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GPS MEASURING APPLICATION ON FIRST IMPOUNDING OF TOKUYAMA DAM - MONITORING RESULTS ON DAM BODY ASSOCIATED WITH THE FIRST IMPOUNDING AND RESPONSE TO THE INITIAL DISCHARGE –

Hideki Soda[1]
Chief, Water Resources Engineering Department, Japan Water Agency,

Mariko Kinoshita[2]
Kawakami Dam Construction Office, Japan Water Agency,

Mikihiro Tanaka
Tokuyama Dam Operation and Maintenance Office, Japan Water Agency,

Koji Hino
Director, Tokuyama Dam Operation and Maintenance Office, Japan Water Agency,

Tomoharu Iwasaki
Shamen-net Division, Kokusai Kogyo Co., Ltd.,
JAPAN

1. INTRODUCTION

The conventional electro-optical distance measurement, which had been mainly used for external deformation/settlement measurement of dam body, raised problems such as time-consuming measurement and result arrangement, expensiveness, and failure in prompt response to necessary measurement in emergency like earthquakes, adding to difficulties in securement of fixed points and visual distance.

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1 former Chief of Tokuyama Dam Operation and Maintenance Office
2 former design division of the Tokuyama Dam Construction Office

Recently in Japan, approaches by Global Positioning System (GPS) have been made for the purpose of displacement measurement of large excavation slopes, landslides, and so on. As far as hardware aspects like GPS antenna, receiver, and so on are concerned, improvement of functions, downsizing, and lower prices have been realized over these 10 years. The authors focused attention on slope observation system by GPS which has become common in recent years and performed experiments with view of application to dams. In measurement showd by the Government Ordinance for Structural Standard for River Administration Facilities, the following three factors were thought to be essential for adequate measurement through consideration of cost: one is to measure accurate values needed, two is to measure point that has importance for inspecting, three is to measure promptly when needed. The first experiment was performed in the Agigawa Dam to examine the basic performance. Based on the result, four issues of GPS measurement were clarified [1].

Providing further insights for solving these issues, some kinds of technological development were made from installation method to data processing. As a result, it was confirmed that GPS measurement could be used for external deformation of the fill dam body in the Tokuyama Dam and implementing measurement with it from the start of first impounding of the reservoir to the present day.

This paper discusses the result of measurement and technological development as well as suggests empirical points of concern when using GPS as measurement instrumentation in dams to further propose dam body measurement.

2. GPS MEASUREMENT SYSTEM USED

2.1. CURRENT STATUS OF GPS MEASUREMENT TECHNOLOGY

As measurement accuracy in millimeters is needed in dam body deformation, GPS has rarely been used. Because of the accuracy and the cost, even if the static positioning, a type of GPS that is highest cost have the measurement accuracy being 2 to5 cm.

Recently, a method for 1 to 2 mm of several fold higher accuracy than the existing one, has been proposed by measuring displacement with GPS for 24 consecutive hours and processing the result with a trend model. Trend model is a statistical smoothing method. Furthermore, an engineering-specific GPS measurement system was developed. In this system, engineering-specific GPS measurement instruments are used to reduce communication cost and boost convenience by utilization of the Internet for data communication.

2.2. OUTLINE OF SYSTEM

The system used in this study consists of small, light, and cheap GPS instrument which was developed specifically for engineering measurement and monitoring center which uses the Internet. Figure 1 shows the concept of this GPS automatic displacement measurement system, and figure 2 demonstrates the outline of GPS instrument for engineering measurement.

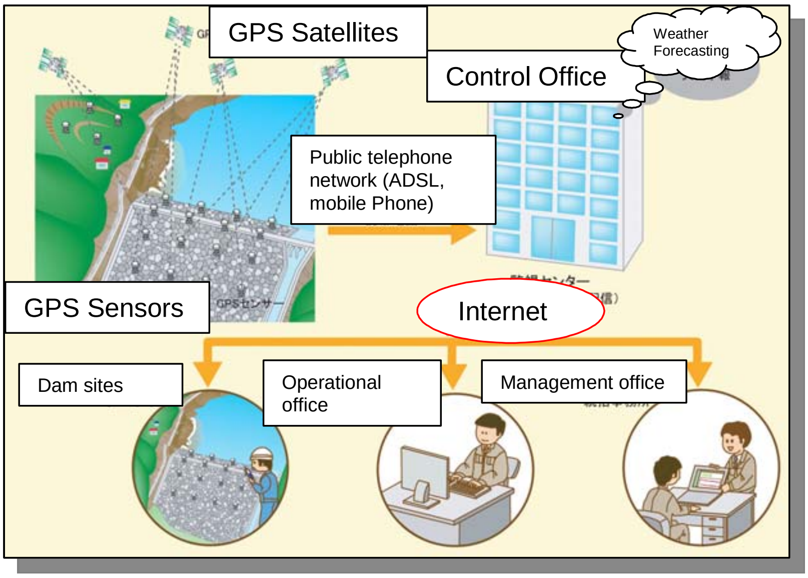
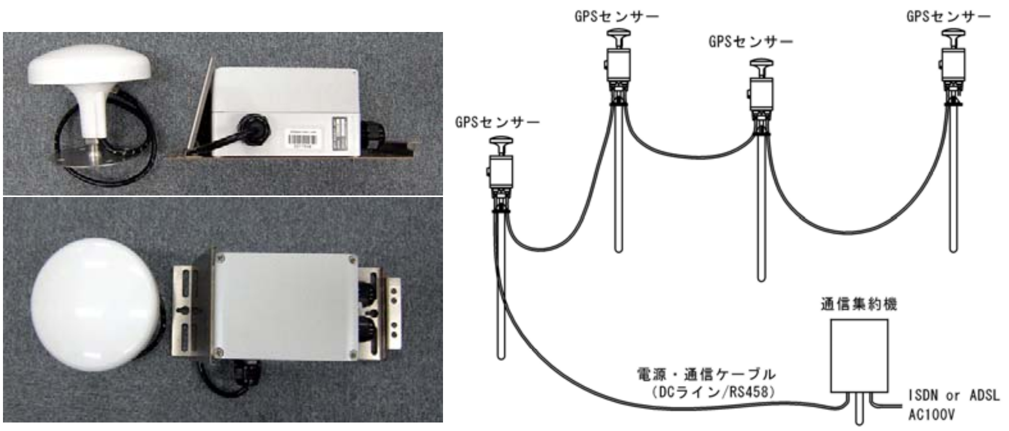


Fig. 1
Concept of GPS automatic displacement measurement system



(a) GPS Sensor (b) Line Layout

Fig. 2

Images of GPS monitoring system

Firstly, GPS sensor and intensive equipment for communication are installed on sites. The data received by the sensor are collected in the equipment to transmit to the monitoring center via public circuit (ISDN, ADSL, 3G Mobile telephone, etc.). In the monitoring center, baseline analysis is performed by static positioning to correct errors by the trend model described below, followed by compiled displacement graph, planar vector chart, and so on. These results are distributed via the Internet hourly to dam managers. Moreover, in the center, engineers stay and monitor on a 24-hour basis, confirm the condition of instruments and values, and make emergency contact with dam managers in case of displacement.

Analyzing and processing intensively GPS values collected from all over Japan, the cost per site can be significantly reduced to provide a benefit of this method. Use of the Internet allows monitoring of the results (available by mobile phones) as well as support of monitoring in the night by fewer engineers, additionally contributing to reduction of communication cost.

Also, in order to ensure security on leakage of results and the related information, entry of ID and password and encrypted SSL are implemented for access to the Internet.

2.3. IMPROVEMENT OF MEASUREMENT ACCURACY BY MODEL

In GPS measurement, various error causes including satellite constitution, skyward angular range of view, the distance between benchmark and measured point, meteorological condition, and reflected wave by trees or mountain induce fluctuation of GPS values, making it difficult to determine displacement in millimeters by usual analysis of base line even with static positioning of the highest accuracy. Then, in the system used for this study, time-series statistical processing (error processing) by the trend model, proposed by Shimizu, *et al.* [2],[3],was introduced.

This method is to estimate actual displacement behavior from GPS values including noise by using a time series analysis model with a probability structure called " trend model [4]" . Specifically the actual displacement u_n at the nth measurement estimated is parameterized in a system equation, a trend components model. Then, actually measured displacement y_n is related to an observation equation to use the below simultaneous model (trend model).

$$\Delta^{\kappa} u_n = v_n \quad \text{(System equation)} \qquad (1)$$
$$y_n = u_n + w_n \quad \text{(Observation equation)} \qquad (2)$$

However, v_n represents system noise with mean value of zero and standard deviation τ while w_n is observation noise with average value of zero and standard deviation σ, following normal distribution. Also, *Δ* means a time difference operator, showing that *Δ κ* is the difference for *κ* times. In analysis, applying the Karman filter algorithm to the trend model, the values are smoothed to evaluate the variance value of observation noise and system noise using maximum likelihood method. Model order *κ* is estimated to minimize AIC (Akaike's Information Criterion) [5].

Yamaguchi, *et al.* [6], and Soda, *et al*. [7] introduced the GPS automatic measurement system on a trial basis for external deformation measurement of fill dam body in some cases. By comparing the results between electro-optical distance measurement and leveling, it was confirmed that time series statistical processing (error processing) with trend model virtually led to GPS measured values with 1 to 2 mm of accuracy.

In this paper, the data are described as GPS values before time series statistical processing and as GPS measured values after the processing.

3. CONSIDERATION OF APPLICABILITY TO ACTUAL DAMS AND TECHNOLOGICAL DEVELOPMENT

Prior experiment in Agigawa dam showed four problems in the measurement, first is issues about displacement measurement, second is issues in snowfall area, third is issues about fluctuation, fourth is cost issues.

1) In earthquakes, etc. when rapid displacement occurs, if it is possible to detect large displacement by using data, for example, after an hour of the outbreak, it is considered very useful in safety management of dams.
2) GPS receiver is usually installed on the supports of measure points. In snowfall areas, however, problems such as impossible measurement due to snow-buried receiver, bent supports induced by snow pressure, and abnormal measured values may occur.
3) "Fluctuation" at points of large elevation difference from the benchmark seems to be caused by atmosphere delay error, which occurs at time of baseline analysis.
4) When this GPS measurement is used for all external target points, the cost for GPS measurement in one point is higher than that for electro-optical distance measurement in one point.

Based on these issues, the following technological development and investigation were conducted according to accuracy, representativeness, and timeliness.

3.1. TECHNOLOGICAL DEVELOPMENT FOR RAPID DISPLACEMENT MEASUREMENT

In recent years in Japan, with large scale earthquakes frequently occurring, many cases reported that fill dam body exposed to strong motion caused permanent displacement/settlement. Inspection on a temporary basis is implemented when an earthquake exceeding 25cm/s^2 of acceleration occurs in dam foundation to measure displacement/settlement. Then, observers need to visit the site and arrange data after electro-optical distance measurement, and this contributes to insufficient promptness of the report. Hourly GPS measurement led to consideration of prompt report about deformation amount at time of earthquakes, etc. Also, two items were considered: investigation of necessary time to determine accurate displacement and investigation of methods to detect large displacement in one to three hours after earthquakes.

Oie, *et al.* [1] showed that, prompt report should made of evaluation by Z estimation(eq.3) until 5 hours later after the shock, and report including reliable numerical information within 24 hours with the trend model. Showed in figure 3 [8].

Figure 3 shows evaluation by Z estimation is the most appropriate model for detection of sudden displacement. In case of 30 mm of displacement, such detection with Z estimation up to three hours after earthquakes at NS direction and up to five hours after these at UD direction should be performed. Subsequently, the values after error processing by the trend model should be used to make prompt report about displacement during two to three hours and such report including reliable numerical information within 24 hours. And more, this system works only in the data centre, and do not require of any changes on the field, so we can use it easily.

$$m = x \pm Z(\alpha/2)\frac{u_2}{\sqrt{n}} = x \pm Z(\alpha/2)\frac{\sigma}{\sqrt{n}} \qquad (3)$$

α: Confidence probability

	Displacement	Standard deviation	Number of data elements
Before earthquake	Known (p)	Known (σ)	100 or more
Immediately after earthquake	Variance (x)	Variance (u)	Variance (n)
After earthquake	Unknown (m)	Known (u_2)= (σ)	100 or more

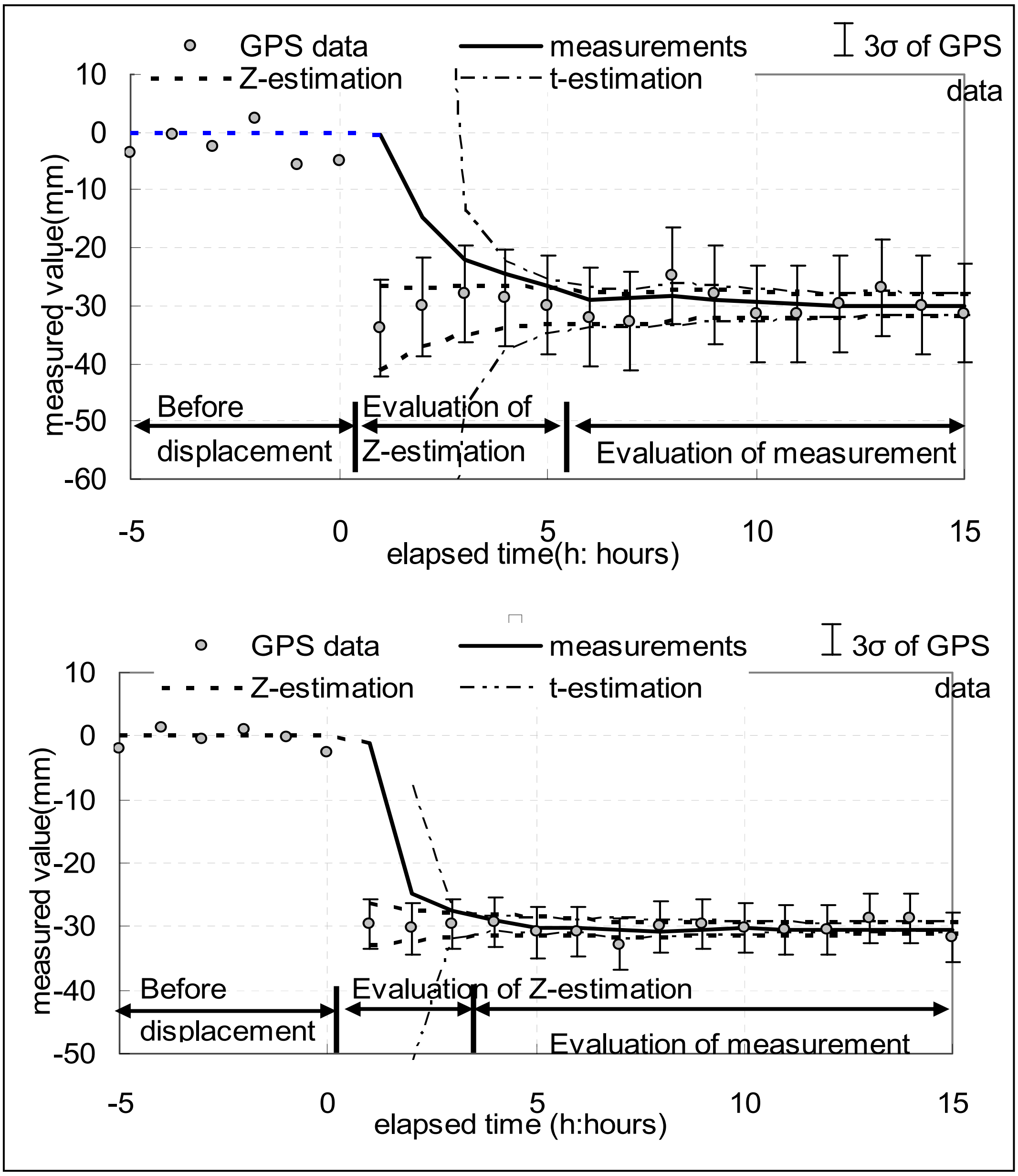


Fig. 3
Result of examination upon occurrence of sudden displacement of 30 mm (GD-6)

3.2. TECHNOLOGICAL DEVELOPMENT FOR FILL DAM MEASUREMENT IN SNOWFALL AREAS

In GPS measurement, antennas are usually installed with about 1 m of supports to improve radio reception condition. Fill dams in snowfall areas, however, have the following problems.

1) GPS measurement instrumentation buried by snowfall may prevent

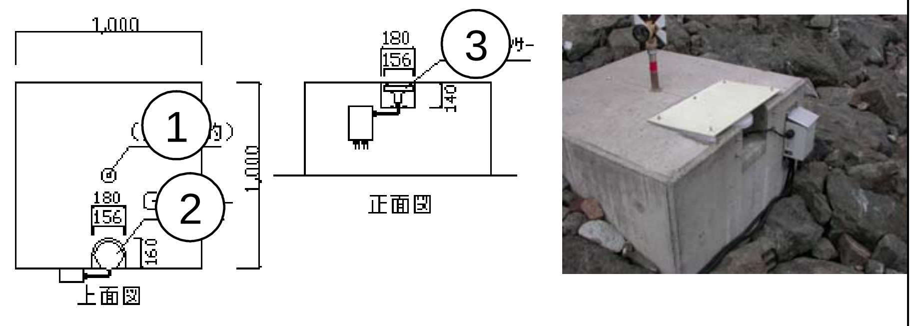
measurement to lead to insufficient timeliness.

2) Snow pressure may cause failure of GPS instrumentation and deformation of supports.
3) GPS instrumentation may be damaged at the time of snow removal.

Then, the authors devised an installation method for easy snow removal, “ target buried type GPS” [9] (figure 4). This aims to avoid damages of instrumentation by burying GPS antenna in external targets and installing FRP (fiber reinforced plastic) cover (6 mm in thickness), which promotes electric wave transmission, into the upper antenna.

Figure 5 shows GPS measurement result of snow resistance type installed at the dam crest of the Tokuyama Dam body. Beginning from the top, the charts represent displacement in upstream and downstream directions, displacement in the dam axis direction, settlement in vertical directions, and reservoir level in time history, respectively. In the displacement graphs, small points show GPS measurement results before error processing while solid lines show results after the processing by the trend model with electro-optical distance measurement ones (white circles).

GPS measurement was started just before the first impounding, having continued stable measurement for about year and a half.



1 Optical target

2 GPS Sensor

3 GPS Sensor

Fig. 4
Target buried type GPS

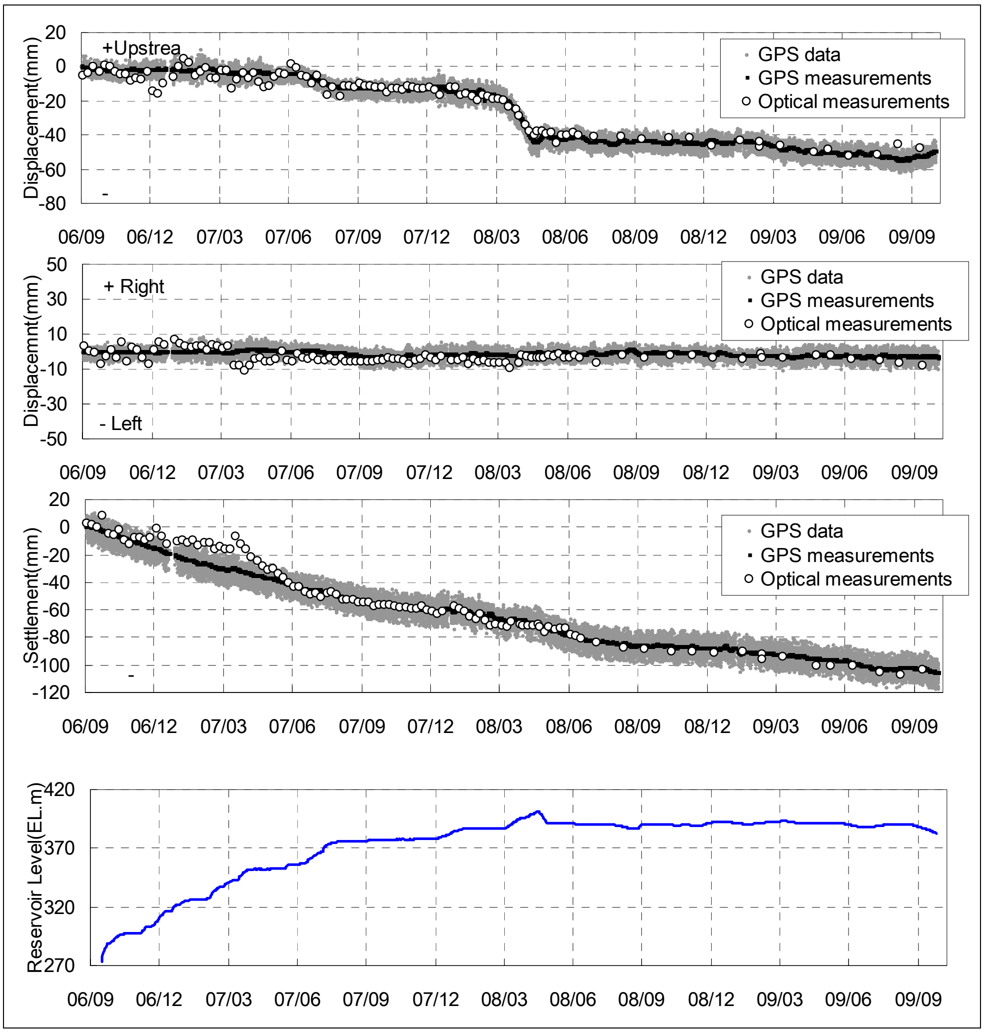


Fig. 5
Measurement result of a Target buried type GPS

The missing data in the figure 5 (between Dec to March, every year) was due to the timing immediately after snow accumulation. Installment of FRP cover facilitated snow removal to shorten the period of missing data. The displacement in GPS measurement, before and after the missing data, showed continuity with no value changes to virtually correspond to that of electro-optical distance measurement.

The above result found out that the target-buried type of GPS installed in the Tokuyama Dam body was convenient for timely measurement even in heavy snowfall areas where missing data occurred due to snowfall. In addition, in snowfall areas, electro-optical distance measurement could not be performed in many cases, but the target-buried GPS could accommodate in such snowfall. What we should do is to kick the snow to remove after the snowfall.

3.3. TECHNOLOGICAL DEVELOPMENT FOR IMPROVEMENT OF “ FLUCTUATION”

The authors have obtained good results under stable operation since measurement start by applying GPS automatic measurement system to external deformation of fill dam body in some cases. Meanwhile, in case of significant difference between benchmark and measured points, minimal seasonal variation (called fluctuation) of vertical GPS measured values has been confirmed. Figure 6 shows relations between vertical GPS measured results and vapor pressure in the largest difference of height (79.3 m) between benchmark and measured points in the Tokuyama Dam body measurement. This figure suggests vapor pressure (amount of water vapor in the air) varies significantly according to the season. In GPS measurement in which the difference of height between benchmark and measured points is large, vertical measured values (black line) indicate fluctuation depending on vapor pressure changes (gray line).

The studies performed by Masunari, *et al.* [10] indicate that fluctuation amount of GPS measured values in the height direction corresponds to the height difference between the benchmark and the measured points and the use of meteorological data (temperature, atmosphere pressure, and relative humidity) near the surface as of measurement allows fluctuation correction.

It is not always easy, however, to incorporate acquired real-time data into GPS measurement in sites. Thick fog and cloud (liquid water floating in the air below the temperature of dew point) sometimes cover the dam sites, may cause the correction deviation only with use of vapor amount. Then, the authors devised a method to estimate fluctuation amount from GPS results by setting benchmarks (fixed points) in two sites of elevation gap.

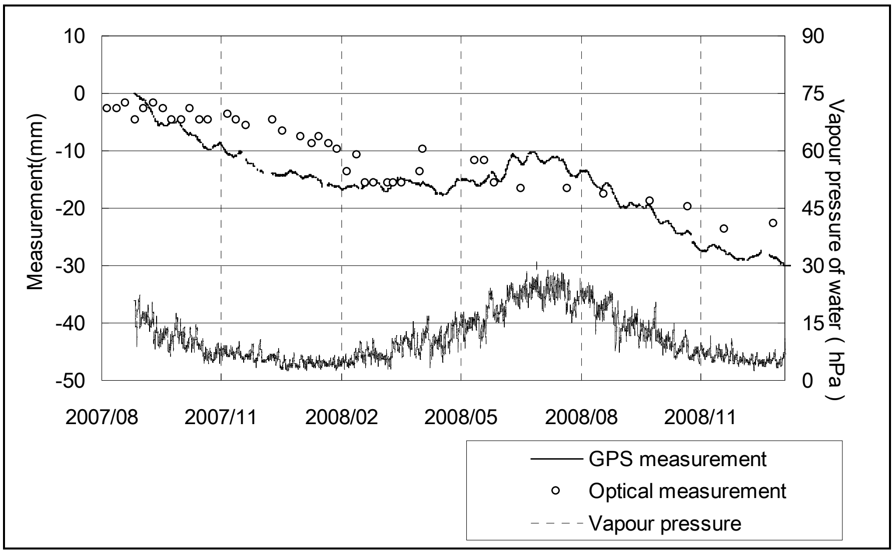


Fig. 6

Relations between vertical GPS measured results and vapor pressure (79.3 m)

Figure 7 shows vertical GPS results between two benchmarks with elevation gap (26.2 m). The displacement between benchmarks, set on the fixed ground, will be always kept nearly at zero but the measured values in the figure demonstrate ±3 mm of fluctuation depending on the vapor pressure variation. Iwasaki, Soda, *et al.* [11] suggest that fluctuation amount is proportional to the difference in elevation between measured points.

Based on the above facts, a method was devised to provide vertical displacement amount between benchmarks of elevation difference Hk or fluctuation amount Tk, and then fluctuation correction value K was calculated according to elevation difference H from benchmarks in measured points.

$$K = M - Tk \times (H/Hk) \qquad [4]$$

K : Fluctuation correction amount (mm)
M : Value before correction (mm)
Tk : Value between benchmarks (mm)
H : Elevation difference between measure point and benchmark (m)
Hk : Elevation difference between benchmarks (m)

In figure 8, the result after correction, which was provided by deducting fluctuation correction amount in equation (4) from GPS measurement result (fine line), was described by bold lines.

As the figure shows, fluctuation correction with use of equation (4) can remove fluctuation in GPS measured values.

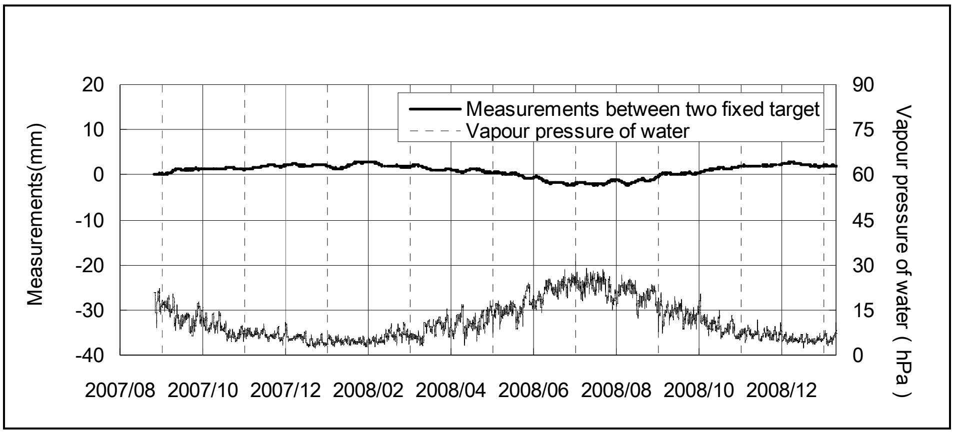


Fig. 7
Vertical GPS results between two benchmarks with elevation gap of 26.2 m

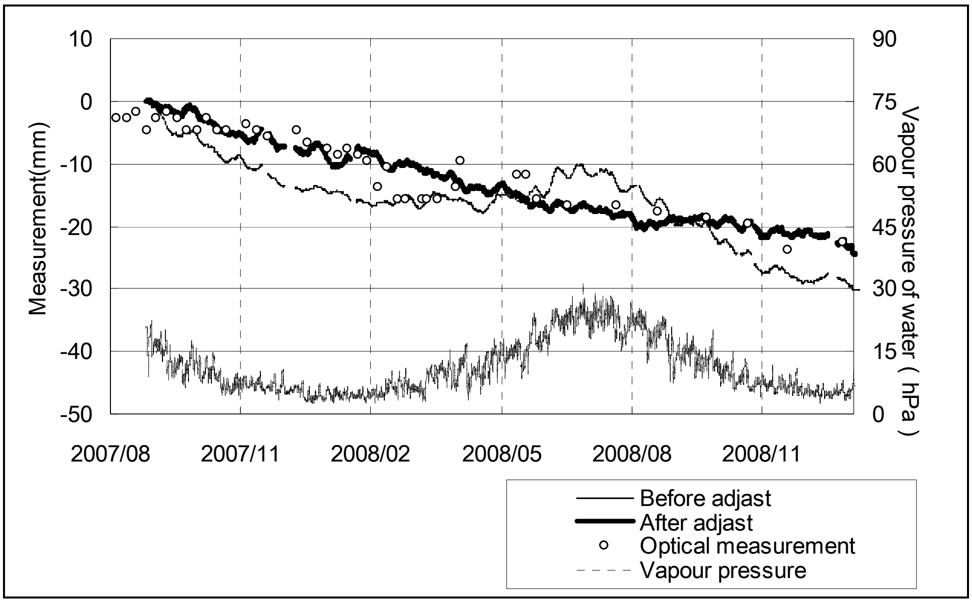


Fig. 8.
Before and after correction of fluctuation by eq. (4)

3.4. INVESTIGATION OF LAYOUT PLAN FOR GPS MEASUREMENT INSTRUMENTATION TO APPLY TO ACTUAL DAMS

This section examines a measurement method to contribute to cost reduction to make up for deficits of existing measurement by using advantages of GPS measurement. When GPS measurement is applied to actual dams, it is highly characteristic to obtain real-time data. That is why GPS measurement in all points will lead to upgrading of measurement but high cost.

For this consideration: 1. GPS measurement should be arranged based on the representativeness of measure points to confirm by existing measurement in case of abnormality detected visually or in GPS measurement; 2. For ensuring measurement accuracy, confirmation of accuracy should be made by using simultaneously existing measurement and GPS for a certain period of time along with routine accuracy examination.These two points are thought to be important.

Figure 9 shows the layout of instrumentation during first impounding in the Tokuyama Dam. In this case, in consideration of terrain conditions, a total of seven instrumentations were arranged at dam crest and maximum cross section of the dam where behavior is most likely to appear. The purpose of this is to monitor continuously displacement and settlement tendency in the dam body, caused by water pressure and gravity. In Tokuyama dam, measurement was started by this layout in Sept. 2006. After that, Yamaguchi, *et al.* (2008) [12] showed how to layout GPS sensors.

Depending on the behavior during first impounding, layout of GPS measurement should be reviewed. In figure 9, circled GD-5 and GD-11 is the layout of several years after the first impounding. Measurement aims to confirm the stability of behavior over time and to serve temporal investigations in earthquakes, etc. Therefore, only two or three of targets can be monitored continuously by GPS, so electro-optical distance measurement in other points is needed only once a year or after an earthquake.

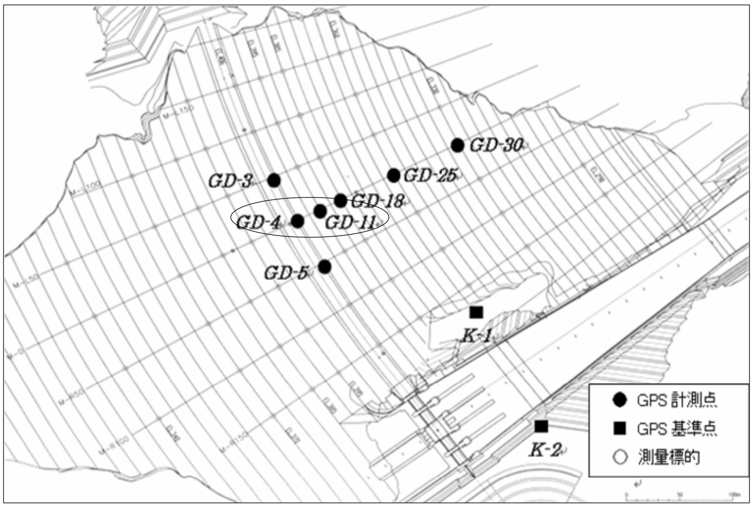


Fig. 9
Layout of GPS measurement during first impounding

4. GPS MEASUREMENT DURING FIRST IMPOUNDING IN ACTUAL DAMS

4.1. ACTUAL DAMS APPLIED

GPS measurement during first impounding in actual dams was carried out in the Tokuyama Dam. The Tokuyama Dam is a central core rock fill dam with 161 m of height and 13,700,000 m3 of volume, the largest rock fill dam in Japan.

Exterior deformation in the dam body has been measured by introducing GPS measurement system since September 2006 when first impounding was started. As mentioned in above, GPS measured points were set in seven external targets of maximum cross section and crest two benchmarks were set on fixed ground with elevation gaps.

As table 1 shows elevation gaps of each GPS measured point and benchmark, the maximum elevation difference was approximately 80 m and GPS measured values in the vertical direction indicated distinct fluctuation. Thus, fluctuation correction, described in the section 3.3, has been performed in all GPS measured points since September 25, 2007. In addition, the dam is located in snowfall area, and " target buried type GPS" , devised in section 3.2, was adopted. " Rapid displacement measurement" devised in section 3.1 was also implemented on the measurement.

Meanwhile, weekly measurement of the dam body has been conducted by electro-optical distance measurement in all points.

Table.1

Elevation gaps between target and benchmarks

Measured point	Elevation difference (m)	
	Benchmark K-1	Benchmark K-2
GD-3	25.4	-0.8
GD-4	25.6	-0.7
GD-5	25.4	-0.8
GD-11	12.1	-14.0
GD-18	2.0	-24.3
GD-25	-23.1	-49.4
GD-30	-53.1	-79.3
K-2	26.2	-

4.2. GPS MEASUREMENT RESULT IN TOKUYAMA DAM

Figure 10 shows the result after fluctuation correction in the dam section of GPS measured points. The figures represent measurement result of the upstream and downstream direction, right and left bank, and settlement in vertical direction orderly from the top. The results by electro-optical distance measurement performed in the same site are also included as circles. At the bottom of each chart, reservoir level in time history are demonstrated. The reservoir level started to rise from around December 15 2007 to reach the highest high-water level as of April 21, 2008 (EL.401.01 m). Subsequently, rapid drawdown up to May 5 2008 virtually remained at EL. 391 m.

According to the GPS measurement results, displacement in the downstream and settlement direction drastically increased in response to the reservoir level increase. Subsequent stabilized water level resulted in gradual increase in displacement. Displacement in the direction of right and left shore was smaller than those in the upstream and downstream direction and the vertical direction while displacement in the downstream and settlement direction was distinctive in the principal section of the body. GD-11 and GD-18 with high dam height indicated large displacement amount with a tendency of smaller displacement amount in accordance with lower dam height.

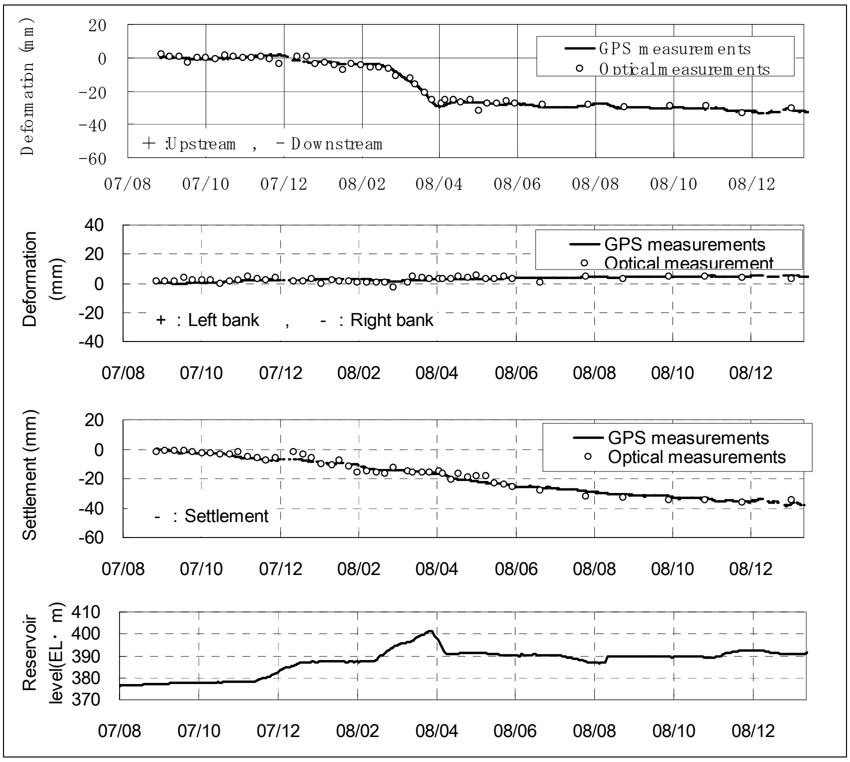


Fig. 10(a)

Measurement result of result after fluctuation correction (GD-4)

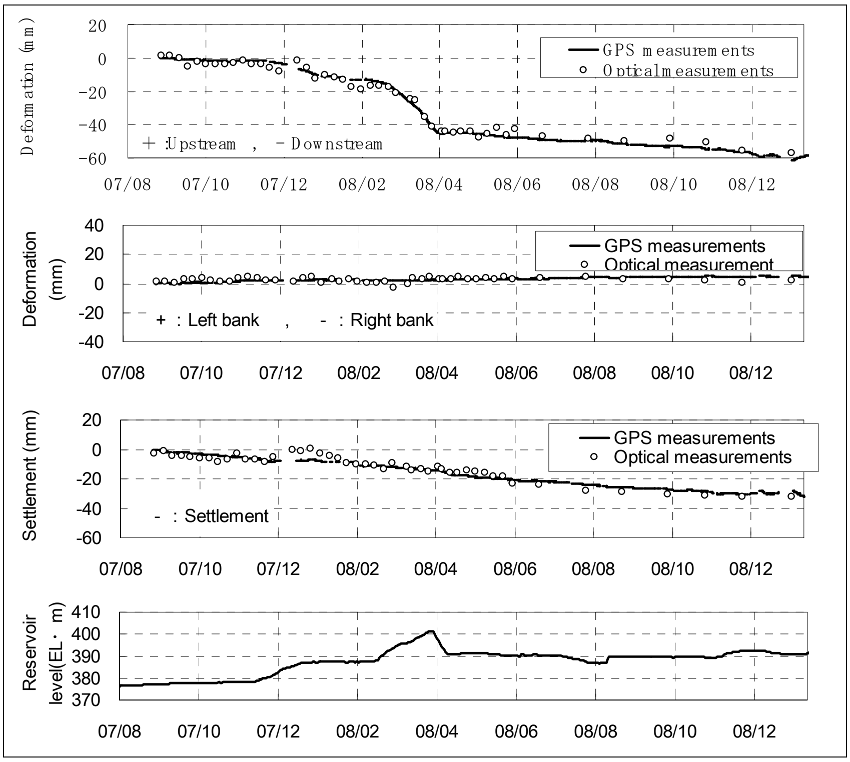


Fig. 10(b)

Measurement result of result after fluctuation correction (GD-11)

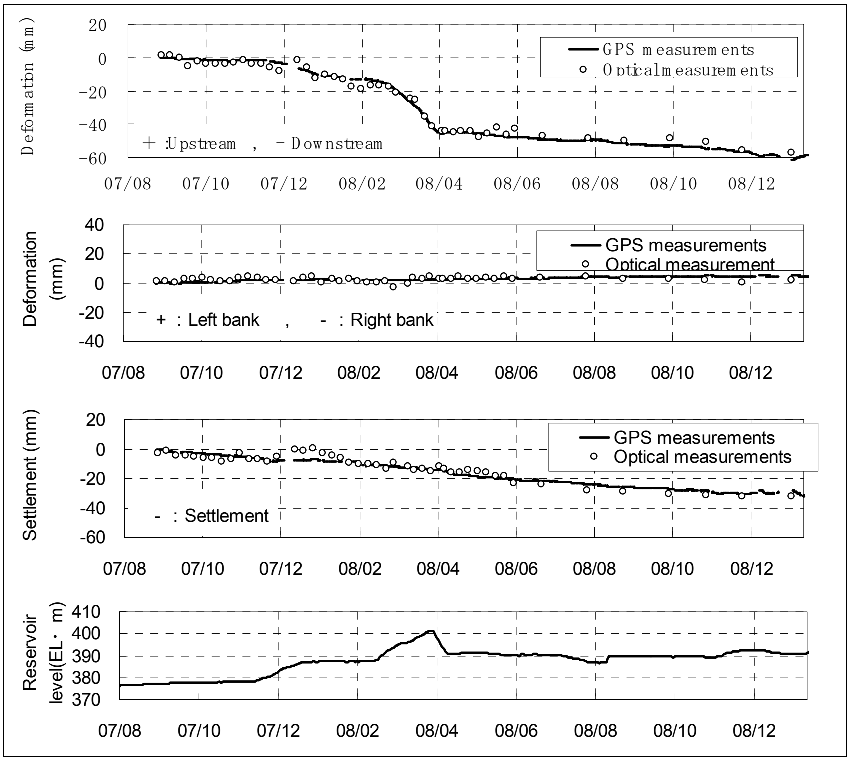


Fig. 10(c)
Measurement result of result after fluctuation correction (GD-30)

4.3. EVALUATION OF MEASUREMENT RESULT IN THE TOKUYAMA DAM

GPS automation measurement system, installed in the Tokuyama Dam body, could continuously obtain data other than in two data missing due to snow, and this system is under steady operation now. Even in the above two failures, adopted " target buried type GPS" enabled the data missing period to shorten dramatically and measurement to resume by simple snow removal with shovels or foot in the target site without long-period measurement failure.
Furthermore, according to the result of electro-optical distance measurement in the same points, both results of GPS measurement and electro-optical distance measurement demonstrated high consistency in all points, proving enough accuracy of GPS measurement in which fluctuation correction was conducted as in 3.3.

5. SUGGESTION OF UPGRADING/RATIONALIZATION IN FILL DAM BODY MEASUREMENT WITH USE OF GPS

Using the above results, application of GPS to fill dam body measurement will be evaluated.

5.1. EVALUATION AS USUAL MEASUREMENT

The findings obtained in the Agigawa Dam and the Tokuyama Dam suggest that GPS measurement is a method with secured accuracy because it provides required accuracy as a usual method. In events like dam behavior during first impounding where certain prediction of displacement distribution can be made as well as displacement at earthquakes, necessity of measurement in all points can be determined based on the behavior of representative points. As far as measurement in snowfall areas is concerned, the buried type instrumentation installment, which prevents damages by snow, can lead to measurement with long durability.

This implies that measurement for fill dam management by GPS measurement and less frequent electro-optical distance measurement in representative points is a rational way with cost effectiveness and reliability.

5.2. NEW EFFECTS FROM GPS MEASUREMENT

In measurement of dam body deformation, electro-optical distance measurement used to be the only method, which entailed errors from various factors. Combined use with GPS measurement will allow consideration methods with higher accuracy of electro-optical distance measurement. Safety management of improved structures, which cannot be addressed by existing methods, will become possible by prompt reports about existence of displacement at time of substantial fluctuation of water level or just after huge earthquakes and accurate measurement of deformation amount within 24 hours.

6. CONCLUSION

The authors have implemented the GPS measurement in fill dam body as an approach to advanced cases. The four issues occurred in this approach could be solved as in section 3.1 to 3.4 respectively. From the approach to these issues, an observation method with both GPS measurement and electro-optical distance measurement was proposed for measurement of fill dam body with accuracy, representativeness, and timeliness.

The possible issues will be feasibility investigation of these methods and further policies for cost reduction.

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SUMMARY

Recently in Japan, approaches by Global Positioning System (GPS) have been made for the purpose of displacement measurement of large excavation slopes, landslides, and so on. In using this system, it was clarified four issues on measurement of displacement of fill dams.

Providing further insights for solving these issues, some kinds of technological development were made from installation method to data processing. As a result, it was confirmed that GPS measurement could be used for external deformation of the fill dam body in the Tokuyama Dam and implementing measurement with it from the start of first impounding of the reservoir to the present day.