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EXTERNAL DEFORMATION MONITORING OF FIVE ROCKFILL DAMS IN THE SAME RADAR SATELLITE DATA

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ABSTRACT

It is important to research new methods of conducting effective measurements of the external deformation of embankment dams. External deformations of five rockfill dams in the same SAR data were measured in about four years, and the results of external deformations using SAR data were compared with those by GPS or conventional survey data. We found that the results of external deformations using SAR data agreed well with those by GPS or conventional survey data and the average error of the external deformations between SAR and GPS or conventional survey was about five millimeters.

1. INTRODUCTION

After the accident of Sasago road tunnel ceiling collapse in December 2012, monitoring of aging infrastructures has become a major social concern in Japan. Ministry of Land, Infrastructure, Transport and Tourism (MLIT) made "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 the year 2020. The situation increasingly requires an efficient and accurate external deformation measurement method for the safety management of dams.

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.

Advanced Land Observing Satellite (ALOS) with a Phased Array L-band SAR (PALSAR) sensor (hereinafter referred to as "ALOS/PALSAR") was launched by Japan Aerospace Exploration Agency (JAXA) in January 2006 and completed the operation in May 2011 (JAXA). In this paper, we used ALOS/PALSAR data for SAR based external deformation monitoring of five rockfill dams in the same ALOS/PALSAR data. The external deformations of five rockfill dams for about four years by SAR were calculated and compared with other methods such as GPS or electro-optical survey.

2. OUTLINE OF SAR AND INSAR

Figure 1 is a schematic drawing of SAR. Conceptually, SAR is a radar system that has a number of virtual antennae placed in an orbital path. (GSI website) The system transmits radio waves and receives echo waveforms a number of times while moving in an orbit, and its resolution is enhanced by synthesizing the reflected signals. In a sense, SAR is a radar system that is capable of synthesizing many small apertures (antennae) into one large aperture.

Interferometric SAR (InSAR) is a basic SAR-based technique to calculate the degree of displacement of land surface. InSAR is a method that compares two (or more) SAR observation data from the same orbit and identifies the differences (interference) in phase between the acquired data. Figure 2 is a schematic drawing of InSAR. (GSI website) An interferogram produced by InSAR is characterized by the appearance of interferometric fringe in response to the phase difference by the displacement of land surface. For details of the analysis method, refer to the paper of Berardio et al. (2002) and Satoh et al. (2012).

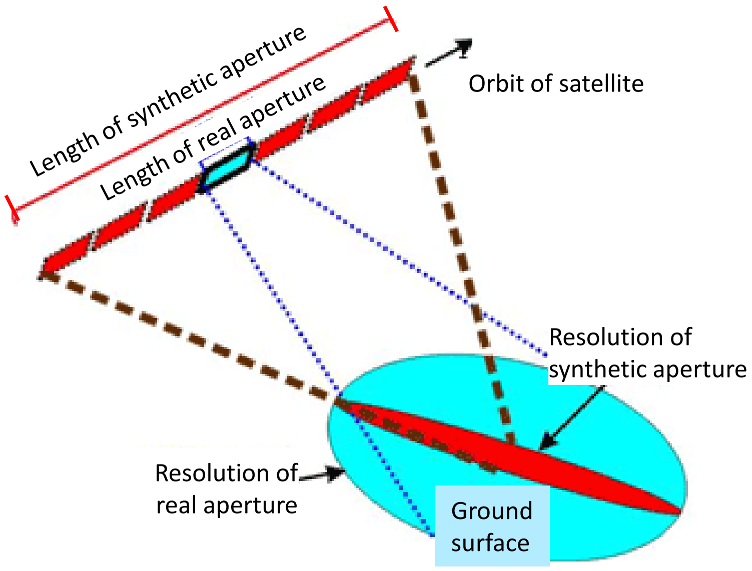

Figure 1. Schematic Drawing of SAR (GSI website)

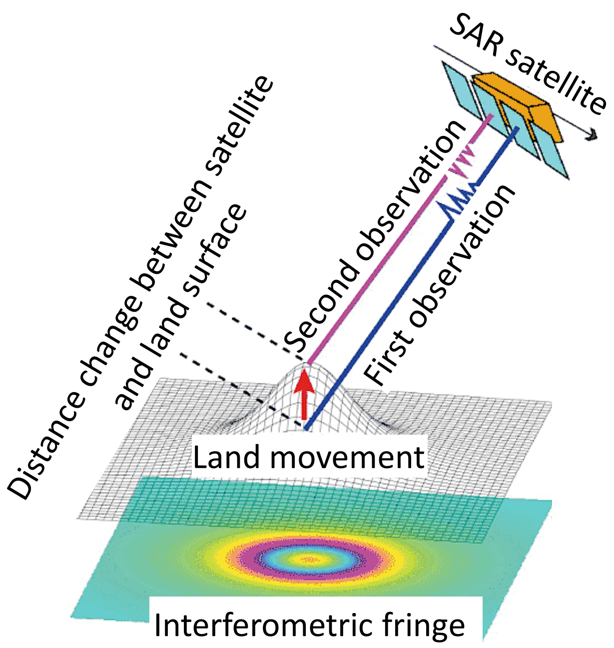

Figure 2. Schematic Drawing of InSAR (GSI website)

3. OUTLINE OF FIVE ROCKFILL DAMS FOR STUDY

Five rockfill dams in the northeast part of Okinawa Island were selected for study. Figure 3 and Table 1 show the locations and the main specifications of the dams, respectively.

Benoki dam is a combined dam and Table 1 shows the specifications of a rockfill dam part of Benoki dam. Although the completion year of Taiho subdam is 2010 in Table 1, construction of the dam body was finished around December 2006 and the pavement of the crest was constructed in around March 2008. Fukuji dam was originally completed in 1974 and reconstruction work on spillway and intake facility was finished in 1990.

Figure 4 shows the conditions of the upstream and downstream surfaces of Taiho subdam. Riprup with maximum size of around 1 meter is generally used to protect the surfaces of the rockfill dam and the crest of the rockfill dam is normally paved with asphalt as shown in Figure 4. Vegetation of the surface of the rockfill dam is regularly cut down. Therefore, the reflection intensity of the microwave of the satellite SAR from the surface of the rockfill dam should be high and the surface of the rockfill dam is thought to be suitable for SAR based external deformation monitoring.

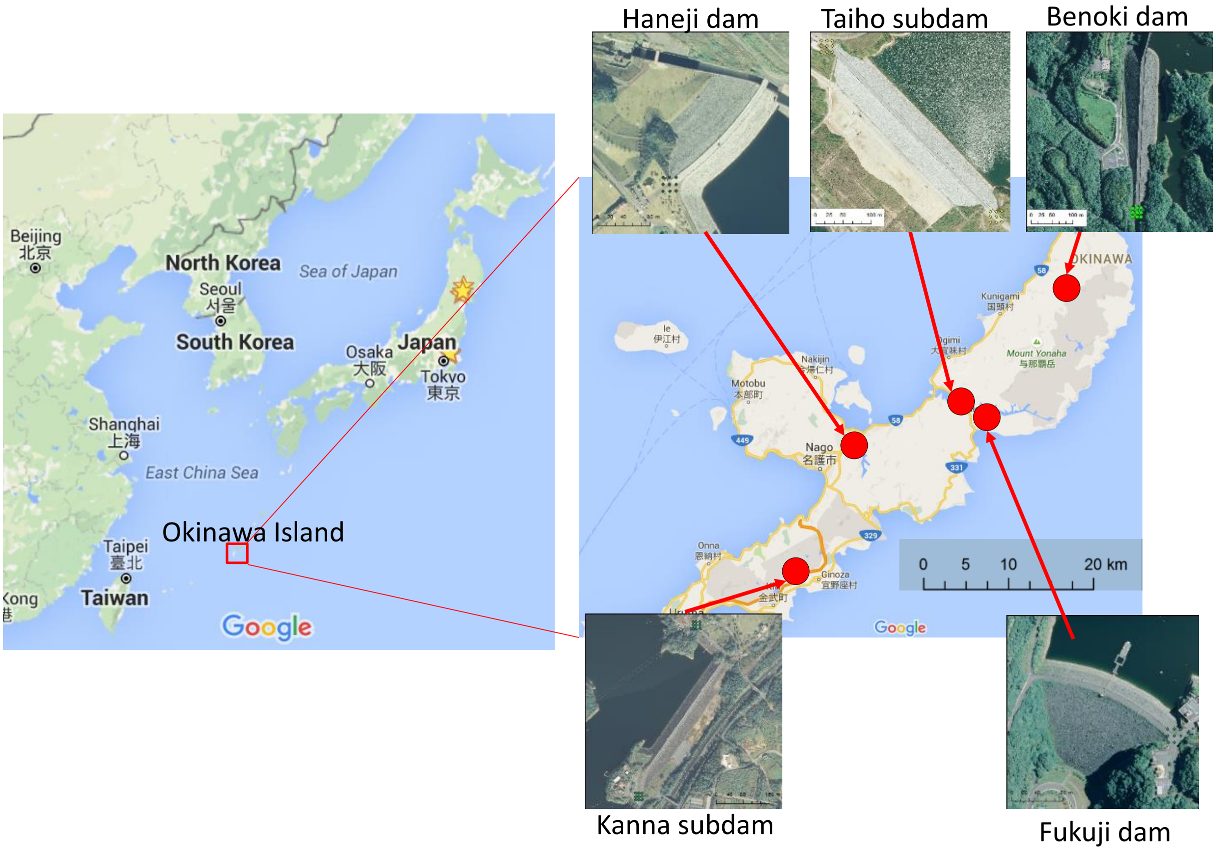

Figure 3. Locations of five dams for study

Table 1. Main specifications of five dams

Name of dam	Taiho subdam	Haneji dam	Kanna subdam	Benoki dam	Fukuji dam
Type	Rockfill	Rockfill	Rockfill	Rockfill	Rockfill
Height (m)	66	66.5	37	35	91.7
Crest length (m)	445	198	500	330	260
Completion year	2010	2004	1993	1987	1974
Upstream gradient	1:3.0	1:2.7	1:3.1	1:2.5	1:2.25
Downstream gradient	1:2.7	1:2.2	1:2.1	1:2.0	1:2.0

Figure 4. Conditions of upstream (left) and downstream (right) surfaces of Taiho subdam

4. SATELLITE SAR DATE FOR STUDY

The wavelength and the spatial resolution of the ALOS/PALSAR are 23.6 cm and 10 m, respectively. There were two observation orbits as shown in Figure 5, ascending and descending orbits. In this paper, 14 scenes of ascending ALOS/PALSAR data from December 6, 2006 to December 17, 2010, and 14 scenes of descending data from January 12, 2007 to January 23, 2011 were used, respectively (Table 2). The number of days from the first observation to the last was about 1500, nearly four years.

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

5. EXTERNAL DEFORMATION BY SATELLITE SAR

Because the number of the pages is restricted, we mainly report the results by the descending orbital data. We confirmed that the results by the ascending orbital SAR data were almost the same as those of descending SAR data.

Figures 6 and 7 show the external deformations by SAR of Taiho subdam and Fukuji dam as representative examples of the newest and the oldest completed dams among the studied five dams, respectively. Figures 8 and 9 show the comparisons of external deformations between SAR and other methods of Taiho subdam and Fukuji dam at the measuring points by GPS or electro-optical survey, respectively. In Taiho subdam, Haneji dam and Fukuji dam, GPS are used for external deformation monitoring. (Yamaguchi and Kobori, 2009)

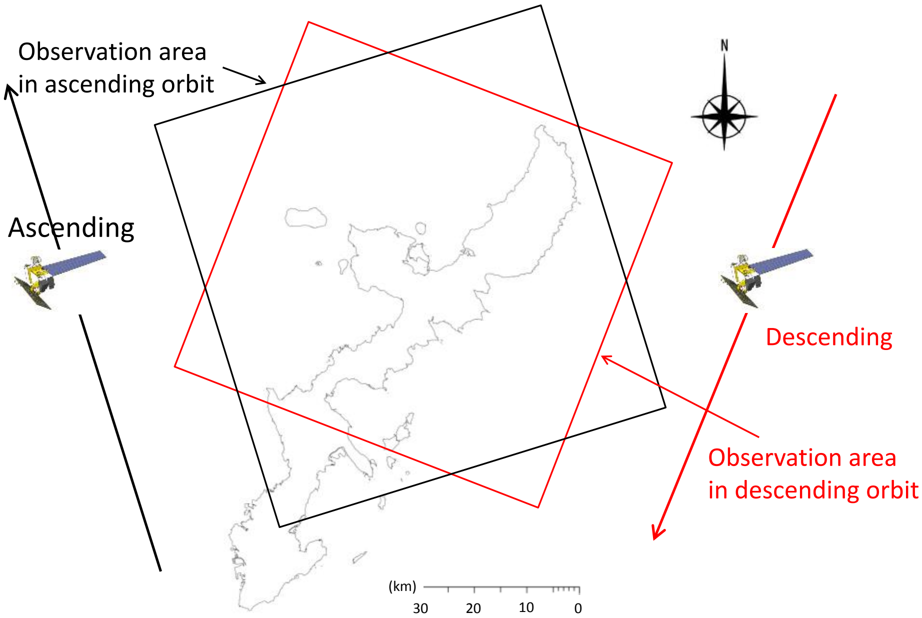

Figure 5. Ascending and Descending Orbits and Observation Areas

Table 2. Observation Days of SAR Data

No.	Ascending	Descending
1	December 6, 2006	January 12, 2007
2	October 24, 2007	April 14, 2007
3	December 9, 2007	August 30, 2007
4	January 24, 2008	October 15, 2007
5	April 25, 2008	November 30, 2007
6	July 26, 2008	January 15, 2008
7	December 11, 2008	April 16, 2008
8	January 26, 2009	June 1, 2008
9	October 29, 2009	September 1, 2008
10	December 14, 2009	January 17, 2009
11	January 29, 2010	April 19, 2009
12	August 1, 2010	September 4, 2009
13	November 1, 2010	January 20, 2010
14	December 17, 2010	January 23, 2011

Because the pavement of the crest was constructed in around March 2008 in Taiho subdam, Figures 6 and 8 show the results using data after March 2008. Displacements in April 16, 2008, in Figures 6 and 8 of Taiho subdam were set to be zero as the first SAR observation data. Also, displacements in January 12, 2007, in Figures 7 and 9 of Fukuji dam were set to be zero as the first SAR observation data.

According to Figure 6, the colours on the dam body surface of Taiho subdam change from blue to green and then to yellow as time goes along. It means that the surface of the Taiho subdam has been receding from the satellite, which means that settlement has been occurred during observation. On the other hands, the colours on the dam body surface of Fukuji dam completed in 1974 are almost blue in Figure 7, which means that almost no settlement has been occurred during observation.

Maximum external deformation of Taiho subdam was about 3 cm during SAR observation period from April 2008 to January 2011 as shown in Figures 6 and 8. Figure 8 shows the comparison of the external deformation by SAR and GPS of Taiho subdam and the external deformation by SAR is similar to that by GPS.

Maximum external deformation of Fukuji dam was almost about 0 cm during SAR observation period from January 2007 to January 2011 as shown in Figures 7 and 9. Figure 9 shows the comparison of the external deformation by SAR and other methods of Fukuji dam and the external deformation by SAR is similar to that by GPS or electro-optical survey.

Figure 10 shows the comparisons of external deformations of five rockfill dams by SAR and other methods at the crests of maximum cross sections. Although there were small variations among the results by SAR, GPS or electro-optical survey, the results of SAR based external deformation monitoring agreed well with the results by GPS or electro-optical survey.

Table 3 shows the average root mean square errors (RMSE) of five rockfill dams to evaluate the accuracy by SAR based external deformation monitoring. Although there were small variations among the results of five dams, the average RMSEs were almost same as around 5 mm. It means that the average RMSEs were thought to be independent from the degree of external deformation and the number of the years after the completion and the observation orbits of SAR.

In Figures 6 and 8, the colours of outside of the dam bodies were likely to be random, because of the noise. We found that the noise of outside of the dam body must be removed from the analysis procedure of the dam body external deformation analysis in order to obtain more accurate external deformation of rockfill dams. We will continue to try to solve the problem to improve the accuracy.

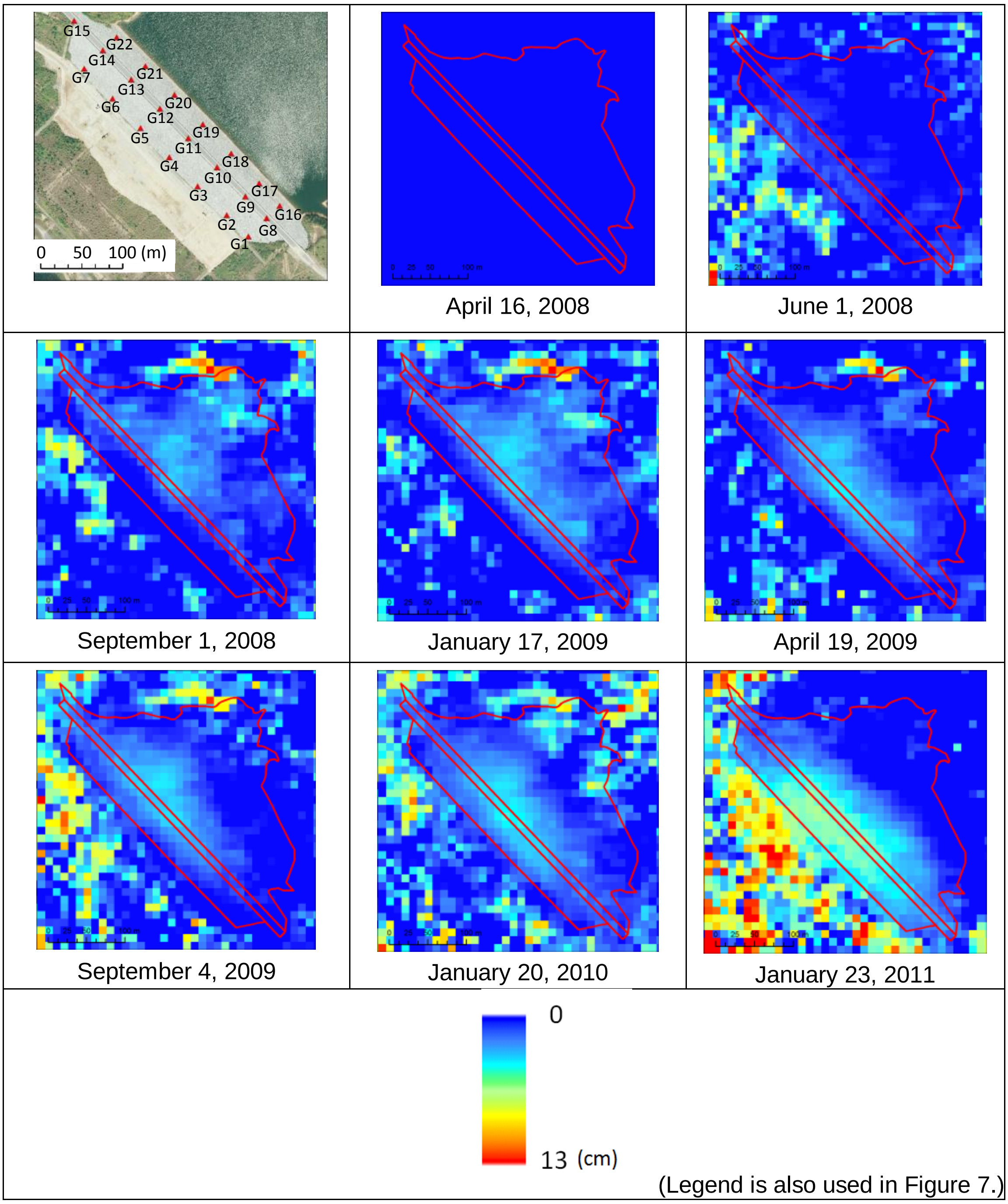

Figure 6. External deformation of Taiho subdam by SAR

6. CONCLUSION

With the aim of carrying out a development of SAR-based external deformation measurement of rockfill dams, this study focused on 5 rockfill dams in northeast part of Okinawa Island in one data of SAR. SAR data of 28 scenes were used, 14 scenes in ascending data and 14 scenes in descending data, over a period of nearly four years from the end of 2006 to the beginning of 2011. External deformations of five rockfill dams were calculated by SAR and compared with GPS or electro-optical survey data.

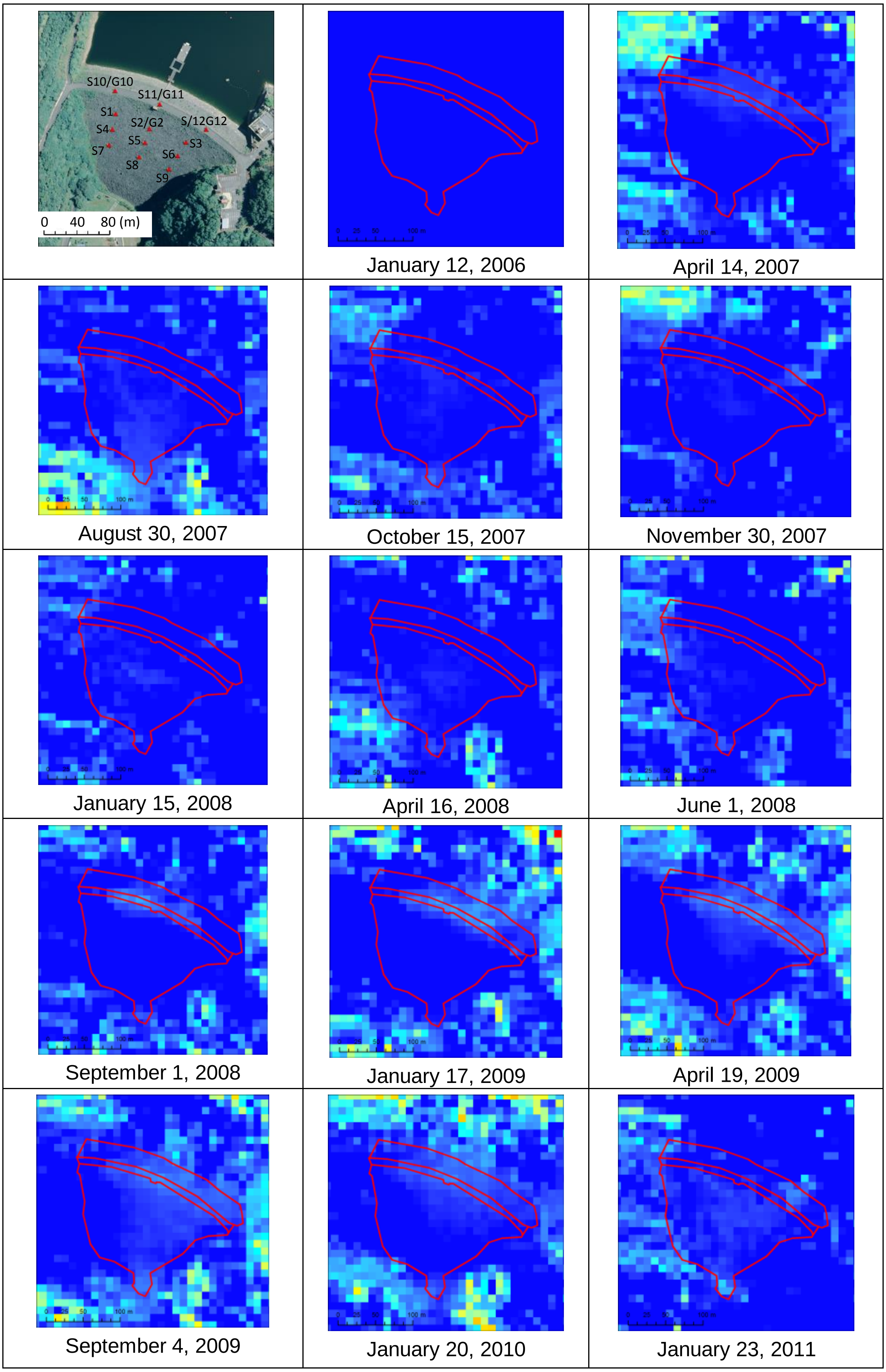

Figure 7. External deformation of Fukuji dam by SAR

(Legend is the same as in Figure 6.)

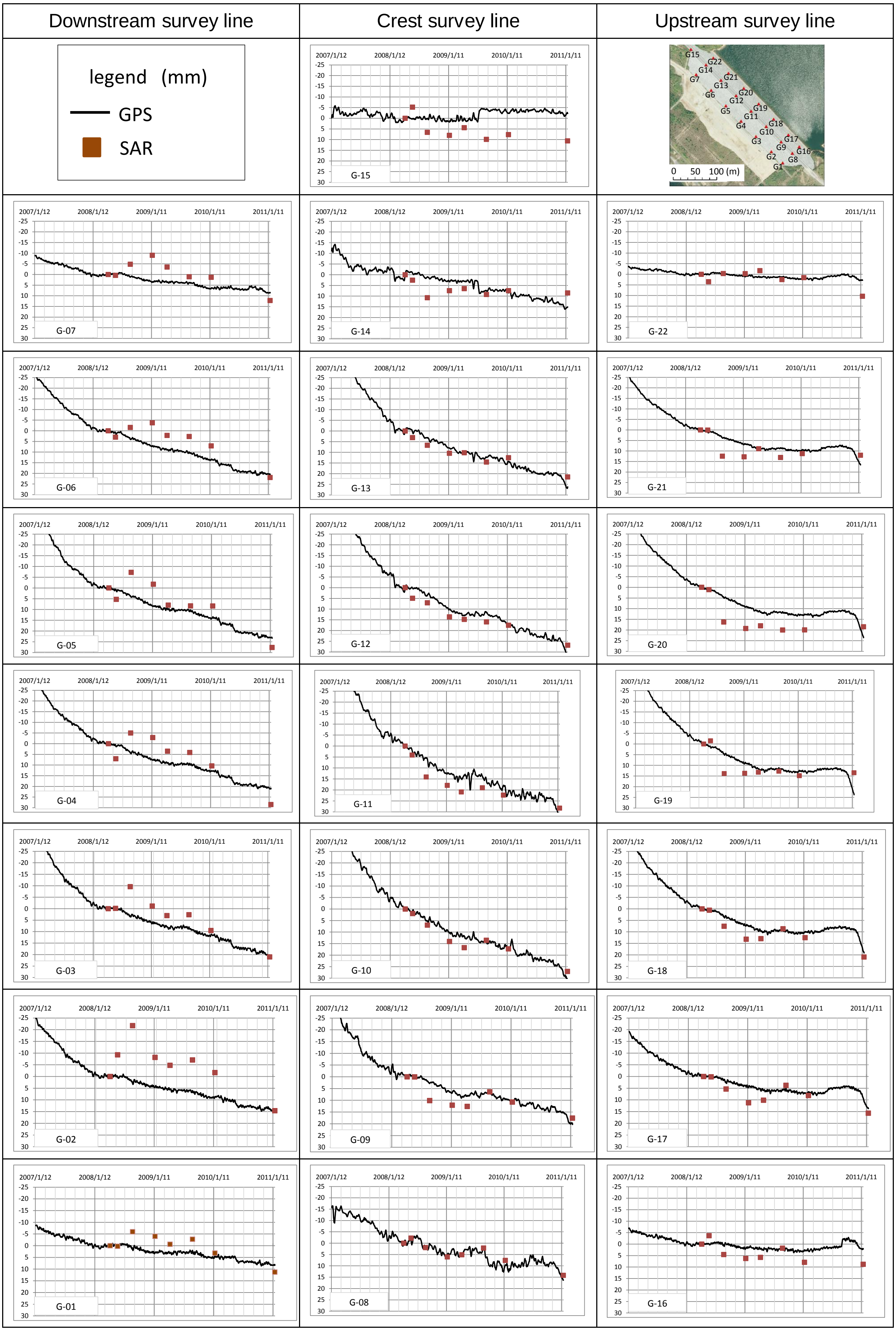

Figure 8. Comparison of external deformations of Taiho subdam by SAR and GPS

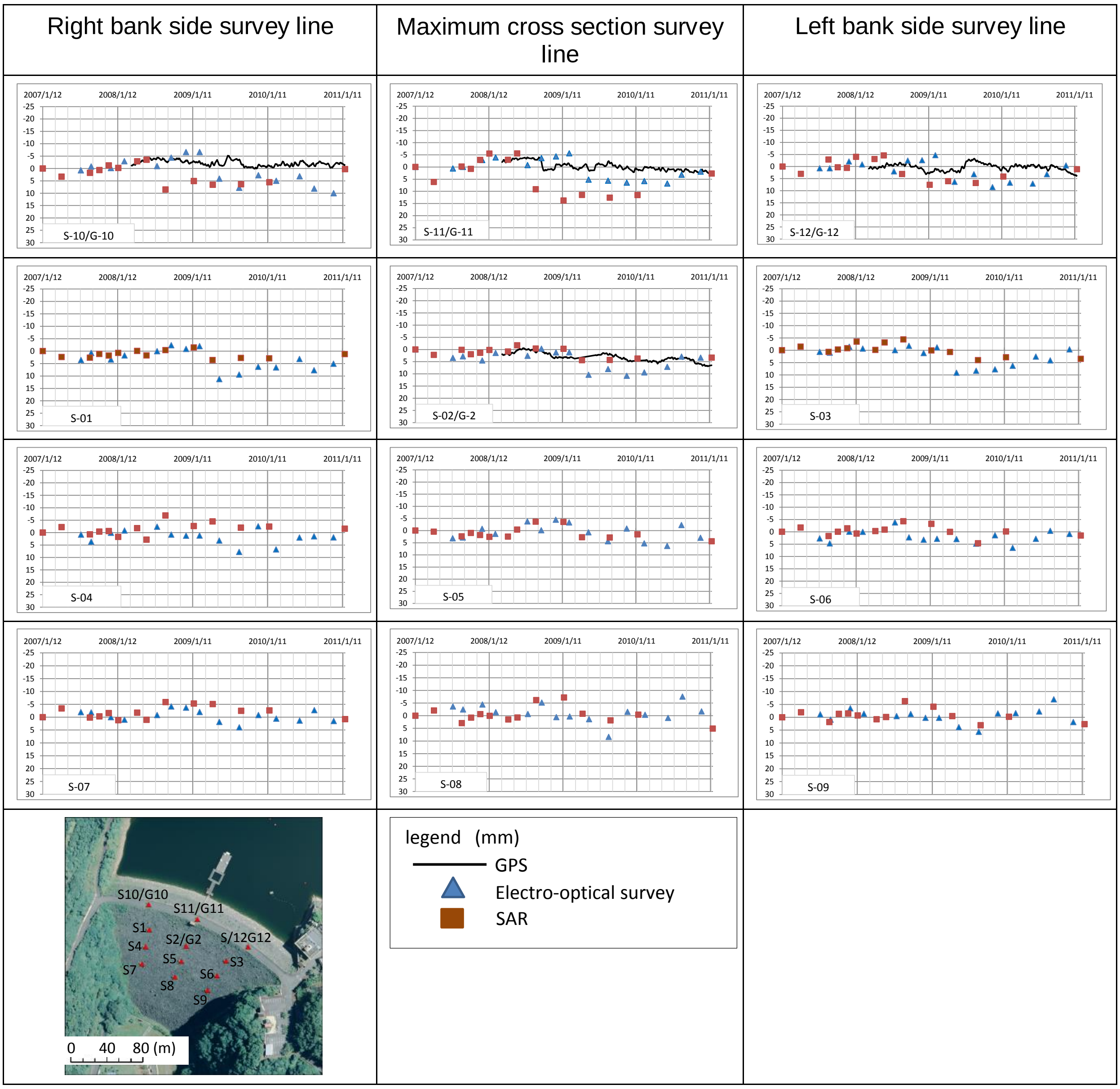

Figure 9. Comparison of external deformations of Fukuji dam by SAR and other methods

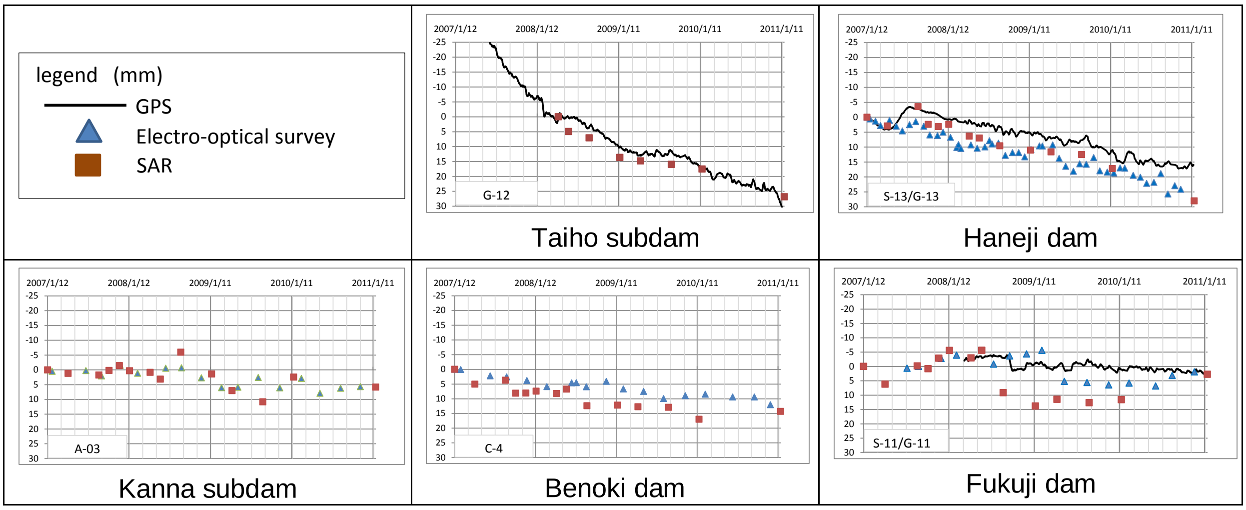

Figure 10. Comparison of external deformations of five dams by SAR and other methods at the crests of maximum cross sections

Table 3. Average root mean square error (RMSE) of five dams

Name of dam	Ascending (mm)	Descending (mm)	The number of measuring points by GPS or electro-optical survey
Taiho subdam	6.2	6.0	22
Haneji	4.1	4.6	14
Kanna subdam	4.5	4.1	12
Benoki	5.6	7.9	17
Fukuji	4.4	6.6	28
Average	5.0	5.9	

We found that the reflection intensity of the surfaces of the rockfill dams was fairly good and the interference fringe images could be obtained through the entire observation period. This indicates that the SAR can be useful for the external deformation measurements of rockfill dams.

Average errors by SAR based external deformation analysis of five rockfill dams were almost same as around 5 mm and independent from the degree of external deformation and the number of the years after the completion.

Although ALOS/PALSAR completed the operation in May 2011, ALOS 2 with a Phased Array L-band SAR sensor was launched by JAXA in May 2014. The spatial resolution and the revisit time of ALOS 2 have been improved from 10 m and 46 days of ALOS/PALSAR to 3m and 14 days, respectively.

Because we think that the SAR-based external deformation measurement of rockfill dams is useful, we will continue to develop efficient and accurate external deformation measuring method for rockfill dams by SAR technique using ALOS 2 data.

7. ACKNOWLEDGEMENTS

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