Rock Displacement Monitoring using Satellite Technologies-GPS and InSAR

N. Shimizu*

Yamaguchi University, Ube, Japan * nshimizu@yamaguchi-u.ac.jp

Abstract

Monitoring rock deformations is important to assessing the stability of rock structures, i.e., slopes, tunnels, dams, foundations, etc., to confirm the validity of the design under/after construction and to assist in answering specific questions on a project, etc. In order to perform monitoring successfully, various instruments and systems have been developed. The Global Positioning System (GPS) and Synthetic Aperture Radar (SAR) have the potential for application to displacement monitoring over an extensive area as attractive new monitoring tools in Rock Engineering.

In this paper, outlines of the methods for displacement monitoring using GPS and SAR (InSAR) are described. Practical and trial applications of both technologies to an unstable steep slope, a large landslide occurring due to heavy rains, dam behavior caused by the attack of a large earthquake, and dam deformation monitoring are introduced

Keywords: Displacement Monitoring, GPS, InSAR, Slope, Landslide, Dam

1. Introduction

Monitoring is important for assessing the stability of structures and for confirming the validity of the design during the construction and operation stages. Monitoring is also useful for predicting risks, for managing safe operations, and for reducing project costs. The ideal monitoring system for projects in Rock Engineering should be able to continuously and automatically monitor the behavior of an extensive area in real time and with high accuracy. In addition, the costs should be low and the handling should be easy.

There are various types of instruments for monitoring displacements in Rock and Geotechnical Engineering, such as extensometers, inclinometers, laser distance meters, etc. Although they are useful for monitoring, they can be applied only in local areas. Conventional surveying methods, like electronic distance meters, leveling, etc., are often used in monitoring the behavior of an extensive area. However, they generally require a lot of time, labor, and financial resources. In addition, the measurement accuracy is not sufficient in comparison to that achieved when using geotechnical instruments.

In order to overcome such problems of the conventional methods, modern satellite technologies for navigation/surveys and earth observation, i.e., GPS (Global Positioning System) and SAR (Synthetic Aperture Radar), have begun to be used in the Rock Engineering field. GPS is a space-based satellite system for navigation and long baseline surveys which provides the three-dimensional coordinates of certain locations on or near the Earth. SAR is a kind of radar which is used to create images of a landscape; these images can be two- or three-dimensional representations of the object. Both technologies can be applied to monitor the displacement/deformation of the ground and the surfaces of structures.

This paper provides outlines of the monitoring methods using GPS and SAR, and introduces examples of their applications to monitoring the displacements of slopes, landsides, and dams.

2. Satellite Technology for Rock Displacement Monitoring

2.1 Global Positioning System (GPS)

The Global Positioning System (GPS) is a satellite-based positioning system developed in the USA. It was established as a navigation system and then as a method for long baseline surveys (e.g.,

Hofmann-Wellenhof et al., 2001; Misra and Enge, 2006). GPS can monitor three-dimensional displacements over an extensive area with high accuracy. It began to be used for displacement monitoring in the mid-1980s in the fields of Civil and Mining Engineering and other related fields. Since then, practical applications have been performed by many researchers, and some guidelines have been published for displacement monitoring (e.g., US Army Corps of Engineering, 2002; Vermeer, 2002; Bond, 2004). Recently, the ISRM Suggested Method for Monitoring Rock Displacements using GPS has been published (Shimizu et al., 2014).

There are two methods for using GPS. The first method is point positioning for navigation. The three-dimensional absolute coordinates of a measurement point, namely, latitude, longitude, and height, are obtained instantaneously. The accuracy of the point positioning is approximately a few meters to ten meters or more.

The second method is relative positioning. Relative positioning uses carrier phase measurements and was established for precise surveying. It provides the three-dimensional relative coordinates between two points with the accuracy of millimeters to centimeters. Therefore, relative positioning can be used for monitoring rock displacements. By continuously observing the coordinates of measurement points, the displacements are obtained as changes in the coordinates. The standard deviation of the measurement can be a few millimeters when the baseline length is less than one kilometer and the installation and data corrections are conducted carefully.

The conventional geotechnical measurement devices, i.e., extensioneters, inclinometers, etc., are usually available only for limited areas of several tens of meters at most. Moreover, it is difficult to measure three-dimensional displacements with them. The advantage of GPS is that it can easily provide three-dimensional displacements with high accuracy over an extensive area.

2.1.1 Displacement monitoring using GPS

A GPS displacement monitoring system using an L1 signal was developed by the authors and their associates, as illustrated in Fig. 1 (Iwasaki et al., 2003; Masunari et al., 2003; Shimizu, 1999; Shimizu and Matsuda, 2002). Sensors, composed of an antenna and a terminal box, are set on measurement points and a reference point. They are connected to a control box into which a computer, a data memory, and a network device are installed. The data emitted from the satellites are received at the sensors and then transferred to the control box through cables. The server computer, which is located in an office away from the measurement area, automatically controls the entire system to acquire and then analyze the data from the control box. Then, the three-dimensional displacements at all the monitoring points are obtained. The monitoring results are provided to users on the web through the Internet in real time. A user only needs to access the home page to see the monitoring results.



Fig. 1. GPS displacement monitoring system

2.1.2 Improvement in the accuracy - error corrections

The most important issue in the practical use of GPS is how to improve the measurement accuracy. The ISRM suggested method (Shimizu et al., 2014) recommends that appropriate error-correction methods be applied to reduce both bias errors and random errors. Generally, measurement value u is composed of exact value u_0 , bias errors ε_p and ε_T and random error ε_R .

$$u = u_0 + \varepsilon_p + \varepsilon_T + \varepsilon_R \tag{1}$$

The typical bias errors in GPS are the signal disturbance, ε_p , caused by obstructions above the antennas, and errors due to tropospheric delays, ε_T . Tropospheric delays occur when signals from the satellite reflect in the atmosphere due to meteorological conditions (Hofmann-Wellenhof et al., 2001; Misra and Enge, 2006). The delay of such signals causes a large error. This is one of the most difficult errors to reduce in monitoring using GPS.

The ISRM suggested method shows that signal disturbances due to obstructions above the antennas can be reduced by the mask procedure, and that errors due to tropospheric delays can be corrected by a tropospheric model using meteorological data. After removing the bias errors from the measurement value, an appropriate statistical model is applied to estimate the exact displacement. The authors used *"the trend model"* (Kitagawa and Gersch, 1984) for this purpose (Shimizu, 1999; Shimizu and Matsuda, 2002).

The above error-correction process can provide monitoring results that are a few times higher in accuracy than the standard GPS (Shimizu, 2009; Shimizu et al., 2011).

2.2 Synthetic Aperture Radar (SAR)

SAR is mounted on an aircraft or spacecraft (artificial satellite); it can create high-resolution radar images of the Earth's surface. It irradiates objects on the Earth's surface by microwaves (L-, C-, X-band) and observes the objects by analyzing the reflected signals. As microwaves penetrate through clouds, SAR can observe land surfaces under all weather condition during the day or night (Curlander and McDonough, 1991; Ferretti et al., 2007).

Since the SAR satellite "SEASAT" was launched in 1978 as the first civilian SAR satellite by USA, several satellites, ALOS, Cosmo-SkyMed, ENVISAT, RADARSAT, SENTINEL, TerraSAR-X, etc., have been placed in orbit to monitor the sea and land surfaces by Canada, ESA (European Space Agency), Germany, Italy, and Japan. In order to apply SAR for monitoring ground deformation, Interferometric SAR (InSAR) and Differential InSAR (DInSAR) technologies have been developed.

2.2.1 Displacement monitoring using SAR- Differential Interferometric SAR (DInSAR)

DInSAR is a SAR-based technique used to obtain the deformation of the land surface. It is a method that makes two SAR observations from the same orbit at different periods and identifies the differences in phase between them (Fig. 2). An interferogram, produced by DInSAR, is characterized by the appearance of an interference fringe in response to the phase difference (Fig.2). The phase difference means the displacement between the different periods in the slant range direction (the direction of the radial line between the radar and each object on the Earth's surface) in accordance with the wavelength used for the observation. In the case of ALOS-1 & 2/PALSAR-1 & 2, operated by Japan, the phase difference of one cycle is equivalent to a displacement of about 11.8 cm (half the wave length of the L-band).

The advantage of DInSAR is that it can provide centimeter-scale deformations of the surface of the Earth over an extensive area, hundreds or thousands of square kilometers, and typically achieve a spatial resolution of 10-30m.



Fig. 2. Schematic image of DInSAR (GSI, 2014)

2.2.2 Improvement in accuracy- decreasing noises

The precise Digital Elevation Model (DEM) of the Earth's surface and the precise location of satellites are required to determine the exact deformation of the ground by DInSAR. In addition, the results of DInSAR still include noises due to ionospheric electron density, water vapor pressure in the troposphere, etc. as in GPS.

In order to decrease such noises, an appropriate method should be applied to the time-series of the results (the interferometric data) of DInSAR. Some algorithms for the stacking or filtering of the interferometric data have been proposed to obtain more accurate monitoring deformation by DInSAR (Berardino et al., 2002; Ferretti et al., 2011).

2.3 Comparison of GPS and InSAR

The features of GPS and InSAR are compared in Table 1 (GSI, 2014). GPS can continuously monitor three-dimensional displacements at certain points 24 hours a day with mm accuracy, whereas InSAR can take one-dimensional displacement measurements of much greater areas usually on a monthly basis with cm accuracy in a spatial resolution area of 10-30m. Therefore GPS and InSAR are complementary to each other.

	GPS	SAR	
Required devices for user	Receivers	Not necessary	
Observable displacements	Point(s)	Over an area	
	T Ollit(3)	resolution)	
Continuous monitoring	Possible	Periodic on a monthly basis	
Absolute amount of deformation	Observable	Not obtained directly	
Principle of observation	One way from satellites to receivers	Two ways between satellite and ground surface	
Dimension of measurement	3-dimensional	1-dimensional (the slant-range direction)	
Observation time	Available 24 hours, continuously	Once a few ten days	
Accuracy	mm level	cm level	

Table 1 GPS and InSAR (GSI, 2014. Modified by the author)

3. Practical Applications

In order to demonstrate the applicability of GPS and InSAR for monitoring displacements in practical Rock Engineering projects, three applications for GPS and one for InSAR are illustrated.

3.1 Unstable steep slope

The GPS displacement monitoring system (see Fig. 1) is applied to monitor the displacements of an unstable steep slope along a national road in Japan (Furuyama et al., 2014).

3.1.1 Monitoring points

Figure 3 presents photographs of the slope and the monitoring area. The slope is composed of mainly tuff and sandstone, and its bedrock is granite. The surface is covered with a colluvial deposit. The left side of the slope, as seen in the photograph of Fig. 3(a), has been gradually failing over the last 20 years, and a concrete rock-shed tunnel has been constructed to cover the road and to protect it.

Two antennas were set at the top of the slope to monitor displacements, and another antenna was set at a fixed point in a stable area as a reference point denoted by K-1 beneath the slope (see Fig. 4). The monitoring points, denoted as G-1 and G-2, were set on the left and right sides of the slope, respectively. Three-dimensional displacements were continuously measured every hour using the static method of GPS. The distance between monitoring point G-1 and the reference point K-1 was 221 m, while that between monitoring point G-2 and the reference point was 258 m. The differences in height between the two points and the reference point were 103 m and 112 m, respectively.



(b) GPS sensors at monitoring points, G-1 and G-2



Fig. 3. Monitoring site; slope beside road

(a) Plan view (b) Vertical section Fig. 4. Monitoring points and reference point

3.1.2 Procedure of error corrections

Since both differences in height between the reference point, K-1, and monitoring points, G-1 and G-2, were more than 100 m, the error due to the tropospheric delays of the signal wave from the satellite could not be ignored. In addition, since the trees around the monitoring points have grown and become obstructive above the antennas, they will cause a disturbance to the signals and a decline in measurement accuracy. In order to correct these types of errors, the error-correction methods described in 2.1.2 were applied.

Figure 5(a) shows the original monitoring results obtained from a baseline analysis using the observed wave phase. Although the slope did not move at all during this period, the results were rather wavy and scattered.

As the first step of correction, the signals obtained from the satellites located behind the obstructions above the GPS antenna were not used when analyzing the data. Figure 6 shows a sky photograph, taken from the above monitoring point G-1, of the satellite paths during a certain one-hour period. The numerals represent the satellite numbers, while the arrows show the satellite paths. At this time, the measurement results are largely scattered. This is because satellite numbers 12 and 25 were moving behind some trees and their signals were disturbed. Thus, the data were analyzed without using the data from satellites 12 and 25. Figure 5(b) presents the corrected results. Comparing

the original and the corrected results (Figs. 5(a) and 5(b)), the scattering that appeared in the original results has been significantly improved. Some periodic behavior, however, still remains.

As the second step of correction, an appropriate model was employed to correct the tropospheric delays. The modified Hopfield model (Hofmann-Wellenhof et al., 2001) was adopted to estimate the amount of tropospheric delays. Figure 5(c) shows the results after correcting both the obstructions and the tropospheric delays. Comparing the original and the corrected results (Figs. 5(a) and 5(c)), the scattering and the periodic behavior appearing in the original results have been improved.

Finally, as the third step of correction to reduce random errors, the "trend model" (Kitagawa and Gersch, 1984) was applied to estimate the exact displacement from the monitoring results (Shimizu, 1999; Shimizu and Matsuda, 2002). The solid lines in Fig. 5(d) show the final results. Although some small scattering still exists, it is found from these results that no displacement has occurred during this period.

Comparing the original and the corrected monitoring results (Figs. 5(a) and 5(d)), it can be seen that the original results have been significantly improved through the above error-correction procedure.





- (d) Monitoring results after error corrections
- Fig. 5. Effects of error corrections for GPS displacement monitoring results



Table 2 Standard deviations of measurement

Meas. Point	Latitude(mm)	Longitude(mm)	Height(mm)
G-1	1.6	2.0	4.5
G-2	1.9	1.6	3.6

(Monitoring duration; March 2013 to January 2014)

Fig. 6. Satellite paths on sky photo above sensor at G-1

3.1.3 Monitoring results

The displacement monitoring results at monitoring points G-1 and G-2 are shown with an hourly amount of rainfall in Figs. 6 and 7, respectively. Monitoring was started in the middle of March 2013. The three-dimensional displacements in the direction of latitude, longitude, and height have been continuously measured every hour.

The standard deviations of the measurements at G-1 and G-2 are shown in Table 2. Since the standard deviations of the conventional GPS are 5 mm and 10 mm in the horizontal and vertical directions, respectively, it is shown that the GPS monitoring system and the correction method used here have been successful. Actually, the monitoring results have been obtained continuously and smoothly without missing any results.

Small displacements of less than 2-3 mm/month were generated at monitoring point G-1 during the low rainfall period from March to early June (see Fig. 7). Whenever heavy rain fell from July to October, the displacement gradually increased. Eventually, it reached 355 mm in the north direction, 234 mm in the west direction, and 137 mm in the settlement by the end of October. However, displacements at G-1 gradually converged and became stable after this rainfall period.

On the other hand, no remarkable displacements were measured at G-2 in this period. The right-hand side of the slope is seen to be more stable than the left-hand side.

Figure 8(a) shows the displacement vectors in the plan view of the slope, while Figs. 8(b) and 8(c) show the vertical sections including G-1 and G-2, respectively. Both directions of vectors for G-1 and G-2 almost coincided with the steepest direction of the slope in the plan view. The direction of the displacement at G-1 was toward the front of the slope in the vertical section until the middle of August. After heavy rainfall at the end of August and early September, the direction changed to be parallel to the slip plane of the slope, and it was toward the front of the slope again after the last large displacement occurred on October 23. On the other hand, the direction of the displacement at G-2 is parallel to the slip plane at the top of the slope in the vertical section.

Figure 9 shows the velocity of the displacement (mm/day) calculated from the monitoring displacements. Regulations (criteria) for traffic safety along this road have been given by the government as follows; when the displacement velocity (mm/day) is beyond 10 mm/day and the total amount of continuous rainfall exceeds 100 mm, one lane of the roadway is temporarily closed. And when the displacement velocity (mm/day) is over 20 mm/day and the total amount of continuous rainfall exceeds 200 mm, both lanes of the road are temporarily closed.

The GPS monitoring results could provide effective information for managing traffic safety, comparing them with the above criteria.





Fig. 9. Displacement velocity at monitoring point G-1

3.2 Large-scale landslide due to a heavy rain

A large-scale slope failure occurred in a mountainous area of Western Japan due to a heavy rainfall brought about by a typhoon. It covered an area that was 650 m long, 410 m wide, and 60 m deep, and the volume of the colluvial deposit was estimated to be 4.1 million m³ (Fig. 10). This huge volume of colluvial deposit blocked a river channel and created a natural (landslide) dam. Then, a debris flow occurred due to the erosion of part of the deposit.

In order to prevent the collapse of the landslide dam and the occurrence of further debris flows, disaster recovery works were carried out. The GPS monitoring system was applied to monitor the behavior of the unstable colluvial deposit (Sato et al., 2014).



Fig. 10. Large-scale landslide and unstable colluvial deposit

3.2.1 Monitoring points

GPS sensors were set at 11 measurement points on the slope of the colluvial deposit (denoted by the red bullets; G-1, G-2, ..., G-8) and at a reference point outside of the area, as shown in Fig. 11. The distance between the measurement points and the reference point were about 100 m - 700 m. Electric power was supplied to the communication base system by means of a solar panel, and the measurement data were transmitted via a mobile phone to the computer at the control office. Extensometers were also set in the upper area of the unstable slope, as shown in Fig. 11 (denoted by S-1 to S-4).

3.2.2 Monitoring results

The monitoring results over three years are shown in Fig. 12. These results show that the total amount of displacement in the lower area of the slope (G-1 to G-8 except G-5 in Fig. 12(b)) was not large and ranged from a few millimeters to 34 mm over the three years.

On the other hand, the displacements monitored by GPS and the extensioneters in the upper area of the unstable slope (G-5, and S-1 to S-4 in Fig. 12(b)) increased up to 540 mm to 3353 mm over the three years. The displacements often exceeded the criteria for the suspension of disaster recovery work; at those times, the monitoring center issued a warning for unstable slope conditions. Then, the work was suspended and the people in that vicinity were evacuated to a safe area.



Fig. 11. Plan view of monitoring site and location of GPS sensors



(a) Monitoring displacements and rainfall at G-5 (b) Displacement vectors in plan view Fig.12. Monitoring results

3.3 Rock-fill dam before and after the Great East Japan Earthquake

Exterior deformation is one of the most important items to measure when managing the safety of rock-fill dams. Exterior deformation is usually measured by a conventional surveying method using targets installed on the crest and the slopes of the dams. It is difficult, however, to measure the deformation by such a method immediately after an earthquake or other emergency. GPS displacement monitoring can continuously monitor the deformation of dams during and after earthquakes. This section describes a case study in which GPS monitoring was able to detect displacements of a rock-fill dam before and after the Great East Japan Earthquake (Kobori et al., 2014).

3.3.1 Monitoring points

The GPS monitoring system was applied to Ishibuchi Dam, which is an old concrete-face rock-fill dam completed in 1953 with a height of 53 m. It is located 216 km away from the epicenter of the Great East Japan Earthquake. Figure 13 shows a plan view and a vertical section of the dam with the monitoring points. The sensors were installed at 17 monitoring points (denoted by G-1 to G-17) and 1 point as a reference point (denoted by K-1) (see Fig. 13). The sensors on the dam were fixed to the surface of the concrete facing with anchor bolts.

The measurements were started on June 26, 2008, which was 12 days after the Iwate-Miyagi Nairiku Earthquake and three years before the Great East Japan Earthquake.



(a) Plan view (b) Cross section (Line no. 20) Fig. 13. Dam embankment and layout of GPS sensors

3.3.2 Monitoring results

The monitoring results at G-4, G-9, and G-14 on section line no. 20, which is the maximum section of the dam (Fig. 13), are shown with the water level of the reservoir in Fig. 14. The three-dimensional displacements in the up-downstream, the dam axis, and the vertical direction were continuously measured every hour.

Upon the occurrence of the Great East Japan Earthquake on March 11, 2011 (denoted by "the main shock" in this paper), a seismograph on a right bank terrace recorded a maximum acceleration value of 184 gal. When the largest aftershock occurred on April 7, the acceleration value of 140 gal was recorded by a seismograph in the same place. The broken and dashed-dotted lines in Fig. 14 represent the time of the main shock (2:46 p.m. on March 11, 2011) and the time of the largest aftershock (11:32 p.m. on April 7, 2011), respectively. It is found that the main shock caused displacements of about 11 mm in the downstream direction, about 3 mm in the right bank direction, and about 11 mm in the settlement direction at G-9. The largest aftershock caused displacements of about 2 mm in the settlement direction.

For the other GPS monitoring points, the main shock and the largest aftershock caused similar displacements to those shown in Fig. 14. After the largest aftershock, no remarkable displacement occurred and the displacements gradually decreased and became stable.



Fig. 14. Displacement measurement results of GPS at monitoring points G-4, G-9, and G-14 located on line no. 20 and water level of reservoir (June 1, 2008 to Sept. 25, 2012)

3.3.3 Detection of displacements caused by the earthquake

Figure 15 focuses on the monitoring results at G-9 during the period before and after the main shock. The three-dimensional displacements were measured every hour.

Before the earthquake, the displacements in all directions were almost zero until 14:00 on March 11. The earthquake occurred at 14:46. After 15:00 on the same day, the GPS monitoring system clearly detected displacements due to the earthquake (red bullets in Fig. 15), i.e., a displacement of 10-15 mm in the direction of the downstream side and a settlement of 10-20 mm.

It is proven that continuous monitoring using GPS is quite effective for detecting displacements due to an earthquake immediately after it occurs.



The author has successfully applied the GPS displacement monitoring system to many other projects; e.g., landslides due to tunnel excavations, rock-fill dams, open quarries, monitoring the stability of cut slopes along an expressway, ground mass movements, etc. (Hirano et al., 2011; Nakashima et al, 2011; Shimizu, 2009; Shitano et al., 2014; Tosa et al., 2014).

3.4 External displacement of rock-fill dam observed by DInSAR

DInSAR is usually applied to monitor the deformation over an extensive area of hundreds or thousands of square kilometers. The applicability of DInSAR to monitoring the displacements of a manmade structure, a rock-fill dam, in a small area within a few square kilometers, is investigated (Honda et al., 2014).

3.4.1 Monitoring results by GPS

The Taiho Subdam, located in Okinawa Prefecture, Japan, is employed to investigate the applicability of DInSAR for monitoring the deformation of a rock-fill dam. The height of the dam is 66 m and the length of the crest line (the top of the dam) is 445 m. The exterior deformation was measured using GPS starting in December 2006 (see Fig. 16) (Iwasaki et al., 2012). The maximum displacement was 114 mm at G-12 during the four-year period, and all the measurement points moved in the direction of the downstream and then settled.



(a) Top view

(b) Cross-section view

Fig. 16. GPS observation points and deformation vectors of Taiho Subdam between December 2006 and December 2010

3.4.2 Monitoring results by DInSAR

The data observed by PALSAR-1 (an active microwave sensor) mounted on ALOS-1 (Advanced Land Observing Satellite) were used for the DInSAR analysis, and the results were compared with the results of the GPS displacement monitoring.

As shown in Fig. 17, two observation orbits exist, i.e., ascending and descending orbits. In this study, 14 scenes of descending orbit data from December 6, 2006 to December 17, 2010 and 14 scenes of ascending orbit data from January 12, 2007 to January 23, 2011 were used (Table 3).

DEM (Digital Elevation Model), provided by the Geospatial Information Authority of Japan (GSI), and local DEM of the Taiho Subdam, created by the authors (Honda et al., 2014), were used to remove the topographic phase.



Table 3 Observation dates of SAR data

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

Fig. 17. Location of dam and observation areas with schematic image of ascending and descending orbits

Figure 18 shows the phase differences for each observation date from the first observation date using ascending data, respectively. Looking at point G-12 on the crest of the standard cross section of the dam as an example, the phase difference is seen to change from blue, green, and yellow to red as time progresses. This indicates that point G-12 has moved away from the satellite. In other words, settlements have occurred during the observation period.

The trends in displacement at G-12 in the slant-range direction obtained by DInSAR and GPS are compared in Fig. 19. The results of DInSAR agree well with those of GPS with a discrepancy of only a few centimeters.

Figure 20 shows the relationship between DInSAR (of both ascending and descending orbits) and the GPS monitoring results at all monitoring points (see Fig. 16). The correlation coefficients are around 80% for the results of both ascending and descending orbits, and a high correlation was found between the InSAR and GPS monitoring results.

DInSAR has the potential for application to the monitoring of even artificial structures with areas of a few hundred meters by a few hundred meters.



Fig. 18. Phase differences from first observation on Dec 29, 2006 using ascending data



Fig. 19. Displacements at G-12 monitored by GPS and DInSAR in slant-range direction (ascending orbit)



Fig. 20. Comparison between DInSAR and GPS monitoring results

4. Conclusions

Satellite technologies, i.e., GPS and SAR, for monitoring rock displacements/deformation, have been outlined, and their practical applications have been demonstrated in this paper.

Methods of displacement monitoring using GPS can provide the three-dimensional displacements of rocks automatically and continuously with high accuracy (i.e., mm level) over extensive areas in relation to various kinds of Rock Engineering projects. The ISRM Suggested Method for Monitoring Rock Displacements using GPS has been published, and this technology will be further expanded as a standard tool in Rock Engineering.

SAR is an attractive tool for monitoring the deformation of areas from a few to thousands of square kilometers without the necessity for any devices by the users, and it has already begun to be applied to various problems in Rock Engineering. Although some difficult issues are still encountered when it is used as an practical engineering tool for monitoring, this technology will be widely applied in Rock Engineering in the near future.

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