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Monitoring of Fill Dams Using GPS-based Displacement Measurement System

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ABSTRACT:
The GPS displacement monitoring system is a new method for measuring ground surface displacements using Global Positioning System (GPS) technology. It can measure the three-dimensional displacements of multiple measurement points on the ground surface automatically and continuously. The present study applies the system for measuring the exterior deformation of two fill dams, namely, the Majimegawa Dam, a 21.9-meter-high earth-fill dam located in Yamaguchi Prefecture, Japan, and the Taiho Sub-dam, a 66.0-meter high rock-fill dam located in Okinawa Prefecture, Japan. This paper reports the observational results and verifies the effectiveness of the displacement monitoring system. From the observational results, we find that the GPS-based displacement measurement system was able to detect with high accuracy the very small movements that followed the changes in the water level of the reservoir and the compression of the dam core.

Keywords: fill dam, exterior deformation of dam body, Global Positioning System, field measurement

1. INTRODUCTION

In the safety management of fill dams after construction, the displacement of the dam body is one of the most important measurement items in addition to leakage and seepage. While the displacement has generally been measured by conventional survey techniques, namely, total station surveys and levelling, more rapid and sophisticated measurements are required these days from the viewpoints of saving labor, reducing costs, and ensuring safety in the measurement works after unusual events.

Global Positioning System (GPS) technology has been utilized in various geotechnical engineering fields as a means to measure the displacements of the ground surface (Kondo et al. 1993; Masunari et al. 2003). This GPS-based displacement measurement system has several advantages in that it can automatically, rapidly, and continuously measure the three-dimensional displacements of multiple measurement points. Also, it is available regardless of the weather and it doesn't require a line-of-sight between the measurement points, which is not the case with conventional survey techniques. This GPS-based displacement measurement system has been examined for its applicability to fill dam management (Yamaguchi et al. 2005), and it is now in operation at several dam sites in Japan.

The GPS-based system has been introduced at the Majimegawa Dam (earth-fill dam) and the Taiho Sub-dam (rock-fill dam) to measure the displacements of the dam bodies. Table 1 shows the dimensions of the two fill dams. This paper presents the observational results and verifies the effectiveness of the system through a comparison of the displacement data with the results of a conventional survey and settlement meters. In addition, the difference in displacement behaviour, depending on the part of the dam body, will be discussed based on the GPS displacement data.

Table 1. Dimensions of the Majimegawa Dam and the Taiho Sub-dam

	Majimegawa Dam	Taiho Sub-dam
Type of dam	Earth-fill	Rockfill
Location	Yamaguchi, Japan	Okinawa, Japan
Construction began	1992	1987
Opening date	2009	2011
Height	21.9 m	66.0 m
Length	209.5 m	445.0 m
Volume	152,000 m^3	1,750,000 m^3
Reservoir capacity	842,000 m^3	20,050,000 m^3
Catchment area	2.41 km^2	13.3 km^2
Surface area	0.13 km^2	0.89 km^2

2. GPS DISPLACEMENT MONITORING SYSTEM

Figure 1 presents a schematic of a GPS receiver and the monitoring system that has been used at the Majimegawa Dam and the Taiho Sub-dam. This system consists of GPS receivers (L1-band) and a control box. Using the static positioning technique, the three-dimensional coordinates of the measurement points are measured every hour with their origin at a fixed reference point.

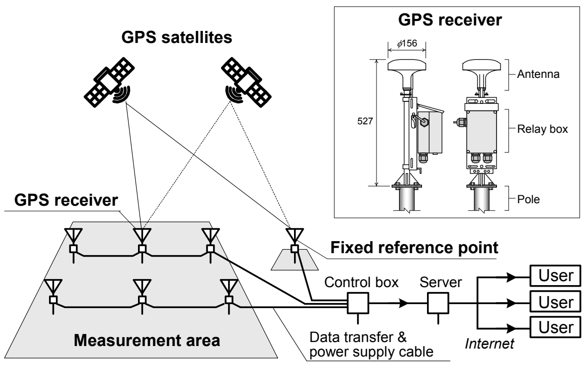


Figure 1. GPS displacement monitoring system

The raw GPS displacement data contains some random noise. The accuracy depends on the number of satellites used, the obstructions, the multipath effects, the atmospheric conditions, and so on. The general accuracy is 5 - 10 mm in the horizontal direction and 10 - 20 mm in the vertical direction even with the precise static relative positioning method. Therefore, statistical treatment is needed to estimate the true displacements. In our system, the trend model, one of the smoothing models based on a polynomial regression model improved by introducing a probability structure (Kitagawa 1993; Shimizu 1999), has been used.

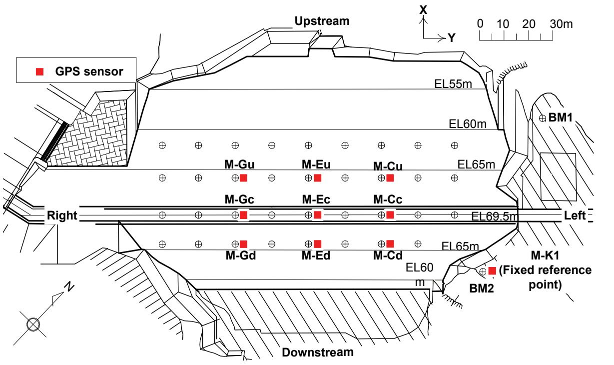
3. GPS MEASUREMENT AT THE MAJIMEGAWA DAM

3.1. Outline of the Majimegawa Dam

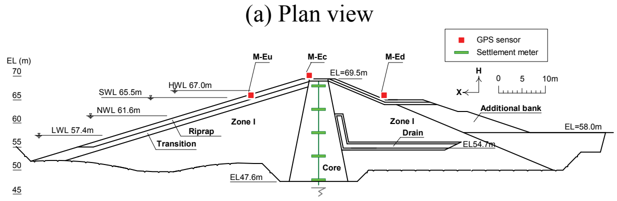
The Majimegawa Dam is a small earth-fill dam, with a height of 21.9 meters, on the Majime River in Yamaguchi Prefecture, Japan. The plan and cross-section views are shown in Fig. 2. The bedrock mostly consists of moderately weathered granite, and its permeability is less than 5 Lugeon in most parts, while partially 10 - 20 Lugeon near the surface. Difficulties such as stiffness and groutability were encountered with the bedrock; thus, the following structural treatments were done (Kawasaki et al. 2010):

– A lower gradient (30.3%) than normal was adopted for the upstream face in consideration of the low bearing capacity of the bedrock.
– Instead of curtain grouting, a core trench was constructed for seepage control.
– A chimney drain was constructed to lower the seepage line in the downstream dam body.
– An inspection gallery was not constructed in consideration of the bedrock weakness.

Regarding the embankment materials, granite soil, granite stone, and clayey schist were employed as the core materials, while Masa-sand and granite stone were employed as the earth fill materials.



(a) Plan view



(b) Cross-section

Figure 2. Schematic of the Majimegawa Dam and layout of the GPS receivers

3.2. GPS Measurement Conditions

Nine GPS receivers were set on the embankment surface as measurement points on the upstream face, the crest, and the downstream face, as shown in Fig. 2. A fixed reference point, M-K1, was set on the downstream side of the left bank. The GPS measurements at this dam were initiated in September 2007, three months after the start of the initial impoundment.

A conventional survey was also conducted using the total station with ± (2 mm + 2 ppm) ranging accuracy and 5" angle accuracy, and an automatic level with ± 1.5 mm/km accuracy.

To measure the compression of the dam core, a multi-layer settlement meter with ± 1 mm accuracy was installed.

3.3. Measurement Results and Discussion

3.3.1. Accuracy of the GPS measurement

Figure 3 compares the horizontal GPS displacements with those of the conventional survey (total station survey). They were measured at M-Ec, a measurement point on the crest in the maximum cross-section. The GPS measurements in the figure are the results smoothed by the trend model. From this figure, the GPS measurements and the conventional survey measurements show almost the same tendency in response to changes in the reservoir level. However, as the survey measurements show considerable variation, it is difficult to track the trend clearly, if we only look at the survey measurements. On the other hand, the GPS measurements provide the trend of the displacements smoothly, and they are sensitive to changes in the reservoir level.

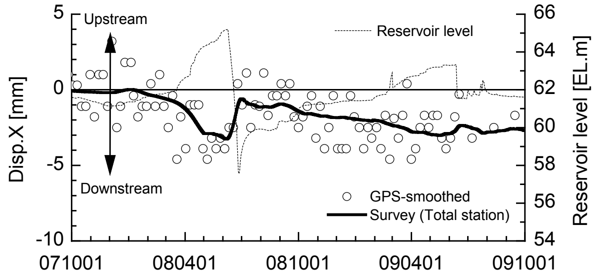


Figure 3. Horizontal displacements at the crest (M-Ec) in the up-downstream direction in the Majimegawa Dam, measured with GPS and the conventional survey (total station)

Figure 4 compares the vertical GPS measurements with those of the conventional survey (levelling) and settlement meter (HLV-5) that is set just below the crest. From this figure, the GPS vertical displacements agree entirely with the settlement meter measurements. This means that the present GPS system can measure vertical displacements with the same accuracy as the settlement meter. As mentioned above, the GPS measurements have 10 - 20 mm vertical accuracy, if we look at their raw data. However, we can improve on this to millimetre accuracy by highly-frequent measurements and by applying an appropriate smoothing treatment. These results prove the effectiveness of the GPS displacement monitoring system for measuring the static deformation of embankment dams.

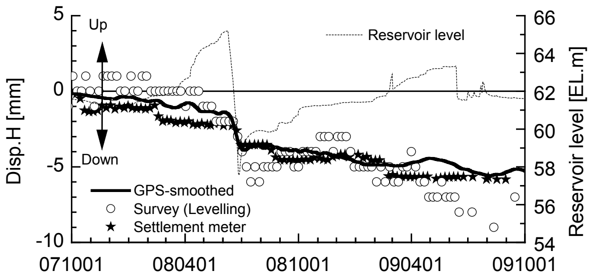


Figure 4. Vertical displacements at the crest (M-Ec) in the Majimegawa Dam with GPS, the conventional survey (leveling), and the settlement meter

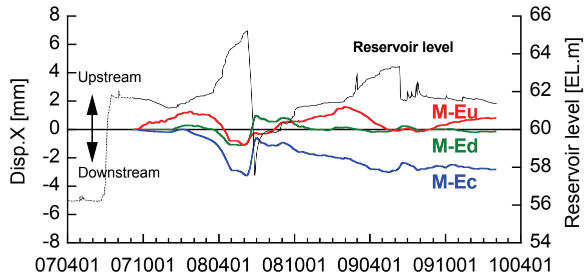
3.3.2. Temporal changes in the GPS displacements

Figure 5 shows the temporal changes in the GPS displacements of the Majimegawa Dam. Figure 5(a) presents the displacements in the up-downstream direction. The measurement points moved to the downstream with the rising of the reservoir, and returned to the upstream with the drawdown of the reservoir. This movement is largely affected by changes in the horizontal load due to the water pressure acting on the upstream face.

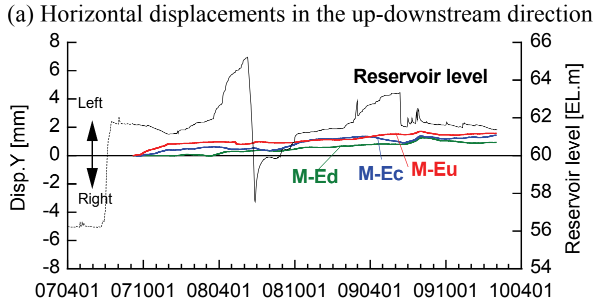
Figure 5(b) shows the displacements in the cross-stream direction. From this figure, the dam body is seen to have moved slightly to the left bank during the 2.5 years.

Figure 5(c) shows the vertical displacements. The upstream face (M-Eu) moved upward and downward in response to the rising and the drawdown of the reservoir level. This movement is assumed to be due to the increase and decrease in buoyancy force. The crest (M-Ec), however, moved downward during the whole period, and the settling is particularly large at the time of the rapid and significant drawdown of the reservoir in July 2008. This vertical movement of M-Ec seems to be due to the self-weight consolidation and the water binding of the dam core.

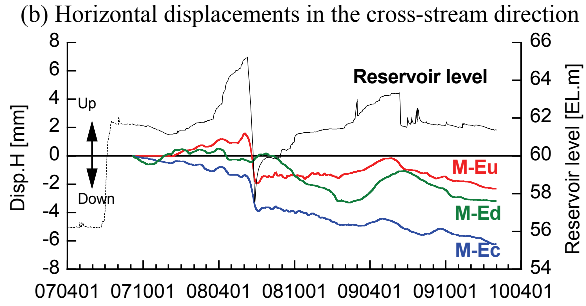
The displacements of the Majimegawa Dam have been less than several millimetres until now. However, the GPS measurements detect such small movements clearly and smoothly.



(a) Horizontal displacements in the up-downstream direction



(b) Horizontal displacements in the cross-stream direction



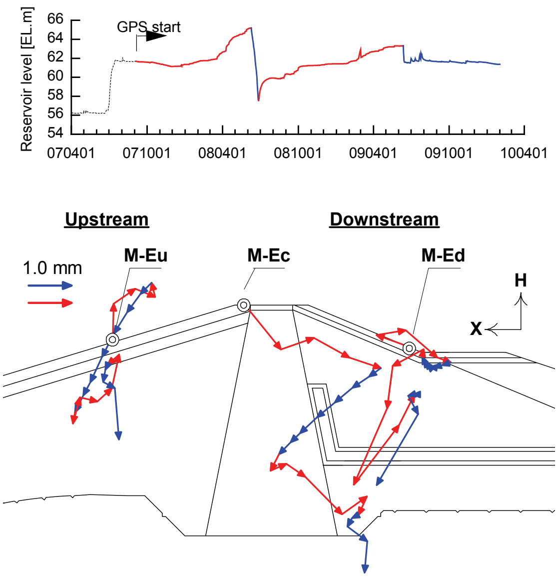
(c) Vertical displacements

Figure 5. Temporal changes in the GPS displacements at the upstream face (M-Eu), the crest (M-Ec), and the downstream face (M-Ed) of the Majimegawa Dam

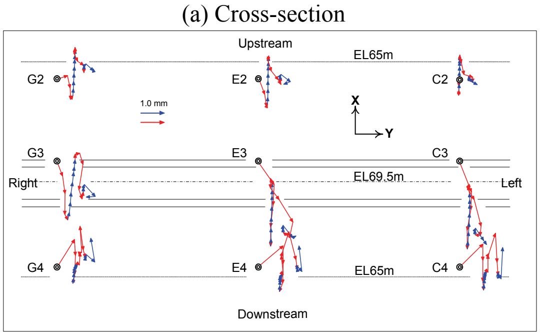
3.3.3. Displacement vectors

Figure 6 shows the displacement vectors by the GPS measurements from September 2007 to February 2010. The vectors were written for every one-meter change in reservoir level. The colours of the vectors, red and blue, indicate the rising and the drawdown of the reservoir, respectively. From this figure, we can see that the upstream face mainly moves vertically and that the behaviour is almost resilient. As for the crest, the settling is dominant, and the forward and backward movements in response to the changes in reservoir level are significant as well. The downstream face (M-Ed) moves along the slope during the initial impoundment and the discharge that follows. However, after the first discharge, the direction of the vector is rotated to be perpendicular to the slope.

Based on the GPS measurements taken up to now, we can roughly assume that the dominant factors of this embankment deformation are 1) the changes in the horizontal force due to the reservoir level, 2) the variation in the buoyancy force due to the changes in the reservoir level, and 3) the self-weight consolidation and the water binding of the dam core.



(a) Cross-section



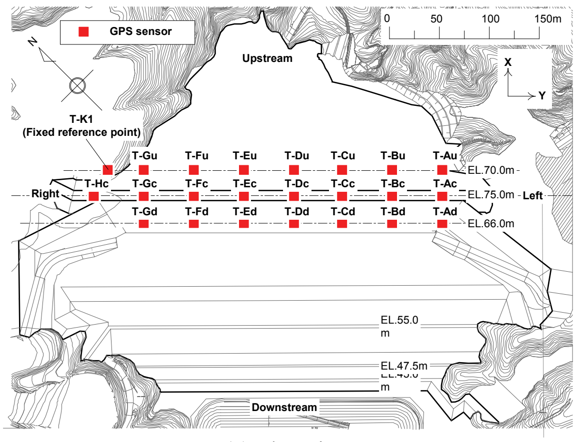
(b) Plan view

Figure 6. Displacement vectors in the Majimegawa Dam from Sept. 2007 to Feb. 2010. The red and blue colours indicate the rising and drawdown of the reservoir level, respectively.

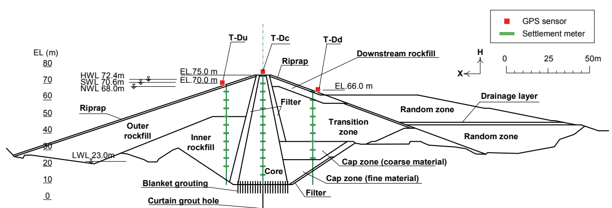
4. GPS MEASUREMENT IN THE TAIHO SUB-DAM

4.1. Outline of the Taiho Sub-dam

The Taiho Sub-dam is a rock-fill dam, with a height of 66.0 meters, on the Taiho River in Okinawa Prefecture, Japan. The plan and cross-section views are shown in Fig. 7. The bedrock mostly consists of fissured phyllite in the deep parts and is covered with an alluvial deposit with a thickness over 20 meters, which includes a pervious layer of gravel on the downstream side. In addition, the groundwater level was originally high to reach almost half of the dam height. Against these geological and hydrological difficulties, 1) curtain grouting along the dam axis, 2) an earth blanket on the downstream of the toe of the core (Cap zone in Fig. 7(b)), and 3) a counterweight embankment on the downstream slope (Random zone in Fig. 7(b)), were designed for seepage control and the stability of the embankment. An inspection gallery was not constructed in consideration of the high groundwater.



(a) Plan view



(b) Cross-section

Figure 7. Schematic of the Taiho Sub-dam and layout of the GPS receivers

4.2. GPS Measurement Conditions

22 GPS receivers were placed on the upstream face, the crest, and the downstream face of the embankment, as shown in Fig. 7. A fixed reference point, T-K1, was on the upstream side of the right bank.

In the Taiho Sub-dam underground GPS antennas, the antennas located inside the man holes were deployed on a trial for the crest points, as seen in Fig. 8(b). FRP lids were used to minimize the radio wave attenuation.

(a) Normal GPS antenna (b) Underground GPS antenna

Figure 8. GPS receivers in the Taiho Sub-dam

4.3. Measurement Results and Discussion

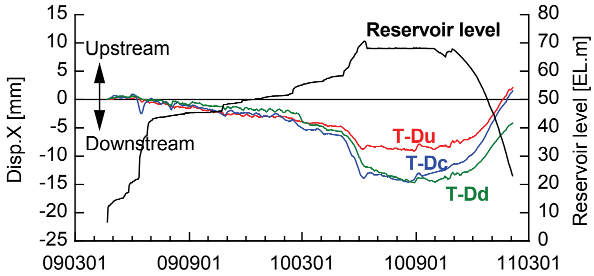
4.3.1. Temporal changes in the GPS displacements

Figure 9 shows the temporal changes in the GPS displacements of the Taiho Sub-dam during the initial impoundment. From Fig. 9(a), we can see that the horizontal displacements in the up-downstream direction are, regardless of the location of the measurement points, largely affected by the changes in the reservoir level. They move to the downstream with the rising of the reservoir, and move back to the upstream with the drawback. From Fig. 9(b), the dam body is seen to move slightly into the left bank in the cross-stream direction. One reason for this is that the groundwater level is higher in the right bank than in the left bank.

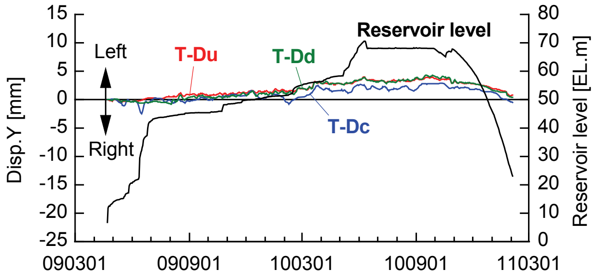
From Fig. 9(c), we can see that the crest (T-Dc) and the downstream face (T-Dd) settle monotonically due to the consolidation of the core zone in the vertical direction. On the other hand, the upstream face (T-Du) shows uplift and settling in response to the rising and the drawback of the reservoir. This is the same movement as for the Majimegawa Dam shown in Fig. 5(c). As shown in Fig. 9(c), the vertical displacement of the crest (T-Dc) shows more short-wave irregularity than the others. This is assumed to be due to the radio wave attenuation brought about by the manhole lids.

4.3.2. Relationship between the reservoir level and the GPS displacements

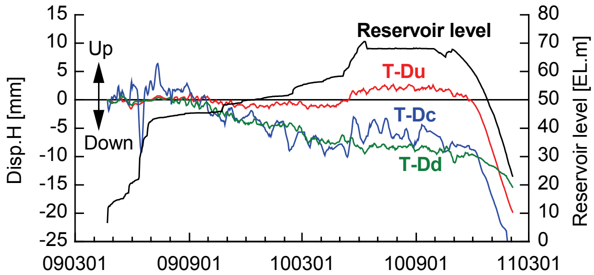
Figure 10 shows the relation between the GPS displacements and the reservoir level in the Taiho Sub-dam. From Fig. 10(a), we can see that the displacements in the up-downstream direction show almost the same tendency regardless of the location, as mentioned above. In addition, the displacements follow a similar path in the rising and drawback process of the reservoir, which implies that the dam body moves elastically in the up-downstream direction. As shown in Fig. 10, the displacements become sensitive to changes in the reservoir level when the reservoir level is more than about EL. 45 m. This is because the groundwater level in the downstream side is about EL. 45 m. The dam body is assumed to show remarkable displacement in response to the water level only after the reservoir level exceeds the downstream groundwater level.



(a) Horizontal displacements in the up-downstream direction

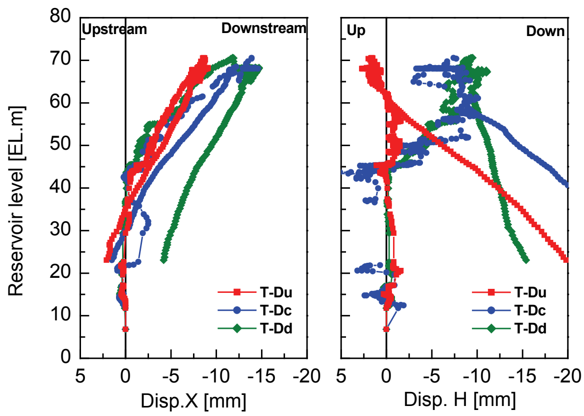


(b) Horizontal displacements in the cross-stream direction



(c) Vertical displacements

Figure 9. Temporal changes in the GPS displacements at the upstream face (T-Du), the crest (T-Dc), and the downstream face (T-Dd) of the Taiho Sub-dam.



(a) Up-downstream direction. (b) Vertical direction.

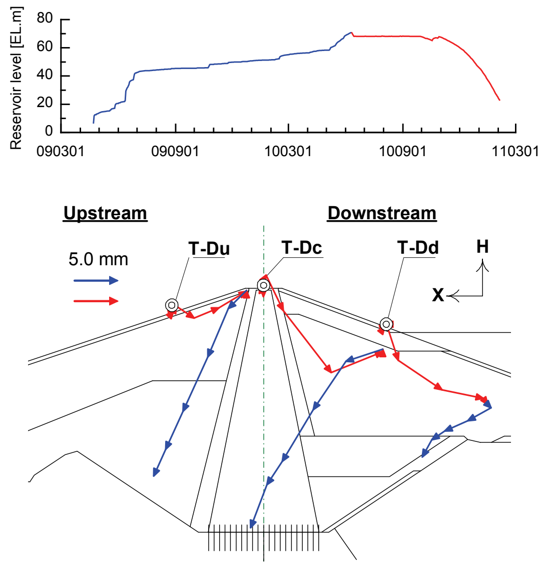
Figure 10. Relationship between horizontal and vertical displacements and reservoir level in the Taiho Sub-dam.

4.3.3. Displacement vectors

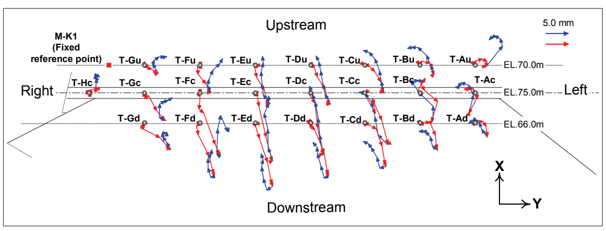
Figure 11 shows the displacement vectors by the GPS measurements during the first impoundment, from April 2009 to February 2011. The vectors were written for every 10-meter change in reservoir level. The colours of the vectors, red and blue, indicate the rising and the drawdown of the reservoir, respectively.

In the horizontal direction, largely affected by the reservoir change, all the measurement points resiliently move to the downstream and upstream depending on the rising and the drawdown of the reservoir. From the planar vector field, the amount of up-downstream displacement is larger around the maximum cross-section (Sections D and E), and it becomes smaller closer to the abutments. In the cross-stream direction, this dam moved slightly to the left bank in the reservoir rising period, but it resiliently returned to the original position.

In the vertical direction, the measurement points basically show settling during this whole period, affected by the self-weight consolidation of the core and the settlement due to submergence. However, the measurement points on the upstream face move upward with the rising of the reservoir. Such movement can also be seen at the Majimegawa Dam, as shown in Fig. 6.



(a) Cross section



(b) Plan view

Figure 11. Displacement vectors in the Taiho Sub-dam from April 2009 to Feb. 2011. The red and blue colours indicate the rising and the drawdown of the reservoir level, respectively.

5. CONCLUSIONS

In this study, a GPS-based displacement measurement system has been utilized to measure the exterior deformation of two fill dams, namely, the Majimegawa Dam and the Taiho Sub-dam. In the Majimegawa Dam, although the dam deformation was less than several millimetres, within the observation period of about two and a half years, the GPS-based displacement measurement system accurately and smoothly measured such small deformations in response to the rising and the falling of the reservoir water level and the self-weight compaction of the core. The combination of highly-frequent measurements at one-hour intervals and appropriate data treatment by the trend model produced more reliable data than the conventional survey technique in which it is measured once a week at most. This study has proved the high measurement accuracy in the vertical direction of the GPS system from a comparison with the settlement meters.

The GPS displacement monitoring system is advantageous in its laborsaving measurements in routine works as well as its prompt measurements under emergency situations, because the whole measuring process, from data collection to processing, is entirely automated. This study has proved the effectiveness of the GPS displacement monitoring system for the management of fill dams. This monitoring system is expected to develop into not only a simple safety monitoring tool, but also a non-destructive or non-contact visualization tool for internal dam bodies.

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