INTERNATIONAL COMMISSION ON LARGE DAMS
76th ANNUAL MEETING
SOFIA, BULGARIA, JUNE 2-6, 2008
Symposium: “Operation, Rehabilitation and Up-grading of Dams”

UTILIZATION OF GPS FOR EXTERIOR DEFORMATION MEASUREMENT OF EMBANKMENT DAMS

Yoshikazu YAMAGUCHI[1], Tadahiko SAKAMOTO[2], Toshihide KOBORI[3],
Ichiro IKEZAWA[4], Hideharu ITAYA[5] and Tomoharu IWASAKI[6]

ABSTRACT

The measurement of exterior deformation is one of the most important measuring items for safety management of embankment dams. By using targets installed on the crest and slopes of embankment dams, their exterior deformation has been measured by conventional surveying methods.

According to the Japanese dam safety management standard, the measurement frequency of exterior deformation of embankment dams is set as once a week at the period of the first filling of reservoir, that is, the first term of dam management, and once every three months in the third term that is the final management stage when behavior of the dam and its foundation come to be stable. But, because the surveying work is relatively time consuming one, rapidly responding after a large earthquake or in other emergencies is a big challenge.

The global positioning system (GPS) is a system that can perform surveys quickly in relatively low cost. GPS is a weather-proof positioning system using satellites that is well known for its role in car navigation and in surveying applications.

The results of our previous research made it clear that we should investigate how to install GPS sensors on the crest in order to fully introduce GPS sensors as the method of measuring exterior deformation of embankment dams. In this research, we develop the backfill type GPS sensors, and make the verification test for them.

INTRODUCTION

Measurements for safety management of dams must be capable of accurately confirming safety of dam bodies and foundations in conjunction with visual inspection. The Cabinet Order Concerning Structural Standards for River Management Facilities (Japan Institute of Construction Engineering, 2000) stipulates items that must be monitored for safety management of a dam in Japan. For embankment dams, the quantity of seepage through the dam body and shallow foundation and their exterior deformation are stipulated as major measurement items for safety management. By using targets installed on the crest and slopes of embankment dams, their exterior deformation has been measured by conventional surveying methods.

According to the Japanese dam safety management standard (Committee on Dam Management, 1999), the measurement frequency of exterior deformation of embankment dams is set as once a week at the period of the first filling of reservoir, that is, the first term of dam management, and once every three in the third term that is the final management stage when behavior of the dam and its foundation come to be stable. But, because the surveying work is relatively time consuming one, rapidly responding after a large earthquake or in other emergencies is a big challenge.

The global positioning system (GPS) is a system that can perform surveys quickly in relatively low cost. GPS is a weather-proof positioning system using satellites that is well known for its role in car navigation and in surveying applications. The results of our previous research (Iwasaki *et al.,* 2002) made it clear that we should investigate how to install GPS sensors on the crest in order to fully introduce GPS sensor as the method of measuring exterior deformation of embankment dams. In this paper, we develop the backfill type GPS sensors, and make the verification test for them to propose the method of full introduction of GPS sensors to measure exterior deformation of embankment dams for their safety management.

EXTERIOR DEFORMATION MEASUREMENTS FOR EMBANKMENT DAMS IN JAPAN

Figure 1 shows an example of the installation of exterior deformation measurement use targets on a rockfill dam with an earth core. Figure 2 shows an example of the detailed structure of targets at a measuring point and a benchmark. Specifically, a grid of appropriately spaced measurement lines is formed on the crest and slopes of a dam body, measurement use targets (measuring point) are installed at each grid intersection point, and the quantity of displacement in the horizontal and vertical directions of the targets (measuring point) from targets installed on the left and right banks (benchmark) are measured based on geodimeter survey and leveling survey.

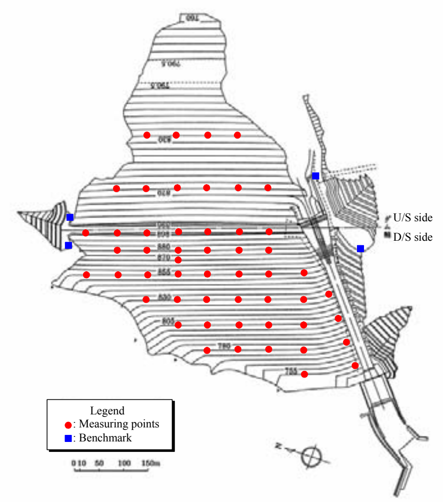
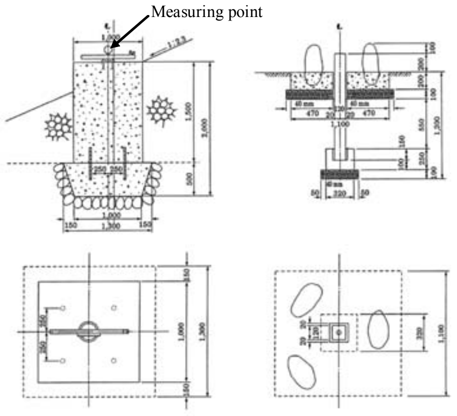


Fig.1 Layout of exterior deformation measurement use targets on a rockfill dam (Naramata Dam)



(a) Measuring point

(b) Benchmark

Fig.2 Detailed structure of targets at measuring point and benchmark (Sagae Dam)

Table 1 summarizes the frequency of measurement for dam safety management in Japan (Japan Institute of Construction Engineering, 2000). The deformation of the embankment dam in the table means exterior deformation. The First Term of dam safety management refers to the duration of first filling of the dam reservoir. The period from the conclusion of the first filling until the stable stage when the dam's behavior has come to be stable and the period after the dam's behavior has reached the stable behavior stage are called the Second Term and the Third Term respectively of dam safety management. The measurement of exterior deformation of an embankment dam is done once a week in the First Term, once a month in the Second Term, and once every three months in the Third Term.

Methods of measuring exterior deformation of embankment dams based on geodimeter and leveling surveys have faced some problems. Because it is relatively time-consuming and expensive to perform measurements and to analyze the results with these methods, it is not always possible to respond promptly to the need for urgent measurements of exterior deformation after a large earthquake or in other emergencies.

Table 1 Frequency of measurement for dam safety management in Japan

Measurement item	Concrete Dam			**Rockfill Dam**		
	First Term	Second Term	Third Term	First Term	Second Term	Third Term
Leakage / Seepage	Once / 1 day	Once / 7 days	Once / 1 month	Once / 1 day	Once / 7 days	Once / 1 month
Deformation	Once / 1 day	Once/1 day	Once / 7 days	**Once / 7 days**	**Once / 1 month**	**Once / 3 months***
Uplift / pore water pressure	Once / 1 day	Once / 7 days	Once / 1 month	-	-	-
Visual inspection	Once / 1 day	Once / 7 days	Once / 1 month	Once / 1 day	Once / 7 days	Once / 1 month

*: The interval of the measurement can be elongated according to conditions.

GPS MEASUREMENT TECHNOLOGY

Present state of GPS deformation measurement technology

Because measurements of the exterior deformation of embankment dam bodies must be precise, to within millimeter units, even when using the most precise GPS method, which is static positioning, this precision has not yet been satisfied, so the method cannot be used to measure the external deformation of an embankment dam. Another major problem hindering the use of static interference positioning is the high price of GPS measuring equipment.

Recently, a method of obtaining precision of between 1 and 2 mm by continuously measuring displacement with GPS and processing the measurement results with a trend model, which is a kind of smoothing method in statistics, has been proposed (Matsuda *et al.*, 1998). In addition, a compact, lightweight, and low priced GPS automatic displacement measuring system especially designed for the measurement for ground deformation has been developed. As a result it is now possible to reduce telecommunications costs and improve convenience by using the Internet and to perform high-precision GPS automatic displacement measurement in real time at relatively low cost.

An example of measurement of exterior deformation of an embankment dam by GPS (1^{st} stage) (Yamaguchi *et al.*, 2007)

Measurement method

The trial measurement of exterior deformation of an embankment dam by GPS was performed at the Haneji Dam, which is a rockfill dam with a central earth core with a height of 66.5 m constructed on the northern part of the main island of Okinawa by the Okinawa General Bureau of the Cabinet Office, the Government of Japan. At this dam, trial filling, which corresponds to the first filling, was done from July 2001 to June 2004 after the dam was completed, and the exterior deformation of the dam body was measured once a week using conventional geodimeter and leveling measurements. Trial filling was followed by periodic measurements of exterior deformation of the dam body at intervals of one month. GPS measurements were started on October 10, 2003 during trial filling. GPS sensors were installed at four locations near the center of the dam body, which were selected from measuring targets at 19 locations for measuring exterior deformation. Figures 3 and 4 show the layout of GPS sensors and the close-up of GPS sensor respectively.

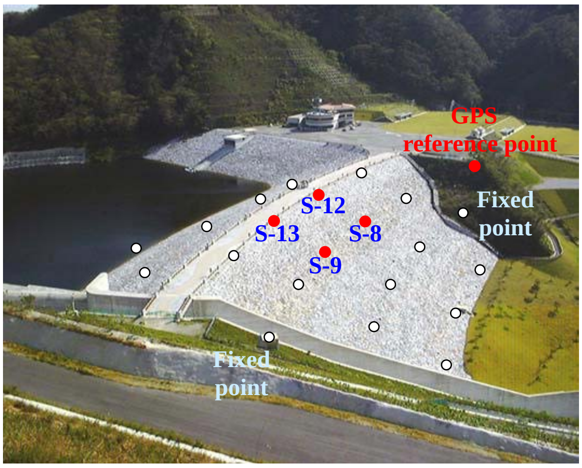


Fig.3 Layout of GPS sensors at Haneji Dam

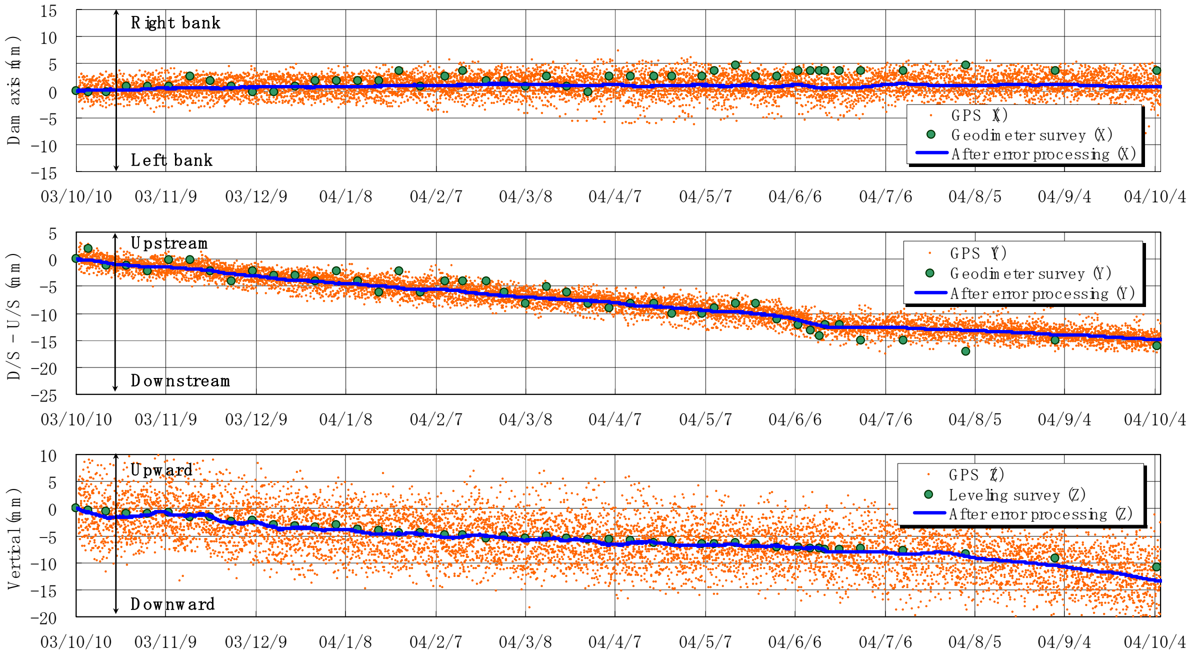
Fig.4 Close-up of an installed GPS sensor

Measurement results

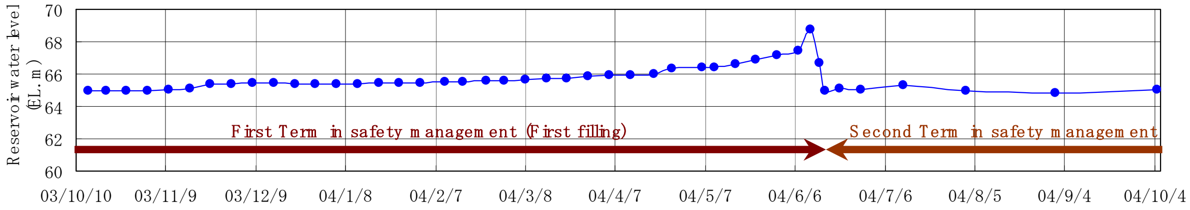
Examples of the measured results by the GPS sensor at S-8, of which device is installed midway on the downstream slope of the dam, are compared with the results of geodimeter and leveling surveying at identical locations in Figure 5. From the top of the figure, displacements in the X (dam axis) direction, Y (upstream-downstream) direction and Z (vertical) direction are shown in succession, and the bottom level shows the change in the reservoir water level over time. All displacements are adjusted to 0 mm when the GPS measurement commenced. The black circles on the displacement graph show the geodimeter and leveling survey results, the dots represent results of GPS measurements before error processing, and the solid lines represent the GPS measurement results at one point for one hour after error processing with the trend model. These data are, assuming that the dam body is not deformed while receiving hourly data, analyzed to obtain a 1-point GPS measurement value by using one-hour's worth of data, measured at intervals of 30 seconds.

The measurement results show that the GPS measured values (dots) before error processing distributed in a range of about 5 mm in the X and Y directions and distributed broadly from 10 to 20 mm in the vertical direction. This scattering of measured values is a result of errors caused by the impact of the ionosphere and troposphere that cannot be removed completely by normal GPS baseline analysis, wrong orbital information, and GPS receiver noise, etc. Previous research has confirmed that if scattering ranges from 10 to 15 mm, it is possible for measured values (the solid line) to be less than 1 mm by error processing, based on a trend model. At this observation site, the extent of the distribution of measured values after error processing is between 1 and 2 mm while the displacement are supposed to be small, indicating the validity of the error processing. Geodimeter measurements were also scattered, due to measurement errors caused by differences in the refractive index resulting from variations in atmospheric mass density.

The GPS measured values after error processing generally conformed to the values obtained by geodimeter and leveling surveys. The GPS measured values after error processing correction were almost identical to the values measured by leveling surveys throughout the measurement period, particularly in the vertical direction, showing that both methods achieve accurate measurements.



(a) Displacements measured at S-8



(b) Reservoir water level

Fig.5 Measured results of GPS with those by geodimeter and leveling surveys

DEVELOPMENT OF BACKFILL TYPE GPS SENSORS (2nd STAGE) (Yokomori *et al.*, 2007)

History of development

GPS sensors installed at the exterior deformation measuring points introduced in the previous chapter were confirmed to be practical by trial application at embankment dams.

However, at many large embankment dams in Japan, the dam crest is used as management roads, so measuring points for surveys are often installed inside manholes on the dam body crests. It is difficult to install standard type GPS sensors on a dam crest under these conditions. Trial applications have revealed problems, such as the inability of GPS sensors installed on the shoulders of embankment dam crests to accurately measure displacement in the vertical direction of the body of these dams.

So to install GPS sensors inside manholes on dam body crests, backfill type GPS sensors were manufactured and their measurement precision while embedded and applicability to the measurement of the dam crest deformation were verified.

Fundamental test of backfill type GPS sensors

Outline of backfill type GPS sensors

A backfill type GPS sensor can be installed in a narrow manhole with its sensor unit and communication box separated, as shown in Figure 6. It was waterproofed, thus permitting operation under the high temperature and high humidity conditions inside a manhole.

Fig.6 Backfill type GPS sensor

Test method

To verify the performance of the backfill type GPS sensor, these devices are installed in dam crest was done in a test field adjacent to the dam body of the Taiho Subdam (dam height of 66.0 m, a rockfill dam with a central earth core) that is now being constructed by the North Dam Construction Office, the Okinawa General Bureau, the Cabinet Office, the Government of Japan. Figure 7 shows the layout of the GPS devices. The verification testing was done by constructing structures identical to manholes and to the measuring point targets to be installed at the crest of the Taiho Subdam, then connecting the backfill type GPS sensor to the measuring point, G-1, as shown in Figure 8. Measuring point G-2, equipped with a standard type GPS sensor, was installed at ground level, as shown in Figure 7 and its measurement precision was compared with that of the backfill type at G-1.

The manhole lid was made of fiber reinforced plastic (FRP, thickness of 37 mm, load-bearing capacity of T-25 that can withstand a large truck passing above) through which radio waves pass easily, fiber reinforced plastic and based on specifications permitting it to be used on an actual dam crest.

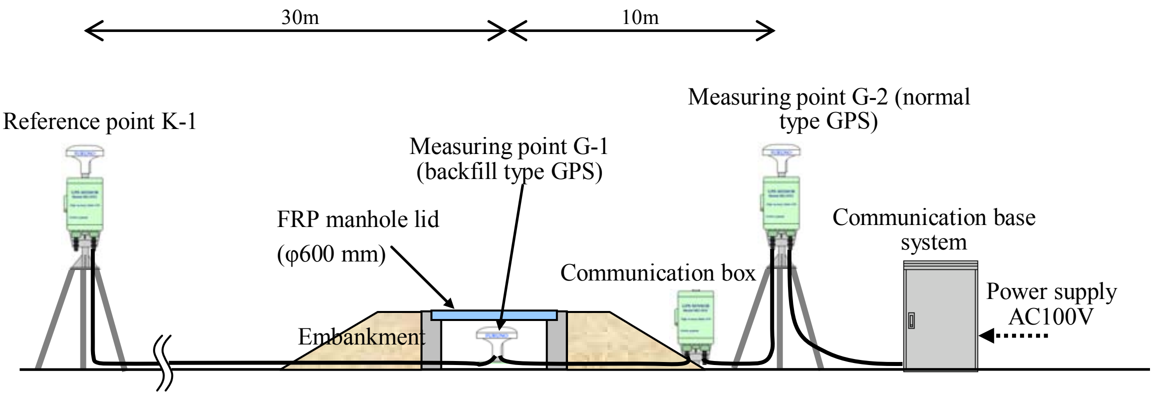


Fig.7 Schematic layout of GPS devices for verification test

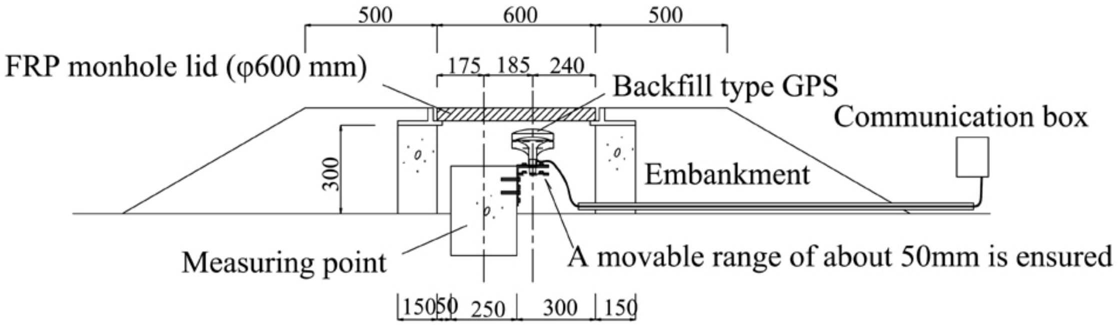


Fig.8 Structural diagram of the manhole - backfill type GPS sensor (G-1) installation

Test results

When a GPS sensor is installed in a manhole, the received signal intensity declines and phase slippage occurs because the radio waves are received through a 37 mm-thick FRP lid and because the deeper its location, the worse its exposure to the sky and the greater the multi-pass impact. There was a concern that under these conditions, it would be impossible to attain the required measurement precision. The test measurements were composed of a series of tests of the three cases summarized in Table 2, which verified the measurement precision evaluated by using standard deviation σ.

Figure 9 shows the results of the test measurements. The figure shows the displacements, from the top, in the NS, EW, and UD directions. The dots in the figure are measured values and the solid lines show the results after error processing with the trend model. Cases 1 and 2 show that even when a GPS sensor is backfilled in a manhole, based on radio waves passing through the FRP manhole lid, scattering of the measurement values is small. This means that it is possible to perform measurements with practical precision. In Case 3, in order to prepare for cases where the device is temporarily submerged because of plugging of the drain hole inside the manhole, water was poured to artificially reproduce conditions whereby the device was submerged to just below the radio-wave-receiving surface of the GPS sensor inside the manhole, but its measurement precision did not decline and the machinery operated normally. It was, therefore, confirmed that there were no problems with the waterproofing of the backfill type GPS sensor.

Table 3 shows the evaluation of the precision of the test measurements. Table 3 (a) shows a comparison of the backfill type sensor, Cases 1 and 3 at G-1 (a clearance of 15 mm between the GPS sensor and the manhole lid) with the standard type at G-2, revealing that the standard deviation at G-1 is almost double, indicating deteriorated precision. Nevertheless, the defect rate is almost zero in both cases and the standard deviations after error processing with the trend model (Table 3(b)) are 0.2 to 0.4 mm in the NS and EW components and 0.6 to 1.5 mm in the UD component, showing that it is possible to perform measurements with relatively sufficient precision. When the study advanced from Case 1 to Case 2, the GPS sensor was moved downward by about 50 mm, as shown in Figure 9 in the GPS measurement results, a downward displacement of 50 mm was observed. However in Case 2, as shown by Table 3 (a), the standard deviation (particularly in the UD direction) and the defect rate were higher. So, when the GPS was backfilled underground, it was necessary to minimize the clearance between the GPS sensor and the manhole lid.

Table 2 Test conditions

Case 1	Measured at a clearance of 15 mm between the GPS sensor and the manhole lid
Case 2	Verification of the gap in measurement precision according to differences in depth by lowering the GPS sensor by 50 mm to create a clearance of 65 mm between the sensor and the manhole lid
Case 3	Returning the GPS sensor to Case 1 position and pouring water to just below the sensor in the manhole to confirm that it is waterproof

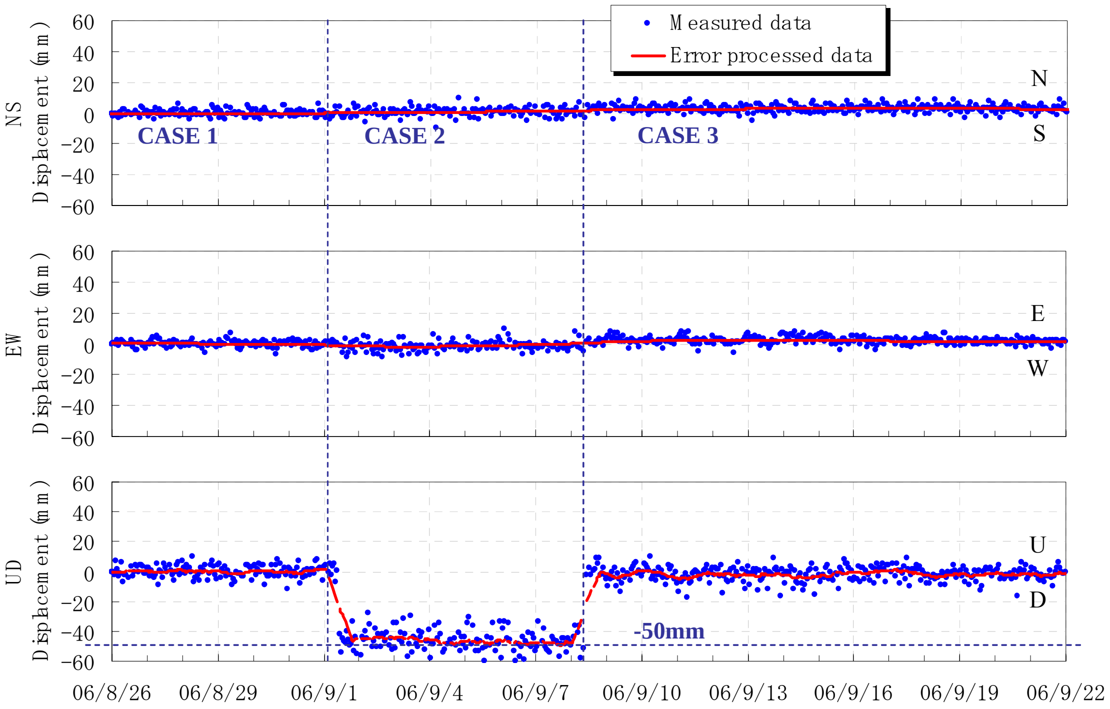


Fig.9 Results of test measurements (measurement point G-1)

Table 3 Precision of test measurements

(a)Before error processing

GPS No.	CASE	Standard deviation σ (mm)			Defect rate (%)
		NS component	EW component	UD component	
G-1	1	2.3	2.2	4.2	1.0
	2	2.8	3.1	7.4	12.5
	3	2.3	2.5	4.9	0.0
G-2		1.0	0.8	2.3	0.0

(b)After error processing with the trend model

GPS No.	CASE	Standard deviation σ (mm)		
		NS component	EW component	UD component
G-1	1	0.0	0.2	0.6
	2	0.3	0.2	1.5
	3	0.2	0.4	1.5
G-2		0.1	0.1	0.0

Verification test of application of the backfill type GPS in heavy snowfall region (Urushiyama *et al.*, 2007)

Purpose of test

At embankment dams constructed in heavy snowfall regions, exterior deformation is measured to manage safety during the winter, which requires considerable snow removal work. This section describes the confirmation of measurement precision and the study of operating methods under snow cover, performed by installing a GPS sensor in a dam crest manhole on a rockfill dam constructed in a heavy snowfall region.

Test method

The testing of the application in heavy snowfall regions was done at the Shirakawa Dam in the Tohoku Regional Bureau, the Ministry of Land, Infrastructure and Transport, the Government of Japan (dam height of 66.0 m, a rockfill dam with a central earth core). The testing included a fundamental test to clarify the relationship between snow cover thickness above the manhole in which the GPS is installed with its measurement precision and an operating test to verify the extent that measurement data can be obtained in the winter by practical snow removal work using a snow removal vehicle and broom to completely clear snow above the manhole. This paper presents the results of the fundamental test.

GPS sensors were installed at two locations, as shown in Figure 10: inside an existing manhole on the dam crest (G-1) and in the measuring point of G-2 on the downstream slope, fixed besides the foundation concrete. Because the existing manhole lid was made of steel, it was replaced with one made of FRP with a thickness of 37 mm, through which radio waves pass easily.

The fundamental test began with a measurement of the specific gravity of the snow near G-1, as shown in Table 4. The specific gravity of the snow remaining on the road after snow was removed from the dam crest by a snow removal vehicle (packed snow condition, thickness of approx. 10 mm) was 0.40. Next, the snow was completely removed from above the manhole to perform a preliminary measurement under snowless conditions, followed by a study of changes of GPS measurement values while artificially changing the condition above the manhole to packed snow with a specific gravity of 0.40, as shown in Figure 11. Around G-2 during the test measurements, snow was removed and measurement was done continuously under good radio reception conditions, so that the results could be compared with the results of measurements at G-1.

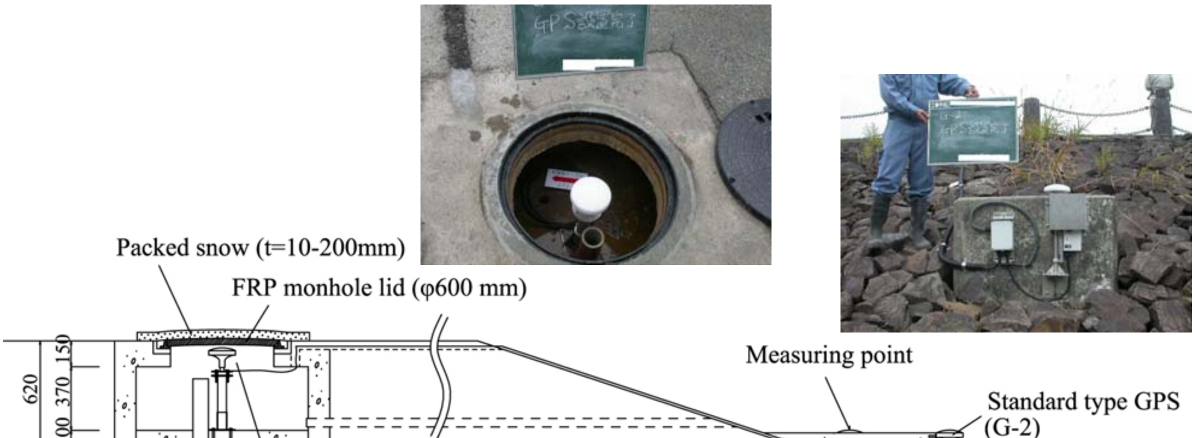


Fig.10 Layout of GPS sensors

Table 4 Specific gravity of snow

Snow condition	Specific gravity	Number of measurements
Packed snow after dam crest snow removal	0.40	3
Residual packed snow on dam crest shoulder	0.37	3
New snow	0.09	2

* Average value of measurements from Jan. 22 to 24, 2007.

Fig.11 View of test site

Test results

The test was performed from January 22 to 25, 2007. Figure 12 shows the results of the test measurement at G-1. In the top chart of this figure, the horizontal axis shows the packed snow thickness, and the vertical axis shows the deviation (difference) in the case where the average of the GPS measurement values obtained by preliminary measurement is considered to be 0. In the bottom chart of this figure, the horizontal axis shows the packed snow thickness and the vertical axis shows the standard deviation σ that indicates the scattering of the measured values.

The packed snow were set on the top of the manhole ranging from 10mm to 200mm thick. Figure 12 shows that the UD direction measurement values varied greatly as the packed snow thickness increased, but the fluctuations in the NS and EW directions were relatively small, revealing that the snow cover primarily impacted on measurement precision in the UD direction.

At a packed snow depth of 10 mm, the standard deviation was almost identical to that of the preliminary measurements, however from 20 mm to 100 mm, as the packed snow increased in thickness, the standard deviation tended to rise. At a depth of 200 mm, it was about three times that of the preliminary measurements in the NS and EW directions, while it was about seven times in the UD direction, far exceeding the normal precision of GPS measurements shown in the measurement regulations (NS and EW: σ = 5 mm, and UD direction: σ = 10 mm), so it can be concluded that the measurement precision exceeds the practical range.

It also confirms that at G-2 where it was possible to remove the surrounding snow to perform measurements under constantly good radio reception conditions, the deviation and scattering of the measurement results were extremely small.

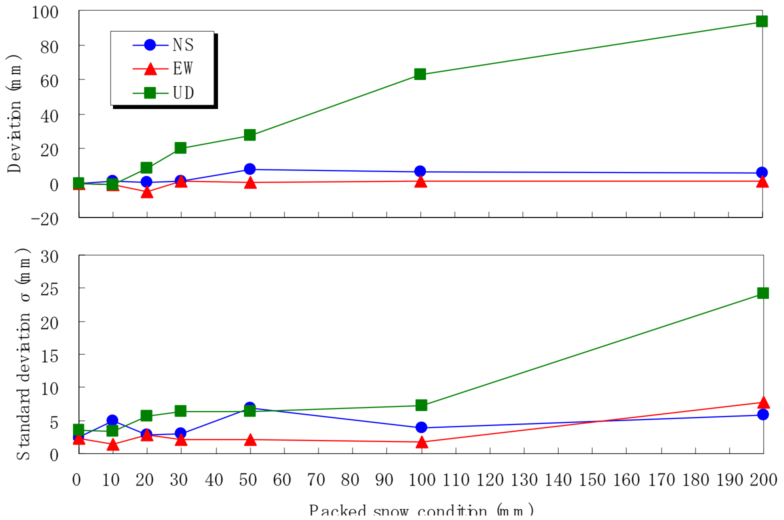


Fig.12 Results of test measurement at G-1

CONCLUSIONS

GPS can be used to measure the exterior deformation of embankment dams at short intervals, almost approximating real time with high measurement precision, thereby permitting more precise safety management. Another benefit, namely its ability to measure displacement in almost real time during emergencies such as a sudden rise in the reservoir water level after a large scale flood runoff or a large earthquake, makes it particularly useful.

This research was undertaken by preparing a prototype of a backfill type GPS sensor to be installed in a manhole on a dam body crest, then verifying its measurement precision and its applicability to dam crest measurement in order to take advantage of the benefits of GPS and provide it at various installation locations. The verification produced the following results.

– The fundamental test of the backfill type GPS sensor clarified that even when a GPS system is installed in a manhole on the crest of an embankment dam, it provides a practical level of measurement precision.

– The trial application of the backfill type GPS in a heavy snowfall region showed that, following snow removal work on a road on a dam crest, if snow is removed completely from only above the manhole containing the GPS system, then valid GPS measurements can be obtained until the packed snow reaches a depth of about 10 mm.

These test results have clarified that exterior deformation measurements of an embankment dam by GPS can offer precision equal or superior to that of conventional geodimeter and leveling measurements, so a practical level of precision can be obtained by improving the method of installing the GPS sensor on a dam crest.

Data is now accumulated to verify how much precision will be attained at the Taiho Subdam by simultaneously performing GPS measurements and conventional measurements until the trial filling begins. A study will also be undertaken for full implementation of GPS measurements of exterior deformation of embankment dams.

REFERENCES

Committee on Dam Management Workshop. Practice of Dam Management. Water Resources Environment Technology Center. Japan (1999). 215-243. (in Japanese)

Japan Institute of Construction Engineering. *The Cabinet Order Concerning Structural Standards for River Management Facilities*. Japan (2000). 95-97. (in Japanese)

Iwasaki, T., Oikawa, N. and Shimizu, N. New GPS Monitoring System for Slope Measurement (2) - Improvement of Measurement Accuracy by Trend Model-. *Proc. 41st Technological Research Symposium of Japan Landslide Society*. Japan (2002). 193-196. (in Japanese)

Matsuda, H., Adachi, H., Nishimura, Y. and Shimizu, N. Displacement Monitoring Using GPS and its Interpretation Method for the Assessment of Slope Stability. Journals of the Japan Society of Civil Engineers. No.715/III-60. Japan (2002). 333-343. (in Japanese with English summary)

Urushiyama, Y., Miyazaki, H., Yamaguchi, Y., Kobori, T., Ikezawa, Iwasaki, T. and Iizima, K. *Examination of Safety Management of Embankment Dam that Uses GPS in Heavy Snowfall Area. Proc. Technological Research Symposium of Touhoku Branch, Japan Society of Civil Engineers,* Japan (2007), II-33 (CD-ROM).

Yamaguchi, Y., Kobori, T., Ikezawa, I., Yokomori, M. and Iwasaki, T. *Exterior Deformation Measurement Using GPS for Safety Management of Embankment Dams, 75th Annual Meeting of the ICOLD,* Russia (2007)

Yokomori, M., Nakazono, K., Yamaguchi, Y., Kobori, T., Ikezawa, I., Shimizu, K., Iwasaki, T. and Iizima, K. *Applicability Examination Backfill Type GPS for Safety Management of Embankment Dam. Proc. Technological Research Symposium of Seibu Branch, Japan Society of Civil Engineers,* Japan (2007), III-107 (CD-ROM). (in Japanese)

---

[1] Principal Researcher, Dam Structures Research Team, Hydraulic Engineering Research Group, Public Works Research Institute, Japan

[2] Chief Executive, Public Works Research Institute, Japan

[3] Researcher, Dam Structures Research Team, Hydraulic Engineering Research Group, Public Works Research Institute, Japan

[4] Collaborating Researcher, Dam Structures Research Team, Hydraulic Engineering Research Group, Public Works Research Institute, Japan

[5] Director, North Dam Construction Office, Okinawa General Bureau, Cabinet Office, Government of Japan

[6] Manager, Shamen-net Group, Business Solution Department, KOKUSAI KOGYO CO., LTD.