July 3–7, 2017
Prague, Czech Republic
85th Annual Meeting
of International Commission on Large Dams

Deformation monitoring of rockfill dams in normal times and after earthquakes using satellite SAR data

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ABSTRACT

For development of efficient and advanced deformation monitoring methods for rockfill dams in normal times and after earthquakes, we studied monitoring methods using satellite SAR (Synthetic Aperture Radar) data. Because satellite SAR doesn't need any sensors on dam surfaces and it can observe entire surface of rockfill dams and obtain data regardless of weather conditions, it is expected to contribute in monitoring of deformation of rockfill dams. In this paper, we evaluate external deformation of a rockfill dam using satellite SAR data in about four years. The dam has three targets on the crest for survey and we compared the results of external deformations by satellite SAR and survey at the points. We found the results of external deformations using satellite SAR data agreed well with those by survey and the average error of the external deformations between SAR and survey was about several millimeters. We also investigated tendency of external deformations of dam surface where survey had not been conducted. In addition, we conducted studies of deformation monitoring after earthquakes using satellite SAR data to grasp damage on rockfill dams by 2016 Kumamoto earthquake. We found satellite SAR data could detect small deformation of rockfill dams by the earthquake.

1. INTRODUCTION

Monitorings and repair works of aging infrastructures have become a major social concern in Japan. Ministry of Land, Infrastructure, Transport and Tourism (MLIT) issued "Guidelines of comprehensive inspection for dams" in October 2013, in order to evaluate the safety of dams which had passed 30 years from the completion. The number of aging dams is rapidly increasing in Japan. It is estimated that the number of over-50-year-old dams will account for 58 % of the total number of existing dams in 2020. In addition, there have been occurred a lot of disasters such as earthquakes and floods in Japan in recent years. The situation increasingly requires an efficient and effective external deformation measurement method for the monitoring of aging infrastructures including dams in normal times and after disasters.

Satellite SAR has been widely used in many fields such as monitoring of crustal movements caused by large earthquakes and has been mainly made great achievements as the monitoring technology at the time of relatively wide area disasters. The surface of the area to be observed by the satellite SAR is a very wide area with dozens km square and the spatial resolution and the analysis methods have been improved in recent years. Because satellite SAR can detect ground surface movement as changes of radar reflection as shown in Figure 1 (website of GSI, Geospatial Information Authority of Japan), no sensors are needed on the ground surface to measure deformations of the surface and external deformations of rockfill dams can be measured which have not been measured thus far. We have investigated the accuracy of deformation measurements of rockfill dams using satellite SAR data (Sato et al, 2016) and we have found that satellite SAR has good accuracy for the external deformation measurements of rockfill dams.

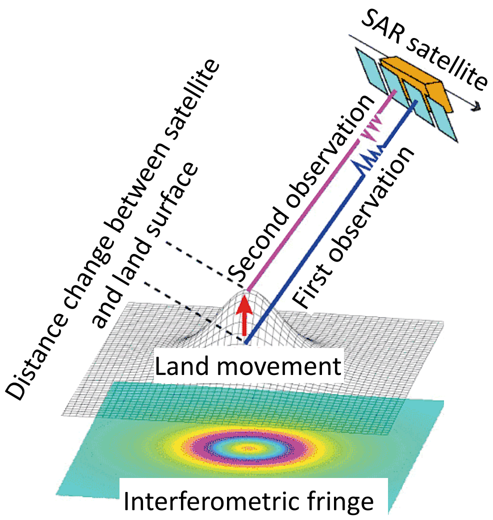


Figure 1. Schematic drawing of deformation monitoring by satellite SAR

In this paper, we used data obtained by COSMO-SkyMed managed by ISA (Italian Space Agency) for an external deformation monitoring of a rockfill dam in normal times. We also used satellite SAR data obtained by ALOS-2 managed by JAXA (Japan Aerospace Exploration Agency) and optical satellite data obtained by SPOT-6/7 managed by AIRBUS Defence & Space for an emergent monitoring of a rockfill dam after the earthquake.

2. EXTERNAL DEFORMATION MONITORING OF ROCKFILL DAMS IN NORMAL TIMES USING SATELLITE SAR DATA

We have been carrying out the measurements of external deformations of rockfill dams using satellite SAR data (Sato et al, 2016) and we have confirmed that satellite SAR data is useful for the external monitoring for rockfill dams in normal times. In this paper, we report another result of the external deformation measurement of a rockfill dam in normal times.

2.1 Outline of a rockfill dam for study

A rockfill dam with a center core and a height of 74.4 meters in the northeastern part of Japan was selected for study. Figure 2 shows the aerial photo of the dam. In Figure 2, three red circles on the crest show existing measuring points of survey for external deformation, a red line on the downstream surface shows the representative measurement line of the external deformation monitoring by SAR and white and yellow arrows show the travelling direction of satellite SAR and the SAR illumination directions, respectively.

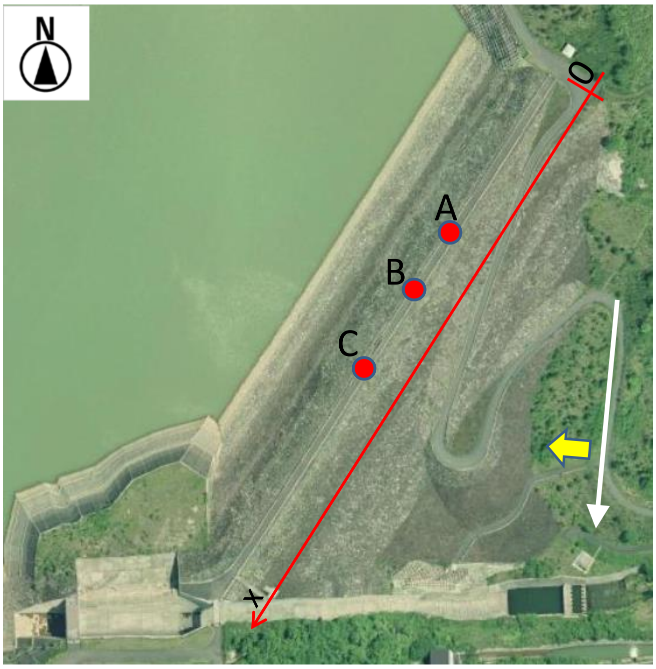


Figure 2. Aerial photo of the dam for deformation monitoring by satellite SAR in normal times

2.2 Outline of satellite SAR data for study

We used satellite SAR data obtained by COSMO-SkyMed managed by ISA for external deformation monitoring of the rockfill dam in normal times. The wavelength and the spatial resolution of the COSMO-SkyMed are 3.1cm (X-band) and 3m, respectively. In this paper, 30 scenes of descending data, from north to south of satellite travelling direction, were used from May 17, 2011 to April 18, 2015 (Table 1). In Table 1, dates of data acquisition are expressed in year, month and day order. The number of days from the first observation to the last was about 1430, nearly four years. Because the dam is located in snowy area, satellite SAR data obtained in winter from December to March were not used in this paper. In addition to SAR data, 2 meters mesh data of Digital Elevation Model (DEM) of study area by Laser Profiler (LP) were used as initial dam body surface model to improve external deformation accuracy by SAR.

Table 1. Observation dates of COSMO-SkyMed Data

No.	Date	No.	Date	No.	Date	No.	Date	No.	Date
1	2011/5/17	7	2011/8/29	13	2012/9/16	19	2013/5/30	25	2014/4/15
2	2011/5/25	8	2011/9/14	14	2012/10/2	20	2013/7/1	26	2014/8/5
3	2011/6/10	9	2011/9/30	15	2012/10/18	21	2013/7/17	27	2014/9/6
4	2011/6/18	10	2012/4/25	16	2012/11/3	22	2013/8/18	28	2014/9/22
5	2011/7/28	11	2012/7/14	17	2013/4/12	23	2013/10/21	29	2014/11/9
6	2011/8/13	12	2012/7/30	18	2013/4/28	24	2013/11/22	30	2015/4/18

2.3 External deformation by satellite SAR data

Figure 3 shows the external deformations from the first observation by SAR of the dam. Negative values in Figure 3 mean that the ground surface deforms away from the satellite and it has almost the same meaning as the direction of the settlement of the dam. According to Figure 3, the colours on the dam body surface change from blue to green and then to yellow and red until May 30, 2013, and then the colour patterns are almost same. It means that the surface of the dam has been receding from the satellite, which means that the settlement has been occurred during observation. The maximum external deformation of the dam was about 50 mm during SAR observation period from May 2011 to April 2015 as shown in Figure 3.

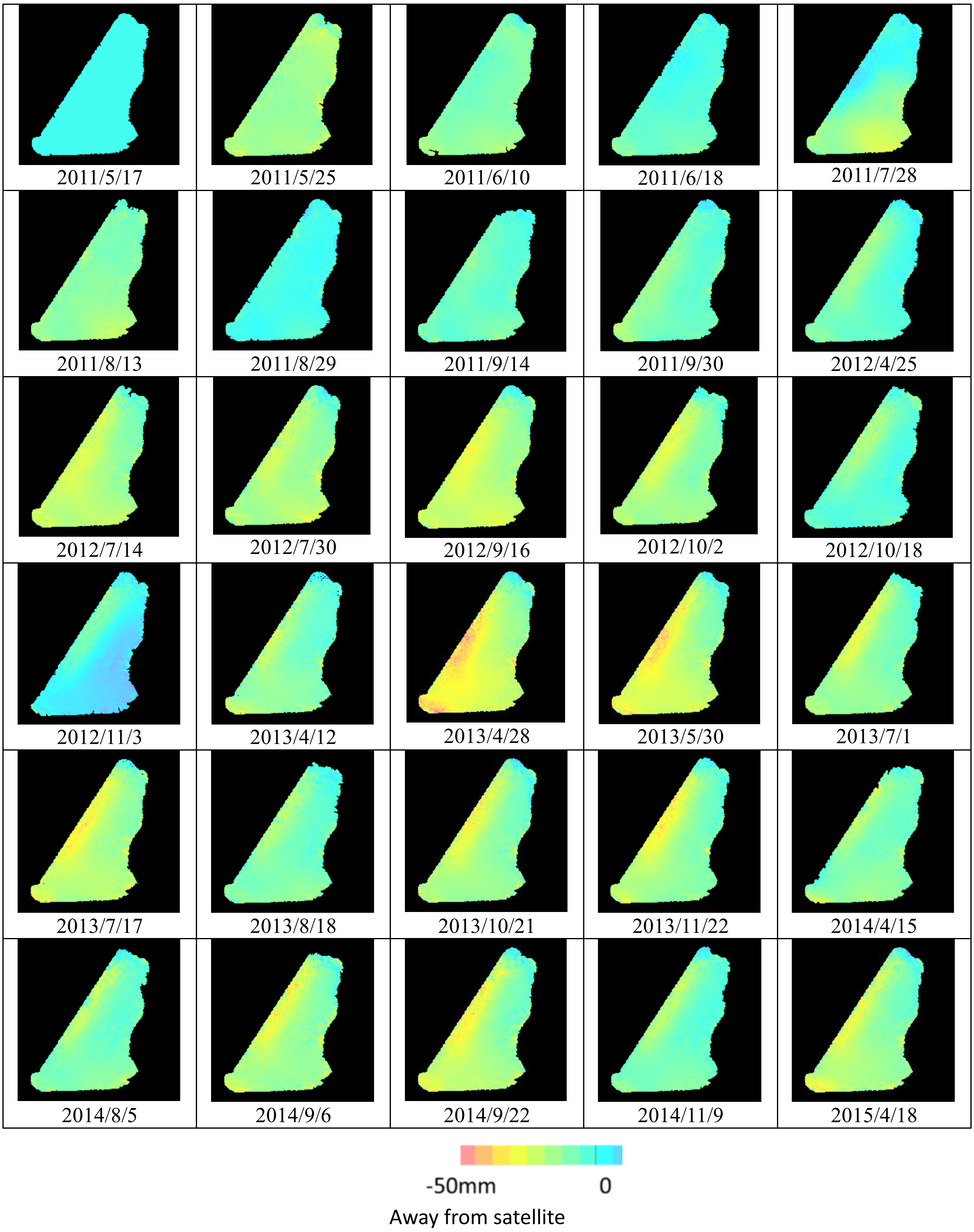


Figure 3. External deformation by satellite SAR

Figure 4 shows the comparisons of the external deformations by SAR and the electro optical survey of the dam at three survey measuring points. Although there are a little variations among the results by SAR and the electro optical survey, the results of SAR based external deformation monitoring agreed well with the results by the electro optical survey. Accuracy of external deformation measurement by SAR was verified by the comparisons of the results between the electro optical survey and SAR shown in Figure 4, and we found the accuracy of external deformations by SAR was about 5 mm in this paper.

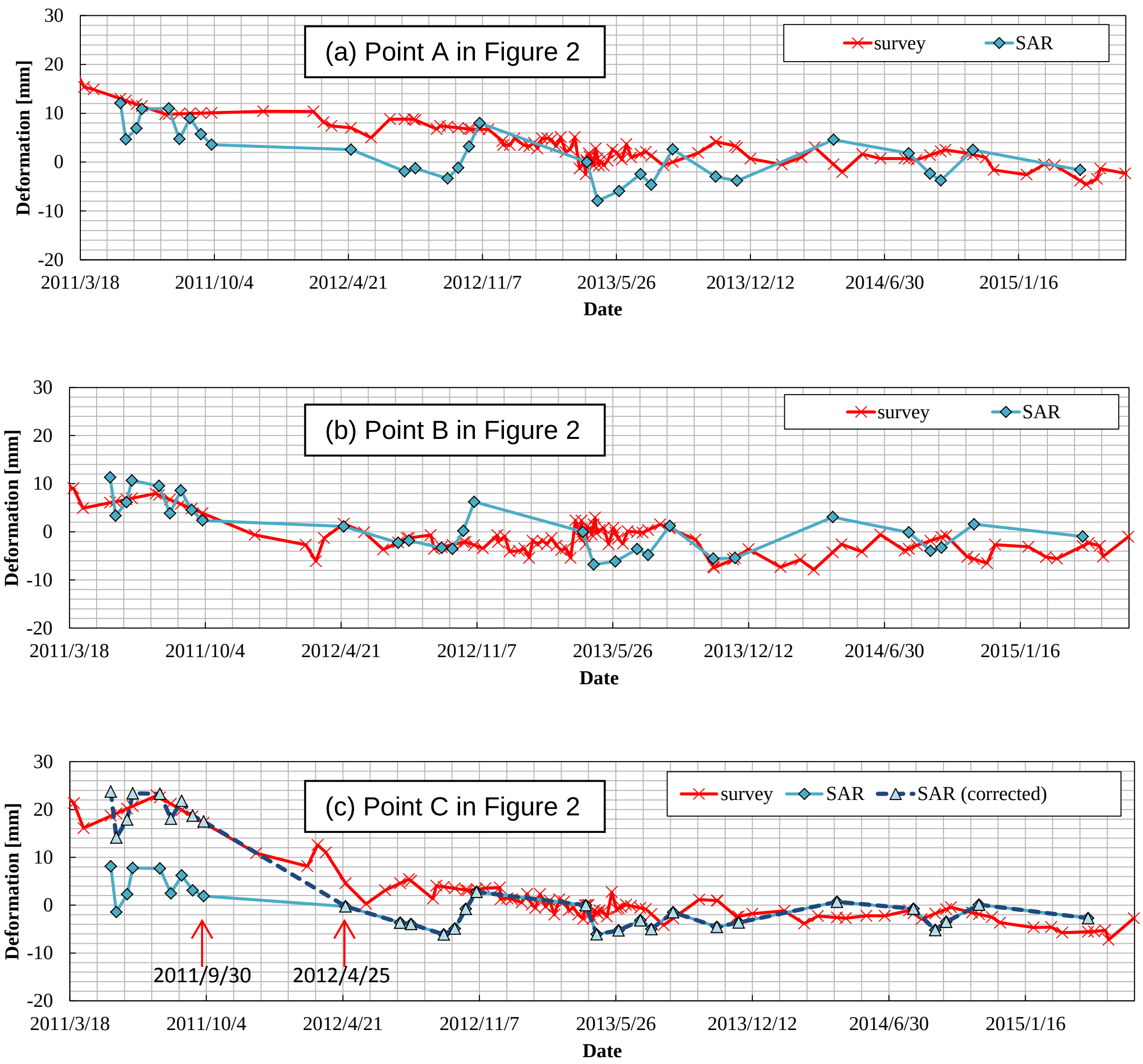


Figure 4. Comparison of external deformation by electro optical survey and SAR at three survey measuring points

In Figure 4 (c), there are some differences of external deformations between SAR and the electro optical survey from September 2011 to April 2012. This is thought to be caused by missing SAR data from October 2011 to March 2012 and the external deformation from September 2011 to April 2012 was larger than the half-wave length. It is known that errors of the results of the deformations measured by SAR are sometimes large when the deformations are larger than the half-wave length of the observation radar. In Figure 4 (c), considering these error conditions, by adding about 15mm equal to half-wave length of the observation radar to the data in 2011, corrected external deformations by satellite SAR data in 2011 are also shown in Figure 4 (c) and the corrected results agree well with the external deformations by the electro optical survey.

The accuracy of the external deformations by SAR were confirmed by the comparisons between the results of SAR and existing survey data as shown in Figure 4. Next, we tried to estimate the external deformations of the places where no existing measurement data were obtained. Figure 5 shows temporal changes of external deformations of the places along the red line on the downstream surface in Figure 2. In Figure 5, the external deformation in May 17, 2011, is set to be zero. From Figure 5, external deformations had been gradually larger and the maximum external deformation was about 15 mm during four years. Although there have been no existing external deformation data on the red line shown in Figure 2, external deformations of whole dam body surface can be evaluated by satellite SAR data shown as Figure 3 without sensors on the surface of the dam body.

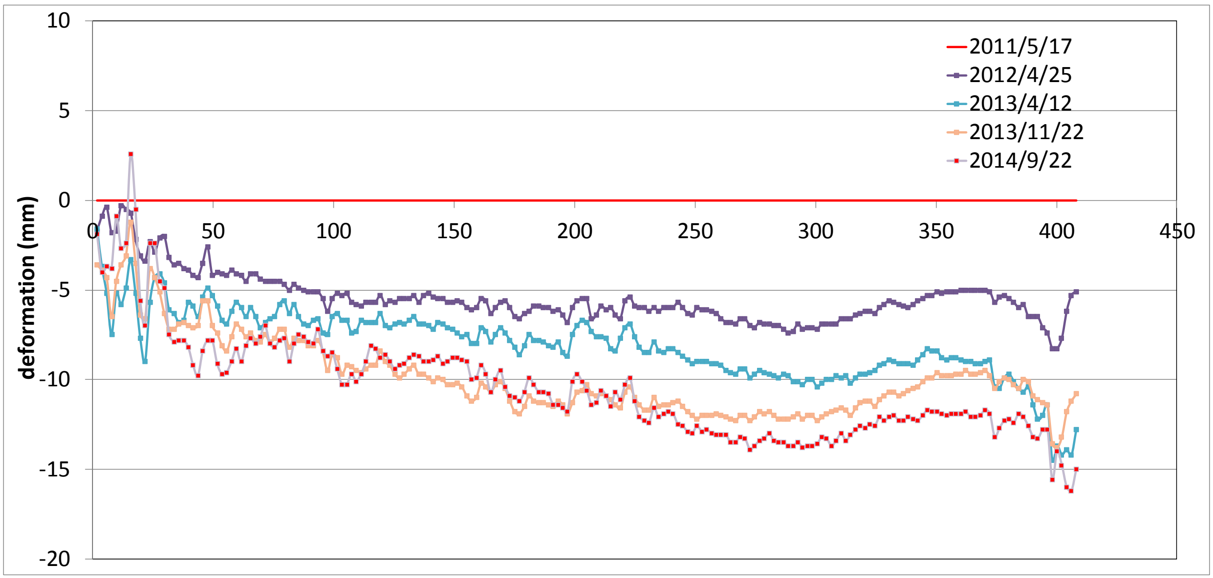


Figure 5. Temporal changes of external deformations of downstream surface line (shown as red line in Figure 2) by satellite SAR data

3. EMERGENT MONITORING OF ROCKFILL DAMS AFTER EARTHQUAKES USING OPTICAL AND SAR SATELLITE DATA

On April 14th, 2016 at 9:26 pm Local Time, a strong earthquake (Magnitude 6.5) occurred in the Kumamoto area in Kyushu island, followed by the main shock (Magnitude 7.3) on April 16th, 2016 at 1:25 am.

Special safety inspections based on the regulations issued by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) were immediately carried out by the managers of dams located within the area where earthquake motions at or above a specified level were observed. No severe damages were observed by the special safety inspections, but minor damages were observed at several rockfill dams such as cracks on the pavement on the crest. One rockfill dam of these dams was selected for study.

Quick confirmation of existence of severe damages after large earthquakes is important. It is sometimes difficult to investigate the damages after earthquakes because of the damage of the road network. If satellite data can be obtained soon after large earthquakes, we can evaluate damages in extensive area including dams and it will lead to reduction of the number of loss of life and effective emergency measures.

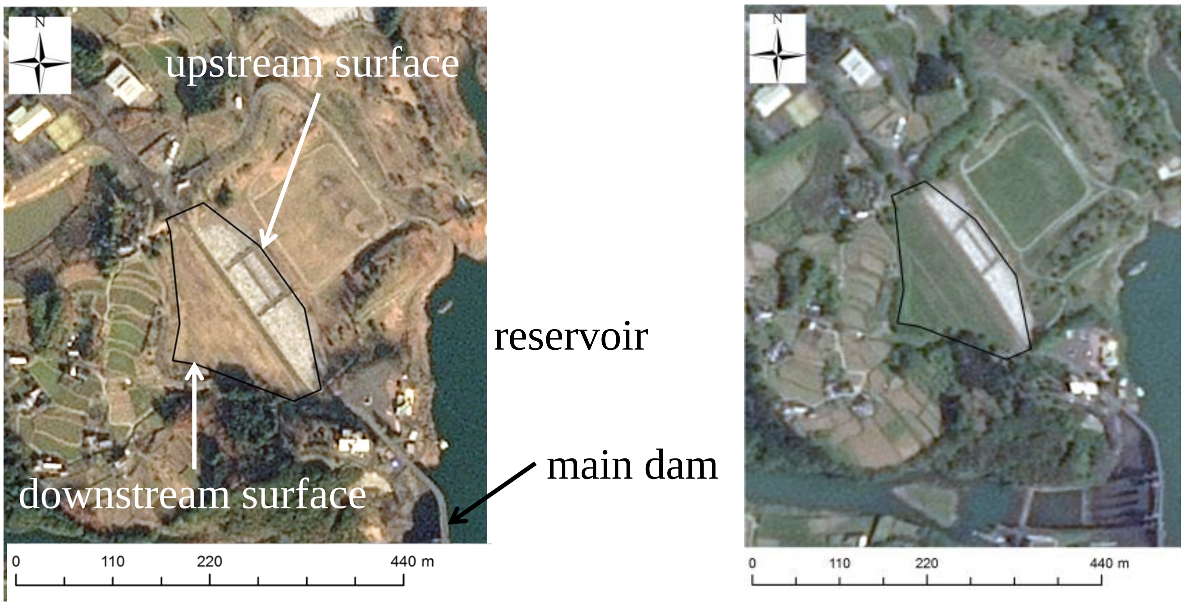
At first, optical satellite data was used to investigate severe damages of the dam near the epicenter of the 2016 Kumamoto earthquake. Next, satellite SAR data was used to evaluate earthquake-induced external deformations of the dam body.

3.1 Outline of a rockfill dam for study

The rockfill dam with a center core and a height of 35 meters was located at about 20 kilometers from the epicenter of the 2016 Kumamoto earthquake. The dam is a subdam of a concrete gravity dam with a height of 76.5 meters. No seismometer was installed for the rockfill dam but two seismometers were installed for the concrete gravity dam. PGA (Peak Ground Acceleration) was 1.18 m/s^2 at the bottom inspection gallery of the concrete dam.

3.2 Outline of optical satellite data for study

In order to confirm the existence of severe damages of the dam after the large earthquake, data of optical satellite, SPOT-6/7, were used in this paper. SPOT-6/7 are optical satellites with 1.5 m spatial resolution operated by AIRBUS Defence & Space. After the 2016 Kumamoto earthquake, SPOT-6/7 have taken aerial photos around the epicenter of Kumamoto area. Figure 6 shows the aerial photos of the dam taken before and after the earthquake. Based on the comparison of the photos taken before and after the earthquake shown in Figure 6, no severe damages were confirmed around the dam.



(a) January 16, 2016 (b) April 17, 2016

Figure 6. Aerial photos of the dam before and after the 2016 Kumamoto earthquake by SPOT-6/7

3.3 Outline of satellite SAR data for study

Data of ALOS-2 managed by JAXA were used for study. The wavelength and the spatial resolution of the ALOS-2 are 23.6 cm and 3 m, respectively. Satellite SAR can obtain data even in times of rain or cloud, whereas optical satellite cannot obtain data about the ground surface.

In addition to SAR data, 2 meters mesh of Digital Elevation Model of study area by Laser Profiler data was used as the initial dam body shapes to improve external deformation accuracy.

3.4 External deformation by satellite SAR data

The reflection intensity and the phase of radar reflection are obtained by satellite SAR data. Deformations of the ground surface are analysed from the phase difference between two SAR data. In Figure 7, left two figures show the reflection intensities of SAR data obtained before and after the 2016 Kumamoto earthquake. Right figures in Figure 7 show the external deformations of the dam between before and after the earthquake. In Figure 7, arrows show the illumination directions from the satellite and the dam body is shown inside the black or yellow lines.

Reflection intensities In Figure 7, white and black colors mean strong and weak reflections of radar from ground surface, respectively. Because the illumination directions are from right to left in Figure 7, downstream surface of the dam is located on the back side and the reflection intensities of the downstream surface of the dam are weak. On the other hand, reflection intensities of the upstream surface are strong. By the comparison of reflection intensities of SAR data before and after the earthquake, noticeable differences cannot be confirmed and we can make a judgement that the dam is not collapsed by the earthquake.

From Figure 6 of aerial photos and Figure 7 of SAR reflection intensities data, no important changes are confirmed between before and after the earthquake. Detail investigations of external deformations by SAR data were conducted and the results are shown in Figure 7.

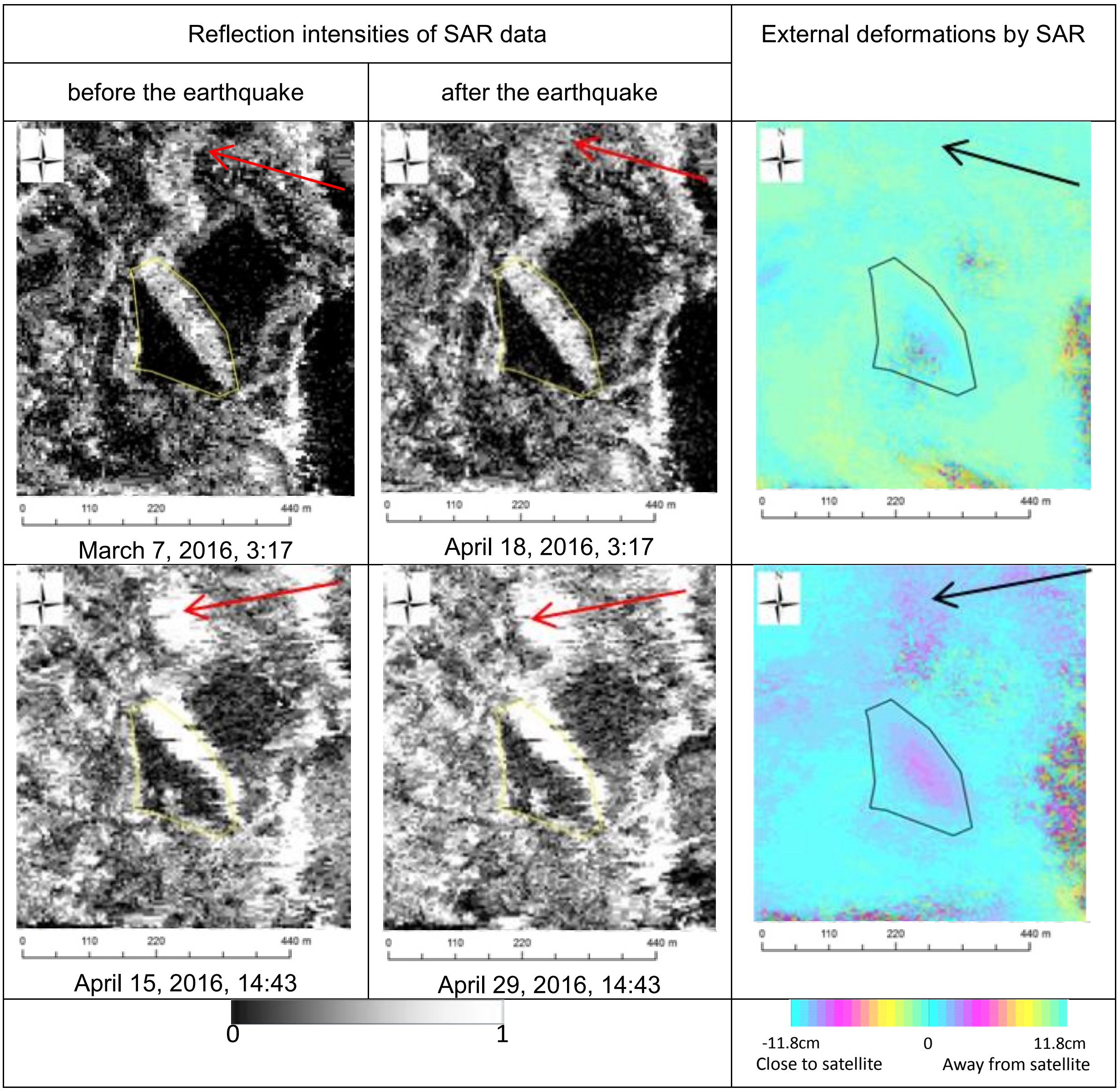


Figure 7. Reflection intensities of SAR data before and after the earthquake and external deformations by SAR

External deformations were also measured by survey by the dam office and we confirmed that the tendency of the results of the external deformations by survey were similar to the results by SAR. We think that external deformations can be measured by SAR where no existing external deformation data have been obtained even after large earthquakes.

4. CONCLUSION

With the aim of carrying out a development of SAR-based external deformation measurement of rockfill dams, this paper focused on a rockfill dam with a center core and a height of 74.4 meters in the northeastern part of Japan for normal time monitoring. 30 scenes satellite SAR data were used in descending orbit data over a period of nearly four years from 2011 to 2015. External deformations of the rockfill dam was measured by SAR and compared with the electro optical survey data at three points. The results by SAR agreed well with the results by the electro optical survey and errors between the results by SAR and the electro optical survey were about 5 mm. Because no sensors are needed on the ground surface, external deformations of rockfill dams can be conducted by satellite SAR even if no external deformation data have been obtained.

In addition, a rockfill dam with a center core and a height of 35 meters in Kumamoto area for emergent time monitoring using optical and SAR satellite data. This dam is located at about 20 km from the epicenter of the 2016 Kumamoto earthquake. Because noticeable differences could not be confirmed by the comparisons of optical and SAR reflection intensity data between before and after the earthquake, we were able to make a judgement that the dam was not failed by the earthquake. Based on the detail investigations of external deformations measured by SAR data, earthquake-induced settlement up to several centimeters was confirmed by SAR data which was obtained after two days from the 2016 Kumamoto earthquake.

As described in this paper, satellite SAR data is useful both in normal times and after earthquakes. Although disasters such as large earthquakes and floods can happen even at night and on rainy days, we can obtain data by satellite SAR even at such times and we can estimate the damage situation.

Now we are investigating external deformations of about 20 rockfill dams using ALOS-2 data. ALOS-2 is a satellite SAR launched in 2014 and we have found that the accuracy of external deformations using ALOS-2 data is very good. We have a plan to report the results next ICOLD meeting.

5. ACKNOWLEDGEMENTS

This research has been supported by the Strategic Innovation Promotion Program (SIP) of the Cabinet Office, Government of Japan.

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