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Displacement Monitoring Using Satellite Technologies for Risk Management of Slopes and Dams

斜面・ダムのリスク管理のための衛星技術を用いた変位監視

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Monitoring rock displacements is important for assessing the stability of rock masses, for confirming the validity of the design and the construction work, and for understanding the in-situ rock behavior. Modern satellite technologies, i.e., Global Positioning System (GPS) and Synthetic Aperture Radar (SAR), have the potential for application to displacement monitoring over extensive areas as attractive new monitoring tools in Rock Engineering. In this paper, outlines of the methods for displacement monitoring using GPS and SAR (DInSAR) are described. Practical applications of both technologies to an unstable steep slope, rock-fill dams, and land subsidence in an extensive area are introduced.

キーワード：GPS, DInSAR, Displacement monitoring　（IGC：C07, H04, H09）

1. INTRODUCTION

Monitoring is important for assessing the stability of structures and to confirming the validity of the design during the construction and operation the structures. Monitoring is also useful for predicting the risks, for managing the safe operation, and for reducing the 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 only be applied in local areas. In order to overcome the problems of such conventional methods, modern satellite technologies for navigation/survey and Earth observations, i.e., GPS (Global Positioning System) and SAR (Synthetic Aperture Radar), have begun to be used in the field of Rock Engineering. GPS is a space-based satellite navigation/survey system which provides the three-dimensional coordinates of locations on or near the Earth. SAR is a radar device mounted on an aircraft or an artificial satellite. It transmits pulse waves to the Earth's surface and receives the reflections. Both technologies can be applied to monitor the displacement 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 of monitoring the displacements.

2. OUTLINES OF DISPLACEMENT MONITORING USING SATELLITE TECHNOLOGIES

2.1 Displacement monitoring using GPS

GPS is a satellite-based positioning system developed in the USA. It was established as a method for navigation and long baseline surveys [1), 2)]. It consists of two methods, namely, single positioning and relative positioning. GPS can monitor three-dimensional displacements by using the method of relative positioning, especially interferometry GPS. The advantage of GPS is that it can easily provide three-dimensional displacements with mm accuracy over an extensive area.

A GPS displacement monitoring system using an L1 signal was developed by the authors, as illustrated in Figure 1[3)～5)]. 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

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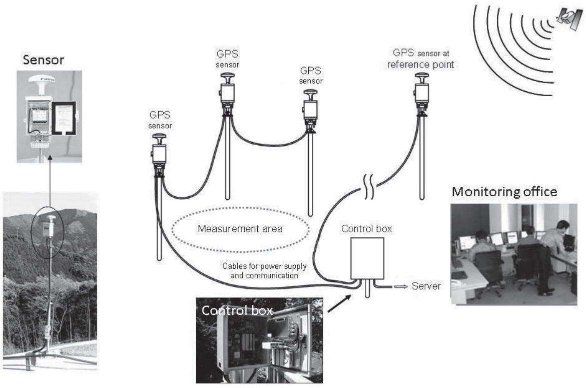


Figure 1: GPS displacement monitoring system

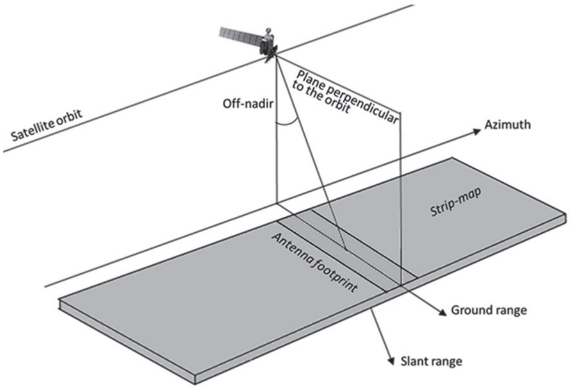


Figure 2: Synthetic Aperture Radar[9].

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.

The most important issue in the practical use of GPS is how to improve the measurement accuracy. The authors and their colleagues have proposed methods for removing errors and estimating the real values of measurements. Those methods succeeded in providing measurements results that are a few times higher in accuracy than the standard GPS[6]. The procedure has been approved as the ISRM suggested method for "Monitoring Rock Displacements Using the Global Positioning System" [7].

2.2 Displacement monitoring using DInSAR

SAR is a radar device mounted on an aircraft or artificial satellite that generates high resolution remote sensing imagery all day and night[8]. Interferometric SAR (InSAR) is a method for taking the signal phase changes (interference) from two scenes of SAR data, which are observed in the same area during different periods by exploiting repeated orbits of the satellite (see Figure 2). Differential Interferometry SAR (DInSAR) is the commonly used term for the production of interferograms from which the topographic contribution has been removed[9]. The advantage of DInSAR is that it can provide centimeter-scale displacements of the surface of the Earth (i.e. the changes in length between the radar and the ground surface) over vast areas of hundreds of square kilometers with a spatial resolution of 3-30 m. In order to obtain the displacements, an appropriate software for the processing system is required.

2.3 Comparison of GPS and DInSAR

The features of GPS and DInSAR are compared in Table1.

Table 1: GPS and InSAR (GSI, 2014. http://vldb.gsi.go.jp/sokuchi/sar/mechanism/mechanism05-e.html. Modified by the authors)

	GPS	SAR
Required devices for user	Receivers	Not necessary
Observable displacements	Point(s)	Entire areas (3-30m spatial resolution)
Continuous monitoring	Every hour, or shorter periods	Periodic - every few weeks/months
Absolute amount of deformation	Observable	Not obtained directly
Dimension of measurements	3-dimensional	1-dimensional
Observation time	Available 24 hours, continuously	Once every few weeks/months
Accuracy	mm level	cm level

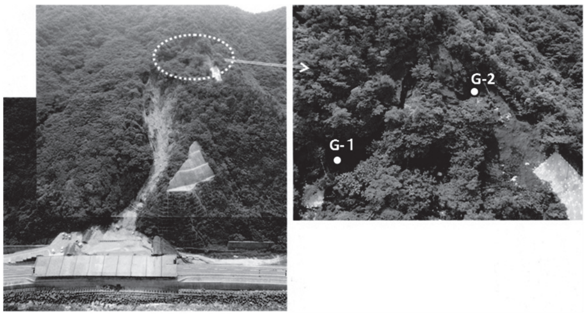
GPS can continuously monitor three-dimensional displacements at certain points 24 hours a day with mm accuracy, whereas DInSAR can take one-dimensional displacement measurements of much greater areas usually once every few weeks/months with cm accuracy in a spatial resolution area of 3-30m. Therefore, GPS and DInSAR are complementary to each other.

3. PRACTICAL APPLICATIONS OF GPS AND DINSAR TO DISPLACEMENT MONITORING

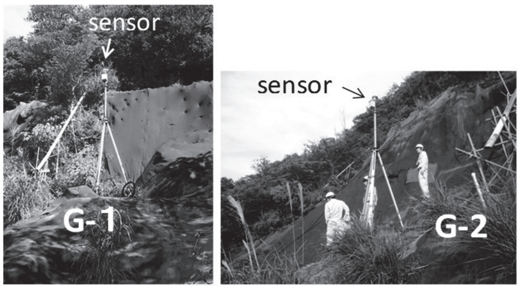
3.1 Application of GPS

3.1.1 Unstable steep slope

The GPS displacement monitoring system (see Figure 1) is applied to monitor the displacements of an unstable steep slope along a road. Since local slope failures have occurred several times over the last 20 years, displacement monitoring has been conducted by borehole inclinometers and surface extensometers. Some of the instruments, however, have

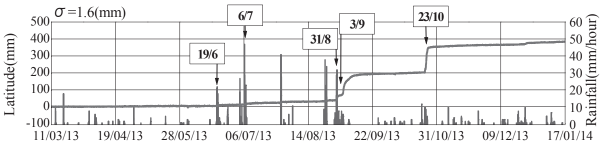


(a) Slope and monitoring area

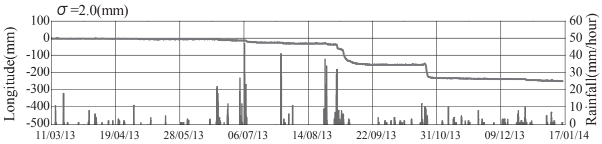


(b) GPS Sensors at G-1 and G-2

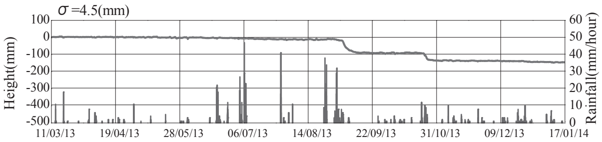
Figure 3: Monitoring site; slope beside road[10)].



(a) Displacement in direction of latitude

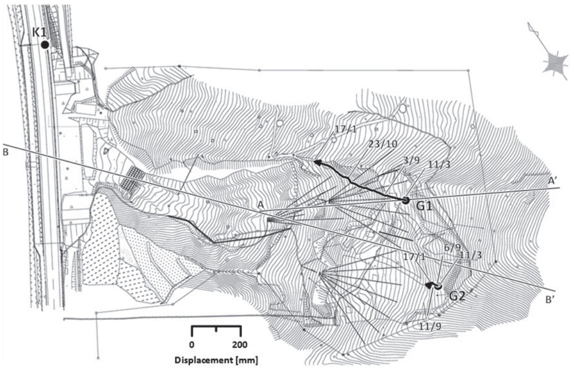


(b) Displacement in direction of longitude

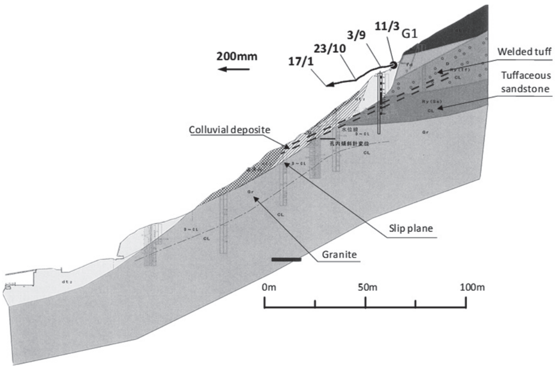


(c) Settlement

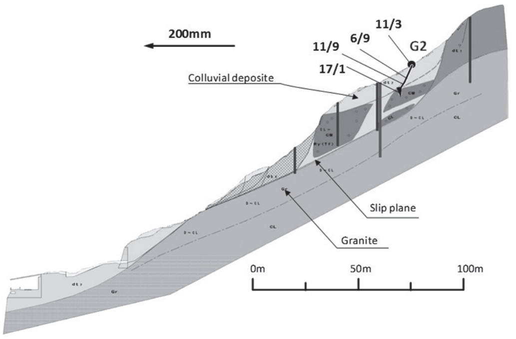
Figure 4: Displacements at measurement point G-1[10)].



(a) Plan view



(b) Section A-A'



(c) Section B-B'

Figure 5: Transitions of displacement vectors[10)].

occasionally not worked well due to large deformations, and it has been difficult to perform the monitoring continuously. In order to overcome such trouble, the GPS monitoring system has been applied for continuous monitoring[10)].

(1) Monitoring site

Figure 3(a) 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 in Figure 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. The monitoring points, denoted as G-1 and G-2, were set on the left and right sides of the slope, respectively (see Figure 3(b)).

The distance between monitoring point G-1 and 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.

(2) Monitoring results

Three-dimensional displacements were continuously measured every hour using the static method of GPS. The

Table 2 Criteria for assessing the stability

	Criteria	Safety Measure
Level 1	Displacement > 10mm/day	One lane of the road is closed
Level 2	Displacement > 20mm/day	Both lanes of the road are closed

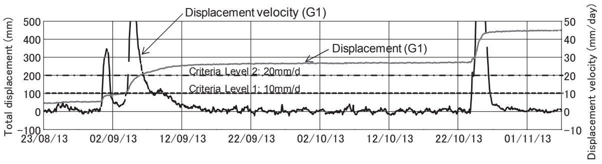


Figure 6: Displacement and velocity (mm/h) at G-1

monitoring results at monitoring point G-1 are shown with an hourly amount of rainfall in Figure 4. 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. 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 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. This means that the right-hand side of the slope is seen to be more stable than the left-hand side.

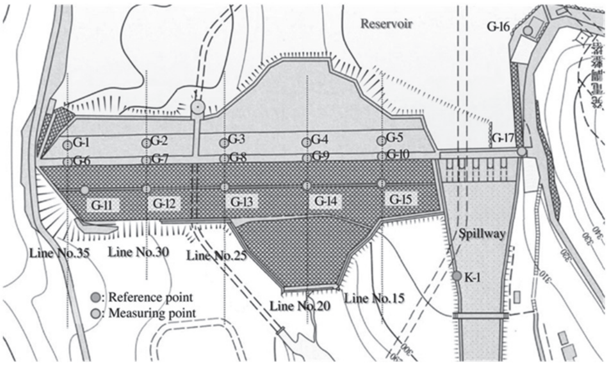
Regulations (criteria) for traffic safety along this road have been given in Table 2. When the displacement velocity (mm/day) is beyond 10 mm/day and the total amount of continuous rainfall exceeds 100 mm, one lane of the roadway is temporarily closed. And when the displacement velocity (mm/day) is over 20 mm/day and the total amount of continuous rainfall exceeds 200 mm, both lanes of the road are temporarily closed.

Figure 6 shows the velocity of the displacement (mm/day) obtained from the monitoring displacement. During this period, the road was closed a few times. The GPS monitoring results are seen to have provided effective information for managing traffic safety, by comparing them with the above criteria.

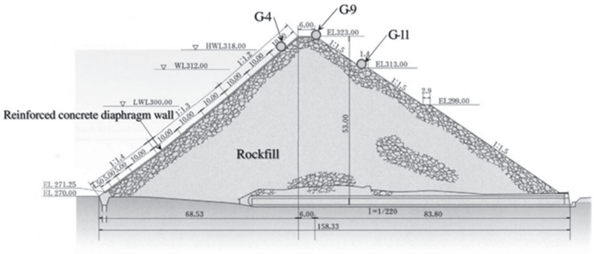
3.1.2 Rock-fill dam in the Great East Japan Earthquake

Exterior deformation is one of the most important items to measure when managing the safety of rock-fill dams. The GPS displacement monitoring system was applied to continuously monitor the deformation of dams, and detected displacements due to the Great East Japan Earthquake[11].

(1) Monitoring site

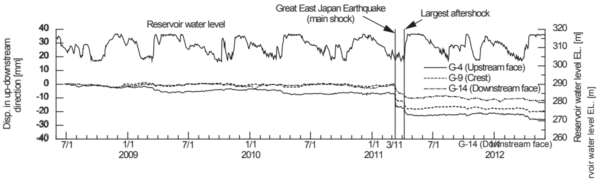


(a) Plan view

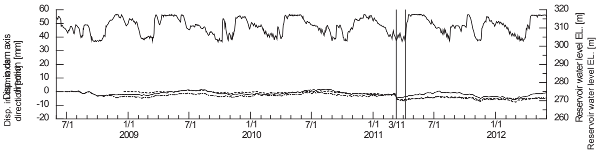


(b) Cross section (Line No. 20)

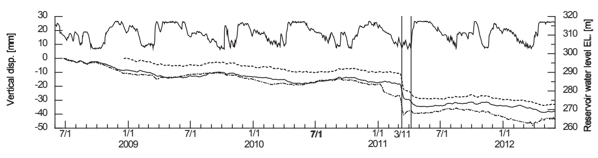
Figure 7: Dam embankment and layout of GPS sensors[11)]



(a) Up-downstream direction



(b) Dam axis direction



(c) Vertical direction

Figure 8: Displacement monitoring results of GPS at G-4, G-9, and G-14 located on line No. 20 and water level of reservoir[11)]

The dam monitored by GPS 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 7 shows a plan view and a vertical section of the dam with the monitoring points. The sensors were installed at 15 points. 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.

(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 (Figure 7), are shown with the water level of the reservoir in Figure 8. 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, a seismograph on a right bank terrace recorded a maximum acceleration value of 184 gal. When the largest aftershock occurred on April 7, an acceleration value of 140 gal was recorded by a seismograph in the same place. The broken and dashed-dotted lines in Figure 8 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 was found that the main shock caused displacements of about 10 mm in the downstream direction, about 3 mm in the right bank direction, and about 10 mm in the settlement direction at G-9. The largest aftershock caused displacements of about 2 mm in the downstream direction and about 2 mm in the settlement direction.

It was proved that continuous monitoring using GPS is quite effective for detecting displacements due to an earthquake immediately after it occurs[11)].

3.2 Application of DInSar

3.2.1 Land subsidence

DInSAR was applied to monitoring the distribution of a land subsidence over an extensive area. A time series analysis of the SAR data was conducted. The technique is generally called Multi-Temporal DInSAR[12)].

(1) Monitoring site

The monitoring site is Semarang City located in the north of Java Island, Indonesia. It is the capital and largest city of the province of Central Java, and has an area of 373.70 square kilometers. Figure 12 shows the location of Semarang City.

(2) Monitoring results

The Multi-Temporal DInSAR was applied to 23 scenes of ALOS-PALSAR operated from 2006 to 2011 by Japan to monitor the land subsidence.

Figure 10 shows a map of the subsidence distribution from January 2007 to December 2010 obtained by the Multi-Temporal DInSAR. It was found that the subsidence increased from the southwest area to the northeast area. Around the northeast area and the coastal area, the large subsidence with a range of 200-320 mm over 4 years is denoted by yellow to dark orange on the map. In the northwest area, the subsidence is observed at a lower rate of about 20-80 mm over 4 years and is represented by blue to green on the map. The area of dark purple mixed with light purple is mainly the center part of Semarang. The maps in Figure 11 show the transition of subsidence during this period.

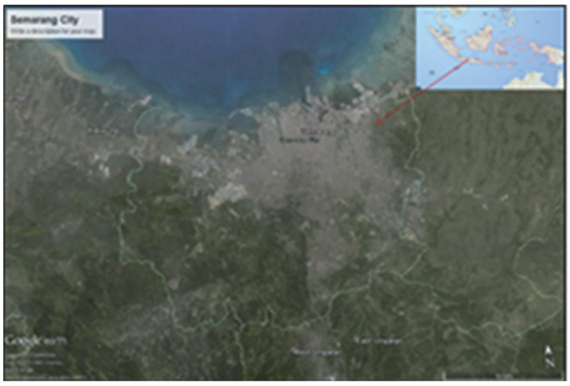


Figure 9. Location of Semarang City (Google Earth image, 2015)

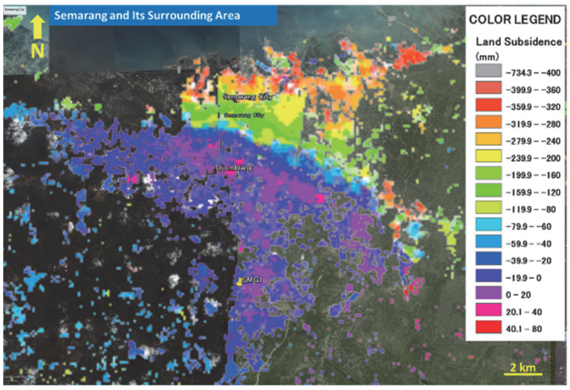
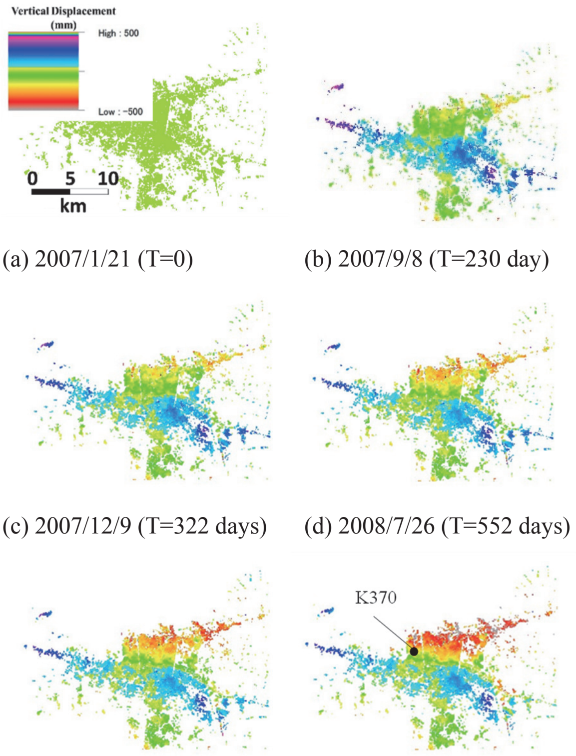


Figure 10 Map of land subsidence from January 2007 to Dec 2010[12)]

Semarang has three main lithologies, namely, volcanic rock, sedimentary rock and alluvial deposits distributed from south to north[13)]. The northern part of the Semarang area is covered with Kali Garang deltaic alluvium up to a depth of 80 to 100 m in the coastal area. Aquifers are found at depths ranging from 30 to 80 m in this alluvium. The northern part of Semarang near the seashore is composed of very young alluvium with high compressibility[14)]. This is one reason why the land subsidence in the north part of Semarang seems to be larger than in other parts.

GPS displacement measurements were conducted four times from 2008 to 2011[13)]. Comparing the two sets of subsidence from 2009 to 2010, the results of DInSAR agree well with those of GPS[12)]. Figure 12 shows the transition of subsidence at K370 estimated by the hyperbolic method[15)].



(a) 2007/1/21 (T=0) (b) 2007/9/8 (T=230 day)

(c) 2007/12/9 (T=322 days) (d) 2008/7/26 (T=552 days)

(e) 2009/6/13 (T=874 days) (f) 2011/2/1 (1472 days)

Figure 11 Transition of the subsidence distribution

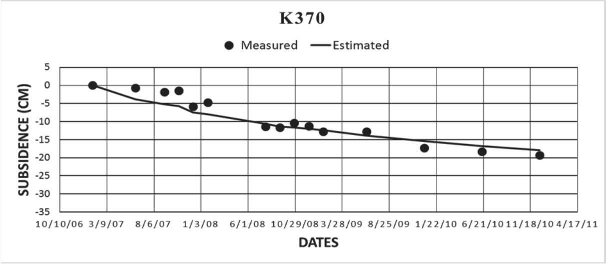


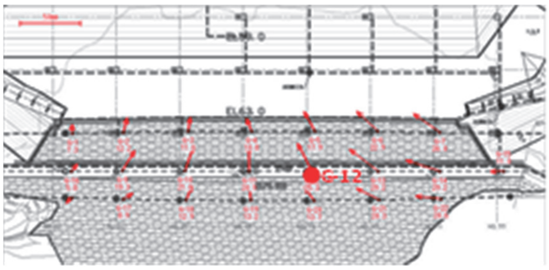
Figure 12: Transition of subsidence at K370

3.2.2 Rock-fill dam

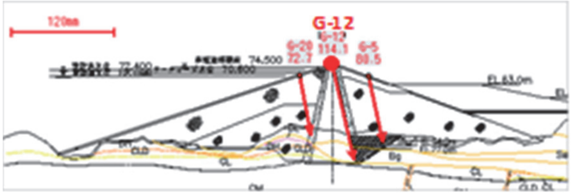
Although DInSAR is usually applied to monitor the deformation over an extensive area, as shown in 4.2.1., it is applicable to smaller areas, such as a rock-fill dams within a few square kilometers[16].

(1) Monitoring site

DInSAR was applied to 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 data observed by PALSAR mounted on ALOS, with 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, respectively, were used for the analysis. GPS was also employed to monitoring the exterior deformation starting in December 2006[17], and the results of GPS displacement monitoring are shown in Figure 13.

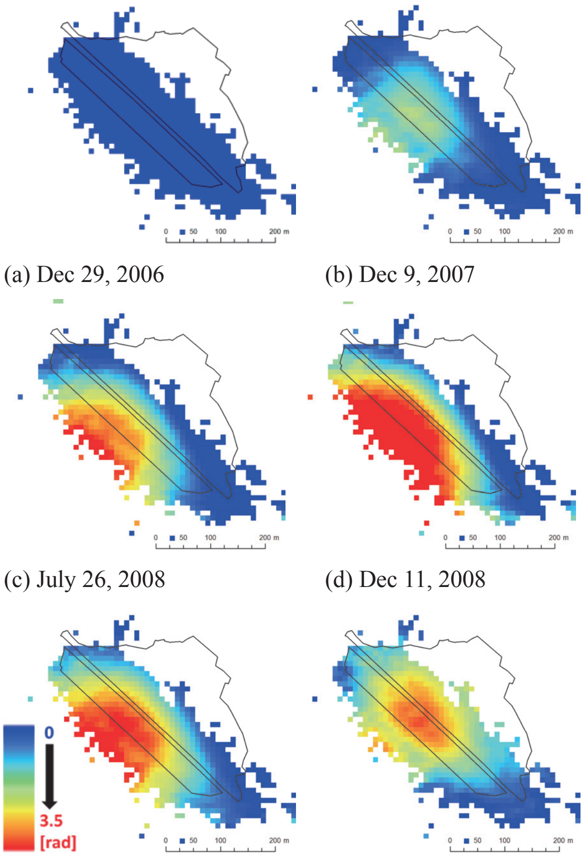


(a) Top view



(b) Cross-section view

Figure 13: GPS observation points and deformation vectors of Taiho Subdam between December 2006 and December 2010[17]



(a) Dec 29, 2006 (b) Dec 9, 2007

(c) July 26, 2008 (d) Dec 11, 2008

(e) Dec 14, 2009 (f) Dec 17, 2010

Figure 14: Phase differences from first observation on Dec 29, 2006 using ascending data[16].

(2) Monitoring results

Figure 14 shows the temporal transition of the phase difference (displacement is proportional to the phase differences) of the dam surface using ascending data, respectively. It is seen to change from blue, green, and yellow to red as time progresses around the center of the

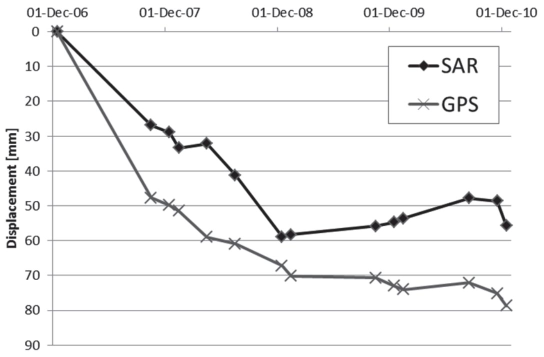


Figure 15: Displacements at G-12 monitored by GPS and DInSAR in slant-range direction$^{16)}$.

down-stream side of the dam. This indicates that the settlements have occurred during the observation period and agree well with those of GPS as shown in Figure 13.

The trends in displacement at G-12 in the slant-range direction obtained by DInSAR and GPS, are compared in Figure 15. The results of DInSAR agree well with those of GPS with a discrepancy of only a few centimeters. Figure 16 shows the relationship between the DInSAR and the GPS monitoring results at all monitoring points. 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 the GPS monitoring results.

DInSAR has the potential for application to the monitoring of even artificial structures with areas of less than one square kilometers.

4. CONCLUSIONS

GPS and SAR have become important engineering tools for monitoring rock displacements.

(1) Methods of displacement monitoring using GPS can provide the three-dimensional displacements of rocks automatically and continuously with high accuracy (i.e., mm level).

(2) 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.

(3) DInSAR is an attractive tool for monitoring the deformation of areas from less than one to thousands of square kilometers without the necessity for any devices by the users

(4) DInSAR has recently been applied to various problems. This technology will be widely applied in Rock Engineering.

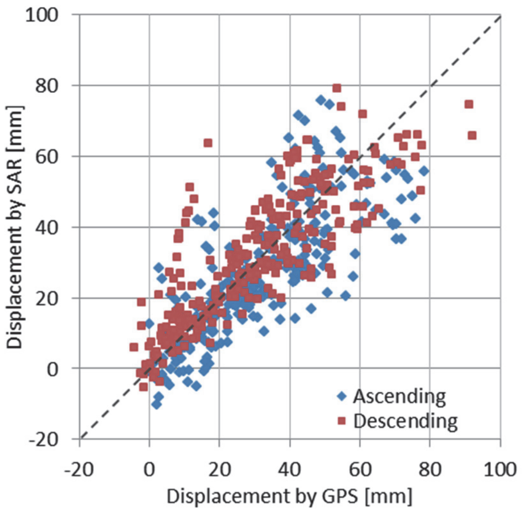


Figure 16: Comparison between DInSAR and GPS monitoring results$^{16)}$.

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