

The Geomorphological Hazard of Machu Picchu Citadel and Aguas Calientes Village

A practical application to assess the natural risks which the Inca citadel of Machu Picchu and the Aguas Calientes village (Cusco, Perú) are subject to was carried out under the INTERFRASI and FORGEO projects. The area is prone to debris flows, low angle rock slides, high-angle rock slides and rock falls. The development of landslides in the bedrock is influenced by the orientation of the joint sets with respect to the topography, whereas those in the coverage essentially depend on the slope angle. The triggering mechanisms are to be found in seismic activity and intense precipitation. In the past, landslides have seriously damaged the archaeological and especially the civil structures, and in Aguas Calientes there have been many casualties. For this reason a procedure to understand the vulnerability and the risks for the anthropic exposed elements, both archaeological and civil, was adopted

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Introduction

The historic sanctuary of Machu Picchu is one of the most important Inca archaeological sites of Peru and, since 1983, the area is included in the UNESCO World Heritage list. The Machu Picchu citadel (Fig. 1) and the other Inca remains attract about 2000 visitors daily, who find accommodation facilities in the village of Aguas Calientes (Fig. 2). The area is a strategic part of the Cusco tourist circuit and a key area for the entire Peruvian economy. Yet, at the same time, tourism

causes a strong human impact on the environment and archaeological structures.

Moreover, the area is subject to natural hazards such as landslides, earthquakes and floods, with a direct effect on the conservation of the archaeological sites, on the accommodation facilities, on road and railway infrastructures, and on the safety of workers, inhabitants and tourists as well. The hazard for the archaeological remains as well as for site residents and visitors was recognized by UNESCO that, in 2008, threatened to expel Machu Picchu from the list of the World Heritage Sites. In addition, past studies (Sassa et al., 2002) hypothesized the presence of a deep-seated planar low angle rock slide, which would lead to a collapse of the ridge on which the citadel of Machu Picchu rises. This hypothesis raised great clamour from the scientific and political points of view, impacting the tourist flow. On these assumptions, a scientific analysis of the risks which the Machu Picchu historical sanctuary, the Machu Picchu

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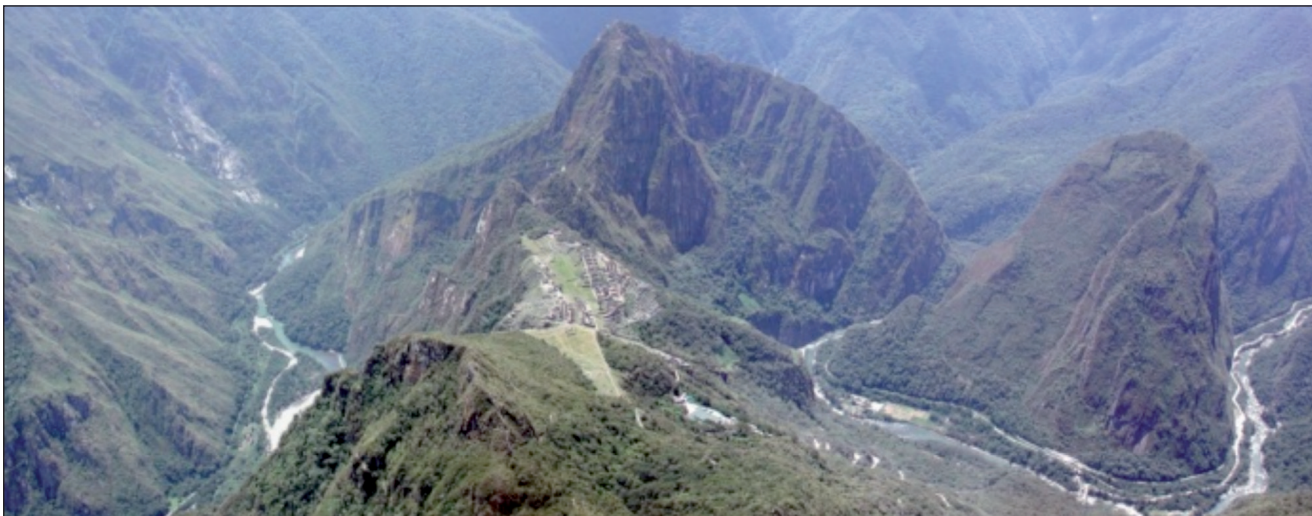


FIGURE 1 View of the Machu Picchu citadel from the Mount Machu Picchu. The shot shows also the Mount Wayna Picchu (in the background) and the Mount Putucusi (on the right) surrounded by the Urubamba river
Source: ENEA

citadel and Aguas Calientes are subject to was carried out under the Interfrasi (2001-2005) and Forgeo (2008-2009) ENEA projects.

Study Area

The Historic Sanctuary of Machu Picchu, 80 kilometers from Cusco, covers an area of 325,92 km²

in the Vilcanota-Urubamba basin (Cusco Region) and is one of the protected areas of the National System of Protected Natural Areas. In the Sanctuary, besides the Machu Picchu citadel (2.430 m a.s.l.) several other archaeological sites and the Aguas Calientes village (2050 m a.s.l.), connected to the citadel of Machu Picchu by a road of about 10km, are present.



FIGURE 2 Aguas Calientes village: view from the Mount Putucusi
Source: ENEA

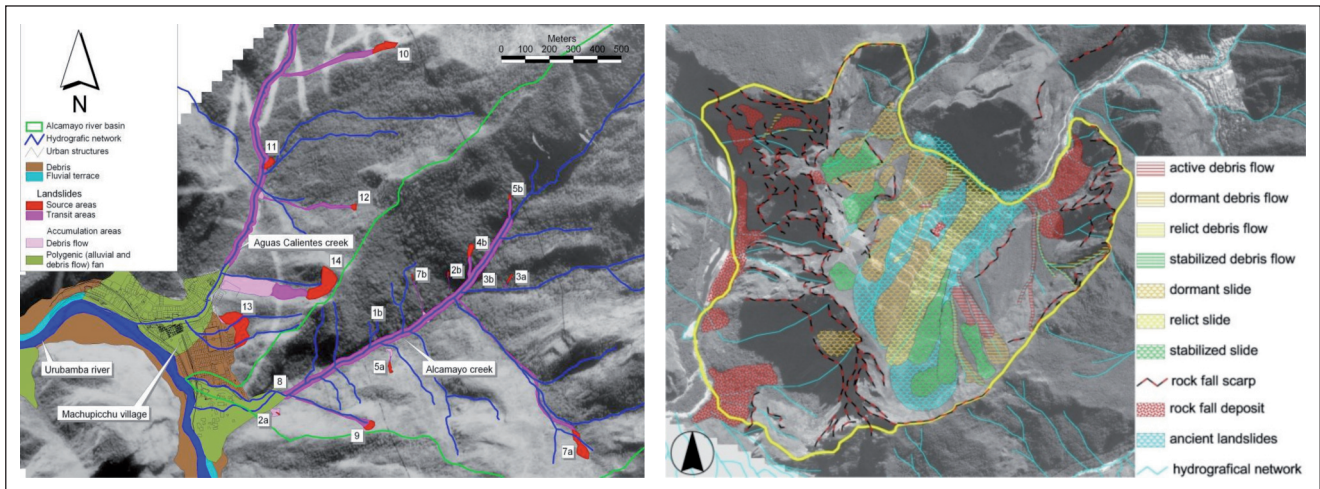


FIGURE 3 Landslides inventory in the areas of the Aguas Calientes village and the Machu Picchu citadel
Source: ENEA

The territory of the Historic Sanctuary of Machu Picchu belongs to the Eastern Cordillera, a WNW-ESE chain characterized by metamorphic and igneous rocks. The high Eastern Cordillera of Peru formed as a result of the inversion of a Late Permian-Triassic rift system. The Quaternary deposits are shaped as terraces and alluvial cones, deposited through mixed fluvial and slope processes, and also characterized by catastrophic dynamics as debris flows. Alluvial fans occur at the mouth of the tributary drainage (e.g., the fans of the Aguas Calientes creek and Aobamba river), and fluvial terraces mainly outcrop along the Vilcanota valley at different altitudes. The deepening of the river beds determines erosion processes at the foot of slopes, favoring landslide phenomena. Considerable talus bodies lie at the foot of the steeper rock slopes, which are mainly composed of heterometric sediments with granite boulders in a sandy-clay matrix. A thick (1-5 m) colluvium mantle resulting from bedrock alteration processes is distributed throughout the slopes. Joints and failure surfaces are widespread structural features of the intrusive bodies (Mazzoli et al. 2005). The morphological features of the area, which is characterized by steep and high-energy slopes, are strictly linked to regional uplifting evolution.

Geomorphological Hazard Analysis

The Machu Picchu Sanctuary is regularly affected by several slope instability phenomena (Canuti et al. 2005; Carreño and Kalafatovich 2006; Vilimek et al. 2007; Carlotto et al. 2009; Puglisi et al. 2011): rock falls, high-angle rock slides, low angle rock slides and debris flows (Fig. 3). Kinematic conditions for landslide type and evolution are closely depending on structural and topographic factors. Besides the structural setting, rock falls and slides are highly dependent on the geomorphological evolution and anthropic activities and are mainly triggered by regional seismic activity. Instead, abundant local rainfall is the main triggering factor for debris flows due to the rapid saturation of the shallow portions of the soil layer.

Historical Analysis

In order to better characterize the geomorphological features, the historical analysis of landslides and floods was conducted. Technical and scientific publications containing information on damage produced by landslides and floods were analyzed. The chronology of floods and landslides that affected the area since 1950 was reconstructed: 12 floods and 13 landslides were identified and classified

as the most significant. In particular, the towns of Aguas Calientes, Santa Teresa and Yanatile seemed to be the most prone to flooding with heavy damage and several victims (e.g., in 1998 and 2004). The most important landslides of the area occurred on December 26th, 1995, and January 1st, 1996, damaging the road that connects Aguas Calientes and the archaeological site. Landslides occurred in 2004 and 2010 affected the Aguas Calientes village causing casualties, damage and interrupting the railways Cuzco-Machu Picchu. None of the cited events affected directly the Machu Picchu archaeological site.

Susceptibility

The geomorphological hazard analysis was conducted with different approaches depending on the landslides, which the area is subject to (Puglisi et al. 2011):



FIGURE 4 Open fractures in the SW flank below the Inca citadel
Source: ENEA

- A) slow evolution in bedrock (low angle rock slides);
- B) rapid evolution in bedrock (high-angle rock slides and rock falls)
- C) rapid evolution in cover (debris flows).

The hazard evaluation of type A and B landslides was performed according to an approach based on the activities and on the speed evolution of the censused landslides.

Among the landslides of type A is included the deep mass movement that affects the citadel (Sassa et al., 2002). The characterization of this potential sliding surface (slope, orientation and nature) was carried out by aerial photo interpretation and field surveys. As result, the orientation of the surface does not seem to be conform to a slip such as that suggested by previous studies, because it dips in the direction NNE (30° E) and not towards the Urubamba Valley (E), situation that makes it incompatible with the rock mass sliding. Furthermore, it has been documented as the rocks overlying the potential sliding surface have an integrity that improves downwards, contrary to what would have been in the case of a slide. In fact, the energies involved in this potential movement, that would develop under a mass of granite over 50 m thick, would have to form a band of rock fragmentation close to the sliding surface. Instead, the rock in this band is almost unaltered. The results of a low environmental impact monitoring system (GPS, multitemporal laser scanner survey, ground based radar interferometry and satellite interferometric synthetic aperture radar) confirm field evidences and the lack of significant deep sliding processes.

Other landslides of type A are inside the citadel along the structural system with orientation 30° and slope 30°, but are currently inactive. Their activation can be dated before the citadel construction, being stabilized during the construction. Also the NE flank below the Inca citadel is affected by type A landslides, that develop prevalently along the 30°/30° and 30°/60° structural sets. The intersection of slope orientation with the structural system makes the slope evolution active with a retrogressive distribution of activities, with slow evolution. The entire SW side has an almost vertical slope and the pattern of joints is determined by the intersection between the 225°/65° and 130°/90° systems (Fig. 4). The frequent open fractures and the

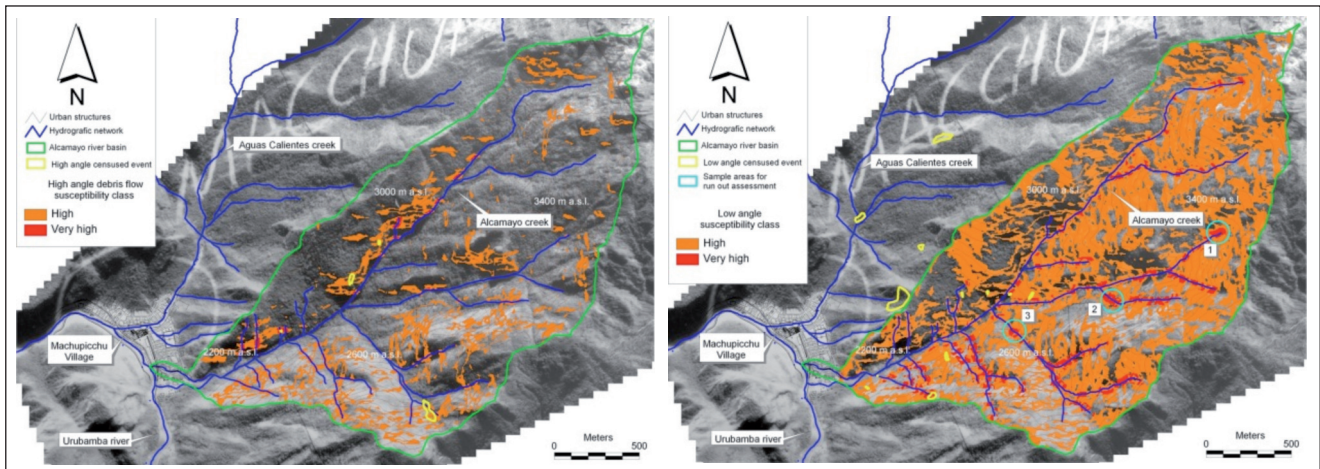


FIGURE 5 High angle (left) and low angle (right) debris flow hazard maps in the Alcamayo catchment above the Aguas Calientes village
Source: ENEA

current deformation of the archaeological structures (andenas) implies that type B landslides are active, and therefore the hazard related to this portion is high. A different approach was used to evaluate the hazard relating to landslides of type C, because these have neoformation character and because they are responsible for the damage and the casualties that occur almost every year in Aguas Calientes. A parametric approach was used to assess the debris flows hazard (Casagli et al., 2004; Abbattista et al., 2005; Leoni et al., 2009), and the base maps produced for the analysis are constituted by: a landslides inventory; a Digital Elevation Model with a 5 m grid. Comparing the landslide inventory and DEM derived maps, slope and aspect classes of the areas affected by landslides in the past have been identified. Two general trends for the source areas have been identified: high angle phenomena occurring on the steeper slopes (50° - 70°), where soil is moderately thick, and low angle phenomena with thicker soil bodies lying on smoother slopes (25° - 55°). Debris flow hazard maps of both types have been produced for the Alcamayo catchment (Fig. 5).

Triggering Factors

The average annual rainfall, registered in the Machu Picchu citadel's meteorological station (2563 m a.s.l.)

between 1999 and 2006 (Registro pluviométrico de la estación de Machupicchu, SENAMHI), reached 2038,70 mm, with a maximum of 333,31 mm in February and a minimum of 60,78 mm in August. According to the hydrological balance calculated for this area, 67% of the precipitation corresponds to superficial runoff and only 18% to infiltration (Carreño and Kalafatovich 2006). The comparison between average monthly rainfall occurred in the year range 1964-1977 and the monthly distribution of collected floods and landslides (Fig. 6) shows that floods and landslide events are strictly connected with the most humid period (November-April). Rock falls and slides are mainly triggered by regional seismic activity. The seismological characterization of the Machu Picchu area was performed by analyzing the information contained in the Catalogue for the Seismic Andean Region and the associated database of local intensity, managed by CERESIS - Centro Regional de Sismología Para America del Sur. The distribution of epicenters and their relative intensities (Fig. 7) allowed the selection of earthquakes most significant for the Cuzco-Machu Picchu area, with epicentral intensity greater than the VI Modified Mercalli scale (MM). These events were critically reviewed on the basis of the available historical-documentary information,

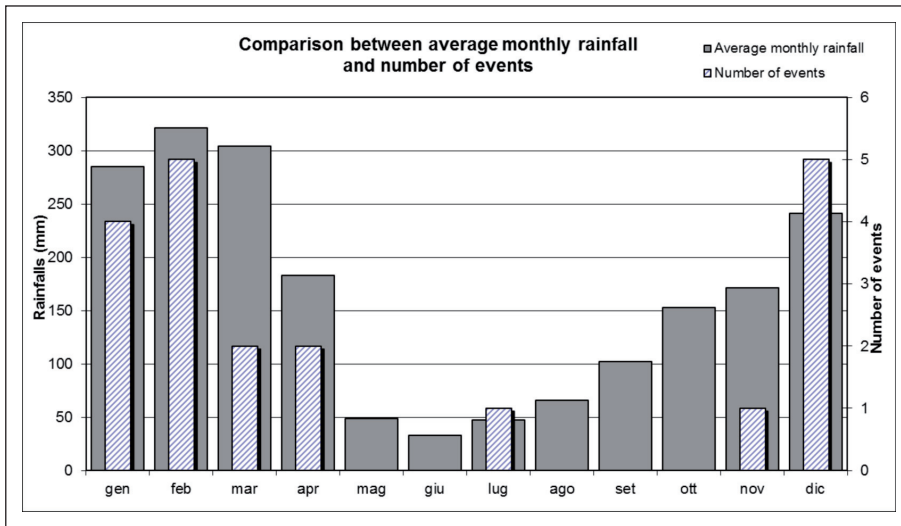


FIGURE 6 Comparison between average monthly rainfall (mm) and the monthly distribution of collected events
Source: ENEA

in order to verify the reliability of seismic and macroseismic parameters.

Exposure and Vulnerability Maps

The analysis of exposure and vulnerability of the remains present in the citadel was carried out by classifying each single Incaic structure (Delmonaco, 2009). 180 different elements at risk have been analyzed, inventoried and stored in a GIS and represented graphically. For each element at risk an Index of Exposure (IE) has been assessed, taking into account two main indicators: an historical/cultural index and an economical/tourist index. For each element at risk an Index of Static Structural Conditions (IS) has been assessed, based on a survey of the specific static-structural conditions and the damage of the structures exposed to landslide risk. Finally, the Vulnerability index (IV) of the area, in terms of capacity resistance, is the combination of the Index of Exposure (IE) with the Static Structural Conditions (IS).

Similarly, elements existing in the inhabited area of the Aguas Calientes village were classified and an exposure map including the location of the elements at risk and the attribution of a relative value index was developed for the Aguas Calientes village.

Risk

GIS overlay of the hazard and vulnerability maps allows to attribute a qualitative level of risk to the study areas. Since there is no evidence about deep active landslides in the citadel area, the geomorphological risk level deriving from the collapse of the whole ridge seems to be very low. Nevertheless, shallow phenomena in the SW flank of the citadel and on the ridge may damage andenas and, for retrogressive evolution, the monumental area, raising the risk level locally. Along the NE slope, the risk level is high for the potential activation of debris flows that may damage the road between Aguas Calientes and the citadel and jeopardize the tourist buses, just as it happened lately.

In the village of Aguas Calientes, buildings located in the morphological depression near the railroad station are in the higher risk areas (Puglisi et al. 2011; Fig. 8). Another important risk for the lower part of the village involves constructions on the banks, very close to the river water level. This scenario raises the damaging potential of the Vilcanota river floods. If a debris flow, originating from one of the tributaries, dams the river downstream of the village, the Vilcanota water level could increase and flood Aguas Calientes. Material accumulated by previous debris flows on the

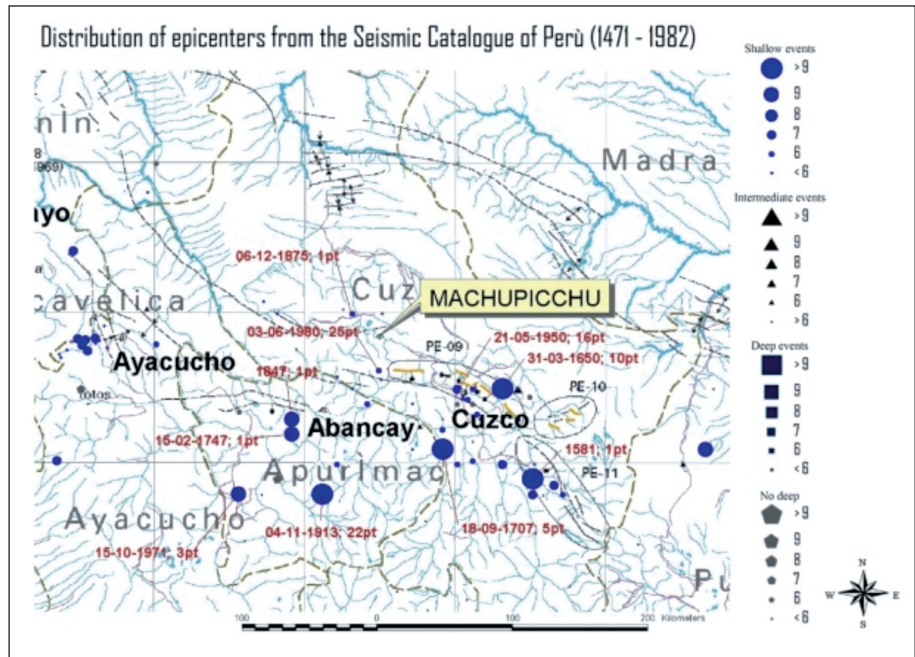


FIGURE 7 Earthquakes occurred in the Cuzco area graduated by focal deep; for the most important events, the date (day-month-year) and the number of points in the macroseismic field (local intensities) are reported
Source: ENEA

river bed could elevate the Vilcanota river bed level and would facilitate the overrunning processes. The damming of the river upstream of the village would be even more damaging. Reopening a complete or partial dam would lead to a dramatic increase in the damage potential.

Conclusions

The ENEA studies in the Machu Picchu Sanctuary exclude any activation of the deep sliding surface above the Machu Picchu citadel, indicated by previous studies as a possible surface of a planar landslide, since morphological and instrumental analysis have detected no actual sign of movement. The surface lesions found on archaeological buildings are due to local tilting caused by the inhomogeneity of the bedrock on which they are founded, formed by loose granite, juxtaposed blocks. Being subject to sudden falls, the SW slope of the citadel shows a higher risk level. Similar level of risk is attributable to the road accessing the citadel, frequently interrupted by small debris flows.

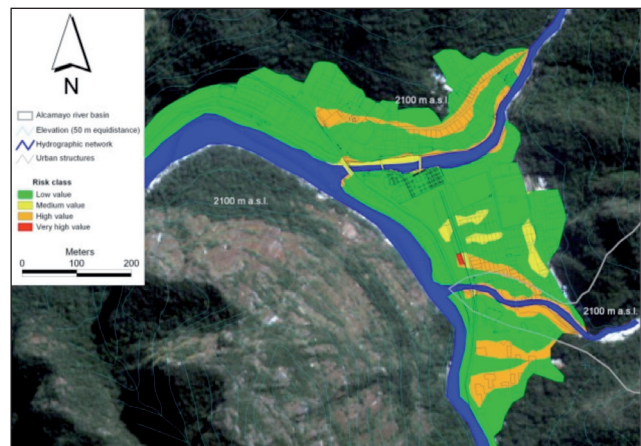


FIGURE 8 Debris flow risk map in the Aguas Calientes village
Source: ENEA

Much more serious is the risk in the Aguas Calientes village, where the periodic occurrence of debris flows in the upstream basins causes annual damage to anthropic structures and consequent casualties, also seriously compromising the usability of the archeological site.



These critical conditions have been further worsened by the rapid urban development over the last few decades. The depressed zones of the fan present an elevated residual risk level and the railway station is characterized by the highest risk of debris flow. At present, aside from proper territorial planning and

the restriction of new settlements, a program that includes real-time monitoring and effective alert and evacuation tools seems to be necessary. The results of both projects have been useful to administrative authorities involved in natural risk management in the Machu Picchu area.

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