Landslide Risk Evaluation in the Machu Picchu World Heritage, Cusco, Peru

Kyoji SASSA[*1], Hiroshi FUKUOKA[*1], Haruo SHUZUI[*2], Minoru HOSHINO[*3]

[*1] Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan
[*2] Osaka Office, Nihon Koei Co. Ltd., Osaka, Japan
[*3] Geographical Survey Institute, Tsukuba, Japan.
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1. INTRODUCTION

1.1 Background and Short History

This paper aims to supplement the theme talk in the Panel Discussion "Machu Picchu World Heritage at Landslide Risk" during the International Symposium on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage.

Prediction or identification of precursor phenomena of large scale landslides is not an easy task. Large-scale landslides do not occur in the same place in a short return period compatible to life period of human beings. It is a kind of geological process and the return period of large-scale landslides are usually very long in the order of thousand years or tens of thousand years or even longer.

Before the Hyogoken-Nanbu earthquake took place, most of the Japanese people regarded that earthquakes occurring in the order of thousand years was almost out of scope in present planning of disaster prevention measures. However, such earthquake caused great damages to mega city area of Kobe. So now it is clearly understood that even infrequent phenomena such as movement of active faults and earthquakes should be seriously considered and people prepared for that. Frequency of active faults and large-scale landslides are rather similar, though the casual forces of phenomena are different; faults by crustal horizontal stress, landslides by gravitational vertical stress.

Protection of mega city from earthquakes is very important, and we, researchers involved in the field of disaster prevention should focus our study toward a more reliable prediction of site and time. Though the disaster caused by landslides are not so great in the number of death comparing to earthquakes, the Mayuyama landslide in Unzen, Japan, 1792 killed 15,000 people (Sassa 1999) and the most recent Las Colinas landslide killed around 600 people in El Salvador in 2001. So landslides cause not a little disaster.

Entering 21st century, we are more and more aware of the value of the environment, especially regarding the invaluable cultural and natural heritage. Those are very fragile treasure for humanity, which cannot be rebuilt once they were destroyed. People worked for economic development in the last century, and the industrial progress and economic development is still very important for the base of society, but at the same time, we have notice that we should protect and leave our invaluable treasures of humanity to the next generation so long as possible.

Fortunately the progress of geosciences is approaching to a level to identify precursor phenomena of large-scale landslides, and assess the location, size, velocity, and hazard area of these landslides. It was recognized during the International Decade for Natural Disaster Reduction to create less hazardous

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world in the last decade of 21st century. The landslide hazard assessment in Lishan (resort palace of Tang Dynasty), Xi'an, China by DPRI/KU and the Xi'an Construction Committee was successful. The landslide risk assessment based on the joint research has convinced the landslide risk to the Chinese government as well as the Shaanxi Provincial Government and the Xi'an city. Based on the landslide risk assessment research, landslide prevention works were initiated before occurrence of any disaster due to landslides. Then, Prof. Edward Derbyshire of the IGCP scientific committee invited DPRI/KU to propose a project. IGCP-425 "Landslide Hazard Assessment and Cultural Heritage". the project was adopted and now on-going. The Machu Picchu landslide was introduced by Raul Carreno as a part of IGCP-425 sub-project "Study and protection of Inca cultural heritage on landslide zone at Cusco, Peru".

DPRI/KU team investigated Machu Picchu in March 2000 with support from staffs of INC and INRENA in Machu Picchu, and installed extensometers in November 2000, and reported those results in the UNESCO/IGCP Symposium on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage in Tokyo, 2001. Those reports were introduced by *Yomiuri Newspaper* in Japan, "*New Scientists*" in UK, *Civil Engineering* by ASCE in USA and others. The article by "*New Scientists*" was sensational, because of other articles in *Yomiuri Newspaper* and in *Civil Engineering* were published after the review by Sassa. However, the New Scientist article was based only on telephone interview and not reviewed. The article was written with serious misunderstandings in some parts. This article caused sensation over the world. Therefore, UNESCO thought the necessity to inform a real state of investigation and published *"Rumbles at Machu Picchu"* article in "*World Heritage Review*," No.20, May 2001 (Bandarin 2001).

During the discussion within the UNESCO/IGCP symposium in Tokyo, participants agreed to establish a new International Consortium on Landslides (ICL) to promote worldwide landslide research. The 2001 Tokyo Declaration proposed the investigation and research on Machu Picchu at landslide risk as its initial project of ICL. It is the result that all participants realized the great significance of investigation of Machu Picchu from both aspects - Sciences and Protection of Cultural Heritage.

DPRI/KU and colleagues investigated Machu Picchu in October and November in 2001 with cooperation from INC and INRENA. Jiri Zbelebil and Vit Vilimek of Czech group of IGCP-425 intended to join the field investigation with support from the Czech government. But the timing was a bit delayed, so joint investigation was not conducted. However, their research is to be presented in the same panel discussion. Those investigations from various aspects or teams will present better view of Machu Picchu landslide risks.

1.2 Outline of Machu Picchu World Heritage

Inca's world heritage is located northwest of Cusco, Peru (Fig.1). It 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 after the collapse of the Inca empire in 1540 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. The photo shown in Fig.1 was taken by H. Shuzui (a member of the Japanese team). You may see a beautiful citadel is constructed on the top of rocky mountain. At the same time, you may find this part of mountain ridge is different from other part of the mountain ridge seen behind the citadel (Una Picchu and Huayna Picchu). The part called as **Plaza** in which the citadel was constructed has a flat area or an even concave area sandwiched by two ridges (Intiwatana in the left side peak in front of Una Picchu and the residential building area in the right side peak). By the eye of landslide researchers, the Plaza area seems to be re-profiled by filling earth or debris to the cracks between two ridges along the dotted line. As shown in the previous report (Sassa et al 2001), the dot line passed through a zone of broken structure in the extension of right bottom of Fig.1. This hypothesis is not yet proved by monitoring, drilling, geophysical exploration or direct excavation or other reliable methods. However, any phenomena to deny this hypothesis is not yet found. Therefore, what is the cause of Plaza geomorphology, which is apparently different from other parts of mountain ridge in this Machu Picchu area, should be investigated.

Fig. 1 Location and view of Machu Picchu Inca citadel on the mountain ridge, Cusco, Peru.

Sassa et al presented a landslide distribution map based on chiefly air photo by Geographical Institute, Peru, 1963 and field investigation from a chartered helicopter and walking in Fig.2. Landslide blocks were drawn on the topographical map used in the report by K. Wright and R. Wright 1997. It is included in Wright and Zengarra, 2000. The ridge connecting Mt. Machu Picchu and Mt. Huayna Picchu separates the slope as a gentle slope where Hiram Bingham Accessing Road is constructed, and a steep slope. We have called the gentle slope with the accessing road as **Front Slope** including Blocks 1, 2 and 3, and the steep slope as **Back Slope**. In this map, No.1 and No.4, No.6 and No.7 are landslides. No.2 is an area, which may develop to an actual landslide or a landslide at precursor stage. No.5 of Intiwatana area shows some phenomena of ground deformation around them (Sassa et al. 2001). The long-term stability of this area is questionable. No.3 was probably the bottom of previous landslides. All landslide debris slid away there. At present the lower half of slope seemed to be not active.

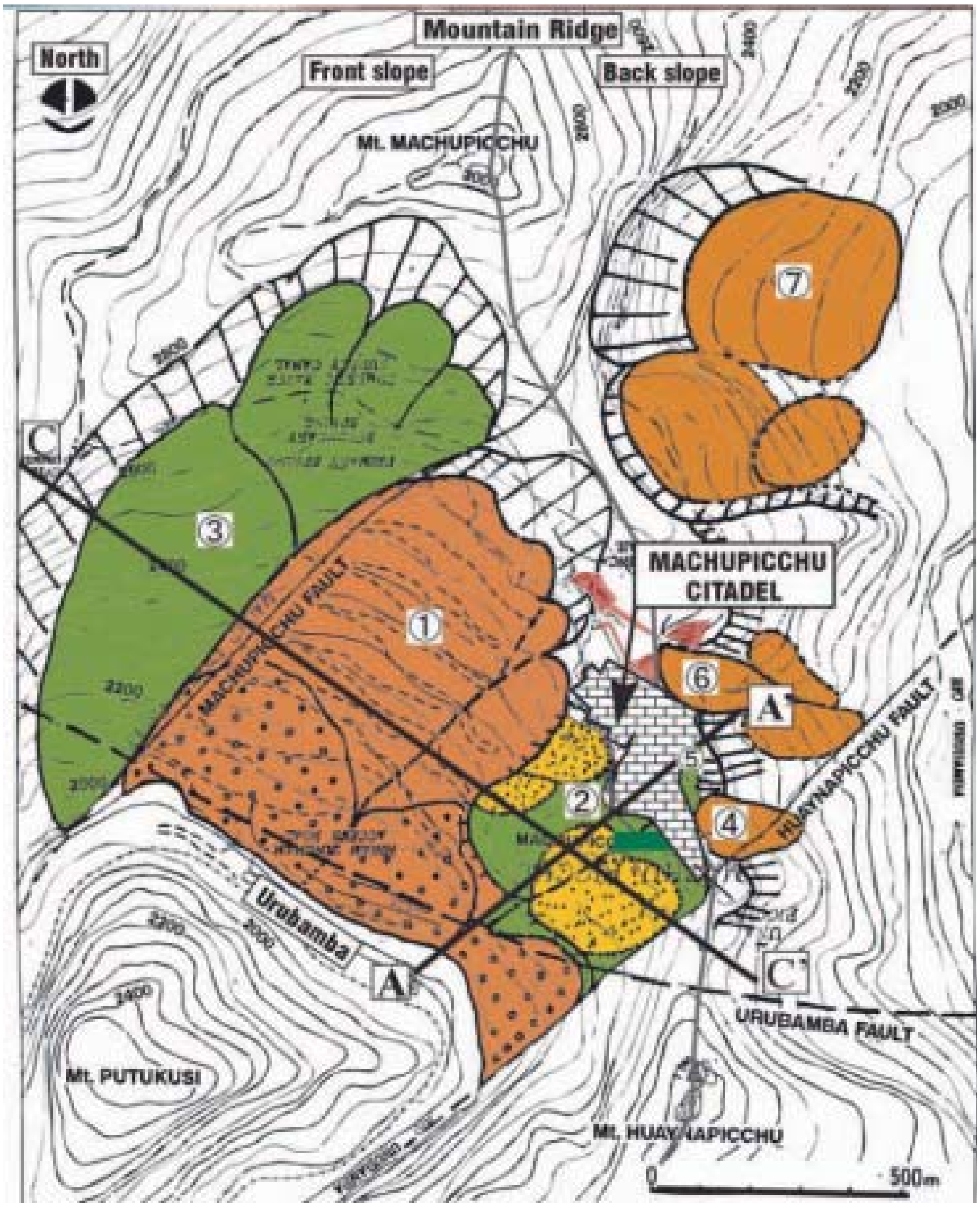

Fig. 2 Landslides and potential landslides around the Machu Picchu Citadel (Sassa et al.2001)

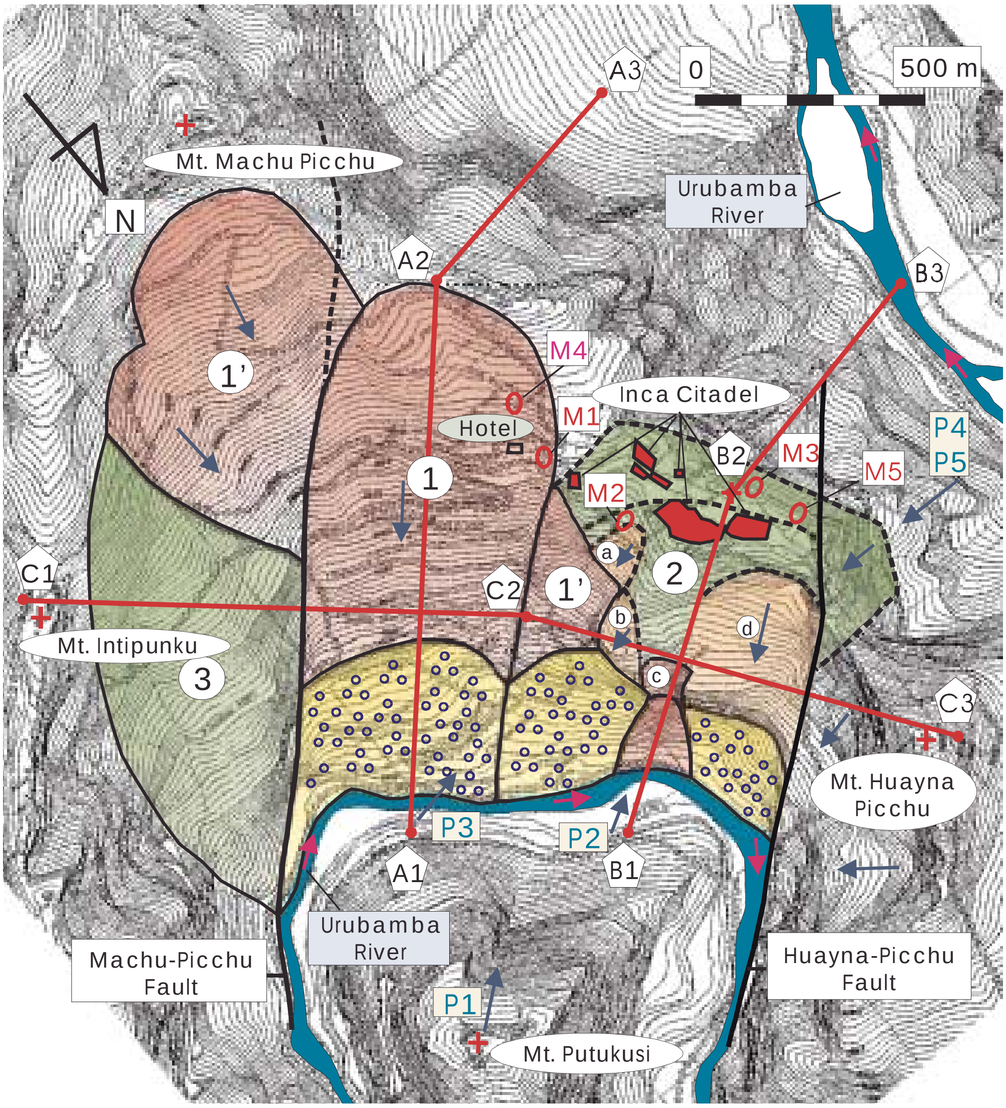

Fig. 3 Working Map of Landslide Blocks 1, 2 and 3 in Front Slope
(Our interpretation on landslides were written on the basic map of 1/5000 provided by UGM)
A1-A3, B1-B3, C1-C3: Lines for Sections for Block 1, Brock 2 and cross sections
①②③: Blocks of landslides or potential landslides.
①': Expanding blocks of Block 1 to Block 2 and 3
a, b, c, d: Sub-blocks of Block 2 which seem to move up towards the citadel area from the border. (a: a retrogressive landslide, b : possible rock topple, c: a recent landslide, d: shallow landslides which have not yet slid so much.)
: Landslide debris at the toe of slope
M1-M5: Locations of extensometers
P1-P5: Photos of Block 2 from various directions

2. FIELD INVESTIGATION OF LANDSLIDE RISK IN BLOCK NO.2

The authors investigated Machu Picchu area, especially Block No.2 during 24 – 28 October 2001, and examined the site for a series of long span extensometers including a span crossing Plaza in the citadel. Based on this investigation, and 1/5000 map we obtained this time from UGM (Machu Picchu Joint Managing Unit), we modified Fig.2 and made another working map for Block No.1 and Block No.2 as shown in Fig.3. Sites of most information which are referred later in this paper were included in this map, as well.

The major findings during our investigation are explained using photos Photo 1- Photo 5 in Fig.4.

Photo 1 presents a view from the top of Mt. Putukusi toward Block (1), (1’) and (2). The color version of this photo is presented in the color gravure. The citadel is constructed on the mountain ridge, Intiwatana is located on its peak in the point of arrow. Sharp cliffs made by landslides (rock slides and rock topples) seem to gradually move upward from the border between (1’) and (2) and the toe of slope to the citadel site. Four deep vertical cracks due to faults subdivided Block 2 as you may find some of them in the toe of Block 2 in the photo, especially one crack is very big.

Photo 2 presents the frontal view of sub-landslide (c) from the opposite bank. Easily supposed from the view, the landslide was not yet eroded and keep the original form of landslide mass, and it is not old landslide (the date is not yet confirmed). We set a central investigation line passing this landslide and Intiwatana. This is the most disturbed area of Block 2. **Photo 3** presents a view from the bridge to Block (1’) and the sub-block (a) of Block 2. You may find previous landslide debris in front of the head scarp. A concave ground surface of sub-block (a) is seen in front of the citadel, though it is not very clear in this photo. It indicates gradual movement and monitoring by extensometers showed a movement though the records are still very limited.

Photo 4 and **5** were taken from the back side of citadel. The arrow A pointed a shear band, which is possibly a potential sliding surface of Block 2. A shear band is gently dipping, and a shear displacement around the shear plane is observed, and furthermore, rocks seem to be slightly dragged below the shear plane. Photo 5 is the close up photo of the shear band. This time we firstly walked around the back slope of Machu Picchu. Therefore, this finding is very important for the planning of further investigation, though it is too early to conclude this shear band (possibly gently dipping fault) as the potential sliding surface of Block 2. However, this is the most likely candidate of the sliding surface at present. The further investigation plan should include the examination of this shear band.

Figure 5 presents two photos taken from a chartered helicopter taken by Kyoji SASSA in March 2000. These two photos gave us another view of this potential sliding surface (arrow A). You will possibly find that this potential sliding surface dips almost parallel to the front slope. The dot line made of round circle (yellow color line in the gravue) points the shear band dipping to the front slope. The dot line made of square mark (red color line in the gravue) shows the possible landslide border of Block 2 on the ground surface. You may notice a landslide debris filling a part of the Urubamba River in the left photo. The landslide debris is gradually flowed out, and such loss of toe support may trigger further landslide as is the common process in many of landslides.

Fig. 4 Photos of Block 2 in the various directions (photo 1 – photo 5 as follows)

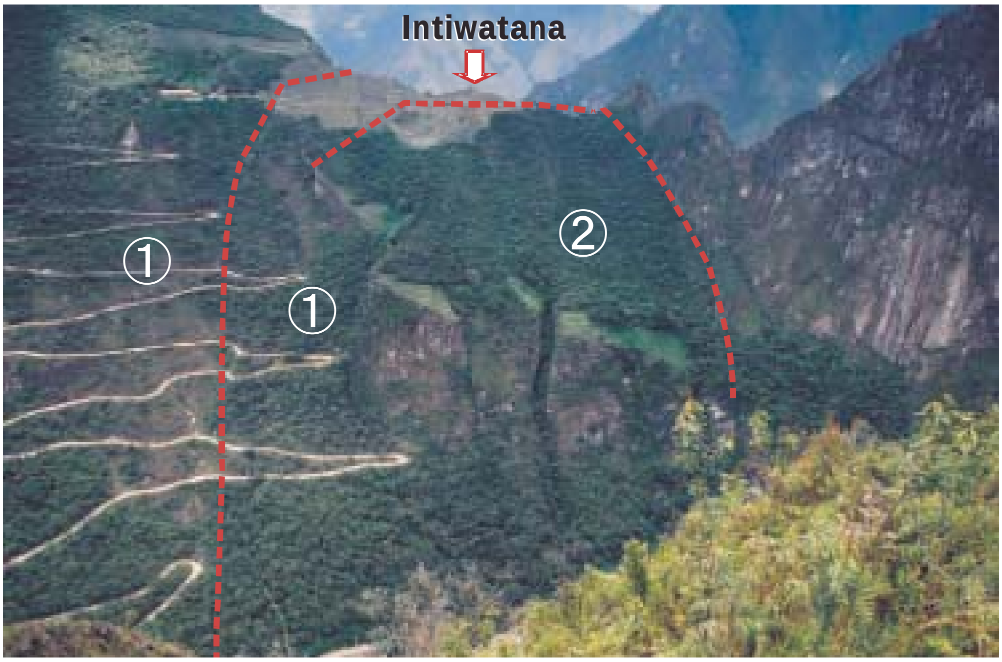

Photo 1 Block No.2 from Mt. Putukusi shooting (taken by H. Shuzui)

Photo 2 A recent landslide in the toe of Block 2 from the opposite bank

Photo 3 Landslides invading the side of Block 2

Photo 4 A shear band, possibly the potential sliding surface of Block 2 is visible in the back slope (arrow A)

Photo 5 A zoomed up photo of the potential sliding surface (shear displacement at the shear band and toppling deformation below the shear band are visible) taken by K. Sassa

3. INTERPRETATION OF POSSIBLE LANDSLIDE PROCESS

To get the general image, an air photo taken from a high altitude will be the best solution. A stereo pair photos in Fig. 6 presents the location of Machu Picchu citadel (a circled part) and its surroundings. The Urubamba River encircled the Machu Picchu area along the strong fault system. You may find the front slope (Block No.1, 2 and 3 in Fig.3) of Machu Picchu seems to have been excavated by previous mass movements. The mountain ridge of the part of citadel seems to have been subjected to landslides, and partly removed. Mt. Putsukusi is not a part of landslide block. It is a stable rock mass as the whole, though surface rock slides are observed. No great flow-mountain as a result of a big landslide is not seen along the Urubamba River. Therefore, it will be supposed that landslides having excavated the front slope were probably not a single gigantic landslide, but a series of retrogressive landslides so as to be seen in Block 1 at present and in the border of Block 2.

To assess the landslide risk, the process of landslides until the present stage should be correctly understood by the field investigation and interpretation. But the investigation is not enough to conclude the process. However, the draft interpretation was presented in the previous symposium (Sassa et al 2001). Fig.7 shows the second draft of interpretation. The stages of landslide evolution were illustrated for Block 1 and 2 in a schematic form. In the old time, probably retrogressive landslides occurred in the front slope of Machu Picchu. (Some landslides occurred in the back slopes, too. But Block 1 and 2 are examined in this paper.) After the whole landslide debris moved out to the Urubamba River, the downward erosion proceeded. The level of Urubamba River was shifted around one hundred meters downward almost to the present level. Three slopes of Block 1, 2, 3 showed the difference in the landslide evolution. The slope of Block 1 had been most heavily subjected to toe erosion of the Urubamba River as easily

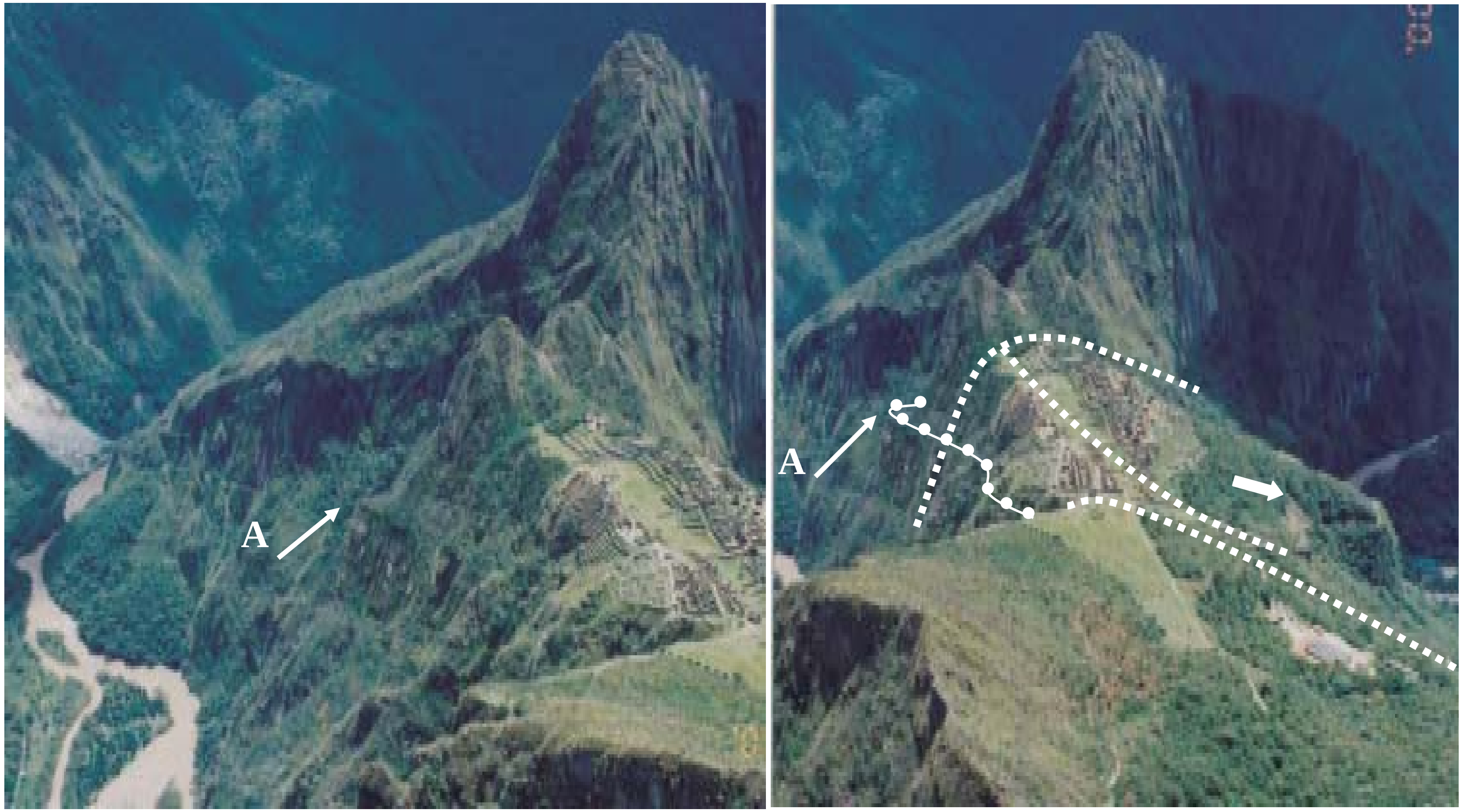

Fig. 5 Photos from a helicopter shooting the potential sliding surface (marked as A) and the potential borders of landslide on the ground surface taken by K. Sassa

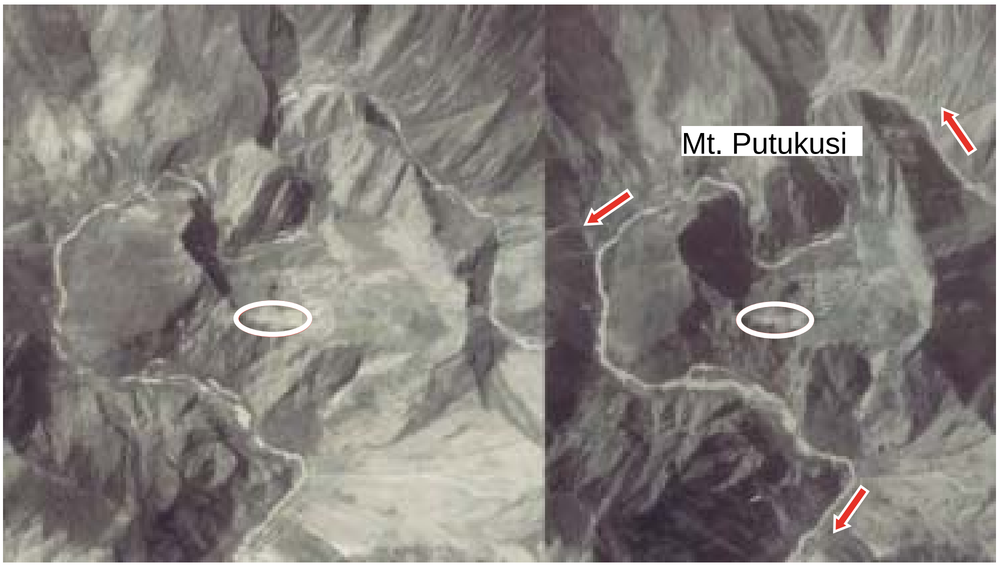

Fig. 6 Airphoto of Machu Picchu (Geographical Institute, Peru)

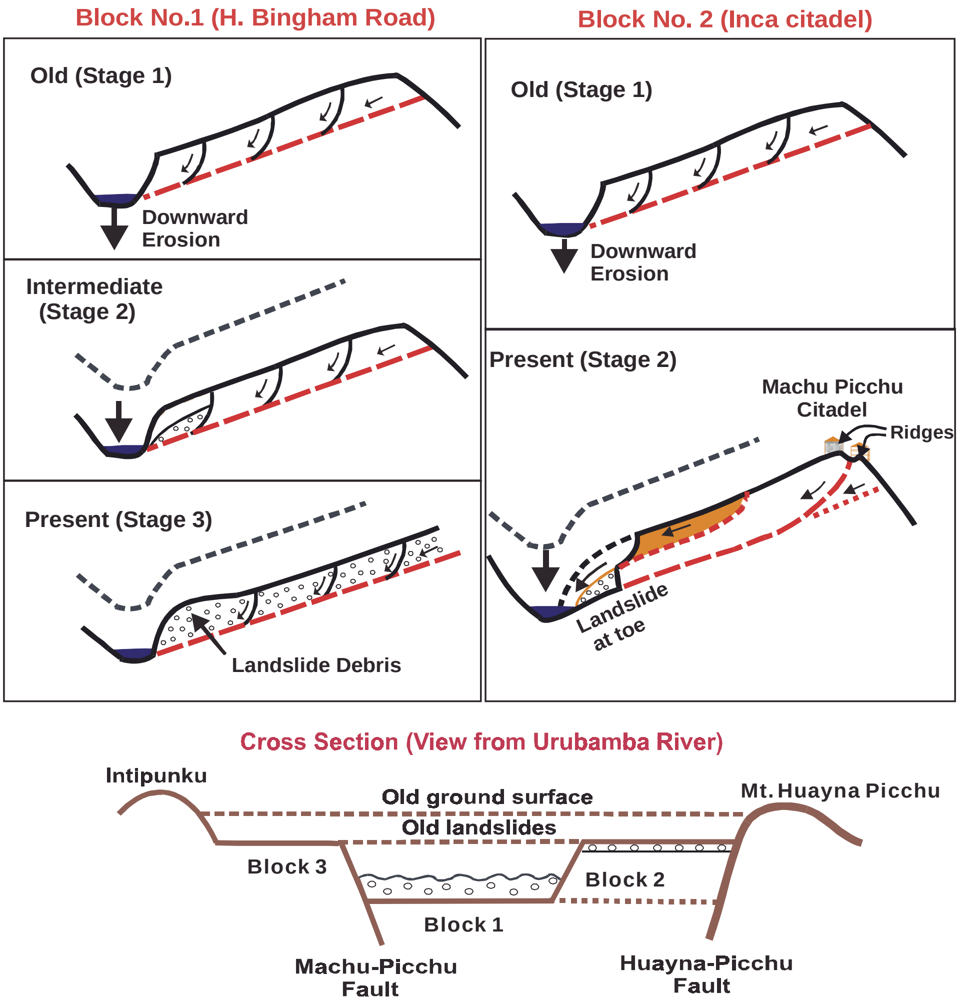

Fig. 7 Hypothesis of landslide process in Machu Picchu

supposed by the curved path of the river and flow direction in Fig.3. Firstly the slope started to slide as illustrated in the intermediate period (Stage 2) of Block 1. The initial landslide retrogressively expanded to the upper slope and toward the side slopes, then the present situation of Stage 3 where active landslide debris covers the slope was formed. You may find in Fig.3 that the Urubamba River was pushed forward by the landslide debris provided by Block 1. So this landslide debris has probably worked for the protection of toe erosion of Block 2. Because of this protection, the evolution of Block 2 was probably much delayed and it is still in the Stage 2. The most delayed block in slope evolution is Block 3. After previous landslide debris moved out, no major landslides occurred because there is almost no river erosion as imagined from Fig.3. The landslide evolution in the cross section is illustrated in the right bottom of Fig.7. Only Block 1 was subjected to major landslides at the present level of Urubamba River and located in the lower elevation which continues to the around present level of the river bed. And Block 2 is now following the process of Block 1. Fig.8 shows the longitudinal section along A1-A2-A3 in Block 1. The depth of landslides is not known, but the whole slope from the mountain ridge to the river is affected by active landslides and covered by landslide debris. Fig.9 presents the longitudinal section along B1-B2-B3 in Block 2. The section B1-B2 shows the active landslide at the toe (c in Fig.3), and others are possibly at the precursor stage. The potential sliding surface will be a shear band found in Fig.4 and Fig.5. If we consider that the potential sliding surface is located in the level as shown in Fig.9, the depth of landslide is around 100-150 m.

Figure 10 presents the cross section along C1-C2-C3. The potential sliding surface seems to be inclined similar to the ground surface, as shown in photos in Fig.4 and Fig.5 and the plot of the shear band in the topographical map suggests. In this figure, the sliding surfaces of real landslides are drawn by a real line though the depth is not yet confirmed. The sliding surfaces of potential or precursor stage of landslides are drawn by a dot line.

There is a **Question** for the reason why the sliding surface goes up to the Plaza in Block 2 (Fig.1, 3, 5, and 9), which may split Plaza of Inca Citadel. The reason is interpreted below from the data obtained up to now:

The ground water will increase in the lower part of the slope collecting ground water from the upper slope because the shear band is probably having a low permeability and dipping parallel with the front slope. As shown in the cross section C1-C2-C3 in Fig.10, the shear band is gently dipping to the Huayna-Picchu fault side. It means that ground water flows from Block 1 or 1’ to Block 2. Therefore, probably the ground water level and pore water is greater in the lower part of Block 2, and almost no ground water near the top of slope. In this case, the top of Block 2 (area of Plaza and Intiwatana) is rather stable, so tensile stress should act in this zone. Accordingly tension cracks may be formed. The concavity in the Plaza likely corresponds to the tension crack, though the concavity was filled possibly by Inca’s people for flatter ground suitable for their living, which is not clearly visible on the ground surface at present.

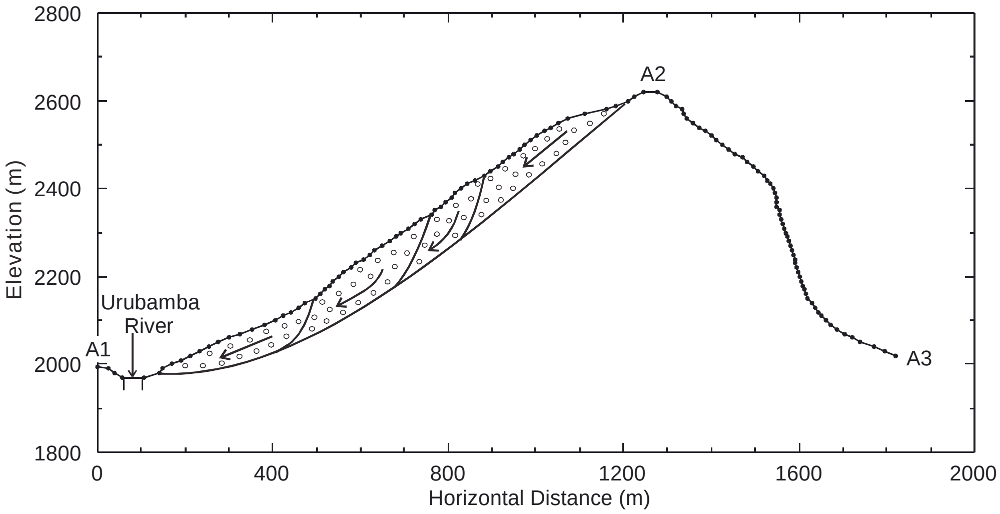

Fig. 8 Longitudinal section (A1-A2-A3) of Block 1

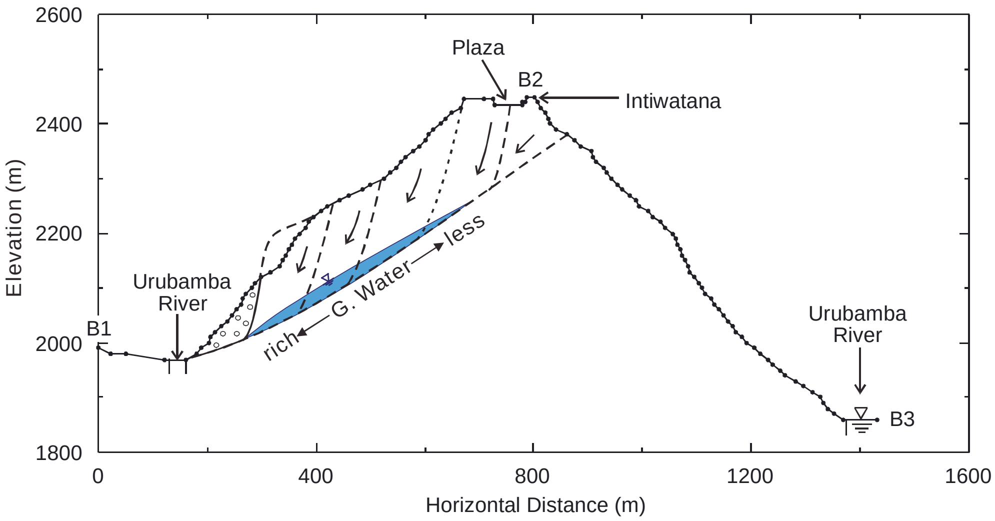

Fig. 9 Longitudinal section (B1-B2-B3) of Block 2

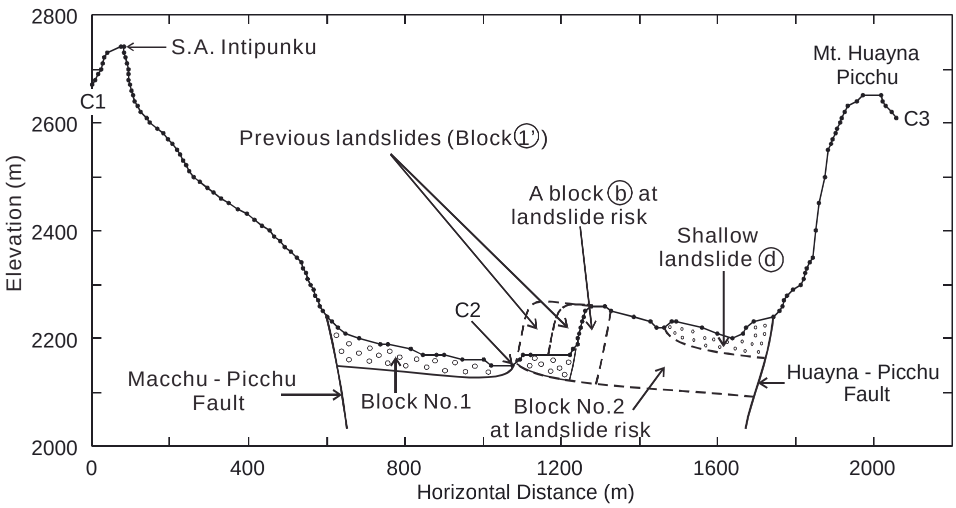

Fig. 10 Cross section (C1-C2-C3) of the front slope of Machu Picchu

Fig. 11 Two types of extensometers

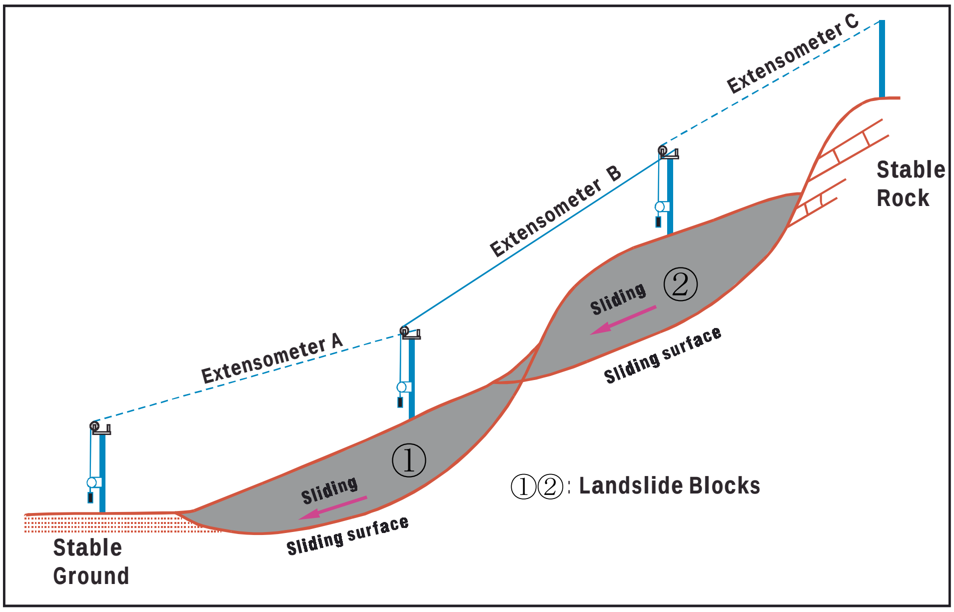

Fig. 12 Illustration of the concept of extensometers

4. MONITORING OF EXTENSOMETERS IN MACHU PICCHU

To evaluate landslide risk, monitoring of the ground deformation, the geological drilling, monitoring of shear displacement and ground water level and/or pore water pressure inside drill holes are vitally important and necessary. Without such investigation, neither landslide risk, nor the safety of slope can be reliably evaluated in the convincing way. Without such reliable landslide risk evaluation, neither effective landslide remedial works can be planned, nor high costs of remedial works can be approved.

As the first step of quantitative investigation, two types of simple extensometers were installed in the Machu Picchu slope. One is a handmade manual reading extensometers as shown in the left photo of Fig.11. Using a pulley and a super invar wire (a special kind of metal with least influence of temperature), movement of the distance between two points is mechanically enlarged by 5 times and indicated on the dial with a pointer. Another type is theoretically the same, movement was also mechanically enlarged by 5 times, and it is recorded on a recording paper continually. The recording drum is rotated by landslide movement, while the recording pen shifts in a steady speed by a dry battery from the left to the right as shown in the right photo of Fig.11.

The concept of extensometer is illustrated in Fig. 12. The height of poles for extensometers is different on the length of span of two poles. When monitoring by a long span, high poles are used to pass the super invar wire over trees and roads, and to avoid possible disturbance by animals and persons. While in the case of monitoring in a short span (which is usual case), low poles are used and the super invar wire is protected by a pipe as shown in Fig.11. Extensometers have merits, which are not affected by moisture, density or atmospheric pressure in the air and cause less trouble and very reliable because of very simple mechanical recording system. They are different from sophisticated monitoring systems such as EDM (electronic distance meter) and GPS (global positioning system).

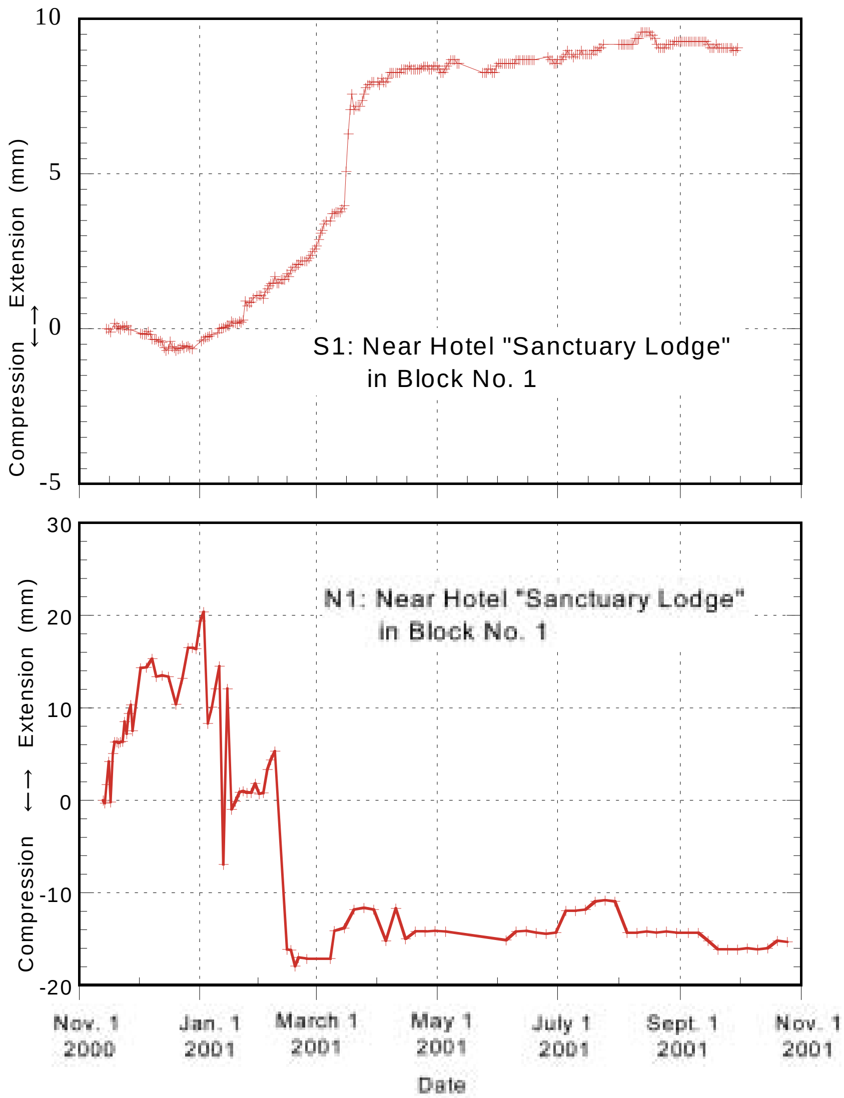

Fig. 13 Records of extensometers (S1 and N1) in the monitoring site (M1) near Hotel Sanctuary Lodge in Block 1

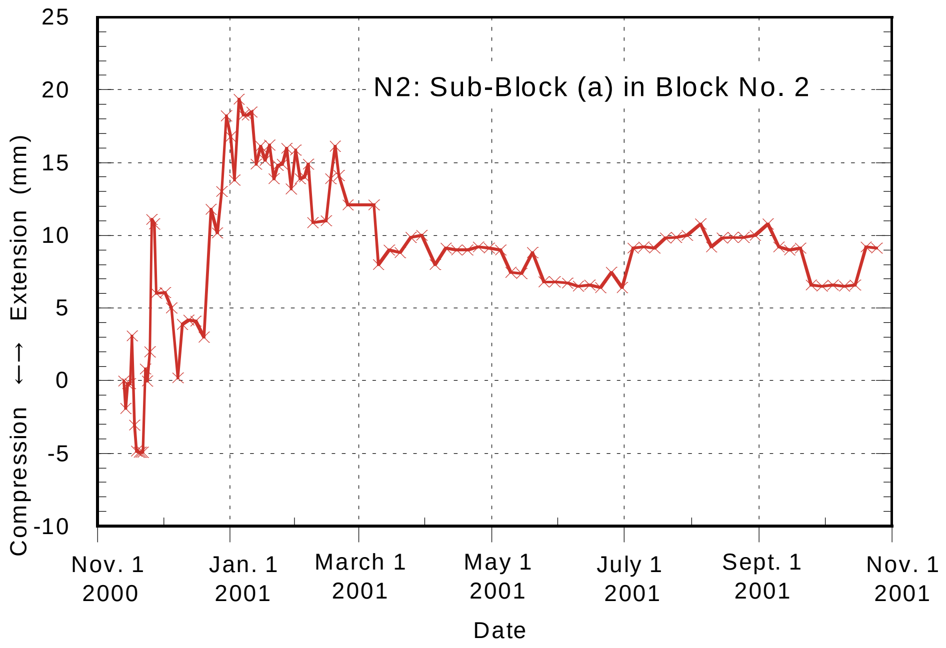

Fig. 14 Records of extensometer (N2) in the monitoring site (M2) in Sub-Block (a) in Block 2

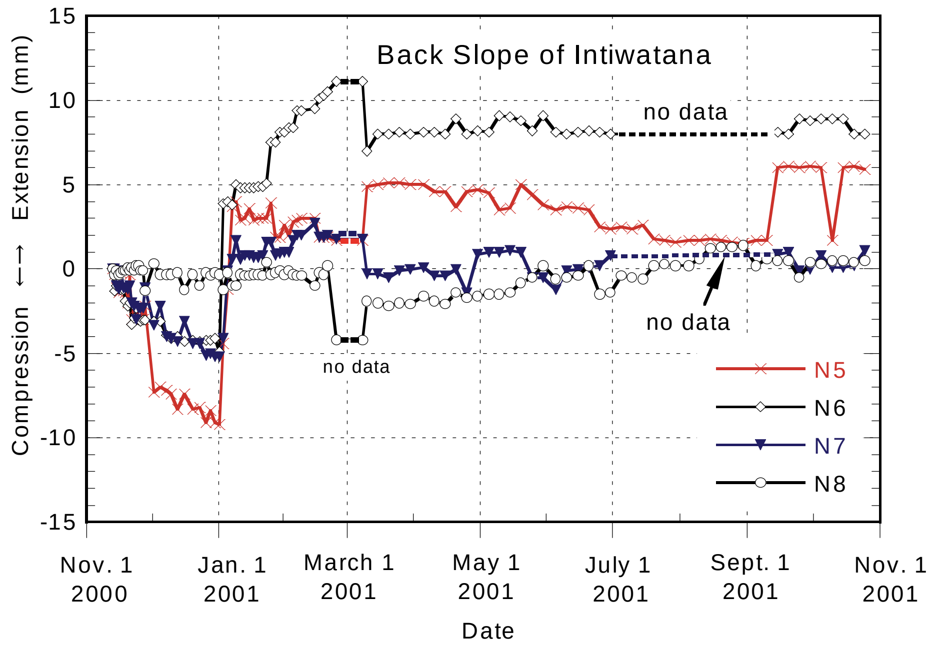

Fig. 15 Records of extensometers (N5,N6,N7,N8) in the monitoring site(M3) in the back slope of Intiwatana

A series of extensometer installation from the stable ground to the stable ground is most desirable to detect landslide blocks. The system is used in Lishan, China (Sassa et al. 2001), and Zentoku, Japan. However, the easiest way to check the existence of movement is to set an extensometer crossing a head scarp to monitor the landslide movement. 12 extensometers were installed in five sites (M1-M5) as shown in Fig. 3. Fig. 13 presents the monitoring results of M1 near the hotel Sanctuary Lodge in Block 1. The extensometer S1 showed gradual extension over a long term, while N1 showed compression after extension from Nov.1 2000 to Nov. 2001. Movement of N1 is rather great. N1 is the manual recording type, and S1 is the paper recording type.

Movement of both extension and compression in the same extensometer is interpreted using Fig.12. When a single extensometer is installed as extensometer B in the figure, extension means the movement of sliding block 1, and compression means the movement of sliding block 2. Movement of sliding block 1 decreases the support of sliding block 2 when two blocks are interconnected. Probably extensometer records of N1, and S1 detect the movement of some of sub-block in Block 1.

Figure14 presents the monitoring of N2 installed in the border of sub-block (a) of Block 2. The movement is rather great in the order of 10 mm. Fig.15 presents the monitoring results of four extensometers installed in the steps (terraces) for farming in the back slope of Intiwatana. In this part, a debris flow occurred probably in 1999 or 2000 and the fresh trace of debris flow was observed from a chartered helicopter in March 2000. These extensometers are planned to detect the possible retrogressive landslides near the source area of the debris flow. Therefore, those extensometers were not aimed to detect a deep seated landslide, but shallow surface landslides. Those do not affect the Inca’s citadel, but it is good exercise to monitor the ground surface movement, and good to totally check the precision, reliability and problems of monitoring.

Figures13-15 present monitoring records of the short span extensometers, and not a series of extensometers as shown in Fig.12. Therefore, the landslide size is not estimated only by those data. However, comparing those data, the recorded movement of S1 shows a gradual movement from January to the early April, though almost extensometers presented the termination of major movement before early March. The movement detected by S1 is probably due to a deep seated landslide. It must be checked by further monitoring.

5. FURTHER LANDSLIDE INVESTIGATION

The results of field investigation and monitoring suggest the possibility of landslides, which possibly affect the Inca’s citadel. The exact understanding of slope conditions and landslide risk evaluation need further investigation. Fig.16 illustrates a monitoring system to be employed in Block 2. A series of extensometers from the Intiwatana (top of the slope) to the opposite bank of Urubamba river is desirable to assess the location and size of landslide and its danger reaching to failure. Monitoring result by a single method is better to be examined by other methods. EDM and GPS methods are appropriate to be applied. GPS has a merit of movement monitoring in wider area because their sets can be installed over the Block 2. EDM has a merit of very long span of monitoring, though both are affected by atmospheric conditions. However, combination of those methods and their integrated interpretation should present reliable results. Drilling and the borehole inclinometer or alternative methods to detect the sliding surface are very necessary to know the depth of landslide. Ground water monitoring is necessary to evaluate the effect of ground water on this landslide.

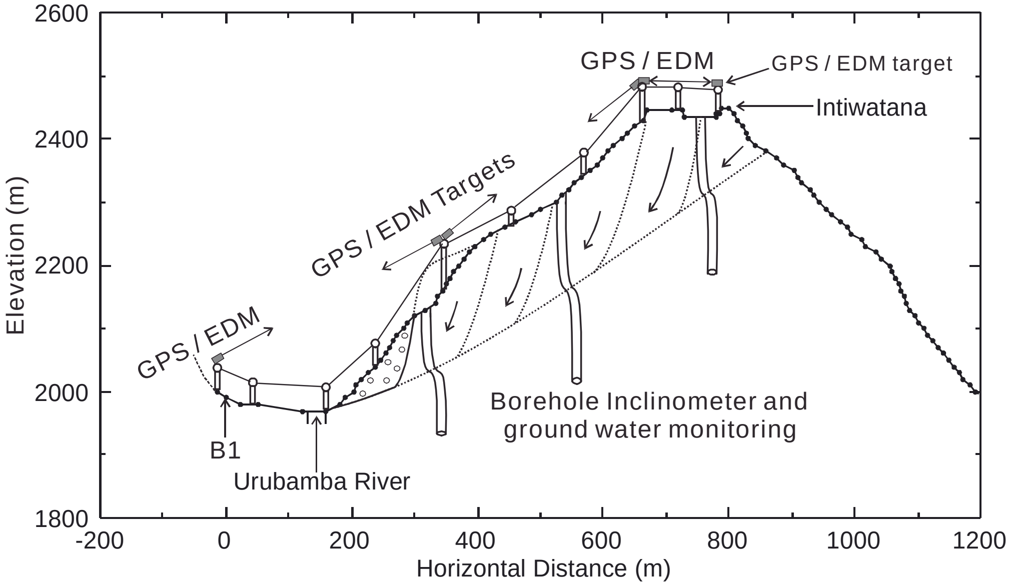

Fig. 16 Illustration of monitoring system for the precise understanding of potential landslides

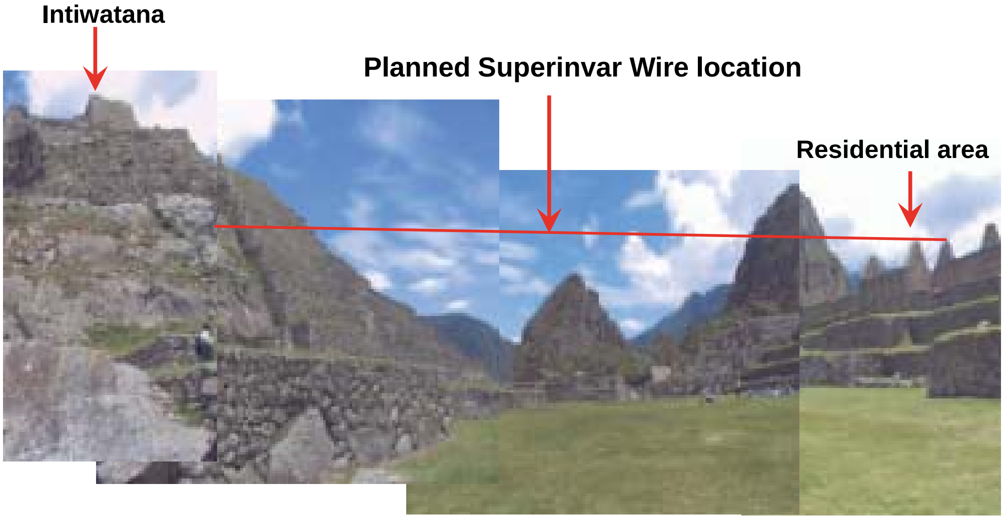

Fig. 17 Photo of a planned super invar wire location crossing the Plaza.

From the field observation, ground water flowing along the shear band with relatively less permeability from the top to the toe and possibly from the Block 1 side to the Huayna-Picchu fault side must be a major causal factor of this landslide. This means that drainage will be effective to stabilize this landslide. The prevention of toe landslides must be very effective in order to prevent further retrogressive landslides.

Finally the photo of the first long span extensometer to be installed crossing Plaza is shown in Fig.17. With cooperation from engineers of INC and INRENA, our team examined the site for a long span extensometer and conducted a trial installation, though the super invar wire and a long span extensometer were not yet installed. However, we have checked that such installation is possible with almost no disturbance of scenery of Plaza under the examination of the archaeologists working for the Machu Picchu World Heritage. A super invar wire is 1.0 mm in diameter though the line was drawn in a visible way in Fig.17, and it is passing high above the walking visitors.

6. CONCLUSION

The results of investigation by the Japanese team conducted in October 2001 was introduced. We could walk around the Machu Picchu slope in addition to the examination of sites for the installation of long span extensometers. Major findings of this investigation are;

1) Retrogressive landslides have probably proceeded in the past and are still on-going in the Machu Picchu slope. The progress of landslide evolution stage is different in Block 1, 2, 3. Present stages of each block are informative for the assessment for the future process of landslide activities.
2) A relatively new landslide at the toe of Block 2, on which the Inca citadel is constructed, was observed though the exact date is not yet known. A shear band, possibly a potential sliding surface of Block 2 was found. It is gently dipping to the front slope, and also gently dipping toward the Huayna Picchu Fault.
3) Ground water is likely to flow downward and also toward the Huayana Picchu Fault direction possibly along the shear band with a relatively low permeability. The ground water must be poor in the top of Block 2 and rich in the lower slope. It may be the cause of possible head scarp splitting Plaza.
4) If ground water along the shear band and the retrogressive landslides in the border between blocks (1’) and (2) and also in the toe cliff will be major causal factors of Block 2, reduction of those causal factors must be effective landslide remedial measures.
5) Reliable understanding of the present state and process of landslides can not be obtained without reliable monitoring of deformation on the ground surface, geological drillings and preferably geophysical exploration, monitoring of the shear displacement and ground water level and/or pore pressure inside the boreholes. However, we may conclude that there is a necessity of further investigation to evaluate landslide risk in Machu Picchu in order to avoid or postpone its possible failure at least.

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