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Hazard mapping related to structurally controlled landslides in Southern Leyte, Philippines

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Abstract. The 2006 Guinsaugon landslide in Saint Bernard, Southern Leyte, is one of the largest known landslides in the Philippines in recent history. It consists of a 15–20 million m^3 rockslide-debris avalanche from an approximately 675 m high mountain weakened by continuous movement of the Philippine Fault. The catastrophic Guinsaugon landslide killed 1221 people and displaced 19 000 residents over its 4.5 km path. To investigate the present-day morphology of the scar and potential failure that may occur, analysis of a 5 m resolution InSAR-derived digital elevation model was conducted using Coltop3D and Matterocking software, leading to the generation of a landslide hazard map for the province of Southern Leyte in central Philippines. The dip and dip direction of discontinuity sets that contribute to gravitational failure in mountainous areas of the province were identified and measured using a lower Schmidt–Lambert color scheme. After measurement of the morpho-structural orientations, potential sites of failure were analyzed. Conefall was then utilized to compute the extent of rock mass runout. Results of the analysis show instability in the scarp area of the 2006 Guinsaugon landslide and in adjacent slopes because of the presence of steep discontinuities that range from 45 to 60°. Apart from the 2006 Guinsaugon landslide site, runout models simulated farther rock mass extent in its adjacent slopes, revealing a high potential for fatal landslides to happen in the municipality of Saint Bernard. Concerned agencies may use maps produced in the same manner as this study to identify possible sites where structurally controlled landslides can occur. In a country like the Philippines, where fractures and faults are common, this type of simulated hazard maps would be useful for disaster prevention and facilitate disaster risk reduction efforts for landslide-susceptible areas.

1 Introduction

1.1 Guinsaugon landslide

One of the largest known mass wasting events in the Philippines happened in the province of Southern Leyte. On 17 February 2006, 10:26 LT, an estimated 15–20 million m^3 (Lagmay et al., 2006) of cascading rocks from a 700 m high mountain buried the entire village Guinsaugon in the municipality of Saint Bernard and killed 1221 people. Identified as a rockslide-debris avalanche (Lagmay et al., 2008), the fatal landslide happened on the slopes of Mt. Can-abag along a steep scarp defined by the Philippine Fault Zone or PFZ (Allen, 1962) (Fig. 1). The landslide was 4.1 km long, 1.5 km wide and had a planform area of about 3.3 km^2.

1.2 Geotechnical consideration

The study area is part of the Southern Leyte segment of the sinistral PFZ, which has an average movement of 0.55 $cm\,yr^{-1}$ (Cole et al., 1989) up to 3.5 $cm\,yr^{-1}$ (Duquesnoy, 1997, as cited by Catane et al., 2006). This has led to formation of regional discontinuities and development of thick clay-rich gouge zones in the surface prominent in the en-

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Figure 1. Location of Southern Leyte in the Philippine map with specifics of the Guinsaugon landslide and the Philippine Fault segment in the province.

tire province and other locations along the PFZ (Hart et al., 2002). As a result of active tectonic movement, poor rock mass quality is evident in many of the mountain ranges of Southern Leyte (Evans et al., 2007) making the region prone to structurally controlled landslides. Other lithologies in the area are ophiolite basement, Paleogene sedimentary rocks and late Pliocene to Pleistocene volcanic rocks.

The Guinsaugon landslide was preceded by continuous downpour of rain from 8 to 14 February amounting to 683.6 mm (Lagmay et al., 2006). Measurements from the Otikon weather station, 7 km away from the landslide, show rainfall was highest during the period 10–12 February ranging from 131 to 171 mm although these are believed to be less than the actual values due to the orographic effect. Around the same time as the landslide, two earthquakes were recorded by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and the United States Geological Survey (USGS) (Lagmay et al., 2006). Each were reported 21 km west and about 2 km north of Guinsaugon, respectively.

1.3 Failure mechanism

The topmost contributing slope of the Guinsaugon landslide is 50 to 60° (Catane et al., 2006) with a post-landslide configuration of the crown exhibiting a distinct four-slip-plane failure. Based on the observed orientation of discontinuities and immense pore pressure developed from accumulated rainfall, a combined wedge, toppling, and planar slide is believed to have caused gravitational failure at Guinsaugon (Catane et al., 2008). At the foot slope of Mt. Can-abag are prehistoric landslide deposits, which were scoured during the 2006 landslide event contributing to the development of the massive avalanche which transformed into debris flows at its frontal edge.

1.4 Objectives

A large part of Southern Leyte, Philippines, is susceptible to structurally controlled landslides. Old landslide scars and large-scale landslide deposits are apparent in the area with the most recent landslide being formed by the 2006 Guinsaugon debris avalanche event. Identifying manually specific areas where landslides may occur in the region is a challenge in terms of resources and scale of effort required. However, advanced methods in computer analysis of landslides may aid remotely sensed and field mapping in the province of Southern Leyte (Luzon et al. (2013), as preliminarily reported in). This study aimed to use numerical models for structurally controlled landslides, complemented by field mapping to identify danger zones. The method only considered translational slides, with either wedge, planar, or toppling type of failure due to presence of discontinuities. It does not encompass circular and complex types of landslides. Using high-resolution topography as base map for the simulations, hazard maps at barangay (village) scale were generated for use in disaster prevention and mitigation efforts in the Philippines.

2 Methods and concepts

2.1 Lineament pattern analysis

For decades, advances in remote sensing have helped the field of natural hazards in terms of scale and workability. Reliability relies greatly on two factors: (1) how accurately the image captivates reality and (2) the approach to generate desired output from the data (Jaboyedoff et al., 2012). In geology, these methods are extensively used considering both factors. Lineament patterns are one of the most observable features using a digital elevation model. They correspond to many fault and crustal fractures thus providing ideas on regional tectonics. In digital modeling, they are sets of relatively adjacent pixels having similar terrain values (Koike et al., 1998). Improvement in such a method comes in two different ways (Raghavan et al., 1995). First is the continuous enhancement of images for extraction through higher resolution imagery and better color or shading representation. Second is in automatic lineament detection using different algorithms (Koike et al., 1994).

In this study we used high-resolution imagery derived from interferometric synthetic aperture radar (InSAR) in identifying structural features for numerical models. The InSAR used is from a 2012 nationwide digital terrain model (DTM) and digital surface model (DSM) data set with 0.5 m vertical accuracy and 5 m pixel resolution. The raw data were acquired using Intermap's STAR-3 InSAR system with an X-band InSAR in a Learjet 36A aircraft flying 4–12 km above mean sea level. DSMs were processed into bare earth terrain models by Intermap where vegetation and infrastructure are removed using filtering algorithms. Shaded relief images generated from these DEMs provided high resolution and shaded relief images that reveal well-defined lineaments and distinct changes in the face of mountain slopes.

2.2 Discontinuity identification

After identifying important lineament patterns in the region, dip and dip direction of slopes corresponding to each trend were measured using Coltop3D. It is a pseudo-3-D topographic analysis software that represents slope aspect and slope angle. It gives unique color for a given combination of dip and dip direction using classical hue saturation value with a Schmidt–Lambert projected stereonet and depicts continuous and similar planar orientations with the same color (Metzger et al., 2009). Slope aspect maps are effective tools for locating target sites that warrant structural investigation and have particularly significant implications for the stability of slopes (Tengonciang, 2008). With Coltop3D, there is added capacity to delimit targets to those significant to the study. Recurring linear patterns are isolated with a particular tolerance and viewed separately. This step allows large amount of computer-generated point cloud data of discontinuity sets necessary for structural analysis that uses stereoplots and rose diagrams. It should be noted that this method assumed structurally homogeneous areas in regional scale as scope (precision) (Jaboyedoff et al., 1999).

2.3 Kinematic analysis and instabilities

Rock strength and friction are factors that could resist the gravitational force pulling down the surface materials. Rock strength is defined by the physical and chemical property of a rock related to any kind of break or gap in a rock while friction is the force resisting the relative movement of materials (Hoek and Bray, 1981). Friction increases with roughness or angularity of a rock, as well as the surface roughness. Slope angle also contributes to the determination of mass wasting occurrence. The closer a slope to being parallel to the downward direction of the material, the easier it is for gravity to overcome friction and rock strength resistance. Other factors that contribute to mass wasting include water, earthquakes as well as human activities. Fractures, joints, faults, and other structural features weaken rock strength. Having these gaps favors water seepage, which contributes to bond weakening through the weathering process.

In the identification of structurally controlled landslides, these discontinuities are treated as the primary cause of slope failure. Once determined, the discontinuity sets are subjected to kinematic analysis using Matterocking software, which in turn is used to identify unstable slopes. Matterocking is an open-source software which was used in this study to compute the mechanisms for planar, wedge, and toppling failure (Jaboyedoff, 2002). The following definitions for the different failure types were observed in the analysis of unstable slopes for the region of Southern Leyte.

2.3.1 Planar failure

A planar failure is a rare occurrence in rock slopes due to the fact that all the geometric conditions required to produce it only happen occasionally on an actual slope (Kliche, 1999). In planar failure, the rock mass only slides on a single surface; for it to continue, certain geometric conditions need to be satisfied (Wyllie and Mah, 2004):

1. The sliding plane must strike parallel or nearly parallel to the slope face.
2. The sliding plane must have its plane dip less than the dip of the slope face.
3. The dip of the sliding plane should be greater than the angle of friction of the sliding plane.
4. The upper end of the sliding plane should intersect the upper slope or where the tension crack terminates.
5. Lateral boundaries of the slide should be defined by the negligible resistance to sliding provided by the release surfaces.

2.3.2 Wedge failure

Wedge failures occur when a mass of discontinuous rock-slides on two intersecting planes (Kliche, 1999). They occur over a much wider range of conditions as well as geologic factors, which is why it is more difficult to study this component of rock slope engineering. Wedge failure has basic mechanics analyzed in terms of its geometry and conditions defined by Wyllie and Mah (2004):

1. The two sliding planes will always intersect in a line. The line of intersection can be represented on a stereonet by the point where the two great circles of the two sliding planes intersect. The orientation of the line is then defined by the trend and plunge of the line.

2. The line of intersection plunge should be less steep than the dip of the slope face and steeper than the friction angle of the two sliding planes. The slope face inclination is determined by the view at right angles to the intersection line. The true dip of the slope face would only be determined if the dip direction of the intersection line is the same as the dip direction of the slope face.

3. The intersection line must dip in a direction out of the slope face for sliding to be possible.

Stereonets can show a wedge failure is kinematically possible. However, the actual factor of safety of the wedge cannot be determined by it. This factor also depends on the geometry of the wedge as well as the plane shear strength and water pressure.

2.3.3 Toppling failure

Toppling failure is the forward rotation out of the rock slope about an axis below the center of gravity of the unstable rock. It is one of the basic landslide mechanisms that leads to serious and hazardous rock slope instability. This failure can be classified into four types: flexural, blocky, blocky flexural, and secondary type. Two mechanisms cause toppling to proceed, one of which is the growth of erosion notches that is produced due to differential weathering. The support area of the rock will decrease and, as a consequence, the center of gravity of the unstable rock will offset outward the slope. Secondly, the development of tension cracks due to tensile stress concentration leads to rotational toppling failure of unstable rocks because of momentum unbalance. This will inevitably occur under self-weight and fissure water pressure water as well.

To summarize, the total toppling failure occurs due to erosion notches and tension cracks and continues on to gravitational transport and accumulation (Wang et al., 2013).

These concepts can be simply illustrated as shown in Fig. 2. Matterocking applies these in an iterative manner to the entire DTM and computes the slopes which satisfy the criteria for instability. It generates a map of potential rockslide zone, which is used as a landslide source for propagation.

3 Results

3.1 Lineament analysis of Southern Leyte

The Philippine Fault is classified as a left lateral strike slip fault. Segment of this 1200 km long geologic feature cuts Southern Leyte on its mountainous regions. Along this lining are conjugate shears and corresponding splays scattered in the whole province. General trends of these lines are identified as shown in Fig. 3. The study took into consideration four sets of regional discontinuities. We used four positions of light source: 315, 225, 135, and 45° all at an altitude of 45°.

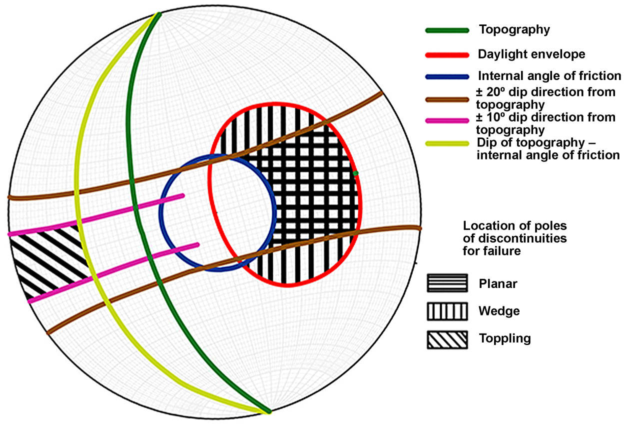

Figure 2. Criteria for discontinuities to cause failure (planar, wedge or toppling) on a given slope (Wyllie and Mah, 2004).

Table 1. List of regional discontinuities identified for Southern Leyte.

Discontinuity set	Dip (°)	Dip direction (°)
DS 1 PF	32	250
DS 2	41	061
DS 3	37	204
DS 4	41	185
DS 5	31	111
DS 6	36	307

3.2 Identification of discontinuities using Coltop3D

Guided by the lineaments produced in the earlier step, slopes to represent each trend are selected. Dip and dip direction of each slopes measured using COLOTP3d are shown in Table 1. These sets of discontinuities are considered for the stability analysis of the slopes in the study area. Measurements are of ±10° on both criteria as limited by the software. First is the obvious plane intersecting the ridge of the mountain trending southwest with dip and dip direction 41/061°. This actually is of the same direction of one of the slip planes of the Guinsaugon landslide. Next is the dip and dip direction of the slopes following the trend of the Philippine Fault. It measures 32/250°. Third is the lineament trending northwest cutting the point of landslide with 37/204°. Fourth is the measured discontinuity of the southwest trending lineament with 36/307° and 32/111°. This is of the same direction of another slip plane of the landslide. Last is the discontinuity set trending east with 31/185°. We can verify these measured dip and dip direction to the actual field measurements considered in a post-disaster report by Catane et al. (2008) as shown in Table 2.

Table 2. Field measurements reported on a post-disaster assessment by Catane et al. (2008).

Discontinuity set	Dip (°)	Dip direction (°)
Bedding	35	252
Fault	45–56	057
Set 1	80–90/65–90	30/205
Set 2	60	185

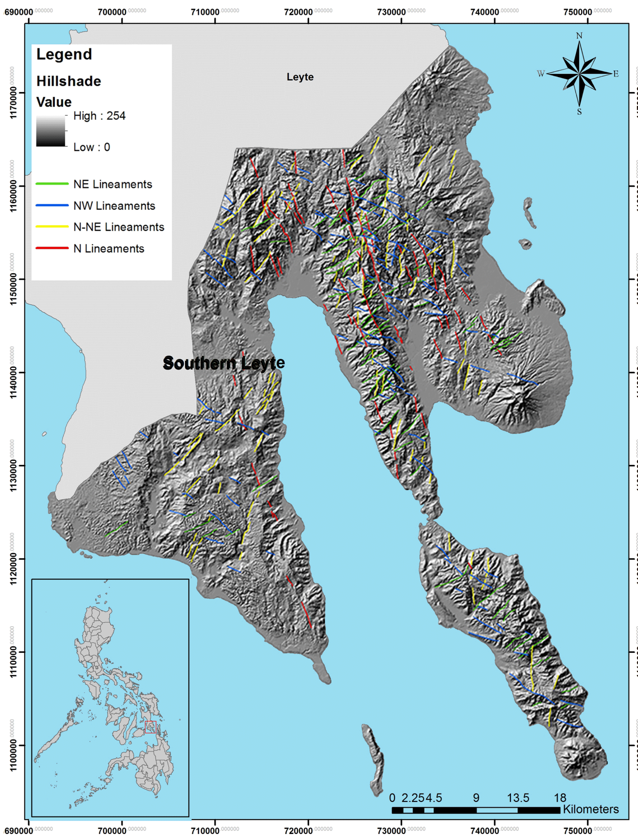

Figure 3. Lineament analysis of Southern Leyte.

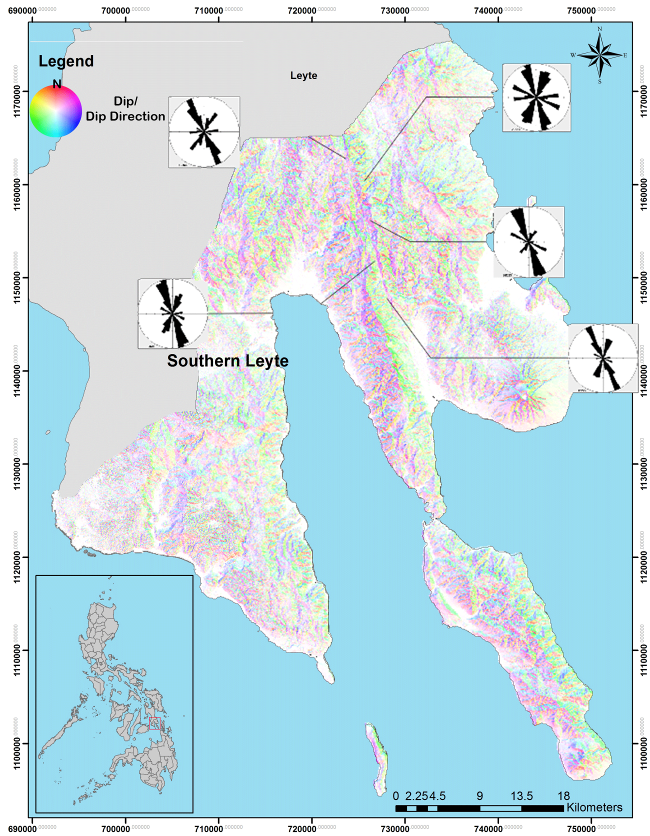

Figure 4. Different rose diagrams of a segment of the Philippine Fault.

3.3 Verifying rose diagrams of discontinuity sets

Selections of discontinuities along the Philippine Fault are also presented in rose diagrams. Shown in Fig. 4 are different segments of the lineament. The diagram is consistent with the usual rose diagram appearance of a left lateral strike slip fault with a main long axis parallel to the master fault (i.e., Philippine Fault) and two other minor orientation directions that represent associated faults such as Riedel shears.

3.4 Potential rockslide zone generated by Matterocking

Failure zones generated by Matterocking are shown in Fig. 5. The province of Southern Leyte is highly susceptible to structurally controlled landslide as clearly presented. This includes the analysis of a planar and wedge failure that may occur due to discontinuities considered. Generally steep slopes in the region and presence of discontinuities due to the segment of PF caused this high susceptibility. Looking closer at the Guinsaugon landslide area, we can expect more failure as for the presence of the scarp before the mass movement happened. This is the case of wedge failure that could trigger most rockslides. This is due to the persistence of intersecting discontinuity sets in the area. About 10 % of the slopes in the province have failure potential according to the model.

Kinematic analysis was performed for several slopes of the Mt. Can-abag east-facing facade as shown in Fig. 6. Slopes covered in red are those that were identified as a rockslide source. These were chosen just to verify and further analyze the mode of failure that could occur as shown in Table 3. Present discontinuity sets in the area were used in the analysis. Results have shown the probability of wedge and planar failure in almost all cases. Intersection of discontinuity sets 41/61 and 41/185 most probably would cause wedge failure on this side of the mountain. Toppling failure could not be taken into account in this case due to lack of very steep recorded discontinuity. We considered the limitation of DEM's resolution that dip angles would always be less than the actual values on the field. Planar slide in S1 follows the

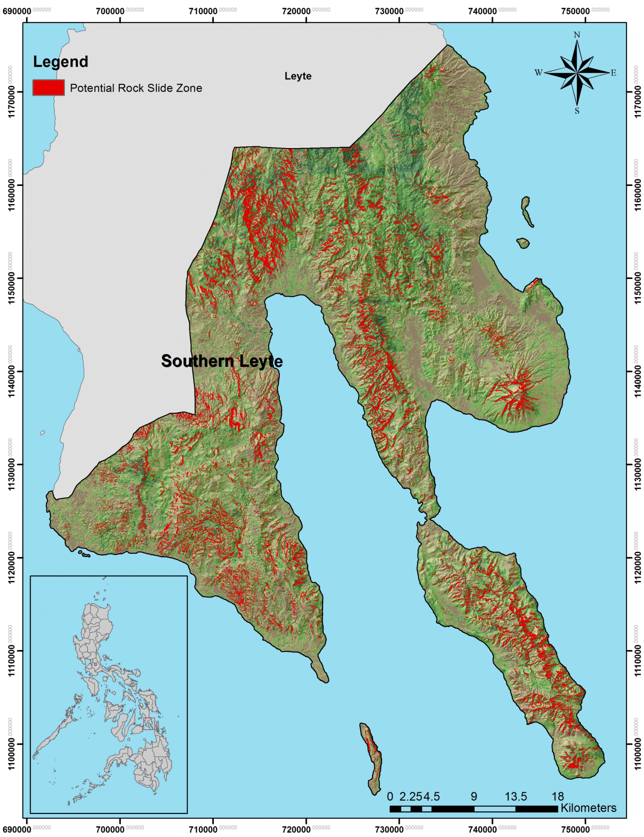

Figure 5. Area of potential rockslide zones in Southern Leyte using Matterocking.

Table 3. Failure modes of selected slopes in Mt. Can-abag.

Slope	Dip/dip direction	Failure
S1	60/054	planar/wedge
S2	56/143	planar/wedge
S3	52/91	wedge
S4	45/132	wedge/planar

configuration slide in one slip plane of the Guinsaugon landslide.

4 Discussion

4.1 Slope angle distribution

It should be noted that this method assumed structurally homogeneous areas in regional scale as scope (precision) (Jaboyedoff et al., 1999). To put into scope the parameter used in determining the friction angle for the region, the slope family concept presented by different studies by Strahler (1954), Baillifard et al. (2005), Jaboyedoff et al. (2004), Loye et al. (2008), and Michoud et al. (2012) is a suitable tool due to prominent slope families produced by active movement in a large part of the province (Cole et al., 1989; Duquesnoy, 1997). The result of Histofit (Loye et al., 2009; Michoud et al., 2012), a program for computing Gaussian fittings for a slope angle distribution, shows a threshold value for a family of steep slopes of 38° (Fig. 7), which corresponds to the internal angle of friction. Direction of discontinuities produced by this movement is also as prominent. Thus, an incorporated effect of critical slope and discontinuity sets is enough for identifying the potential source of failure.

Landslide hazard mapping does not end with identifying failure zones. It also requires the projection of possible runout extent to which the landslide mass will propagate. These areas are as exposed to landslide hazards as the failure zones and are important to locate to get communities out of harm's way. Here we show the method used to determine the likely areas exposed to the hazard of structurally controlled landslides.

4.2 Propagation extent

A number of models use an angle from source to extent of a landslide to determine possible runout within the area of interest (Dorren, 2003). Studies differ on what H/L ratio to use in determining this limit angle as shown in Fig. 8, either the highest portion of the foot slope or the top failure plane. Evans and Hungr (1993) suggested that the minimum shadow angle is preferable (H is the lowest portion of the failure block). To come up with an acceptable value of this angle, a certain amount of landslide events' runout should be considered. A study by Onfri and Candian (1979) used 98 rockfalls to suggest a minimum *Fahrböshung* in Italy from structural instability to be 28.34°. Evans and Hungr (1993) used 16 profiles of rockfall paths suggesting a minimum shadow angle of 27.5° in British Columbia. Several studies also reported lower values (i.e., 22–24°) for shadow angles in smooth surfaces, such as those in snow- and grass-covered areas (Evans and Hungr, 1993). The use of this approach is widely accepted in terms of capturing real-event scenarios.

This study uses a 20° shadow angle. This is a conservative approach based on the literature presented but is a reasonable choice considering that debris avalanches have a long runout. Conefall uses this shadow angle to compute the runout zone in a GIS environment given a digital elevation model (DTM) according to the following relationship (Eq. 1):

$$0 < \triangle x^2 + \triangle y^2 - \tan\left(\frac{\pi}{2} - \phi_p\right)^2 \times (z_0 - z)^2, \qquad (1)$$

where z must be less than the surface height. The estimated runout in 3-D is the cone envelope (Fig. 9) covered by the aperture angle from the source point (Loye et al., 2008).

4.3 Potential runout zones using Conefall

Since the sources of rockfall/slide were already identified, zones where it will propagate were also mapped using Cone-

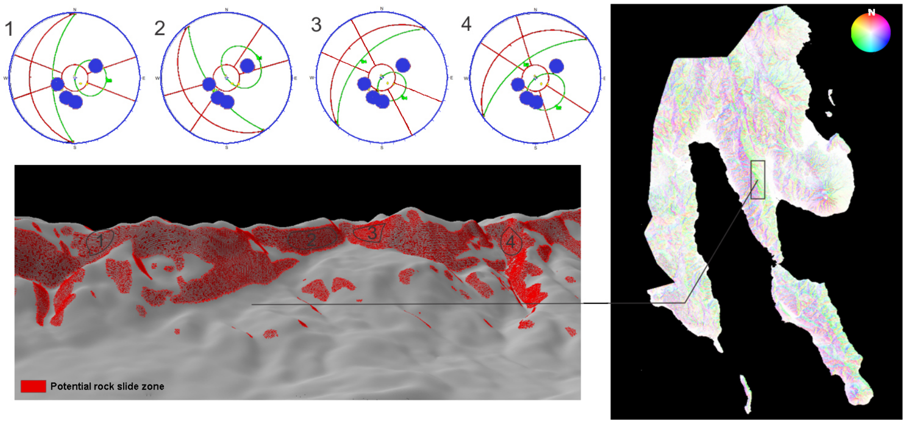

Figure 6. Kinematic analysis of portion of Mt. Can-abag facing Saint Bernard with the blue circles as identified discontinuity sets, green and red line representing the slope and the critical values for failure respectively, as discussed above.

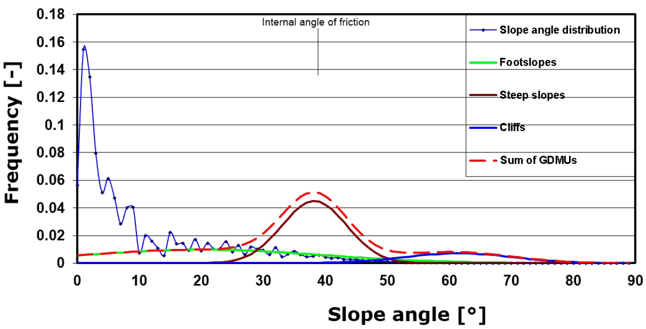

Figure 7. Slope families method using Histofit for the slope angle distribution of Southern Leyte, Philippines.

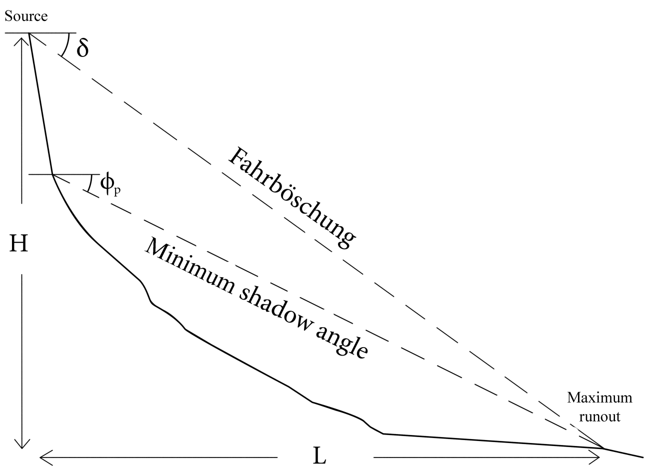

Figure 8. Simplified scheme using an empirical approach to determine runout projection.

fall. The study utilized a runout angle of 20° as discussed above. Ratio of "safe" zones from structurally controlled landslide to high susceptibility area is 2 : 1. Shown in Fig. 10

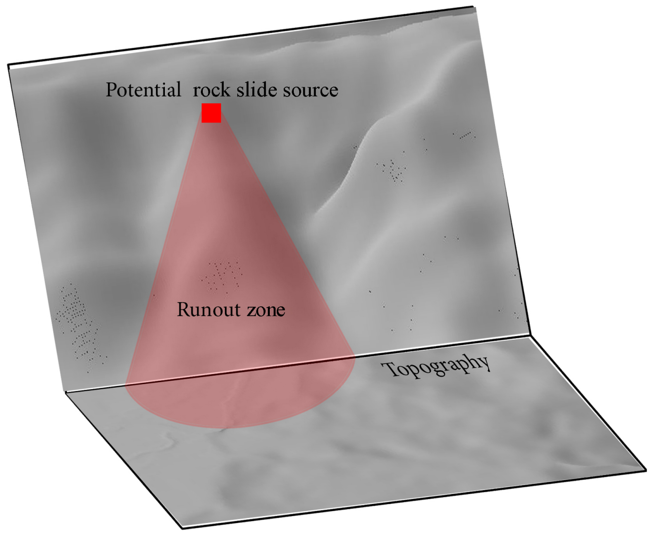

Figure 9. The cone method applied to simple topography in estimates of the runout zone using Conefall modified from Loye et al. (2008).

is the combined map for the source and propagation extent of Southern Leyte.

5 Conclusions

On 27 February 2006, one of the largest known non-volcanic debris avalanche events in the Philippines happened in the province of Southern Leyte. Gravitational failures initiated along the Philippine Fault were a collapse of a sector of a 700 m high mountain, which buried the entire village of Guinsaugon in the municipality of Saint Bernard killing 1221 people and displacing 19 000 residents over its 4.5 km path.

Using high-resolution imagery derived from interferometric synthetic aperture radar (InSAR), fractures were identi-

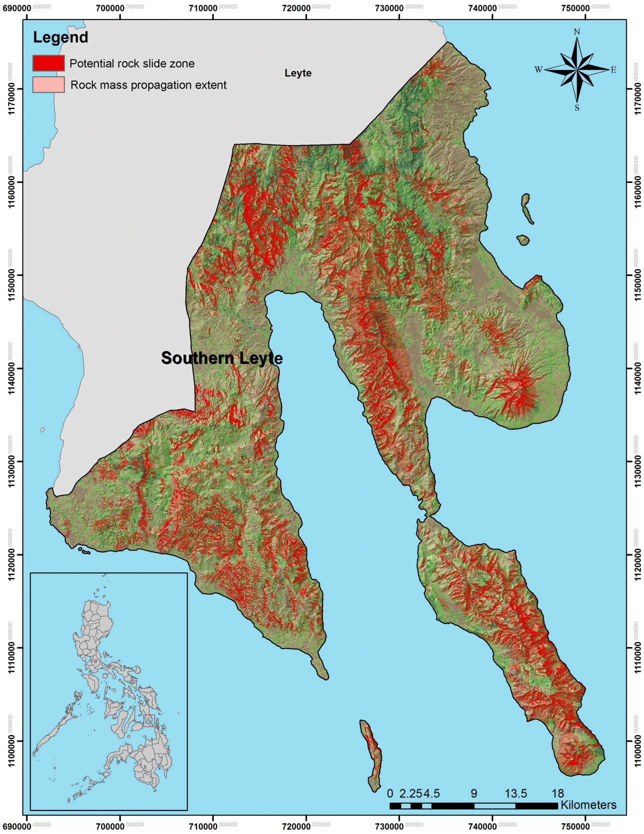

Figure 10. Combined map of potential rockslide zone sources and propagation extent for Southern Leyte.

fied to interpret structural instability of mountainous areas in the province. Discontinuity sets, kinematic analysis of structures, and classification of sites as planar, wedge, and toppling failure were identified using the Coltop and Matterocking software. Combined use of these numerical tools enabled the rapid characterization of the entire Southern Leyte in terms of its susceptibility to fracture-controlled landslides.

Apart from the old landslide scars and large-scale landslide deposits apparent in the area with the most recent landslide being formed by the 2006 Guinsaugon debris avalanche event, the study shows that large parts of Southern Leyte are susceptible to structurally controlled landslides. Identification of these potential sites for gravitational failure, which normally would have been a challenge in terms of scale of resources and effort required to map them all out, was done in a relatively short period of time. Production of these high-resolution landslide susceptibility maps through these advanced methods greatly aids field mapping of these potential sites of failure. Moreover, the numerical methods presented not only quickly map sites of mountain-side instability but also depict the likely path and deposition of the landslide, which produce susceptibility maps that are critical input to a nationwide effort of the Philippine government to prevent and mitigate this type of natural hazard.

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