Application of Global Positioning System for Dam Deformation Monitoring

H. Arizono, H. Okumura & H. Onishi
Electric Power Development Co., Ltd, Tokyo, Japan
hiroki_arizono@jpower.co.jp

N. Shimizu
Yamaguchi University, Ube, Japan

ABSTRACT:
Renovation of safety monitoring system of existing dams has been becoming one of main issues for dam owners. In this regard, Global Positioning System (GPS) has been applied for dam external deformation monitoring in considerable numbers of existing dams in Japan. Electric Power Development Co., Ltd. which is one of the electricity utility companies in Japan, and owns rather old dams for hydropower stations, has started to utilize GPS for dam deformation monitoring for some years, and it has been applied in five dams. Since GPS enables to obtain the data more frequently than those obtained by the conventional manual measurement, it is useful to figure out deformation characteristics and its long-term trends more precisely. In addition, since digital data can be obtained automatically and transmitted online, it is also useful to acquire the status in real time, even if personnel cannot access to dams. On the other hand, the accuracy of GPS data is prone to be affected by some external factors such as climate conditions, surrounding plants growth. This paper shows continuous monitoring data of dam deformation by GPS through case histories in five dams and their effectiveness as well as countermeasures actually provided to improve foresaid matters.

Keywords: GPS, dam deformation monitoring, renovation of dam safety monitoring

1. INTRODUCTION

Global Positioning System (GPS) has been actively applied to numbers of existing dams in Japan recently for observation of those external deformations. It is expected that monitoring works on dam safety will be highly automated and facilitated by applying GPS. Japan Society of Dam Engineers published guidelines on dam safety monitoring method by using GPS in 2014. The guidelines (Japan Society of Dam Engineers, 2014 ; Shimizu, N., et al. 2014) offered basic information and standards on the system and devices of GPS, selection of measure points, maintenance methods, etc. GPS is expected to prevail widely in Japan as an effective system for monitoring of behaviour and safety of dams.

J-Power (Electric Power Development Co., Ltd.) has conducted observation of deformations of dam bodies by applying GPS at its own five sites of which names are Numappara, Akiha, Funagira, Kuromatagawa No.2, and Miboro. Numappara and Miboro are rock fill type, Akiha and Funagira are concrete gravity type and Kuromatagawa No.2 is concrete arch type. Fig. 1 shows locations of the dams. All the dams were constructed by J-Power for hydropower generation purpose. The following sections present the result of observation by using GPS, its technical knowhow, improvement measures, and other information obtained through the works at each site. Some recommendations for further effective use of GPS are also given based on the experiences on use of the system during some years.

Figure 1. Locations of 5 dams where GPS applied

2. MONITORING WORK AT NUMAPPARA DAM

2.1. General Features of the Dam

Numappara dam is an Asphalt Facing Rockfill Dam and is located in Tochigi Prefecture. It was constructed in 1973 for the upper pond of 675 MW pumped storage hydropower station. The height, the crest length and the volume of dam body are 38 m, 1,597 m and 1,260,000 m^3 respectively. The upper pond provides 4,220,000 m^3 of effective capacity for generation with 40 m drawdown.

2.2. System and Equipment

As shown in Fig. 2, GPS survey unit at Numappara dam is composed of 3 measure points and 2 benchmarks at present. At the time of starting the observation, only K-1 benchmark was located on the northern slope adjacent to the dam, and K-2 benchmark was added on the southern side slope after the 2011 Off the Pacific Coast of Tohoku Earthquake which brought a certain movement of the K-1 benchmark. The dam is located about 280 km from the seismic center. This is the first case of application of GPS for survey of dam deformation among the five dams. The system has functioned and recorded the data for over 8 years since its installation in 2007.

Before introducing GPS, the survey works at Numappara dam was limited to only the period from spring to fall except for winter season due to its hard weather condition with frequent snowfalls and blizzards. The application of GPS changed the situation and enabled continuous survey works throughout the year including winter season by its functions of digital measurement and automatic data transmission.

A specific condition at Numappara site was revealed in the initial stage of the observation using the K-2 benchmark. Fig. 3 shows a upward half-sphere view from the K-2 benchmark. Usually, GPS signals from the direction near the ground surface, mostly in the area lower than 15 degrees of elevation angle, are omitted from the analysis to prevent negative influence to the data by noise or reflection at around the surface. However, growing trees on the east side of K-2 exceeds the standard omission area as shown in Fig. 3. It was serious concern that the signals through the trees were strongly disturbed or deteriorated by moisture in and around the trees. After check of the signals at the site, the data processing methods was improved to expand omission area as shown in Fig.3.
Fig. 4 shows a comparison of analysis results with and without the improved mask processing. The result indicates a clear difference of data dispersion between two groups and better convergence of the data in case of the improved mask processing (Hisano, A., et al. 2015).

2.3. Result of Observation

J-Power has conducted the deformation survey of the dam body by two methods; GPS and the conventional manual survey, in parallel so as to check and verify reliability of the data. Fig. 5 shows the observation results comparing two sorts of the data; surveyed by GPS and by conventional manual survey. Both the data show comparatively good conformity as shown in Fig. 5.
When the 2011 Off the Pacific Coast of Tohoku Earthquake occurred, the asphalt surface of the dam was damaged, and a considerable amount of leakage was caused accordingly. Not only the leakage data but the dam deformation data by GPS were continuously transmitted to the site administration office, even though the access road to the dam was closed due to the heavy snow, which was very useful to know the dam's state just after the earthquake.

Numappara dam was the first site where GPS was planned and employed for the survey of dam deformation in the company. Various technical knowhow on the proper survey method, the problems and measures, and the improvement technique obtained from the work at the site have been referred and reflected to succeeding cases of observation by using GPS at the other sites.

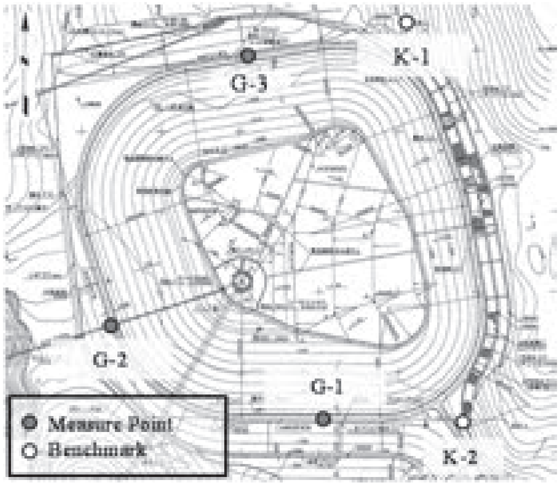

Figure 2. GPS Equipment Layout at Numappara dam

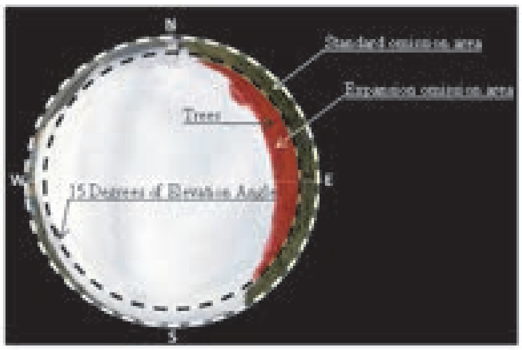

Figure 3. Upward Half-sphere View from K-2

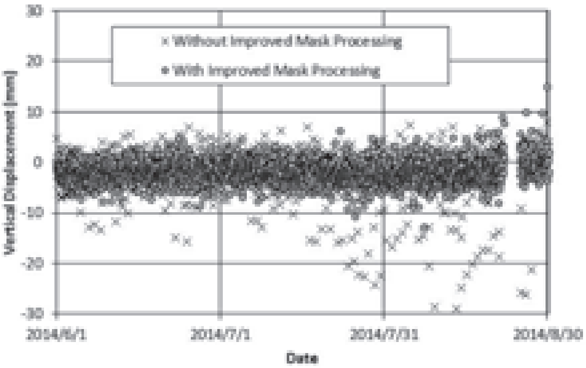

Figure 4. Comparison of Analysis Method

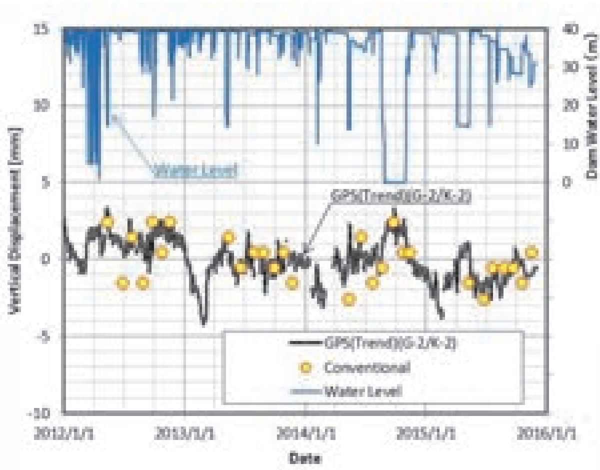

Figure 5. Comparison of GPS/Conventional Survey

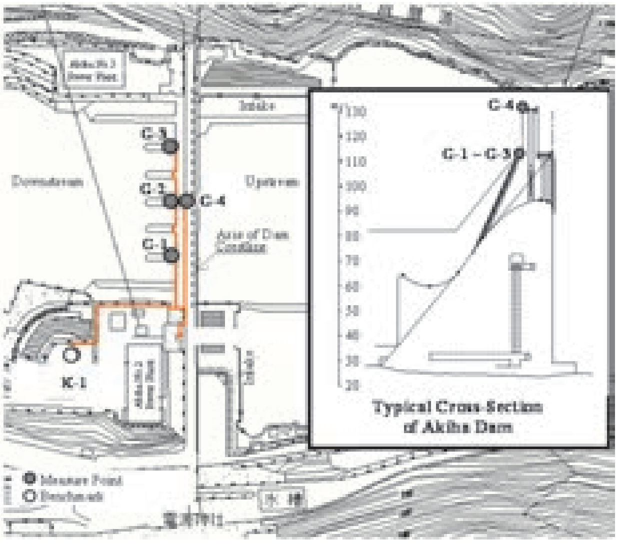

Figure 6. GPS Equipment Layout at Akiha dam

3. MONITORING WORK AT AKIHA DAM

3.1. General Features of the Dam

Akiha dam is a Concrete Gravity Dam which is located at 47 km upstream from the Tenryu River mouth in Shizuoka Prefecture. It was constructed in 1955 for 127 MW hydropower stations. The height, the crest length and the volume of dam are 89.0 m, 273.4 m and 515,000 m^3 respectively. The reservoir provides 7,750,000 m^3 of effective capacity for daily regulation in the operation. Available drawdown is 5.0 m in depth.

3.2. System and Equipment

As shown in Fig. 6, GPS survey unit at Akiha dam is composed of 4 measure points and 1 benchmark.

There is a disadvantageous condition at three measure points (G-1, G-2 and G-3) among four. These 3 measure points are installed under the gates hoist bridges of the spillway structure which obstructed the upward visual areas. Fig. 7 shows the upward half-sphere views from G-2 and G-4 as examples. The condition of G-2 may adversely affect stable reception of GPS signals.

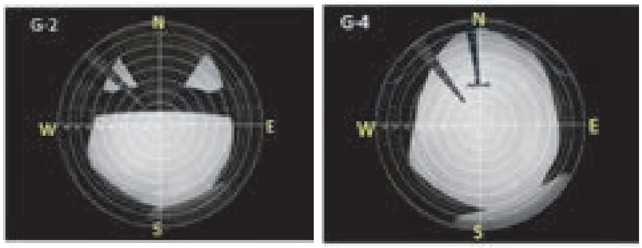

Figure 7. Upward Half-sphere Views from G-2 and G-4

3.3. Result of Observation

Fig. 8 shows an observation result of upstream-downstream displacement at the measure points, G-2 and G-4. The long term trends of displacement are periodical and steady. The trend line at the point G-2 indicates approximate 5 mm of yearly displacement toward upstream side in summer and downstream side in winter. G-4 indicates a bit larger displacement than that of G-2 due to difference of their vertical locations. It seems to be a normal behaviour of concrete gravity dams because such seasonal displacements are caused by expansion and shrinkage of the downstream concrete face due to difference of the temperature. In this case, the obstruction of upward half-sphere view seems not to cause adverse effect for GPS signals reception. The reservoir is operated within 5.0 m drawdown depth, however, the displacement is hardly affected by the operational water level.

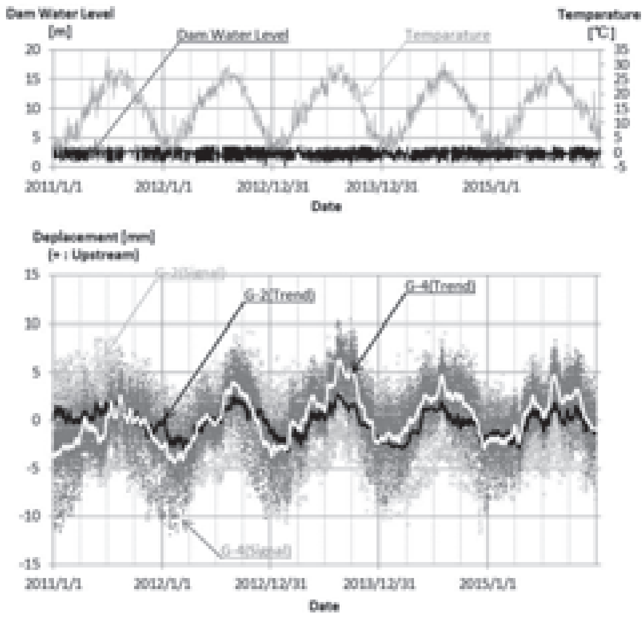

Figure 8. Observation Result at Akiha Dam

4. MONITORING WORK AT FUNAGIRA DAM

4.1. General Features of the Dam

Funagira dam is a concrete gravity dam which is located at 30 km upstream from the Tenryu River mouth and 17 km downstream of Akiha dam in Shizuoka Prefecture. It was constructed in 1977 for 32 MW hydropower generation, water supply and irrigation purposes. The height, the crest length and the volume of dam body are 24.5 m, 220 m and 54,000 m^3 respectively. The reservoir provides 3,600,000 m^3 of effective capacity for daily regulation, and available drawdown of 2.2 m in depth.

4.2. System and Equipment

GPS survey unit at Funagira dam is composed of 8 measure points and 3 benchmarks as shown in Figs. 9 and 10. All the measure points were set on the top of spillway piers but below the hoist bridges of spillway. They have a similar condition on upward views as that in Akiha dam accordingly.

There are three benchmarks named K-1, K-2 and K-3. K-1 is installed on the upstream right bank, K-2 is on the concrete structure at the right abutment, and K-3 is on the filling area just on the downstream left bank of the dam respectively. K-2 is the main benchmark for regular observation among them because of its high reliability of fixation. The concrete base of K-2 may generate a slight displacement due to change of the temperature, but it is negligible comparing with the long term behaviour of the dam body. K-1 on the natural rock had moved a little by the past rain washing and may have a possibility of further error. K-3 on the well compacted filled material has been stable so far but has some risk of unexpected movement in case of earthquake. K-1 and K-3 have been used for subsidiary purpose. The accumulated knowledge on the various foundations for benchmark at Funagira site will be very useful information for establishment of more reliable observation system in the future case.

4.3. Result of Observation

A survey result of the upstream-downstream displacement at the point G-5 is given in Fig. 11. The trend line shows around 8 mm of yearly periodical displacement. The amplitude and cycle of the movement are steady and constant throughout the observation period. The influence by water drawdown is assumed to be negligible because of its limited depth; 2.2m.

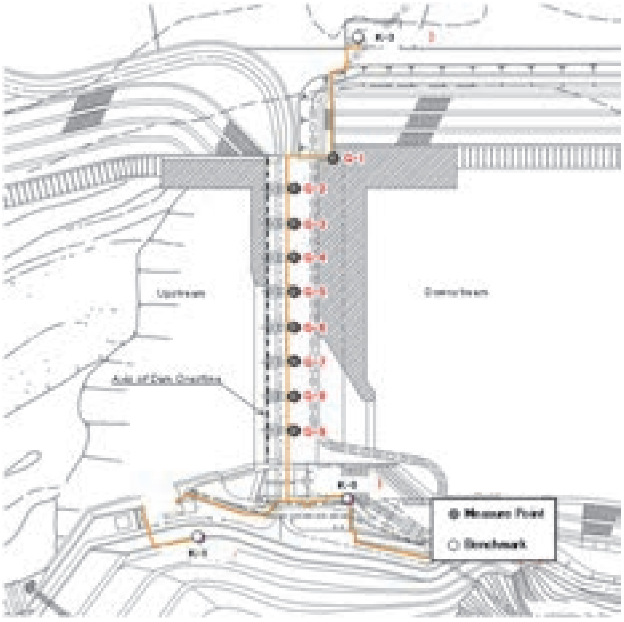

Figure 9. GPS Equipment layout at Funagira dam

Figure 10. K-1 to K-3 Benchmarks

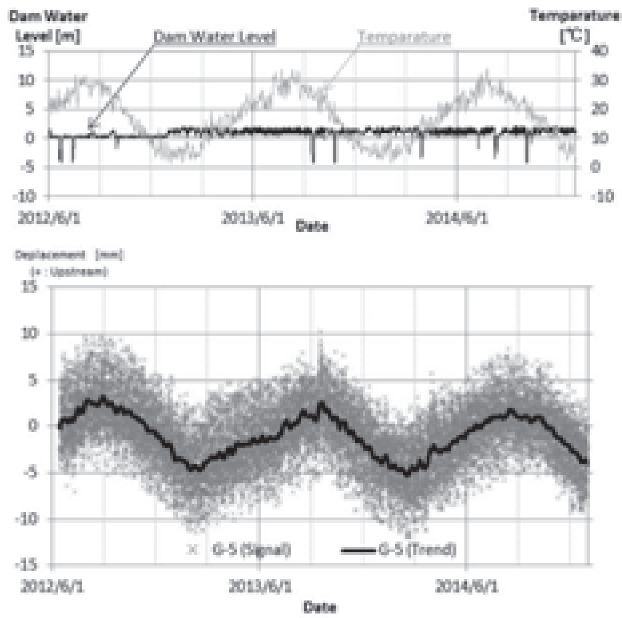

Figure 11. Observation Result at Funagira Dam

5. MONITORING WORK AT KUROMATAGAWA NO.2 DAM

5.1. General Features of the Dam

Kuromatagawa No.2 dam is a Concrete Arch Dam which is located at the upstream of the Kuromatagawa River in Niigata Prefecture. It was constructed in 1964 for 17 MW hydropower station. The height, the crest length and the volume of dam are 82.0 m, 235 m and 91,000 m^3 respectively. The reservoir provides 50,000,000 m^3 of effective capacity, and available drawdown is 37.0 m in depth.

5.2. System and Equipment

As shown in Fig. 12, GPS survey unit at Kuromatagawa No.2 dam is composed of 3 measure points and 2 benchmarks. The dam is located in the heavy snowfall mountainous area, therefore, the sensors for the measure points and the benchmarks were designed to be workable under the heavy snowfall and icy condition in winter. The sensor poles were also designed to be higher than the expected snow depth at the site. Standard height of the poles was 4.0 m.

5.3. Result of Observation

Application of GPS enabled the observation of the dam in all seasons including winter period in which the access and works at the site are difficult as same as that in Numappara dam due to heavy snow. Fig. 13 shows an observation result of the upstream-downstream displacement. The figure indicates three results of displacement based on the local benchmarks (K-1, K-2) and the national GPS-based Control Station named "Sumon" which is located around 10 km away from the dam site. The lines show high correlation with temperature and reservoir water level, like that the dam body moves to the upstream along with the temperature rising and moves to the downstream along with the water level rising. The results by GPS well conform to those data obserbed by the conventional manual survey.

The results obtained by the local benchmarks K-1 and K-2 in Fig. 13 show different trend in winter seasons of year 2013 and 2015 comparing with that in 2014. The reason is assumed that the local benchmarks were affected by heavy snow pressure during the winter and restored to the original condition along with snow melting. Both 2013 and 2015 are known as years having snowy winters.

The result suggests that the national GPS-based Control Station is useful for verification of availability and accuracy of the local benchmarks and measure points in heavy snowfall region.

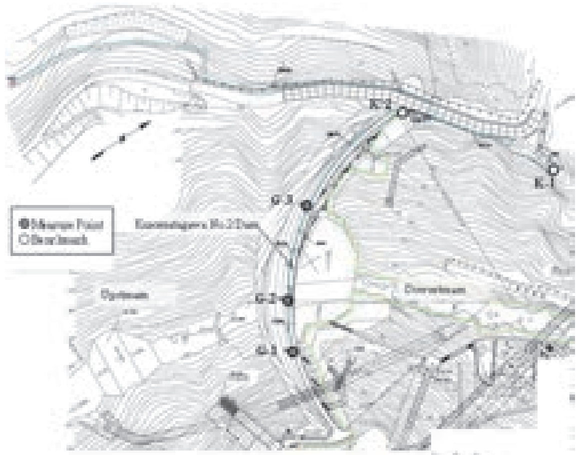

Figure 12. GPS Equipment Layout at Kuromatagawa No.2 dam

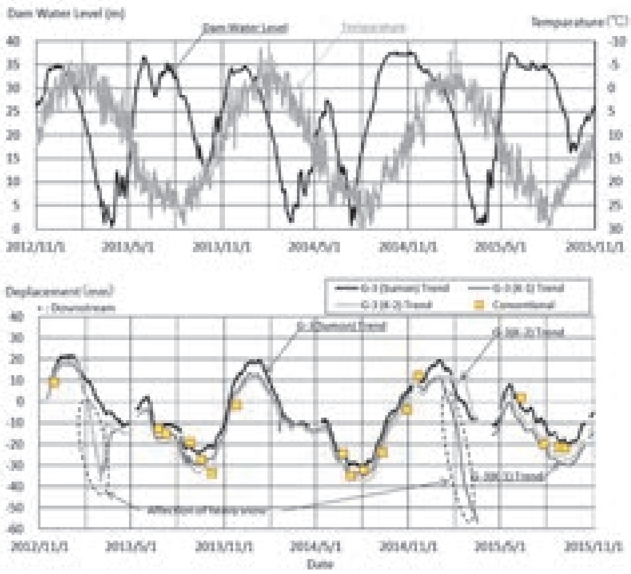

Figure 13. Observation Result at Kuromatagawa No.2 Dam

6. MONITORING WORK AT MIBORO DAM

6.1. General Features of the Dam

Miboro dam is a Rockfill Dam with Center Impervious Core which is located at the upstream of the Shokawa River in Gifu Prefecture. It was constructed in 1961 for 215 MW hydropower generation. The height, the crest length and the volume of dam are 131.0 m, 405 m and 7,950,000 m^3 respectively. The reservoir provides 330,000,000 m^3 of effective capacity, and available drawdown is 65.0 m in depth.

6.2. System and Equipment

GPS survey unit at Miboro dam is composed of 5 measure points and 3 benchmarks as shown in Fig. 14. Since the dam also is located in the heavy snowfall area similarly to Kuromatagawa No.2 dam, the sensors for the measure points and the benchmarks were designed to be workable under the heavy snowfall and icy condition as well. Height of the sensor poles was set as 3.5 m considering the expected snow depth at the site.

6.3. Result of Observation

Fig. 15 shows an observation result of upstream-downstream displacement. It shows a clear trend that the dam body moves to the upstream when the reservoir water level is lowering. The measured data by GPS basically conform to the data by the conventional manual survey.

Miboro dam is a typical annual operation resevoir among the five cases. The water level is lowered to around the lowest level by the end of winter for impounding snow melting water in spring season to utilize the river water effectively. On the contrary, the water level is kept comparatively stable high water level throughout the year except winter. A difficulty of the survey in winter season is a common problem at the sites located in deep snowfall region. Therefore, the dam behaviours during winter season were not been made cleared until GPS was adopted. The relationship between the dam behaviour and water level fluctuation throughout a year is understandable by GPS.

Two benchmarks, K-2 and K-3, of three are installed on the dam abutment at both right and left sides and another one, K-1, is on the spillway structure at the upstream rock foundation. Fig. 15 shows the displacement trends at G-6 point by three benchmarks and a considerable difference between K-2/K-3 and K-1. It is assumed that K-2 and K-3 were also affected by the movement of the dam body along with water level. K-1 kept its stable position independently with the firm foundation.

Figure 14. GPS Equipment Layout at Miboro dam

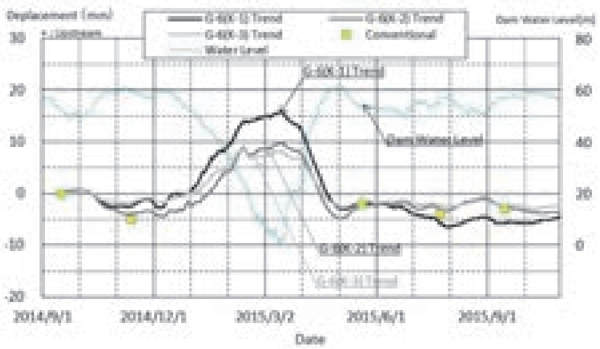

Figure 15. Observation Result at Miboro Dam

7. CONCLUSION

As the conclusion, the merits of GPS confirmed through the experiences of the abovementioned five instances are summarized as follows:

1) GPS enables always monitoring of dam behaviour throughout a year regardless weather conditions of the site.
2) GPS survey is useful for immediate check and monitoring of the dam safety in case of natural disasters such as earthquakes or sudden floods.

Also some recommendations for further effective use of GPS are given as follows:

1) The conventional manual survey should be continued in combination with GPS survey after its application. Comparison of two sorts of data is beneficial for verification and improvement of data reliability.
2) Accuracy of GPS is negatively affected by surrounding condition and visibility at the site, however, such influence can be mostly eliminated by proper measures such as the masking process described in Section 2.
3) Plural number of benchmarks should be provided to prevent sudden trouble or interruption of observation due to unexpected damage or movement of a benchmark.
4) GPS-based Control Station, if available near the site, is useful for verification of accuracy of local benchmarks.

REFERENCES

Japan Society of Dam Engineers (2014): GPS using manual concerning about measuring of fill dams, Japan Society of Dam Engineers. (in Japanese)

Shimizu, N., Nakashima, S. & Masunari T (2014): ISRM Suggested Method for Monitoring Rock Displacements Using the Global Positioning System (GPS), Rock Mech. Rock Eng., 47:313-328. DOI 10.1007/s00603-013-0521-5.

Hisano, A., Okumura, H., Koyama, K. (2015): Application of GPS to The Deformation Monitoring of Numappara Dam, Electric Power Civil Engineering, Vol. 378, pp. 66-70. (in Japanese)