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Geomorphological research of large-scale slope instability at Machu Picchu, Peru

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Abstract

A multidisciplinary approach has been adopted to study the slope movements and landscape evolution at the archaeological site of Machu Picchu and its immediate surroundings. The basic event in the paleogeomorphological evolution of the area was the large-scale slope movement, which destroyed the originally higher ridge between Mt. Machupicchu and Mt. Huaynapicchu. Within remnants of that primary deformation, several younger generations of slope movements occurred. The laboratory analyses of granitoids revealed highly-strained zones on the slopes of Mt. Machupicchu, which strongly affect the largest slope deformation. The borders of the largest slope deformation are structurally predisposed by the existence of fault zones. The majority of various types of slope movements on the so-called Front Slope (E facing) and Back Slope (W facing) are influenced by the alignment between topography and joints. Along with slope movements, fluvial erosion and tectonic disturbance of the rocks have been affecting the evolution of the landscape. A monitoring network for dilatometric and extensometric measurements was used to detect the present-day activity of rock displacements within the archaeological site. In addition to standard mapping of surface hydrogeological phenomena, eleven express slug tests were conducted to verify the infiltration potential of precipitation. The results of these surveys indicate that recent large-scale slope movement as suggested by some previous studies is doubtful, and the detected movements can be explained by individual movements of rock blocks or several other mechanisms including sinking of archaeological structures, subsurface erosion and annual changes in the water content of the soils.

Keywords: Large-scale slope deformation; Landscape evolution; Geohazards; Machu Picchu; Peru

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1. Introduction

The famous archaeological site of Machu Picchu is situated in southeastern Peru, approximately 100 km to the northwest of Cusco. The citadel of Machu Picchu was built on a steep ridge, about 500 m above the incised meanders of the Urubamba River (Figs. 1 and 2). UNESCO declared Machu Picchu a World Heritage site in 1983. This site was discovered for modern archaeology by Hiram Bingham in 1911, and since then, it has been under continuous scientific study. Despite this,

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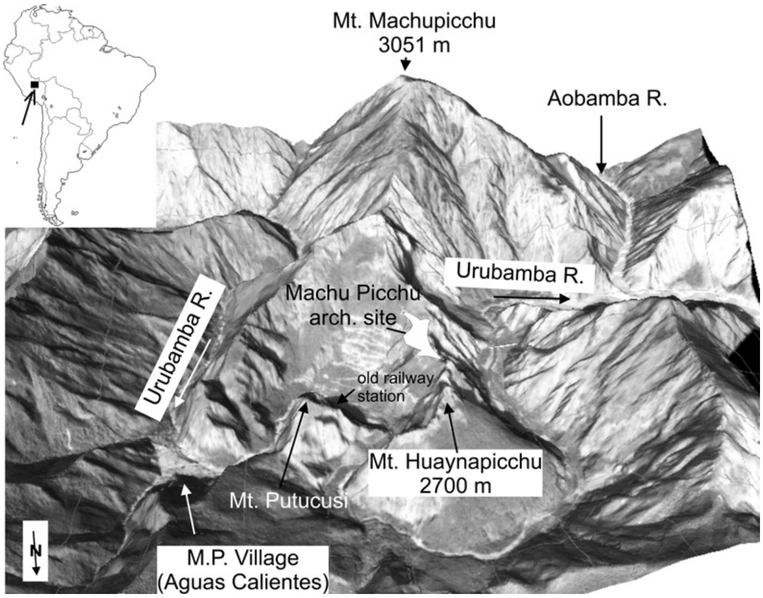

Fig. 1. 3D view of the study area at the Machu Picchu meander, with draped air-photo imagery. No vertical exaggeration.

geomorphology and engineering geology had been, until recently, on the periphery of scientific interests. Carreño et al. (1996) and Carreño and Bonnard (1997) first brought attention to the problem of rock slope stability and possible catastrophic slope movement endangering the archaeological site. Since then the site has been incorporated into the UNESCO/IGS project IGSP 425 for thorough investigations of slope stability (Sassa et al., 2000, 2001; Vilímek and Zvelebil, 2002).

Unfortunately, some preliminary findings and initial ideas, especially those related to damage to the site by a large rockslide, were distorted in newspaper/magazine reports. As a world-famous tourist location, Machu Picchu suddenly became the focus of worldwide public attention in relation to landslides, and the primarily purely scientific theme became biased by political and economical aspects. The media tended to stress the possibility of hazardous landslides, although some geotechnical and archaeological experts have expressed serious doubts about the existence of dangerous slope movements (McEvan and Wright, 2001).

Four rock falls with volumes of thousands of cubic meters, which occurred in December 1995 and January 1996 (Carreño et al., 1996), attracted interest in the instability of the rock slopes at the archaeological site. Two of these failures, whose main scarps were at an altitude of 2380 m a.s.l. (immediately below the ruins), destroyed part of the Bingham Road, the only access from the valley bottom to the archaeological site (Fig. 3). The third rock fall occurred on Mt. Putucusi on the opposite side of the Urubamba valley (Fig. 1). Rock blocks hit the railway tracks near the old Machu Picchu railway station (Fig. 1). The fourth rock fall took place from a large cliff along the Urubamba fault on the right bank of the Urubamba River, approximately 1.5 km NE from the archaeological site (Fig. 3).

These rock falls may indicate present-day activity of much larger, deep-seated slope failures, which increase the disintegration of the rock mass and increased instability on the “Front Slope” (the East facing slope below the Machu Picchu meander where the Bingham Road is located; see Fig. 3). The large-scale deformation on the Front Slope of Machu Picchu Ridge was estimated to have activated at least 6×10^6 m^3 of rock. The repeated destruction of the Bingham Road by ground sinking in the vicinity of the Machu Picchu hotel was considered to be another indicator of present-day activity of that large-scale slope movement by Sassa et al. (2000).

A land displacement monitoring network, recommended by Carreño and Bonnard (1997), was established by Sassa et al. (2000). Twelve sites were instrumented with wire extensometers. Two of them were equipped with an automatic registration device. The results of direct monitoring measurements (Sassa, 2001; Sassa et al., 2001) suggest displacement rates of mm per month or higher. Sassa et al. (2000) also described seven main rockslide bodies and classified them into active and potentially active ones. According to them, the Front Slope deformation is a multi-generation one, taking place mostly along discontinuities striking W–E with dips 30–50° towards the valley. The