LANDSLIDE RISK AT INCA'S WORLD HERITAGE IN MACHU PICCHU, PERU

世界遺産マチュピチュにおける地すべり危険度評価

佐々　恭二*・福岡　浩*・釜井　俊孝*・守随　治雄**

Kyoji SASSA, Hiroshi FUKUOKA, Toshitaka KAMAI and Haruo SHUZUI

ユネスコ世界遺産の中で最も顕著な、ペルー国、マチュピチュのインカ遺跡において、ペルー国文化庁、自然資源庁、地球物理研究所地の協力を得て、予備調査として2000年3月に綿密な地質・地形踏査と空中写真判読を実施した。その結果に基づき簡易型伸縮計10台と自記式伸縮計 2 台を2000年11月に設置し予備観測を開始した。世界遺産マチュピチュは、大規模な岩盤崩壊地形の真上に位置し、クラックや小崩壊などの危険な兆候を示していることがわかってきた。

本論文は、地すべり危険度軽減と文化・自然遺産保全における、UNESCO/IGCPシンポジウム（2001年、 1月15日～19日）の国際会議にて発表したものである。

Key Words *: Machu Picchu, World Heritage, Landslide, Monitoring, Risk-Mitigation*

1．INTRODUCTION

The Inca Citadel in Machu Picchu, at northwest of Cusco, Peru, (**Fig.1**) was declared a World Heritage of Humanity in terms of both cultural and natural property by UNESCO in 1983. It is also an ecological sanctuary because of its ecological richness. The present style of citadel was probably built by the Incas in the 15th century. It remained untouched through the colonial period because of its isolated location on the top of a steep mountain. Machu Picchu became known to the world after its "scientific discovery" by Prof. Hiram Bingham in July 1911. As time passed, it seemed that Machu Picchu citadel possibly has been affected by landslides. Ten years ago, the director of the Geophysical Institute of Peru (Instituto Geofisico del Peru = IGP) visited the Disaster Prevention Research Institute, Kyoto University and requested an investigation of the area. And in 1997, R. Carreno and C. Bonnard published a paper "Rock slide at Machu Picchu, Peru." Carreno proposed a study of this slide as a sub-project of IGCP-425 in 1998, and it was approved. During the IGCP-425 meeting and UNESCO Conference on Cultural Heritage at Risk at UNESCO in September 1999, his report on the subproject attracted considerable interest from participants.

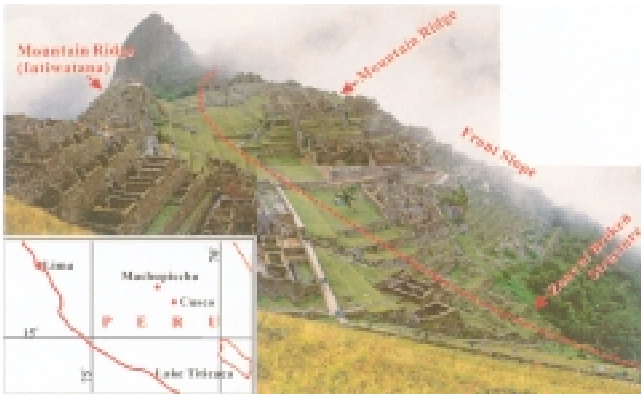

Fig. 1　Location and view of Machu Picchu Inca Citadel, Peru

Sassa, Fukuoka, Shuzui, and others investigated this area and collected information in Lima and Cusco from 14 to 20 March 2000 to evaluate the possibility of landslide risk and to make a research plan. From 9 to 16 November 2000, Fukuoka, Kamai and others installed 12 sets of extensometers in Machu Picchu citadel for preliminary monitoring of active / potential landslide

＊　京都大学防災研究所　地盤災害研究部門
＊＊　大阪支店　技術第二部

blocks. The investigation was in cooperation with the Peruvian INC (Instituto National de Cultura), INRENA (Instituto National de Recursos Naturales), and IGP.

2. GENERAL VIEW

Fig. 1 (photo) presents the Inca Citadel at Machu Picchu. The citadel was constructed on top of a mountain. The east slope (at the right side of the photo) is relatively gentle, and the access road (H. Bingham Road) and sightseeing hotel are constructed in this side of the slope. We call this side of slope as *Front Slope*. As reported in Carreno and Bonnard (1997), the *Front Slope* is the dip slope, in which the joints of the rock mass are aligned almost parallel to the slope. In this slope, we found a "zone of broken stone structure," as indicated in **Fig.1**. The stone structures seemed not so strong type there, but still the zone of broken structures is likely to be a shear zone of a potential landslide in the precursor stage.

The other side (west side) of the mountain is very steep, and has no access road from the Urubamba river to the Inca Citadel. We call this slope the *Back Slope* (**Fig. 2**). The *Back Slop*e is a cross-dip slope, and has a high resistance to shear. As a result, the slope angle is very steep. However, there are many large and small pre-existing landslides. The landslide marked by an arrow in **Fig. 2** is large and relatively young. The white trace in the opposite bank is the deposit of a recent landslide. Most landslides on the *Back Slope* are rock falls or topples.

Fig. 2 Inca Citadel and the Back Slope.
(Taken from a chartered helicopter by K. Sassa on 19 March 2000)

We found the trace of a very recent small debris flow on the back slope of Intiwatana ridge (symbolic, most popular and the highest part of the Citadel; see **Fig. 1**). However, the debris flow trace is not visible in the photo of **Fig. 2** because it is behind a small ridge. The location is marked "debris flow" in **Fig. 2**. A line of cracks and deformation of structure (Principal Temple) was found in other side. Therefore, the block that includes Intiwatana is expressed as a potential landslide block (No. 5) in **Figs. 4, 6 and 11.**

The center of the citadel seems to be slightly concave (i.e., nearly flat). This flat area was allegedly used for festivals and games by the Inca people. Its topography is similar to that of double ridges (two mountain peaks) as marked in **Fig.1**. The double ridges are known as a feature of topography that is formed as the result of creep movement of a mountain, including the ridge. However, a detailed examination will be necessary to judge whether this flat or concave area is the result of slope movement or not, and it can be considered to be a precursor slope deformation to a possible catastrophic landslide, or not.

3. LANDSLIDE DISTRIBUTION AT MACHU PICCHU

Fig. 3 is a stereo pair airphoto of the entire Machu Picchu area. The access road (H. Bingham Road) climbing up to the Inca Citadel is easily visible. In addition, the area shows the form of a large-scale landslide. The Urubamba River makes an almost full turn around this area. The influence of the fault system is very strong. Mount Putukusi on the opposite side of H. Bingham Road may seem to be the displaced landslide mass in this photo, but it is at almost the same elevation as the citadel. The base of the mountain seems to be intact, although its surface has been modified by rock slides. This photo has been published previously in Landslide News No.10 (Carreno and Bonnard 1997).

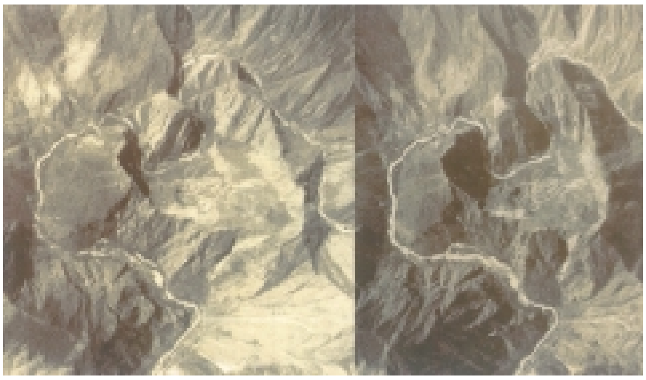

Fig. 3 Airphoto of Machu Picchu.
(By the Geographical Institute, Peru on 28 July 1963)

The airphoto of **Fig. 3** was used for interpretation, in addition to other airphotos and visual observations from a chartered helicopter. The landslide distribution, including active, inactive, and potential landslides in the precursor stage were delineated. This landslide distribution map provides kind of working

Fig. 4　Landslides and potential landslides around the Machu Picchu Citadel.

hypothesis for the planning of future geological borings and geophysical monitoring. Locations of existing landslides and potential landslides around in the vicinity of the Machu Picchu Citadel are presented in **Fig. 4**. The Macupicchu citadel area is expressed as dark shaded part. Recently active landslides (Blocks No. 1, 4, 6, 7, the smaller sub-blocks of No. 2 and the upper half of Block No. 3), landslide debris (along the river), potential landslides (Blocks No. 2 and 5) and inactive landslides (the lower half of Block No. 3) are shown in **Fig. 4.**

Fig. 5 shows the *Front Slope* and the side view of major landslide blocks No. 1, 2, and 3. All blocks moved toward the Urubamba River, and Block No.1 is about 100 m lower than Blocks No. 2 and 3 in its center. Thick landslide debris seems to have been deposited in the lower part of Block No. 1. The sliding surface of this landslide block (No. 1) seems to connect to the present level of the Urubamba River. Therefore, the last activity of Block No.1 is relatively young. Activity in Blocks No.2 and 3 probably took place during the time when the bed of the Urubamba River was one step higher (at the elevation of the present surfaces of Blocks No. 2 and 3), as shown in **Fig. 5**. The bedding of the rock is almost parallel to the *Front Slope*.

Fig. 5　Side view of Blocks No.1, 2 and 3 in the Front Slope

4. HYPOTHESIS FOR THE LANDSLIDE PROCESS AT MACHU PICCHU

A hypothesis for the slope evolution at Machu Picchu as obtained from the field investigation and airphoto interpretation is explained using **Figs. 4, 5, and 6**. **Fig. 6** illustrates the slope evolution (in the sense of working hypothesis) along schematic sections A-A' of Block No. 1 and B-B' of Block No. 2. The locations of these sections are shown in **Fig. 5**. The slope of Machu Picchu slid along joint in granite that are inclined toward the Urubamba River at depth. As shown in **Fig. 4**, the sliding surface of the 1st slide ① in Block No.1 is likely to be at the present ground level of Block No. 2 including the Inca Citadel and its farm area, and also at the present ground level of Block No. 3 (see section C-C' at the bottom right of **Fig. 6**). The second landslide ② occurred in Block No. 1 due to river erosion and the lowering of the level of the river bed. The present situation at Block No.1 seems to be a "reactivation" of this earlier landslide mass. The previous landslide ① in Block 2 removed the mountain ridge (**Fig. 3**) and formed topography suitable for construction of the citadel. Similar to the case at other landslide areas, landslide activity formed a relatively gentle slope and soils suitable for farming in this rocky area.

The effect of landsliding aided successful excavation for ground water in Blocks No. 1 and 2. Enough water was available to supply this area of a rocky high mountain top. Springs issuing forth as the result of landsliding (especially below the head scarp of Block No.1) were used for irrigation. Thus, the Inca Citadel with its adjoining farm land was able to be developed. After the Inca Citadel construction, many smaller landslides have gradually occurred in the vicinity. Now the citadel itself seems to be at risk from landslide activity as illustrated in section B-B' of Block No. 2 in the second part of **Fig.6**. The second large landslide ② could include the entire area of the Inca Citadel or could split the citadel. In addition, smaller landslides are gradually approaching the citadel from both slopes. The schematic cross section through Blocks No.1, 2 and 3 along section C-C' is shown at the bottom right of **Fig. 6**. The level of Block No.1 is lower than that of Blocks No.2 and 3 because of the second slide ② in Block No. 1.

Fig.7 is an oblique airphoto of Block No. 2 and the Machu Picchu Citadel, it shows some part of landslides and potential landslides of **Fig. 4**. Block No.1 is a reactivated landslide; the landslide topography is visible, the border being indicated by a solid line. Another long solid line at the top of the figure is the Hynapicchu fault, between the rock cliff and the forest. This was the border of the first landsliding ① which removed the mountain ridge at this location and provided a site suitable for the citadel. The possible head scarp, forming a double ridge

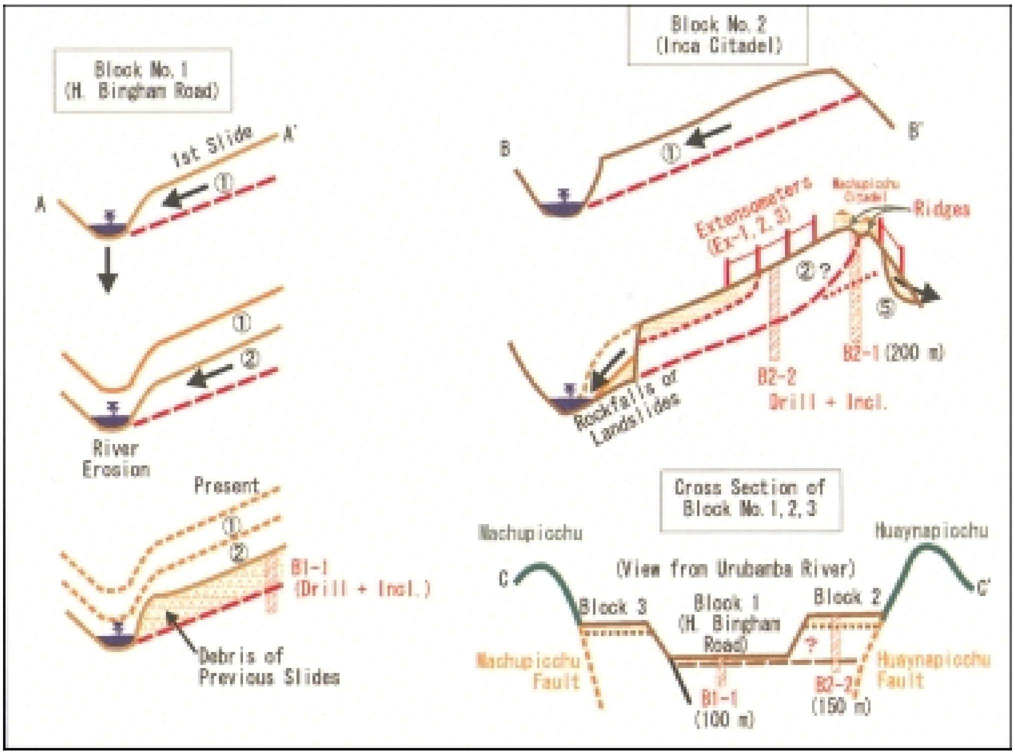

Fig. 6 Hypothesis of the landslide process in Machu Picchu.

Fig. 7　Oblique airphoto of the Inca citadel, indicating delineation of exsting and potential landslides.

crossing the central flat area of the citadel is expressed as a dotted line. Block No. 5 including "Intiwatana," the highest point of the citadel is surrounded by a dotted line. There is also the possibility that the entire block, including the citadel, may slide along the rock joint in the same way as the sliding ② in Block No. 1, or previous landsliding ① in Block No. 2. All dotted lines are still hypothetical, and need additional study.

5. INVESTIGATION, AND MONITORING AND POSSIBLE COUNTERMEASURES

The possibility of landslides that may destroy this invaluable World Heritage site has been manifested by this study. However, this investigation was not supported by quantitative data. Therefore, by itself it is not enough to allow any convincing conclusions as the basis for extensive investment into protection measures. Landslide-risk mitigation requires a large budget for such large-scale landslide activity. However, we hope that the results of this study are interesting enough to initiate detailed geological investigations and precise monitoring of slope movement in preparation for a reliable landslide-risk evaluation. The investigation should be done step by step, but the first steps should be initiated immediately so that it may not be too late. This study can serve as the frontier for scientific research in the field of prediction of large-scale landslides in the precursor stage, as well as for landslide-hazard assessment and risk mitigation. It will necessitate development of a reliable and practical monitoring system, as well as long-distance data transfer in a developing country and a location that is not easy to access.

6. BASIC INVESTIGATION

A detailed topographical map at a scale of 1/1000 or 1/2000, based on aerial photographs, is absolutely necessary. The present available map at a scale of 1/25,000 is not enough for landslide investigations. Mapping should carefully express the features of landslides and related phenomena. A detailed geological map based on reconnaissance also is necessary, especially for Blocks No.1 and 2. Footpaths need to be constructed in the forested areas; they will be used for repeated investigations and regular field observation of surface deformation.

7. GEOLOGICAL BORINGS AND INSTALLATION OF MONITORING EQUIPMENT

Several borings of 100-200 m deeps will be necessary at Block No. 2 to better understand landslides at immediate risk to the Inca Citadel. Borings also are needed in Block No.1 to protect the access road and hotel, though these borings would be for the ordinary type of investigation for reactivated landslides. An inclinometer casing should be inserted into each borehole in order to periodically monitor movement along the sliding surface. A vertical extensometer for continual record of deformation should be placed in the same borehole.

Surface extensometers are sensitive and reliable monitoring instruments. At least several extensometers should be installed. A series of extensometers should be positioned crossing the possible shear zone of the "zone of broken structure" shown in **Fig. 1**, and also on the head scarps of landslides (Blocks No. 4, 5, 6) on the Back Slope to check retrogressive movement at the citadel.

8. INSTALLATION OF EXTENSOMETERS IN MACHU PICCHU CITADEL AND PRELIMINARY MONITORING RESULTS

(1) Non-recording type extensometers and selfrecording type extensometers

For preliminary monitoring of potential landslide blocks in Machu Picchu citadel, authors have developed 10 sets of simplified, non-recording type extensometer system, which consists of super-invar wire, weights, pulley, dial and pointer (**Fig. 8**, left). These were designed with purposes of (1) simple mechanism with no power supply, (2) enough resolution and precision up to 0.2 mm, and (3) easy maintenance and high durability in the field. However, this cannot record on any media by itself, so the Peruvian operator must record its readings

Fig. 8 **Two types of extensometers installed in Machu Picchu citadel.Left:Simplified type extensometer (#1 in Fig. 9) which was developed for monitoring of active / potential landslides in Machu Picchu citadel.Right:Self-recording type extensometers (S-1 in Fig. 9).**

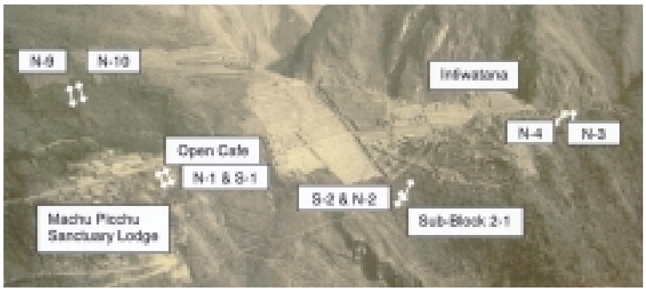

Fig. 9 **Location of extensometers in the Front Slope of Machu Picchu citadel.**

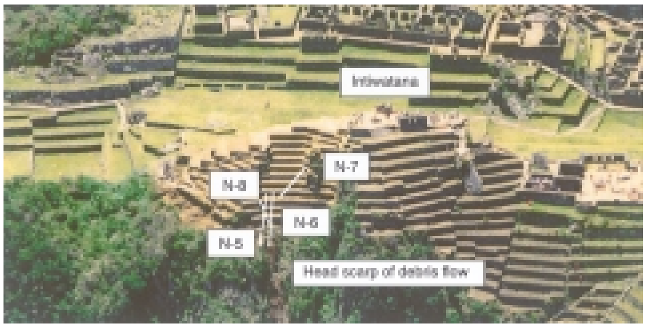

Fig.10 **Location of the foue sets of simplified type extensometers (N-5,6,7 &8) installed in the Back Slope beneath the Intiwatana at risk of retrogressing landslide.**

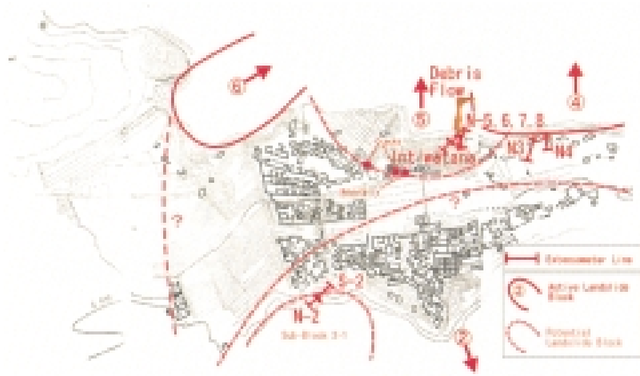

Fig.11 **Plan map of Machu Picchu sitadel showing active / potential landslide blocks and location of extensometers. "N-3" shows exetnsometer No.3 of non-recording type. "S-2" shows extensometer No.2 of self-recording type.**

periodically and manually.

Besides, two sets of self-recording type extensometers (**Fig. 8**, right) were brought to Machu Picchu citadel to be installed at most apparent active landslide blocks. These extensometers are of most popular type in Japan and can record continuous data on recording sheet on rotating drum which is connected with its pulley. Movement of super-invar wire is exaggerated by 5 times on the recording sheet by the pulley and drum.

(2) Installation of extensometers and their monitoring results in November - December 2000

During 9 - 14 November 2000, two of the authors (Fukuoka and Kamai) visited Machu Picchu citadel again for geological investigation and installation of the extensometers. They installed the extensometers of both types in four active / potential landslide blocks of Machu Picchu citadel. Location of each extensometer in the Front Slope and Back Slope is shown in **Figs. 9, 10, and 11**. INC and INRENA have started monitoring of the 12 extensometers in November 2000. Preliminary results by the extensometers for about one month between 13 November and 16 December 2000 are shown in following sections.

1) Forecourt and back slope of the Machu Picchu Sanctuary Lodge

The open cafe in the forecourt of the Machu Picchu Sanctuary Lodge is suffering from ground deformation for years. There are new cracks on the ground, which imply this site is head scarp of a small landslide. Every day a lot of tourist take rest at this cafe and the instability of its foundation must be a serious problem. One set of non-recording type extensometer (N-1) and one set of self-recording type extensometer (S-1) were installed crossing the cracks. The back slope of the Machu Picchu Sanctuary Lodge showed an old landslide topography and two sets of non-recording type extensometers (N-9, N-10) were settled at its head scarp to monitor retrogressive movement of the block.

Observed data of the non-recording extensometers are shown in **Fig. 12**. The extensometer at the open cafe showed almost cumulative extensive movement of about 15 mm in this period. Extension was expected at this site because the extensometer span was installed at the head of a small landslide scarp. The extension of the first week (about 5 mm) might be caused by stretching of super-invar wire itself due to loading by weight. However, about 10 mm of further cumulative movement still continued thereafter. This movement might be interpreted as a

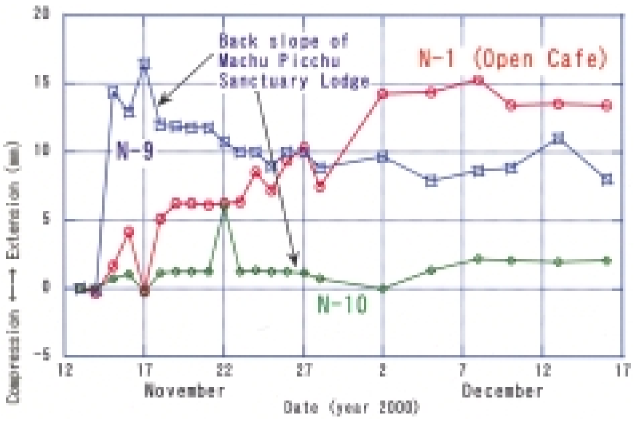

Fig.12 Monitoring record of the simplified extensometers before the open cafe and back slope of the Machu Picchu Sancetuary Lodge.

Fig.13 Cracks progressing in the wall and their temporal reinforcement by timbers inside the Luggage Check beneath the open cafe of Machu Picchu Sanctuary Lobge

result of landslide activity because the 10 mm movement is larger than scattering of 3 - 5 mm. In Machu Picchu district, the rainy season is from December to March, however, precipitation record is not yet obtained and cannot be compared at this moment. Cracks are obvious in the beam of the cafe and they are progressing inside the walls of the Luggage Check just beneath the cafe (**Fig. 13**, left). The hotel made temporal reinforcement by timber wood (**Fig. 13**, right). This deformation due to the ground subsidence are caused by landslide activity just before the cafe. On the other hand, N-9 extensometer showed exceptionally large extension of about 15 mm in the first week and in turn, gradual compression motion of about 4 mm in the next 3 weeks. The N-10 extensometer showed almost no displacement. These two extensometers need further monitoring to judge the instability of this block.

2) Back slope of Intiwatana

At the peak of Intiwatana, there is a ancient solarium made of intact rock on top of the steep hill and the most popular tourist spot in the Machu Picchu citadel. According to the observation from the helicopter in March 2000, a debris flow was observed on the *Back Slope* just beneath the peak of the Intiwatana ("Head scarp of debris flow" in **Fig. 10**). The head scarp of this debris flow has obviously retrogressed and it has become visible from the peak of the Intiwatana in 2000. It is certain that the next retrogressive failure will give damage to the steps of the back slope of Intiwatana. These steps might be restored after Bingham's discovery by the Peruvian government. This slide is most significant among all of the potential landslides in Machu Picchu citadel. Four sets of non-recording type extensometers were installed on the back slope of Intiwatana for monitoring the reactivation of debris flow as well as the possible instability of the lower steps on the back slope (N-5,6,7&8 in **Fig. 10**). Two of the spans connected from inside of the debris flow head scarp to the artificial step beneath Intiwatana. Other spans connected lower step to higher ones. If the instability of the steps become obvious, urgent remedial work would be necessary.

Fig. 14 is the monitoring result of the extensometers N-5,6,7 & 8. Three of the four extensometers show cumulative compression of 4 - 8 mm in about one month. On the other hand, N-8 extensometer shows almost no change. These results strongly imply that the lower steps of the back slope of Intiwatana is unstable and already starts downslope movement.

3) Sub-block 2-1 and imminent rock fall sites in Block 4

In order to monitor the activity of the Sub-Block 2-1, one set of self-recording type extensometer and one set of non-recording type extensometer were installed in-line in the slope direction. In Block 4, two of large rocks show serious cracks which show recent progressive opening. Two sets of non-recording type extensometers are settled between ground and the imminent rock fall mass. Monitored records of Sub-Block 2-1 shows larger scatter of 10 mm and no cumulative movement. Other two

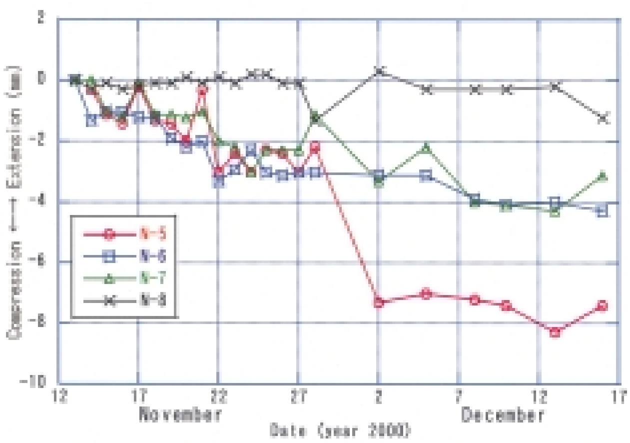

Fig.14 Monitoring record of the four extensometers installed on the bacslope of Intiwatana.

extensometers for rock fall monitoring show comparatively small scatter and no cumulative movement in the monitoring period.

(3) Plan of further monitoring

In the preliminary monitoring of the extensometers shows obvious cumulative movement in the two blocks. This suggests at least the two landslide blocks are active. For further detail, precise and continuous monitoring, authors are planning to install electronic extensometers and crack gauges in Machu Picchu citadel. Extensometer data will be stored in computer and be transmitted to responsible organization for monitoring such as INRENA, INC, IGP and DPRI-KU through handy-phone and Internet.

9. RISK-MITIGATION WORKS.

The Inca Citadel is at landslide risk in various ways: rock falls and rock topples on the Back Slope, a large-scale translational landslide and retrogressive landslides (slumps) from the toe and also from the border between Blocks No. 1 and 2 on the Front Slope, and reactivated landslides in Block No. 1. The first step in mitigation will be a reliable landslide-hazard assessment and risk evaluation. The second step will be cost estimation for risk-mitigation works for each phenomenon. Step number three will be decision making for risk mitigation works and their funding. This will be based on the significance of the economical and cultural value of this site and also on the significance of scientific and technical development of landslide-risk mitigation works, which are applicable in other areas. The landslide-risk mitigation works can include, A-- Indirect and relatively inexpensive measures: 1) Drainage of surface and ground water to decrease triggering factors and to reduce the rate of weathering, 2) Prevention of toe erosion along the Urubamba River. Heavy river erosion is a basic factor in triggering landslides, and slopes affected by landslides are "attacking slope by river flow due to curvature of its course," 3) Stabilization of shallow landslides because they may increase instability of deep landslides, B-- Direct measures 1) to prevent rock topples and rock falls on the very steep Back Slope by means of rock anchor or retaining frame works, and 2) to stabilize large-scale landslides by means of steel piles or shaft works (reinforced-concrete piles as much as a few meters in diameter), and any new method to stabilize the very deep translational slide of Block 2, which is the most difficult and needs new development.

CONCLUSIONS

Extensive landslide investigations and risk-mitigation measures require much larger budgets, as well as high levels of scientific and technical knowledge. However, the great expense might be acceptable if we consider the cultural and historical value of this World Heritage site, and also its great economic value in attracting almost one million tourists per year. In addition, the landslide-risk evaluation must be reliable and convincing to decision makers. Taking into consideration the scientific, technical, and economic situation in Peru and the global value of Machu Picchu, scientific, technical, and financial support and cooperation from the world are very necessary. In this regard, the IGCP-425 group has taken a very positive attitude toward the investigation of landslides at Machu Picchu. This work to predict a potential large-scale landslide and to mitigate the landslide risk is at the frontier in the field of landslide science and technology. The research at Machu Picchu must contribute to the progress of natural-disaster reduction and protection of cultural and natural heritage sites worldwide.

ACKNOWLEDGEMENT

The Japanese investigation team was well received by the related agencies in Peru and obtained significant support and cooperation. We acknowledge the following institutes and persons for their cooperation to this investigation: Dr. Mutsumi Ishitsuka, Director of the Ancon Observatory, IGP, has cooperated in all aspects as the counterpart of this investigation in Machu Picchu. The executive director of Instituto National de Cultura (INC), Gustavo Benza Pflucker, gave a special permission to fly over the Machu Picchu Inca Citadel by chartered helicopter, and provided necessary supports to us. The Director General of Areas Naturales Protegidas y Fauna Silvestre, Luis Alfaro Lozano of Instituto National de Recursos Naturales (INRENA) and their staffs in Cusco and Machu Picchu provided personnel necessary for field investigation. The vice director of IGP, Hernan Montes, and his staff cooperated in importing monitoring apparatus, and Ms. Susana Kalafatovich, PROEPTI, Cusco provided support in Cusco.

REFERENCES

Sassa, K., H. Fukuoka & H. Shuzui. 2000. Field investigation of the slope instability at Inca's World Heritage in Machu Picchu, Peru. Landslide News. No.13, pp.37-41.

Carreno, R. and C. Bonnard. 1997. Rock slide at Machupicchu, Peru. Landslide News, No.10, pp.15-17.