APPLICATION OF A GPS DISPLACEMENT MEASUREMENT SYSTEM FOR CONCRETE GRAVITY DAMS

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ABSTRACT

Displacement is one of the most important measuring items for safety management of dams. We made a research to develop a GPS (Global Positioning System) displacement measurement system for monitoring exterior deformation of embankment dams in Japan, then verified that this system can achieve sub millimeter level resolution using appropriate error processing. Also, we created "Engineering Manual on the Introduction of GPS to the Displacement Measurement for Safety Management of Embankment Dams (2014)" (JSDE, 2014). In the next step, we applied the system to measure dam body deformation of concrete gravity dams, where displacement is smaller than that at embankment dams. Gravity-based plumb lines with high precision are generally installed in concrete gravity dams. However, it is difficult to install several plumb lines in a dam because of restriction in cost and workability. This paper introduces three case histories of GPS displacement measurement system application to concrete gravity dams: strong correlation between GPS data and plumb line data could be found. Finally, we proposed an appropriate application method of the GPS displacement measurement system for concrete gravity dams.

1. INTRODUCTION

In the safety management of dams in Japan, displacement monitoring for dam bodies by means of the Global Positioning System (GPS) is being developed and introduced. GPS displacement measurement system has already been introduced and applied to many embankment dams in Japan, thereby helping rationalize and enhance safety management.

The displacement of concrete gravity dams is now measured primarily using plumb lines. This is an extremely high precision method, but because it is costly and greatly impacts the construction works, they are generally installed in 1 or 2 representative blocks (monoliths). But because a concrete gravity dam is constructed with transverse joints dividing the dam body into blocks, adjacent blocks can display differing displacement behavior according to geological and topographical conditions of dam foundation. It is extremely important to perform the inspection with such characteristics in mind when inspecting a displacement behavior, in particular after a large-scale earthquake. To settle these issues, we have conducted a study to verify the applicability of a GPS displacement measurement system, which has already been developed and applied to many embankment dams, to concrete gravity dams.

2. APPLICATIONS OF GPS DISPLACEMENT MEASUREMENT SYSTEM FOR DAMS

In Japan, a GPS displacement measurement system has so far been introduced mainly in embankment dams. This system is introduced to rationalize and save labor in measurement in normal states. Then, when an earthquake occurs or in other emergencies, much speedier measurement can be performed than in conventional practice (Kobori et al., 2015). Thus, this system that enables 3D displacement to be measured automatically and continuously has been introduced, and applied to more than 20 embankment dams to help rationalize and enhance safety management. “Engineering Manual on the Introduction of GPS to the Displacement Measurement for Safety Management of Embankment Dams (2014)” (JSDE, 2014) has been compiled to demonstrate an effective and efficient method for applying GPS displacement monitoring to embankment dams in Japan.

3. GPS DISPLACEMENT MEASUREMENT SYSTEM

Figure 1 shows what a typical structure of GPS displacement measurement system applied to dams in Japan. Each GPS displacement measurement system is composed of a GPS sensor and a data logger with communication function. The sensor is connected by cable to the data logger with communication function in order to send and receive data, and supply power (Yamaguchi et al., 2007). For three case histories explained later in this paper, we: [1] observed the carrier phase of the signal sent from an GPS satellite at time intervals of 30s, [2] determined the coordinates of different measurement points by the static method of relative positioning (Yamaguchi et al., 2007) based on observation data, and [3] measured displacements based on changes in the coordinate values of the measurement points every hour.

Moreover, in measuring displacements of the dam body by GPS, it is necessary not only to perform baseline analysis, but also to apply various corrections and smoothing to increase measurement precision. Measurement precision is enhanced by smoothing using the trend model (Yamaguchi et al., 2007), and as necessary by reducing the influence of overhead obstacles (Masunari et al., 2008) and correction by tropospheric delays (Masunari et al., 2007).

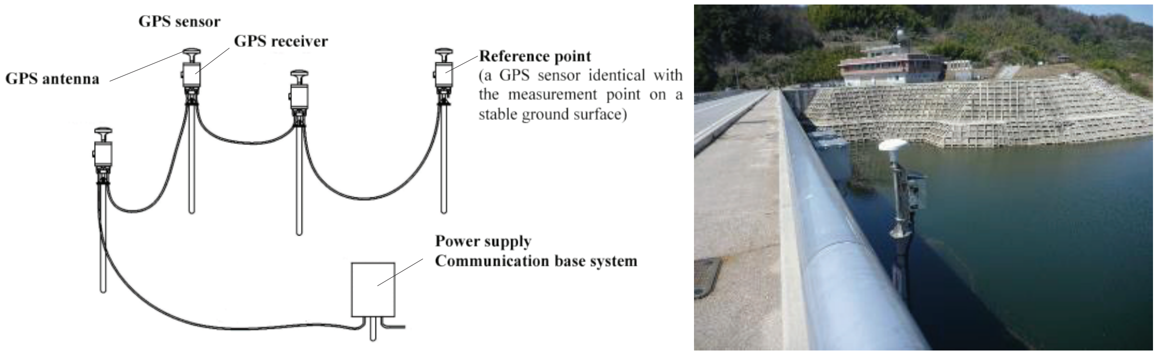


Figure 1 : GPS displacement measurement system

4. EXAMPLES OF GPS DISPLACEMENT MEASUREMENTS OF GRAVITY DAMS

This paper presents some application examples of GPS displacement measurement system to concrete gravity dams. The dams presented here are three concrete gravity dams of the order of 100 m height in Japan, as shown in Table 1. Table 1 also indicates the objectives of the measurements taken for each dam.

4.1 Nagai Dam (Kobori et al., 2012)

4.1.1 *Overview of GPS displacement measurement*

At the Nagai Dam, we performed trial measurements in order to compare displacements measured by an existing plumb line, with those measured by a GPS displacement measurement system.

Figure 2 is an upstream longitudinal section marked with the positions where the GPS sensors are installed. The GPS sensors were installed as follows: three moving points, G-1 to G-3, on the top of the dam, and a fixed point as the reference point on the left bank mountain which is unaffected by dam displacement behavior. In the figure, the positions of the GPS sensors are shown, G-1 was installed on BL15 with the normal plumb line (abbreviated as “NPL” in the figure), DN-2, while G-2 was installed on BL20 with NPL, DN-1 and the reverse plumb line (abbreviated as “RPL” in the diagram), DR-1 is installed. DR-1 is designed to monitor the displacement behavior of a portion along a low-dip fault, CF-12.

4.1.2 *Displacement measurements*

Among the displacement measurements, upstream/downstream (U/D) displacements are introduced here.

(1) GPS measurements

Figure 3 (a) shows U/D displacements measured by GPS. U/D displacements measured by GPS did not show much downstream displacement while the reservoir water level remained at about the low water level (EL.322.0 m, hereafter “L.W.L.”) from the start of trial impounding until March 2010. Then, as the reservoir water level was raised from L.W.L. to the normal water level (EL.367.30 m, hereafter “N.W.L.”), every measurement point showed a downstream displacement of about 5 mm. After that, as the reservoir water level was raised to the surcharge water level (EL.392.10 m, hereafter, “S.W.L.”) on April 29, 2010, the downstream displacement rose according to a change in reservoir water level, resulting in a maximum downstream displacement of 29.0 mm at G-1 at S.W.L.

Table 1 : Dams presented

Name of dam	Manager of dam	Height/ Crest length/ Dam volume	Duration of displacement measurement by GPS	Objectives of measurement
Nagai Dam	Tohoku Regional Development Bureau, MLIT*	125.5m /381.0m/ 1,200,000m^3	Nov. 2009 to July 2011	- Comparative assessment of measurements by GPS and plumb line
Obara Dam	Chugoku Regional Development Bureau, MLIT*	90.0m/ 440.8m/ 690,000m^3	Measurement ongoing since Nov. 2010	- Displacement measurement of neighboring blocks - Behavior monitoring of an upstream/ downstream cross section by measuring the top and the toe of dam - Correction by tropospheric delays in GPS measurement
Tsugaru Dam	Tohoku Regional Development Bureau, MLIT*	97.2m/ 342.0m/ 759,000m^3	Measurement ongoing since Dec. 2014	- A study of the effects of multi-pass and snowfall on measurements taken by GPS - A study on reducing the influence of overhead obstacles

*MLIT= Ministry of Land, Infra-structure, Transport and Tourism, Japanese Government

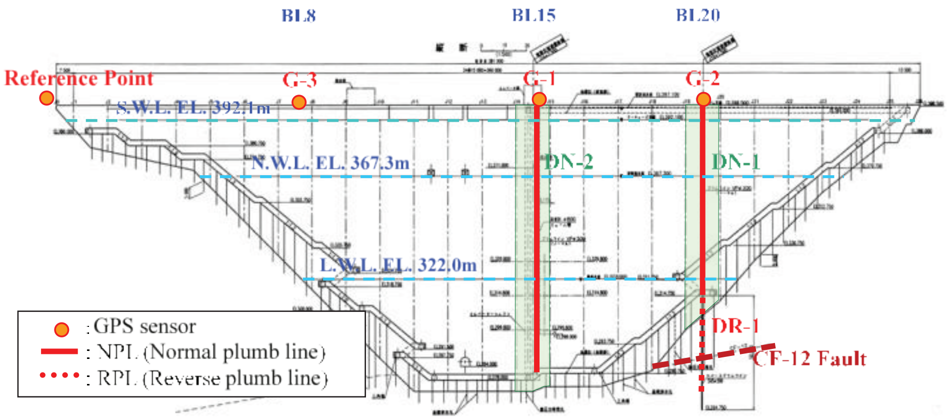
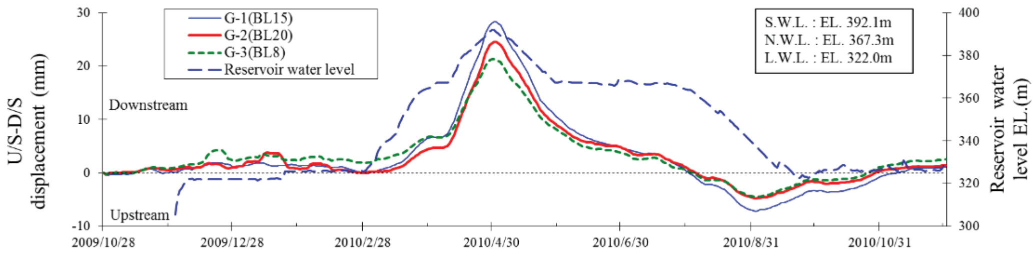


Figure 2 : Locations of the GPS sensors in upstream longitudinal section

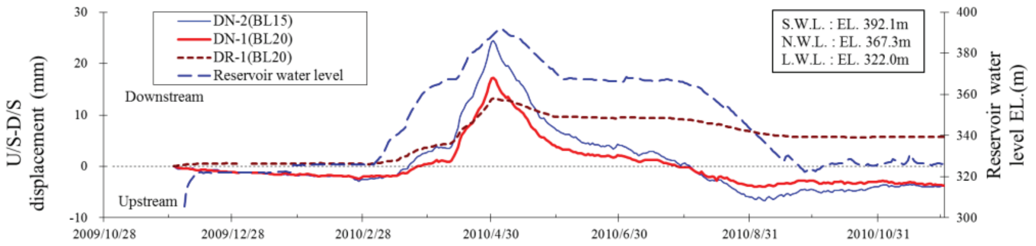
After S.W.L. was reached, upstream displacement occurred as the reservoir water level declined. The reservoir water level was lowered to N.W.L. on May 30, 2010, and then the reservoir water level remained at N.W.L. for about two months, and upstream displacement progressed slightly even on July 26, 2010. One cause of this is presumably that, for this upstream displacement, the portion of upstream face in contact with the reservoir water in the dam changed little in temperature, while the downstream side became distorted due to concrete expansion and shrinkage due to external air temperature, sunshine, and other effects. After that, upstream displacement continued up to an EL. of about 340 m, which is a midway point of the reservoir water level declining to L.W.L. Later, however, downstream displacement occurs again and, since the reservoir water level was kept at L.W.L., it has been approaching the level attained at the start of the measurement.

(2) Plumb line measurements

Figure 3 (b) shows U/D displacements measured by plumb line. U/D displacements measured by plumb line showed upstream displacement by several millimeters for NPLs, DN-1 and DN-2, after trial impounding was started, and while the reservoir water level was kept constant at L.W.L. On the other hand, RPL, DR-1, showed hardly any displacement. While the reservoir water level was at N.W.L., all measurements showed downward displacement. As the reservoir water level was then raised to S.W.L., DN-2 showed a displacement by 23.7 mm, while a displacement by 30 mm occurred as the sum of DN-1 and DR-1, i.e., the sum of the displacement of the dam body itself, and the relative displacements of the dam body and the rock foundation. After that, as the reservoir water level went down to N.W.L., NPLs, DN-1 and DN-2 converted to an upstream displacement, and tended to re-vert to the displacement that occurred at the start of the measurement. RPL, DR-1, however, showed hardly any change. DN-1 and DN-2, which are installed inside the concrete dam body, behaved relatively elastically in response to changes in reservoir water level, while DR-1 anchored in the rock foundation behaved plastically. While the reservoir water level was downward and remained constant at N.W.L.,



(a) GPS measurements



(b) Plumb line measurements

Figure 3 : U/D displacement measurement results obtained by GPS and plumb line

DN-1 and DN-2 kept showing upstream displacement, while DR-1 showed hardly any displacement. It is presumed that here, similarly to GPS measurements, displacement occurred due to the effects of external air temperature and sunshine. The amount of displacement, however, tended to be smaller than GPS measurements. After that, while the reservoir water level was lowered from N.W.L. to L.W.L., DN-1 and DN-2 showed downstream displacement at an EL. of about 340 m similarly to the GPS measurements. Since the reservoir water level remained constant at L.W.L., downstream displacement has been tending to stop.

4.1.3 *Comparison of measurements between GPS and plumb line*

For G-2 and DN-1/DR-1 in BL20, Figure 4 shows the relationship between the reservoir water level and measured displacements. For U/D displacements shown in Figure 4, both DN-1 and DR-1 measurements were smaller than GPS measurements in view of the time when the reservoir water level was upward. For the measurements of both plumb lines, as illustrated in the schematic diagram of measuring locations in Figure 5, the normal plumb line measurement showed NA point displacement with the fixed point NB in the dam body as reference, and the reverse plumb line took measurements of RA point displacements with the fixed point RB in the rock foundation as reference, so the GPS presumably measured the displacement behavior of the dam top with regard to the immovable point in the rock foundation. Now, a synthesis of DN-1 with DR-1 is shown in the diagram DN-1 + DR-1 (hereafter, plumb line synthesis value). As the result of the synthesis, the U/D displacements showed similar trends with regard to measurements taken by GPS and plumb line synthesis value. Looking at the details, however, at a reservoir water level midway during the decline of the reservoir water level, the GPS measurements showed upstream displacement from the initial value of the measurement, while the plumb line synthesis value showed no upstream displacement from the initial value of the measurement. Eventually, the GPS measurement was 1.4 mm in the downstream direction, while the plumb line synthesis value showed a similar measurement: 2.1 mm in the downstream direction.

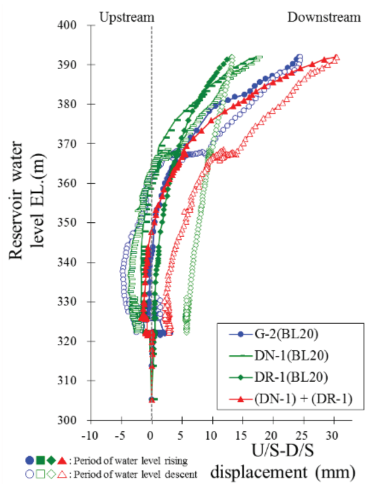


Figure 4 : Comparison of U/D displacement measurements of G-2 and DN-1 + DR-1

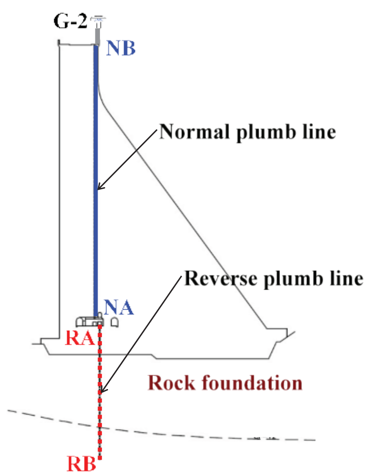


Figure 5 : Schematic diagram of measuring points in BL20

4.2 Obara Dam

4.2.1 *Overview of GPS displacement measurement*

At the Obara Dam, we took measurements to monitor displacement behavior between blocks by measuring the displacements of neighboring blocks, and to clarify the detailed displacement behavior of the dam for the measured blocks in the U/D directions. The latter was done by measuring the displacements of the dam in the same block at the top and at the downstream toe of the dam.

Figure 6 is a downstream longitudinal section showing the locations of the GPS sensors. The GPS sensors were installed as follows: four movable points at the top, G-1 to G-4, and one point at the dam downstream toe, G-5. As a reference point, we installed one sensor on the right bank mountain. We relocated it during measurement to avoid the influence of vegetation causing radio disturbance. The GPS sensor G-3, on the other hand, was installed in BL20 similarly to the normal plumb line [PL (BL20)], as shown in Figure 6.

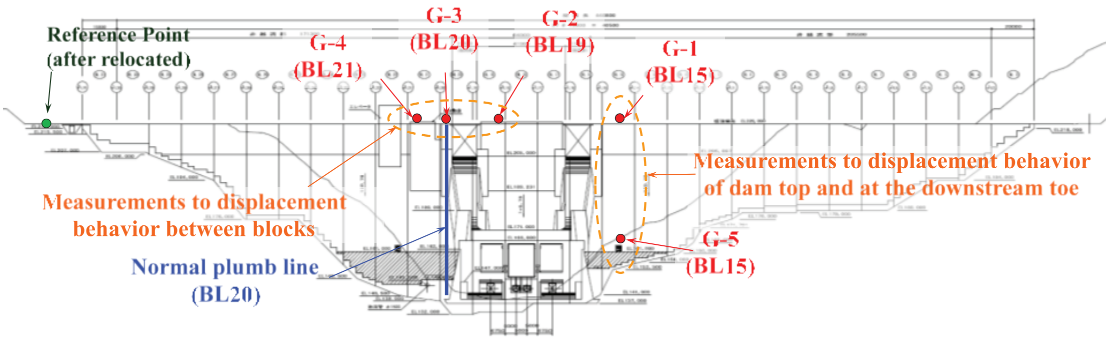


Figure 6 : Locations of GPS sensors in downstream longitudinal section

4.2.2 *Overview of GPS displacement measurement*

Figure 7 shows the displacement measurements taken by the GPS and plumb line (marked "PL" in the diagram). The figures indicate (a) upstream/downstream direction, (b) dam axis direction, and (c) vertical direction, respectively.

Among the GPS measurements, those for the summers in 2013, 2014, and 2015 were regarded as lacking because, in those seasons, no precise measurements could be taken due to thickly-growing plants near the reference point, which blocked radio waves from the GPS satellite. To combat that issue, we relocated the reference point in December 2015 to

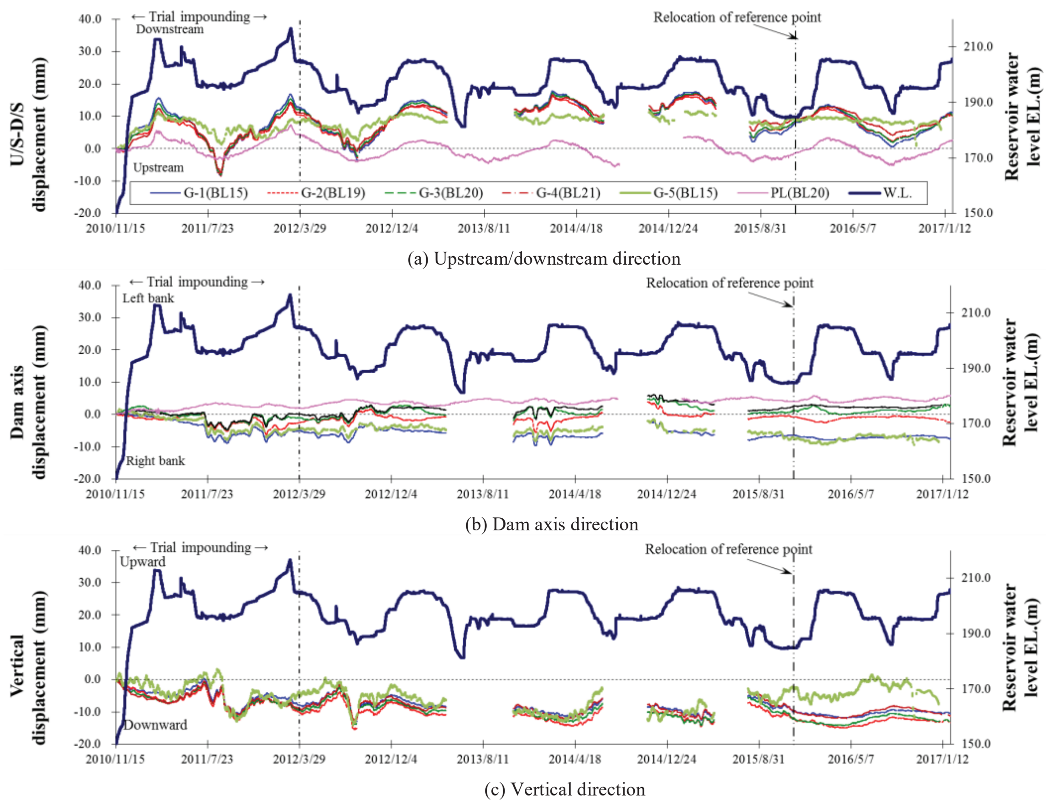


Figure 7 : Displacement measurements

the "relocated reference point", as shown in Figure 8, in order to obtain a sufficient field of view in the sky without being affected by thick vegetation in summer. The plumb line, on the other hand, was faulty in its measurement part between August 2014 and February 2015, and no measurements were subsequently taken.

G-5, which was installed near the downstream toe, on the other hand, underwent a large difference in level between the reference point and the measuring point, resulting in a periodical change in vertical displacement. This prompted us to use corrections by tropospheric delays to reduce the periodic change in vertical displacement (Masunari et al., 2007).

(1) Upstream/downstream displacements

For U/D displacements, the GPSs, G-1 to G-4, installed at the top of dam, showed U/D displacements according to changes in reservoir water level. The GPS, G-5, installed near the dam toe, showed U/D displacement that matches changes in reservoir water level, similarly to the GPSs, G-1 to G-4. It, however, showed a smaller value than other measurement points. Plumb line measurements, on the other hand, proved smaller than those taken by GPSs, G-1 to G-4.

(2) Dam axis displacements

Displacements in the dam axis direction continued toward the left or right bank for some time after the start of trial impounding. In about 2015 and onward, however, displacement showed smaller changes. From the locations of the GPS sensors in Figure 6, the displacements of GPSs, G-2 to G-4, and plumb line, which are on the right bank from the river center, tended toward the left bank, while the displacements of GPSs, G-1 and G-5), which were on the left bank from the river center, occurred in the direction of the right bank. That is, displacement in dam axis direction occurred in a manner trending toward the river center.

(3) Vertical displacements

Vertical displacements tended to decline regardless of changes in reservoir water level. Since December 2015, when consecutive data managed to be obtained at the reference point, the GPSs, G-1 to G-4, installed at the dam top, showed periodic changes. On the other hand, the GPS, G-5, installed near the dam toe, had behaved similarly to the dam top before September 2015, but behaved differently from the dam top in and after September 2015.

Figure 8 shows the measurements taken of the reservoir water levels, and those of U/D displacements, at G-2 in BL19, G-3 in BL20, and G-4 in BL21, installed in three blocks next to each other during the trial impounding period. From the diagram, we can see that the U/D displacements of G-2, G-3, and G-4 showed similar behavioral tendencies. This fact serves as the precondition for our considerations made in the next section.

4.2.3 *Comparison of measurements between GPS and plumb line*

Next, we considered how to use the G-5 installed near the dam toe. To compare dam body displacements, we compared measurements of plumb lines showing the behavior of the dam body at BL20 with the behavior of the entire dam including the rock foundation of G-1 at BL15, less the behavior of a part near the dam toe at G-5, that is, the behavior of the dam body itself at BL15, (G-1 - G-5). This study was conducted in view of U/D displacement.

As a study of dam body displacements, Figure 9 shows the relationship between U/D displacement and the reservoir water level. The figure reveals that the plumb line and (G-1 - G-5) tended to be displaced under changes in reservoir water level, and behaved similarly to maximum values in downstream displacement and other values.

This leads us to conjecture that GPS sensors installed at the top and near the toe of a dam make it possible to measure the behavior of the entire dam including its rock foundation, parts near the dam base, and the dam body, with a certain degree of accuracy.

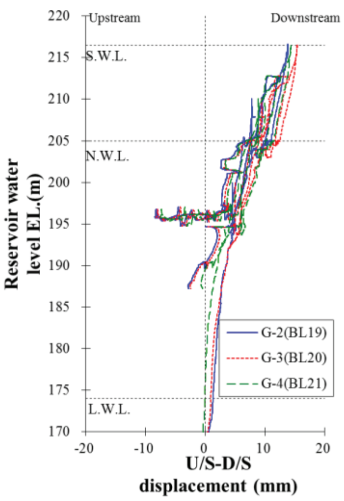


Figure 8 : Comparison of U/D displacements measured at G-2, G-3, and G-4 during trial impounding

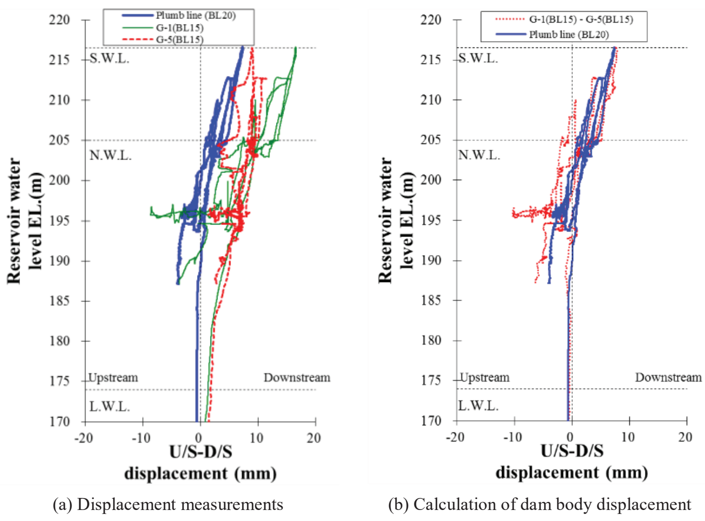


Figure 9 : Dam body displacements

4.3 Tsugaru Dam

4.3.1 *Overview of GPS displacement measurement*

At the Tsugaru Dam, we assessed the measures taken to combat snowfall during GPS monitoring, and to reduce the influence of overhead obstacles on the reference point.

Figure 10 is an upstream longitudinal section showing the locations of the GPS sensors installed. Three GPS sensors were installed: two movable points, G-1 and G-2, on the tops of the dam, and one fixed point, K-1, as the reference point on the left bank mountain which is unaffected by dam behavior. The GPS sensors are, as shown in the diagram, installed as follows: G-1 at BL6, G-2 at BL8 similarly to the normal plumb line 8BL-NP and reverse plumb line 8BL-RP.

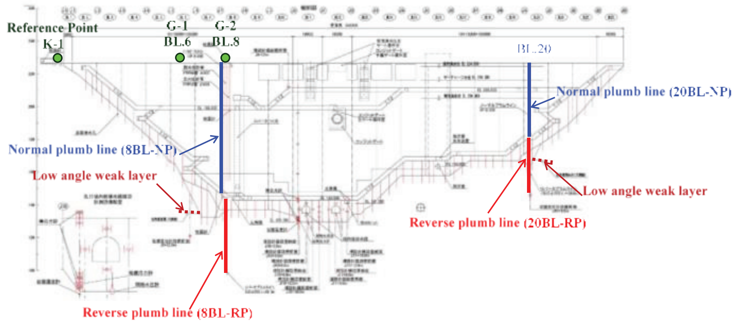


Figure 10 : Locations of GPS sensors (upstream longitudinal section)

4.3.2 *Displacement measurements*

As examples of the displacement measurement results obtained, G-1 measurement results are shown in Figure 11. In the figure, the solid dots indicate the GPS measurements taken before error processing, while the solid lines represent the measurement results obtained after error processing by the trend model. The figure also indicates the reservoir water level.

GPS measurement began in February 2014. Trial impounding at the Tsugaru Dam was launched in February 2016.

The measurements taken reveal that from December 2014, that is, immediately after the start of measurement, to February 2015 [period (1) in the diagram], the GPS measurements showed great disturbance, thereby indicating that no error processing was appropriately done by the trend model.

During the snow-free period, from March 2015 to November 2015 [period (2) in the diagram] also, for both G-1 and G-2, the dispersions of the measured displacement data in the upstream/downstream, dam-axial and vertical directions, and lack of measurement, showed greater results than at positions where displacement was previously measured with GPS at concrete gravity dams.

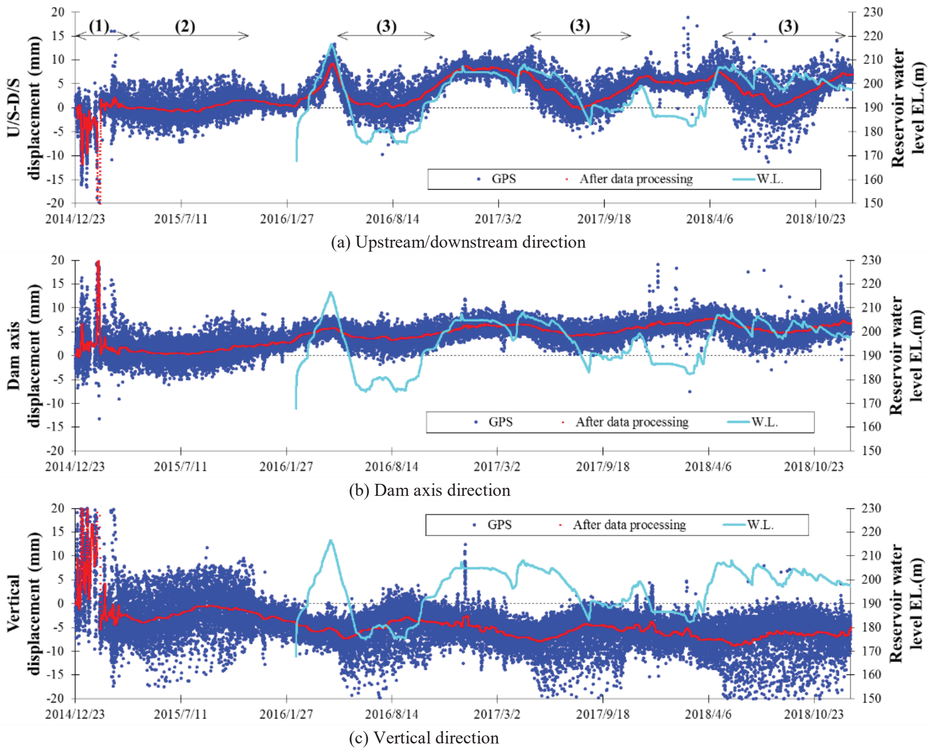
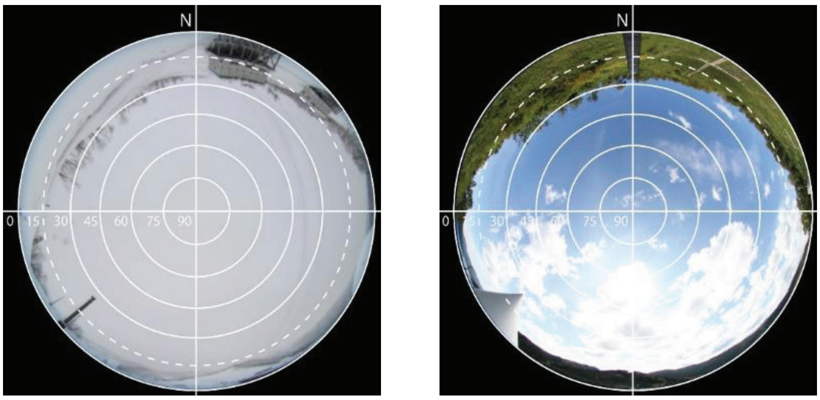


Figure 11 : GPS measurements at G-1 in BL6

This was presumably because the GPS antennas were installed at heights lower than the handrails at the top of the dam in the first days after their installation, so that precision declined in winter [period [1] in the diagram] due to snowfall on the handrails, and during the other period [period (2) in the diagram] due to the worsening of the field of view in the sky because of thickly- growing trees, as mentioned later, and to the multi-pass, that is, waves reflected from the handrails. We therefore relocated the GPS antennas to a location above the top of the handrails in November 2015. This made dispersions smaller particularly on the vertical protrusions than before the antennas were relocated, resulting in a measurement precision similar to that obtained in other dams.

On the other hand, between about May and October inclusive after December 2015 [period (3) in the diagram], too, for both G-1 and G-2, upstream/downstream and vertical dispersions proved to be larger than GPS displacement measurements taken from other concrete gravity dams.

The figure shows how GPS dispersions increased gradually from spring onwards, peaked in summer, and declined little by little in autumn. From the correspondence of these periods to the times when the trees in these areas grow thickly and let their leaves fall, we learn that the precision decline stemmed, as shown in Figure 12, from the thick growth of the leaves of the trees around reference point K-1, resulting in the GPS's field of view in the sky being blocked, which then led to radio disturbance. The satellite trajectory received at reference point K-1 is shown in Figure 13. The blue line in the diagram represents the satellite orbit received by radio waves, while the red line indicates the satellite trajectory that radio waves failed to receive because of blockage by trees and other objects on the earth. The spots encircled in the diagram are ranges where radio waves from the GPS are presumed to have entered between the tree leaves. Using theses radio waves in the analysis results in poor precision. We therefore re-analyzed the ranges with a reduced influence of overhead obstacles, shown as the green portions in the figure, including the blue lines near the borders with the red lines. The ranges with a reduced influence of overhead obstacles are set to be larger than the ranges of the trees seen in Figure 12 in view of tree growth and other circumstances. Figure 14 compares the situation before and after reducing the influence of overhead obstacles. The figure shows examples of the vertical measurements taken. As shown in the diagram, the dispersions in measurements finally reduced considerably.



(a) View in winter (b) View in summer

Figure 12 : Field of view in the sky and trees around reference point K-1

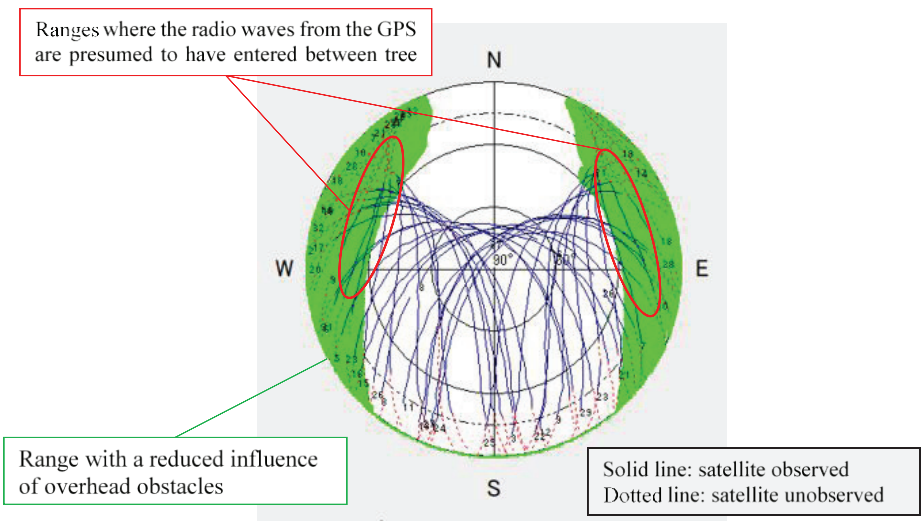
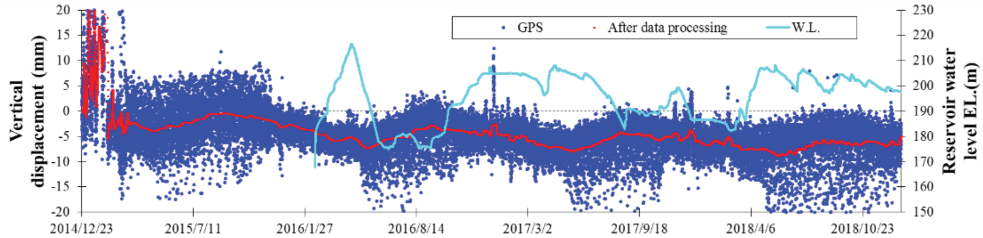
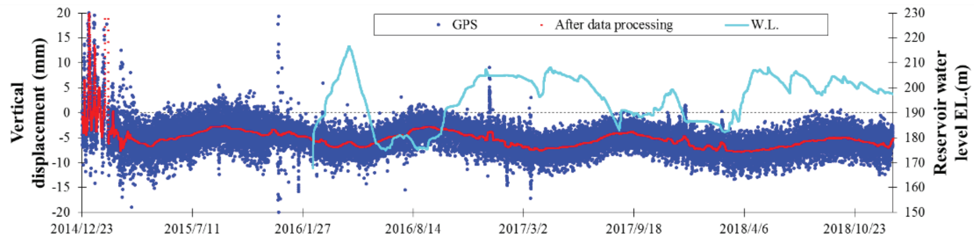


Figure 13 : Range with a reduced influence of overhead obstacles at reference point K-1



(a) Before reduced influence of overhead obstacles



(b) After reduced influence of overhead obstacles

Figure 14 : GPS vertical displacement measurements taken before and after reducing the influence of overhead obstacles at G-1 in BL6

5 CONCLUSIONS

As the result of our study to verify the applicability of a GPS displacement measurement system to concrete gravity dams, we learned the following:

- GPS sensors installed at the top of the dam

  It should be noted that these measurements reflect the behavior not only of the dam body to be measured with a plumb line, but of the entire body including the rock foundation as well (from examples of the Nagai Dam and the Obara Dam).

- GPS sensors installed at the dam top and near the dam toe

  It is considered that it is possible to estimate, in isolation, not only the behavior of the entire dam including the rock foundation, but the behavior of portions near the dam rock foundation and the dam body as well (from an example of the Obara Dam).

- Comparison of measurements between GPS and plumb line

  When compared with the plumb line, which achieves measurement with a detection precision as high as ±0.1mm, the GPS achieves a precision of only the order of a millimeter, which is somewhat lower. However, it did produce measurements in similar trends (from examples of the Nagai Dam and Obara Dam).

- Locations of the GPS sensors

  Depending on where a GPS sensor is installed, it is vulnerable to the effects of multi-pass, that is, reflected waves due to waves reflected from obstacles, snowfall, and other circumstances. Increase of measurement precision requires measures to be taken to achieve a sufficient field of view in the sky (from an example of the Tsugaru Dam).

- Insufficient field of view in the sky

  Measurement precision may be increased by reducing the influence of overhead obstacles, where baseline analysis is performed without using radio waves received from a GPS satellite in the sky via an obstacle (from an example of the Tsugaru Dam).

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