



Large scale shallow landslides hazard assessment of the Inca Historical Sanctuary area (Peru)

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The Inca Historical Sanctuary of Machu Picchu (Peru) is a large archaeological area (ca. 30 sq km) located in the Andean chain in the region of Cuzco, in the high Eastern Cordillera, a Permo-Liassic rift system including a variety of rock types, dominantly granites and granodiorites. The seismicity of the area is mainly connected to the main Quaternary faults systems of the Cuzco region that have caused in the past the most destructive earthquakes, generally characterised by superficial hypocentres.

The sanctuary, located along the Urubamba River Valley (NW orientation), includes, besides the well-known Machu Picchu citadel, several “minor” archaeological sites, located in the forest area, reciprocally connected by the “Inca trail”. The elevation varies from 4,000 to 1,700m a.s.l. The slope gradient is generally very high, with average slope angle $>40^\circ$. Due to geological and sub-tropical climate characteristics, the granitoid rocks usually develop a heavily weathered soil cover of 1-2m depth along the slopes. Geomorphological evidences from bibliography, field surveys and aerial photo analysis report shallow landslides (mostly debris flows) triggered by heavy rainfall as the most frequent landslide types. Landslides potential failure surface usually corresponds to the contact between soil cover and granitoid bedrock (1-2m depth). Slope movements are triggered by pore pressure increase due to rapid infiltration of rainfall along the slopes that usually exhibit a scarcely developed drainage system. After the initial mobilisation, a rapid failure and displacement occur in a chaotic mixture of coarse and fine materials, from silty-sands to rock blocks. Shallow landslides may cause severe damage to the archaeological sites of the Inca sanctuary that present slope deformation and active strain processes in the ancient structures. The general homogeneity of the area in terms of outcropping soil types, morphology and climate conditions promote shallow landslides characterised by similar kinematics of movements. This situation enables the possibility to implement a spatial analysis for shallow landslides hazard assessment using the potentiality of a GIS. A physically-based approach using a simple geotechnical model (infinite slope) coupled with a rainfall infiltration temporal model, based on available historical precipitation records, has been implemented for the area of the Inca historical sanctuary providing a landslide hazard map. The same model has been applied also under pseudo-static conditions using the Newmark’s method based on historical seismic analysis of the area. The data have been integrated by macroseismic observations collected through a specific historical-bibliographical investigation mainly based on the strongest earthquakes occurred in the area. The pseudo-static analysis has been calibrated on the seismic event occurred on 31st March 1650, with epicentral intensity of IX-X MSK, that produced induced shallow landslides in the surrounding valleys of Cuzco. The event can be associated to a 101km-length and 25km-width fault with main orientation similar to the main tectonic structures of the area. Probabilistic seismic hazard provide a maximum horizontal acceleration, for a 10%-exceeding probability, of 0,27g (50 yrs) and 0,31g (100 yrs) respectively. The landslide hazard maps can be used by local authorities as predictive tool for calibrating landslide mitigation measures, land use planning and management and for improving the resilience of the Inca Sanctuary to natural hazards.