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Hazard assessment of rainfall-induced landslides: a case study of San Vicente volcano in central El Salvador

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Abstract The San Vicente volcano in central El Salvador has a recurring and destructive pattern of landslides and debris flows occurring on the northern slopes of the volcano, and in recent memory, there have been at least seven major destructive debris flows. There has been no known attempt to study the inherent stability of these slopes and determine the factors that might lead to slope instability. Past events on the volcano were used to perform a 2D slope stability back analysis and to estimate the unknown model parameters. This analysis confirmed that the surface materials of the volcano are highly permeable and have very low shear strength. Additionally, the analysis provided insight into the groundwater table behavior during a rainstorm. Slope geometry, rainfall totals and initial groundwater table location were found to have the greatest effect on stability. A methodology is outlined for creating a stability chart to be used during rainfall events for monitoring slope stability. This chart could be used by local authorities in the event of a known extreme rainfall event to help make evacuation decisions. Finally, recommendations are given to improve the methodology for future application in other areas as well as in central El Salvador.

Keywords Landslides · El Salvador · Debris flows · Central America · Mitigation

1 Introduction

El Salvador, the smallest and most densely populated country in Central America, is a country regularly subject to major natural disasters. Estimates indicate that over the last 30 years earthquakes and tropical storms alone have cost the country of El Salvador $4.57 billion and nearly 4,000 lives (GFDRR 2011). Its location in the tropics on the Pacific coast of Central America, along the Middle America Trench and the Pacific Ring of Fire, results

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in its high vulnerability to earthquakes, tropical storm-related hazards and volcanic activity. Of particular concern to El Salvador are rainfall-induced landslides and related debris flows in volcanic terrains associated with the four major volcanoes, Santa Ana, San Salvador, San Vicente and San Miguel, near which almost half of the country's population lives (Major et al. 2004). This combination of the geological setting and socioeconomic situation of El Salvador has led to a potent combination of high population densities located in and near hazardous areas (Rose et al. 2004). This unique situation is the motivation behind the current study, which is an attempt to define and assist in the mitigation of hazards from debris flows on the San Vicente volcano (Fig. 1).

The problems of rainfall-induced shallow landslides and debris flows in volcanic terrains are of significant concern in El Salvador, particularly near the major volcanoes. Major et al. (2004) reports at least 20 rainfall-initiated debris flows in recent recorded history: two on San Salvador volcano, 11 on San Miguel volcano and 7 on San Vicente (Jibson et al. 2004; Crone et al. 2001). The largest and most destructive debris flows that have occurred in recent decades on San Vicente volcano are those associated with Hurricane Ida in 2009.

In November 2009, following the passage of Hurricane Ida through the Caribbean, San Vicente volcano experienced more than 480 mm of rainfall on the upper slopes of the volcano in less than 2 days, with a peak rainfall intensity of over 80 mm/h (Schweig et al. 2010). During the peak intensity of this storm, shallow landslides high on the western cone (see Fig. 1 for location) of the volcano initiated a series of destructive debris flows during the early morning hours of November 8. These debris flows tore through several communities on the northern flanks of the volcano, causing much destruction in the communities of Verapaz and Guadalupe and were responsible for over 200 deaths.

The debris flows associated with Ida led to a plethora of support and resources to better prepare and educate the local population for possible future events (GFDRR 2009). Since 2009, numerous non-governmental organizations (NGOs) as well as the newly formed Salvadoran civil protection agency have been holding training workshops with the communities most affected in the past and at risk in the future (Rivas and Melara 2012). In addition to preparations and support, it is necessary for organizations and individuals making decisions during times of elevated threat to have the best information available to make an informed decision (GFDRR 2009). This work fills in some of the gaps and will provide a tool that these individuals and organizations can use as part of the decision making process.

The objectives of this research were threefold:

1. Back analyze the shallow landslides that occurred during Hurricane Ida to determine critical thresholds of various destabilizing factors (rainfall, groundwater location, etc.) that triggered slope instability at San Vicente volcano.
2. Evaluate the rainfall-induced landslide hazard on the northwest flank of San Vicente volcano.
3. Develop a useful tool for Salvadoran stakeholders to determine the hazard from rainfall-induced slope instability on the northwest flank of San Vicente volcano, which in turn would help to determine threatened communities in an emergency event.

2 Motivation

Geographic information system (GIS)-based spatial analysis methods are commonly used for evaluating slope instability and debris-flow potential. This method typically uses past
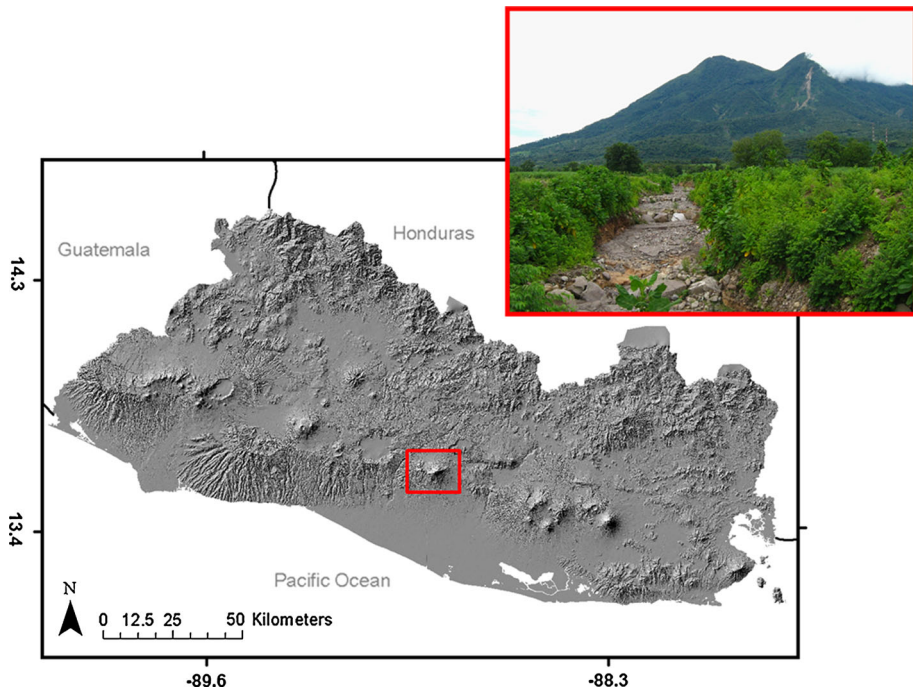
Fig. 1 Study location in central El Salvador. *Inset* photograph shows San Vicente volcano with landslide scar visible on right cone of the volcano and debris flow channel in the lower left

records of slope instability and geomorphological criteria, such as slope angle, soil type and maximum rainfall. (Ramakrishnan et al. 2013, 2008; Gabet and Mudd 2006; Godt et al. 2008; Larsen and Simon 1993; Montgomery et al. 1998). The output of these GIS analyses is empirical and reported as a likelihood of occurrence based on a given situation. These models predict slope instability based on the input parameters and are a simple and effective way to know when a few key criteria that commonly cause slope instability are met (Harp et al. 2009). GIS-based spatial analysis is effective when there is sufficient inventory of past events and detailed data on geomorphological criteria. However, in places like El Salvador, where there is limited data availability outside the capital city region and not enough of an inventory of past events, it can be difficult to create an effective GIS-based model.

Another major limitation of a GIS-based approach is the fact that typically, it does not consider the strength properties of various soils in the region. Godt et al. (2008) demonstrated that when site-specific information can be obtained, a model that takes into account more of the strength properties of the soil proves beneficial. Additionally, the GIS-based models typically are not governed by the physics of transient groundwater and geotechnical slope stability analysis. This project approaches the issue of rainfall-induced shallow landslides and the potential resulting debris flows differently than is typical. Because of the remote nature of the study area, much of the information required to create an effective model using GIS-based methods is lacking. Instead, a slope stability analysis was performed on the areas that experienced landslides in 2009. Using this back analysis, variables

involved in the initial slope failure were isolated. These conditions were then applied to a forward model to evaluate the potential hazard.

The current hazard assessment for debris flows on the San Vicente volcano was provided by the USGS in the form of a general map showing potential inundation areas for debris flows of three given volumes initiating from any of the major valleys and drainages coming from the volcano (Major et al. 2004). The volumes used in their assessment were based on estimates from past events, and no particular attention was given to specific areas of failure initiation or communities that would be impacted the most. As provided and utilized concurrently with established rainfall thresholds, this is a very useful tool for planning purposes and community awareness if it is known where the failure is going to initiate. However, with the current tools, there is critical gap for decision makers to decide where the next failure would initiate during a storm event. This information is important to develop timely evacuation plans and to communicate the hazard of slope instability to communities. This research seeks to answer that critical need.

This study focuses on the development of a tool that decision makers in civil protection or even community leaders who are part of monitoring and reporting can use during an event to evaluate the current hazard presented by a storm. This tool is based on Limit Equilibrium-based slope stability analysis that accounts for transient groundwater conditions during rainfall. This tool allows using the initial water table location and the cumulative rainfall totals to determine the likelihood of a possible slope failure. The sensitivity of the base model to various factors is analyzed, and an example final tool is given, along with suggestions for improving the framework for future application elsewhere.

3 Description of study region

The central volcanic chain is one of the major geologic and geographic regions of El Salvador. This chain of volcanoes is situated in a line paralleling the coast about 170 km from the Middle America Trench, where the Cocos Plate is subducting beneath the Caribbean Plate and includes the Santa Ana, San Salvador, San Vicente and San Miguel volcanoes as well as several other areas of past volcanism. The volcanic arc dominates the geology and soils of the region, creating steep slopes that are susceptible to landslides and debris flow events.

San Vicente volcano (Fig. 1) is a paired stratovolcano covered by coffee plantations and dense cloud forest continuing to the 2,182 m summit. The last known activity of the volcano is approximately 1,700 years ago (Major et al. 2001). In this study, the northern flank of the volcano is the focus of research. On the northern flank, at multiple locations high on the eastern cone, local workers in coffee plantations have noticed large cracks forming near the tops of several drainages. These cracks are believed to be surface tension cracks. The cracks have been steadily growing, up to several centimeters in width and unknown in depth, during recent rainy seasons and are of great concern. Their location above drainages that could devastate several nearby communities, including parts of the large city of San Vicente, makes understanding the potential for slope instability and debris flows critical.

Because it is inactive and is not believed to pose an imminent eruptive threat, the San Vicente volcano is notably less studied than the San Salvador or San Miguel volcanos. The internal structure of the volcano is not well documented, but the core of the volcano is believed to consist mainly of andesitic lava flows and pyroclastic deposits associated with

past eruptive activity of San Vicente (Rotolo et al. 1998). This core is overlain by a relatively thick (~25 m) layer of pyroclastic and ash deposits from past eruptions of San Vicente interbedded with deposits from the nearby Ilopango caldera. These Ilopango deposits, known collectively as the Tierra Blanca (TB) series, are very common in the central part of El Salvador (Rolo et al. 2004).

The volcano has a recurring and destructive pattern of landslides and debris flows occurring on the northern slopes of the volcano (Crone et al. 2001; Jibson et al. 2004; Major et al. 2004). Smaller debris flows that remobilize from past debris flow deposits are relatively common higher on the volcano, and there have been at least 10 major events recorded in the last 250 years (Bommer and Rodrıguez 2002; Major et al. 2004). As Fig. 1 indicates, this pattern of recurring debris flows is not surprising given the very steep slopes of the volcano and its exposure to the intense rains of tropical storm events.

El Salvador experiences a tropical climate common at similar latitudes worldwide. This climate is characterized by a distinct wet and dry season. The majority of annual precipitation occurs during the wet season, which typically lasts from May until November each year. Coincident with the rainy season is the hurricane and tropical storm season for the northern Atlantic and Pacific Oceans. Every few years a major hurricane or tropical storm affects El Salvador with intense rainfall and potentially with flooding and landslides. Events of the last 15 years include Hurricanes Mitch (1998), Stan (2005), Adrian (2005), and Ida (2009) as well as Tropical Depression 12E (2011). Hurricane Ida produced some of the highest measured intensities of rainfall in central El Salvador in recent history, a major factor in the destructive landslides that occurred during the storm.

4 Methodology

In this study, the evaluation of the past and the potential for future landslides on the north slopes of San Vicente were analyzed using 2D limit equilibrium-based slope stability analyses. The inputs for the analyses, including soil properties and slope geometry, were obtained from a combination of field data collection and literature evaluation. The focus of the field data collection was to understand the internal structure of the volcano and the geotechnical properties of various soil layers overlying the volcano. During field work, efforts were made to identify the 2009 failure zone and its dimensions. Back analysis was performed using the information on this past failure together with estimated geotechnical properties to estimate unknown parameters. These parameters were then used for a systematic analysis of slope stability of north slopes of San Vicente and to establish relations among stability of the slopes, groundwater level, cumulative rainfall and rainfall intensity.

In May 2012, a collaborative field campaign to San Vicente volcano was organized by Michigan Tech and included representatives from University of El Salvador, national police, local civil protection and stakeholder communities. Work performed during this field campaign included field permeameter tests for hydraulic conductivity, vane shear tests for undrained shear strength, and collection of soil samples for laboratory testing. These tests were chosen to provide a reasonable estimate of soil properties, considering the remote and nearly inaccessible sites. Sites visited included the initiation zone of the 2009 debris flows, as well as several locations around the volcano where suspected tension cracks have formed but no large failures have yet occurred.

Samples of the materials at each field site were brought back for laboratory testing. The samples were small and not intact, restricting some of the testing methods. Grain size analyses were performed on the available samples. Occasionally, more information was

necessary than was available from field work. This additional information was obtained from a comprehensive study of engineering characteristics of the Tierra Blanca deposits (Rolo et al. 2004).

A 2D limit equilibrium method (LEM)-based slope stability model of the volcano was created using Slide v6.011 (Rocscience Inc 2011). This model was used to constrain and quantify as best as possible the failure mechanisms for the slopes.

The structure of the volcano is not well documented, especially higher up where shallow slope failures occur. The model was constructed using a simple approach that minimized assumptions and took all known characteristics into account. Based on observation of small outcrops in multiple locations and conversation with locals familiar with the terrain, we assume the soil profiles are similar in most areas.

A typical cross section through the slopes of interest consists of three main (Fig. 3):

1. *Tierra Blanca Joven (TBJ)* The youngest Tierra Blanca deposits can be found to a depth of several meters everywhere on the northern slopes of the volcano.
2. *Weathered volcanic soils* Below the TBJ, older Tierra Blanca deposits as well as deposits from past activity on San Vicente volcano can consistently be found to a depth of ∼25 m.
3. *Lavas and pyroclastic rock* Beneath the two volcanic soil layers is a more or less solid core of denser lavas and older volcanic rock.

Each material type used in the model was defined using a classification method for slope stability of volcanic material proposed by Del Potro and Hürlimann (2008). This approach outlines four basic material types: lava, autoclastic breccia, pyroclastic rock and volcanic soil. Using these categories and geotechnical behavior of materials in the upper two layers of this model, TBJ and weathered volcanic soils were classified as volcanic soils, while the inner part of the volcano was classified as a dense pyroclastic rock or lava.

The volcanic soil layers were assigned similar properties based on grain size analysis and literature values as outlined in Table 1. Due to additional weathering found in the weathered volcanic soils, a higher friction angle was used, representing the higher degree of cementation witnessed in this material. Both materials were assumed to be non-cohesive based on observation, vane shear test, and the literature review (Rolo et al. 2004). Field permeameter tests verified that both the materials have similar hydraulic conductivity. Thickness of TBJ was based on field observation, and the 25 m overall depth of volcanic soils was based on geophysical data (resistivity and seismic reflection) collected in November 2011 near the observed tension cracks on the eastern cone of San Vicente. These geophysical data suggest that unconsolidated soil exists to a depth of about 25 m and denser material is present beneath it. By using the suggested classifications mentioned above, unknown material properties in the model not borrowed from Rolo et al. (2004) were assumed from typical values reported from del Potro and Hürlimann (2008). In keeping with the simplicity of the model and lacking any information suggesting otherwise, the layer thicknesses were kept constant throughout each profile. The material properties are summarized in Table 1.

To evaluate the unsaturated behavior of the soils during the transient analysis, it was necessary to create a soil water characteristic curve (SWCC) for each material. Using a method outlined in Chin et al. (2010) for non-plastic soils, the Fredlund and Xing (1994) SWCC parameters *a, m* and *n* were calculated using the grain size distribution (Chin et al. 2010; Fredlund and Xing 1994). The calculation of Fredlund and Xing parameters (*a, m,* and *n*) for TBJ and weathered volcanic soils were done using the method outlined in Chin et al. (2010) and compared to typical reported values in the literature for similar soil types.

Table 1 Summary of material properties for volcanic soils used in model

Material	Thickness (m)	Cohesion (kPa)	*Friction angle φ (degrees)	*Unit weight (kN/m^3)	K_{sat} (m/s)
TBJ	3	0	35	13	4.6×10^{-5}
Weathered volcanics	22	0	38	13	4.6×10^{-5}

An asterisk (*) before property indicates property derived from literature values

Further, the Fredlund and Xing parameters were used to develop the SWCC using Rocscience Slide. This SWCC is then applied during different stages of the stability analyses to compute unsaturated shear strength dependent on the estimated moisture content at each stage in the transient groundwater analysis. Table 2 lists the Fredlund and Xing parameters used for this study.

With material properties assumed, it was possible to back analyze the shallow landslide that occurred during Hurricane Ida. This analysis was performed using the limit equilibrium method (LEM) and took into account rainfall data from the Hurricane Ida event and the mapped failure surface. The location of the 2009 landslide is shown in Fig. 2. The profile analyzed is depicted in Fig. 3, with the failure surface bounded by paired arrows shown in the middle of the section. The arrows represent the failure area used in the back analysis, which was based on field observations. This back analysis, coupled with sensitivity analysis, provided insight into two major unknowns: depth to water table and appropriateness of assumed material properties, specifically sensitivity to changes in friction angle, φ. Because of the lack of groundwater monitoring, it was critical to estimate depth to water table.

The back analysis was performed using a block search method with a non-circular failure surface. This failure method mimics the translational failures common in shallow landslides. A failure line at a depth of about 5 m was used, and the upslope and downslope angles of potential failure surfaces were varied to account for numerous failure scenarios. The method utilized for the LEM analysis was the Bishop simplified method. This method is commonly used in 2D slope stability analyses and is typically found to be conservative for irregular slip surfaces, making it a good choice for this application (Ahmad et al. 2013; Singh et al. 2013a, b; Hungr et al. 1989). The program chooses the failure surface that has the lowest factor of safety (FOS) of all possible surfaces. The FOS is a ratio of the available shear strength of a material to the shear strength required for equilibrium. Because of inconsistencies in geologic materials, a FOS of 1.0 or higher cannot necessarily be assumed stable. Recommendations for relative stabilities in slope analysis have been given to evaluate slopes: Typically, slopes with a FOS > 1.5 are said to be stable. Slopes with 1.3 < FOS < 1.5 are said to be moderately unstable and 1.0 < FOS < 1.3 are said to be inherently unstable. A FOS < 1.0 means that the slope is at failure (Hoek 2007).

5 Results and discussion

The back analysis showed that slopes can fail catastrophically in response to intense rainfall events. Because hourly data were available for the transient groundwater analysis and the approximate time window of the slope failure was known, it was possible to vary the water table in the analyses to estimate a reasonable initial water table elevation that calibrated the model to actual events. The time of slope failure corresponded to the highest

Table 2 Fredlund and Xing parameters used to create SWCC		a	m	n
	TBJ	7.93	0.81	1.36
	Weathered volcanics	7.06	0.82	1.52
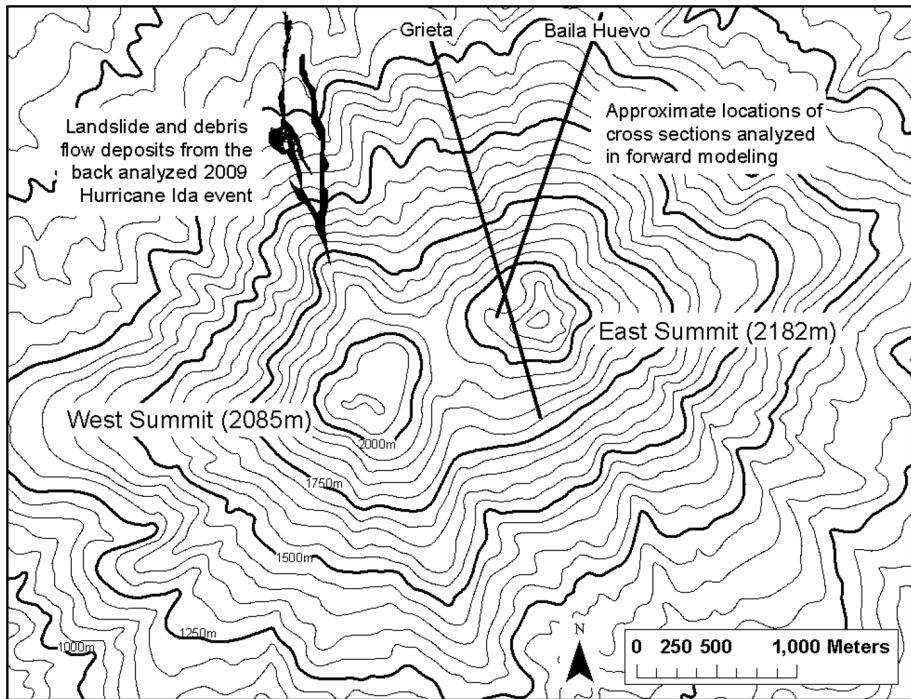
Fig. 2 Contour map of the upper slopes of the San Vicente volcano. The distinct double cone shape of the volcano is apparent along with the very steep slopes on all sides. 2009 Hurricane Ida landslide shown, along with approximate locations of forward modeling sites

rainfall intensities, around 35 h into the rainfall event, and the model suggests that an initial water table elevation approximately 15 m below the surface can result in a simulation consistent with the observed events. This value matches best estimates made by local residents familiar with regional hydrology and falls in with the observance that steep residual soil slopes typically have a deep groundwater table and large unsaturated zone (Rahardjo et al. 2010). The estimated depth to water table at time of failure ranges from 2 to 4 m. It is important to note that the initial water depth is derived from simulations based on the assumptions described above. The model does not account for antecedent moisture conditions, which can considerably affect slope stability (Collins and Znidarcic 2004; Rahardjo et al. 2007; Rahimi et al. 2011; Singh et al. 2013c). Figure 4 provides insight into the decreases in the FOS with rising cumulative rainfall from Hurricane Ida, and Fig. 5 details the failure surface associated with initial water table depth at 15 m.

The simplifying assumptions used in the model were based on the best available information. All assumptions were made to be conservative in recognition of the
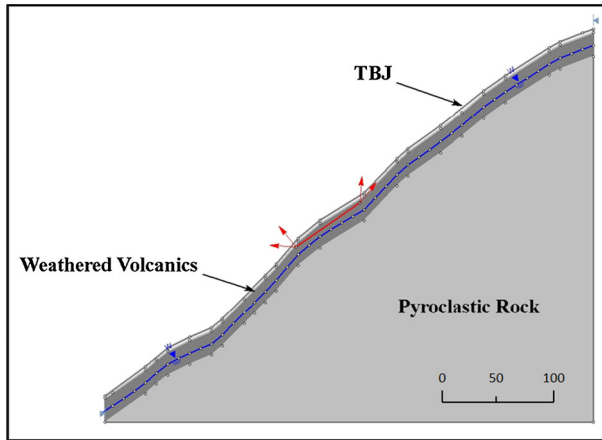
Fig. 3 Typical cross section used for slope stability analysis. The *red arrows* indicate the boundaries of the back analysis. TBJ, Tierra Blanca Joven. *Scale* is in meters both vertically and horizontally; no vertical exaggeration
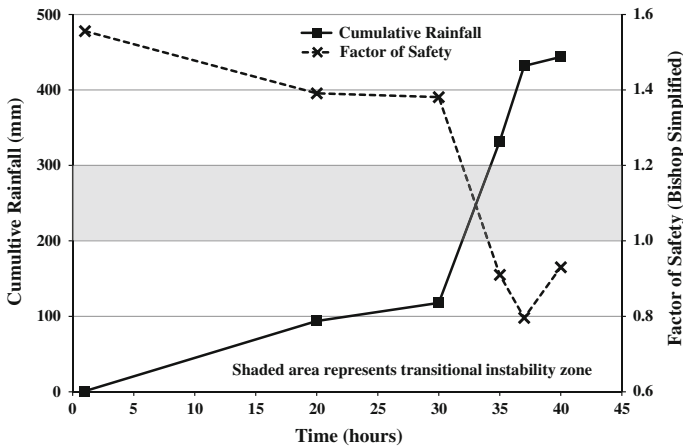

Fig. 4 Cumulative rainfall from Hurricane Ida and FOS for back analysis with water table at a depth of 15 m. *Shaded* area represents inherent instability

uncertainties about the geological setting. The simplifying assumptions believed to have the biggest potential impact on minimum FOS included uniform soil thickness, initial depth to water table and uniformly distributed and constant precipitation rate along the entire surface of the profile. Variations of each of these parameters were modeled in order to assess the possible effects of these simplifications. The profile was modeled with varying soil and water table depths. Variations of as much as ±10 m from the original were tested. The effects of varying precipitation along the profile were also tested (Fig. 6).

Several variations had marked effects on the model outcome (Table 3). Varying the soil depth (simulating thicker soil deposits lower on the slopes and thinner higher up, while keeping the average at 25 m) resulted in a FOS 18 % higher. Varying the water table depth
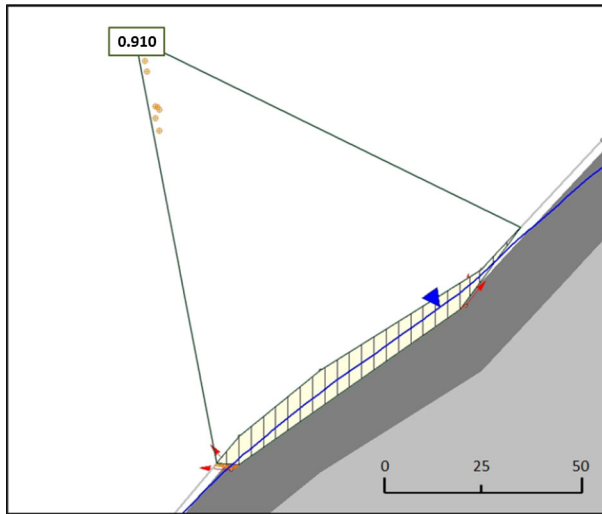
Fig. 5 Back analysis cross section showing failure surface at time 35 h. The resultant FOS is 0.910 and the water table is at a depth of less than 5 m. *Hatched* area represents slices used for LEM analysis. *Scale* is in meters both vertically and horizontally; no vertical exaggeration

(simulating a deeper water table higher on the slopes and shallower water table lower) resulted in a FOS 28 % higher for average 15 m depth, and a FOS 9 % lower for average 12.5 m depth. These results for an average depth of 15 m were significantly higher than a constant water table depth of 15 m, but raising the water table to 2.5 m produced a drastic drop in FOS. Notably, the effects of varying precipitation with altitude were significant. To simulate possible orographic effects on rainfall, the precipitation on the lower half of the cross section was reduced to 50 % of that on the upper slopes. This variation resulted in a 32 % higher FOS. Also notable was the large difference in model results when using a varying water table. With the exception of using a 12.5-m deep water table, these variations all resulted in higher FOS values, meaning that the model was conservative in all cases. The possible impacts of these variances are discussed below.

The sensitivity of the back analysis model to the input material properties were analyzed by varying the friction angle and cohesion. These analyses showed little sensitivity of the slope stability to variations of the friction angle or cohesion within typical values reported by Rolo et al. (2004). Typical values reported by Rolo et al. (2004) for similar soils to those modeled in this study were found to have friction angles of 35 or 36 degrees and cohesion of 10 kPa or less. Varying the friction angle between 35 and 40 degrees, the largest change in FOS was 11 %. Using a value of 10 kPa for cohesion, the maximum expected value based on similar soils in Rolo et al. (2004), the FOS varied 12 %. Based on these effects, neither of these material properties was considered as a significant factor in the analysis (Fig. 7). When the effects of all the various parameters and model constructions on model output were compared to the effects of simply varying the initial water table depth, it became clear that the elevation of the water table was the dominant unknown factor in this analysis.

The results listed in Table 3 and depicted in Fig. 7 both show that the model returns results that are conservative. The calculated FOS from using the model as constructed from back analysis is generally lower than the variations that could be used. In disaster
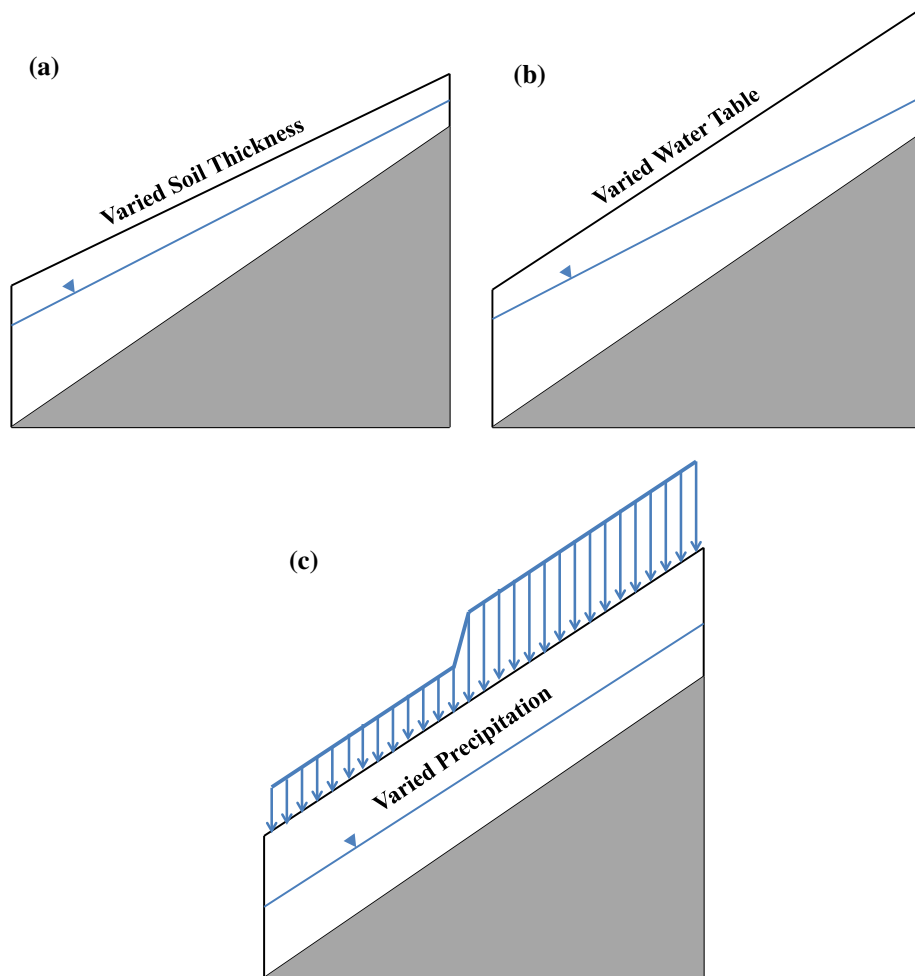
Fig. 6 Variations of back analysis cross section modeled. Results for each are shown in Table 3

Table 3 Select FOS results at time of failure using varied model construction

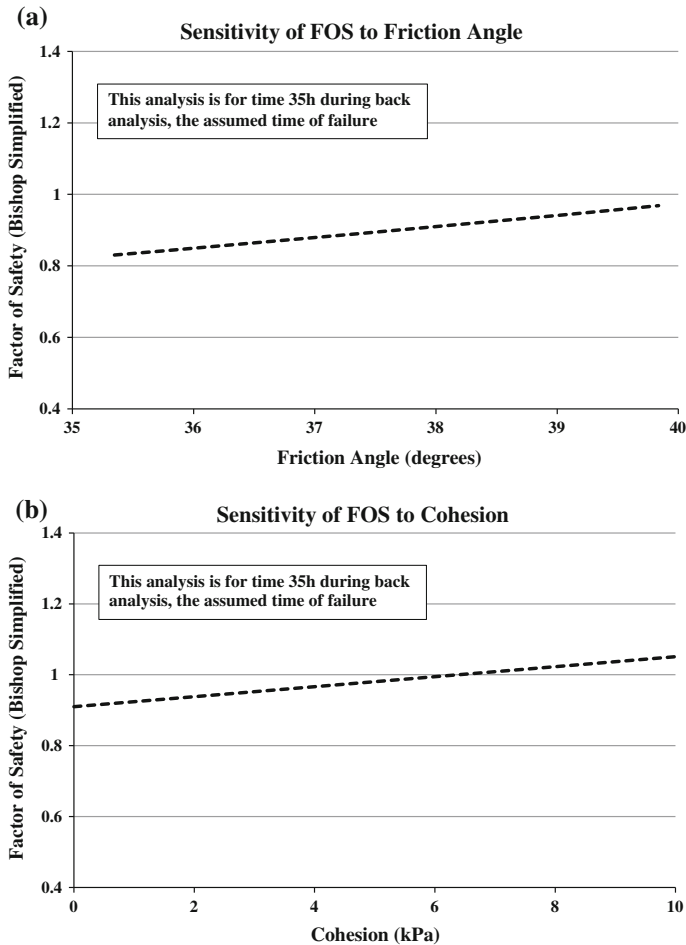|	Factor of safety (Bishop simplified)	Difference from initial model (%)
Initial model	0.910	n/a
Varied water table (average 15 m)	1.292	28
Varied water table (average 12.5 m)	0.854	−9
Varied precipitation	1.370	32
Varied soil thickness	1.146	18

(a)

Fig. 7 Sensitivity Analysis of FOS to friction angle (**a**) and cohesion (**b**) at time of failure during back analysis of existing landslide from Hurricane Ida

preparation, it is important to adopt conservative estimates in order to be better prepared for the eventuality.

   The back analysis of a shallow landslide caused by Hurricane Ida in 2009 enabled estimation of the depth to ground water table and evaluation of geotechnical properties of the various soil layers. Further, these data were used for analyzing potential landslides on the northeast flank of the volcano in several locations where there are concerns for future landslides and debris flows. Given the limitations of the model and available resources, a stability chart was determined to be the most potentially useful tool in the event of extreme rainfall. This chart would outline the conditions that could potentially produce shallow slope failures leading to debris flows on the volcano and could be used in real time as agencies monitor a storm. From the back analysis, it is apparent that cumulative rainfall, rainfall rate, and initial groundwater table are the important variables to include in the stability chart.

Hourly rainfall data from the volcano are available for the years 2005–2010. A detailed review was carried out of the tropical storms and hurricanes that affected central El Salvador during this time. Several periods within those 6 years were missing, but included within available data were two major storms that dumped more than 400 mm of rainfall each: Hurricane Ida in 2009 and Hurricane Adrian in 2005. As discussed earlier, Hurricane Ida caused several large and destructive debris flows while there is no record of any destructive events associated with Adrian.

Both of these hurricanes had single continuous rainfall events that produced approximately 350 mm of precipitation in less than a day, but there is a marked difference in the distribution of that rainfall. The intense event associated with Ida was only about 12 h and had a 1-h peak intensity of 81 mm/h, whereas the peak rainfall event in Adrian was 18 h and contained a prolonged period of 8 h with rainfall intensities of 30 mm/h. These two storms were used as the models for extreme cases of two basic storm types: a short storm that has a burst of very intense rainfall and a more drawn out event that has a period of prolonged medium intensity precipitation. Figure 8 shows the design storm used during modeling for each case.

Utilizing the design rainfall events, an iterative slope stability analysis was performed and coupled with finite element method (FEM)-based transient groundwater analysis. A mesh was created using the cross section, and boundary conditions were assigned to simulate transient infiltration conditions. The program then used these conditions and calculated pore pressures and water table locations at predetermined intervals. For this analysis, a time step of 2 h was used. At each time step, the water balance was calculated for the mesh, and using this information, a slope stability analysis was performed (Fredlund and Rahardjo 1993; Pentland et al. 2001; Rocscience Inc 2011).

This analysis was performed at two sites on the volcano because of their suspected potential for failure and the impact of failure on cities and towns located downstream (Fig. 2). A representative cross-sectional profile through each area was developed for slope stability analysis in Slide (Fig. 9).

Because the model was sensitive to groundwater table location, each profile was analyzed with three initial groundwater table depths: 15, 12.5, and 10 m. For each of the three initial groundwater table depths modeled, 14 precipitation events were used in the transient groundwater analysis. These events included the modified versions of Hurricanes Ida and Adrian, including storms that varied about the reported amount by 10, 20 and 30 %. The transient analysis calculated the minimum Bishop simplified FOS at 2-h increments for each of the 14 rainfall events at all three initial water tables for both sites. This temporal resolution provided insight into the variation of FOS over time with cumulative rainfall, and using the two different storm types, showed the effects of rainfall rate on FOS. The results of this analysis provided the information to create a stability chart based on initial groundwater table depth and the expected cumulative rainfall.

The forward modeling of both cross sections affirmed the results and assumptions of the back analysis as well as provided sufficient data for the creation of stability charts for monitoring landslide potential. When modeled under the same circumstances that simulated an existing failure in the back analysis, neither profile produced any FOS that would indicate a likely failure (Table 4). With an initial water table depth of 15 m, as suggested by the back analysis, both profiles used for the analysis appeared to be able to withstand significant rainfall from either storm type. The lowest FOS from the conditions of Hurricanes Ida and Adrian are shown in Table 4. The lowest values for Ida occurred at a time of 10 h, and for Adrian, the low values occurred at time 14 h. These minimum values are correlated with the maximum rainfall rates for each storm type. The values in all four cases
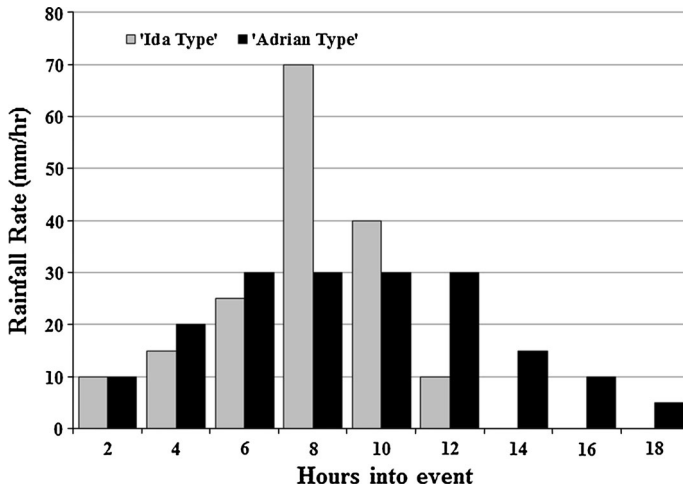
Fig. 8 Design storms used to mimic the distinct rainfall distributions of Hurricane Ida (distinct peak of high intensity) and Hurricane Adrian (no distinct peak, but prolonged mid-intensity)
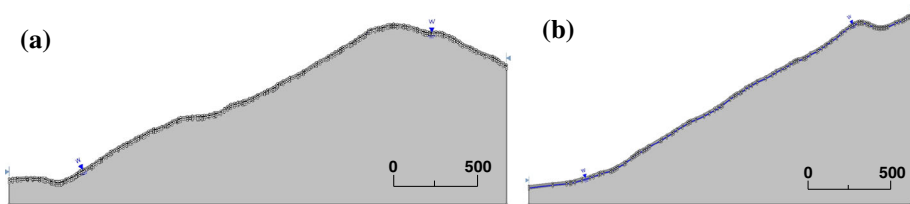

Fig. 9 Profiles used for modeling slope stability: **a** Grieta cross section and **b** Baila Huevo cross section. Soil profiles are the same as in Fig. 3. See Fig. 2 for profile locations. Horizontal and vertical scale is in meters; no vertical exaggeration

are sufficiently high to suggest that the slopes would not have failed during these rainfall events. Since neither location experienced landslides nor debris flows during these actual events, the results provided further justification for the initial assumed water table was at least 15 m deep.

A stability chart was developed using the results from each profile. The most important factors in the analysis were determined to be initial water table depth, rainfall rate and cumulative rainfall. The initial water table depth was found using back analysis of an existing landslide and modeled for multiple scenarios. Rainfall rate was accounted for by modeling the transient changes in FOS of known slopes during two distinct storm types with varying rainfall intensities. These storm types accounted for high intensities as well as longer times of intermediate intensities. Cumulative rainfall was kept independent and constrained based on past rain events. Taking into account the interrelated effects of rainfall amount, groundwater location, and rainfall rate on slope stability, it was possible to develop a preliminary stability chart as depicted in Fig. 10. This chart reflects slope stability relatively, using an estimated FOS provided from modeling in slide.

Figure 10a shows the results of modeling at the *Grieta* location, and Fig. 10b shows the results from Baila Huevo. The results include each designed rainfall, displayed as a curve

	Ida	Adrian
Table 4 Minimum Bishop simplified FOS using precipitation data from hurricanes Ida and Adrian at forward model cross sections		
Grieta	1.394	1.442
Baila Huevo	1.265	1.325

fitted to the FOS values for each cumulative rainfall. In both graphs, the three groups of curves each represent a different initial water table elevation and the lines within each grouping represent the different rainfall events modeled. The various initial water table depths each show a somewhat linear trend in response to the 14 different modeled rainfall events. In each case, the initial response, especially for the first 200–250 mm of rainfall, is strikingly similar and the results only begin to differ significantly at the higher values of total rainfall in an event. Also, it is noted that the FOS results from the Hurricane Ida model storms are consistently lower by a small amount (Fig. 10). This difference is typically 10–12 % at the highest rainfall totals, but the margin is smaller at lower rainfall amounts. The Hurricane Ida results can be distinguished by the "hook" shape at the higher rainfall amounts; this hook is attributable to a slight lowering of the water table accompanying the abrupt decrease in rainfall rate during this storm type. Again, this difference in results is pronounced at the higher rainfall amounts.

The data contained in Fig. 10 were then adapted into a stability chart that could be used for real-time monitoring during a known extreme rainfall event (Fig. 11). Because of the very similar response of the initial water table to the various rainfall events, it was possible to group the storms. An important consideration in the development of the stability chart was to ensure its simplicity and usability by individuals not familiar with slope stability analysis. Therefore, one of the distinct changes made from the initial plots seen in Fig. 10 is the replacement of FOS with low, moderate and high likelihood of occurrence categories, which are simpler to comprehend by non-experts (Fig. 11). The low likelihood zone was assigned FOS > 1.3, moderate likelihood was assigned FOS between 1.0 and 1.3, and FOS < 1.0 was assigned high likelihood. These values were adapted from suggestions provided by previous studies (Hoek 2007; Schaefer et al. 2013). The moderate likelihood zone allows accounting for the uncertainties in the model inputs.

The zones used for each water table were assigned relative rainfall intensities. These values were based on the difference between the Hurricane Ida and Hurricane Adrian results in the modeling, described above. The Ida design storm involves much higher intensities of rain for a shorter period, and the FOS values in all cases are slightly lower. Thus, the low end of the zones can be said to represent rainfall intensities close to that to be expected in Ida. Likewise, the lower intensities seen in Adrian represent the higher end of the zones. The results from Ida follow the same general trend up to approximately 150 mm of rain, and then, the FOS values diminish more steeply. This trend matches precisely with the intense spike of rainfall seen in the Ida type model storms. Based on this trend, the zones associated with each initial water table act as a sort of continuum whereby results would be read off of the lower FOS side of the zone for higher rainfall intensities (such as those seen with Hurricane Ida) and off of the higher FOS side for lower intensities (like Adrian).

Three inputs, all of which are potentially obtainable by non-experts, would be necessary to utilize these stability charts (Fig. 11): groundwater table depth, cumulative rainfall and approximate rainfall intensities. In other words, if regular monitoring activities allow that
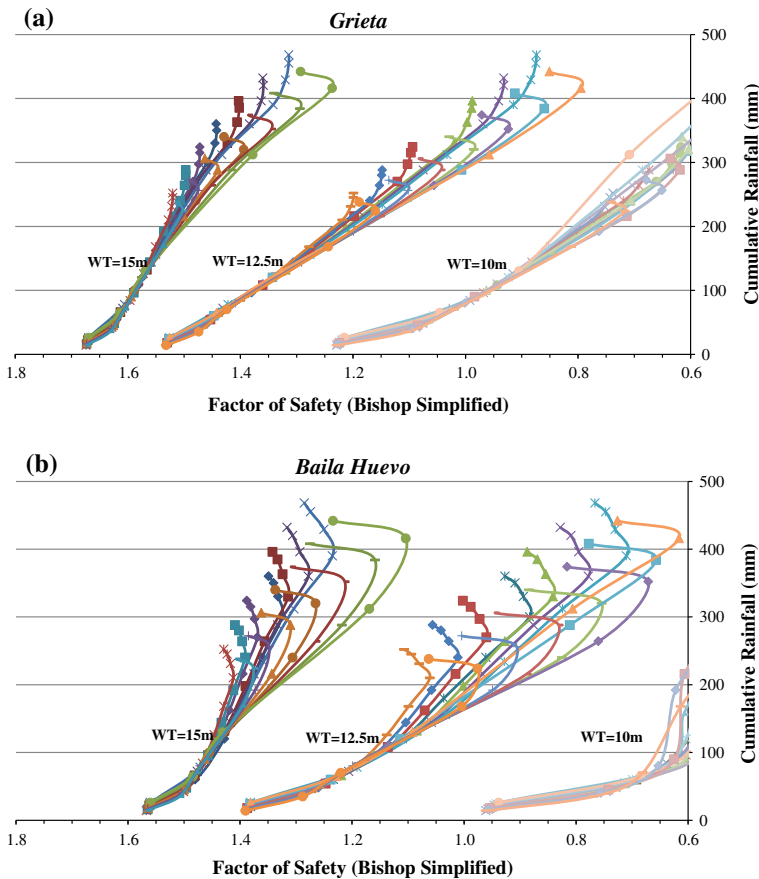
Fig. 10 Model results for each cross section at three initial water table depths. Modeling included the design versions of Hurricanes Ida and Adrian, varying rainfall about the reported amount by 10, 20 and 30 %. Each *curve* represents a set of FOS values for a distinct design storm at a distinct initial water table elevation; *symbology* is varied to show distinction between each modeled event. These *curves* are used in the development of example stability charts

the approximate groundwater depth in the area is known ahead of an intense rainfall event and the rainfall during the event was monitored in real time, these charts could be used as guides to predict the likelihood of slope failure. The first step would be to consult the current initial depth to water table as a starting point. With this information, the individuals monitoring the storm would be able to predict the total rainfall at which slope instability is likely to be an issue. Rainfall intensity can be factored into this prediction by accounting for the example rates shown in each zone.

The areas analyzed for the creation of these example charts were chosen because of the existence of apparent tension cracks high on the volcano. These cracks are a cause for concern by many of the local monitoring agencies. They fear that the cracks may signal an imminent slope failure and debris flow during the next extreme rainfall event. This analysis was undertaken to create simple charts that would benefit individuals monitoring storms and give them more information to factor into decisions to evacuate. The similarity of both
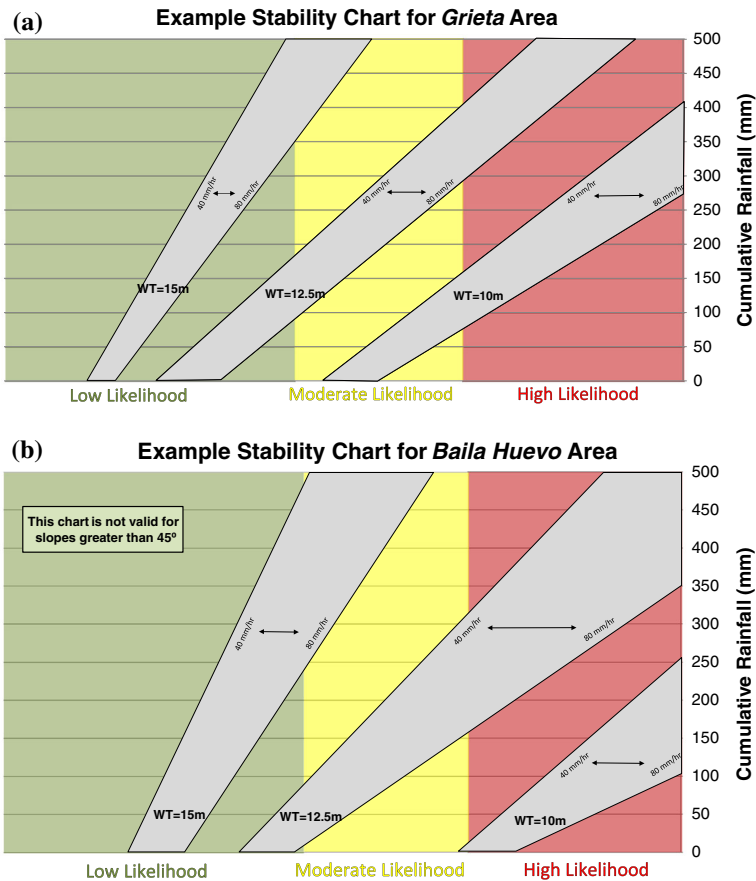
Fig. 11 Example stability charts for Grieta and Baila Huevo locations, as they might appear for use by decision makers during an event. The similarity of the results from both profiles suggests a combined chart could be created with both for use as a general reference for the northern slopes of the San Vicente volcano

charts suggests the possibility of combining them into a single, area-generalized chart. A combined chart that uses both sets of curves and generalizes for all similar slopes in a region could be used in future application to represent the slopes of a region, for example, north slopes of San Vicente volcano.

The following is an example (using Fig. 11a) of how these charts could be used by civil protection or local leaders when monitoring a rainfall event. Suppose that the groundwater depth was recently measured at 12.5 meters as part of the regular monitoring efforts. Additionally, a known tropical storm is making its way toward El Salvador. This storm is expected to bring heavy rains over one to 2 days and believed to be capable of 300 mm of rainfall in less than 24 h, similar to Hurricanes Ida or Adrian. By analyzing the chart and using the zone for initial water table of 12.5 m, one could clearly see that in a storm containing high rainfall intensities (80 mm/h), rainfall totals of even 150 mm would be enough to be considered "moderate likelihood" and therefore be on alert for potential slope failures. Real-time-hourly rainfall monitoring on the volcano (as it is currently done) would result in rainfall rates and amounts regularly reported to local agencies in charge of

disaster planning and evacuation. With these reports, the decision makers would know ahead of time that total rainfalls approaching 300 mm would be of concern. Thus, if these levels of rainfall were experienced or expected to occur, they could begin preparing to evacuate.

Current monitoring efforts, though effective, could benefit from the addition of the information that can be analyzed with this tool. This method not only takes into account the local groundwater conditions at the time of rainfall, but also attaches the method of using rainfall intensity as a threshold to the overall precipitation experienced during an extreme precipitation event. If local civil protection offices were given this information and basic training about how to analyze and interpret the charts, they could be an extremely useful tool.

Certainly, the biggest assumption that goes into using charts of this type is that the individual using them would need to know the approximate groundwater table depth prior to a storm event in order to properly assess the hazard posed by rainfall. This would necessitate a regular groundwater monitoring program, along with the equipment and expertise to accompany it. Recommendations have already been made to agencies in the San Vicente area that this be pursued, and the installation of groundwater monitoring wells and equipment in locations higher on the volcano is underway. With the addition of this one critical piece of information, stability charts like these could be used with all the other currently available information.

6 Conclusions and limitations

Back analysis of shallow rainfall-induced landslides that occurred during Hurricane Ida led to the determination of several thresholds for slope instability at San Vicente volcano in El Salvador. Groundwater table depth was found to have the highest impact on potential slope instability. Other potential critical factors leading to instability are cumulative rainfall amounts and rainfall intensities. Using the results from this back analysis and field work, a slope stability model was created for analyzing the potential effects of various rainfall amounts and intensities on slope stability. The results of this iterative modeling were used to create stability charts that can be used as a tool for real-time monitoring efforts during an extreme rainfall event. These charts could cue decision makers on conditions where evacuation would be warranted. It is believed that this method could be improved and applied elsewhere for similar purposes to assist in hazard monitoring in areas where shallow landslides and the resulting debris flows pose a threat to populations.

The creation of the stability charts presented in this work involved simplifying assumptions. Although these assumptions were conservative, collectively they very likely lead to overly conservative results. However, in this case, they are based on the best available information and no alterations or model complications were used where there was no direct evidence to justify doing so. The assumptions used in this application that would most likely affect the results are the constant and uniform rainfall amounts, uniform depth to the water table and soil thickness for the entire profile. Based on the sensitivity analyses, these model simplifications likely lead to conservative results. The assumed material properties are also significant. Again, properties used for this example were based only on available information and several key parameters were based on literature values.

A very critical assumption in our model is that the soil is cohesionless. There was much evidence of this during field testing and it was supported by a literature review. The difficulty of obtaining and transporting intact samples from such remote field sites makes it

difficult to ascertain the strength properties. Obtaining more accurate cohesion values would allow for more precise calibration of the model. However, if simple material properties like cohesion or a better measurement of SWCC parameters were available, it would add much more confidence to this model. Another area where the model could be improved is factoring antecedent moisture conditions into the analysis. Several studies have shown that it is a key component in slope stability, though it is difficult to account for and accurately predict without good monitoring capabilities and equipment (Godt et al. 2009; Rahardjo et al. 2007, 2010; Rahimi et al. 2011). The effects of antecedent moisture on the stability of the slopes are very evident when examining the difference between Hurricane Adrian and Ida. Adrian occurred in May, when the soil would have very low moisture content at the start of the wet season, while Ida occurred in November, at the end of the wet season, when the soil has as high moisture content as it is likely to have. Using the approach outlined in this paper, stability charts of similar fashion could be created and calibrated by accounting for these factors as best as possible.

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