INTERNATIONAL SYMPOSIUM ON
DAMS FOR A CHANGING WORLD
-Need for Knowledge Transfer across the Generations & the World
Kyoto, Japan June 5, 2012

Application of Advanced Displacement Measurement System Using GPS to Concrete Gravity Dams

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ABSTRACT:
The measurement of displacement is one of the most important measuring items for safety management of concrete gravity dams. It is usually done with plumb lines. This displacement measurement method is highly accurate; however is cost-consuming, and the settings up works have a large effect on the dam construction works
The Public Works Research Institute has made enthusiastic research on effective utilization of GPS to measure displacement of embankment dams, which have generally larger displacement compared to concrete gravity dams. If we can confirm the applicability of this measurement system to concrete gravity dams, there is the possibility to make the displacement measurement for concrete gravity dams more sophisticated and inexpensive. In this study, we introduced the displacement measurement system with GPS to a concrete gravity dam, and examined its applicability.

Keywords: GPS, concrete dam, displacement, measurement, safety management

1. INTRODUCTION

The “Cabinet Order concerning Structural Standards for River Management Facilities, etc” (The Japan Institute of Construction Engineering, 2000) stipulates that the items which must be measured in order to manage the safety of a concrete gravity dam with height of 50m or more are leakage, displacement and uplift pressure. Of these, displacement of concrete gravity dams is now measured primarily using plumb lines. Measuring displacement using plumb lines is an extremely high precision method, but because of their locations, it is costly and greatly impacts the construction works, and generally they are only installed on 1 or 2 representative sections. But because a concrete gravity dam is constructed with transverse joints dividing the dam body into blocks, adjacent blocks can display differing displacement behaviour 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 behaviour, in particular after a large-scale earthquake..

Therefore, that if it is possible to verify the applicability to displacement measurement of concrete gravity dams of a GPS displacement measurement system, which has already been confirmed to previous adequate precision for practical use based on past research on displacement measurement of natural slopes (Shimizu, 2009) or embankment dams (Yamaguchi et al., 2005), more advanced and lower cost measurement of displacement and management of safety at concrete gravity dams will be performed.

This research involved a trial introduction of a GPS displacement measurement system to measure displacement at the Nagai Dam, concrete gravity dam with height of 125.5m, and then confirming the displacement behaviour of the concrete dam obtained by the GPS displacement measurement system and comparing its precision with that of plumb lines to verify its applicability.

2. INSTALLING GPS ON A CONCRETE GRAVITY DAM

Table 1shows the specifications of the Nagai Dam. where the GPS displacement measurement system was installed. Fig. 1 is the upstream-side longitudinal section and Fig. 2 shows two measuring cross section. A total of four GPS sensors were installed, three at movable points (G-1 to G-3) on the crest of the dam and one at a fixed point on the left bank as a reference point. As shown in Fig. 1, because low dip-angled faults are distributed directly below the dam site, G-1 was installed on block 15 along with the normal plumb line DN-2, G-2 was installed on block 20, which is the location of the normal plumb line DN-1 and the inverted plumb line DR-1, and G-3 was installed on block 8. The reference GPS sensor was installed on the dam concrete near the left bank-dam body connection part. Fig. 3 shows a view of the installation of G-1 as an example of the GPS sensor installation method. The GPS sensors were installed on the railing on the downstream side of the dam crest. The external shape of the antenna, which is the principal component of the GPS sensors used for this study, was 156mm diameter ×116mm height, its weight was 0.6kg, and the sensors are small, so even including the case shown in Fig. 3, they can be installed in many places such as inside the man-holes on dam crests (Yamaguchi et al., 2009).

Table 1. Specifications of the Nagai Dam

Type	Concrete gravity dam
Dam height	125.5m
Dam crest length	381m
Dam body volume	1,200,000 m^3

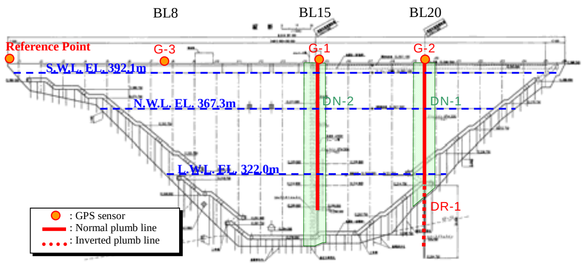


Figure 1. Installation Locations of GPS Sensors (Upstream Face)

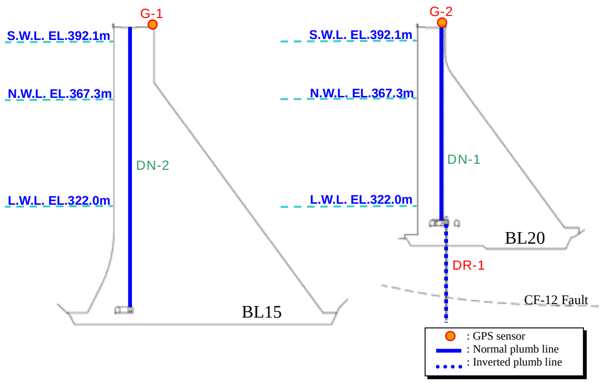


Figure 2. Installation Locations of GPS Sensors (BLs 15 & 20)

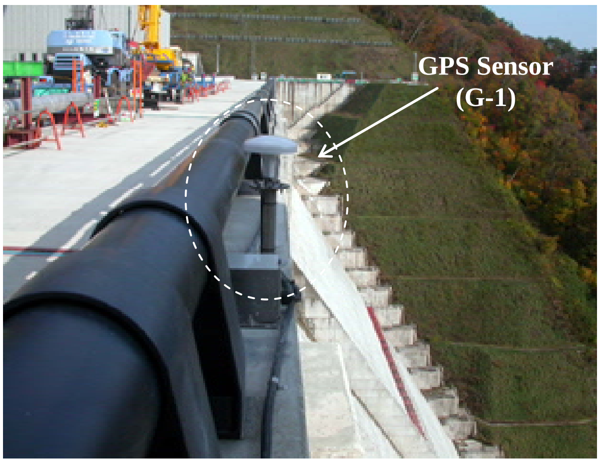


Figure 3. Installation Location of a GPS Sensor (G-1)

3. RESULTS OF MEASUREMENTS OF DISPLACEMENT BEHAVIOUR OF THE DAM

This section shows the results of measurements of displacement obtained by the GPS displacement measurement system and by the plumb lines. The results obtained by the GPS displacement measurement system cover the period from November 1, 2009, when the GPS sensors were installed, until December 1, 2010, while the results obtained by the plumb lines cover the period from December 1, 2009, when trial impounding began, until December 1, 2010.

3.1. Results of Measurement of Displacement Behaviour by GPS

Fig. 4 shows the results of GPS measurements of displacement of the Nagai Dam along with reservoir water level. The figure shows (a) upstream-downstream displacement and (b) dam axis displacement at, from top to bottom, G-1 to G-3. The following are the characteristics of each type of behaviour.

(a) Upstream-downstream displacement

The results for upstream-downstream displacement show that during the period the reservoir water level remained almost at L.W.L. from the start of trial impounding until March 2010, almost no downstream direction displacement occurred. And at part “A” shown in the figure, unique upstream-downstream direction displacement behaviour is seen. This is assumed to be a result of the fact that snow accumulated around the GPS sensor, causing multi-path, which is scattered reflection of radio waves from the GPS satellites. In fact, it was confirmed that removing snow suppresses fluctuation.

Next, as the water level rose from L.W.L. to N.W.L., downstream direction displacement of about 5mm occurred at every measurement point. Later, when the water level was raised to S.W.L. on April 29, 2010, downstream direction displacement up to 29.0mm occurred at G-1 as a result of water level change.

And later, as the water level fell, upstream direction displacement occurred. The water level was lowered to N.W.L. on May 30, 2010, then even on July 26, 2010 when it had been maintained at N.W.L. for about 2 months, the upstream direction displacement advanced slightly. This upstream direction displacement continued until the reservoir water level neared EL. 340m as it was lowered to L.W.L., but after that, downstream direction displacement resumed, and after the water level was maintained at L.W.L., it approached the values obtained when measurements started.

(b) Dam axis direction displacement

Displacement in the dam axis direction occurred beginning about December 2010 after the start of trial impounding. At G-1 and at G-2, it was left bank direction displacement, and at G-3, it was right bank direction

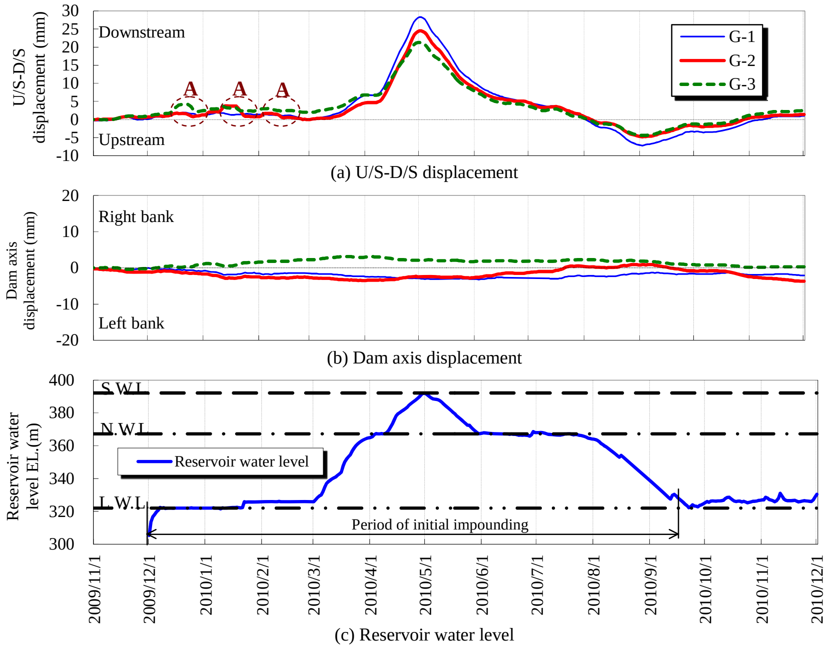


Figure 4. Results of Displacement Measurements by GPS

displacement. This displacement advanced gradually until March 1, 2010 while L.W.L. was maintained. During this period, no upstream-downstream direction displacement behaviour was seen, so it is assumed that relatively large water pressure did not act on the dam body. But displacement occurred, although only about 2mm at each measurement point. One reason for this displacement is assumed to be the impact of the temperature at the installation location, so in the future, a study on the impacts of exterior air temperature and dam body temperature must be done.

According to the results of upstream-downstream direction measurements, during the period when the water level rose from N.W.L. to S.W.L., a period when large water pressure presumably began to act on the dam body, at G-1, almost no displacement occurred, but at G-2 and at G-3, right bank direction displacement and left bank direction displacement respectively occurred. Next, as the water level was reduced, almost no change occurred at G-1 and G-3, while at G-2, inversely, left bank direction displacement occurred as the water level increased. Later, when the reservoir water level approached EL. 340m while being lowered to L.W.L, at G-2, left bank direction displacement occurred again.

Next, the plane displacement of upstream-downstream direction displacement and dam axis direction displacement were arranged. Displacement conformed to displacement arrangement conditions based on reservoir level in Fig. 5.

Fig. 6 shows charts plotting these behaviours as plane direction displacement vectors. In the charts, the solid line arrows show period displacement and the broken line arrows show cumulative displacement from the start of measurements.

They show that as the water level rose, the cumulative displacement was displaced downstream as if it was directed towards the centre of the dam, but focusing on the period displacement shows that during “Period 4”, when the maximum water pressure acted on the dam, the displacement vector occurred as if it were expanding towards the mountain side of both banks.

3.2. Results of Measurements of Displacement Behaviour by Plumb Lines

GPS sensor G-1 was installed on the same block as normal plumb line DN-2, and GPS sensor G-2 was installed on the same block as normal plumb line DN-1 and inverted plumb line DR-1. The plumb-line measurement was performed automatically.

Fig. 7 shows the results of measurements of displacement by plumb lines. The figure shows (a) upstream-downstream direction, (b) dam axis direction, and (c) reservoir water level, from top to bottom. The figure also shows the total of the displacement measured by the normal plumb line DN-1 and the inverted plumb line DR-1. The normal plumb line cannot, unlike GPS, measure displacement in the vertical direction. The following are the characteristics of each behaviour.

(a) Upstream-downstream direction displacement
Examining the upstream-downstream direction displacement shows that during the period after impounding had started and the water level remained constant at L.W.L., upstream direction displacement up

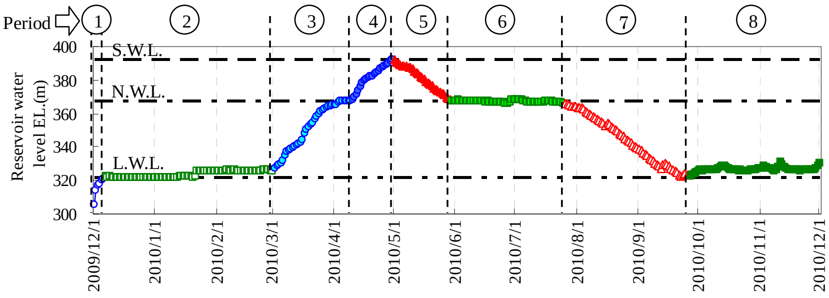


Figure 5. Displacement Arrangement Conditions Based on Reservoir Water Level

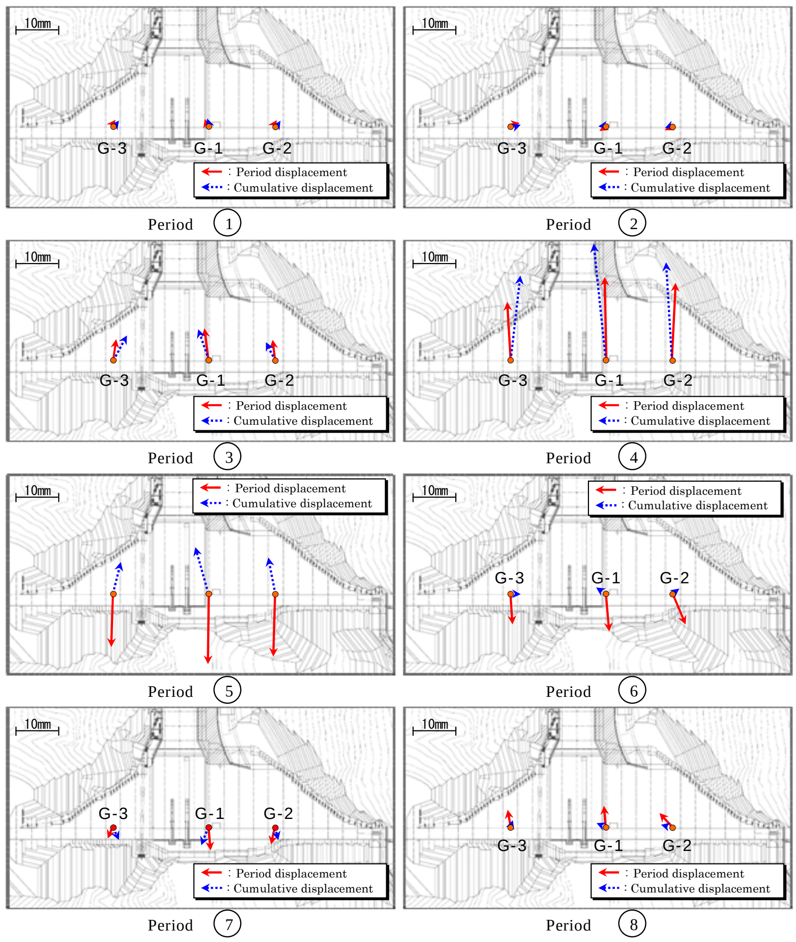


Figure 6. Plane Direction Displacement Vectors

to 3mm was measured at both DN-1 and DN-2. Almost no displacement occurred at DR-1. When the water level was increased to N.W.L., during this period, upstream direction displacement was obtained by all measurements. When the water level rose to S.W.L., DN-2 measured displacement of 23.7mm while DN-1 and DR-1 measured a total of 30mm of displacement. Later, as the water level fell to N.W.L., displacement at DN-1 and DN-2 changed to upstream direction displacement, and tended to return to the original displacement, but almost no change was observed at DR-1. DN-1 and DN-2, which were installed inside the concrete dam body, showed elastic behaviour, while DR-1, which was installed inside rock foundation, showed plastic behaviour. During the period when the water level was constant at N.W.L., DN-1 and DN-2 revealed continuous upstream direction displacement, and tended to return to the value at the start of measurement, but almost no displacement was measured by DR-1. Later, while the water level was being lowered from N.W.L. to L.W.L. like the results of GPS measurements near EL.340m, at DN-1 and DN-2, downstream direction displacement occurred, and after the water level become constant at L.W.L., this downstream displacement was prevented.

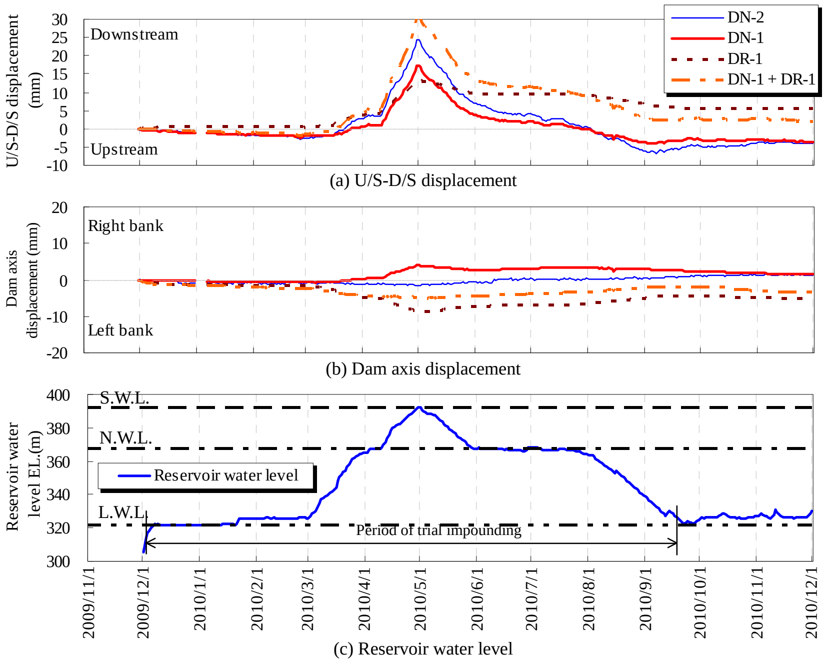


Figure 7. Results of Measurement of Displacement by Plumb Lines

(b) Dam axis direction displacement

Almost no dam axis direction displacement occurred during the period when the water level was maintained at L.W.L., but beginning in March, 2010, when the water level was raised to N.W.L., right bank direction displacement occurred at DN-1, left bank direction displacement occurred at DR-1, which is inside the rock foundation at the same location, while almost no displacement occurred at DN-2. This displacement continuously increased until the water level was raised to S.W.L. When the water level was lowered after reaching S.W.L., at DN-1, left bank direction displacement occurred, while at DR-1, which is inside the rock foundation at the same location, right bank direction displacement occurred, but both displacements were extremely small at 2mm each. During this period, at DN-2, right bank direction displacement occurred gradually.

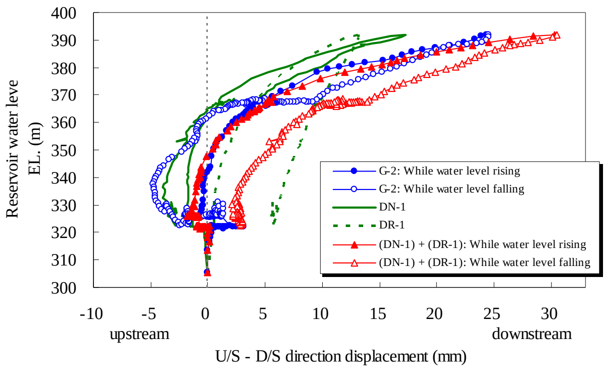
3.3. Comparison of Results of Measurements of Displacement by GPS and Plumb Lines

This section compares the results of the measurements by G-1 and by DN-2, which were installed on the same block, and by G-2 and by DN-1 and DR-1, also on the same block. The measured values were organized with December 1, 2009, which is the starting date of the measurements by plumb lines, adjusted to the value zero, in order to compare the two measurement methods.

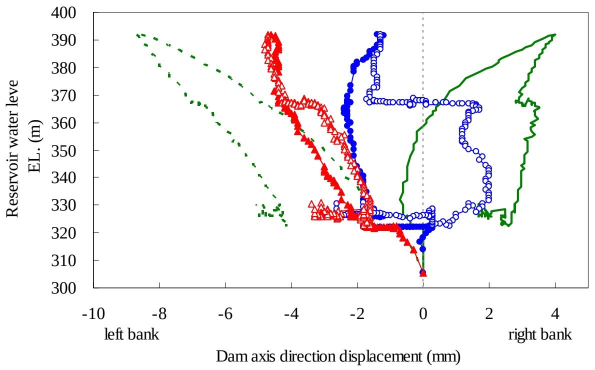
Fig. 8 compares G-2 with DN-1 and DR-1, permitting a comparison of GPS measurement results with normal plumb line and inverted plumb line measurement results.

Examining the upstream-downstream direction displacement in Fig. 8 (a), and paying particular attention to the period when the water level rose, reveals that the results of measurements by plumb line DN-1 and the inverted plumb line DR-1 are smaller than the results of GPS measurements. The results of measurements by plumb lines reveal that, as shown by the measurement location schematic diagram, Fig. 9, the normal plumb line shows displacement at location NA with fixed point NB inside the dam body as its datum point, and that the inverted plumb line shows displacement at location RA with fixed point RB inside the rock foundation as its datum point, and that the GPS measured all behaviour including the rock foundation. So the results of synthesizing DN-1 and DR-1 are shown in the figure [(DN-1) + (DR-1)] (below, “plumb line synthetic value”). As a result of the synthesis, the same tendencies were shown in the upstream-downstream direction displacement values measured by GPS and by the synthesized plumb line values while the water level was rising, but while the water level was falling, in contrast to the GPS measurement results which show upstream direction displacement from the initially measured values, the synthesized plumb line values show no upstream direction displacement from the initial measured values. Finally, GPS measured values show upstream direction displacement of 1.4mm while synthesized plumb line values show upstream direction displacement of 2.1mm; or almost identical measured values.

The dam axis direction displacement shown in Fig. 8 (b) reveals that the behaviours shown by the individual plumb lines DN-1 and DR-1, are completely different from those seen in the GPS measurement results. As in Fig. 8 (a), the figure shows the plumb line synthetic value. The plumb line synthetic value reveals tendencies



(a) Upstream-downstream direction



(b) Dam axis direction

Figure 8. Comparison of G-2 with DN-1 and DR-1

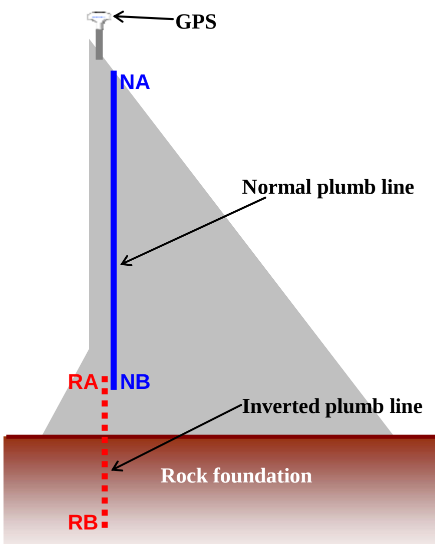


Figure 9. Measurement Location Schematic Diagram

similar to the GPS measurement results, but differences up to 4mm can be seen in the quantity of displacement.

In the future, a detailed analysis of behaviour by applying numerical simulation is scheduled in order to make a detailed study of the behaviour at each location where a plumb line is installed.

4. CONCLUSION

The purpose of this research was the trial introduction of a GPS as a practical method to measure the displacement behaviour of a concrete gravity dam system at the 125.5m high Nagai Dam ; a measurement of the displacement behaviour, and its comparison with the behaviour obtained with the plumb lines method measurement system. The measurements obtained the following results.

a) It is possible for a GPS displacement measurement system to obtain measurement results showing the same trends as those obtained by plumb lines.

b) Installing GPS sensors at multiple locations, e.g., three locations at the Nagai Dam can measure behaviour of the dam body, behaviour of rock foundation, and behaviour of individual blocks during impounding, measurements unobtainable by past plumb line displacement measurements. In the future, the factors causing these behaviours will be analyzed.

c) The results of measurements by the GPS displacement measurement system tend to be larger than the results of measurements by plumb lines. This is a result of the fact that a GPS displacement measurement system measures all behaviour including that of rock foundation, while plumb lines measure displacement between fixed points where they are installed at the crest and inside the inspection gallery, or in other words, displacement of only the dam body.

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