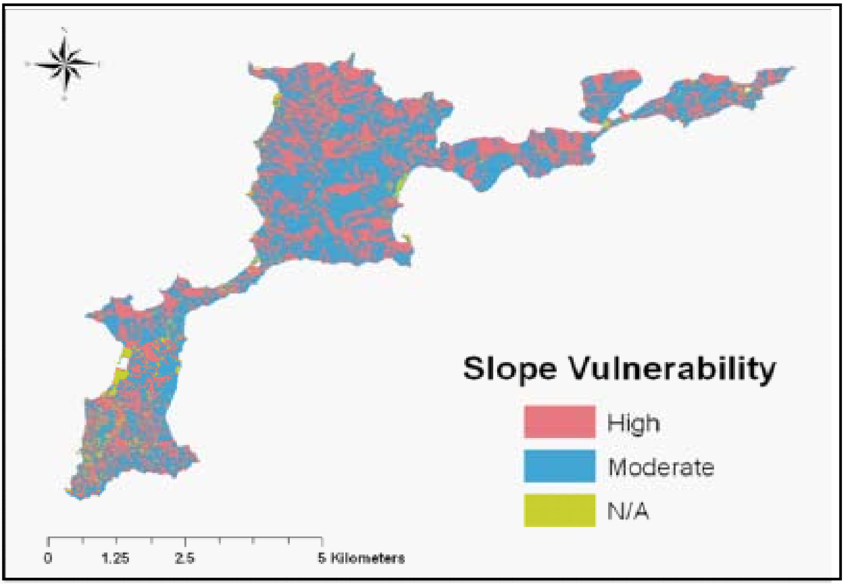

Figure 10: Virgin Gorda Cut Slope Vulnerability Map

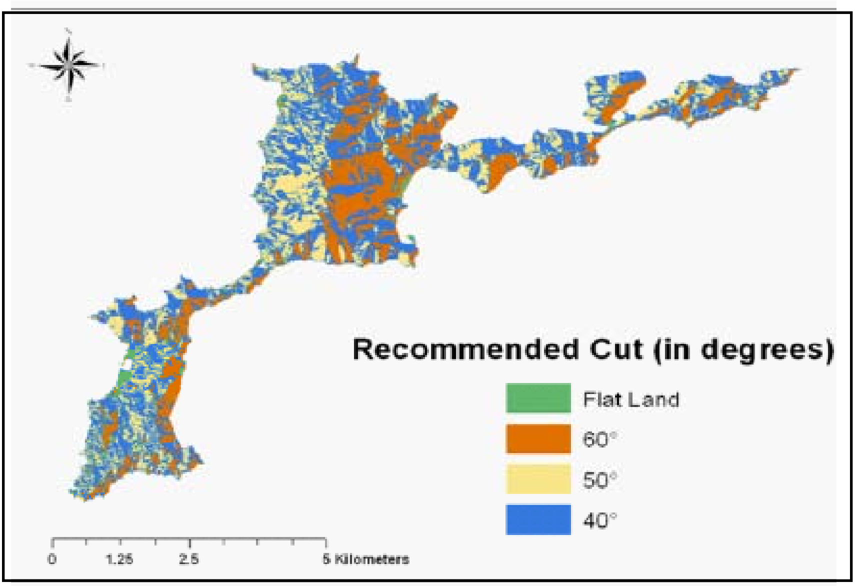

Figure 11: Virgin Gorda Cut Slope Stability Map

Understanding Your Building Site and How to Excavate for Safe Development

In order to bring the finalized maps to public attention and encourage their utilization, two days of workshops were sponsored by the Department of Disaster Management of the Government of the British Virgin Islands and partially supported by the UNDP R3I project. The first day was attended by local contractors and excavators and the second day by engineers, architects and planners. The workshops consisted of presentation and explanation of the maps and discussion on their utility. This was followed by field experiences on the islands of Tortola and Virgin Gorda. The objective of the field experience was to allow for visualization of the concept of the maps, recognition of joint control over slope stability and the utility of knowing beforehand the geologic conditions that will affect the site and the stability of excavations. The site visits focused on examples of cut slope stability problems caused by unfavorable joint orientations.

Tortola Field Experience

The Jean's Hill Landslide site above Road Town was visited as an example of a joint wedge failure landslide (see Photos 6-8) to help participants to understand a joint wedge failure and the impact of overly steep cut slopes in directions vulnerable to this type of joint controlled failure.

A recommended construction site above Sea Cow's Bay provided an example of over-cutting on geologically problematic slope faces with outward inclined planar joints.

The Sea Cow's Bay construction site, shown in Photo 10, provided a great example of overcutting and inadequate cut slope and retaining wall design to address the obvious slope instability related to joint orientation and intense fracturing of the rock in the cut. The rock cut exposes a complex geology consisting of highly fractured and altered rock in a large fault zone on the left side of the cut and closely spaced, outward inclined systematic joints in more solid rock on the right. A rock fall - avalanche failure scar along the fault zone behind the wall attests to instability of the steep high cut.

Photo 10: Recently excavated cut slopes above Sea Cow's Bay, Tortola

Failure along the closely space outward inclined joint faces or of the unstable highly fractured rock above the undersized wall will overtop the wall and could lead to its collapse. A site-specific geotechnical and geological evaluation was strongly recommended before continuing with the construction.

Conclusion

This methodology is an exercise which can be conducted with sufficient GIS data in order to inform planning and land development decisions. BVI has already incorporated the use of the maps into their planning approval process, whereby permission is conditional on either adherence to the recommended slope angle or on implementing appropriate mitigation measures.

Similar exercises were replicated in Sint Maarten, which also has a very mountainous terrain, and Anguilla, which suffers with similar issues on its coastal cliffs.

Application of the vulnerability and stability maps by the planning, engineering and construction community can provide a simple but effective risk mitigation measure which can save many lives and properties.

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