Multi-temporal monitoring of landslides in archaeological mountainous environments using optical imagery: The case of El Tambo, Ecuador

Freddy Yugsi[1], Henri Eisenbeiss[2], Fabio Remondino[2], Wilfried Winkler[1]

[1]Geological Institute, ETH Zurich
E-mail: <freddy.yugsi><wilfried.winkler>@erdw.ethz.ch
Web: http://www.erdw.ethz.ch
[2]Institute of Geodesy and Photogrammetry, Chair of Photogrammetry and Remote Sensing - ETH Zurich
E-mail: <henri><fabio>@geod.baug.ethz.ch
Web: http://www.photogrammetry.ethz.ch

1 Introduction

Ground-based techniques for landslide analysis, as geotechnical characterization, geophysical surveys or field based geodetic monitoring, are often used in preliminary stages of landslide investigations. These methods provide very accurate punctual information, but they do not take in account, neither the anisotropy of the parameters that control the processes nor the asymmetric displacement of the moving masses into the landslide. Besides, the more precise the analysis is required, the more number of tests are needed. Generally, this is not always cost-effective, especially in developing countries where both land use planning and risk policies are under-valued and therefore few funds are assigned for natural hazard investigations.

Remote sensing imagery has proved to be useful for early stages in landslide analysis. Aerial photo-interpretation has been used in landslide detection since several years. Digital photogrammetry has become during last years a powerful tool for landslide detection and monitoring using large scale aerial photographs (1:10 000 or larger) taken with some periodicity. Unfortunately in the case of developing countries archives do not have periodicity and most of the photographs sets have been taken in a small scale (1:40 000 or smaller).

Mountains have always been considered as zones prone to the occurrence of landslides. Its instability could be increased for local geologic conditions like the presence of active tectonic faults. In the case of El Tambo (southern Ecuador), it has been favored by its geologic and climatic characteristics. Hence, large-size landslides have occurred in the area, most of them were active for a long period of time affecting around 25 000 people living in the two principal locations of El Tambo and Cañar.

In our work, field recognition, aerial photo-interpretation and mapping are used to identify the different areas where active landslides are located. A set of three DEMs (Digital Elevation Models) and orthophotos are created from different aerial image sets ranging from 1977 to 1995 to assess the variations of the most active landslides in the area.

2 Geographical Setting and Archaeological Heritage

The villages of El Tambo, Cañar and Ingapirca are situated in southern Ecuador, extending from 2° 28’ S to 2° 40’ S and 79° W to 78° 50’ W around 45 km away of Cuenca, the third important city of Ecuador. The elevation varies from 2700 m.a.s.l., in the vicinity of the Cañar River, to 3900 m.a.s.l. to the north, covering a surface of around 350 km^2 (Fig. 1)

The most important Incan site in Ecuador is at Ingapirca, (Alcina Franch, 1978) towards the east of the area. Here a temple complex incorporating classic Inca stonework was built over earlier Cañari structures. During the Incan empire time its centre was a temple of the sun. The surrounds comprised of a great plaza and of a good number of buildings that must have included official residences, stores, houses and barracks.

3 Geological Setting

The area of El Tambo is settled in the northwestern corner of an inter-mountainous Middle-Late Miocene sedimentary basin (Cuenca basin) limited at both sides for two N-S striking cordilleras forming the Andes: the Cordillera Occidental at the west and the Cordillera Real at the east. The filling activity of the basin was divided into two different periods (Steinmann, 1997): (1) a deltaic to marine/brakish environment (15-9 Ma) with a source of material from the east (Cordillera Real) and (2) a second phase (8-5 Ma) composed by intermontane series whose source was the west (Cordillera Occidental). Between 9.5-8 Ma a major E-W compressive deformation event occurred causing the appearance of large thrust, reverse faults and folds. After the time of activity of the basin, the area was covered by glacier deposits (moraines) and volcanic products, during Pleistocene and Holocene.

Locally, the basin has been divided in three different tectonic units (Lahuathe, 2005) separated by large thrusts (Fig. 2):

1. The Cocha Huma Unit, comprises sequences of phyllites and cuarcites (Junin Fm.), shales, sandstones, conglomerates and greywakes (Yungilla Fm.) and

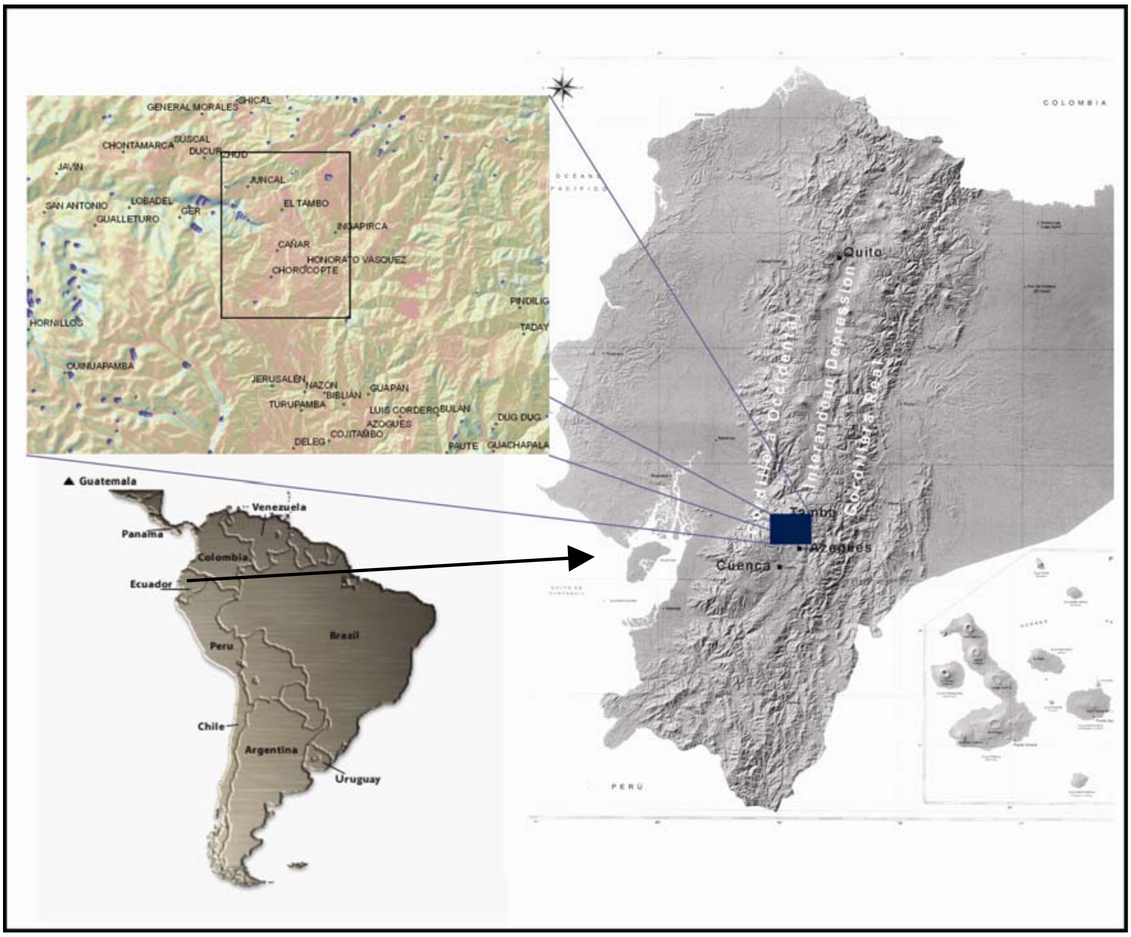

Fig.1: The area of interest of El Tambo, Ecuador.

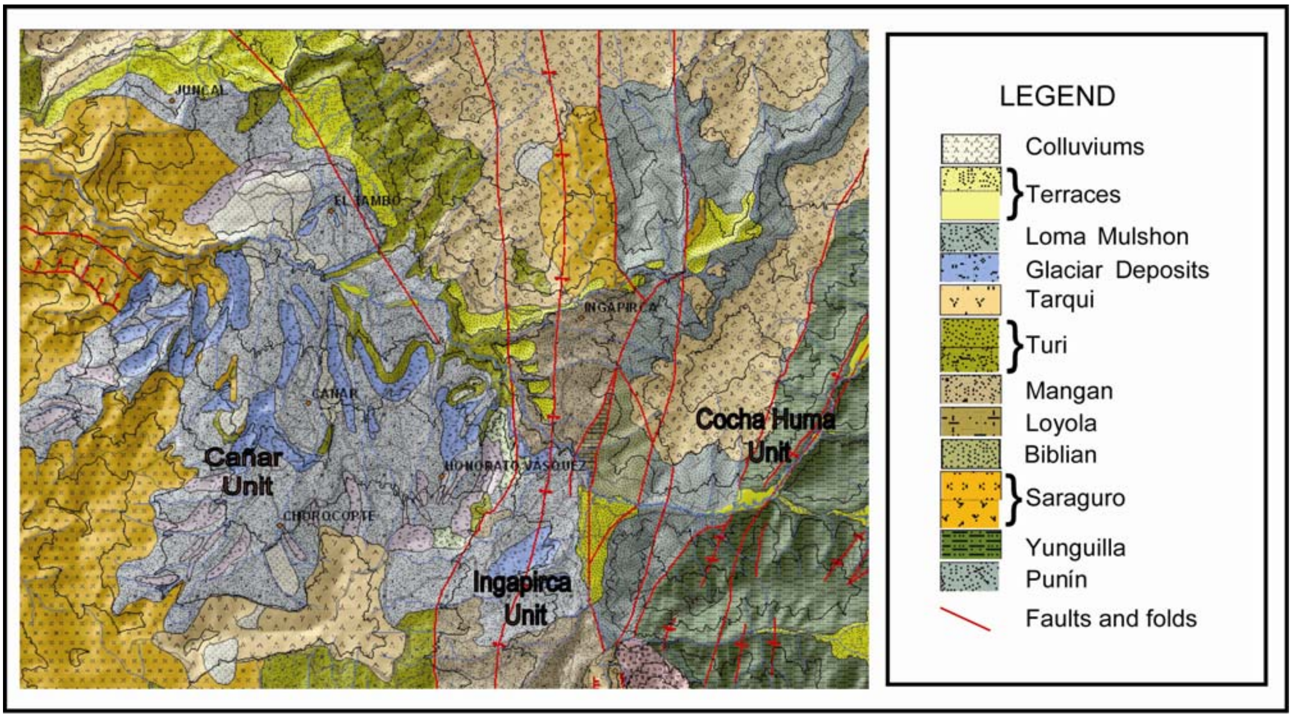

Fig.2: Geological setting of the archaeological area in danger of landslides (based on Lahuathe, 2005).

andesitic and dacitic breccias (Cerro Tablillas Fm.) ranging since Jurassic to Oligocene.
2. The Ingapirca Unit consists of clays, sands and silts weakly cemented (Biblian Fm.), shales and siltstones (Loyola Fm.), shales, siltstones and sandstones from a metamorphic source (Mangan Fm.) and volcano sediments, andesitic breccias and lavas strongly weathered (Turi Fm.). The age of these materials correspond to Middle-Late Miocene and are covered persistently by quaternary moraines.
3. The Cañar Unit includes riolitic tuffs and breccias hydrotermally affected (Cerro Caucay Fm.), clays, silts and sands poorly consolidated and conglomerates (Turi Fm.). Their age vary from Oligocene to Late Miocene.

Pliocene and Quaternary deposits have been considered as covertures and consist mainly of volcano sediments, glacier deposits, alluvial terraces and colluviums. They are overlaying discordantly the rest of units and are spread along the center west and south of the area.

The Cuenca basin, due to the mechanical characteristics of its constitutive materials, has been affected by several large landslides usually with complex mechanisms. Few local attempts for understanding their distribution and genesis have been made (e.g. Erazo, 1965). Unfortunately most of the efforts have aimed to describe the geometry without taking into account causes and triggering factors.

The PRECUPA Project (Prevention-Ecuador-Cuenca-Paute) carried out between 1994 and 1998 (Basabe & Bonnard, 2002), has been the most complete study for the Cuenca basin. However, the area of el Tambo was not taken in account. Natural hazards were monitored, analysed and mapped into an area of approximately 3700 km^2 including the cities of Cuenca and Azogues and some of the geological units that also exist around el Tambo. Its main activities comprised: geological and geotechnical mapping, landslide inventory mapping, creation of landslides-related hazard maps and pilots studies on vulnerability (Basabe et al, *1998*).

4. DTM Generation and Orthophoto Production

The generation of a precise and reliable Digital Terrain Model (DTM) is a pre-requisite for mapping, landslide documentation and multi-temporal change analysis.

For the area under investigation, 3 sets of aerial photographs, corresponding to 1977, 1989 and 1995 respectively, were used (Table 1). They are part of the National Archive held by the Instituto Geográfico Militar in Ecuador..For the digital processing, the photos were scanned at a resolution of 15 µm. Ground control points were also acquired from the geodetic control archive of the Instituto Geográfico Militar.

Three software packages were employed for photogrammetric image processing: LPS (Leica Photogrammetry Suite) as well as the in-house BUN and SAT-PP (Satellite Imagery Precision Processing) programs. The complete photogrammetric working process goes from project definition, interior orientation computation, measurement of tie and control points, bundle adjustment image triangulation and absolute orientation and finally to DSM generation and orthophoto production (Fig. 3). A similar approach for the documentation of archaeological areas is presented in Eisenbeiss et al (2005).

Bad conditions on the film storage as well as the high relief of the area caused inaccuracy during triangulation phase within LPS Core. Therefore LPS Orima and the in-house program BUN were employed to reduce the triangulation RMSE values by detecting blunders to acceptable levels. With BUN we obtained a RMSE of residuals of 2m in x&y direction and 3m in height.

For the DTM generation, the in-house software SAT-PP was employed. The matching approach is a coarse-to-fine hierarchical solution with a combination of multi image matching algorithms and automatic quality control (Zhang, 2005). After image pre-processing and pyramids generation, three kinds of primitives (feature points, grid points and edges) are detected on the original resolution image and matched between all the available images. To ensure a correct matching in cliff areas, some manually measured breaklines are also imported. Then a regular DTM is derived (Fig. 4a).

Finally, orthophotos for every data set were generated. Cutlines between images as well as color balancing and feathering were corrected with some image processing.

In Fig.4b a 3D visualizations of, the 1989 data set is shown.

Acquisition date	N° Pictures	Scale	Camera	Focal length
1.11.1977	8	1:60000	RC-10 JET	152.68 mm
17 & 25.08.1989	6	1:60000	RC-10	153.03 mm
16.02.1995	10	1:35000	RC-10	153.03 mm

Table 1: Characteristics of the used aerial images.

5. Identification and Characterization of Landslides

The analysis of the orthoimages was useful for field recognition and mapping of the area. Information contained in EPN, 1997 and Basabe et al, 1998 was used as a reference. 24 places were identified as affected by landslide processes involving a total area of about 15.5 km^2 (4.4% the whole area), which were clustered in five different groups regarding their geological and geomorphological characteristics, level of activity as well as their geographical position (Fig. 5).

Zone 1, marked with red, is located in the northern flank of the Cañar River. It contains the most active landslides in the area affecting mainly moraines and ancient colluviums poorly consolidated and strongly weathered. Well developed features of water erosion (trenches) can be seen along the area but are stronger concentrated by the river. The river itself has an important role in the instability processes; stream erosion has caused differential acceleration of the in-motion masses and, consequently minor scarps at the toe of the largest landslide (aprox. 4.2 km^2) in zone 1. The scarp of the same landslide has had a retrogressive behavior, forming a stepped surface with an important vertical component of displacement. Indirect indices of movement like roadways and houses show evidence of important displacements.

Zone 2, marked with orange, is settled on the southern flank of the Cañar River, in front of zone 1 and corresponds to glacier deposits (2 different levels of moraines) which are affected by creeping in a large area (5.3 km^2). Based on stratigraphic profiles in vertical excavations carried out by the municipality of Cañar (2005) creeping is a shallow process restricted to glacier deposits, its limit is the contact with the Miocene units (Turi Fm.). Close to the Cañar River, stream erosion causes an increment in the velocity of displacement and also involves underneath deposits.

Green zone, named zone 3, goes along the eastern flank of Quebrada Pucahuaycu, a tributary of Cañar River running in N-S direction trough glacier deposits and conglomerates from Turi Fm. Undercutting is present along the eastern flank by the village of Cañar causing block falls in the steeper parts of the gully. Downwards, close to its mouth, inclination of the slope decreases and gorges gradually disappear. Block falls are replaced by creeping of the glacier materials.

Zone 4 (yellow) is located on unconsolidated glacier deposits and sandstones well cemented with conglomeratic lenses. Morphological features of a relict landslide can be seen to the south. Apparently, no presence of current activity exists. Northwards, creeping (constraint to the vicinity of the Cañar River) on glacier deposits as well as slight water erosion on sandstones are the current phenomena.

Into the zone 5 (light blue), 3 small dormant landslides (less than 0.2 km^2) on well consolidated conglomerates (Mangan Fm.) has been identified. They could have been triggered for undercutting caused by fluvial erosion of the Cañar River. No apparent signals of movement have been observed.

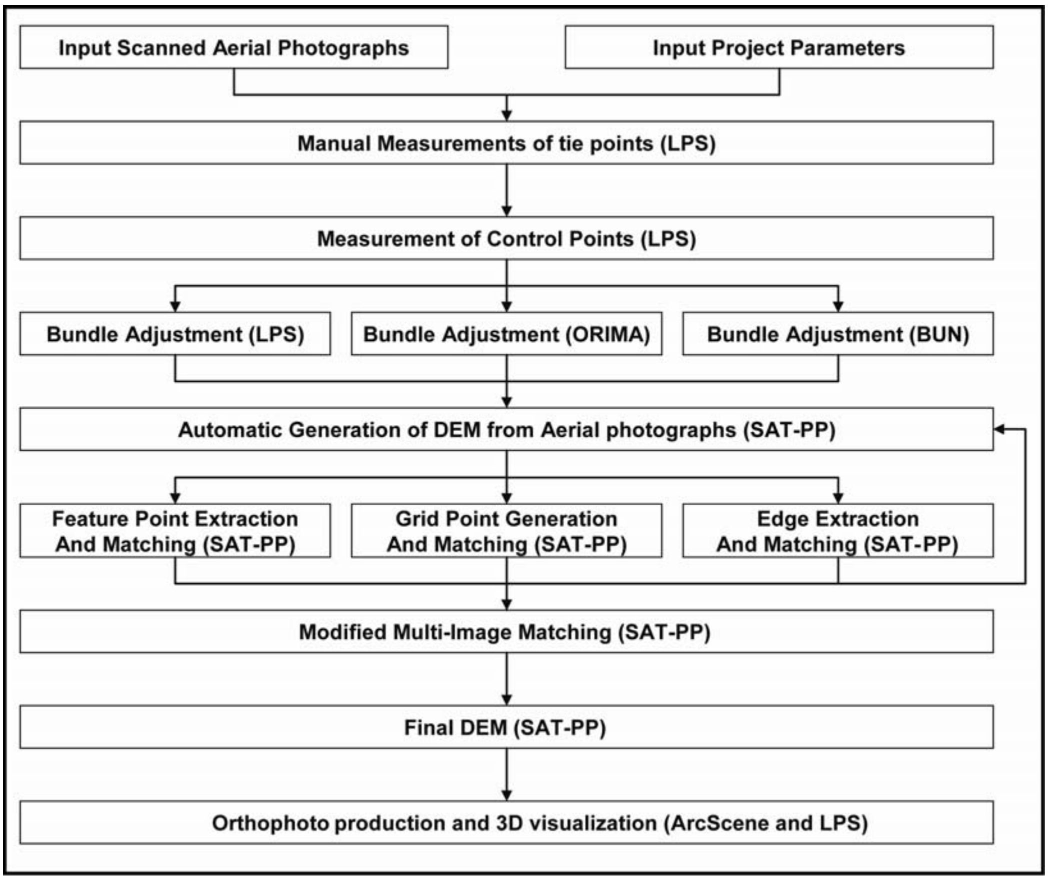

Fig. 3: Photogrammetric pipeline for DTM generation from aerial images.

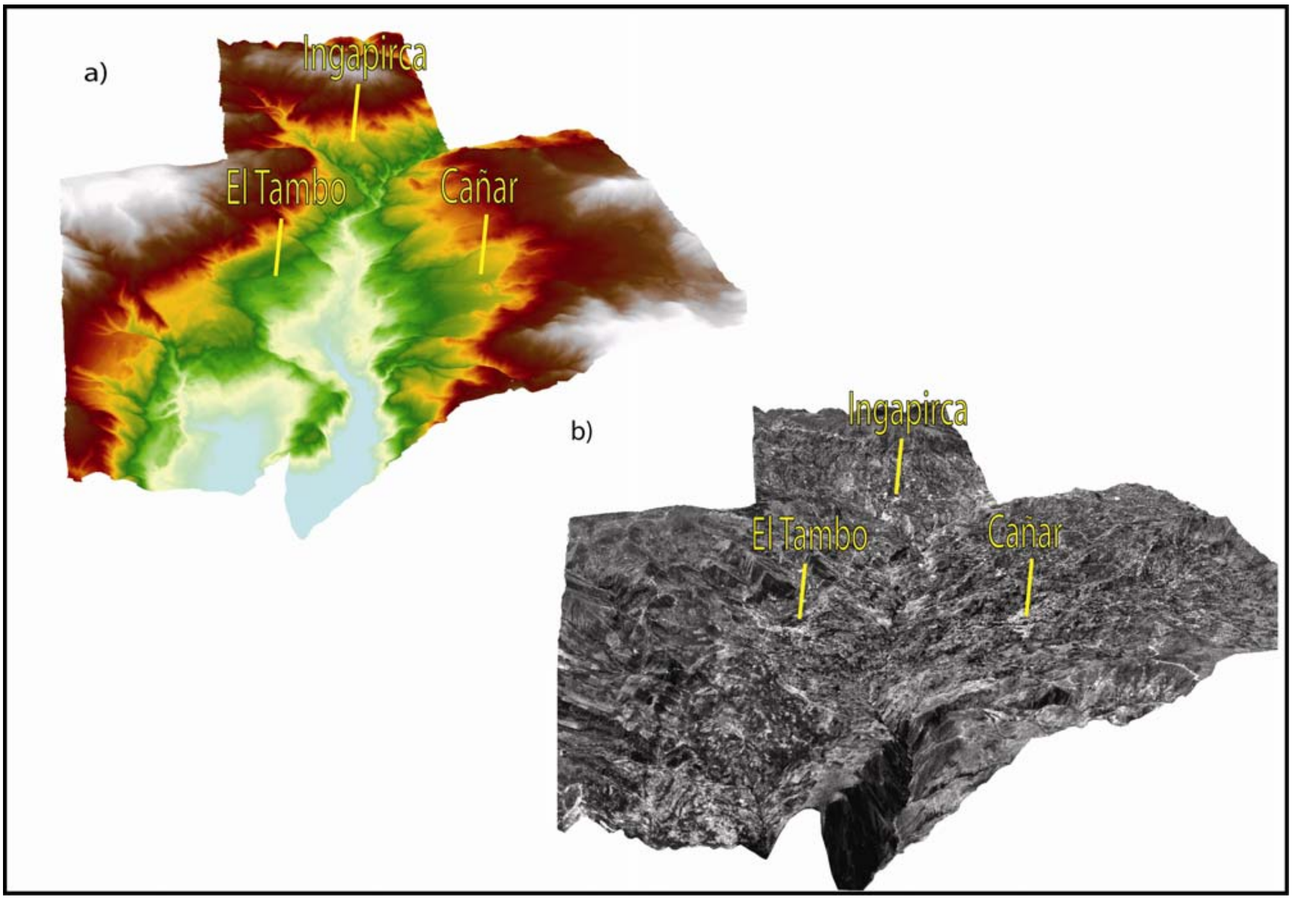

Fig. 4: 3D model derived from the aerial image set of 1989; a) DEM; b) Orthophoto

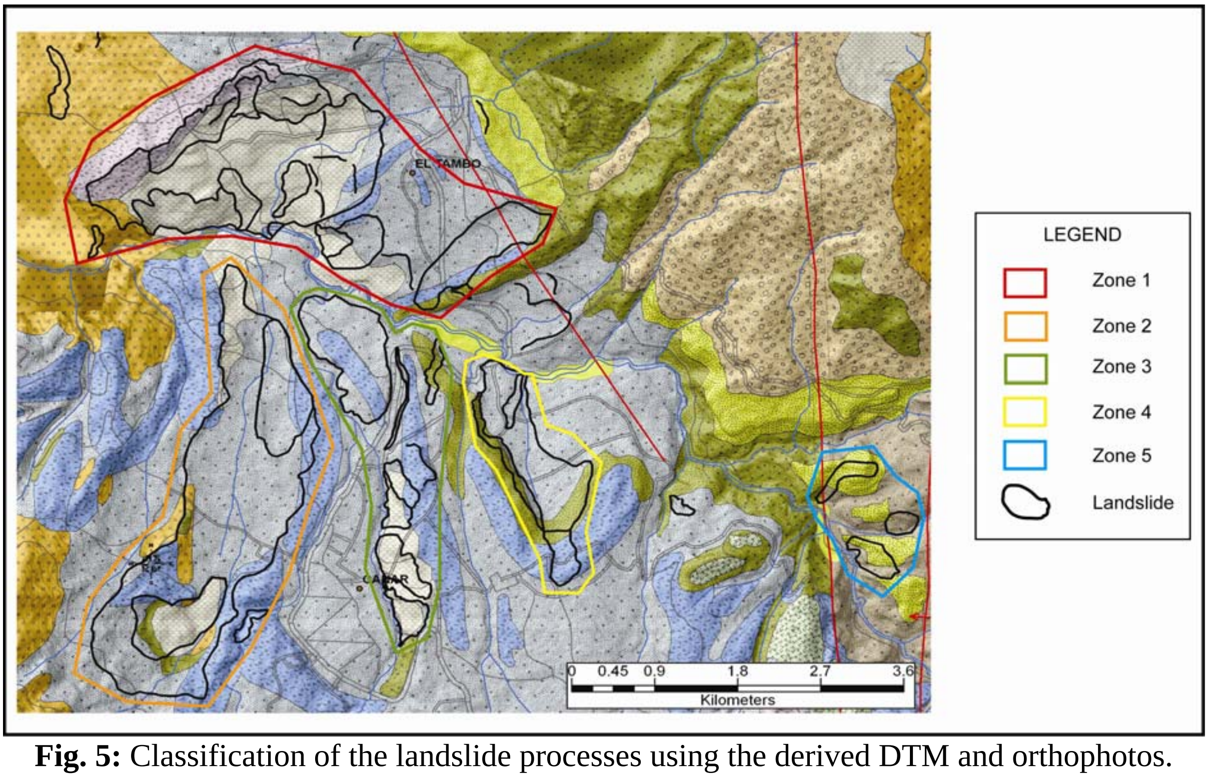

Fig. 5: Classification of the landslide processes using the derived DTM and orthophotos.

6. Conclusions

In this contribution we have shown how remotely sensing image data can be used for the investigation of archaeological areas and landslide analysis and monitoring. Using 3D visualizations and orthophoto interpretation we have been able to describe most of the slope instability processes that are occurring in the area and to correlate them with other key factors like type and level of erosion or type of material. The multi image matching method used for DSM generation has demonstrated being appropriate to create good quality models based on poor quality images. The entire method would be useful for the same kind of analysis in regions where photographic archives have not been well preserved, which is frequent in most of the developing countries.

From the analysis of results, we can say that water has a strong influence on unstable slopes either as a potential triggering factor or contributing indirectly on unstable areas (by gully erosion or undercutting). Mainly, poorly consolidated materials as glacier deposits or conglomerates have developed instability processes in the area even in gentles hill slopes, just ancient events could be identified in stiffer materials some of them, probably related with different climatic or geomorphological conditions.

In the future, comparison between the different DSMs created during the project will lead to assess rate and direction of displacements in the most active zone.

7. References

ALCINA, F.J. 1978 Ingapirca: arquitectura y áreas de asentamiento. Revista Española de Antropología Americana, Departamento de Antropología y Etnología de América, Madrid, Vol. 8: 127-146.

BASABE, P. & BONNARD, C. 2002 Instability Management in Ecuador - From Policy to Practice, Proc. Of the Int. Conf. on Instability-Planning and Management, Isle of Wight, United Kingdom. Ed. Thomas Telford.

BASABE, P., NEUMANN, A. ALMEIDA, E. GARCIA, E. ONTANEDA, P. 1998 Informe Final del Proyecto PRECUPA. de Cooperación entre el CSS, DNDC, INECEL, INAMHI, Munic. de Cuenca/ETAPA, U. Cuenca y Consejo de Programación por La Josefina. Para la prevención de desastres naturales en la cuenca del rio Paute. Temas: Topografía/geodesia, Geología/geotecnia, Hidro-meteorología, Sismología, Limnología, Capacitación/difusión y apoyo a Defensa Civil., CSS, 1998, pp. 369, Cuenca-Ecuador.

EISENBEISS, H. LAMBERS, K. SAUERBIER, M. ZHANG L. 2005 Photogrammetric documentation of an archaeological site (Palpa, Peru) using an autonomous model helicopter, Proceedings of the XXth CIPA International Symposium, Torino, Italy In International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXIV-5/C34: 238-243.

ERAZO, M. 1965 Estudio de los deslizamientos del suelo en el Austro. Cuenca-Ecuador.

ESCUELA POLITÉCNICA NACIONAL (EPN) 1997 Cartografía de Terrenos Inestables. Estudio Regional Zona Cañar-El Tambo. Provincia de Cañar. EPN-Quito, 41 pp.

LAHUATHE, J.C. 2005 Levantamiento Geológico y análisis de la deformación tectónica entre las latitudes: 2° 28´S y 2° 37´S. Provincia de Cañar, Engineering Thesis, EPN-Quito, 124 pp.

MUNICIPALITY OF CAÑAR 2005 Estudio de mecánica de suelos. Proyecto: Regeneración de plazoleta “El Campanario”. Ciudad de Cañar. 11 pp.

STEINMANN, M. 1997 The Cuenca basin of southern Ecuador: tectono-sedimentary history and the Tertiary Andean evolution, PhD Thesis, ETH-Zürich, 176 pp.

ZHANG, L. 2005 Automatic Digital Surface Model (DSM) generation from linear array images. Diss. ETH No. 16078, Technische Wissenschaften ETH Zurich, 2005, IGP Mitteilung N. 90