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Abstract The paper presents the long-term collaboration of the Czech research group organized under the World Centre of Excellence with Peruvian experts from the National Archaeological Park of Machupicchu (*Parque Arqueológico Nacional de Machupicchu*). The collaboration monitored potentially dangerous slope movements at the archaeological site. This was achieved with the installation of an environmentally friendly network of dilatometric instruments, taking into consideration the strict requirements for site protection and the provision of long-term, reliable results. The 17-year-long monitoring (not continuous) identified no major hazard to the archaeological site which used to support decision of site managers to limit the entrance of tourists to the Intiwatana hill since 2019. Historical photographs of Czech travellers (from 1949, 1950, 1954, and 1961) were shared with Peruvian experts, who compared them with the oldest photos from the explorer Hiram Bingham and the most recent situation. The photographs were used to document the historical development of selected structures inside Machupicchu as well as landslide occurrences on the surrounding slopes. We think this is a good example of a successful collaboration in the adoption of a robust and reliable monitoring approach into the regular practices of the site mangers.

Keywords Landslides · Risk reduction · Master plans · Movement monitoring · Machupicchu · Photo monitoring · Peru

Introduction

The archaeological site of Machupicchu (also referred to as the llaqta of Machupicchu is here termed as Machupicchu according to local usage and not Machu Picchu) is located in the Cusco Region in the SW of Peru and belongs to the Cordillera Oriental mountain range of the Andean mountain system. The core area of the archaeological site lies between 2440 and 2500 m above sea level (m a.s.l.) in the saddle between Waynapicchu Mt. (2700 m a.s.l.) and Machupicchu Mt. (3051 m a.s.l.) in the core of the meander of the Urubamba River. The river flows under the E slope of Machupicchu at an altitude of 2000 m a.s.l. The site was easily accessible to its builders by a network of paths and roads connecting it with Cusco, the capital of the Inca Empire. The surrounding mountain ridges are glaciated. The Verónica Mt. (5750 m a.s.l.) is situated to the NE and the Cordillera Vilcabamba (Salcantay Mt., 6246 m a.s.l.) stretches to the SW from the archaeological site.

In terms of modern archaeology, Machupicchu was scientifically discovered by the explorer Hiram Bingham in 1911, and since then, it has been under continuous scientific study. The Archaeological National Park of Machupicchu was declared a "protected natural area" in 1981 by the government of Peru and consequently inscribed in the "World Heritage List" of UNESCO in 1983. It is not only one of the most famous heritage sites in the world but according to Zan and Lusiani (2011), it is also a liable site, because of overgrowing tourism.

Over the last few decades, geoscientists have been engaged in research mostly dealing with various types of geohazards. They have also focused on hydrogeology and topics of the Inca's hydraulic works (Wright et al. 1997, 1999; Patzelt et al. 2006) as well as the regional geological setting (Carlotto et al. 2009). Fujisawa and Sudo (2001) were interested in the seismological hazard of the area. They did not confirm an imminent danger of collapse, but they left future development open, in the event of a major earthquake. Numerous researchers have focused on mapping and monitoring of various types of slope movements within the archaeological site (Carreño and Bonnard 1997; Sassa et al. 2000; McEvan and Wright 2001; Vilimek et al. 2005, 2007). The intensive landslide research began in 2001, because a warning of the potential collapse of Machupicchu was issued in March 2001 attracting the worldwide attention of the scientific community (e.g., Sassa et al. 2000; Brown 2001; Delmonaco et al. 2009). Parallel works of several research groups resulted in multidisciplinary geomorphologic research using various methods including extensometric and dilatometric monitoring (Vilimek et al. 2009), GPS monitoring network (Delmonaco et al. 2009), terrestrial radar systems (InSAR, LISA Radar, Canuti et al. 2009), historical aerial, satellite and ground images, as well as geophysical research (Best et al. 2009). According to these findings, slope instabilities occur in the weathered mantle or in the fractured rock mass on the slopes around the archaeological site. Their results also stressed the importance of research focusing on the surroundings of the archaeological site (e.g., Canuti et al. 2009; Klimes 2013) where Machupicchu modern village (former Aguas Calientes) is located. It has been subject to numerous flash floods and debris flows causing damage and claiming lives (Vilimek et al. 2006). The possible mitigation of this hazard was suggested earlier and only temporal test operation of Geohazard Monitoring System (Bulmer and Falquhar 2010).

The archaeological site is mainly composed of a flat central part with an artificially levelled surface (Fig. 1). This area is probably a former depression between two small parallel crests, which were filled by Incan builders. Both of the crests are located in the source area of a prehistoric rock-slide (Vilimek et al. 2007), and we assume that they may be considered as a former "double crest." Several large rock blocks were found that could not be reworked by the Incas and open fissures, and caves were identified in several places (Vilimek et al. 2007).

The E facing slope of Machupicchu (the so-called Front Slope) is at a much lower inclination than the general rock slopes of the

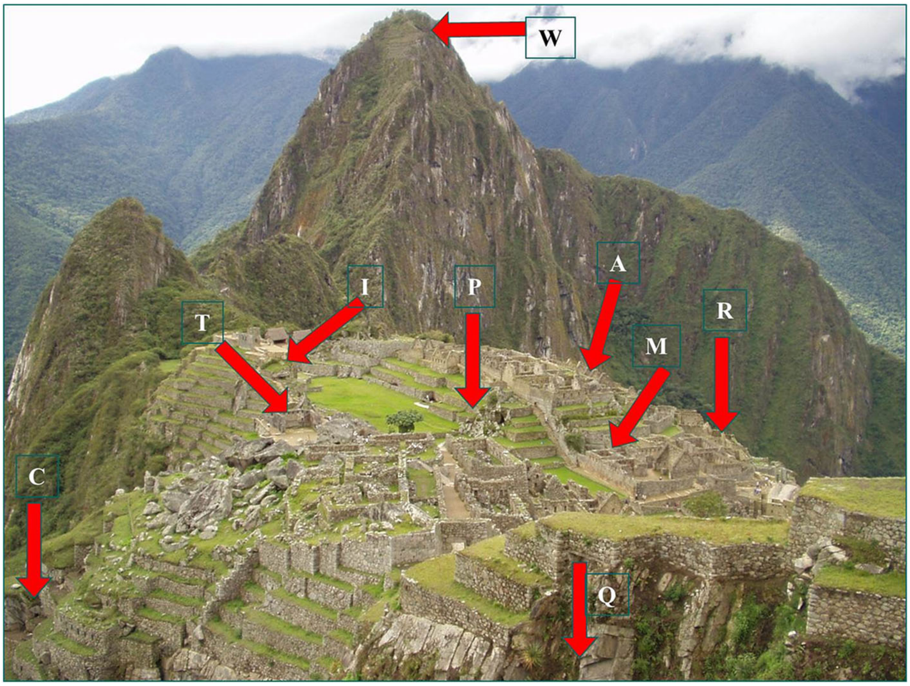

Fig. 1 Location of the dilatometric measurements (view to the N with Waynapicchu Mt. in the background). The flat central part of the Machupicchu site represents the main square between points T and P. The inset shows manual measurements with a rod dilatometer. C = Cave, T = Principal Temple, I = Intiwatana, P = Plaza, W = Waynapicchu, A = Acllawasi, M = Mirador, R = Rodadero, Q = Qhata

area (35° compared to 50–80°). Deep open fissures are visible in several places inside the archaeological site as well as on the Front Slope. Monitoring performed between 2002 and 2005 inside the archaeological site did not show any significant slope movements of the rock blocks (Vilimek et al. 2007).

This paper summarizes the collaboration between the Czech WCoE (World Center of Excellence on Landslide Risk Reduction) and managers of the Machupicchu historical site (Parque Archeológico Nacional de Machupicchu – National Archaeological Park of Machupicchu) on long-term, sustainable landslide risk reduction. Experience from the implementation and sustainable operation of a dilatometric monitoring network (Vilimek et al. 2009) along with the use of historical photographs are described. Possible future challenges of landslide risk reduction at Machupicchu are also outlined.

Conservation management of the Machupicchu archaeological site

According to certain authors (e.g., Regalado-Pezúa and Arias-Valencia 2006), the Machupicchu archaeological site is under conflict-ridden tension between conservation and exploitation; therefore, potential landslide hazards need to be considered seriously. Responsibilities are shared between Machupicchu and the surrounding natural protected area. Machupicchu and the more than 60 archaeological sites and prehispanic roads in the National Archaeological Park are managed by the Ministry of Culture (through the Direccion Desconcentrada de Cultura de Cusco, DDC Cusco), whereas the Ministry of Environment (through the SERNANP) is in charge of natural aspects of the area. The third involved actor is district of Machupicchu which capital Machupicchu village (former Aquas Calientes) is the main access to the archaeological site (around 656,000 people per year in 2007, DDC-Cuzco). The train service from Cusco (via Ollantaytambo town) as well as bus transport from Machupicchu village up to the archaeological site is operated by private companies. Since 2011, the average number of daily visitors to Machupicchu has grown constantly. Starting in 2013, annual attendance has topped a million tourists and reached around 1.5 million visitors per year during 2019.

The archaeological site of Machupicchu and Machupicchu village cannot be separated in terms of a master plan or the ongoing geodynamical processes. They are close to each other, facing landslide hazard and also connected via tourism. Machupicchu village is in fact outside the control of urban planning in several places, and its limits are not respected by the inhabitants. The exposure to landslides and flood threats is mentioned in the master plan. In order to reduce the risk of natural disasters, the district authorities along with the DDC – Cusco, SERNANP and local companies have formed a platform for civil protection. Most of the village population is actually not of local origin but come to the area to work in tourism. These people do not usually have any personal connections to the site.

Collaboration between the Czech WCoE and the Machupicchu archaeological site managements

After the initial field inspection in 2002, a review of published papers, and discussion with director of the DDC-Cusco, it was decided to begin monitoring potentially landslide-affected areas within the Machupicchu archaeological site (Vilimek et al. 2009). Severe constrains regarding the impact (visibility, damage) of the monitoring technology on the World Heritage Cultural site had to be respected while providing easy to handle technology for long-term, reliable monitoring of rock displacement. Therefore, we selected and agreed on low-impact and environmentally friendly monitoring methods represented by portable extensometric (Vilimek et al. 2009) and dilatometric measurements. These require only very limited permanent on-site installation, and the measurement instruments are robust, mechanical devices providing sufficient measurement resolution and precision.

The selected sites for dilatometric measurements (Fig. 1) represent individual outcrops of rock blocks separated by fractures where differential movements of the blocks may lead to damage of the Inca structures or under specific conditions, they may indicate damaging slope movements within the wider area. At the selected sites, nails were attached to the rock surface firstly using special glue due to conservation reasons. Nevertheless, this installation in most cases failed after 2 to 3 years and the nails had to be drilled into the rock. The portable rod dilatometer used (Zvelebil and Stemberk 2000) is capable of detecting a minimum distance change of 10^{-1} mm with a measurement range of 10 mm across a distance of 700 mm.

Due to technical problems (damage to the measurement device), there were three separate measurement periods, 2002–2005, 2006–2015, and 2016 to recent. Since the measurement sites and methodology were kept the same, it is possible to compare the movement trends (fracture opening or closing) during the separate monitoring periods. The measurements were performed monthly by several trained Peruvian experts (usually geologists). The long-term collaboration was negatively affected by personnel changes, which affected the quality of the data sampling, but never caused a total disruption or termination of the measurements, which highlights the high professional level of site management who adopted the measurements in to their internal procedures. Since 2014, the readings have been taken by a single expert; therefore, this period had not been affected by fluctuations in the quality of the data. The Czech experts visited Machupicchu each year (2002 – 2010) to check the devices, control the measurements and discuss the interpretation of the results as well as the need to install equipment at additional sites with the Machupicchu management. The last site visit of the Czech experts was in 2015, although they remain in touch with the Peruvian experts providing technical and methodological support (e.g., consulting on repairs of the measurement instrument in 2018).

The extensometric measurement profiles were set up to identify movements across the detachment zone of a hypothesized large, deep-seated landslide (e.g., Sassa et al. 2000). The two profiles run across the main square crossing the supposed detachment zone with measuring points (anchors drilled into the rock) fixed into the large rock blocks and rock outcrop. The measurements were taken between 2002 and 2005 but where terminated due to the damage to the instrument.

Historical ground photographs taken by Hiram Bingham played an important role in the conservation effort of the Machupicchu archaeological site as they provide a description of the original state of the archaeological site after its scientific discovery in 1911. The Machupicchu site management has some 160 of these images but lack newer historical photographs, which could document the progress of conservation or show important information with respect to the possible instability of or damage to the Inca structures. To fill this gap, historical photographs of the Czech travellers taken in 1949, 1950, 1954, and 1961 and stored in the archive of the Museum of South-eastern Moravia (Czech Republic) were provided in 2017 to the Machupicchu site managers. They were compared with the current situation in terms of possible changes to the Inca structures as well as the surrounding environment (e.g., open fractures in the stone walls and rock-outcrops, damaged agricultural terraces, and changes in vegetation cover or tourist infrastructure). Such data may also help to identify areas of ground instability, which may be related to landslide processes or progressive damage to the Inca constructions.

Results of the collaboration between the Czech WCoE and the Machupicchu archaeological site management

Dilatometric measurements

Results from the first period of dilatometric measurements (2002–2005) were published in Vilimek et al. (2007). Between 2006 and 2015, no evidence of gravitationally induced movement was recorded at any of the monitored sites. The recorded variations were very small and did not pose any threat to the archaeological site. Similar conclusions were made by evaluating the previous monitoring during years, that is 2002–2005.

Since the last visit of the Czech experts in 2015, the dilatometric measurements have been performed independently by the Department of Maintenance and Conservation (Fig. 2). Geologists and technicians are taking the measurements on the 18th of each month, and the results are reported quarterly to the department chair. If the results show significant variations in the measured distances, their possible causes are identified, and if the situation represents a hazard to the archaeological structures, the relevant measures are taken to mitigate. In the worst case, regulation of the movement of tourists within the Machupicchu site is adopted. This was the case of Intiwatana hill, where visitors' entrance has been allowed only between 7.00 a.m. and 10.00 a.m. since May 2019.

Historical photographs

Historical ground photographs were used for landslide hazard assessment of the slopes surrounding the Machupicchu archaeological site, since they provided information about landslide occurrences preceding the available aerial images from 1963 (Klimes 2013). They were especially helpful in identifying sites of landslide reactivation with long recurrent periods (Fig. 3). Such information led to an increase in the landslide hazard of these sites where the historical photographs extended the available historical record of the landslide occurrences. In some cases (building development around the hydroelectric power plant, Fig. 3), it may be assumed that if the historical information about landslide occurrence has been available and properly considered, the damage caused by the 2002 debris flow could have been avoided or reduced. Comparing historical and recent photographs of the Inca buildings and structures is helpful in evaluating the development of their damage (Fig. 4). In all of the compared cases within the Machupicchu site, no worsening of the damage (e.g., fracture widening, wall collapsing) was observed, which may indicate that the applied conservation and management strategies are appropriate or that the conditions responsible for the original damage did not progress or worsen during the respective time period.

The historical photographs provided in 2017 by the Museum of South-eastern Moravia (Czech Republic) are now available not

Fig. 2 Dilatometric measurements taken by an expert of the Department of Maintenance and Conservation, DDC-Cusco below the summit of Waynapicchu Mt. (site "W" on Fig. 1)

only to the experts directly responsible for the management and investigations at the Machupicchu site, but also to the DDC-Cusco as the images also portray other historical sites in the region (e.g., Pisac). In addition to their use described above, they proved to be helpful to document the historical development of selected structures inside Machupicchu, providing additional information to the archaeological research (Bastante and Fernández 2018). Further on, they will be used to identify archaeological structures now covered by vegetation or evaluate the possible effects of the 1950 Cusco earthquake (Erickson et al. 1954) on the historical buildings.

Discussion

Zan and Lusiani (2011) identified various weaknesses of the master plan of the Machupicchu village including a lack of staff training and poor organization and participation of the local population. The Czech WCoE activities contributed to these topics through collaboration with the Machupicchu site management and by sharing our results with the local population through public talks in Cusco and Machupicchu village. The collaboration with the staff of the National Archaeological Park of Machupicchu has been based on open communication, knowledge sharing and joint interpretation of results ensuring that all involved parties benefited from it. This intensive participatory approach (compare with Klimeš et al. 2019) resulted in the adoption of dilatometric measurements as a part of the internal management procedures of the management of the site.

Conclusion

The enormous historical, cultural, and spiritual importance of the Machupicchu site requires the application of sensitive and environmentally friendly methods for monitoring the natural hazards that may potentially affect it. The threat from natural hazards continues especially because of potential earthquakes and intensive precipitation, which lead to the triggering of landslides. The

Fig. 3 The historical photograph (left, Ingriš, © Archiv H+Z, Muzeum jihovýchodní Moravy Zlín) showing a small debris flow before 1949 in the same place as the larger event in 2002 (right, photo 2003), which damaged buildings around the hydroelectric power plant in the Urubamba Valley

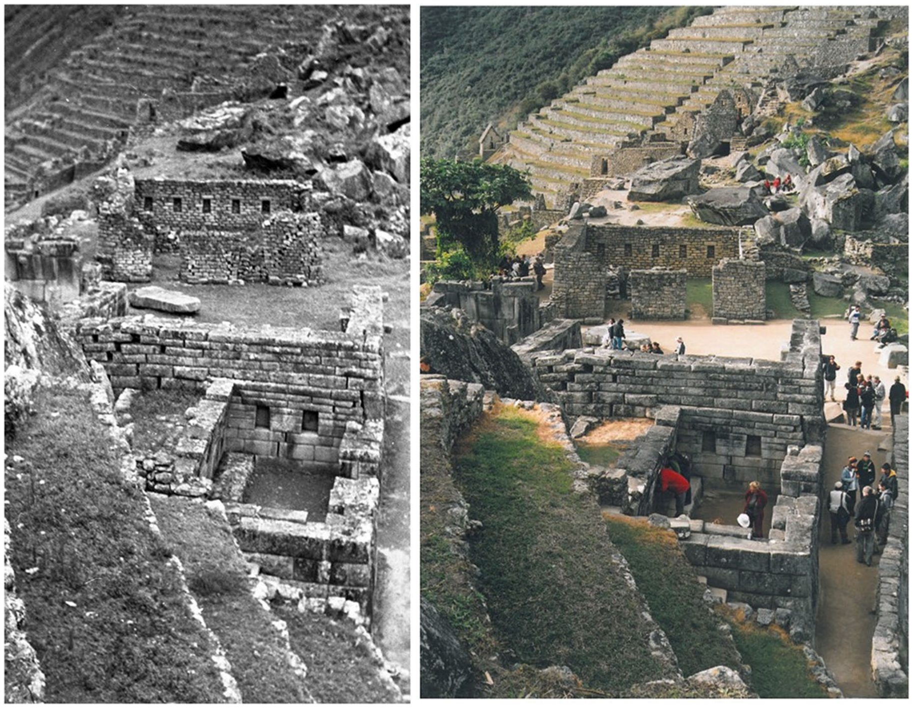

Fig. 4 The historical photograph (left, Hanzelka and Zikmund, © Archiv H+Z, Muzeum jihovýchodní Moravy Zlín) showing no identifiable development of the fractures in the walls of the Main Temple between 1949 and 2005.

dilatometric and extensometric monitoring network established in 2003 helps to address these hazards and fully meets the strict site requirements while providing applicable long-term data. The landslide hazard of the archaeological site has to be considered seriously, even though the monitoring data show no signs of active slope deformations inside the core area. A high level of precaution is needed because of the globally exceptional value and stress produced by tourism. The choice of long-term, low-cost, and environmentally friendly dilatometric monitoring is an example of working cooperation for proper hazard management.

To supplement the period of direct in situ monitoring for the hazard evaluation, we used a comparison of historical photographs, which revealed that Inca structures inside Machupicchu have not been affected by slope movements or other damaging processes. On the other hand, historical photographs (from archives in the Czech Republic) were useful for landslide hazard assessment in the surroundings of the archaeological site and have been made available to the Machupicchu managements since 2017.

The collaboration of the Machupicchu managements (DDC-Cusco) and the Czech WCoE (World Center of Excellence on Landslide Risk Reduction) has always been built on a participative approach in problem definitions, suggestions for their solving as well as knowledge and result sharing and their joint presentation. The management and experts of the Machupicchu archaeological site have assumed full responsibility for the application of the monitoring methods and the use of the archive photographs. Therefore, the role of the Czech WCoE remains at the consulting level responsible for long-term support of the adopted techniques. In terms of cooperation in research and conservation in the near future, both sides will profit from the above-described collaboration results.

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