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EXTERIOR DEFORMATION MEASUREMENT FOR CFRD AFTER A LARGE-SCALE EARTHQUAKE USING GPS

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1. INTRODUCTION

Among measurements performed to manage safety of dams, the measurement of displacement is one of the most important measurements stipulated under the Cabinet Order concerning Structural Standards for River Management Facilities, etc. [1] which have been enacted under the provisions of the River Law. The measurement of exterior deformation of an embankment dam is performed by measuring the horizontal and the vertical displacement of measurement use targets installed on the dam body. But it is difficult to perform prompt measurements of exterior deformation using conventional surveying methods to confirm the safety of the body of an embankment dam after an earthquake or other abnormal event. To find a way of resolving this problem, the

Public Works Research Institute (PWRI), Japan, has been studying the introduction of dam displacement measurement systems applying GPS (Global Positioning System) [2]. Based on the results of the research, the system is now actually operated as a safety management tool at many embankment dams. And a study of its application to concrete dams in addition to embankment dams is now underway.

This paper reports on the results of the installation of an external displacement measurement system using GPS at the Ishibuchi Dam which was damaged by the Iwate-Miyagi Nairiku Earthquake of June 14, 2008 immediately after the earthquake, and the subsequent use of the system to perform safety management based on real-time displacement measurement.

2. INSPECTION OF DAMAGE TO THE ISHIBUCHI DAM BY THE IWATE-MIYAGI NAIRIKU EARTHQUAKE

2.1 OUTLINE OF THE IWATE-MIYAGI NAIRIKU EARTHQUAKE [3]

The large earthquake, the Iwate-Miyagi Nairiku Earthquake in 2008, mainly struck the mid Tohoku Region in northeastern Honshu Island, Japan at 8:43 am on Saturday morning, June 14, 2008. The strongest shaking was measured in Oshu City, Iwate Prefecture and Kurihara City, Miyagi Prefecture, both at 6 Upper of the Japan Meteorological Agency (JMA) seismic intensity.

No nuclear power plant was shut down following this earthquake, unlike the case of the Kashiwazaki-Kariwa nuclear power plant after the Niigataken Chuetsu-oki Earthquake in 2007. Several sections of express highways in the Tohoku Region were closed, then all were reopened by nightfall, except for one section where a traffic restriction was maintained because of repair works. Some East Japan Railway Company (JR East) train services were suspended on the Shinkansen, Japanese superexpress, and local lines, then resumed from the first trains on the following day.

The Technical Emergency Control Force (TEC-FORCE) organized by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Government of Japan, dispatched many experts to the event area to investigate damage to infrastructures and houses and provide technical support for emergency countermeasures on the day of the earthquake. To conduct emergency investigations of dams, several dam engineering experts including one of the authors, were dispatched to five dams damaged by this earthquake from June 14 through 16, 2008.

2.2. EMERGENCY INSPECTION IMMEDIATELY AFTER THE EARTHQUAKE [3]

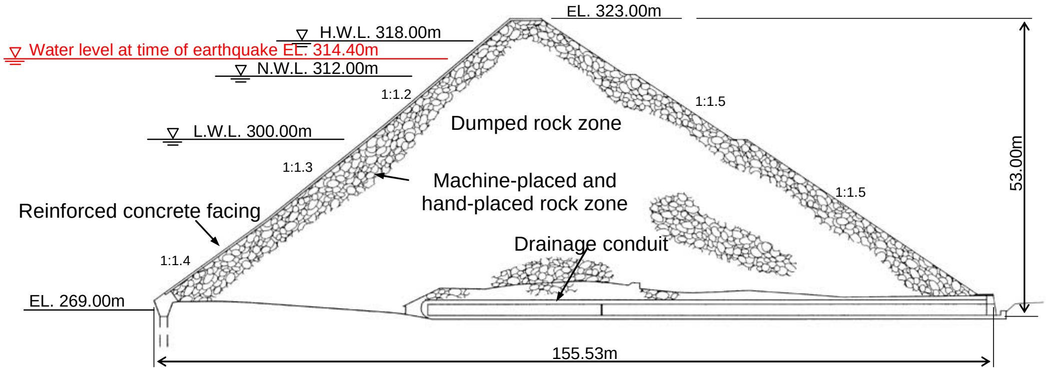
Ishibuchi Dam is a concrete faced rockfill dam (CFRD) with a dam height of 53m completed in 1953, and managed by Tohoku Regional Bureau, MLIT. Fig. 1 is the cross section and longitudinal section of the dam. The upstream concrete face maintains the water tightness of dam body of this type of dam. No severe damage was found in the concrete face and its joints shown in Fig. 2.

At the crest of the dam, the pavement was waved and cracked, as shown in Figs. 3 and 4. And gaps appeared on the boundary between the railing and pavement on the shoulder of the slope at the crest. On the downstream slope surface of the dam, projections were observed on the rock materials at the protruding parts of the wave on the crest pavement shown in Figs. 5 and 6, but damage of this kind was limited to the higher elevations. This dam was constructed by the dumped rock construction method as shown in Fig. 7. The piers for the railroad from where trucks dropped rock materials were left buried in the dam body. It is hypothesized that the whole dam body settled due to the earthquake, while the areas near the buried piers only settled a little. The maximum differential settlement is supposed to be about 50cm.

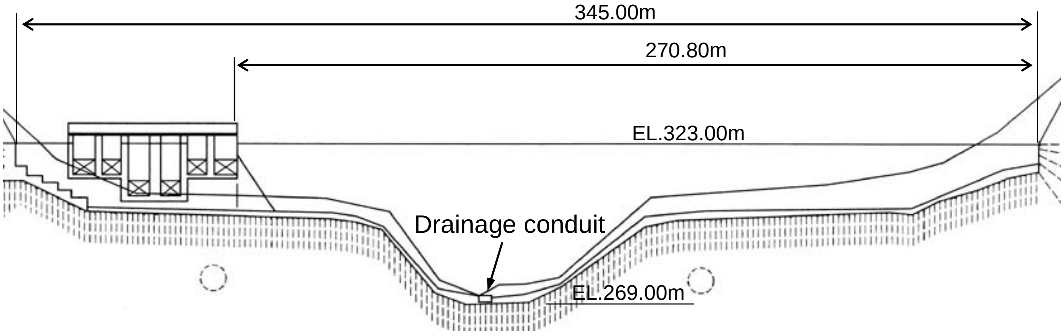
Leakage through the upstream concrete face and the shallow foundation, which is measured at the downstream slope toe, has increased since the occurrence of the earthquake. However, its amount was below the maximum amount which had ever been observed at the dam and it has behaved stably depending on the reservoir water level. Turbid leakage water was also observed after the earthquake, but it returned to normal after a few days.

A seismometer installed on the top of the downstream slope (elevation of the crest) recorded the maximum acceleration of 1,461 gal in the stream direction and 2,070 gal in the vertical direction, but this record might include local shaking of the large size rock on which the seismometer was installed, so further analysis is necessary.

Based on the results of the emergency investigation, it was decided that no serious problems threatened the safety of the dam, but careful monitoring has been continued and a technical committee has been established to make a detailed survey to prepare for restoration of the dam.



(a) Cross section



(b) Longitudinal section

Fig. 1

Cross section and longitudinal section of the Ishibuchi Dam

Fig. 2
Concrete faced upstream slope on which no damage was found at the Ishibuchi Dam June 15, 2008. [3]

Fig. 3
Overview of the crest and downstream slope of the Ishibuchi Dam on June 15, 2008. [3]

Fig. 4
Cracks and waving of the crest pavement of the Ishibuchi Dam on June 15, 2008. [3]

Fig. 5
Gaps between the railing and pavement on the crest of the Ishibuchi Dam on June 15, 2008. [3]

Fig. 6
Projection of the riprap rocks around the top of the downstream slope of the Ishibuchi Dam on June 15, 2008. [3]

Fig. 7
Ishibuchi Dam under construction by the dumped rock method in the 1950's. [3]

3. DEFORMATION BEHAVIOR OBSERVATIONS USING GPS AFTER THE EARTHQUAKE AT THE ISHIBUCHI DAM

3.1. BACKGROUND

It was determined that the Iwate–Miyagi Nairiku Earthquake caused protrusion of large blocks of rock on the dam body crest and at high elevations on the downstream slope, but conspicuous damage was not found on the upstream concrete face. Riverbed leakage observed at the downstream toe of the dam body increased sharply immediately after the earthquake, but later it changed according to the reservoir water level. But assuming that during the detailed inspection of damage due to the earthquake and the design of repair measures in response to the inspection results, it was necessary to measure not only leakage, but deformation, at short time intervals, a GPS based embankment dam external displacement measurement system was adopted as a post-earthquake displacement observation method.

3.2. GPS DISPLACEMENT MEASUREMENT SYSTEM

The GPS sensors used to perform external displacement measurements at the Ishibuchi Dam are designed with the power supply system, communication devices, memory, and other components combined in an integrated communication unit. Installing only a GPS sensor at each measurement point reduced the size and weight without lowering measurement precision. Fig. 8 is a schematic diagram of the configuration of the GPS displacement measurement system. The use of the trend model based error processing method [4] achieves precision after error processing in the vertical direction, which is less precisely measured than the horizontal direction, of 1 to 2mm, ensuring precision equal to or superior to that of conventional measurements. When the trend model based error processing method was used, it was necessary to perform measurements for about 3 hours in order to detect displacement within an error of 1mm in the horizontal direction.

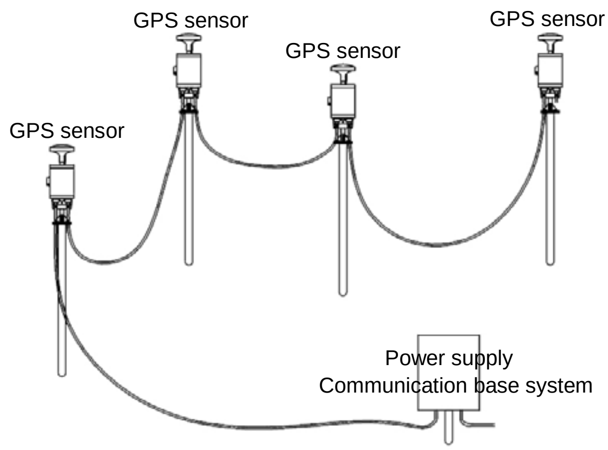


Fig. 8
Wiring for GPS displacement measurement system

3.3. GPS SENSOR INSTALLATION

The GPS sensors were, as shown in the plane diagram in Fig. 9, installed at a total of 18 points: 5 points on the reinforced concrete facing on the upstream side of the dam body (G-1 to G-5), 5 points near the dam crest (G-6 to G10), 5 points on the downstream side of the dam (G-11 to G-15), on the top of the boat house on the left bank of the dam body (G-16), on top of the spillway pier (G-17), and at a reference point (K-1). The measurements started on June 26,2008, which was 12 days after the earthquake.

Fig. 10 is a detailed structure of GPS sensors installed on the upstream and downstream slopes of the dam. The sensors were fixed with anchor bolts on top of the reinforced concrete facing and the rock material and their bases were protected by mortar. Figs. 11 and 12 show installed sensors.

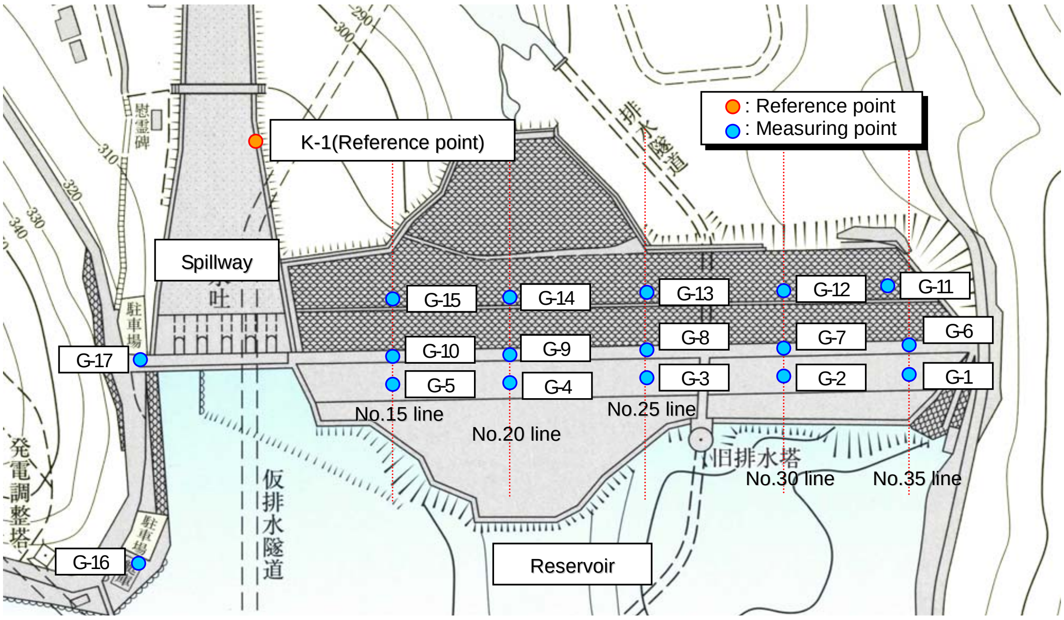


Fig. 9

Layout of GPS sensor installation points

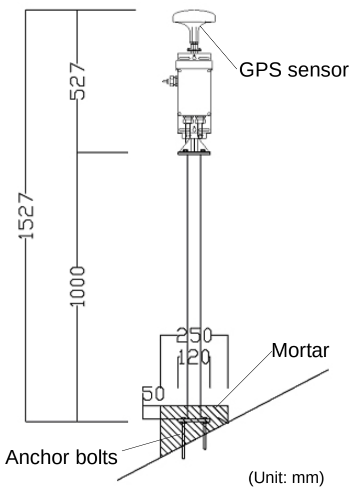


Fig. 10

Structure of GPS sensor installed on the upstream and downstream slope of the dam

Fig. 11

GPS sensor installed on the reinforced concrete facing on the upstream slope of the dam

Fig. 12

GPS sensor installed on the rock block on the downstream slope of the dam

3.4. MEASUREMENT RESULTS

As an example of a GPS measurement result, Fig. 13 presents the results of measurement on No. 20 Line (see Fig. 9) which is the maximum section. There are 3 measurement points on No. 20 Line: G-4 on the upstream concrete face, G-9 near the dam crest, and G-14 on the rock block on the downstream side of the dam. The Fig. 13 shows, from the top to the bottom chart, (a) displacement in upstream-downstream direction, (b) displacement in dam axis direction, (c) vertical displacement, and (d) reservoir water level and rainfall.

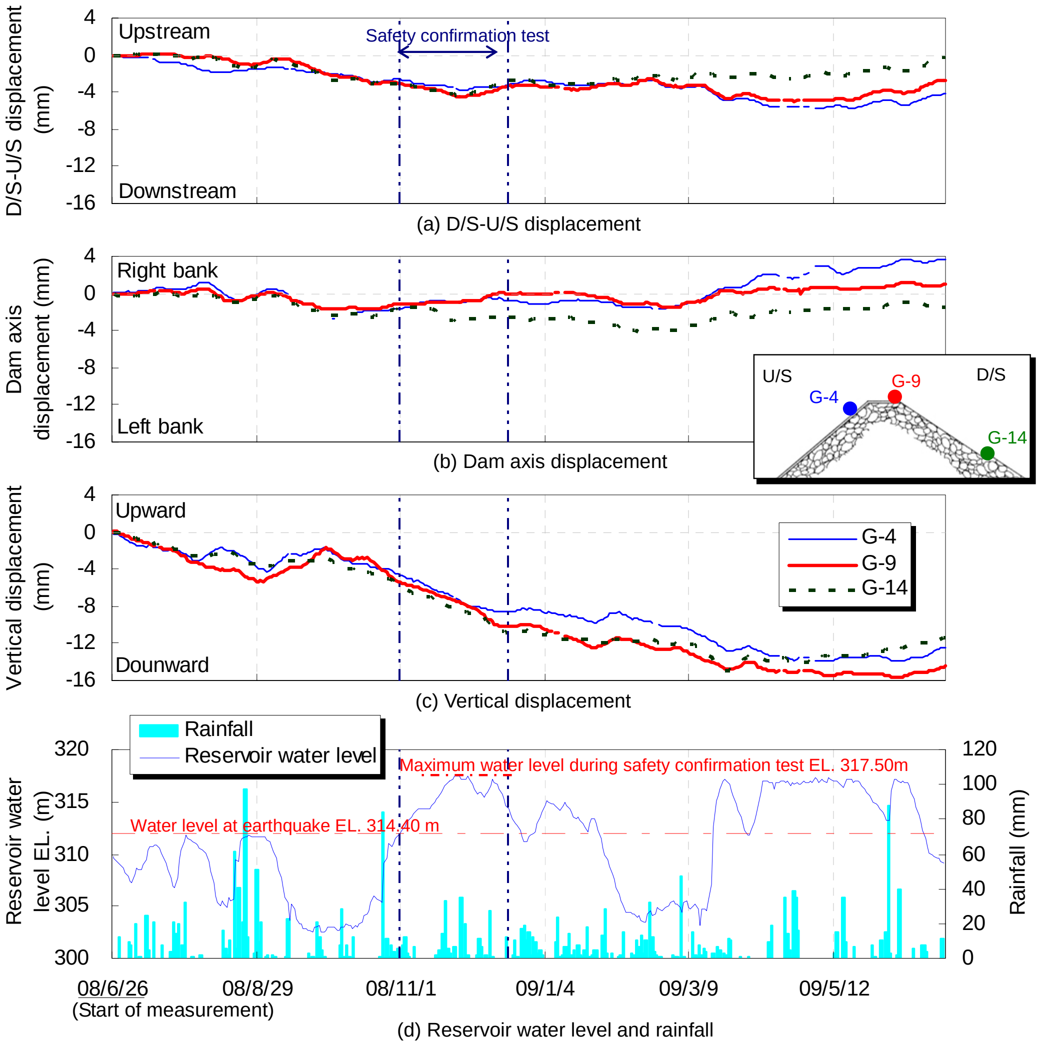


Fig. 13

Results of GPS measurement of dam deformation on No. 20 Line

The following are the characteristics of each measurement result.

(a) Upstream-downstream displacement

Behavior from the start of observations includes a similar slight displacement forward the upstream side trend over time at every measurement point, and displacement up to a maximum of 4mm to the downstream side during the safety confirmation test. When the reservoir water level was again increased from EL. 305m to EL. 317m beginning on March 17, 2009, at G-4 on the upstream concrete face and G-9 near the dam crest, similar behavior was seen, with the rising reservoir water level accompanied by displacement downstream, and a tendency to return to the upstream side as the reservoir water level fell. But beginning March 17, 2009, at G-14 on the rock block on the downstream side of the dam, almost no downstream displacement occurred as the reservoir water level rose and while it was constant, but when the reservoir water level was lowered, displacement to the upstream side occurred.

(b) Dam axis displacement

Fluctuation of the reservoir water level was initially accompanied by similar behavior at every measurement point, but their behaviors differed from those before the safety confirmation test. The maximum displacement was 4mm towards the right bank at G-4. Normal behavior of rockfill dams during impounding appears as upstream-downstream displacement and compressive vertical displacement, primarily under the strong impact of fluctuation of the reservoir water level. Dam axis displacement revealed by the measurements are not large values as absolute quantities, so strict analysis and consideration is difficult, but it is possible that it is the result of three-dimensional deformation behavior under the impact of water pressure acting on the upstream side concrete face.

(c) Vertical displacement

Behavior from the start of observations showed a similar trend at every measurement point, and during the safety confirmation test, displacement at a maximum of 8mm occurred. Later, the settlement continued, and on June 10, 2009, displacement of -15.7mm (settlement) was measured at G-9 near the dam crest. Until March 5, 2009, even when the reservoir water level was maintained at a constant level (Sept. 17, 2008 until Oct. 14, 2008 and from Feb. 11, 2009 until March 5, 2009), the settlement tended to progress. Later, from March 17, 2009 until June 14, 2009, the reservoir water level was kept at the high level of EL.317m, but continued settlement was not measured during that period. So it is assumed that the settlement behavior has stabilized.

Periodical surveys performed up to the time of the earthquake show that during the 10 years before the earthquake, settlement of 2.7mm per year occurred at a measurement point on the upstream side of the reinforced concrete facing on the No. 20 Line (G-4), settlement of 2.4mm per year at the crest (G-9), and settlement of 1.3mm per year on the downstream side rock block (G-14). The No. 20 Line is, as shown in Fig. 9, at the maximum section of the dam body, and its settlement before the earthquake was larger than that at the other lines.

The GPS measurement results show a tendency for settlement to stabilize after the earthquake, but it is assumed that continuous measurements based on the average annual settlement before the earthquake will be necessary in the future.

3.5. CONSIDERATION OF THE MEASUREMENT RESULTS

The results of measurements on No. 20 Line have been arranged by, as shown in Fig. 14, classifying the reservoir water level conditions during the measurement period as reservoir water level rising time (solid lines), reservoir water level falling time (dotted lines) and constant reservoir water level time (dashed-dotted lines). And Fig. 15 shows resultant vectors of upstream-downstream and vertical displacement at the G-4 point on the upstream concrete face, the G-9 point near the dam crest, and the G-14 point on the rock block on the downstream slope of the dam. On the Fig.15, the horizontal axis is the upstream–downstream displacement and the vertical axis is the vertical displacement.

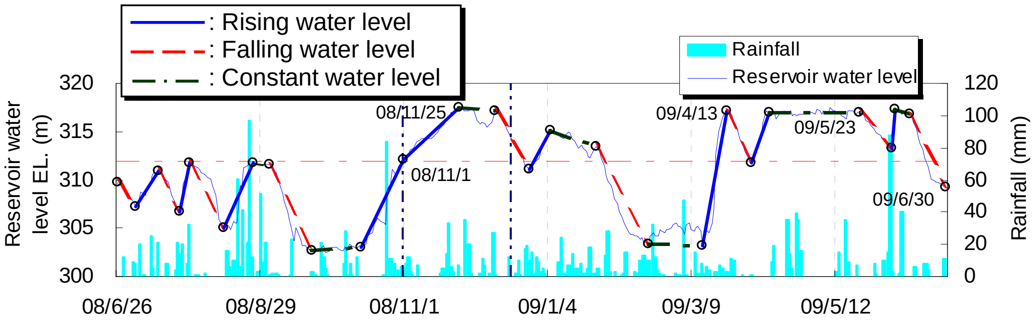
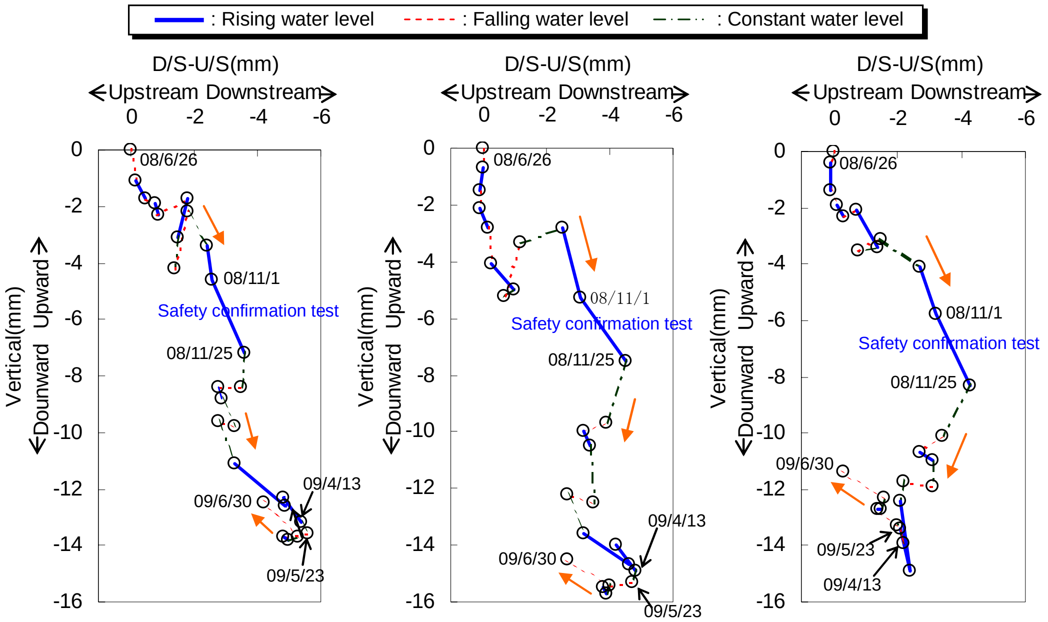


Fig. 14

Displacement categorization conditions according to reservoir water level



(a) G-4 (b) G-9 (c) G-14

Fig. 15

Displacement vectors in the dam upstream-downstream and vertical directions

The overall trend can be divided at the maximum reservoir water level during safety confirmation testing (EL. 317.50m). Before the maximum water level during the safety confirmation test, when the reservoir water level is rising, downstream displacement and settlement occur, and even when the reservoir water level is falling or constant, downstream displacement occurs. But after the maximum reservoir water level during the safety confirmation test, when the reservoir water level is rising, downstream displacement and settlement occur, but when the reservoir water level is falling or is constant, upstream displacement and settlement occur. And the reservoir water level was operated at a high reservoir water level of approximately EL. 317m from April 13, 2009 until May 23, 2009, but almost no displacement occurred, neither in the upstream-downstream direction nor vertically. Later, as the reservoir water level fell, upstream displacement occurred.

At G-4 on the upstream concrete face, settlement continued over time, but upstream-downstream displacement was downstream displacement even after the maximum reservoir water level during the safety confirmation test, and the maximum downstream displacement was measured while the reservoir water level was constant from April 13, 2009 until May 23, 2009. At G-9 near the dam crest, gradual settlement tended to continue after the safety confirmation test, but upstream-downstream displacement occurred according to reservoir water level fluctuations. At G-14 on the rock block on the downstream slope of the dam, upstream displacement occurred along with settlement after the maximum reservoir water level during the safety confirmation test.

Fig. 16 schematically presents the deformation behavior measured by the GPS method. Until the maximum reservoir water level during the safety confirmation test, regardless of the rise or fall of the reservoir water level, settlement occurred over time, accompanied by gradual downstream displacement (from A to B on the Fig. 16). It is hypothesized that this might be a result of loosening which occurred in the dam body, particularly near the crest and surface on the downstream side as a result of a large-scale earthquake.

Later, as a result of the safety confirmation test, relatively high water pressure acted on the dam, and downstream displacement at the G-9 point near the dam crest where the impact of the water pressure is relatively low, and at G-14 on the rock block on the downstream slope of the dam receded and the displacement was primarily only settlement (B to D in the Fig. 16). At the G-4 point on the upstream concrete face, which was strongly impacted by the water pressure, downstream displacement occurred, but the absolute value of this displacement was small. Beginning on April 13, 2009 (C in the Fig. 16), looseness near the surface presumably caused by a large-scale earthquake is assumed to have generally constrained the displacement.

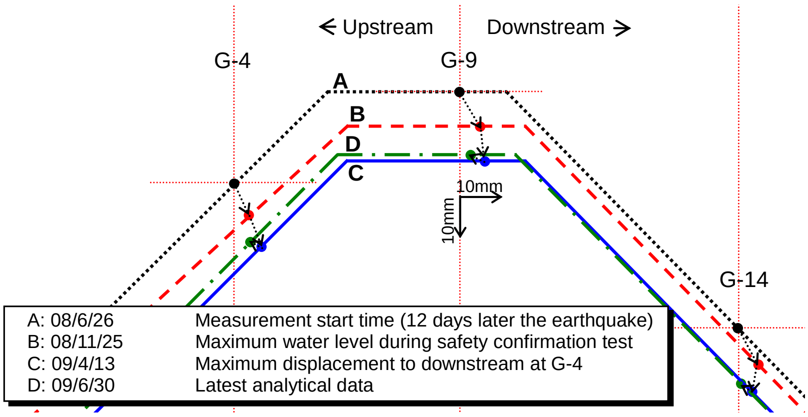


Fig. 16

Schematic displacement diagram

4. CONCLUSIONS

It has been confirmed that at the Ishibuchi Dam, the Iwate–Miyagi Nairiku Earthquake of June 14, 2008 caused large blocks of rock to protrude on the crest and at high levels on the downstream slope of the dam body. But no conspicuous damage was seen on the concrete face on the upstream side. Leakage observed on the downstream side increased rapidly and sharply after the earthquake, but later, it changed according to the reservoir water level.

The results of GPS observations of dam body displacement show that at G-19 on the crest on the No. 20 Line on the maximum section, settlement of 7.5mm occurred between the start of measurement on June 26, 2008 and the end of the safety confirmation test, and later fluctuation of the reservoir water level caused further settlement accompanied by some repeated upheaving and settlement, and maximum displacement was 15mm. And the results of later continual measurement show a tendency for the settlement to converge, and it is assumed that displacement caused by looseness near the surface layer, presumably caused by the earthquake, generally converged. Table 1 shows the upstream-downstream and vertical maximum displacement at all of the other GPS based measurement points. The maximum upstream–downstream displacement occurred on the No. 15 and the No. 20 Lines. The maximum vertical displacement occurred on the No. 20 Line on the maximum section.

At the Ishibuchi Dam, a GPS based displacement measurement system was installed after the earthquake as the real-time displacement measurement method. This system will be installed at many dams before future earthquakes, a trend counted on to measure the state of displacement immediately after earthquakes quickly and with high precision, contributing to performing safety inspections. In addition, a study has begun of the application of the system at concrete dams where displacement is smaller, in addition to its use at embankment dams.

At the Ishibuchi Dam, the displacement caused by the earthquake has been repaired. The safety confirmation testing has also been performed, by analyzing the results of GPS based measurements and results of leakage and other measurements, and the safety of the dam's functions has been confirmed. Therefore, regular operation of the dam began in January 21, 2009.

Table 1

Results of GPS Displacement Measurement

(a) Maximum upstream–downstream displacement

Line	No.15		No.20		No25		No.30		No.35	
Downstream	G-15	-1.4	G-14	**-4.3**	G-13	-2.7	G-12	-4.1	G-11	-
Crest	G-10	**-5.8**	G-9	-4.9	G-8	-4.3	G-7	-5.6	G-6	-
Upstream	G-5	**-6.5**	G-4	-5.7	G-3	-3.7	G-2	-3.9	G-1	-5.2

+: upstream, -: downstream, Unit: mm

(b) Maximum vertical direction displacement

Line	No.15		No.20		No25		No.30		No.35	
Downstream	G-15	-5.2	G-14	**-14.9**	G-13	-5.9	G-12	-5.4	G-11	-
Crest	G-10	-7.9	G-9	**-15.6**	G-8	-10.2	G-7	-8.6	G-6	-
Upstream	G-5	-7.5	G-4	**-13.9**	G-3	-8.9	G-2	-6.9	G-1	-8.6

+: Upward, -: Downward, Unit: mm

*G-11 and G-6 omitted because of data abnormality

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SUMMARY

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 Japanese dam safety management standards, the measurement frequency of exterior deformation of embankment dams is set as once a week at the first filling period, that is, the first term of dam management, and once every three months in the third term that is the final management stage after behavior of the dam has stabilized. But, because the surveying work is relatively time consuming, rapidly responding after an earthquake or in other emergencies is a big challenge. We have developed safety management for dams using the global positioning system (GPS) to perform quick surveys at relatively low cost.

The large earthquake, the Iwate-Miyagi Nairiku Earthquake mainly struck the mid Tohoku Region, Japan on June 14, 2008. It damaged the Ishibuchi Dam located near the epicenter of the earthquake, a concrete faced rockfill dam (CFRD) with a dam height of 53m completed in 1953. The measured maximum differential settlement was about 50cm. Therefore, a careful measurement of exterior deformation of the dam body was performed during the investigation and the damage was repaired. We installed 18 GPS sensors at the Ishibuchi Dam after the Iwate-Miyagi Nairiku Earthquake for this purpose. This paper will report the results of the measured deformations and considerations of the deformation behavior of the Ishibuchi Dam.

KEY WORDS

Embankment dam, CFRD, Safety management, Exterior deformation, GPS