Measurement Accuracy of External Deformation of Rockfill Dam by PSInSAR Analysis Using Sentinel-1 SAR Data

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Abstract *The external deformation measurement of a rockfill dam is one of the most critical measurements for dam maintenance as it enables the evaluation of the behavior of an entire embankment. Permanent Scattering interferometry (PSInSAR) analysis was applied to obtain highly accurate measurements solely for the displacement of permanent scattering points. The surface of a rockfill dam is covered with a rock material called a riprap, which can obtain many permanent scattering points. The PSInSAR analysis requires extensive SAR data to be observed under the same conditions. Sentinel-1 SAR data were employed, with a substantial amount of data available at intervals of 12 days (6 days considering a two-unit system) under the same conditions. Displacement measurements using PSInSAR analysis were carried out on a large rockfill dam with annual displacements of up to approximately 10 mm and six large rockfill dams with annual displacements of up to approximately 2 mm using Sentinel-1 SAR data for approximately six years from 2017 to 2022 for the ascending and descending orbits, respectively. The accuracy of PSInSAR analysis was evaluated by comparing the external deformations with the survey. The accuracy of displacement measurement by PSInSAR analysis is on the order of millimeters, with numerous permanent scattering points obtained over the entire dam embankment. The results indicate that PSInSAR analytical measurements are effective for maintaining and managing rockfill dams.*

Keywords : Rockfill dam, Deformation monitoring, PSInSAR, C-band SAR, Sentinel-1

Introduction

Many studies have used synthetic aperture radar (SAR) to measure the displacement of structures and ground surfaces in order to maintain and manage infrastructure facilities[1)~6)]. Among the measurements for the maintenance of a rockfill dam, the measurement of external displacement is one of the most important ones because it can evaluate the behavior of the entire dam embankment. In Japan, after the behavior of a rockfill dam has reached a stable state, measurements of external deformation are conducted once every three months to confirm the Dam's behavior.

In this study, PSInSAR analysis using Sentinel-1 SAR data was conducted for a rockfill dam that has been continuously measuring an external displacement of up to approximately 10 mm per year, even though it is already in the stabilization phase. In addition, PSInSAR analysis was conducted for six rockfill dams that were displaced up to approximately 2 mm per year. The displacement accuracy obtained from satellite SAR data was verified by comparing the analysis results with the surveyed data.

Study Dam and External Deformation Surveying

The rockfill dams of the TEPCO RP, listed in Table 1, were studied. The most recent dam M was constructed 19 years ago and the next most recent dam M was constructed 24 years ago.

The external deformation of dam M was measured continuously (eight times a day) using a total station, surveying instrument with a built-in rangefinder function, and longitude and latitude measuring instrument after its completion until March 2021. The external deformation measurements of dams A to F were conducted four times a year, using level surveying in the vertical direction and sight surveying in the upstream and downstream directions. The number of external deformation measurement points is listed in Table 1, ranging from 12 to 26, depending on the size of the dam.

Table 1 : Study dam and external deformation surveying

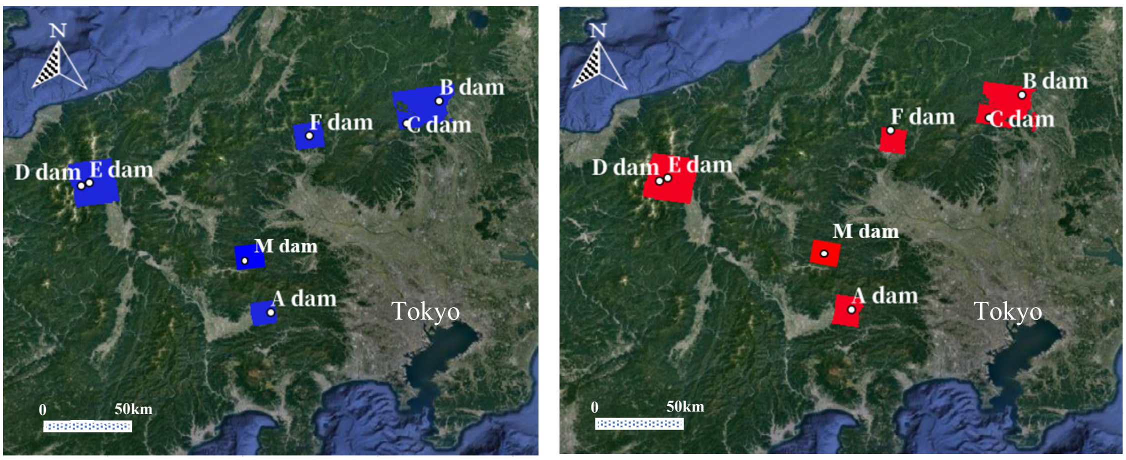
Dam	Dam type	Height (m)	Length (m)	Year of completion	External deformation surveying		
					Frequency	Number of Measurement Points Total number and number from the top row	
M dam	Central Soil Barrier	136	444	2005	every day	22	7,1,5,1,4,1,3
A dam	Central Soil Barrier	87	494	1999	four times a year	15	5,5,3,2
B dam	Surface Barrier	90.5	263	1994	four times a year	15	7,3,3,2
C dam	Central Soil Barrier	97.5	340	1988	four times a year	12	4,3,3,2
D dam	Central Soil Barrier	176	362	1978	four times a year	26	6,6,6,4,4,
E dam	Central Soil Barrier	125	340	1978	four times a year	15	5,5,5
F dam	Central Soil Barrier	116	570.1	1977	four times a year	19	8,5,4,2

Analysis Method and Data

PSInSAR analysis, which is a time series analysis using satellite SAR data, estimates the time changes of displacement with high accuracy using the time changes of phase in pixels with little noise, called PS (Persistent Scatterer) points. Since the riprap on the outer surface of a rockfill dam is well reflected by radar and many PS points can be obtained over the entire outer surface of the rockfill dam, PSInSAR analysis can be carried out to evaluate the behavior of the entire dam embankment.
StaMPS (Stanford Method for Persistent Scatterers) [7)～13)] developed by Andrew Hooper et al. at Stanford University was used for the PSInSAR analysis.

Table 2 : Sentinel-1 SAR data

Dam	Orbit	Study data		Snow Effects	Final Use
		Period	Number of Scenes		
M dam	Ascending	2017/4/1 ～2021/12/12	137	15	122
	Descending	2017/4 ～2021/8	132	22	110
A dam	Ascending	2017/4/1 ～2022/12/12	136	2	134
	Descending	2017/4/12 ～2021/12/30	159	3	156
B・C dam	Ascending	2017/4/1 ～2021/12/12	136	32	104
	Descending	2017/4/19 ～2021/8/20	132	22	110
D・E dam	Ascending	2017/4/6 ～2021/12/17	117	46	71
	Descending	2017/3/31 ～2021/12/30	160	58	102
F dam	Ascending	2017/4/1 ～2021/12/12	136	52	84
	Descending	2017/4/12 ～2021/12/30	159	61	98



(a)Ascending (b) Descending

Figure 1 : Analysis area

The C-band (wavelength: 5.6 cm) Sentinel-1 SAR data ascending and descending at intervals of 12 days for approximately five years were used, as shown in Table 2. The final data excluded those affected by snow cover. Figure 1 shows the locations of the seven dams and the PSInSAR analysis area. The relationship between the dam axis and the east-west direction is shown in Table 3 and Figure 2. The DEM was a 5m×5m mesh numerical elevation model from the Geospatial Information Authority of Japan.

Table 3 : Relationship between east-west direction and dam axis

Dam	Type of relationship between east-west direction and dam axis	Angle A(°)	Direction of downstream slope
M dam	Vertical	115	west
A dam	Parallel	8	west
B dam	Between horizontal and vertical	40	east
C dam	Between horizontal and vertical	52	west
D dam	Between horizontal and vertical	60	east
E dam	Vertical	104	east
F dam	Parallel	13	west

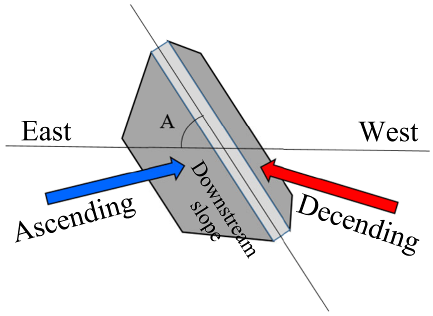


Figure 2 : Relationship between dam axis and east-west direction

Conversion of surveyed values to satellite line-of-sight displacements and RMSE

The displacement obtained by PSInSAR analysis is the displacement in the line-of-sight direction between the satellite and Earth's surface.

The displacements in the satellite line-of-sight direction of the ascending and descending PS points are expressed as $d_{LOS(A)}$ and $d_{LOS(D)}$, respectively, as shown in the equation below, where the direction closer to the satellite direction is positive.

$$d_{LOS(A)} = -\ d_{North} \sin\theta_a\ \sin\beta_a - d_{East} \sin\theta_a \cos\beta_a + d_{Vertical} \cos\theta_a \quad (1)$$

$$d_{LOS(D)} = -\ d_{North} \sin\theta_d\ \sin\beta_d + d_{East} \sin\theta_d\ \cos\beta_d + d_{Vertical} \cos\theta_d \quad (2)$$

Where d_{North} is the displacement in the north-south direction, d_{East} is the displacement in the east-west direction, $d_{Vertical}$ is the vertical displacement, θ is the angle of incidence, and β is the angle between the south and north and the satellite flight direction.

The Root Mean Squared Error (RMSE) was calculated to evaluate the error in the PSInSAR analysis results. The RMSE is defined by the following equation, where $d_{sur,i}$ is the surveyed value, and $d_{PSI,i}$ is the displacement from the PSInSAR analysis.

$$\mathrm{RMSE} = \sqrt{1/n\ \ \Sigma\ (d_{PSI,i} - d_{sur,i})^2} \quad (3)$$

The displacements from the PSInSAR analysis were compared with the surveyed values on a day close to the day of the observation. Although PSInSAR analysis can accurately measure displacements, it cannot completely eliminate errors owing to atmospheric effects. Therefore, the displacements were evaluated using moving average values (three data). However, if there is a possibility of discontinuous displacement owing to seismic effects, the moving average is evaluated as a reference.

PSInSAR Analysis Results

a. PS Points

The locations of the PS points for dam M are shown in Figure 5, dam A in Figure 7, and dams B to F in Figure 9. For all seven dams, many PS points were obtained over the entire external surface of the dam, and PSInSAR analysis using satellite data could be used to measure the external surface deformation of the dam from an areal perspective.

The number and density of PS points obtained for each dam are listed in Table 4. The number of PS points were obtained ranged from 136 to 880 points and the density of PS points ranged from 0.4 to 1.1 per 100 m^2.

Table 4 : Number and density of PS points

Dam	Ascending		Descending	
	Number of PS points	Density of PS points (Per 100 m^2)	Number of PS points	Density of PS points (Per 100 m^2)
M dam	280	0.5	340	0.6
A dam	407	0.6	386	0.6
B dam	136	0.4	246	0.7
C dam	289	0.9	373	1.1
D dam	880	1.0	530	0.6
E dam	577	0.9	355	0.5
F dam	571	1.0	378	0.7

b. Average annual displacement in satellite line-of-sight direction

The satellite line-of-sight annual mean displacement of dam M is shown in Figure 5, dam A in Figure 7, and dams B to F in Figure 9. The annual mean displacement of the PSInSAR analysis was measured as a greater displacement at higher points in the center of the dam and a smaller displacement from the center of the dam closer to the left and right banks, indicating that the behavior of the entire dam was measured with high accuracy.

The displacement of the downstream slope of a dam generally occurs with subsidence, as well as downstream displacement. The displacement in the line-of-sight direction of the ascending orbit of the satellite is due to subsidence away from the satellite for dams M, A, C, and F, which is canceled out by displacement downstream closer to the satellite. The displacement in the line-of-sight direction of the descending orbit for dams B, E, and D is the subsidence away from the satellite, which is canceled by the displacement downstream of the approaching satellite.

Figure 3 shows the relationship between the satellite line-of-sight displacement obtained from the PSInSAR analysis and the surveyed values at the surveyed location where external deformation was measured at dam M. The RMSE was about 0.9 mm/year that means that the error is less than ±0.9 mm/year with a 69% probability, that the error is less than ±1.5 mm/year with a 90% probability, and that the error is less than ±1.8 mm/year with a 95% probability.

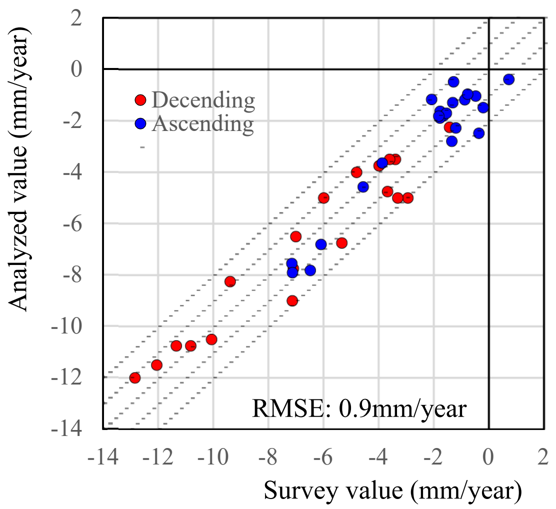


Figure 3 : Satellite line-of-sight annual mean displacement of dam M

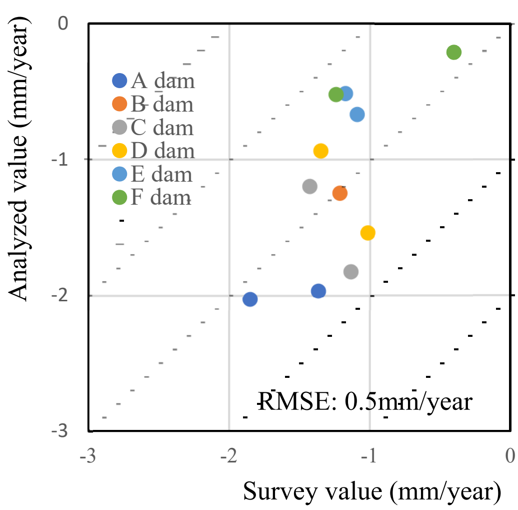
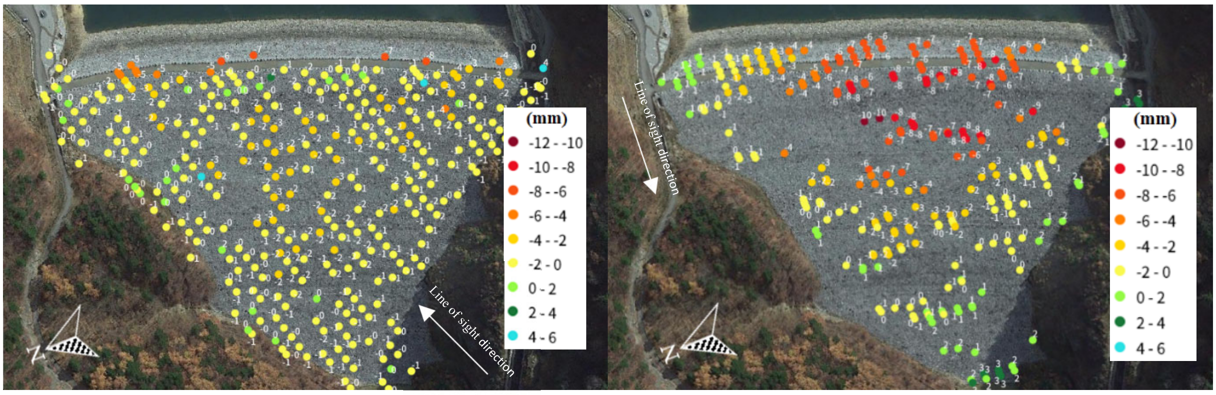
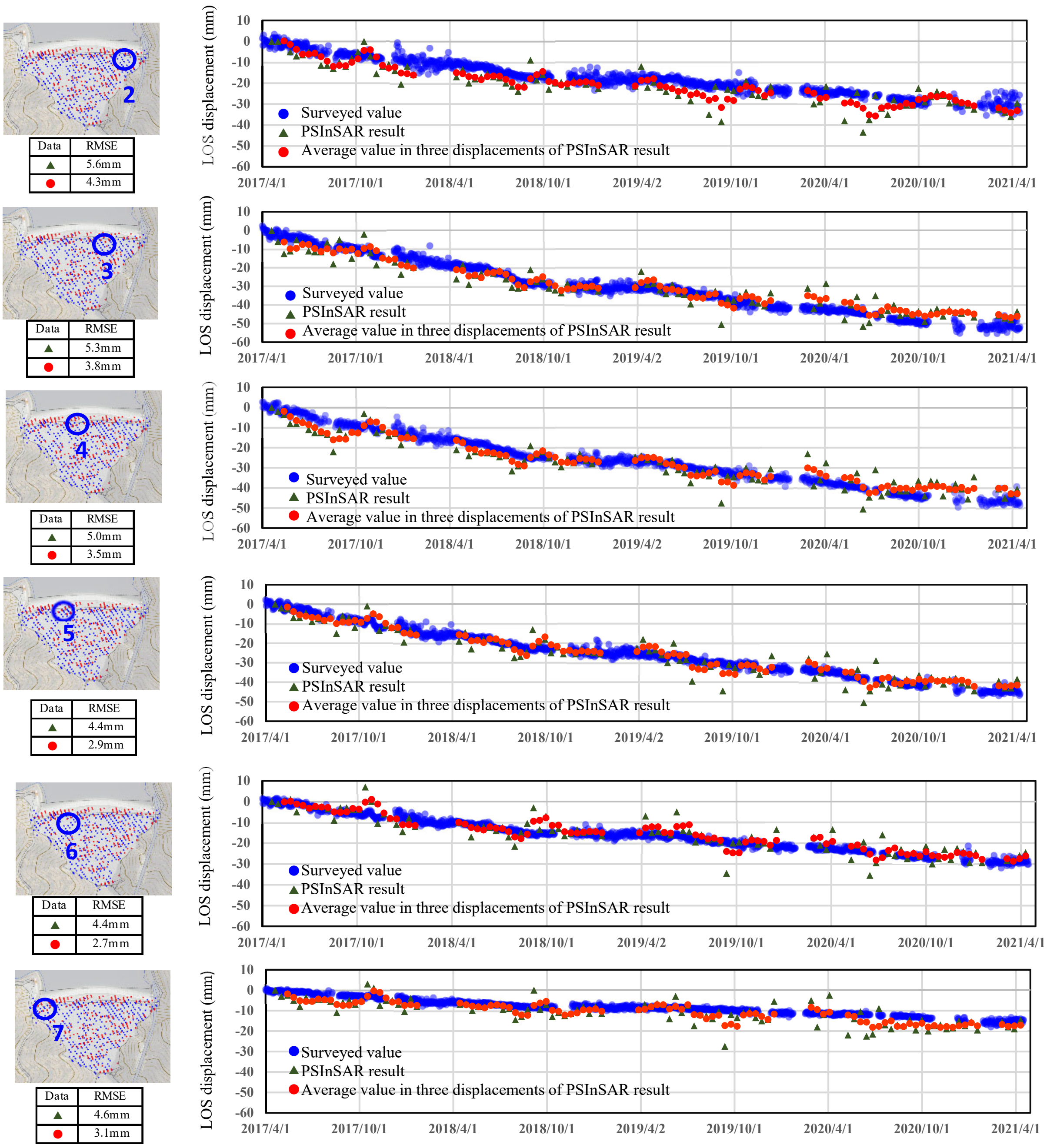


Figure 4 : Satellite line-of-sight annual mean displacement of dams A to F



(a)Ascending (b) Descending

Figure 5 : Satellite line-of-sight annual mean displacement of dam M



Data	RMSE
▲	5.6mm
●	4.3mm

Data	RMSE
▲	5.3mm
●	3.8mm

Data	RMSE
▲	5.0mm
●	3.5mm

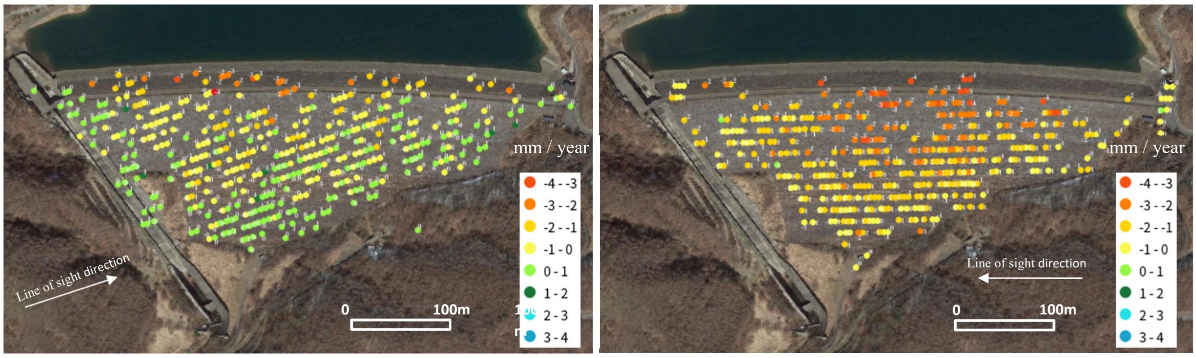
Data	RMSE
▲	4.4mm
●	2.9mm

Data	RMSE
▲	4.4mm
●	2.7mm

Data	RMSE
▲	4.6mm
●	3.1mm

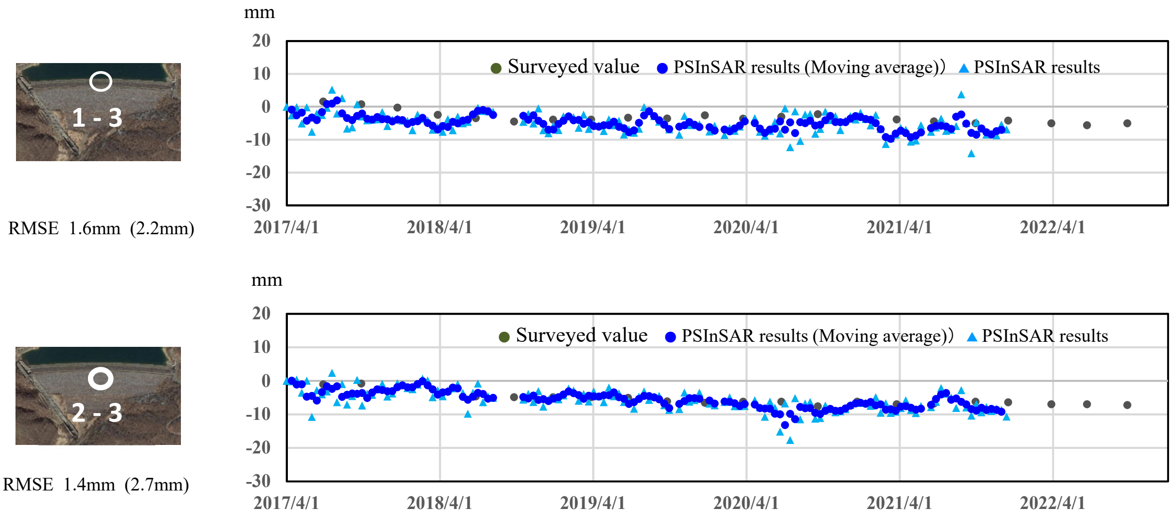
Figure 6 : Satellite line-of-sight displacements of the PS points with surveyed values (dam M)

Figure 4 shows the relationship between the satellite line-of-sight displacement obtained from the PSInSAR analysis and the surveyed values at the surveyed location, where the external deformation was measured at two relatively large displacement points at dams A to F. The RMSE is approximately 0.5 mm/year. As shown in Figure 4, the annual average displacement of dams A to F, where the displacement is small, can also be measured with high accuracy.

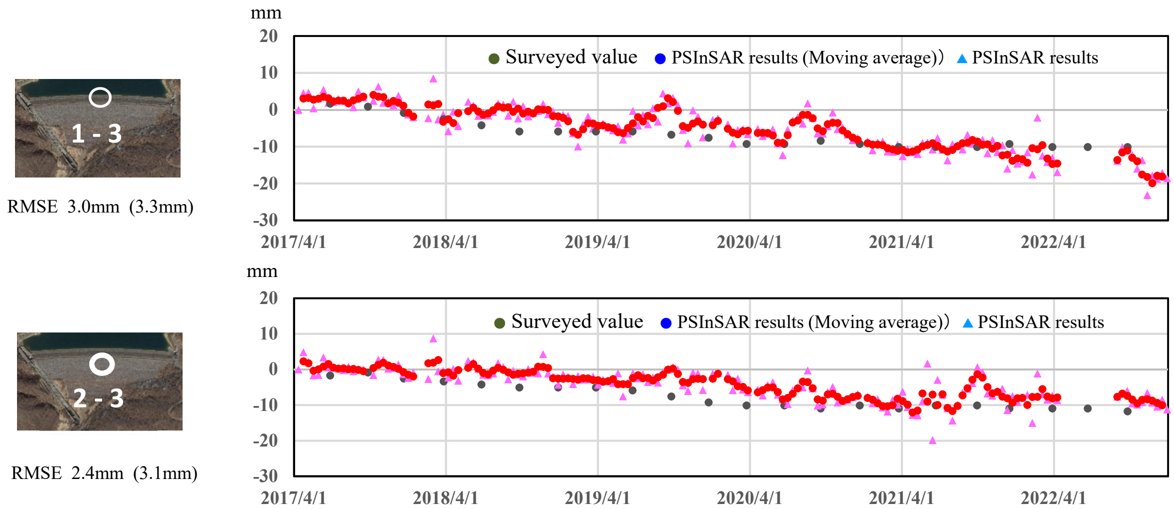


(a)Ascending (b) Descending

Figure 7 : Satellite line-of-sight annual mean displacement of dam A

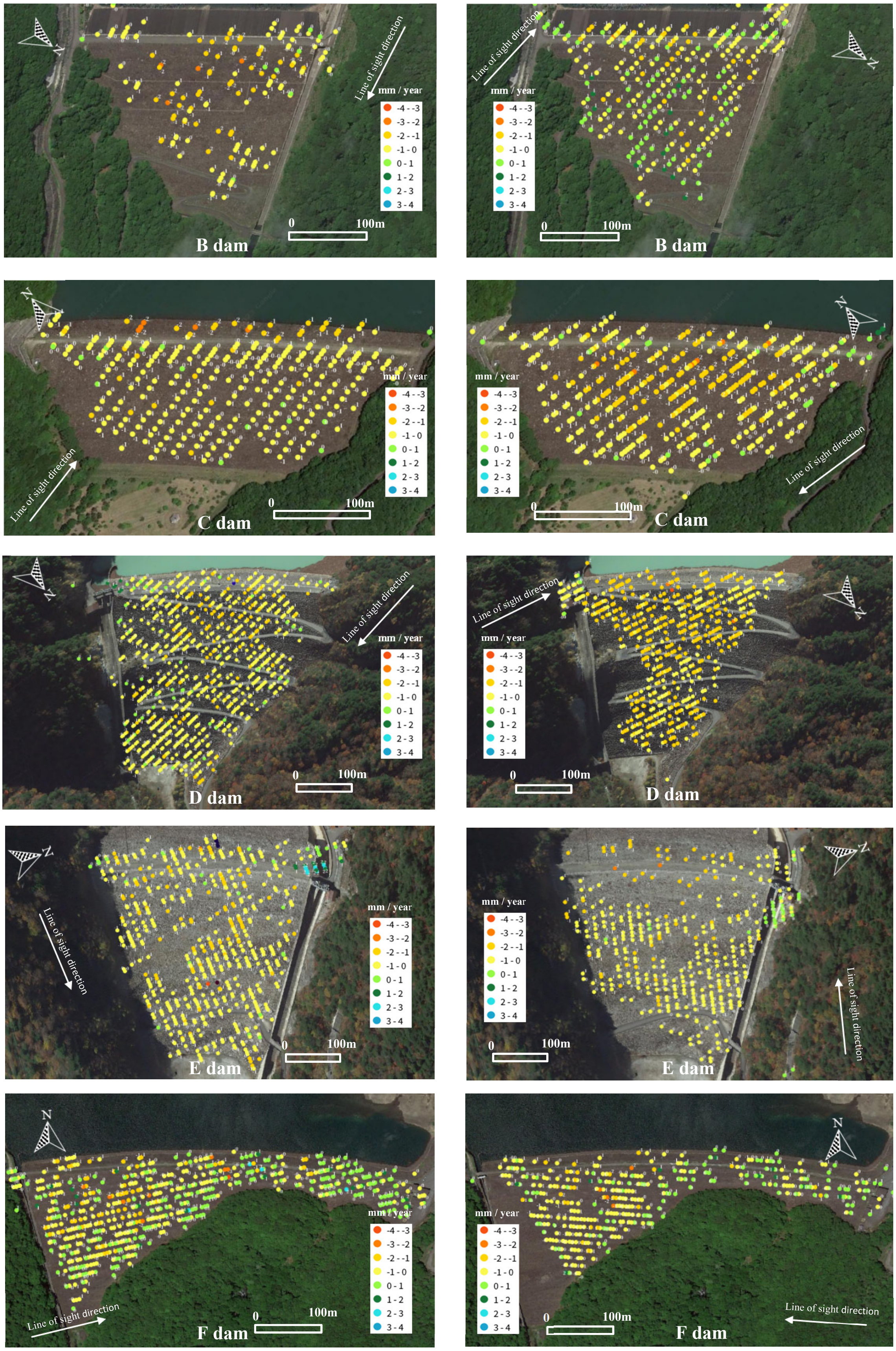


(a)Ascending



(b) Descending

Figure 8 : Satellite line-of-sight displacements of the PS points with surveyed values (dam A)



(a)Ascending (b) Descending

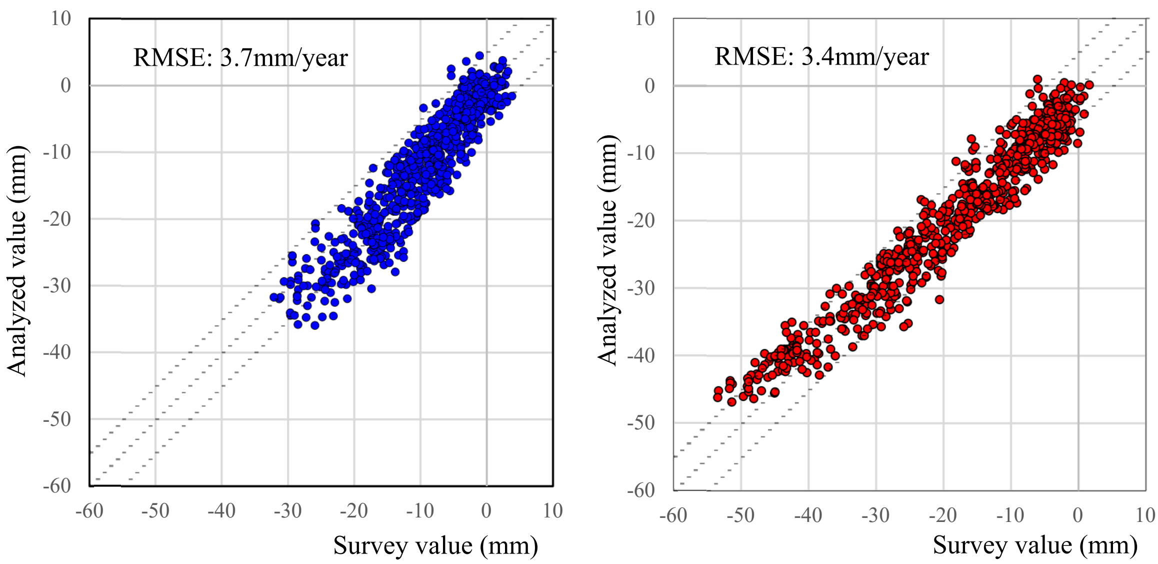
Figure 9 : Satellite line-of-sight annual mean displacement

c. Measurement accuracy of external deformation of dam M by PSInSAR Analysis

The changes over time in the displacements of the PS points for the descending orbit at six locations in the upper-central part of dam M, where the displacements are large, with the surveyed values, are shown in Figure 6. At survey points 3 and 4 near the center of the dam, a cumulative displacement of approximately 50 mm over a four-year period was confirmed from the survey, and PSInSAR analysis was able to measure this displacement change. At survey points 2 and 7, which are located near the left and right banks of the dam, the cumulative displacements were approximately 30 mm and 20 mm, respectively, and the PSInSAR analysis was able to measure this displacement change as well. The moving average RMSE of these six points ranges from 2.7 to 4.3 mm, indicating that the displacement measurements are on the order of millimeters by PSInSAR analysis.

The relationship between the displacement in the satellite line-of-sight direction between the surveyed and analyzed values from the PSInSAR analysis is shown in Figure 10. The satellite line-of-sight displacements shown in Figure 10 for both the ascending and descending orbits are based on four years of data at 12-day intervals at seven surveyed locations of the dam top. The moving average RMSEs for ascending and descending orbits are 3.7 mm/year and 3.4 mm/year, respectively.

The RMSE at each PS point at dam M ranged from 3 mm to 5 mm, confirming that the PSInSAR analysis using Sentinel-1SAR data can measure displacement with high accuracy on the order of millimeters.



(a) Ascending (b) Descending

Figure 10 : Satellite line-of-sight displacement

d. Measurement accuracy of external deformation of dams A to F by PSInSAR Analysis

The changes over time in the displacements of the PS points for ascending and descending orbits at two locations in the upper central part of dam A, where the displacements are large, with surveyed values, are shown in Figure 8. At survey points of No. 1-3 and 2-3 in near the center of the dam, a cumulative displacement of approximately 10 mm over a five-year period for the descending orbit was confirmed from the survey, and PSInSAR analysis could measure this displacement change. The moving average RMSE of these points ranges from 1.4 mm to 3.0 mm, indicating that the displacement measurements are on the order of millimeters by PSInSAR analysis.

The annual mean displacements in the satellite line-of-sight direction of the PS points in the ascending and descending orbits of dams C to F are shown in Figure 9. The displacements of dams C to F are smaller than those of dams M and A, because they have been completed for a longer period of time.

The displacements of the ascending and descending orbits in the satellite line-of-sight direction tend to increase with height and from the left and right banks to the center of the dam, indicating that the behavior of the dam embankment could be properly monitored.
Table 5 shows the RMSE of the displacement of the PS points for the ascending and descending orbits at the two survey points from the upper-central part of dams C to F, where the displacement is large. The RMSE of the moving average of the satellite line-of-sight displacement for the ascending and descending orbits ranges from 1.4 to 3.8 mm, confirming that the displacement can be measured accurately even at dams with small displacements.
The relationship between the displacement in the satellite line-of-sight direction of the surveyed values and the analyzed values from the PSInSAR analysis is shown in Figure 12. The satellite line-of-sight displacements shown in Figure 12 are based on approximately six years of data at 12-day intervals at two surveyed locations on the top of the dam. The RMSE of dams A to F is 3.1 mm/year.
Similar to dam M, the RMSE at each PS point from dams A to F ranged from 3 mm to 5 mm, confirming that the PSInSAR analysis using Sentinel-1SAR data can measure displacement with high accuracy on the order of millimeters.

Table 5 : Root mean square error at surveyed locations for dams C o F

Dam	RMSE (mm)							
	Ascending				Descending			
	Uppermost center		Upper center		Uppermost center		Upper center	
	Moving average	Analyzed value	Moving average	Analyzed value	Moving average	Analyzed value	Moving average	Analyzed value
B dam	1.6	2.2	1.4	2.7	3.0	3.3	2.4	3.1
C dam	2.1	2.6	2.6	2.9	3.0	4.0	2.9	3.8
D dam	1.6	2.2	1.4	2.7	3.0	3.3	2.4	3.1
E dam	1.6	2.2	1.4	2.7	3.0	3.3	2.4	3.1
F dam	2.0	3.3	2.5	3.0	3.8	4.3	4.5	5.0

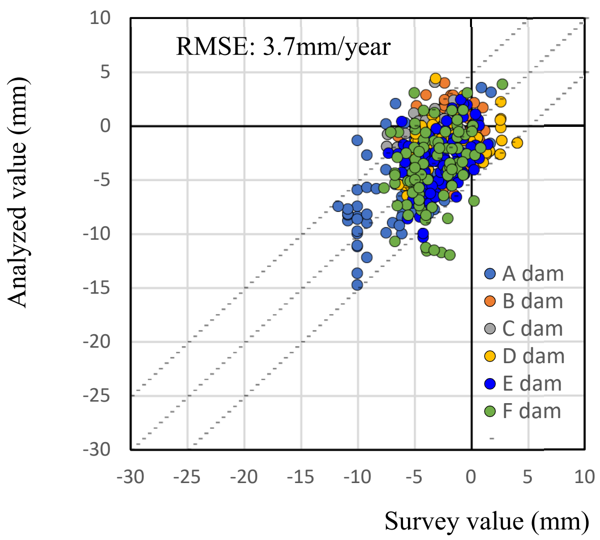


Figure 12: Satellite line-of-sight displacement of dams A to F

Conclusion

The accuracy of measuring the external deformation of rockfill dams by PSInSAR analysis using Sentinel-1 SAR data was verified by comparing the results of the PSInSAR analysis with survey results for seven rockfill dams. The study dams were rockfill dams with a maximum annual displacement of approximately 10 mm that was surveyed daily, and six rockfill dams with a maximum annual displacement of approximately 2 mm or less were surveyed four times a year. Sentinel-1 SAR data used for PSInSAR analysis were collected for approximately six years from April 2017 to December 2021, excluding data affected by snow cover, with 71 to 156 scenes for ascending and descending orbits. The measurement accuracy and points to note for measuring the external deformation of rockfill dams via PSInSAR analysis using Sentinel-1 SAR data are presented below.

- Because the riprap of rockfill dams has good radar reflection characteristics, a large number of PS points were obtained for seven dams in this study. Therefore, the PSInSAR analysis can be used to measure the areal displacement of the outer surface of the dam embankment.
- The annual mean displacement of the PSInSAR analysis was measured as a greater displacement at higher points in the center of the dam and a smaller displacement from the center of the dam closer to the left and right banks, indicating that the behavior of the entire dam was measured with high accuracy.
- The results of the accuracy verification of the rockfill dam, which displaces up to about 10 mm per year and was measured by daily surveying, show that the RMSE of the average annual displacement is 0.9 mm/year, and the RMSEs of the overall data are 3.4 mm and 3.7 mm for the ascending and descending orbits, respectively. The RMSE at each PS point can be measured with high accuracy in the order of millimeters, ranging from 3 mm to 5 mm.
- The results of the accuracy verification of the six rockfill dams, which displaces up to about 2 mm per year and was surveyed four times a year, show that the RMSE of the average annual displacement is 0.5 mm/year, and the RMSE of the overall data is 3.7 mm. The RMSE at each PS point can be measured with high accuracy in the order of millimeters, ranging from 2 mm to 5 mm.
- For the external displacement measurement of the dam using PSInSAR analysis, SAR data on days when the dam was covered with snow were not used.
- To ensure measurement accuracy, the reference point should be appropriately set to a PS point near the reference point of the survey, or at a point where no displacement has occurred.

Considering the measurement accuracy, number of measurement points, and frequency of measurement, it is possible to apply the displacement measurement by PSInSAR analysis to the maintenance and management of rockfill dams.

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