APPLICATION OF THE GPS FOR MONITORING EXTERIOR DEFORMATION OF EMBANKMENT DAMS

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ABSTRACT

The measurement of exterior deformation is one of the most important measuring items for safety management of embankment dams. We enthusiastically made the research to develop the GPS automatic displacement measurement system for measuring exterior deformation of embankment dams. At present, this system has already been installed at many embankment dams. In this paper, we systematically summarize the results of our previous studies and other researchers' studies on this topic. In addition, we introduce the outlines of engineering manual on this technology, which we are preparing.

INTRODUCTION

In recent years, the rising number of dams in operation in Japan and the rising number of years since they were constructed have steadily increased the difficulty, both technically and economically, of managing dam safety. And large earthquakes such as The 2008 Iwate-Miyagi Earthquake and The 2011 Tohoku Earthquake which have occurred recently, have caused relatively large-scale damage to some irrigation use earthfill dams (Matsumoto et.al 2011). So advancing safety management of dams during earthquakes as well as at normal times is now a pressing challenge.

To manage the safety of dams, it is important to perform measurement along with visual inspections. Items which must be measured are stipulated by the Cabinet Order concerning Structural Standards for River Management Facilities, etc. It stipulates that at embankment dams, items which must be measured to manage safety are leakage and external deformation. By using targets installed on the crest and slopes of an embankment dam, its exterior deformations measured by surveying.

But the following problems with external deformation measurements based on conventional manual surveying methods have been pointed out.

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[1] It takes a long time to perform the measurements and organize the results, and prompt measurements are not always possible in the event of an earthquake or other emergency.

[2] The precision of measurements is scattered by differences between technicians or measuring instruments.

[3] During the first filling of a dam reservoir and until the behavior of a dam body and its foundation reaches a steady state, the measurement frequency should be high and management is costly.

So we have worked to use a GPS automatic displacement measurement system to measure external displacement of embankment dams as a method of replacing conventional manual geodimeter or leveling surveys. In a GPS (Global Positioning System), GPS receivers at a measurement point and at a reference point simultaneously receive radio waves from GPS satellites operated by the United States, to obtain relative three-dimensional coordinates from the reference point. Benefits of GPS are that it can obtain three-dimensional position coordinates free of the impact of rain, mist, and other weather conditions to measure a measurement point ranging from slight displacement to extremely large displacement without relocation or reinstallation.

So in the late 1990s, we developed a receiver and an automatic measurement system specialized to measure displacement of ground and structures, performed research to improve precision, and achieved millimeter unit three-dimensional automatic displacement measurements. And they conceived and partly achieved an automatic measurement system intended to be used for safety management of embankment dams (Yamaguchi et.al (2005), Soda et.al (2010) and Kawasaki et.al (2011)). Yamaguchi et.al (2005) proved, through the field test at a real rockfill dam, that exterior deformation measurements of an embankment dam by GPS can provide precision equal or superior to that by conventional surveying instrument.

This system is already used to measure external deformation at about 20 embankment dams in Japan, and trial applications of this system have been done to measure dam body deformation of concrete gravity dams (Kobori et.al (2012)), where displacement is smaller than that at embankment dams. This report integrates the results of these researches to give a detailed explanation of the constituent parts and analysis technology of the GPS automatic displacement measurement system which has been applied, and at the same time presents the results of a verification of its applicability to measuring the external deformation of an actual embankment dam. And a technical committee of the Japan Society of Dam Engineers (JSDE) has, with the participation of the authors, prepared Engineering Manual Concerning the Introduction of GPS to the Measurement of Deformation for Safety Management of Embankment Dams. This report also gives an introduction of this engineering manual.

GPS AUTOMATIC DISPLACEMENT MEASUREMENT SYSTEM

Because surveying use GPS measurements are expensive and difficult to handle, a compact, lightweight, and low cost GPS automatic displacement measurement system was developed without reduced measurement precision by removing functions and parts unnecessary for displacement measures from the surveying use GPS instrument to devise an instrument configuration which is simple as possible. Figure 1 shows the instrument configuration of the GPS automatic displacement measurement system, and Figure 2 shows the structures of GPS sensor.

The GPS sensor (Figure 2 and Table 1) has a simple configuration: only an antenna unit for a single-cycle (L1) receiver, and a control unit which controls the communication of the received data. Because it is not necessary to install an expensive receiver, recording unit, and power source unit etc. at every measurement point, as is necessary using surveying use GPS instruments, this system can be made relatively inexpensively.

The movable surveying targets (monuments) on the embankment dam body surface are only equipped with low cost GPS sensors (Figures 1 and 2), data received by GPS sensors are integrated and recorded in the communication aggregator through a multi-core cable, then transmitted sequentially to the analysis and mapping use analysis system. And electric power is transmitted to each GPS sensor through the same multi-core cable.

Such an instrument configuration means that even when multiple movable targets are measured, all that is necessary is to install many relatively inexpensive GPS sensors. And it is possible to reduce the overall number of instruments in the system by combining the equipment and materials necessary for other measurements in a single communication aggregator installed at the site. So it was possible to lower the cost of instruments below the cost when surveying use GPS instruments are used.

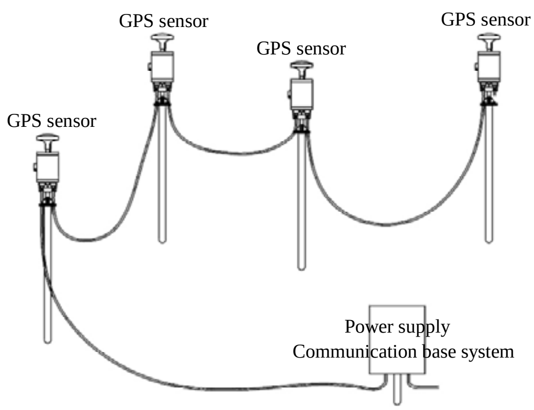


Figure 1. Instrument Configuration of the GPS Automatic Displacement Measurement System.

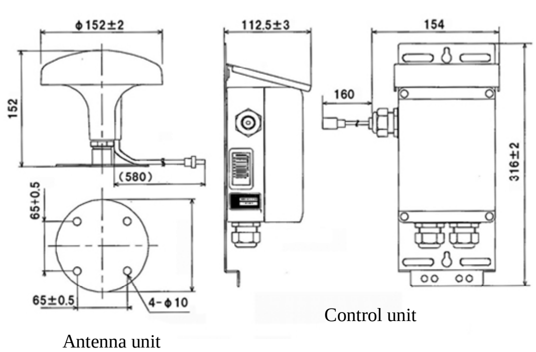


Figure 2. GPS Sensor.

Table 1. Specifications of the GPS Sensor.

Item	Specifications
Receiving frequency	L1 band (1575.42MHz), C/A cord, and carrier wave
Number of receiving channels	12ch
External form of the sensor	Antenna: (diam.)156×116mm Control box: 160mm×210mm
Weight of the sensor	0.8kg
GPS cable	Device net cable (4 cores)

TROPOSPHERIC DELAY COMPENSATION

If a GPS based measurement is done where there is a certain degree of elevation difference between the reference point and measurement point as shown in Figure 3, the radio wave path length may differ according to the elevation difference, resulting in an error remaining in the measurement results if only normal analysis is done. According to Masunari et.al (2009), this error is mainly related to water vapor pressure in the atmosphere near the ground surface and it is possible to compensate for it using ground surface atmospheric data (air temperature, air pressure, relative humidity) near the site in a case where the baseline is shorter than about 1km. This compensation work is called tropospheric delay compensation.

Figure 4 shows the results of GPS measurements at the Choja Landslide in Kochi Prefecture. This figure shows an actual example of tropospheric delay compensation in a case where the elevation difference between the reference point and measurement point is 92m and the baseline length is 538m. Figure 4(a) plots the value after error correction by the trend model of GPS measurement results in a case where tropospheric delay compensation is not done. And in Figure 4(b) the quantity of water vapor in the atmosphere obtained based on weather data (air temperature, air pressure and relative humidity) observed at the Kochi Weather Observation Station closest to the observation point is represented as the water vapor pressure.

As shown in Figure 4(a), GPS measured values of the height constituent show fluctuation in the annual cycle, revealing that it is correlated with change of water vapor pressure in Figure 4(b). The measured values in the NS direction and EW direction show almost no change in the annual cycle, revealing that the state of water vapor in the atmosphere impacts the measured value mainly in the height direction.

Next, Figure 4(c) shows the results of GPS measurement in a case where weather data (air temperature, air pressure and relative humidity) observed by the Kochi Weather Observation Station closest to the measurement location was used to perform tropospheric delay compensation. After tropospheric delay compensation, annual change of the height constituent was almost entirely removed, and it is presumed that the compensation calculation was effectively performed.

The GPS automatic displacement measurement system applied by this research, can automatically obtain weather data from weather observation stations throughout Japan and perform tropospheric delay compensation as needed, to remove the impact on GPS measured values of water vapor near the ground surface.

And regarding tropospheric delay (Soda et.al 2010, and Iwasaki et.al 2009), used the reference points installed at two locations with different elevations to clarify the relationship between elevation difference and tropospheric delay compensation in advance, then proposed a method of relatively easily compensating the impact of water vapor near the ground surface. This method is expected to be introduced as a practically applied method in the future.

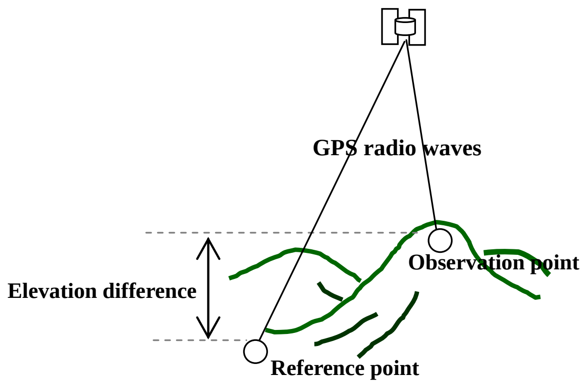
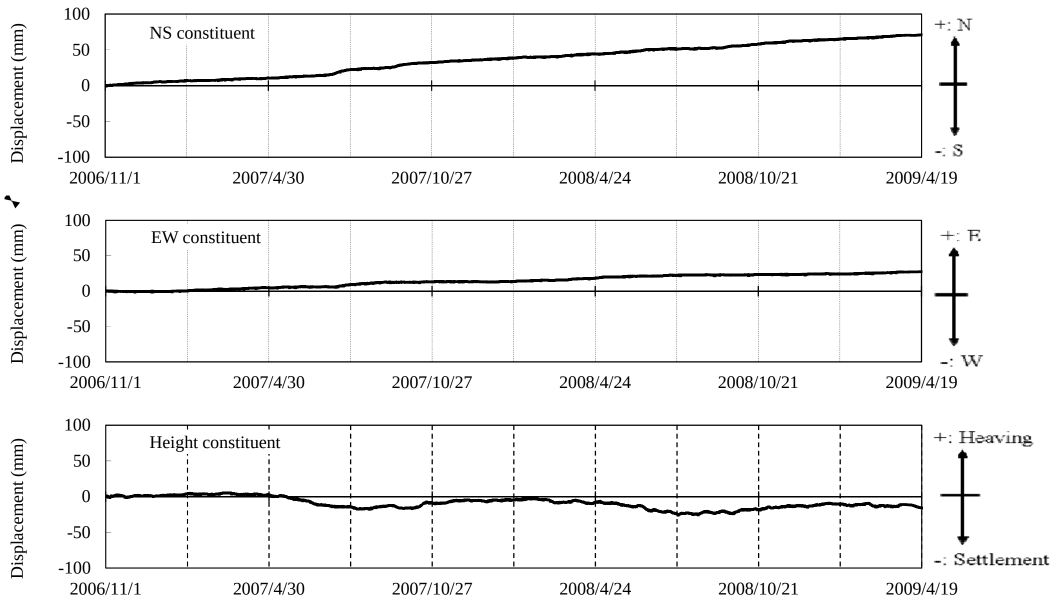
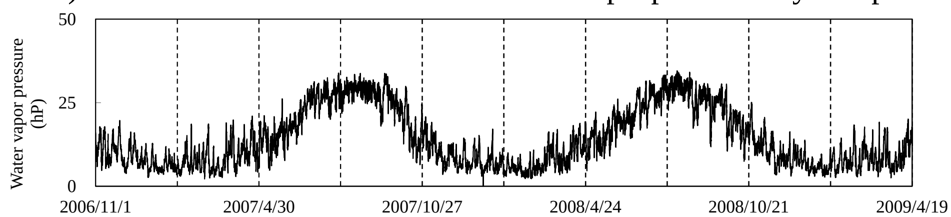


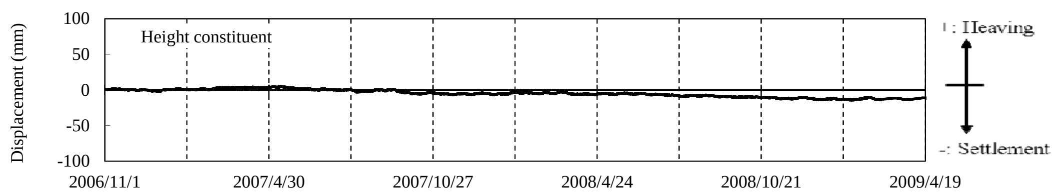
Figure 3. Differences in Radio Wave Path Length Caused by an Elevation Difference.



a) Results of GPS measurements before tropospheric delay compensation



b) Change of water vapor pressure



c) Results of GPS measurements (height) after tropospheric delay compensation

Figure 4. Comparisons Before and After Tropospheric Delay Compensation.

INSTALLING GPS SENSORS ON EMBANKMENT DAM BODIES

Figure 5 shows an example of a case where GPS sensors were installed on movable targets used to measure external deformation of a rockfill dam with an internal earth core, which is the standard form used to construct large-scale embankment dams. The movable targets in Figure 5 are survey studs placed on the center of the top of the concrete foundation (1,000mm×1,000mm×2,000mm). GPS sensors were fixed in place using stainless steel support columns at locations displaced from the survey studs on top of the concrete foundation so that they would not obstruct the performance of survey work. But, in cases where movable targets are embedded in dam crests, or in regions of heavy snowfall, the installation method such as that shown in Figure 5 would make it difficult to perform stable measurements, so the following method was developed.

Installation of a Movable Target on a Dam Crest

At many embankment dams, the dam crest is used as a management use road, so at such dams the movable targets used to measure external deformation are often installed inside a manhole on the crest of the dam. If a normal GPS sensor is installed on the movable target inside a manhole on the crest of a dam, problems occur. [1] Because its water protection function is poor, there is a high probability of the sensor malfunctioning if rainwater seeps into the manhole and [2] iron manhole covers block radio waves, preventing measurement.

So a GPS sensor designed to be embedded in the ground surface or a structure was developed and provided with a waterproofing function for use when it is placed in a manhole. And manhole covers were replaced by FRP (fiber reinforced plastic) manhole covers, which are easily penetrated by radio waves, permitting GPS measurements on dam crests (Yokomori et.al 2011).

Snow Cover Countermeasures

In heavy snowfall regions, GPS sensors are damaged by snow and snow accumulates above GPS sensors, preventing the sensors from receiving satellite radio waves, preventing measurements. So snow cover countermeasures such as the following were studied.

(1) Use of embedded GPS sensors

When embedded GPS sensors shown in Figure 5 have been installed on movable targets, which are composed of surveying stud and foundation concrete, on the crest of an embankment dam, GPS measurements can be performed if the snow is removed from the top of the manhole.

Urushiyama et al.(2011) have confirmed that if an embedded GPS sensor is used, GPS measurements can be performed temporarily immediately after snow is removed as part of normal dam management, showing that it is possible to clarify the state of displacement of the dam body with a certain degree of frequency, even during the winter.

And using this method, it is possible to easily clarify the state of displacement quickly if snow is removed from above dam body crest manholes in an earthquake or other emergency.

(2) Movable target concrete embedded GPS

In heavy snowfall regions, a method of preventing breakage of GPS instruments by snow cover by simply and cheaply embedding GPS sensors in the foundation concrete of a movable target on a dam body slope is useful (Figure 6). This method cannot be used to perform GPS measurements during the winter when there is a snow cover, but when clarifying dam body deformation is important, during first filling of reservoir or at the time of an earthquake or other emergency, it permits GPS measurements to be immediately restarted by removing the snow cover. And installing an FRP plate, through which radio waves pass, on the top of the embedded part in order to protect the GPS sensor, can protect the instruments from damage during snow cover and snow removal work.

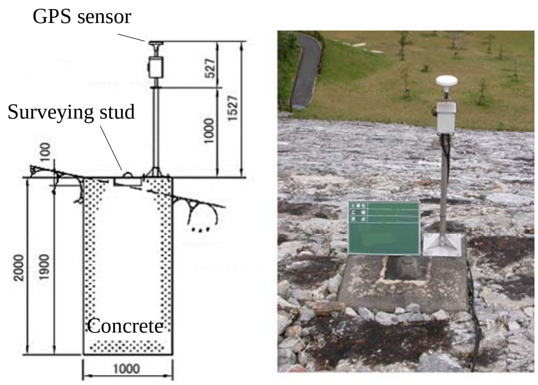


Figure 5. Example of the Installation of a GPS Sensor on a Movable Target.

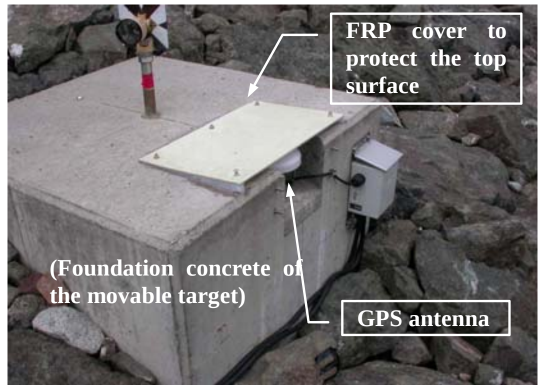


Figure 6. Example of GPS Embedded in the Movable Target Foundation Concrete.

RESPONSE AND SHARING OF INFORMATION DURING AN EARTHQUAKE OR OTHER EMERGENCY

It is stipulated that when an earthquake motion record with maximum acceleration of 25gal or higher has been observed in dam foundation ground, or when a weather observation station near a dam has observed seismic intensity of 4 on the Japan Meteorological Agency scale or higher, an emergency inspection is performed to confirm the safety of the dam body and its foundation, whether deformation did or not occur is quickly confirmed and the information is shared among concerned organizations. But, when measurement of the external deformation of the dam body of an embankment dam was done by the conventional geodimeter or leveling surveying methods, it took a long time to organize and to report the measurement work and measurement results in an emergency.

So for the GPS automatic displacement measurement system used for this research, a system was constructed to transmit the data obtained on the site to a monitoring center where the measurement results are analyzed and drawings prepared, and to transmit the result of this process to concerned parties through the internet, permitting information about the external deformation of the dam body to be shared not only a normal times, but immediately after an earthquake or other emergency. Figure 7 shows an outline of information sharing using the internet.

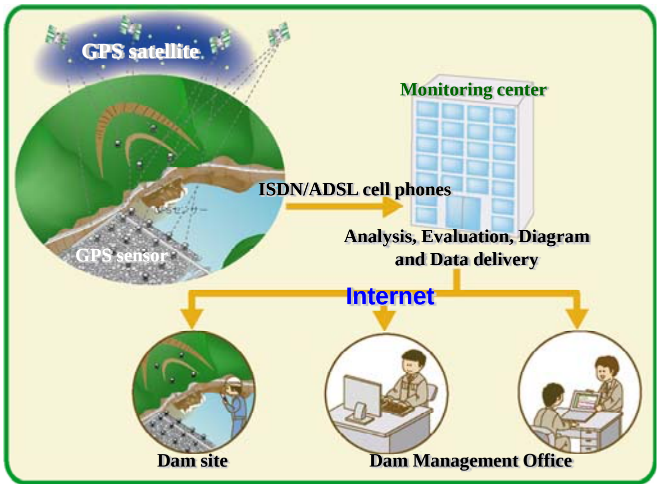


Figure 7. Outline of the GPS Automatic Measurement System using the Internet.

PREPARATION OF ENGINEERING MANUAL

The results of past research have resolved a number of technical challenges to applying the GPS displacement measurement system to measure the external deformation of an embankment dam. In order to apply displacement measurement technology using GPS to actual dams in order to clearly position it as a tool which can be appropriately used for safety management in the future, it will be necessary to summarize GPS instrument development technologies, positioning related technologies, and technologies to evaluate the results of measurements based on the precision needed to assess the safety of a dam. The most suitable way to achieve such goals efficiently and to then transfer the results obtained widely and quickly to dam technologists, is to gather technologists and researchers from industry, government, and academia and integrate their studies. So the Japan Society of Dam Engineers (JSDE) established the Measurement Management Technical Subcommittee, which has prepared the Engineering Manual Concerning the Introduction of GPS to the Measurement of Deformation for Safety Management of Embankment Dams (below called, “the engineering manual”). And while the engineering manual summarizes present technologies, they do not standardize GPS displacement measurement technologies. Table 2 shows the content of the engineering manual.

Table 2. Content of the Engineering Manual Concerning the Introduction of GPS to the Measurement of Deformation for Safety Management of Embankment Dams.

1. Introduction
2. Safety management of dams
2.1 Present state of and challenges to safety management of dams
2.2 Required performance of GPS measurement at dams
3. GPS positioning
3.1 Outline of GPS positioning
3.2 GPS positioning methods used to measure embankment dam bodies
3.3 GPS positioning theory
3.4 Causes of errors and compensation technologies
3.5 Positioning results and calculating displacement
3.6 Modernization of GPS and GNSS
4. GPS measurement devices
4.1 Specifications of the GPS automatic displacement measurement system to measure dam bodies of embankment dams
4.2 Configuration of the GPS automatic displacement measurement system
4.3 GPS automatic measuring instruments installed on the site
4.4 Analysis system
5. Selection of measurement locations
5.1 Deformation behavior of dams
5.2 Concept of the introduction of GPS measurements
6. Instruments installed on site: installation methods and precautions
6.1 GPS measurement points: installation methods and precautions
6.2 GPS reference points: installation methods and precautions
6.3 Data loggers etc.: installation methods and precautions
6.4 Lightning protection devices: installation methods and precautions
6.5 Snow cover, frost heaving, and icing countermeasures and precautions
7. Reporting
7.1 Saving and managing records
7.2 Organizing and summarizing data
7.3 Reporting when an earthquake occurs
7.4 Saving and managing records
8. Maintenance
8.1 Daily inspections
8.2 Regular inspections and maintenance
8.3 Emergency inspections in emergencies
8.4 Confirming immobility of a GPS reference point
8.5 Years of use and replacement

CONCLUSIONS

This research applied the GPS automatic displacement measurement system to measure the external deformation of embankment dams as a method to replace the conventional geodimeter and leveling surveying methods. The following are the achievements of this research.

[1] It is possible to automatically and precisely measure the external deformation of an embankment dam using the GPS displacement measurement system.

[2] Introducing error processing by the tropospheric delay compensation realized high precision measurements which are more reliable than conventional surveying methods.

[3] An embedded GPS sensor effectively measures displacement at the crest of a dam body.

[4] The internet was used to build a system to constantly distribute measurement results, permitting immediate sharing of information when an earthquake or other emergency occurs.

[5] GPS instrument development technologies, installation method related technologies, and technologies to assess measurement results based on precision required for dam safety management have been summarized to prepare Engineering Manual Concerning the Introduction of GPS to the Measurement of Deformation for Safety Management of Embankment Dams.

Introducing the GPS automatic displacement measurement system can be counted on to cut measurement cost by about 20% during the first filling of a dam reservoir (Phase I of management) of an embankment dam, and a few percent in the term until the behavior of a dam body and its foundation reaches a steady state (Phase II of management). But after the behavior of a dam body and its foundation reaches a steady state (Phase III of management), when measurements by conventional surveys are performed with low frequency, inversely costs would rise by about 20%, so further lowering the cost of GPS measurements is a problem to be resolved in the future.

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