DOI: 10.4408/IJEGE.2013-06.B-49

RESERVOIR BANK SLOPE IN LAXIWA HYDROPOWER STATION, CHINA

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ABSTRACT

Laxiwa Hydropower Station is situated on the main reach of the Yellow River, China. The construction was started in October 2001, and impoundment started in March 2009. However, from May 2009, the right-bank slope of the reservoir, about 700 m high and 1000 m wide about 500m far from the dam, was found to be deforming greatly and continuously. Although this slope had been identified as an old landslide, the survey before the construction of the dam concluded that this slope is stable and will be stable even after the impoundment. Thus, the slope was not monitored before the visible deformation occurred after the impoundment. To identify the relationship between the slope deformation and impoundment, we utilized D-InSAR and ALOS Prism data to analyze the slope deformation before and after impoundment. We found that there was no identifiable deformation before the impoundment, and the maximum horizontal displacement reached approximately 7.5m during the period of 3 April 2009 to 22 May 2010 after impoundment. Although the potential sliding surface has not been identified irrespective of the performance of a lot of survey works, we concluded that the instability of this high and steep slope will be great threaten to the dam as well as to the downstream residents.

KEY WORDS: *remote sensing, D-InSAR, ALOS prism, hydropower station, slope deformation, impoundment, risk assessment*

INTRODUCTION

In the construction of dams, the landslides on the banks of the reservoir are always a challenging problem to both geologists and engineers. This kind of landslide can not only affect the function of the dams, but also result in great disaster to the downstream of the dam. For example, the catastrophic failure of the left bank slope of the Vajont Reservioir resulted in more than 2600 casualties (MÜLLER, 1964), sweeping away several villages completely. More recently, it has been reported that a huge number of landslides were triggerd or reactivated in the resovoir area of the Three Gorges Dam due to the impudement, causing great loss on both lives and economy, threntening the safe function of the dam, and forcing the government to relocate another some 100,000 people (YIN, 2004). Although the instability problem of bank slopes had been widely studied since the Vajont event, understanding on this kind of bank slope instability is still limited. This can be examplified by a big landslide on the upper stream of the dam of Laxiwa Hydropower station. This landslide seems to be very similar to the case of Vajoint dam and is directly threatening the safety of the dam and people living downstream. The local authoriteis had paid great concern to this problem, and further survey had been conducted to better understand the possible deformatin/sliding mechanism. In this study, we used satellite remote sensing-based method to detect the deformation of the slope before and after the impudement. Some preliminary investigation results will be introduced in this paper.

Laxiwa Hydropower Station is a large on-construction hydropower station on the main reach of the Yellow River. It locates between Guide County and Guinan County, Qinghai Province, about 134 km far from Xining City, Qinghai Province (Fig. 1). This station is the second cascade hydropower project to the Longyangxia Hydropower project on the upper stream of Yellow River. The dam is a 250 m high concrete double-curvature arch dam with its crest length being about 460 m. The primary purpose of the dam is hydroelectric power generation and it is designed to support a 4200 MW power station. The normal reservoir water level is 2452m, dead water level is 2440m, the total reservoir capacity is about 1.08 billion m^3, and the active reservoir capacity is 0.15 billion m^3.

The construction of Laxiwa Hydropower Project was strated in October 2001. In April 2006, the first concrete was cast and on March 1, 2009, impoundment began, and on May 18, 2009, the first two electric generators were put into function. However, soon after the impoundment (in late May 2009), the right-bank slope (Guobu slope) on the upper stream of the dam showed remarkable deformation (Fig. 2). Many cracks appeared and was keeping widening on the crest of the slope. Also rocks dropped off the slope into the river frequently. Recongnizing the risk of occurence of catastrophic landslide, the deformation of the slope had been monitored by installing a deformation-monitoring network immeadialty since July 2009. This monitoring network included many monitoring techniques, such as airborne topographic laser scanner for obtaining topography of the crest and the slope in high precision, total station (39 observation points were newly setup on the slope for direct measuring). Six borings were drilled and five exploration tunnels were newly dug into the slope to identify the potential sliding surface. All the monitored results revealed that the slope is deforming greatly and continuously. However, borings failed to reach the target depth, because the deforming landslide mass made the drilling impossible. The deforming slope is about 700 m high (from the original river bed to the crest of the sliding slope) and 1000 m wide in average, and also very close to the dam site (about 500 m far from the dam). Therefore, if collapse failure occurred to this slope, the dam and all other facilities will be greatly damaged or destroyed, and over-topping reservoir water may flood the wide downstream area, greatly threatening the people living on downstream and the safe function of another big hydropower station (Lijiaxia) 73 km downstream. Namely, this dam is facing the potential occurence of catastrophic disaster similar to that occured in Vajont dam (Müller, 1964).

Fig. 1 - Location of Laxiwa dam site

After the setup of monitoring system, the deformation/displacement of the slope had been monitored continuosly, and the deformation/sliding patten and tendency with increase of reservior water level had been made clear. Nevertheless, the defromation/sliding mechanism has not been made clear, because (1) the deformation/sliding feature of the downslope area was not clear due to submersion under water, (2) those borings or exploration tunnels were not deep or long enough, such that no evidence for the identification of sliding surface was found, and (3) no monitoring data was availabe for the slope before the impoundment. To understand the initiation mechanism of instability and then provide proper countermeasures for lowering or releasing the risk of collapse failure, it is necessary to undestand the possible developing history of this landslide and also the spatial information of the slope deformation. As part of a project for investigating the movement mechanism, this study aimed at using interferometric analysis of synthetic aperture radar (InSAR) and also satellite optical images with very high-resolution to grasp the possible deforming areas and also to analyze the ground displacement level before and shortly after the impundment.

GUOBU LANDSLIDE

The landslide is located on the right bank upstream from the Laxiwa Hydropower station, 500-1700 m far from the dam (Fig. 2). The valley here is narrow and steep with the right slope's angle ranging from 38 to 46 degrees. The original water surface was 2,254 ~ 2,257

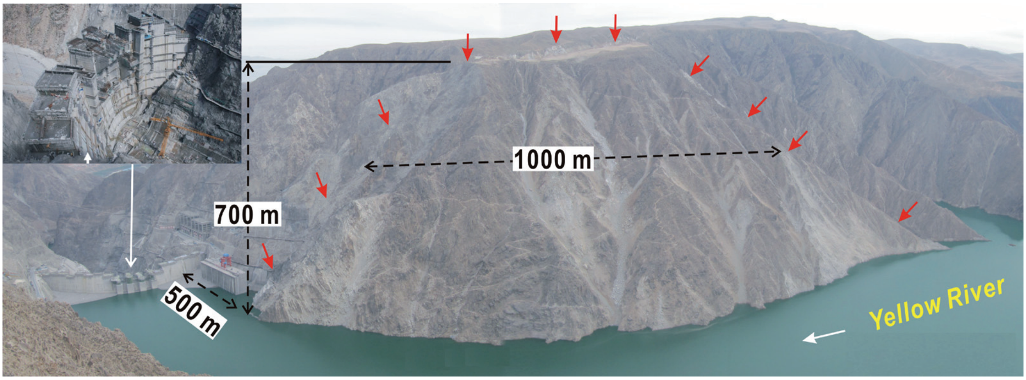

Fig. 2 - View of Guobu slope on the upper stream of Laxiwa dam after impoundment (Photo on 2010/1/14). Arrows show the boundary of the landslide

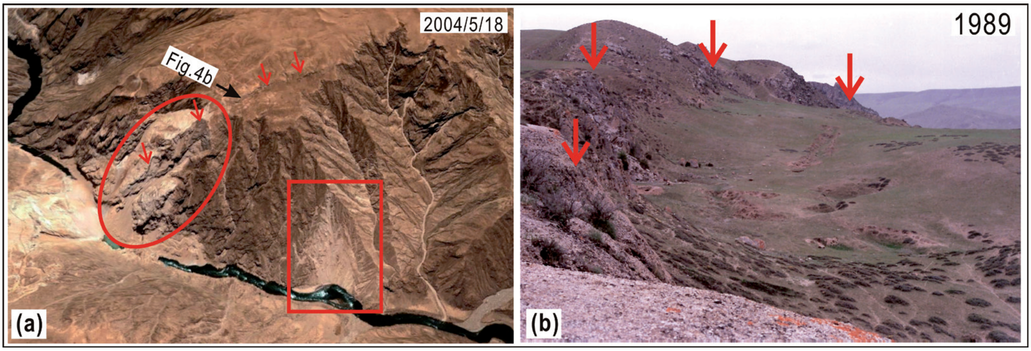

Fig . 3 - Oblique view of Guobu slope(a) from Google Earth, and the views of crest of Guobu slope at different time (b)

m a.s.l. Fig. 3a shows a view of the whole area from Google Earth that was based on the satellite images of May 18, 2004, while Fig. 3b shows the handmade photo of the crest that were taken in 1989. The crest of Guobu Slope is a triangular in plan view and relatively flat 'terrace', 750 m long and 50~290 m wide at 2930~2950 m a.s.l., ~700 m above the river bed. It is bounded by a distinct scarp, and talus can be seen in two areas outlined by the circle and the square in Fig. 3a.

According to the geological map of this area, the bedrocks mainly consist of Mesozoic granites, Tertiary sandstone, Triassic slate and Quaternary sediments, while Laxiwa dam site and the landslide area are Mesozoic granite (Fig. 4).

There is a stepped topography on the crest of the slope indicating that Guobu slope might be an old deep-seated landslide. Detailed geological survey had been performed on this slope since 1989, which gave a conclusion that this landslide is an ancient one. However, only four simple observation piles were installed to monitor the slope deformation, and the monitoring had been conducted during the period from 1991 to 1997. The results showed that there was no obvious displacement. On the other hand, no visible cracks or deformation appeared on the crest before 2003 (i.e., before the impoundment).

Tension cracks appeared on the crest of Guobu

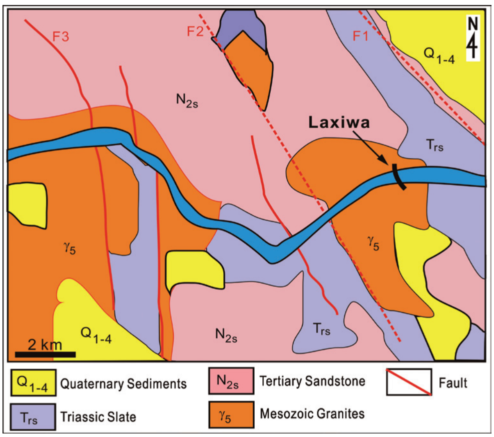

Fig. 4 - Geology map of Laxiwa dam site area

slope in May, 2009, about two months after the impoundment. These cracks extended along the direction of North-South with linear features, being parallel to the main cliff. The terrace showed a settlement of 1.0~1.5 m. Also, there were some small-scale rockfalls on different parts of the slope, with rocks dropping into the reservoir. Acknowledging the potential of catastrophic landsliding, urgent reconnaissance had been conducted to the slope, including the setup of slope deformation monitoring system, geophysical survey, drilling exploration, tunnel investigation at differing altitudes and site reconnaissance. The deformation monitoring system started to work in August 2009. The monitored data showed that the whole slope was deforming significantly and continuously with the increase of the reservoir water level. Some monitoring points indicated a daily displacement of several centimeters, and the total displacement in five months (from middle August 2009 to middle January 2010) reached several meters, and the displacement rates showed good correlation with the variation of water level. It is noted that although a lot of monitoring data had been obtained, they are not available at present, and will be open only after countermeasures being performed. Here we present two photos (Fig. 5) from which the scale of the displacement can be briefly understood through the subsidence appearing on the crest of the slope. The crest had a settlement of about 20 m by 12 March 2010 (Fig. 5a). A further settlement of 6 m was identified seven months late (Fig. 5b).

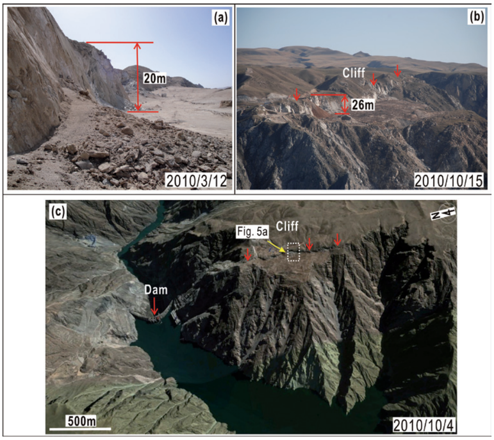

Fig. 5 - Deformation on the crest of Guobu slope after the impoundment

The topography map with a contour interval of 10 m was surveyed by airborne laser scanner after May 2009 (Fig. 6a). A longitudinal section along the line connecting point 'P1' and 'P2' in this figure is given in Fig. 6b, where the sliding surface is just an inferred one. As mentioned above, there is yet not clear evidence showing the location of sliding surface. If this sliding surface be correct, the total volume of the potentially unstable massif will be approximately 120-150 Mm^{3}. This volume will be about one half of that of the Vajont landslide (Müller, 1964; Genevois & Ghirotti, 2005).

D-INSAR RESULTS FROM ALOS PALSAR IMAGES

Differential Synthetic Aperture Radar Interferometry (D-InSAR), is a microwave remote sensing technology based on the Interferometric Synthetic Aperture Radar. It has the advantage of high-accuracy, high-resolution, all-weather, low-cost and wide-range, which enables us to analyze very small ground movement and to cover in continuity large areas. So INSAR becomes very useful in detecting ground movement and studying landslide hazard.

We use interferometric synthetic aperture radar (InSAR) to obtain spatially detailed maps of ground-surface deformation. This technique has been applied

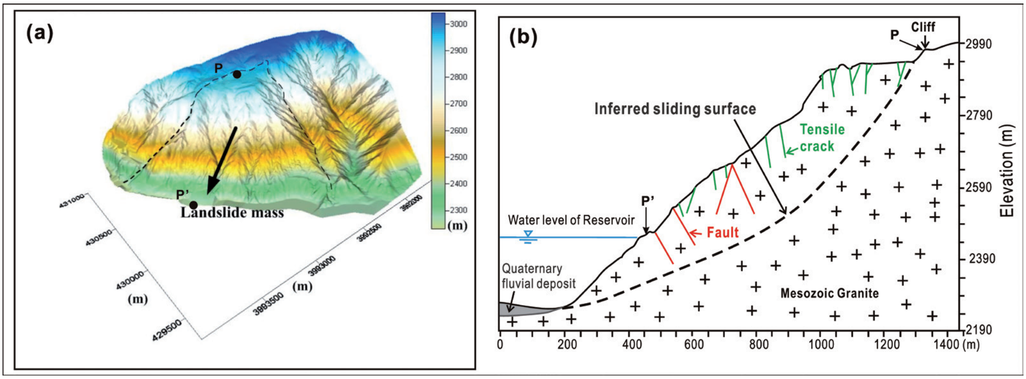

Fig. 6 - (a) Topography of Guobu slope area (a), and (b) longitudinal section along line P-P' in Fig.6a

previously to investigate earthquakes (Massonet *et alii*, 1993), volcanoes (Masson *et alii*, 1995), land subsidence (Massonet *et alii*, 1997; Fielding *et alii*, 1998; Galloway *et alii*, 1998), and also landslide acitivities (Antonello *et alii*, 2004; Singh *et alii*, 2005; Colesanti & Wasowski 2006; Riedel & Walther 2008; Casagli *et alii*, 2010; Yin *et alii*, 2010a, 2010b).

Remote sensing images are the basis of monitoring deformation. The investigation and selection of image sources play a crucial role in interpreting the images. It is understood that appropriate monitoring time and spatial scales should be carefully combined with existing SAR images to fit different types of surface deformation monitoring.

We checked all the synthetic aperture radar (SAR) images acquired by the European Earth Remote-Sensing (ERS) satellites from 2003 to present, and found that most of the images are ascending-orbit ones, and no image covered Laxiwa dam site area until late 2007. However, the satellite images taken by the Advanced Land Observing Satellite (ALOS) of the Japan Aerospace Exploration Agency (JAXA) from 2008 to present are available for the dam site area. These ENVISAT images of ERS have a resolution of 30 m, whereas the ALOS images have higher resolution. The unipolar PALSAR images have a resolution of 10 m, the images taken by the AVNIR-2 sensor have a resolution of 10 m, and those taken by the PRISM sensor have a resolution of 2.5 m. Considering the available period and the resolutions of these images, we collected ENVISAT ASAR images from the later half of 2007, and PASAR images from 2008 to present.

Image number	Data Mode	Orbit no	Frame	Acquisition Date (y/m/d)
ALPSRP099860710	FBS	477	710	2007/12/9
ALPSRP106570710	FBS	477	710	2008/1/24
ALPSRP113280710	FBS	477	710	2008/3/10
ALPSRP126700710	FBS	477	710	2008/6/10
ALPSRP207220710	FBS	477	710	2009/12/14
ALPSRP213930710	FBS	477	710	2010/1/29
ALPSRP209700710	FBS	478	710	2009/12/31
ALPSRP216410710	FBS	478	710	2010/2/15

Tab. 1 - ALOS PALSAR Image list

Master image	Slave image	Revisiting time/d	Baseline/m
ALPSRP099860710 2007/12/9	ALPSRP106570710 2008/1/24	46	834
ALPSRP106570710 2008/1/24	ALPSRP113280710 2008/3/10	46	570
ALPSRP113280710 2008/3/10	ALPSRP126700710 2008/6/10	92	722

Tab. 2 - 2007-2008 ALOS PALSAR Image Pairs

Image number	Orbit no	Frame	Date (y/m/d)
ALPSMW096142875	140	2875	2007/11/14
ALPSMW129692875	140	2875	2008/7/1
ALPSMW169952875	140	2875	2009/4/3
ALPSMW176662875	140	2875	2009/5/19
ALPSMW230342875	140	2875	2010/5/22

Tab. 3 - ALOS PRISM Image list

In the present study, we use ALOS PALSAR as the main image source to interpret the radar images (Table 1). We analyzed the slope deformation during two periods (December 2007~ June 2008; December 2009 ~ February 2010). Table 2 shows the combination and baselines of 4 pairs of images.

Concerning the coverage ranges, image quality and phase distribution, ALOS PRISM panchromatic images are finally chosen to be the image source for interpreting images (Tab. 3). For the period of December 2007 ~ June 2008, four images that were taken on December 9, 2007, January, 24 2008, March 10, 2008, June 10, 2008, were used. The first 3 images have a time interval of 46 days (one revisit cycle) between each of them, and the last two have a time difference of 92 days (2 revisit cycles). For the period of December 2009~February 2010, four images for two pairs were selected and analyzed. One pairs were taken on November 14, 2009 and December 31, 2009 respectively; the other pairs were taken on January 29, 2010 and February 15, 2010, respectively, at a differing orbit. Table 4 shows the basic information of these images.

We processed three pairs of interference images taken from 2007 to 2008. The processing procedure involves mainly seven stages: image focusing, geometry calibration, generation of differential interferograms, phase unwrapping, atmospheric effect assessment and reduction, deformation map generation, and result geocoding from radar coordinates to Universal Traverse Mercator. The final results shown in Fig. 7 indicate that it is feasible to apply D-InSAR to monitor the deformation of Guobu slope, irrespective of the fact that the slope is steep. The selected four images have good coherence. As shown in Figs.7a and b, the pairs of 20071209-20080124 and 20080124-20080310 show a high coherence, while the coherence in the final pair of 20080310-20080610 (Fig. 7c) is relatively lower. The deformation value at the platform (within the polygon) corresponds to light green-light blue on the color bar. Therefore, we estimated that the deformation at the slope platform was quite small within the range of allowable error during the period from 10 March 2008 to June 10 2008. Namely, no obvious deformation occurred during this period before the impoundment. It is noted that we also tried

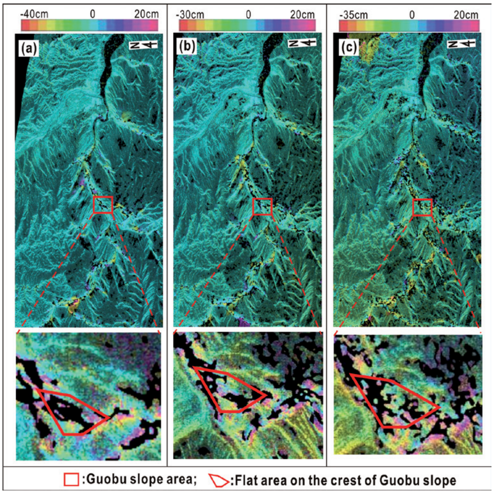

Fig. 7 - Interpreted deformation for different periods. (a) For the period of 2007/12/9 to 2008/1/24; (b) for the period of 2008/1/24 to 2008/3/10; (c) for the period of 2008/3/10 to 2008/6/10

to use two pairs of images (20091214 and 20100129; 20091231 and 20100215) to examine the slope deformation after the impoundment, but we failed to obtain useful results, because (a) there are many shadows and overlapping in the slope area along the riverside, and (b) these two pairs of images showed very low coherence, probably due to the fact that the deformation was simply too large for the D-InSAR.

We analyzed high-resolution optical images to verify the results from D-InSAR analyses before the impoundment, and also to understand the slope deformation after the impoundment. It is well known that from optical imagery slope deformation can also be estimated through image processing applied to multi-temporal data. We used ALOS-PRISM images for the interpretation of slope deformation. Therefore, the phases of two images were made to match each other at first. And then by means of multi-bands synthesizing method, the panchromatic-bands images in the later phase were put to the blue channel, and the panchromatic-bands images in the former phase were put to red and green channel. Finally, false-color images were synthesized by using these three-color channels on the basis of RGB principle. The gray value of the area without deformation would be close to it before synthesis. In contrast, the area where deformation occurred will show blue or yellow color in different phases. By comparing and analyzing the changes in color, the area with deformation can be identified and positioned accurately.

Using the ALOS PRISM images listed in Tab. 3, we obtained three interpreting results as shown in Fig. 8, where Fig. 8a presents the result for the period of 14 November 2007 ~1 July 2008, Fig. 8b for the period of 1 July 2008 to 3 April 2009, and Fig. 8c for the period of 3 April 2009 - 22 May 2010. From Fig. 8a, it can be noticed that on the crest part (the platform) of Guobu slope, the gray value after synthesis is close to that before the synthesis, indicating that no obvious deformation occurred on this part during this period. The blue area on the toe part of the slope (within the red cycle) may result from the local failure accompanying the river incision.

From Fig. 8b, it can be noticed that on the platform of Guobu slope, the gray value after synthesis is also close to the one before synthesis. This indicates that the slope deformation, if any, should be smaller than the value that could be detected by one pixel. Because the resolution of the images is 2.5 m, we conclude that the deformation was less than 2.5 m during the period before and soon after the impoundment. The topographic change indicated by the yellow color resulted from the water level change due to impoundment. However, from Fig. 8c it can be noticed that remarkable change occurred during the period from 3 April 2009 to 22 May 2010. Large blue areas appeared on the slope and platform (marked by yellow circle), indicating that the whole slope showed remarkable deformation. Comparing two images of different phases in the same window enabled us to capture a maximum deformation of about 3 pixels (about 7.5 m) on the leading edge of the platform, directing toward NW280º~300º. This result showed good consistency with the ground-based monitoring results.

It is noted that the vertical deformation of the landslide can also be identified by comparing the Google Earth images shown in Fig. 2b (taken on October 4, 2010) and Fig. 3a (Taken on May 18, 2004). Many fractures spreading along the slope outside the initial limits of the settled block are also visible on the recent Google Earth. The photos taken from the upper cliff at different dates (Fig. 9) showed that the crest of the landslide deformed greatly. The terrace that was relatively flat before the impoundment became lumpy due to the occurrence of wide cracks and great settlement (Fig. 9a). The crest had been shaped later, but new cracks can be easily identified from the photo shown in Fig. 9b. Through these deformation occurred on the crest, we may infer that the whole slope is not deforming or sliding as an en-mass.

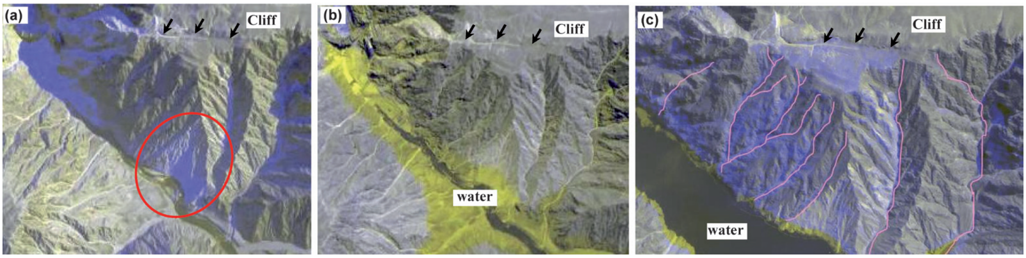

Fig. 8 - ALOS-PRISM image interpreting results for the period of 2007/12/14 to 2008/7/1 (a), 32008/7/1 to 2009/4/3 (b), and2009/4/3 to 2010/5/22 (c), respectively

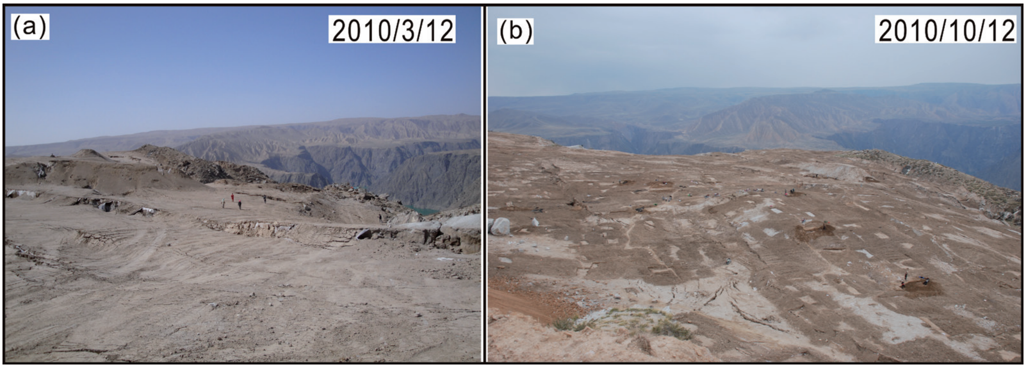

Fig. 9 - Deformed crest of the landslide at different dates

DISCUSSION

By now, although the displacement of Guobu landslide had been monitored and the movement features had been made clear, the sliding surface had been keeping unclear. The possible failure mechanisms of this slope are still in discussion. This impedes the conduction of proper countermeasures. There are differing opinions on the location of sliding surface. One opinion is that the sliding surface may be in the high position of around 2700 m in Fig. 6b, another one is around 2550 m. The sliding surface shown in Fig. 6b is the third one, namely, the worst case. However, from the features of the terraced crest of Guobu landslide and also the monitored displacement data, we inferred that this landslide is a gravitational deep-seated landslide, and the sliding surface should have reached the lowest part of the slope, namely near the river bed, because (1) in granite area, weathering in deeper location of the slope is normally serious, which will results the frequent occurrence of shallow landslides, and also large deep-seated landslides within the weakened rock massif, (2) reactivation of an old landslide during the impoundment normally results from the increase of buoyancy. This increasing buoyancy will lower the effective normal stress and then lower the shear resistance that could be provided by the submerging part, and then lower the stability of the whole slope. If the sliding surface is not in such a lower location, the increased water level will have little, if any, effect on the whole slope. Nevertheless, concerning our reference, further investigation, such as monitoring the displacement of submerging slope or other geophysical survey, will be needed. It is also noted that although the present study presents only some preliminary information of the slope deformation, it may provide valuable information for the plan of countermeasures to lower/ mitigate the risk of catastrophic landslide.

SUMMARY

In this study, we used ALOS PALSAR and ALOS-PRISM images to examine the deformation of Guobu slope in differing time with the purpose of examining the relationship of Guobu landsliding and impoundment. The results can be summarized as follows.

(1) The results of differential interferometry indicate that the deformation of Guobu slope during this period from November 2007 to June 2008 was very small. The image interpreting results from ALOS PRISM also shows that no obvious deformation occurred on Guobu slope during the period from November 2007 (before impoundment) till

April 2009 (one month after the impoundment).

(2) Through comparing the ALOS PRISM images, it is found that Guobu slope had obviously deformed (with the horizontal displacement up to 7.5 m) during the period from April 2009 (after the impoundment) to May 2010.

(3) The response of sliding to the increasing water lever suggests that the sliding surface may be locating near the river bed. The cracks occurring on the terrace crest of the slope and the continuing deformation reveals that the slope may not be sliding as a whole.

ACKNOWLEDGEMENTS

The research work described herein was funded by the National Nature Science Foundation of China under Grant No. 40772187. The financial supports are gratefully acknowledged.

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