Effects of landslides on Machu Picchu Cultural Heritage

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Abstract. Scope of the present work is to provide a possible interpretation from geological and geomorphological point of view of the deformations patterns which exists upon the archaeological structures and buildings, underlying the link between natural geomorphologic process and anthropogenic ones (e.g. local subsidence, underground caves, structural deficit or deformation patterns due past seismic activities). The main input to such interpretation came from the census activities realized during the last three field of survey (2003-2004 and 2005), of the entire structural conditions of the citadel. The study has been performed by the development of a specific and detailed vulnerability and damage data sheet for archaeological exposed elements. All the data has been analyzed trough processing techniques (vectorial intersection and spatial analysis). Damage and vulnerability analysis has been correlated by exposed element positions versus potential landslides map. The main purpose of this work is to provide basic data and geological and geomorphologic evidence to support the above theory. A damage/vulnerability map has been carried out through the synoptical reading of a multi layer project implemented on a GIS platform; providing various building typologies (exposure), their tensional and deformation paths (vulnerability) and the morphological view of the area.

Keywords. Landslide risk, Vulnerability, Cultural Heritage, Machu Picchu

1. General setting of the archaeological site of Machu Picchu

The monumental complex of Machu Picchu (Lat. 13° 09'South, Long. 72° 31'West), designated by Unesco as World Heritage Site in 1983, was discovered on 24 July 1911 by Hiram Bingham, an American historian and professor of archaeology at Yale University.

Although the citadel is only 80 kilometres far from Cuzco in line of air, the whole site was never found during the Spanish conquest; the detail is important to understand the particular shape and geographical asperity of the area.

The archaeological site is indeed located on the crest of two mountains, 2430 m.a.s.l., with the Urubamba river at its foot in a very inaccessible zone of Andean forest (fig.1). All the theories provided so far are based on studies and archaeological discoveries but there are no historical sources which provide information as to what happened in the "Lost City".

Actually, the site is affected by geological risk due to frequent landslide phenomena that threaten security and tourist exploitation. In the last years, the landslide scientific community has promoted a multi disciplinary joint programme for the monitoring and control of superficial deformation, with remote sensing techniques and field survey analysis to define the typology and magnitude of potential landslides. During the last geological field surveys it was possible to reconstruct in detail the geological model of the area.

Fig. 1 General view of the archaeological site of Machu Picchu citadel (photo by D. Spizzichino)

2. Geological setting

The area is characterized by granitoid bodies that had been emplaced in the axial zones of the main rift system that are now exposed at the highest altitudes, together with country rocks (Precambrian and Lower Paleozoic metamorphics) originally constituting the rift 'roots'. The Machu Picchu batholith is one of these Permo -Triassic granitoid bodies. The bedrock of the Inca citadel of Machu Picchu is mainly composed by granite and subordinately granodiorite.

This is mainly located in the lower part of the slopes (magmatic layering at the top). Superficially, the granite is jointed in blocks with variable dimensions, promoted by local structural setting. The dimension of single blocks is variable from 10^{-1} to about 3x10 m^3. Soil cover, widely outcropping in the area, is mainly composed by individual blocks and subordinately by coarse materials originated by chemical and physical weathering of minerals.

Part of the slopes exhibit debris accumulation as result of landslide activity. Grain size distributions of landslide accumulation are closely related to movement types and evolution. Talus and talus cones are composed by fine and coarse sediments, depending from local relief energy. Alluvial deposits outcrop along the Urubamba River and its tributaries.

They are composed by etherometric and polygenic sediments, that may be in lateral contact with the talus deposits. Anthropic fill and andenes, on top of Citadel, reflect the work of Inca activities in the area (fig. 2).

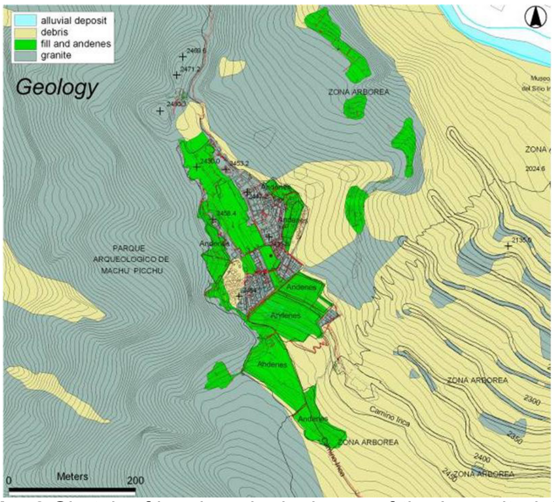

Fig. 2 Sketch of local geological map of the Inca citadel of Machu Picchu (by Canuti et alii, 2005)

3. Geomorphological setting

The general morphological features of the area are mainly determined by the regional tectonic uplift and structural setting. As consequence, kinematic conditions for landslide type and evolution are closely depending on the above factors. Several slope instability phenomena have been identified and classified according to mechanism, material involved and state of activity. They are mainly related to the following: rock falls, debris flows, rock slides and debris slides. The area of the citadel has been interpreted as affected by a deep mass movement (Sassa et al. 2001, 2002) that, if confirmed by the present day monitoring systems, it could be referred to a deep-seated gravitational slope deformation (DSGSD), probably of the type of the compound bi-planar sagging (CB) described by Hutchinson (1988).

A main trench with NW-SE trend, related to a graben-like structure, is located within the archaeological area and supports this hypothesis. Other trenches are elongated in the dip direction of the slope. Rock slides and rock falls may produce blocks with dimension variable from 10^{-1} to 10^{2} m^3. Debris produced by rock slides and rock falls, as well as from weathering processes is periodically mobilized as debris slides and debris flow. Debris slides and debris flows are characterized by an undifferentiated structure varying from chaotic blocks immersed on coarse sand matrix. The grain size distribution is mainly depending on the distance from the source areas and slope angle. Finally, it is interesting to notice, on the NE side, the presence of a large debris accumulation, just below the citadel, presently being eroded by all around dormant slides. The accumulation it is probably the result of an old geomorphological phenomena now stabilized, still not clear in its original feature. Anyway, the mass movements occurred certainly before the Inca settlement since some of their terraces ("*andenes*"), are founded over this accumulation area.

4. Exposure, Vulnerability and Damage of Cultural Heritage

The concept of value during exposure and damage analysis cannot be merely applied to Cultural Heritage (CH) due to their singularity, peculiarity and un-repeatability. In addition, the assessment of the damage severity based on money refund for restoration can be difficult to estimate due to the impossibility, in most of cases, to reproduce the original features of the damaged element. Vulnerability as usually defined as the degree of loss on an element or group of elements at risk, resulting from the occurrence of a natural hazard (landslide) of a given intensity (Varnes et al., 1984).

Usually the vulnerability is expressed in a scale from 0 (no loss) to 1 (total loss) and is a function of the landslide intensity and of the typology of the element at risk $V=V(I;E)$. In practical terms the vulnerability is expressed by the link between the intensity of the landslide and its possible consequences.

Formally, the vulnerability may be expressed in terms of conditioned probability (Einstein, 1988):

$V = P\ (damage|event)$;

namely by the probability that the element at risk is prone to a certain degree of damage under the occurrence of a landslide of a given intensity. In the same time the vulnerability should consider also an assessment of the damage severity.

5. Methodological analysis for vulnerability assessment

The vulnerability assessment of an exposed element may be performed through the analysis of damage of an element with same structural characteristics affected by a given landslide type with the same intensity. The methodological process should consider the following steps:

1. definition of the localisation of the element at risk; historical and/or direct analysis of damage of the element at risk, in correlation with different landslide typologies with different intensity;
2. intensity/damage analysis of classes of elements at risk characterised by the same building/structural typology;
3. implementation of a vulnerability function depending on each class of exposed elements with respect to minimum/maximum expected landslide intensity.

6. Methodology for the analysis of static-structural conditions of the site

For each typology of element at risk a value of damage has been defined, after the stage of inventory and filling of a field survey catalogue (fig. 3). The field catalogue for the survey of the static-structural conditions of CH exposed at landslide risk has been derived from similar experiences carried out for the assessment of seismic vulnerability/degree of damage. In particular, the following parameters have been adopted:

- geometric properties of the CH in terms of height and wall thickness, in order to correlate these data with e.g. the impact force of fast slope movements;
- presence of restoration works, useful to understand past damage and, as well, the present capability to resist to a landslide with a given intensity;
- presence or absence of coverage is a fundamental parameter to understand the impact of weathering on structures;
- presence of cracks in order to reconstruct damage derived from the interaction between structure and soil;
- analysis of active strain processes (i.e. sinking, swelling, tilting) and degradation (i.e. humidity, decreasing of resisting sections) sub-divided into vertical and horizontal elements;
- classification following the main building typologies and their static-structural characteristics.

Fig. 3 Examples of cracks collected in the archaeological structures and buildings (photos by D. Spizzichino)

7. Conclusion

All the damage and vulnerability data collected for the citadel has been spatialised by GIS techniques and linked by geomorphological dynamics and processes acting on the area (fig. 4). A preliminary good correlation between retrogressive phenomena on the N- East portion of the citadel and deformation patterns along the archaeological builds has been performed by mapping a first damage catalogue evidencing tension cracks, patterns, caves and superficial deformations.

All the collected data and their interpretations should be helpful for the future development of the research activities in order to promote a landslide hazard and risk assessment, a stability model along a schematic profile (fig. 5) and design of low impact mitigation measures for the entire archaeological site.

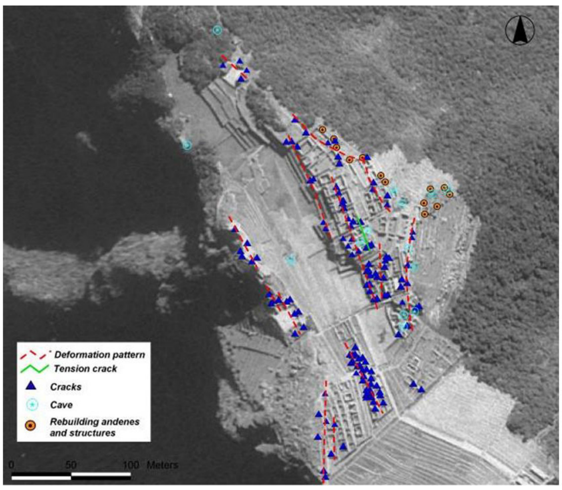

Fig. 4 Deformation patterns, tension crack, rebuilding *andenes* and structures and cave existing on the Citadel

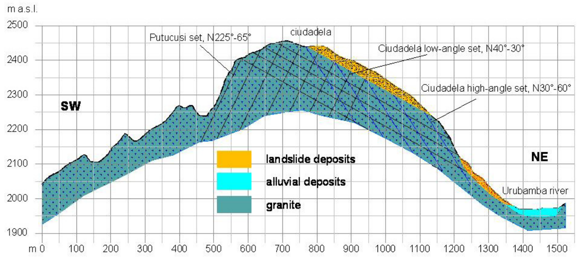

Fig. 5 Schematic profile for the implementation of stability model

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