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Geo-structural modelling for potential large rock slide in Machu Picchu

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The monumental complex of the Historical Sanctuary of Machu Picchu, declared as World Heritage Site by UNESCO in 1983, is located in the Andean chain at approx. 80 km from Cuzco (Peru) and at an elevation of 2430 m a.s.l. along the Urubamba River Valley. From a geological point of view, the Machu Picchu granitoid pluton, forming part of the larger "Quillabamba granite", is one of a series of plutons intruded along the axial zone of the high Eastern Cordillera Permo-Liassic rift system including a variety of rock types, dominantly granites and granodiorites. The most evident structures at the outcrop scale consist of planar joint sets that may be variably reactivated and exhibiting 4 main orientations. At present, the site is affected by geological risk due to frequent landslides that threaten security and tourist exploitation. In the last years, the international landslide scientific community has promoted a multi-discipline joint programme mainly finalised to slope deformation monitoring and analysis after the warning, launched in 2001, of a potential collapse of the citadel, caused by a huge rock slide. The contribute of the Italian research team was devoted to implement a landslide risk analysis and an innovative remote sensing techniques. The main scope of this work is to present the implementation of a geo-structural modelling aimed at defining present and potential slope stability conditions of the Machu Picchu Citadel. Data have been collected by geological, structural and geomechanical field surveys and laboratory tests in order to reconstruct the geomorphological evolution of the area. Landslide types and evolution are strictly controlled by regional tectonic uplift and structural setting. Several slope instability phenomena have been identified and classified according to mechanism, material involved and state of activity. Rock falls, debris flows, rock slides and debris slides are the main surveyed landslide types. Rock slides and rock falls may produce blocks with dimensions variable from 10^{-1} to 10^{2}m^{3} that form the toe accumulation on steeper slopes. The area of the citadel has also been interpreted as affected by a deep mass movement (>100m) that, if confirmed by the present day monitoring systems, 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). The analysis of active strain processes (e.g. tension cracks) along with the damage pattern surveyed on archaeological structures (e.g. sinking, swelling, tilting) suggest that the potential failure of a large rock slide may be located at a depth of *ca.* 30m. The various data sets have been integrated in order to obtain a general geo-structural and geotechnical model (strength and deformation parameters, seismic input) of the citadel at the slope scale. This represents a first step in implementing a slope stability analysis capable of reconstructing present and potential landslide evolution under static and dynamic conditions. This multi-discipline study, based on geological and structural analysis integrated with geotechnical and geomechanical interpretation, will aid defining actual landslide hazard and risk levels, indispensable for the design of low impact mitigation measures to be applied at Machu Picchu Citadel.