COMMISSION INTERNATIONALE DES GRANDS BARRAGES

VINGT-SIXIÈME CONGRÈS DES GRANDS BARRAGES
Autriche, juillet 2018

DOI 10.3217/978-3-85125-620-8-070

EXTERNAL DEFORMATION MONITORING OF NINETEEN ROCKFILL DAMS USING SATELLITE SAR DATA

Hiroyuki SATO
Senior Researcher, HYDRAULIC STRUCTURE DIVISION, RIVER DEPT.

Masafumi KONDO
Head, HYDRAULIC STRUCTURE DIVISION, RIVER DEPARTMENT

Toshihide KOBORI and Ryotaro ISHIKAWA
Researcher, HYDRAULIC STRUCTURE DIVISION, RIVER DEPARTMENT

Takashi SASAKI
Research Coordinator for River Structures, RIVER DEPARTMENT

NATIONAL INSTITUTE FOR LAND AND INFRASTRUCTURE MANAGEMENT

Wataru SATO
Manager, DISASTER PREVENTION AND MITIGATION DEPARTMENT

Naruo MUSHIAKE
Manager, REMOTE SENSING GROUP, GEOSPATIAL TECHNOLOGY DEPT.

Takumi SATO
Senior Engineer, DISASTER PREVENTION AND MITIGATION DEPARTMENT

Ken'ichi HONDA
Engineer, REMOTE SENSING GROUP, GEOSPATIAL TECHNOLOGY DEPT.

KOKUSAI KOGYO CO., LTD.

JAPAN

COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

VINGT-SIXIÈME CONGRÈS DES
GRANDS BARRAGES
Autriche, juillet 2018

EXTERNAL DEFORMATION MONITORING OF NINETEEN ROCKFILL DAMS USING SATELLITE SAR DATA

Hiroyuki SATO
Senior Researcher, Hydraulic Structure Division, River Department,
Masafumi KONDO
Head, ditto,
Toshihide KOBORI
Researcher, ditto
Ryotaro ISHIKAWA
Researcher, ditto,
Takashi SASAKI
Research Coordinator for River Structures, River Department,

NATIONAL INSTITUTE FOR LAND AND INFRASTRUCTURE MANAGEMENT

Wataru SATO
Manager, Disaster Prevention and Mitigation Department,
Naruo MUSHIAKE
Manager, Remote Sensing Group, Geospatial Technology Department,
Takumi SATO
Senior Engineer, Disaster Prevention and Mitigation Department,
Ken'ichi HONDA
Engineer, Remote Sensing Group, Geospatial Technology Department,

KOKUSAI KOGYO CO., LTD.

Japan

1. INTRODUCTION

Satellite SAR (Synthetic Aperture Radar) is one of remote sensing technologies which makes it possible to measure distributions of ground surface deformations over a wide area, and it has been commonly used to evaluate crustal displacement due to earthquakes and volcanic activity, as well as landslides.

Recently, researches on external deformation measurements for dams using satellite SAR data have been conducted [1] to [8]. For the purpose of technological development to contribute to the rationalization and efficiency of dam deformation measurements, the authors have already shown the external deformations of five rockfill dams using satellite SAR data [6]. The authors have found that the satellite SAR produced external deformation measurements which were with an accuracy of about 5 mm when compared with the external deformation measurements obtained by GPS or electro-optical survey.

This paper reports on the results of external deformation monitoring of nineteen rockfill dams in Japan using satellite SAR data. The external deformation of dams for about two years by satellite SAR was measured and compared with other existing geodetic measurements such as GPS or electro-optical survey.

2. EXTERNAL DEFORMATION MONITORING OF NINETEEN ROCKFILL DAMS USING SATELLITE SAR DATA

2.1. OUTLINE OF NINETEEN ROCKFILL DAMS AND SATELLITE SAR DATA FOR STUDY

Fig. 1 shows the locations of the dams for study. Table 1 shows main specifications of nineteen rockfill dams and observational data of satellite SAR for study. In Table 1, ASC and DSC mean ascending and descending orbits of satellite SAR shown in Fig. 2, respectively. A total of 135 scenes of SAR data was used.

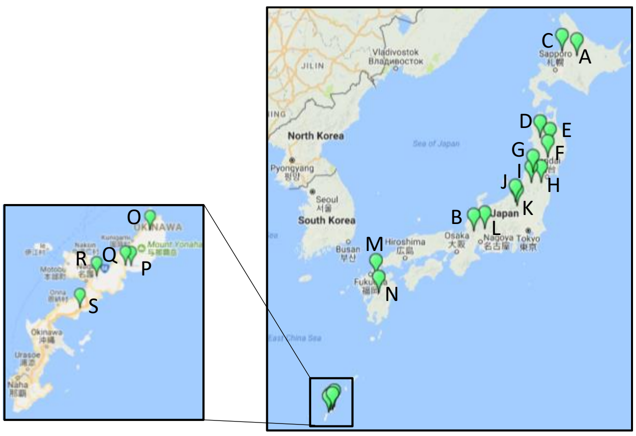


Fig. 1
Locations of Nineteen Dams for Study

Table 1
Main Specifications of Dams and Observational Data for Study

Name of dam	Height(m)	Crest length(m)	Orbit of satellite SAR	Numbers of data used	Observation day (year/month/day)					
A	78.5(*1)	595(*1)	ASC	6	2015/7/30	2015/8/13	2015/11/5	2016/5/5	2016/6/16	2016/7/28
B	161	427.1	DSC	6	2014/8/24	2015/9/20	2015/11/29	2016/3/6	2016/6/12	2016/8/21
C	41.2	440	ASC	5	2015/5/23	2015/6/6	2015/10/24	2015/11/7	2016/6/4	
D	89.9	786	ASC	6	2015/4/7	2015/5/19	2015/6/16	2015/7/28	2015/9/8	2016/6/28
E	52.5(*1)	210(*1)	ASC	6	2014/9/4	2014/10/16	2015/5/28	2015/8/6	2015/10/29	2016/5/26
F	127	723	ASC	6	2015/4/7	2015/5/19	2015/6/16	2015/7/28	2015/9/8	2016/6/28
G	112	510	ASC	5	2014/9/9	2015/6/2	2015/8/11	2015/11/3	2016/5/31	
H	90	565	ASC	8	2014/10/21	2014/12/16	2015/2/10	2015/3/10	2015/6/30	2015/8/25
					2015/11/17	2016/6/14				
I	66	348.2	ASC	5	2014/9/9	2015/6/2	2015/8/11	2015/11/3	2016/5/31	
J	119.5	419.5	DSC	6	2014/10/28	2014/11/11	2015/6/23	2015/9/15	2015/11/24	2016/6/7
K	158	520	DSC	10	2014/10/9	2015/5/7	2015/5/21	2015/6/4	2015/6/18	2015/7/2
					2015/7/16	2015/10/22	2016/4/21	2015/7/14		
L	127.5	366	DSC	7	2014/9/30	2014/10/14	2014/11/25	2015/10/13	2016/4/12	2016/7/5
					2016/9/13					
M	83	420	ASC	8	2014/10/24	2015/2/27	2015/5/22	2015/6/5	2015/9/11	2015/11/6
					2016/2/12	2016/6/3				
N	35	244	DSC	15	2015/2/9	2015/2/23	2015/9/7	2015/9/21	2015/11/30	2016/3/7
					2016/4/18	2016/5/2	2016/5/16	2016/6/13	2016/6/27	2016/7/11
					2016/7/25	2016/8/8	2016/9/5			
O	35(*1)	330(*1)	ASC	8	2014/10/11	2014/12/20	2015/4/25	2015/7/18	2016/1/2	2016/4/9
					2016/5/21	2016/7/16				
P	91.7	260	ASC	8	2014/10/11	2014/12/20	2015/4/25	2015/7/18	2016/1/2	2016/4/9
					2016/5/21	2016/7/16				
Q	66	445	ASC	7	2014/9/26	2015/4/10	2015/7/3	2015/12/18	2016/3/25	2016/5/6
					2016/7/1					
R	66.5	198	ASC	7	2014/9/27	2015/4/11	2015/7/4	2015/12/19	2016/3/26	2016/5/7
					2016/7/2					
S	37	500	DSC	6	2015/2/28	2015/3/28	2015/9/26	2015/12/5	2016/3/12	2016/6/18

ASC : Ascending, DSC : Descending
*1 : Rockfill dam part of combined dam

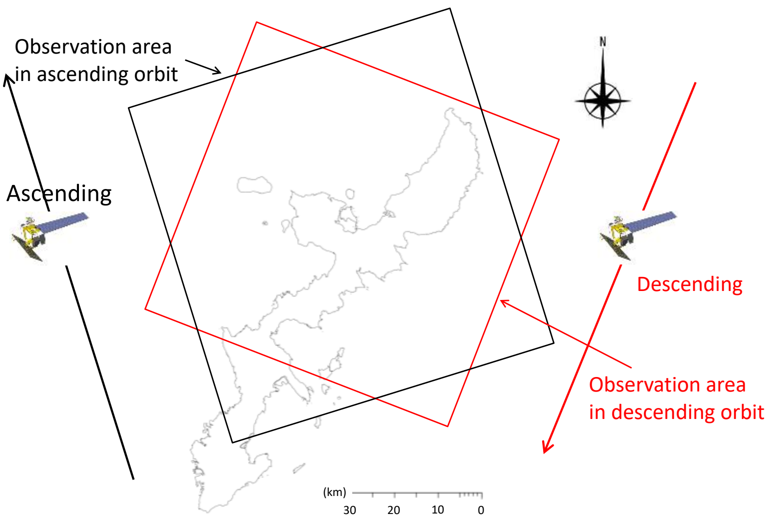


Fig. 2
Ascending and Descending Orbits and Observation Areas

In this paper, we used satellite SAR data obtained by Advanced Land Observing Satellite 2 (ALOS-2) with a Phased Array L-band SAR (PALSAR) sensor (hereinafter referred to as "ALOS-2") [9]. ALOS-2 was launched by Japan Aerospace Exploration Agency (JAXA) in January 2014 and is currently operated. The wavelength and the spatial resolution of the ALOS-2 are 23.6 cm and about 3 m, respectively.

In addition to SAR data, 2 m Digital Elevation Models (DEM) of study areas by Laser Profiler (LP) were used as initial dam body shapes to improve external deformation accuracy.

2.2. EXTERNAL DEFORMATION MONITORING USING SATELLITE SAR DATA

Fig. 3 shows external deformations of nineteen rockfill dams by satellite SAR in the line-of-sight direction from the first SAR observation to the last SAR observation day shown in Table 1. The red arrows in Fig. 3 show the observation directions of the ALOS-2. From the results of preliminary examinations, the multi-look [10], [11] for noise reduction of SAR data was set at 2 x 2 pixels (a spatial resolution of about 5m) in this paper, and the distributions of external deformations in Fig. 3 are expressed with a spatial resolution of about 5 m. Negative values in Fig. 3 mean that the dam surface deforms away from the satellite and it is almost the same direction of settlement of the dam. In the case of Dam N in Fig. 3, which showed a relatively large amount of external deformation, it was clarified with electro-optical survey after the Kumamoto earthquake in April 2016 that there had been settlement of several centimeters due to the earthquake, and earthquake-induced settlement was well measured by satellite SAR.

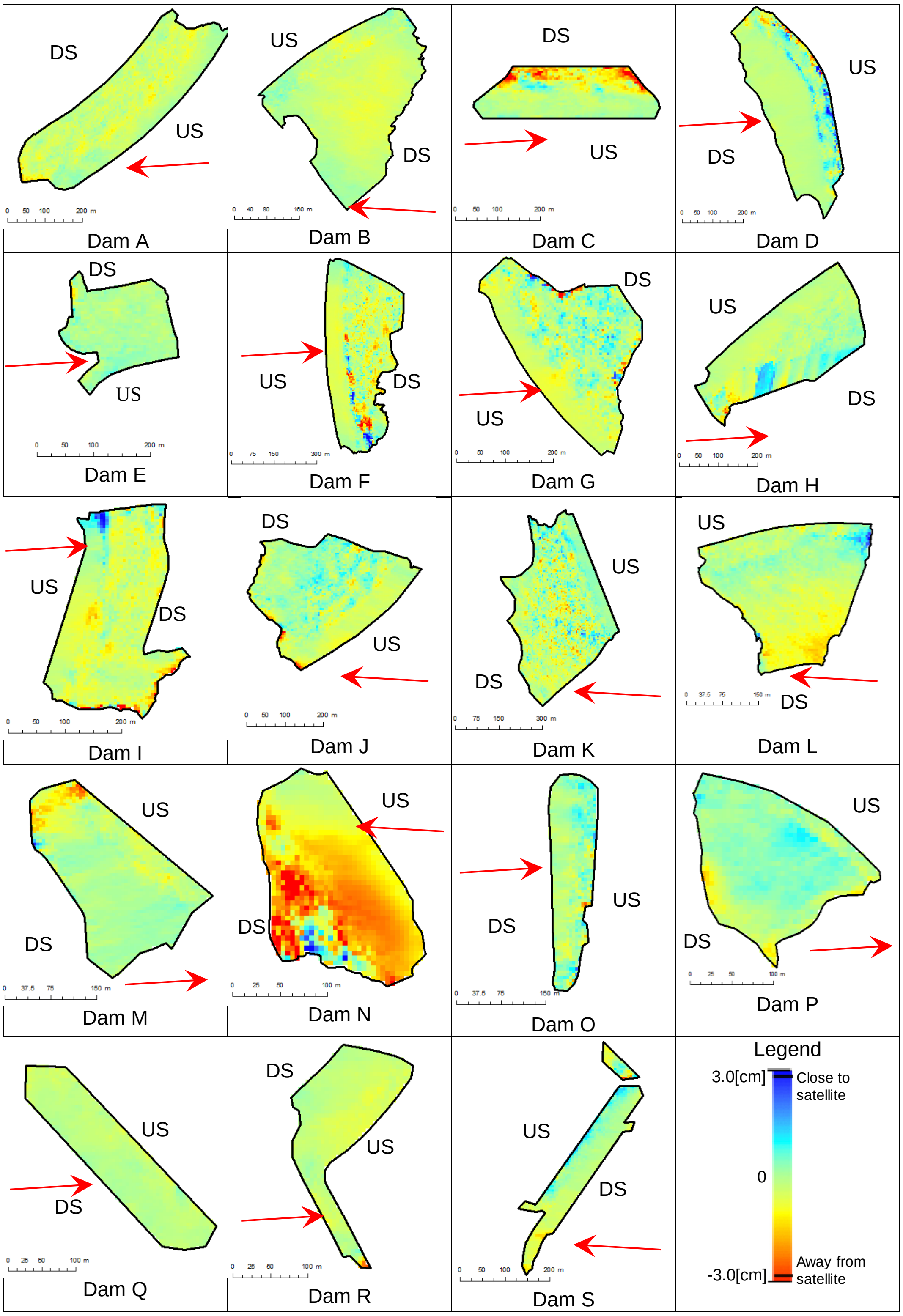
In order to evaluate the accuracy of satellite SAR based external deformation monitoring, Fig. 4 shows root mean square error (RMSE) distributions at existing GPS or electro-optical survey measurement points. RMSE is calculated using Eq. [1].

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(u_{SAR} - u_0)^2} \qquad [1]$$

Where n is the number of satellite SAR data, u_{SAR} is the external deformation measured by satellite SAR, and u_0 is the external deformation measured by GPS or electro-optical survey, respectively. If GPS data has been obtained, RMSE in Eq. [1] is calculated from the differences of external deformations between SAR and GPS measurement values at the GPS measurement points. If no GPS data has been obtained, external deformations by electro-optical survey at the SAR observation days were estimated by linear interpolation of two electro-optical survey data and RMSE was calculated from the differences of external deformations between SAR and electro-optical survey at the electro-optical measurement points.

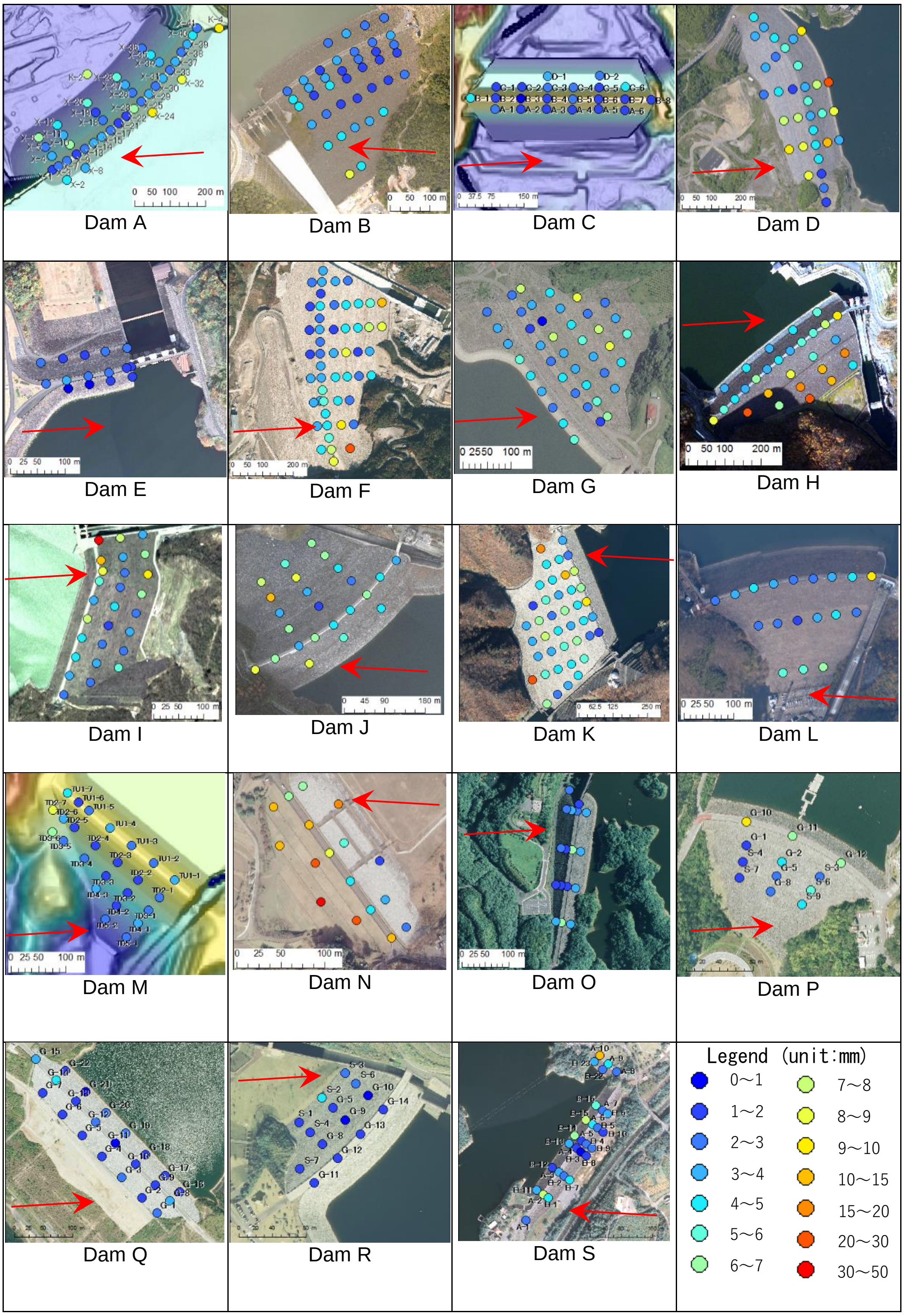
Most RMSE values show less than 5 mm in Fig. 4 and it means that external deformations by satellite SAR have good accuracy by comparing to GPS or electro-optical survey.

Fig. 5 shows the comparisons of temporal changes of external deformations by SAR and GPS/electro-optical survey at the existing geodetic measurement points on the crests in the maximum cross sections of nineteen studied dams. Although there were small variations among the results between



US : Upstream Side, DS : Downstream Side
Red arrows show line of sight directions of ALOS-2.

Fig. 3
External deformations of nineteen rockfill dams using satellite SAR data



Red arrows show line of sight directions of ALOS-2.

Fig. 4
RMSE of external deformations between SAR and GPS/electro-optical surcey
at existing geodetic points

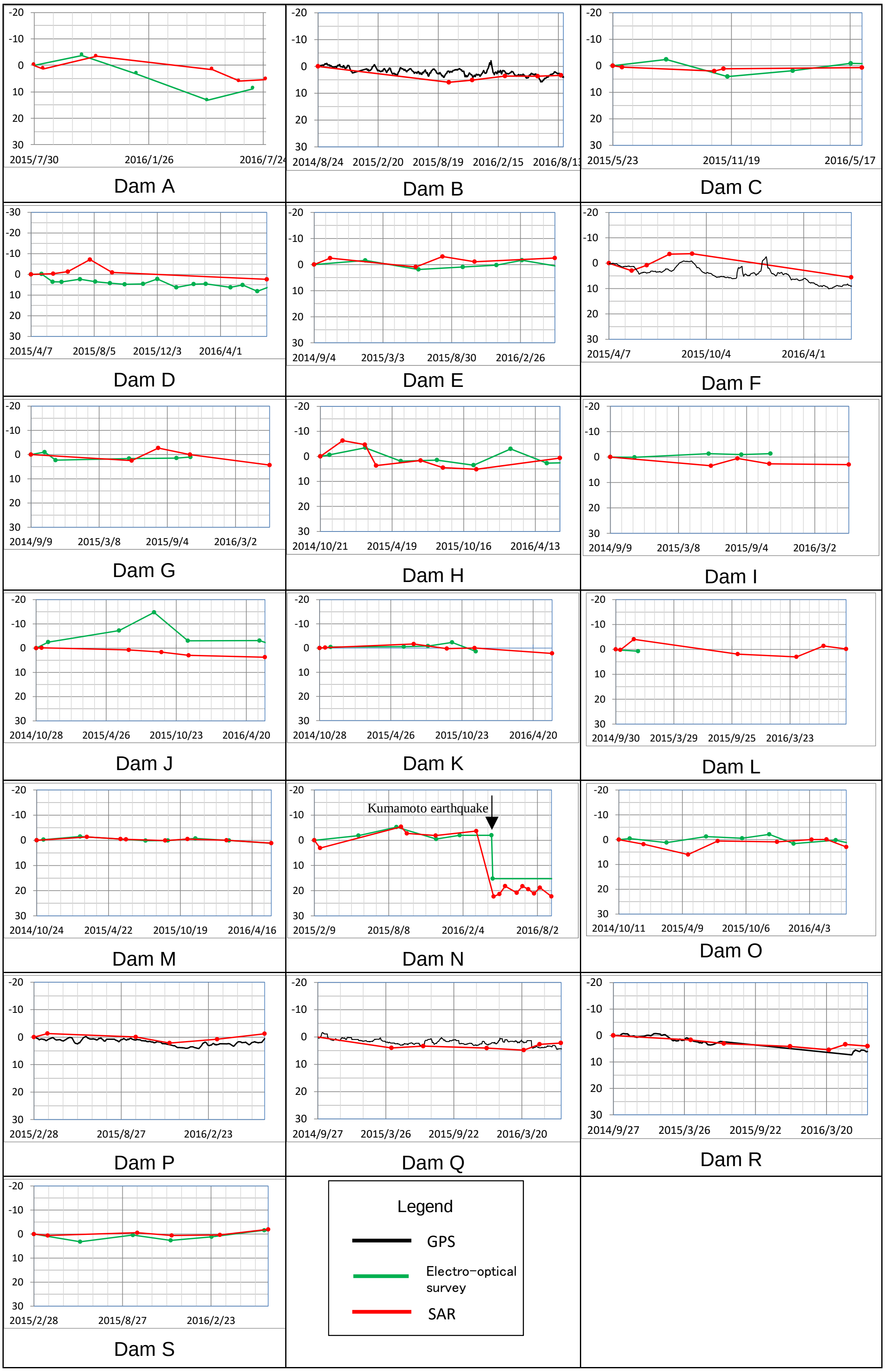


Fig. 5
Comparisons of external deformations between SAR and GPS/electro-optical survey at crests of maximum cross sections

SAR and GPS/electro-optical survey, the results of satellite SAR based external deformation measurements agreed well with the results by GPS or electro-optical survey. In the case of Dam N in Fig. 5, which showed a relatively large and sudden settlement by the Kumamoto earthquake in April 2016, earthquake-induced settlement was well measured by satellite SAR.

Table 2 shows the average RMSE on upstream, crest and downstream surfaces and all existing geodetic points of nineteen rockfill dams. Although there are some variations among the results of RMSEs in Table 2, more than half of the average RMSEs are less than 5 mm and most values are less than 10 mm. On the other hand, several RMSEs in Table 2 show more than 10 mm and the RMSE of the downstream surface of Dam N shows more than 20 mm. It is well known that deterioration in accuracy of SAR based deformation measurements occurs when ground surface is covered with vegetation [10]. Because downstream surface of Dam N has been covered with vegetation, it leads to the relatively large RMSE of downstream surface of Dam N. Table 2 shows that external deformation monitoring using satellite SAR data is generally accurate, but we must pay attention to factors that cause reduction of the accuracy such as ground surface vegetation.

Table 2
RMSE of external deformations between SAR and GPS/electro-optical survey on upstream, crest and downstream surfaces

Name of dam	Height(m)	Crest length(m)	Orbit of satellite SAR	Numbers of data used	RMSE (mm)			
					All	Upstream surface	Crest	Downstream surface
A	78.5(*1)	595(*1)	ASC	6	4.4	7.5	3.2	4.4
B	161	427.1	DSC	6	3.2	2.8	2.9	3.4
C	41.2	440	ASC	5	2.3	1.7	2.1	2.8
D	89.9	786	ASC	6	7.3	11.8	4.1	6.0
E	52.5(*1)	210(*1)	ASC	6	2.2	1.4	2.5	2.2
F	127	723	ASC	6	6.0	3.3	4.6	7.4
G	112	510	ASC	5	4.6	4.2	2.9	5.2
H	90	565	ASC	8	10.2	4.3	5.9	14.5
I	66	348.2	ASC	5	7.9	−	11.4	4.6
J	119.5	419.5	DSC	6	6.3	6.5	5.5	6.7
K	158	520	DSC	10	6.9	−	6.0	7.0
L	127.5	366	DSC	7	4.4	−	4.6	4.2
M	83	420	ASC	8	3.3	−	3.1	3.4
N	35	244	DSC	15	14.7	7.4	8.9	23.8
O	35(*1)	330(*1)	ASC	8	3.4	3.6	4.4	2.3
P	91.7	260	ASC	8	4.6	−	7.5	3.1
Q	66	445	ASC	7	2.1	1.7	2.5	1.9
R	66.5	198	ASC	7	2.0	−	1.5	2.1
S	37	500	DSC	6	4.3	5.0	3.8	3.1

*1 : Rockfill dam part of combined dam.
“-“ means no existing geodetic measurement data has been obtained.

3. CONCLUSION

With the aim of carrying out a development of satellite SAR-based external deformation measurement of rockfill dams, this paper focused on nineteen rockfill dams in Japan. A total of 135 scenes of satellite SAR data was used over a period of nearly two years from late 2014 to early 2016 for study. External deformations of nineteen rockfill dams were measured by satellite SAR and compared with existing GPS or electro-optical survey data. The average RMSE of nineteen rockfill dams between SAR and existing geodetic measurements was about 5 mm. As earthquake induced settlement up to several centimeters was also well measured by satellite SAR data, satellite SAR data is useful both in normal times and after earthquakes. In order to conduct accurate external deformation measurements using satellite SAR data, it is important for us to pay attention to factors that cause reduction of the accuracy such as ground surface vegetation.

Because we find that the satellite SAR based external deformation measurement of rockfill dams is accurate and useful, we will continue our research to put our research results into practical use.

ACKNOWLEDGEMENTS

This research has been supported by the Strategic Innovation Promotion Program (SIP) of the Cabinet Office, Government of Japan. We would like to thank to dam management offices in Japan which provided valuable data for our research.

REFERENCES

[1] EMADARI L., MOTAGH M., HAGHIGHI M.H. Characterizing post-construction settlement of the Masjed-Soleyman embankment dam, Southwest Iran, using TerraSAR-X SpotLight radar imagery, *Engineering Structures*, 143, pp.261–273, 2017.

[2] GRAZANIC G., LIER O., EKSTROM I., LARSEN Y., LAUKNES T.R. Adopting remote sensing dam surveillance, *82nd Annual Meeting of ICOLD*, pp. 688-697, 2014.

[3] HANSSEN R. Detecting instabilities in dams using satellite radar interferometry, *81st Annual Meeting of ICOLD*, 2013.

[4] LAZECKY M., BAKON M., PERISSIN D., PAPCO J., GAMSE S. Analysis of dam displacements by spaceborne SAR interferometry, *85th annual meeting of ICOLD*, 2017.

[5] MILILLO P., BÜRGMANN R., LUNDGREN P., SALZER J., PERISSIN D., FIELDING E., BIONDI F., MILILLO G. Space geodetic monitoring of engineered structures: The ongoing destabilization of the Mosul dam, Iraq. *Scientific Reports,* 6, 37408, 2016.

[6] SATO H., SASAKI T., KOBORI T., ENOMURA Y., YAMAGUCHI Y., SATO W., MUSHIAKE N., HONDA K., SHIMIZU N. External Deformation Monitoring of Five Rockfill Dams in the Same Radar Satellite Data, *84th annual meeting of ICOLD*, 2016.

[7] SATO H., SASAKI T., KONDO M., KOBORI T., ONODERA A., YAMAGUCHI Y., YOSHIKAWA K., SANGO D., MORITA Y. Deformation monitoring of rockfill dams in normal times and after earthquakes using satellite SAR data, *85th annual meeting of ICOLD*, 2017.

[8] WANG T., PERISSIN D., ROCCA F., Liao M.S. Three Gorges Dam stability monitoring with time-series InSAR image analysis, *Science China Earth Sciences*, Vol. 54, No. 5, pp. 720-732, 2011.

[9] Japan Aerospace Exploration Agency (JAXA), Advanced Land Observing Satellite 2 (ALOS-2), http://global.jaxa.jp/projects/sat/alos2/.

[10] Geospatial Information Authority of Japan (GSI). Synthetic Aperture Radar Interferometry, http://vldb.gsi.go.jp/sokuchi/sar/index-e.html.

[11] BERARDIO P., FORNARO G., LANARI R. and SANSOSTI E. A New Algorithm for Surface deformation Monitoring Based on Small Baseline Differential SAR Interferograms, *IEEE transaction on geoscience and remote sensing*, Vol. 40, No. 11, pp.2375-2383, 2002.

SUMMARY

It is important to develop a new method of effective and efficient monitoring of dams such as external deformation measurement of embankment dams. External deformations of nineteen rockfill dams in Japan using satellite SAR data were measured in about two years, and the results of external deformations using SAR data were compared with those by GPS or electro-optical survey data. We found that the results of external deformations using satellite SAR data agreed well with those by existing geodetic data and the average error of the external deformations between SAR and existing measurements was about five millimeters. Although external deformation monitoring of rockfill dams using satellite SAR data is generally accurate, it is important to pay attention to factors that cause reduction of the accuracy of satellite SAR based deformation monitoring such as ground surface vegetation.