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The use of photogrammetry for landslide inventory in the Northern Range, Trinidad

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ABSTRACT. Landslide hazards occur in many places around the world and pose serious threats to settlements, structures that support transportation, natural resources management and tourism. The knowledge of the past occurrence of landslides in a specific location can assist in estimating future landslide occurrences and hazard. Photogrammetric techniques have great potential in bridging the gaps in data and information needed for forecasting and managing landslides hazard and risk. This paper reports on the use of photogrammetric techniques for the detection and extraction of historical landslide forms. The study area is within Trinidad; a mountainous small island situated in the southern Caribbean. The tropical environment of the island poses challenges in detecting landslide scarps on aerial photographs since any exposed soil or rocks would almost immediately be covered by vegetation. This study makes use of 45 aerial photographs acquired in March of 1994 at scale of 1:25,000 that covered the western part of the Northern Range of Trinidad. The outcome is a GIS-based inventory of eleven historical landslides that have been successfully identified in mainly forested low-grade metamorphic terrain of the study area.

Key words: Photogrammetry; Geomorphology; Landslides; Tropical Regions; Trinidad.

1. INTRODUCTION

Trinidad is a tropical island of approximately 4,800 km^2, located at the south fringe of the Caribbean Sea, northeast of Venezuela. The island experiences a warm tropical climate with a dry season from January through May, and a wet season from June through December. The most prominent feature in the island's topography is the presence of three mountain ranges that run east to west (**Figure 1**). Among them, the Northern Range is the most noteworthy in terms of size, formation, and height. Geologically, the Northern Range is a deeply divided mountain system that consists of low-grade metamorphic rocks of upper Jurassic to Cretaceous age, folded into a broad anticline (DeGraff et al., 1989).

Recurrent landslide activity is a common problem in the island. The majority of landslides cases in the Northern Range are concentrated along roadways, caused by slope-disturbing activities where roads cross steep slopes, and triggered by intense rainfall. Slope failures on natural slopes are also present in the Northern Range, though they tend to be significantly larger and deeper-seated than those associated with roads (DeGraff et al., 1989).

Figure 1. Location of the study area in Trinidad, lighter tone represents higher elevation.

With the advent of each wet season, more slides are expected to occur and coincide with heavier rainfall. As a case in point, the national authorities recorded 159 landslides, 59 mudslides, 4 collapsed bridges and hundreds of fallen trees during the month of January 2005 that saw a record high rainfall that surpassed those previously recorded (Alexander, 2005). In view of this, some US$30 million dollars was allocated for the investigation, repair and maintenance of landslides in Trinidad and Tobago. In contrast, the average annual cost for such tasks by the early 1980's was about US$1.6 million dollars (DeGraff et al., 1989).

The impact of slope failure on the human and economic environment along the Northern Range is considerable and may lead to catastrophic consequences if the relevant authorities do not initiate proper analysis, planning and mitigation. Moreover, the development of areas in the Northern Range under the pressures of increasing population and urbanization would further increase the susceptibility to landslides and may lead to loss of life and property.

The objective of this study is to provide an inventory of historical landslides along the Northern Range from Chaguaramas in the western peninsula to Chapura Bay east of Las Cuevas Bay (**Figure 1**) utilizing photogrammetry and geographic information systems. The findings of this study can serve as a genesis for the future detection and analysis of landslides for the entire Northern Range. Experts would then have an improved basis for making better-informed decisions about future development in areas prone to landslides or mass wasting.

2 LANDSLIDES

Landslides are defined as the movement of a mass rock, debris or earth down a slope (Cruden, 1991). The materials may move by falling, toppling, sliding, spreading, or flowing. Different types of landslides can be differentiated by the kinds of material involved and the mode of movement. Rotational slides are the type in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide. While in translational slides, the landslide mass moves along a roughly planar surface with little rotation or backward tilt. A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as slurry that flows downslope (Soeters and Van Westen, 1996).

Landslides are usually the result of a complex interaction between environmental factors (e.g., lithology, slope gradient, shape of the hill slope, land cover, microtopography) and human factors that modify those environmental conditions (e.g., land use practices) (Metternicht et al., 2005). Landslides can be triggered by a variety of factors (such as intense rainfall and earthquakes) that cause a rapid increase in shear stress or decrease in shear strength of slope-forming materials. In addition, human activities (such as deforestation or excavation of slopes for constructing roads and buildings) have become important triggers for landslide occurrence as development expands into unstable hill slope areas (Dai et al., 2002). In addition, the climate change may increase the frequencies of future landslides (Walstra et al., 2007).

Landslides account each year for enormous property damage in terms of both direct and indirect costs. Landslide activity worldwide is increasing, and this trend is expected to continue because of: the increased urbanization and development in landslide-prone areas; continued deforestation of landslide-prone areas; and increased regional precipitation caused by changing climatic patterns (Dai et al., 2002; Schuster, 1996).

The prediction of potential landslide areas has been very difficult because of the complexity of the factors involved and the relationship to each other. The landslide hazard can normally be predicted based on the assumption that landslides are most likely to occur in conditions similar to those that have caused past failures (Soeters and Van Westen, 1996). Hence, the knowledge of the location, type and distribution of landslides occurring over time is essential for forecasting the future evolution of landslides in an area, and would provide a better understanding of their underlying mechanisms (Walstra et al., 2007). However, there is a severe shortage of reliable and compatible datasets in Trinidad and in the Caribbean region in general. Information needed for accurate planning is often outdated, non-existent, or very expensive and time-consuming to collect (Al-Tahir et al., 2006). This information poverty makes planning and decision making for managing the landslides hazard and risk both challenging and error-prone.

3 AERIAL PHOTOGRAPHS FOR LANDSLIDE DETECTION

In contrast to field techniques for landslide mapping and monitoring, applying photogrammetric techniques to historical aerial photographs would effectively provide spatial and quantitative data about past movements (Walstra et al., 2004). The advantage of aerial photographs in such a task stems from the fact that they provide high spatial resolution and synoptic view of an entire area that allows the user to see features, patterns, and trends that cannot be seen on the ground. Moreover, they can be repeated at different time intervals permitting multi-temporal analysis (Ciciarelli, 1991; Karsli et al., 2004).

The use of stereoscopic aerial photographs in slope instability studies is considered valuable and indispensable because of the diagnostic morphology created by some mass movements (e.g., disrupted vegetation cover, scarps) that can clearly be seen in large-scale aerial photographs. Considering the size of most landslides and debris flows, the most useful photographic scale that enables mapping slope instability features and other individual elements of a landslide is around 1:15,000 to 1:25,000 (Metternicht et al., 2005). Some of the most recent uses of photogrammetric technique for landslide inventory and study are those reported in Duman et al. (2005), Kajiyama et al. (2004) and Walstra et al. (2007).

There are, however, several challenges with use of archival photography. Generally, there is a lack of precise photo-control available at the time of photography and similarly, it is rare to get hold of the camera calibration certificate. Additionally, due to the time that has elapsed since the photo mission was undertaken, it is difficult to conduct field verification to assess the quality of the extracted morphological data from the archival photography (Walstra et al., 2004).

3.1 Photo Interpretation and Stereoscopic Viewing

Photo interpretation is the act of examining photographic images for the purpose of identifying objects and judging their significance (ASPRS, 1997). It utilizes the skill of the interpreter to detect and identify objects of interest on aerial photographs. In order to properly carry out the interpretation the interpreter relies generally on eight elements; tone, size, shape, texture, pattern, shadow, site and association. While these photo interpretation elements are all monocular, interpretation may also be aided by binocular vision.

Stereo photogrammetry is a quantitative approach that uses aerial photographs for the creation of a three-dimensional model of the terrain, and allows measurements on the model. When two overlapping aerial photographs are placed in a stereo plotter, they would be arranged and combined in such a way that they form, when viewed stereoscopically, a true-scale three-dimensional terrain model (Mikhail and Bethel, 2001). The use of control points obtained from ground surveys or existing maps to create a stereo model will render the stereo model referenced within some geographic framework. Subsequently, any point measured or extracted from that model will have its geographical (map) coordinates.

The stereo photogrammetry technique is particularly useful in providing metric data critical to the study of landslides (Walstra et al., 2007). The stereo models depict three-dimensionally the typical morphologic features of the landslides and the state of the surrounding vegetation. This can provide diagnostic information that can reveal the type of slide, depth, vegetation and drainage conditions of the landslide.

3.2 Detecting Landslides with Aerial Photographs

Light-toned vegetation clearances of scarps may be the most straightforward clue for detecting landslides. However, scarps of historical landslides may not be detectable on aerial photographs, as they most likely have been subsequently covered by vegetation. This is most definitely the case in a tropical environment. Additionally, other geological clues, such as rocks, bedrock and unconsolidated material and geological structure may not be evident either. Landslides must then be inferred from geomorphologic and other associated clues seen on the photographs.

For that purpose, the elements of photo interpretation should be translated into some diagnostic patterns and indicators of landslides, based on morphology, vegetation, and drainage patterns that are seen in the stereo model. Several of these indicators are discussed in Ciciarelli (1991) and Soeters and Van Westen (1996); however, the following underscores the most relevant and significant of these in relation to tropical mountainous environment. It is expected that one would perceptively consider and be guided by these indicators when inspecting aerial photographs for landslides. In the category of morphology and topography, these are:

- Unnatural topography, such as spoon-shaped trough or concave/convex anomalies in the terrain, would indicate landslide niche and associated deposit.
- Light-toned scarp on steep slopes, associated with sharp line-of-break at the scarp or the presence of tensions, cracks, or both, would refer to the head part of slide with outcrop of failure plane.
- Oval or elongated depressions with imperfect drainage conditions identify rotational movement of slide blocks.
- Coarse surface texture contrasting with smooth surroundings would highlight hummocky and irregular slope morphology that indicates shallow movements or small retrogressive slide blocks.

• Anomaly in valley morphology may imply mass movement deposit of flow-type form causing accumulation of debris in drainage channels or valleys.
• Land masses undercut by streams, road cuts, railroad cuts, or building excavations.
• Inclined trees, utility poles, fence posts, and walls caused by creep.

Using the vegetation as a guide, one may look for the following signs:
• Light-toned elongated areas at crown of mass movement identify vegetation clearances on headscarp where vegetation has not been re-established.
• Bare areas showing light tones, often with linear pattern in direction of movement indicate slip surface of translational slides and track of flows and avalanches.
• Irregular and sometimes spotty grey tones indicate disrupted, disordered, and partly dead vegetation due to slide blocks and differential movements in body.

Another set of observable characteristics of landslides relays on the drainage patterns:
• Tonal differences with darker tones associated with areas of higher moisture content that point to areas with stagnated drainage associated with landslide niche, back-tilting landslide blocks, and hummocky internal relief on landslide body.
• Light-toned zones in association with convex relief forms indicate excessively drained areas caused by out-bulging landslide body (with differential vegetation and some soil erosion).
• Drainage line abruptly broken off (on slope by steeper relief) caused by head scarp.
• Closely spaced drainage channels.

4. METHODOLOGY

The methodology adopted in this study relies on using aerial stereo photogrammetry for the detection of landslides and the quantification of their physical characteristics. Geographic Information Systems (GIS) will also be used for the linkage of spatial and attribute data of each slide detected for the inventory. The final output will be in the form of a map with tabular data indicating the landslide types within the study area. The DVP-GS digital photogrammetric software system will be used for the extraction of landslide forms, their spatial positions and the depths. Arcview 3.2 will be used for the input of attribute data and display of the spatial positions of the landslides forms.

The first phase in this process is to identify and acquire relevant aerial photographs. Forty-five panchromatic photographs at scale of 1:25,000 were found covering the study area. They are arranged in three strips; the upper strip is made of photographs 21-30 from line LSTT07, the middle strip contains photographs 123-134 from line LSTT01 and photographs 124-129 from line LSTT07, and the lower strip consists of photographs 83-101 from line LSTT01. These photographs are part of the comprehensive mission of aerial photography in March 1994 that was used for the production of the national base map. The photographs were then scanned at 800 dpi resolution that rendered a pixel ground size of about 80 cm. This task is essential in order to prepare the aerial photographs for input into the softcopy photogrammetric system.

4.1 Orientation of a Stereo Model

The second phase in the methodology is the orientation of the stereo models, which is vital for establishing the true geographic position, scale and tilt of the stereo model before any qualitative or quantitative measurements can be made. The orientation of a stereo model has three stages; interior relative and absolute orientations. The interior orientation aims at re-establishing the internal geometry of the camera at the time of exposure; this requires having the aerial camera calibration data. The relative orientation deals with establishing the spatial relationship between two consecutive photographs relative to each other. By the end of this stage, each ray from one photograph will intersect with the corresponding ray from the other photograph, creating the stereo model. Such a model is a scaled down three-dimensional version of the real terrain (Mikhail and Bethel, 2001).

The last stage is the absolute orientation of the stereo model, by which the stereo model is related to the geographic reference frame. This system depends on having control points with ground (map) coordinates to properly scale and level the stereo model (Mikhail and Bethel, 2001). Considering the photo scale and the difficulty of gaining access to the area, the use of maps at a scale of 1:25,000 was deemed sufficient for providing control for this task. Five specific map sheets were consulted for this study and they were from the E804 (D.O.S. 316/1) series and numbered sheet 3, 4, 12, 13 and 14.

4.2 Information Extraction

This phase is concerned with the collection of significant information related to landslide forms through the use of stereo photogrammetry. Each of the forty models was set up to the stage of relative orientation, and was then inspected for the presence of landslides. Following the photo interpretation

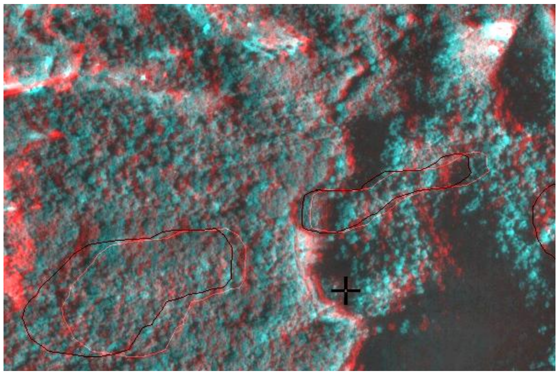

Figure 2. Two landslides as depicted on the photographs.

principles outlined in section 2.2, the inspection of landslides drew on identifying their concave upslope source and convex down slope deposit, as well as inspecting the main scarps. Additionally, the vegetation and drainage of these historical landslides were examined. Overall, the concavity coincided with tonal differences in the vegetation, as shown in **Figure 2**.

Only stereo models that were identified to contain landslides were then processed through absolute orientation. The floating marks were placed on the slide form and the boundaries of the slide were traced out. Since the stereo models were georeferenced in a geographic framework, the landslide would also have map coordinates. By the end of this phase, eleven landslides were detected and categorized as translational landslides, rotational landslides and an earth flow. The landslide forms that were detected were mainly on slopes that were exposed to weathering, where the vegetation was dense and the slide forms overgrown. Based on the vegetation coverage and the morphology, all detected landslides appear to be of an historical nature rather than a recent occurrence.

4.3 Data Development and Results

As the final stage, the detected landslides were appropriately converted into polygon themes in ArcView. Tables were then created to include fields such as slide's identification number, type, location (Easting, Northing), area (in square meter), depth (metres), volume (in cubic metres), as well as the types of vegetation and activity in its surroundings. These attribute data were entered by adding records to the table. The georeferenced landslide now has attribute data associated with it, where by clicking on each slide, a table with attribute would appear.

5. RESULTS AND ANALYSIS

The mapping and distribution of the landslides within the study area were detected with the aid of aerial photo interpretation and aerial stereo photogrammetry. The spatial characteristics of detected landslides were extracted by stereo photogrammetry and brought into GIS software where attribute data were added to each landslide. The final maps portrayed the distribution and geographic location of the historical landslides detected by this study. The results were presented in the form of a tabular inventory of the historical landslides that were detected within the study area (**Table 1**), as well as in the form of maps (**Figure 3**) that depicts the distribution and the geographic extent for these landslides.

Based on 45 aerial photographs at a scale of 1:25,000, a total of 39 stereo models was created and inspected. Eleven landslide forms were detected; six translational landslides, four rotational landslides and one earth flow slide. This outcome is consistent with the findings of (DeGraff et al., 1989) that rotational and translational slides are the two main failure modes in the Northern Range. Some of the detected landslides are close to roads as seen in **Figure 3**, while the rest fall far away from the road network.

This is a plus point for the method as it could identify slides that could not have been reported before. On the other hand, it would be difficult to access and verify these slides in the field due to obstacles imposed by the rough terrain and dense vegetations. However, the detected landslides were compared with a recently produced landslide susceptibility map for Trinidad based on historic records of landslides in the island (Baban et al., 2006). This has substantiated the possibility of the detected landslides to have occurred.

6. CONCLUSIONS

This study demonstrated the value of aerial photographs as a contributor of data invaluable for understanding the dynamics of landslides. In an assessment of the method at the end, one may confirm the expectations associated with the technique of aerial photo interpretation for the detection of landslides, more specifically:

- Photo interpretation gave the interpreter an appreciation of the terrain surrounding landslide sites based on wider coverage.
- Photo interpretation allowed the interpreter access to remote and inaccessible areas and provided information that was not available before.
- Photo interpretation proved to be a very cost effective method.

Table 1. Attributes of Landslide Inventory

ID	Slide Type	Easting	Northing	Area (m^2)	Depth (m)	Volume (m^3)	Vegetation	Activity
1	Translational Slide	671669	1182890	231781	38	8807678	Dense	Stable
2	Translational Slide	664516	1185237	20233	15	303495	Dense	Stable
3	Translational Slide	673316	1189960	50114	10	501140	Dense	Stable
4	Translational Slide	665999	1187987	20624	14	288736	Dense	Stable
5	Translational Slide	667456	1190886	28526	18	513468	Dense	Stable
6	Translational Slide	676529	1191587	47052	41	1929132	Dense	Stable
7	Rotational Slide	666849	1183044	28052	15	420780	Dense	Stable
8	Rotational Slide	670978	1182758	103798	23	2387354	Dense	Stable
9	Rotational Slide	674152	1190050	16308	43	701244	Dense	Stable
10	Rotational Slide	673681	1191911	21397	16	342352	Dense	Stable
11	Flow slide	673894	1190144	673894	18	12130092	Dense	Stable

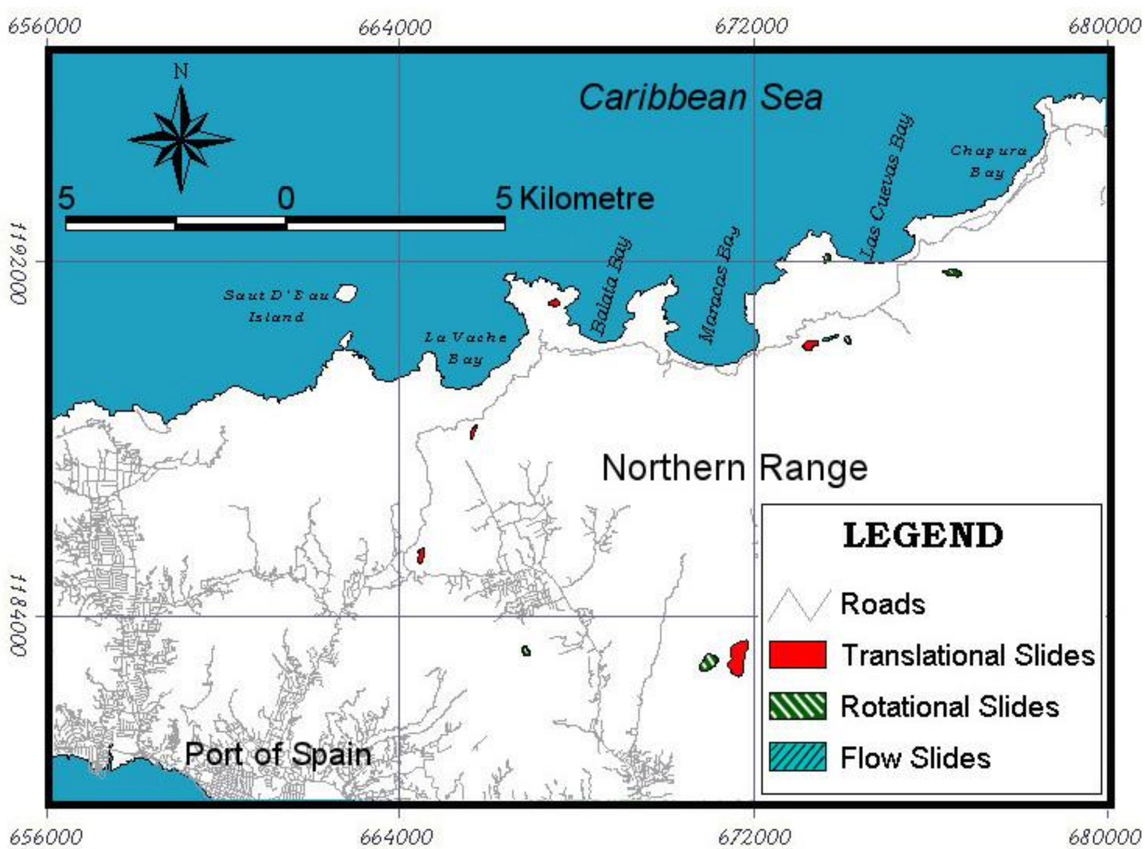

Figure 3. Location of landslides detected in the study area.

• The use of topographic maps at scale of 1:25,000 as the source for ground control points was proved to be suitable for this project.

• Aerial photography at scale 1:25,000 was verified to be suitable for this project

In parallel to these, this study had its specific limitations in the use of photo interpretation. Only photographs of 1994 were investigated since aerial photographic coverage at an appropriate scale for the area at a different time was not available. Thus, this condition hindered temporal comparison and analysis. On another front, the remote areas where the landslides were detected were inaccessible. The lack of proper road networks to the landslide sites and the relief of the terrain made the field verification exercise very difficult. The densely vegetated natural forest added further hindrance to the field verification exercise. Furthermore, this study is confined to a forested low-grade metamorphic terrain as opposed to the large-scale slop movements in a clay substrata common in southern Trinidad.

Nevertheless, the utilization of the technique of photo interpretation can be of benefit to the prediction of landslides in areas where there have been similar occurrences of landslides or mass wasting. Aspects of the environment, soil characteristics, vegetation, morphology and drainage conditions are of significant importance in this respect. The benefits of photo interpretation and stereo photogrammetry can be enhanced when integrated with GIS. Through the use of spatial analysis, predictions can be made about future landslides and their characteristics. This can benefit agencies involved in the planning as well as the mitigation and repair work that can be very costly.

Another useful use of such technique is to develop a reliable multi-temporal mapping and monitoring of landslide through a comparison between aerial photographs obtained over a period of several years. Such a database would also be useful to assess changes in the activity status of a specific landslide and other relevant changes of land cover and use.

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