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Preliminary Landslide Hazard Assessment of Leyte Province☆

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1. Background

On 7 November 2013 Supertyphoon Yolanda (international name Haiyan), packing maximum sustained winds of 235 kph and gusts of 275 kph, made an initial landfall in Guian, Eastern Samar then made its second landfall in Tacloban, Leyte at 0700H on November 7. After traversing several provinces in the Visayas, it then exited the Philippine Area of Responsibility on 9 November (Fig.1). In its wake, it left a trail of devastation that resulted in 4,011 persons dead, 18,557 injured and 1,602 missing. It also inflicted a total damage of nearly PhP12.5 billion with PhP1.9 billion for infrastructures and PhP10.5 billion for agriculture [1].

Typhoons are already a fairly common occurrence in this region, and with a continuing increase in the heat content of the oceans that contribute to formation of low pressure areas, extreme weather events in the form of more intense rainfall intensities and tropical cyclones, turbulent winds, storm surges, landslides and other rainfall-induced hazards increase the vulnerability of communities located in low-lying and shallow coastal areas [2].

In light of this disaster, we present a preliminary landslide hazard assessment for the province of Leyte to help communities identify safer areas in Leyte. This study made use of satellite imagery to identify recent landslides, generate stability index and structurally-controlled landslide susceptibility maps, identify alluvial fans, and simulate potential debris flow occurence.

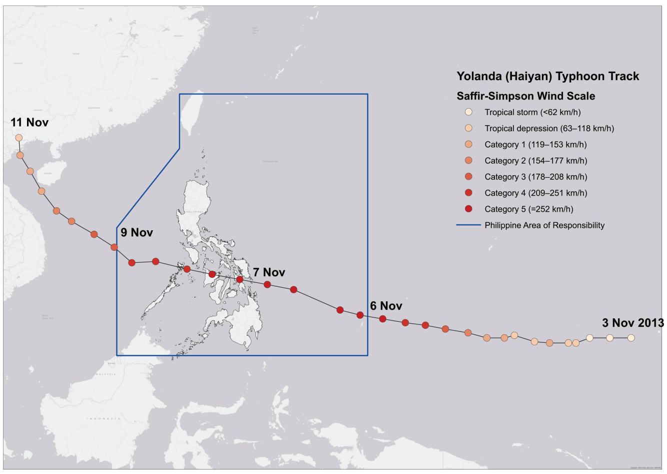

Figure 1: Path of Supertyphoon Yolanda (Haiyan).

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2. Physiographic Setting

In the northwestern perimeters, fronting the bay of Ormoc are the low Northwestern Highlands. Adjacent to this, where Ormoc city lies and extending northward, the landscape is low-lying. This lowland is called the Ormoc Valley. It is separated from the also low-lying eastern side of the island by mountain ranges that make up the Central Cordillera, notably Mt. Lobi in the north and Mt. Mahagnao in the south. The Central Cordillera is the most distinguishable land feature in Leyte. To the northeast, between the Central Cordillera mountain range and the low Northeastern Highlands that lie adjacent to the San Juanico strait, is the most extensive lowland in Leyte, called the Leyte Valley. Other lowlands in the area occur as deltas, where the river systems drain the precipitation from the mountainous regions to the seas. Coastal areas in the island experience land submergence.

3. Relief and Topography

The province of Leyte is generally mountainous and is broken by steep slopes. Along the eastern part of the province, a narrow caostal plain is present bordering along the San Juanico strait. These plains are bounded on the west by a range of low hills. The slope of this range meets the plain abruptly. Along the borders of the plain, the hills are low, smooth, and partly cultivated. The largest plain in the province is found in the area south of Palo to Abuyog and from Palo to Barugo. This plain has swamps and isolated hills which occurs sporadically along the eastern flank of the plain as in Palo, Tanauan, Tolosa, Dulag, and Abuyog. The central Cordillera of Leyte is narrower on the north from Baybay to Capoocan but steeper and much higher than the range south of Baybay. The area from Villaba to the end of San Isidro and those at Merida are dominantly hilly. The Pagsangahan Plain, which is a big valley is wide and almost level. This plain is found in between the western range of the hills and the northern part of the Central Cordillera[3].

4. Geologic Setting

The province of Leyte is one of the islands that the Philippine fault traverses. The Philippine fault is a 1300 km-long strike-slip transform structure that runs the length of the Philippines from Ilocos Norte in Luzon to Davao del Sur in Mindanao. This structure, of which the genesis has yet to be clearly understood, seems to have formed due to the oblique collision of the westward moving Philippine Sea Plate with the eastward moving Eurasian Plate. This collision has determinedly brought about the development of trenches on either side of the Philippine archipelago; the Philippine trench to the east, and the Manila trench and its extension, the Sulu trench, to the west. Subduction rates are estimated to be from 6-8 centimeters per year.

The Leyte segment of the Philippine fault is about 250 kilometers long, oriented northwest-southeast. Along this lineament, a chain of volcanoes have developed, manifesting the volcanism along the fault.

In Ormoc, the Philippine fault has cut across and offset the Mt. Bao volcano located in the northern part of the island.

With respect to its tectonostratigraphy, Leyte is subdivided into three main terranes; Northwestern Leyte, the Leyte Central Highlands, and Northeastern Leyte.

Northwestern Leyte is composed of a sedimentary sequence of a marginal basin. This basin comprises the northeastern segment of the Visayan Sea Basin. A north-northwest trending anticlinorium is observed in this area. In the southwest, the rocks have an ophiolitic basement and Paleogene sedimentary affinity.

Malitbog Ophiolite, which is Late Cretaceous in age, forms the basement rocks of western Leyte. Typically found are serpentinized harzburgites, dunites, gabbros, diabase sheeted dike complexes, pillow basalt and pelagic sedimentary rocks. Also of the Late Cretaeous is the Lagawan Gabbro, found mostly in the Maasin area, and the Cagbaon Basalt which is comprised of pillow basalts and breccias found also in the Maasin area. Tigbauan Formation of limestones, shales, cherts and sandstones is also dated Late Cretaceous and lies conformably over the Cagbaong Basalt. The Lagawan Gabbro is unconformably overlain by the Amontay Sandstone, aged Middle to Late Eocene, and is composed of limestones, shales, siltstones, sandstones and calcareous breccia. Lying atop the Gilonon Formation are conglomerate, sandstone, siltstone and tuff rock types of the Late Eocene. Unconformably lying over the volcanic rocks is the Late Oligocene to Early Miocene Kantaring Limestone. The Batang Formation, which has an age of Late Oligocene to Early Miocene, contains sandstones, siltstones and mudstones. This is overlain by an Early Miocene clastic sequence. The Taog Formation of sandstones, shales, coal, and conglomerate, dated Early Miocene, also lies unconformably over the basement rocks. Lying unconformably over it is the Middle Miocene Tagnocot Formation made up of shales, limestones and conglomerates. The Calubian Limestone is also dated Middle Miocene and it lies over the Middle Miocene Laboon Conglomerate. It is recognized for its coralline limestone and marly rock types. The Late Miocene Bata Formation overlies the previously mentioned Tagnocot Formation. It is also unconformable over the Calubian Limestone, and is unconformably overlain by the Early Pliocene Hubay Limestone. The Bata Formation has a lithology of tuffaceous marl and tuff, with sandy and silty mudstone interbeds, conglomerate, sandstones, and some lenses of limestone. Like the Bata Formation, the Kadlum Conglomerate is also Late Miocene in age which is unconformable over the Tagnocot Formation. Conglomerate with interbeds of mudstone and calcareous tuff comprise the Late Pliocene Inopacan Formation, which lies over the Pangasugan Formation of central Leyte unconformably. The Tuktuk Formation, unconformably overlying the Calubian Limestone, is Early Pleistocene in age and is comprised of tuffaceous sandstones, shales and intercalations of pumice and marl. The San Isidro Limestone of Late Pleistocene unconformably overlies these older formations.

Oldest of the formations found in the Central Highlands region is the Albuera Diorite dated Eocene. The Kanturao Volcanic Complex of andesites, basalts, dacites and other pyroclastic rocks are Late Oligocene to Early Miocene in age and is unconformably overlain by the Dolores and Pangasugan Formations. The latter is Late Miocene to Early Pliocene in age, and is composed of conglomerates, volcanic and pyroclastic rocks and sandstone and shale lenses. The Dolores Formation, on the other hand, is unconformable over the Pangasugan Formation and is dated Late Pliocene. It is made up of conglomerates, sandstones, shales and limestones.

Over the Dolores Formation unconformably lies the Visares Limestone of the Late Pliocene. Intruding and overlying old volcanic rocks in Leyte is the Leyte Volcanic arc complex, aged Late Pliocene to Recent. These are andesitic volcanic cones and flows and basalt rocks. This is found along the lineation of the Philippine fault.

Eastern Leyte is host to the Cretaceous-aged Tacloban Ophiolite, characterized by serpentinized harzburgites, gabbro, sheeted dikes, basalts and pelagic sedimentary rocks. Also Cretaceous in age is the Tagawili Ultramafic Complex of serpentinized harzburgites and dunites. The Tigbao Gabbro is also dated Cretaceous, and so is the Paglaum Diabase Complex and the Caibaan Basalt. The former is comprised of diabases, gabbros and basalts, and the latter is composed of pillow basalts. Capping the Caibaan Basalt is the Palanog Formation of chert, mudstone, shale, sandstone and vitric tuff, also Cretaceous in age. The Early Miocene San Jose Formation is composed of conglomerates, sandstones, shales and foine tuffaceous sequences with intercalations of volcanic flows. It is seen in some outcrops as overlying the older volcanic rocks. The San Ricardo Formation is Middle Miocene in age and is comprised of conglomerates, sandstones, shales and occasional limestone interbeds. It unconformably overlies the Tacloban Ophiolite and San Jose Formation rocks. Unconformable over the San Ricardo Formation is the Bagahupi Formation. It is composed of sandstones and marly tuffaceous shales with basal conglomerates, and is dated Late Miocene to Pliocene.

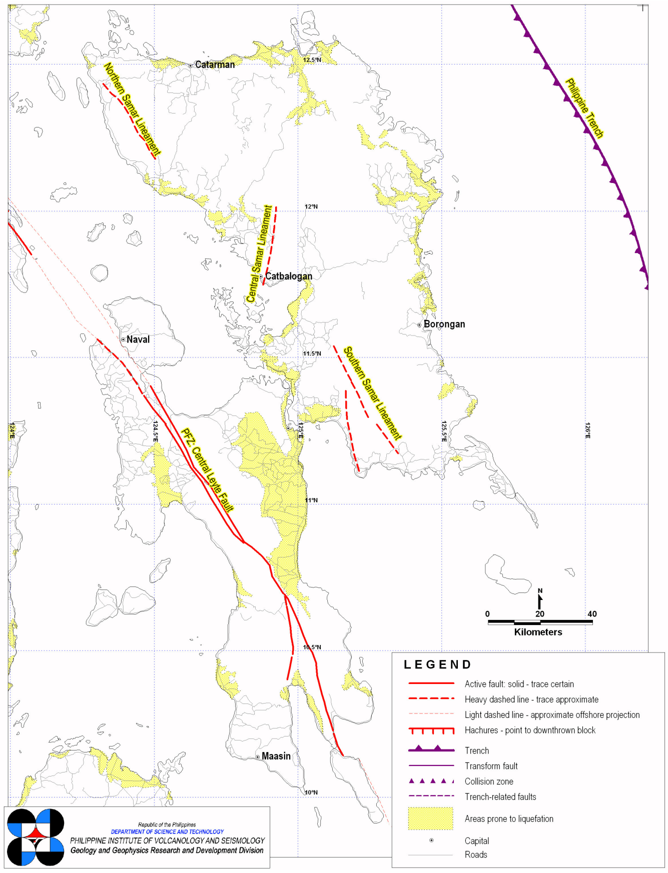

Figure 2: Active faults and liquefaction susceptible areas in Region 8 (source: http://www.phivolcs.dost.gov.ph).

5. Soil and Land Cover

The soils of the province are categorized into four: poorly drained flat lowland; moderately drained flat lowland; well-drained flat lowland; and well-drained rolling uplands [3].The poorly drained soils in Leyte are found in the following areas: low lying areas around Palo,Tanauan, and Alangalang (Pawing Series); around the municipality of Palo, extending to the inner regions at the foot of the central Cordillera near Jaro and Dagami, Alangalang and Barugo on the north and in Abuyog on the south (Palo Series). Pawing and Palo series developed from recent alluvial deposits and both have minimal soil profile development.

The moderately drained flat lowland soils belong to the soil series of San Manuel, Umingan, Dagami, Mandawe, and Bantog series. These soils are found in the following areas: Babatngon, Palompon, Hilongos; alluvial soil formation on Western Leyte from Ormoc to Baybay; in the municipality of Dagami; along the Hilongos and Bangerahan rivers; and in the municipality of Villaba. These soils developed from alluvial deposits, show moderate soil profile development, and have level to nearly level topography. These soils are mostly cultivated for agriculture.

Under well drained flat lowland soil is Obando series. This series is found in the eastern shores of Leyte, occupying the narrow coast from Palo to Abuyog. Obando series developed from marine deposition. This soil series has low organic matter content and has a coarse sand to fine sandy loam texture.

The well drained rolling upland soils are divided into two categories: the noncalcareous and calcareous soils. The noncalcareous soils include the following soil series: Guimaras, Tacloban, Guimbalon, Luisiana, Palompon, Malitbog, and Maasin. These soils are found in the following areas: foothills of the eastern slope of the range running from Palo to Babatngon; low range of hills and mountains between Palo and Babatngon; in Ormoc and in between Capoocan and Dagami; upper area of Ormoc and in Barugo; in the municipalities of Villaba and Palompon; small area south of Baybay; and in the interior regions from Inopacan to Malitbog. Another soil series found in Leyte is the Lugo series which is a calcareous soil. It is found in the municipalities of San Isidro, Calubian, and in some areas of Villaba [3].

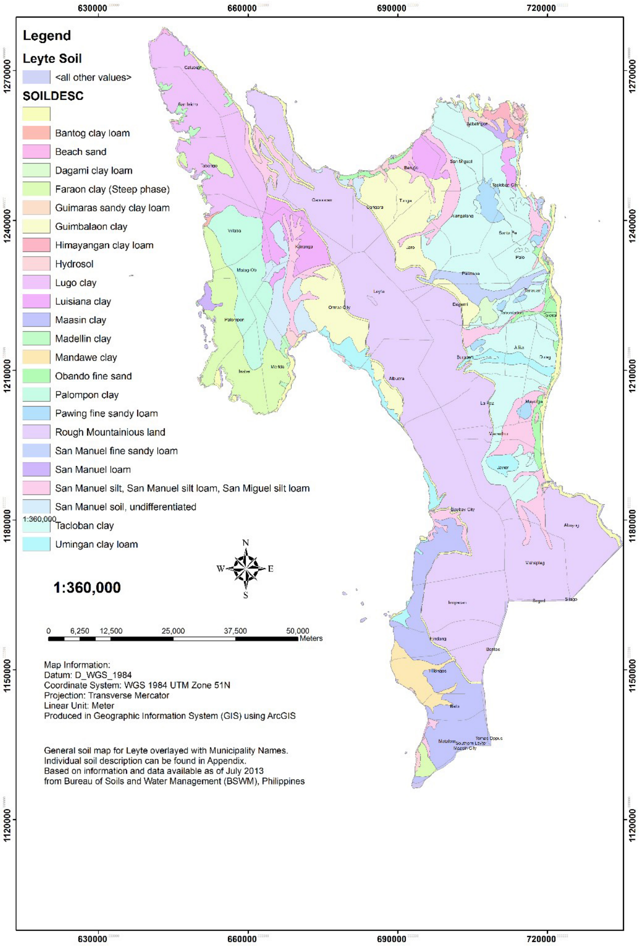

Figure 3: Soil Map of Leyte Province

Closed forest	Open forest	Mangrove	Total
3,962	57,332	4,683	65,977

Table 1: Forest cover of Leyte Province in hectares. Modified from [4].

6. Watershed and Drainage

Leyte has two forest watershed reserve: the Palompon Watershed Forest Reserve which covers Palompon and Villaba, and Patag-Gabas Watershed Forest Reserve which covers Baybay[5]. Leyte has 11 river watersheds. These are: Magon-Bucan, Bao, Binahaan, Bito, Daguitan, Gibuga, Guinarona, Mainit, Pongso, Palo, and Salug. These river watersheds cover several municipalities. These are the following: La Paz, Macarthur, Inayopan, Ormoc City, Kananga, Capoocan, Carigara, Jaro, Pastrana, Dagami, Abuyog, Baybay, Burauen, Albuera, Julita, Dulag, Sta. Cruz, Alangalang, Barugo, Tunga, Palo, Sta. Fe, Tacloban City, Hindang, Hilongos, and Inopacan[6].

The largest plain in Leyte is drained by several rivers. These are the Binahaan, Guinaroma, Daguitan, and Marabang rivers. The headwater of Binahaan River is Lake Danao. These rivers drain into the sea. The drainage on the plain can be considered

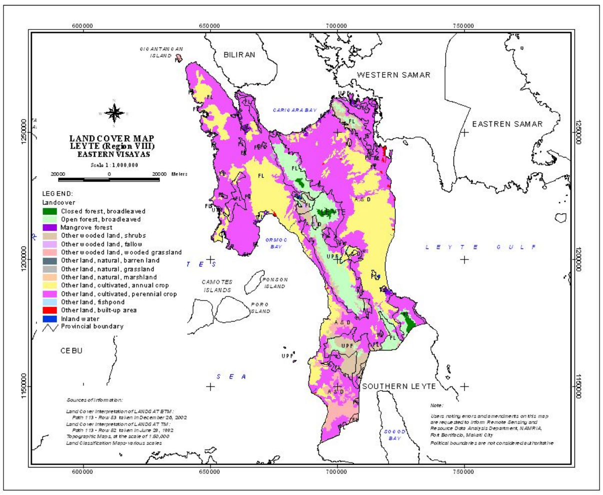

Figure 4: Leyte Province land cover [4].

as unsatisfactory. Drainage on the cultivated hills is excessive and the rivers are short and intermittent. The western side of the hilly range drains toward the Visayan Sea while those on the eastern side merges with Pagsangahan river and then empties into Ormoc Bay. The plain coast of Ormoc has a better drainage than the Pagsangahan Plain[3].

7. Recognition and Characterization of Alluvial Fans

Alluvial fans around Leyte were initially delineated in ENVI using 90-m resolutiion digital elevation models (DEM) of the Shuttle Radar Topographic Mission(SRTM). Using a mapping software, watersheds were extracted and contour maps were generated from the DEM as shown in figure ().

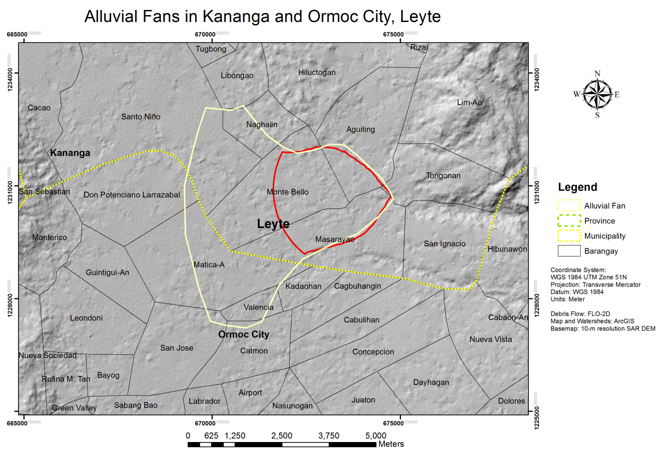

Figure 5: Alluvial Fans in Kananga and Ormoc, Leyte Province

By generating at least 5-meter interval contour maps on ENVI and by veryfing this using available topographic maps from NAMRIA, the outline of the alluvial fans were delineated. Each alluvial fan was delineated from its apex to its inverted triangular base. The fan polygons were then overlaid on aerial imagery to check the source and tributaries. Aerial and satellite imageries were also used to map the land cover and built-up areas within the alluvial fans to check if there are communities on these zones.

The delineated polygons were overlain on a geologic map to check if the underlying lithology covered by the fans is Quaternary alluvium, the primary deposit that can be found on alluvial fans. Using both geologic and soil reports, alluvial deposits were classified according to grain size and sorting. The fan polygons were used for the identification of villages at risk of debris flow and flooding.

Based from the apex of the alluvial fan located in the municipality of Kananga, Leyte, a total of 15 barangays are at a risk of debris flows as enumerated in Table **??**. Out of the 15, barangays San Ignacio, Tongonan, Aguiting, Masarayao, and Monte Bello face the highest risk for the possibility of a debris flow. These barangays are located near or at the apex of the alluvial fan, where the impact of the debris that may be deposited during heavy rainfall is greatest.

8. Debris Flow Simulation

Meanwhile, the resulting debris flow hazard map shows similar risks in the same areas. While the debris overlaps the alluvial fan, it is safer to assume that duing a debris flow, the debris will most likely not travel beyond the boundaries of the alluvial fan. The simulation used a digital elevation model with the lowest resolution as higher resolution images are still undergoing simulation.

The legend on the map shows that in the event of a debris flow, areas covered in red will most probably be buried 1 meter or above (at least 3 feet) of debris. Areas in orange, pose a lower threat, with a debris depth of 0.2 meter to 1 meter (from 7 inches to below 3 feet).

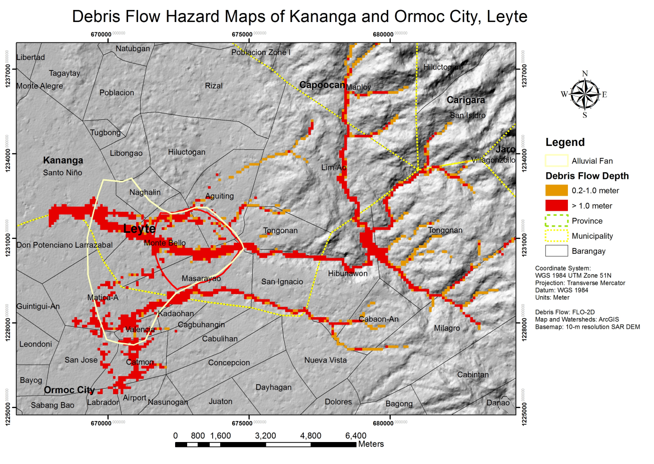

Figure 6: Debris Flow Hazard Map of Kananga and Ormoc, Leyte Province

It is also important to note that the simulation on the figure has not yet been validated in the field. Field assessment needs to be accomplished first before a more accurate extent of the area covered by debris on the map can be verified.

9. Landslide Inventory

The landslide inventory map produced for the province of Leyte was done through the use of high-resolution satellite imagery. Sets of satellite images covering the study area were viewed and inspected for landslides, which were then delineated as polygons and marked with 'dots' using a geographic information system (GIS) computer software. Data such as the total area of landslides (total damaged area in the province) and the total area of landslides with respect to the area of the province were also computed.

The satellite imageries used include SPOT, Quickbird, and Worldview. SPOT imagery has a spatial resolution of 5 to 10 meters; Quickbird, 0.6 to 2.4 meters; and Worldview, 0.5 meters [**?**]. The satellite images used are from the years 2002 to 2012. The dates of the satellite images, however, are not uniform throughout the study area. Which satellite images can be used depended on their availability in Google Earth, a computer freeware.

Landslides seen in the satellite image were marked with 'dots' and delineated as polygons. These dots and polygons were saved as shapefiles (.shp extension) for them to be easily accessed and analyzed using GIS programs. The types of landslides that are easily identified on satellite imagesand were mainly considered in this inventoryare flows and slides.

The areas of the individual landslide polygons were computed using the Calculate Geometry function in ArcGIS. The total area of landslides for the study area was subsequently computed along with the total area of landslides with respect to the area of the province.

Landslide inventory for the provinces of Leyte and Southern Leyte, yielded a total of 130 points (table **??**), each of which were identified and delineated for calculation of damaged area. Together, the calculations on the two provinces resulted to a total damage area of 1,018,585.03 sq.m (Leyte - 227,413 sq.m. and Southern Leyte: 894,117.11 sq.m). The landslides within the province of Leyte were noticably concentrated into two regions: western and eastern group, separated by the flat plains within the municipalities of Kananga, Ormoc City and Leyte. Most of the hazards occurred at the elevated region of the province which in turn coincides with the path of the Central Leyte Fault. The same holds true for the landslides in Southern Leyte. The municipality of Sogod in Southern Leyte, which was identified as a second income class municipality and has a population of 41,411 (as of May 1, 2010)[7], has the most number of landslides - 24 points and a damage area of 201,995 sq.m. The muncipality of Silagod, Southern Leyte has the highest damaged land cover at 289,231.04 sq m.

10. Shallow landslide susceptibility

The map was produced using SINMAP (Stability INdex MAPping) software, an ArcViewTM 3.x extension developed

Municipality	No. of landslides	Damaged area (DA) in sq. m.	DA/Total DA [%]
Abuyog	5	41569.53256	18.27926356
Alangalang	2	7834.178337	3.444903075
Albuera	2	3081.407497	1.354979387
Dagami	1	1861.407783	0.818512053
Hindang	4	3371.862367	1.482700359
Kananga	2	41040.46323	18.04661726
Mahaplag	9	16061.54542	7.062702025
Matalom	1	3397.724073	1.494072461
Merida	1	10305.49186	4.53160741
Ormoc City	14	84419.75276	37.12168059
Tacloban City	4	14470.24099	6.362961827
Bontoc	5	31517.98911	3.52504039
Hinunangan	4	10731.26181	1.200207639
Libagon	12	238547.299	26.67964828
Liloan	8	62657.1838	7.007715588
Malitbog	4	30589.97313	3.421249066
Padre Burgos	1	4997.756279	0.558959922
Saint Bernard	4	8189.241678	0.915902584
Silago	19	289285.4293	32.35431101
Sogod	24	201995.0951	22.59157036
Tomas Oppus	4	15605.87664	1.745395155

Table 2: Inventory of landslides per municipality in Leyte(above the line) and Southern Leyte(below the line)

by Pack and others (1998) for use in a geographic information system (GIS). SINMAP computes a factor of safety using the infinite slope model (Pack et al., 1998) and (Hammond et al., 1992) based on the input hydrologic, soil and topographic data (1.1)for each pixel on a LiDAR (Light Detecting And Ranging)-derived digital elevation model grid. The factor of safety (FS) is a dimensionless number that represents the ratio of the stabilizing forces to destabilizing forces at a location. A FS<1 indicates unstable conditions, whereas a FS>1 indicates stable conditions given the assumptions and parameters input into the model. SINMAP then assigns a stability index based on the computed factors of safety. The six stability zones are assigned relative hazard rankings (high, moderate, and low) based on the calculated stability index ranges, and known slope movement occurrences.

Model input parameters include upper and lower bounded values for recharge to the shallow groundwater system, soil transmissivity (soil permeability or hydraulic conductivity multiplied by soil thickness), and other soil properties (i.e., unit weight, thickness, effective internal friction angle, and effective cohesion). SINMAP randomly samples the bounded input parameter values using a uniform probability distribution to account for the variability and uncertainty inherent within the natural system. Soil classiffcations, descriptions, and test results, along with literature values for soil properties given in Hammond and others (1992) were used to constrain reasonable ranges of soil input parameters for the stability index modeling. Parameter values (primarily dimensionless cohesion, soil thickness, internal friction angle, and hydraulic conductivity) were then adjusted within reasonable ranges to maximize the number of slope movement locations per area.

To stimulate the landslide susceptibility of the area, information on geology, soil type and elevation are acquired. The soil texture is generally clayey (Table 3).

Parameters		Clay
T/R	Lower	40
	Upper	400
Cohesion	Lower	0.606
	Upper	1
Phi	Lower	18
	Upper	26
soil		1746

Table 3: Calibration parameters used as input to SINMAP.

11. Deep-seated landslide susceptibility

11.1. Rockslide zone identification

Structurally-controlled landslides were mapped with software such as Coltop3D and Matterocking. Coltop3D is used to simulate a 3D model of the DEM showing the dip and dip direction of its different discontinuity sets. Matterocking computes and estimates the locations where rock instabilities can occur according to the identified discontinuity sets that allow sliding. The software require binary or ASCII format files for import. Digital Elevation Maps (DEM) taken via Synthetic Aperture Radar (SAR) were converted to binary and ASCII format files. The conversion was done through Global Mapper.

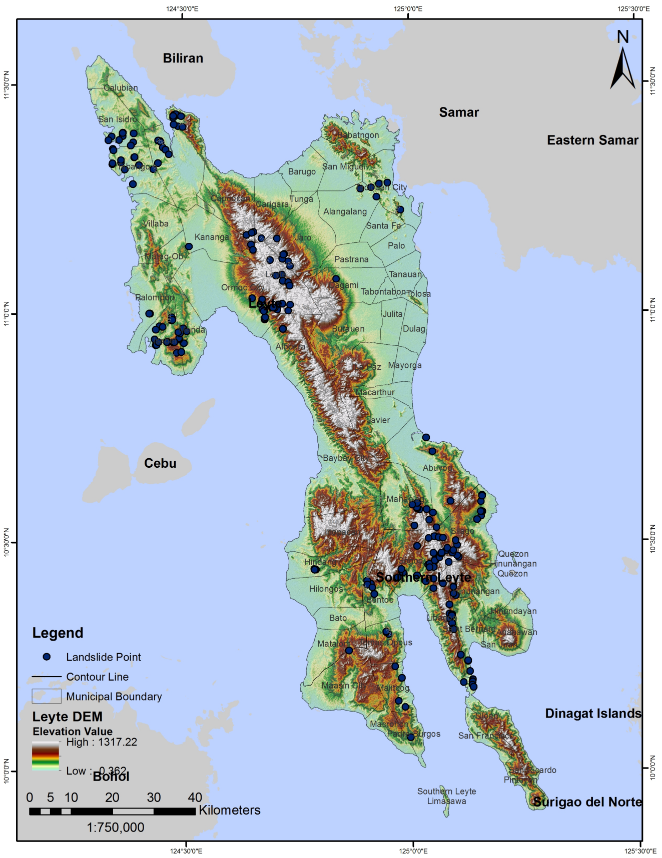

Figure 7: Landslide Inventory for Leyte Province

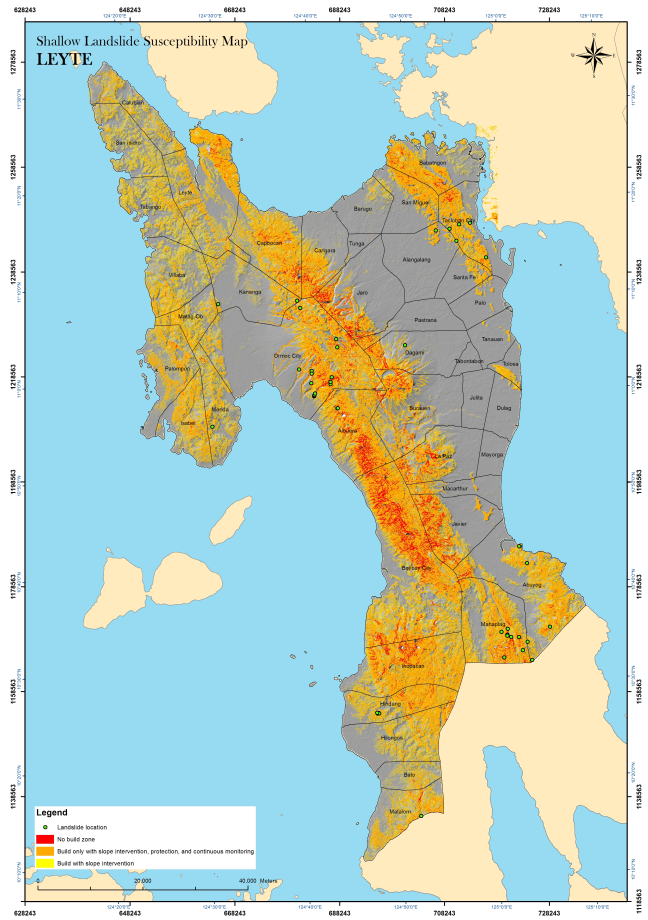

Figure 8: Shallow Landslide Susceptibility Map

The binary floating-point value file of the DEM was imported to the Coltop3D software where pyramid intervals of 1.00 was used. Using the Selection tool, discontinuity sets that are dominant in the area are identified. Only discontinuity sets, with azimuth from 0°-345°, with dip angle greater than 45° were considered.

Matterocking, using the Intersection (yes/no) treatment, uses the identified discontinuity set orientations to create a file containing 1 and -1 which corresponds to the zones where the discontinuity can produce rock slope failures or not, respectively. All the files created by Matterocking are then overlain in a basemap using ArcMap, showing the different zones in the area which are prone to sliding.

11.2. Parameters

The criterion used in this method of detecting zones of potential instabilities is based on topographic slope. It is assumed that the steeper the slope is, the more it contain instabilities. Based on the rock type, a critical slope can be established wherein rock instabilities could occur [**?**]. The 45° dip angle is considered to be the critical angle for failure based on a general rock type.

11.3. Results

The Tacloban area is generally low lying in topography. The discontinuity sets in the area were identified to have orientations with up to 45°-50° dip angles with some other orientations reaching up to 55° dip angles. According to the simulated maps, the barangays of Barangay 91, 92, 95-A, 106 and 107 are possible zones for a structurally controlled rock failure.

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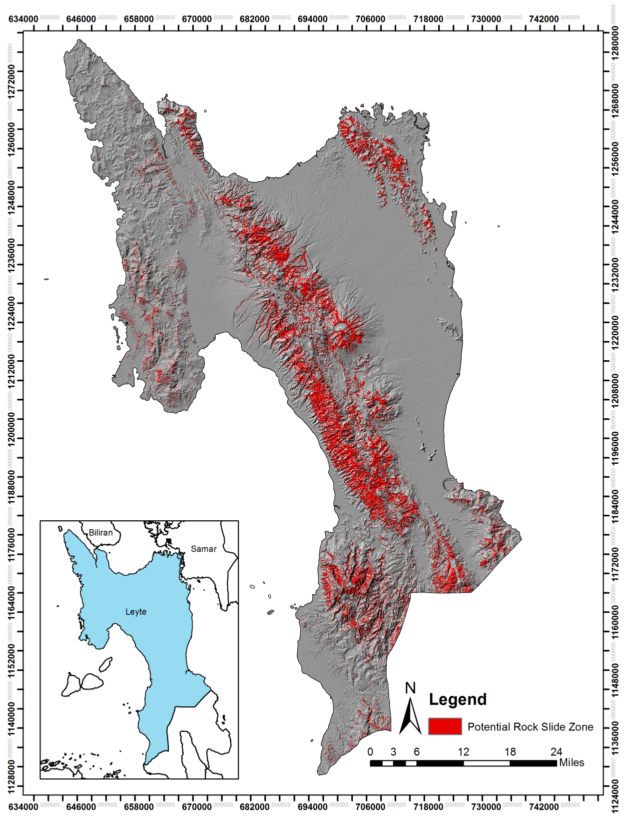

Figure 9: Potential Rockslide Zones of Leyte Province.