Strategy and application of slope monitoring over dam basin in regular periods and during emergencies using SAR and GNSS

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ABSTRACT: Monitoring the behavior of slopes around the sites of hydroelectric power plants and dam reservoirs over dam basins is important for their stable operation and a reduction in the risks of accidents and disasters. However, since there are numerous slopes widely located over a dam basin, it is generally not feasible to efficiently monitor the behavior of all the slopes over such an extensive area. Satellite technology, SAR and GNSS, will contribute to overcoming this difficulty. In the present paper, a strategy is proposed for slope monitoring over a dam basin in regular periods and during emergencies using SAR and GNSS. Then, practical applications are demonstrated for regularly monitoring the slopes and for detecting unstable slopes during an emergency brought about by an extremely heavy rainfall in Japan.

Keywords: Monitoring, Slopes, Dam basin, SAR, GNSS.

1 INTRODUCTION

It is important to regularly monitor the behavior of slopes around the sites of hydroelectric power plants and dam reservoirs over dam basins from the viewpoints of their stable operation and a reduction in the risks of accidents and disasters. Moreover, during emergencies, such as earthquakes and heavy rainfalls associated with typhoons and storms, monitoring is expected to aid in the early detection and prediction of slope failures. However, since there are numerous slopes widely located over a dam basin, it is generally not feasible to efficiently monitor the behavior of all the slopes over such an extensive area.

Satellite technology, SAR (Synthetic Aperture Radar) and GNSS (Global Navigation Satellite System), will contribute to overcoming this difficulty. SAR is a high-resolution radar device that is mounted on an artificial satellite. It can provide the displacement distribution over extensive areas of more than several hundred square kilometers without the use of any sensors on the ground surface. GNSS can continuously locate three-dimensional displacements in target slopes.

In this paper, a strategy is proposed for slope monitoring over a dam basin in regular periods and during emergencies using SAR and GNSS. Practical applications are demonstrated for regularly monitoring the slopes around a dam basin in Japan and for detecting unstable slopes during an emergency brought by an extremely heavy rainfall event.

2 STRATEGY OF MONITORING OVER DAM BASIN IN REGULAR PERIODS AND DURING EMERGENCIES

2.1 Monitoring displacements using SAR and GNSS

SAR is a radar device mounted on an artificial satellite. It travels in ascending (northward) and descending (southward) orbits, transmitting a microwave to the Earth’s surface and observing the reflection of the microwave from the ground surface (Figure 1). Differential Interferometric SAR (DInSAR) is the term for the method of producing ground surface displacements from two SAR data images which are observed in the same area at different periods. The advantage of DInSAR is that it can provide the displacement distribution of the ground surface over a vast area without the use of any sensors on the ground (Ferretti 2014).

GPS/GNSS is a satellite-based positioning system. It can provide three-dimensional displacements of the ground with mm accuracy in extensive areas (Shimizu et al. 2014).

The combination of SAR and GNSS, together with other instruments (Figure 2), will be useful for effectively monitoring the ground behavior in small to vast areas.

This paper focuses on the use of SAR for monitoring over an extensive dam basin. It is divided into two terms, namely, monitoring in regular periods and monitoring during emergencies.

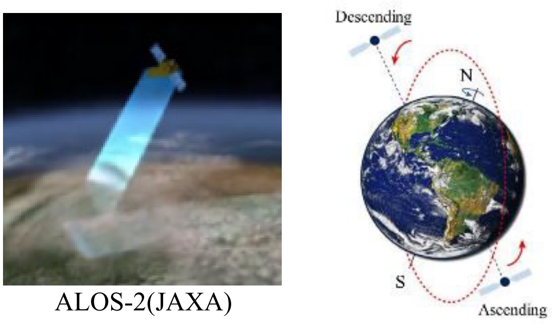


Figure 1. SAR and its orbits.

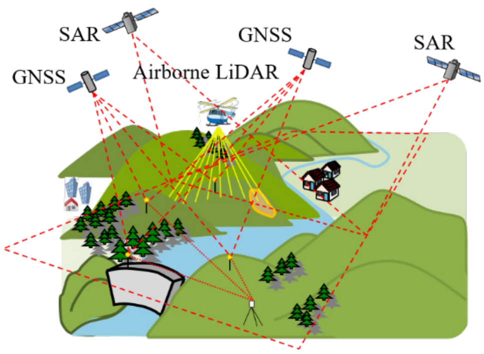


Figure 2. Monitoring slopes over dam basin using SAR, GNSS, and other methods.

2.2 Procedure for monitoring in regular periods

It is important to regularly monitor the behavior of slopes around the sites of hydroelectric power plants and dam reservoirs for the early detection of the unstable slopes existing among the numerous slopes in a vast dam basin. The strategy for slope monitoring over dam basins in regular periods is as follows.

1. Collect information, such as topography, geology, past disaster maps, and optical satellite images, in a mapping system using GIS (Geographic Information System) (Figure 3).
2. Gather new SAR data, when they have been observed and are available, and apply DInSAR to update the displacement distribution over the target dam basin.
3. Superimpose the displacement distribution onto the mapping system (Figure 3) to investigate and detect the unstable and/or unstable-prone slopes in the target area, incorporating information on the topography, geology, history of deformation, etc.
4. Once the unstable and/or unstable-prone slopes have been detected, investigate and confirm the actual behavior of the slopes by means of a laser or drone survey, GNSS, conventional geotechnical instruments, etc. Back analysis is one of possible methods for assessing the stability of slopes based on measured displacements (Shoji, et al. 2021).

2.3 *Procedure for monitoring during emergencies*

SAR enables observations to be made under all weather conditions without going the site. It is suitable for the early detection of damaged and collapsed slopes over the area of concern during emergencies, such as earthquakes and heavy rainfalls. The strategy for monitoring during emergencies using SAR is as follows.

1. Collect the latest SAR data observed during emergencies and find the changes in the ground surface conditions firstly using the RGB composite method. This method using the observed backscattering intensity of the microwave reflection is different from DInSAR which uses the observed phase of it. The method can easily and quickly find the locations and areas where the surface conditions have changed due to a slope collapse, inundation, etc.
2. Superimpose the results of the RGB composite method onto the mapping system (Figure 3) to find the locations of the slope failures and/or inundation areas using information on topography, geology, history of deformation, etc.
3. Once the locations of the damaged areas and their conditions have been detected, report such results to a responsible department, e.g., Emergency Response Section.

The procedure for the above proposed strategy is summarized in Figure 4.

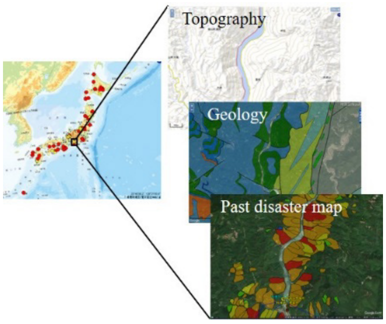


Figure 3. Mapping system with data on topography, geology, and damage history around dam basins.

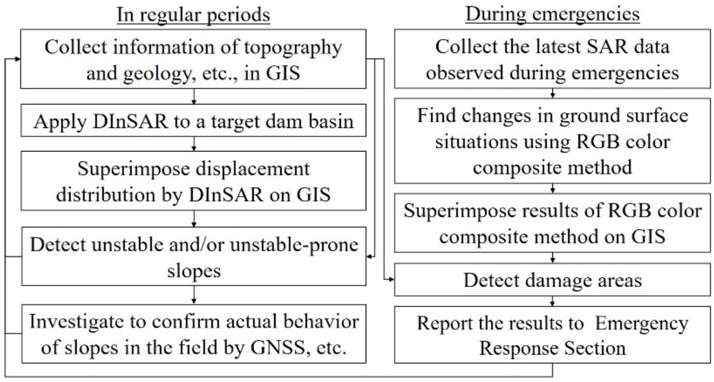


Figure 4. Strategy for slope monitoring over dam basin in regular periods and during emergencies using SAR and GNSS.

3 PRACTICAL APPLICATIONS

In this chapter, a practical application of the regular monitoring of the slope behavior in an extensive dam basin is firstly demonstrated. Then, a case study is described in which the locations of unstable slopes and inundation areas around a dam, during an emergent event, i.e., an extremely hard rainfall, are detected.

The target site is located in a mountainous area of Japan covered with dense vegetation. Since the X- and C-band SARs are not adequate for use in such areas of dense vegetation, the L-band SAR, namely, ALOS-2/PALSAR-2 operated by JAXA (Japan Aerospace Exploration Agency), is employed.

3.1 *Monitoring in regular periods*

3.1.1 *Study area*

SBAS-DInSAR (Bernadino et al. 2000), using ALOS-2 data, is applied to monitor temporal displacement distributions in order to detect the unstable and/or potentially unstable slopes around a dam basin. Figure 5 shows the study area around Akiba dam basin along the Tenryu River in central

Japan. Unstable and/or potentially unstable slopes exist on both sides of the Tenryu River. The Kudari landslide is one of the well-known unstable slopes in this area (Figure 6). The Kudari landslide is 260 m in width, 810 m in length, and 450 m in height, and the slope angle is about 33 degrees. The bedrock of the landslide is composed of crystalline schist of the Sanbagawa Matamorphic Belt, which forms the outer zone of southwest Japan. The crystalline shist is easily exfoliated and has been severely weakened due to the loosening and weathering of the surface layer.

Fifteen ALOS-2 SAR data images on the ascending pass, observed from August 2014 to February 2020, and 17 images on the descending pass, observed from December 2014 to November 2019, were collected for this analysis.

Figure 5. Study area of SBAS-DInSAR for monitoring in regular periods.

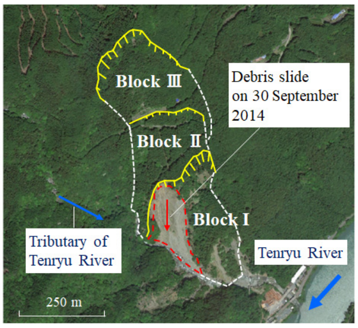
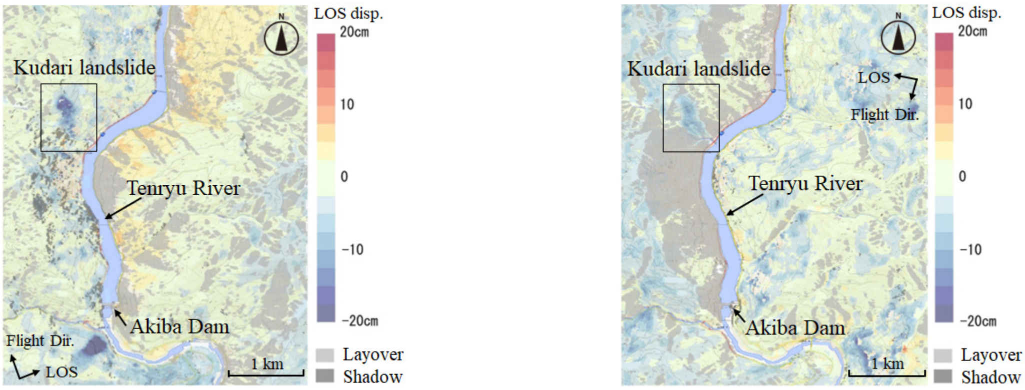


Figure 6. Kudari landslide (Blocks I, II, and III).

3.1.2 *Results of SBAS-DInSAR and LOS displacements in Kudari landslide*

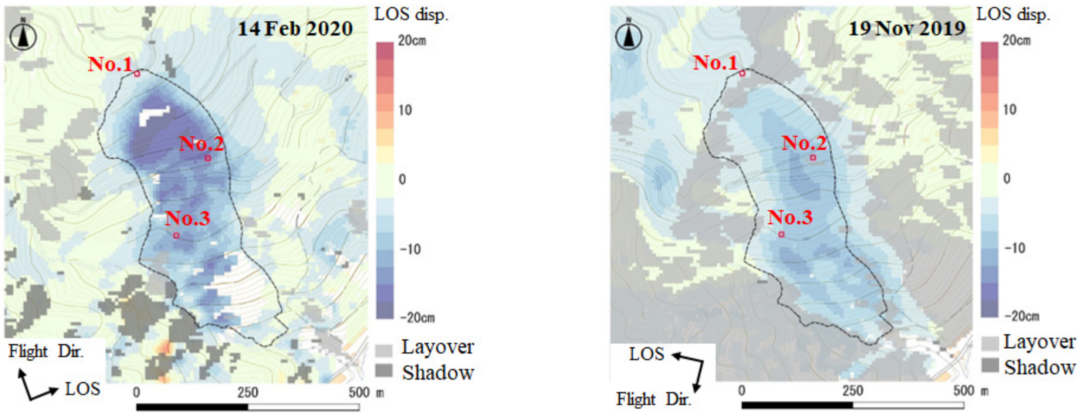
Figure 7 shows the LOS displacement distributions using ascending and descending data for the Akiba dam basin. Displacements have been acquired, except in the areas of layover or shadows occurring in the SAR images. It is seen by the dark blue areas that the LOS displacements increased to about 20 cm over six years (3 cm per year). Since those areas are recognized as being much more active, in comparison to other areas, it should be noted that the slopes in those areas will be potentially unstable during heavy rainfall events.

Figure 8 shows the LOS displacement distributions focused on the Kudari landslide using ascending and descending data. The results reveal an area in which the displacements have increased, and this area is consistent with the actual range of the Kudari landslide. Figure 9 shows the time-transitions of the LOS displacements at three points (pixels): No. 1, No. 2, and No. 3. LOS displacements at these three points are seen to have increased on the negative side (extension) with time. Currently, the displacement of the ground surface is being monitored by extensometers (Figure 10). The SBAS-DInSAR results agree with those of the extensometers (Shoji et al. 2022). Therefore, DInSAR has the potential to be regularly used as a screening tool for detecting unstable and/or potentially unstable slopes over an extensive area.



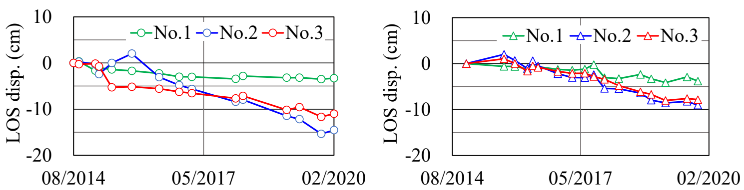
(a) Ascending (Aug 2014 to Feb 2020) (b) Descending (Dec 2014 to Nov 2019)

Figure 7. LOS displacement distributions by SBAS-DInSAR in Akiba dam basin.



(a) Ascending (b) Descending

Figure 8. LOS displacement distributions on Kudari landslide.



(a) Ascending (b) Descending

Figure 9. Time-transitions of LOS displacements in Kudari landslide (-: extension, + compression).

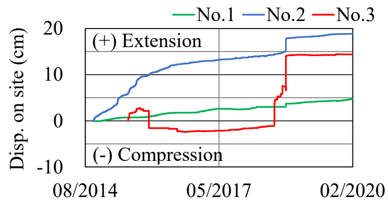


Figure 10. Time-transitions of displacements measured by extensometers.

3.2 Monitoring in regular periods

3.2.1 Study area

On July 4, 2020, heavy rainfall of over 200 mm fell in a span of three hours in the Kyushu region of western Japan. Emergent SAR observations were performed in this region by ALOS-2. Figure 11(a) shows the study area around Setoishi dam basin.

3.2.2 Inundation areas and slope failures detected during heavy rainfall event

Two hours after the emergent observation was conducted, an RGB color composite image by SAR data was produced. Then, seven hours after the emergent observation was conducted, inundation areas were detected from the RGB color composite image around Setoishi dam basin, and a preliminary report of the results was provided to the Emergency Response Section and the Dam Management Office. Bad weather with heavy rainfall continued for a week and an aerial survey could not be carried out. Therefore, the RGB color composite image was useful for detecting unstable slopes and inundation areas during the continuous heavy rainfall event.

Figure 11(b) presents an example of the detection of the inundation areas from the RGB color composite image. In order to verify these results, they were compared with an optical satellite image of the same area observed by SPOT7 (Satellite pour l'Observation de la Terre), as shown in the right-hand side photo in Figure 11(b). Areas shown in red in the RGB color composite image agree well with the inundation areas appearing in the optical satellite image. Figure 11(c) shows an example of the detection of slope failure from the RGB color composite image. The area of slope failure is shown in blue and indicated by a dotted line in the left-hand RGB color composite image. These results agree well with the area given in the aerial photograph, indicated in the right-hand photo in Figure 11(c). On the other hand, it took time to detect such damage areas around the dam basin from the RGB color composite image using information on topography, geology, history of deformation, etc. In order to perform this procedure more efficiently, an AI (Artificial Intelligence) method is required.

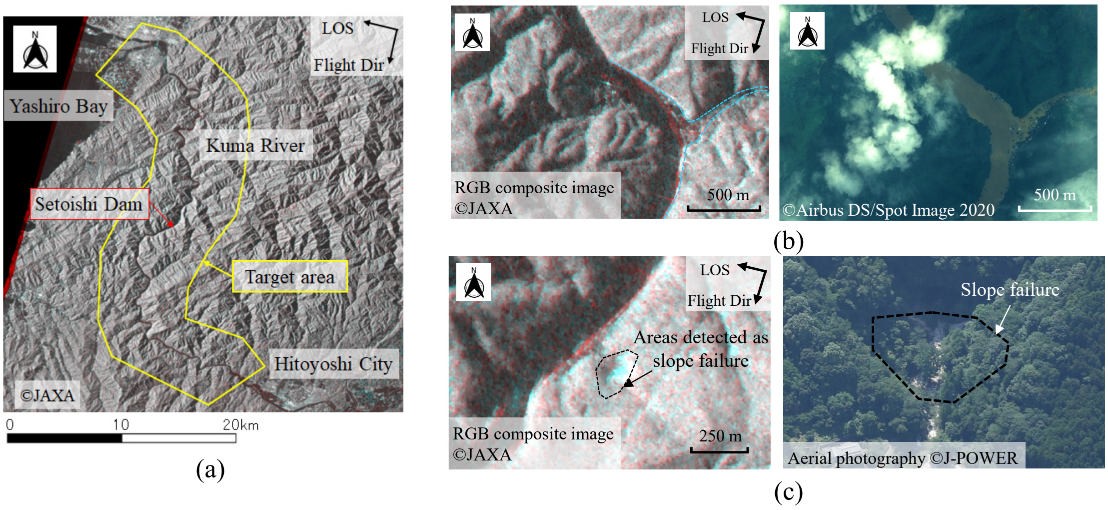


Figure 11. RGB color composite image produced by SAR data for monitoring during emergencies: (a) target area, (b) inundation area, and (c) slope failure.

4 CONCLUDING REMARKS

This paper described a strategy for slope monitoring over a dam basin in regular periods and during emergencies using SAR and GNSS, etc. Practical applications were demonstrated for the regular monitoring of the slopes around a dam basin and for detecting unstable slopes and inundation areas during an emergency brought about by an extremely heavy rainfall event. Those applications were successful, and it was proved that the proposed strategy could be useful for monitoring dam basins. More examples of its application must be provided in order to enhance its practical use.

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