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REAL-TIME MONITORING OF EXTERIOR DEFORMATION OF EMBANKMENT DAMS USING GPS [*]

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JAPAN

[*] *Surveillance en temps réel des déformations extérieures des barrages en remblai au moyen d'un système de positionnement global (GPS).*

1. INTRODUCTION

A Global Positioning System (GPS) can be used for the real-time measurement of the exterior deformation of an embankment dam. This is, therefore, an extremely effective method during emergencies: when the reservoir water level is abruptly increased by a large flood or when a large earthquake occurs.

Statistically processing the data measured by GPS, a process called a trend model, can ensure precision from 2 to 3mm in the vertical direction which has been less precise than the horizontal direction, permitting the measurement with precision that is equal to or superior to conventional surveying based measurements.

We have developed (1) GPS sensor which is installed on foundations of the survey targets on the slope of an embankment dam and (2) backfill type GPS sensor that can be installed in a variety of locations such as the center of a dam crest, and have performed verification measurement at an actual embankment dam. The results clearly show that by applying GPS to measure exterior deformation of embankment dams, it is possible to set the measurement points at the same locations as those used for conventional geodimeter and leveling surveys and that it is also possible to ensure measurement precision equal or superior to these, achieving a practical system that can measure exterior deformation of embankment dams using GPS.

Based on these results, a study is now being carried out to prepare to replace safety management based on measuring exterior deformation by conventional surveying methods with safety management using GPS at the Taiho Subdam (ER, height: 66m, crest length : 445m, dam body volume: 1,750,000m^3) constructed by the Okinawa General Bureau of the Cabinet Office, the Government of Japan. At the Taiho Subdam, GPS sensors were installed at all the exterior deformation measurement targets for conventional surveys. Specifically, GPS sensors are installed at a total of 24 locations: two benchmarks for GPS measurement and 22 points of measurement targets.

This paper describes how GPS sensors were installed at the Taiho Subdam and the results of a verification of their measurement precision. It also proposes a scenario for replacing the conventional measuring methods for exterior deformation of embankment dams: either with an exclusively GPS based system or with a combined system with GPS as the principal method.

2. EXTERIOR DEFORMATION MEASUREMENTS FOR EMBANKMENT DAMS IN JAPAN

Fig.1 shows an example of the installation of exterior deformation measurement targets on a rockfill dam with an earth core. Fig.2 shows an example of the detailed structure of targets at a measuring point and a benchmark. Specifically, a grid of appropriately spaced measurement lines is formed on the crest and slopes of a dam body, measurement targets (measuring points) are installed at each grid intersection point, and the quantity of displacement in the horizontal and vertical directions of the targets (measuring points) from targets installed on the left and right banks (benchmarks) are measured based on geodimeter survey and leveling survey.

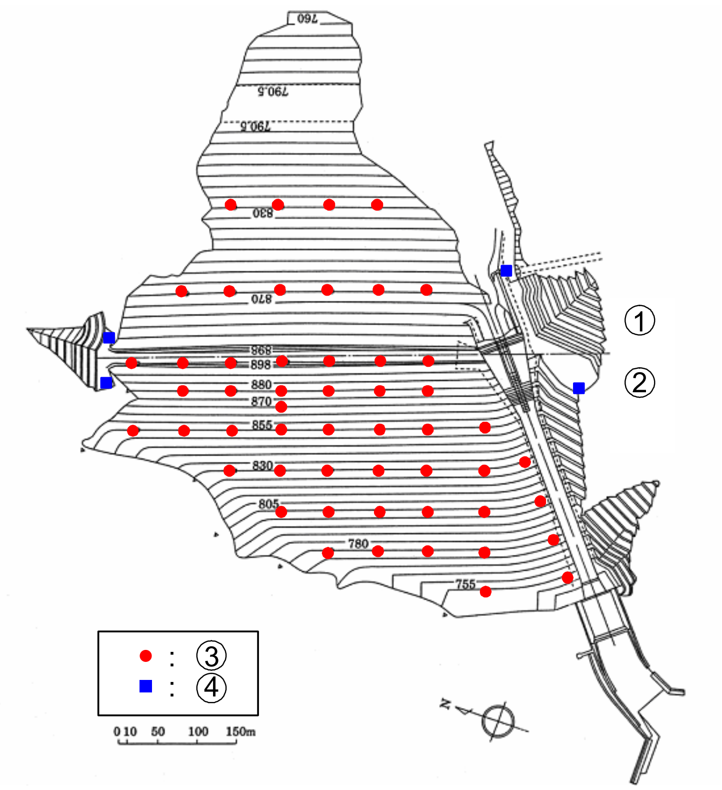
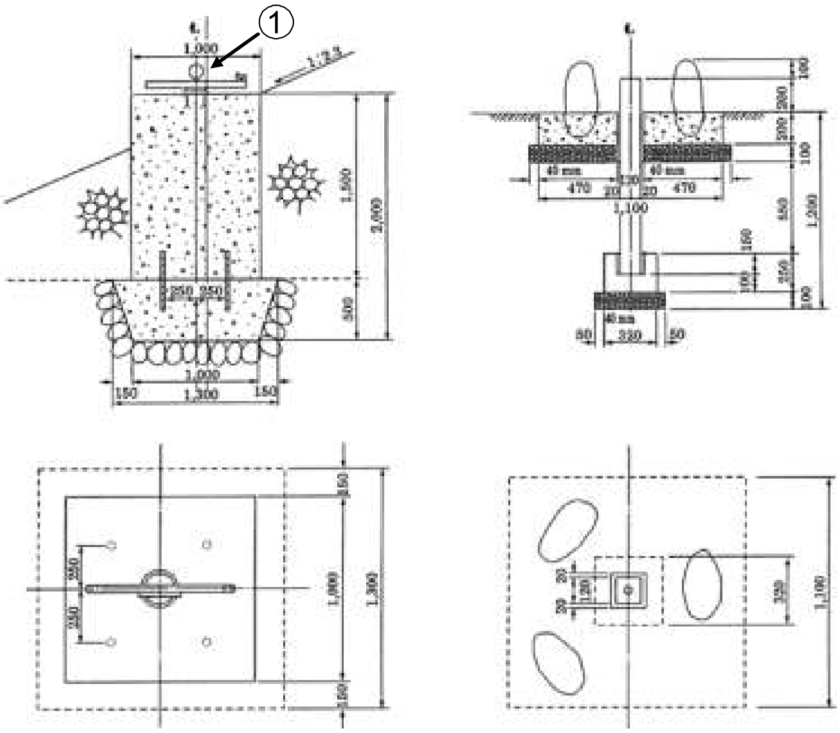


Fig.1

Layout of exterior deformation measurement targets on a rockfill dam (Naramata Dam)

Localisation des points de mesure cibles des deformations extérieures sur un barrage en enrochement (Barrage de Naramata)

1	U/S side	*1*	*Côté en amont*
2	D/S side	*2*	*Côté en aval*
3	Measuring point	*3*	*Point de mesure*
4	Benchmark	*4*	*Points de repère*



(2) (3)

Fig.2

Detailed structure of targets at measuring point and benchmark (Sagae Dam)

Structure détailles des cibles aux points de mesure et points de repère

(Barrage de Sagae)

1	Measuring point	*1*	*Point de mesure*
2	Measuring point	*2*	*Point de mesure*
3	Benchmark	*3*	*Point de repère*

Table 1 summarizes the frequency of measurement for dam safety management in Japan [1]. The deformation of a rockfill dam in the table means exterior deformation. The First Term of dam safety management refers to the duration of the first filling of the reservoir. The period from the conclusion of the first filling until the stable stage when the dam’s behavior has come to be stable and the period after the dam’s behavior has reached the stable behavior stage are called the Second Term and the Third Term respectively of dam safety management. The measurement of exterior deformation of an embankment dam is done once a week in the First Term, once a month in the Second Term, and once every three months in the Third Term.

Methods of measuring exterior deformation of embankment dams based on geodimeter and leveling surveys have faced some problems. Because it is relatively time-consuming and costly to perform measurements and to analyze the results with these methods, it is not always possible to respond promptly to the need for urgent measurements of exterior deformation after a large earthquake or in other emergencies.

Table 1
Frequency of measurement for dam safety management in Japan
Fréquence des mesures concernant la gestion de la sécurité des barrages au Japon

Measurement item	Concrete Dam			**Rockfill Dam**		
	First Term	Second Term	Third Term	First Term	Second Term	Third Term
Leakage / Seepage	Once / 1 day	Once / 7 days	Once / 1 month	Once / 1 day	Once / 7 days	Once / 1 month
Deformation	Once / 1 day	Once/ 1 day	Once / 7 days	**Once / 7 days**	**Once / 1 month**	**Once / 3 months***
Uplift / pore water pressure	Once / 1 day	Once / 7 days	Once / 1 month	---	---	---
Visual inspection	Once / 1 day	Once / 7 days	Once / 1 month	Once / 1 day	Once / 7 days	Once / 1 month

*: The interval of the measurement can be elongated according to conditions.

3. GPS MEASUREMENT TECHNOLOGY

3.1. GPS SENSORS [2], [3]

This study used a GPS sensor that is compact, light weight, and low-cost. Statistically processing the measured data, a process called a trend model [2], achieved measurement precision between 2 and 3mm, even in the vertical direction in which the measurement precision is lower than in the horizontal direction. This is a level of precision equal or superior to that possible with a conventional surveying method.

Fig.3 shows the GPS sensor that was installed on the foundation of survey target. Installation on survey target foundations permits cross-checking of the GPS measurement results with the conventional survey results.

But according to installation location, it may be impossible to accurately measure deformation behavior of an embankment dam by GPS, particularly on embankment dam crests where the larger deformation is measured. Dam crests are often used as management roads, so survey targets are usually installed inside manholes on these crests. But it is difficult to install a normal GPS sensor inside a manhole on a dam crest.

A backfill type GPS sensor was developed so that GPS sensors can be installed inside dam crest manholes. Fig.4 shows a backfill type GPS sensor. Even when a backfill type GPS sensor is installed inside a manhole on an embankment dam crest, it provides measurement precision after data processing in the vertical direction that is equal to that obtained if it were installed outside the manhole, because the steel cover of the manhole is replaced with one made of FRP (Fiber Reinforced Plastic) that is easily penetrated by radio waves.

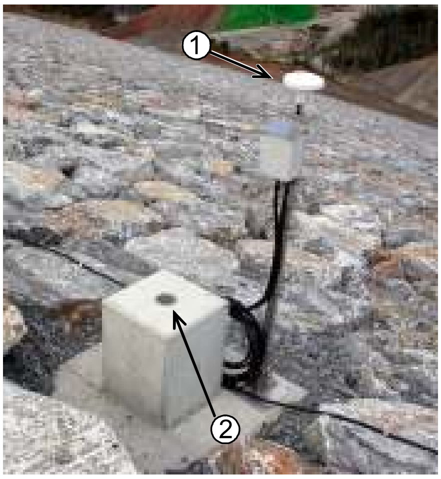


Fig.3
GPS sensor installed on survey target foundation
Capteur GPS installé sur les fondations ciblées utilisées pour l'étude

1	GPS sensor	*1*	*Capteur GPS*
2	Measuring point	*2*	*Point de mesure*

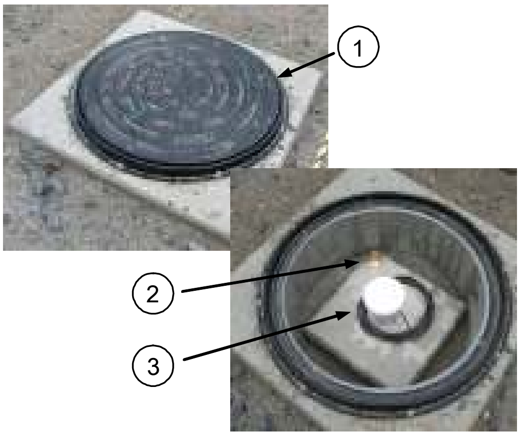


Fig.4
Backfill type GPS sensor installed inside a dam crest manhole
Capteur GPS de type à remblai installé à l'intérieur d'un trou d'homme situé à la crête déversante du barrage

1	FRP manhole	*1*	*Trou d'homme FRP*
2	Measuring point	*2*	*Point de mesure*
3	Backfill type GPS sensor	*3*	*Capteur GPS de type à remblai*

4. FULL ADOPTION OF GPS MEASUREMENTS

4.1. INSTALLATION OF GPS SENSORS AT THE TAIHO SUBDAM

Our previous studies have shown that GPS measurements of exterior deformation of embankment dams can ensure precision equal to or superior to the conventional geodimeter or leveling survey methods, and that improvement of the GPS sensor for crest installation has ensured measurement precision adequate for practical application of the method.

In response to these results, a study has been carried out at the Taiho Subdam now under construction by the Okinawa General Bureau of the Cabinet Office, the Government of Japan, to consider completely replacing conventional methods of measuring exterior deformation with GPS measurement methods.

Fig.5 is a plane map of the Taiho Subdam. At the Taiho Subdam, GPS sensors were installed on all conventional survey target foundations. GPS sensors were installed at a total of 24 locations: 2 GPS benchmarks and 22 survey target foundations. Backfill type GPS sensors were used for the measurement on the crest.

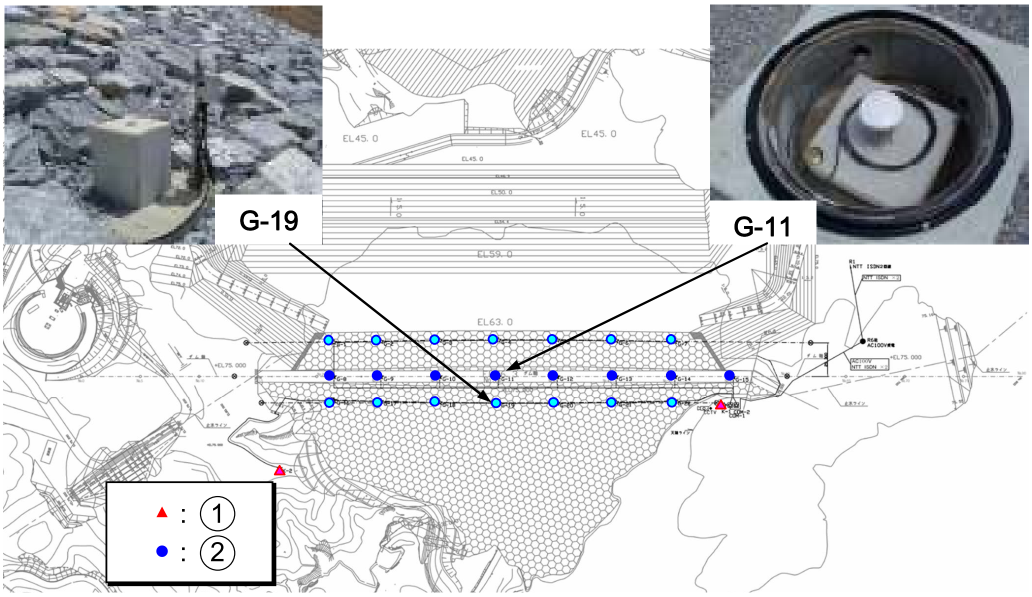


Fig. 5
Plane Diagram of Taiho Subdam
Diagramme plane du barrage subsidiaire de Taiho

1 GPS sensors for benchmarks
2 GPS sensors for measuring points

1 Capteurs GPS pour les points de repère
2 Capteurs GPS pour les points de mesure

4.2. RESULTS OF MEASUREMENTS AT THE TAIHO SUBDAM

As examples of measurement results before the impounding of the reservoir, Fig.6 shows results of measurement at G-19 on the upstream slope of the dam and Fig.7 shows results of measurement at G-11 on the dam crest dam. At G-11, a backfill type GPS sensor was installed.

From the top to the bottom chart, the measurement results shown are upstream–downstream, dam axis, and vertical direction displacement. Displacement in the upstream–downstream direction is positive on the upstream side, in the dam axis direction, it is positive on the left bank side, and in the vertical direction, it is positive in the upward direction. The observed displacement was arranged treating the value at the measurement start time as 0. The results measured by GPS were arranged assuming that the results of conventional survey measurements performed when GPS measurement began are equal to the GPS measured values.

The dots on the displacement graphs show GPS measurement results before data processing and the solid lines show GPS measurement results after data processing by the trend model. These data were GPS measurement values obtained by data processing analysis performed using data for 1-hour periods measured at 30 second intervals assuming that the dam body is not deformed while 1-hour's data is received. The survey results are shown by large circles.

In the results of measurements at measuring points installed on the upstream slope of the dam shown in Fig. 6, the GPS measurement values before data processing are widely distributed at approximately 5mm in the upstream-downstream and the dam axis directions, and approximately 10mm in the vertical direction. Such scattering of measured values is the result of errors caused by the impacts of the ionosphere and the troposphere which cannot be completely removed by normal GPS baseline analysis, orbital errors of satellites, and noise of GPS receivers. However, the range of the distribution of measured values after data processing is between 1 and 2mm in contrast to the range of distribution of measured values before data processing, revealing that it is possible to effectively process data.

As shown in Fig. 7, when installed inside a manhole on a dam crest, the GPS measurement values before data processing were distributed about 10mm in the upstream–downstream and the dam axis directions, and about 20mm in the vertical direction. Due to placing them in manholes, the results are more widely distributed that those from GPS installed on slopes, but the range of distribution of measured values after data processing is 1 to 2mm, revealing that effective data processing is performed.

As a result, the geodimeter and leveling survey values generally conform with GPS measured values after the processing of the results, revealing that both are good measurement methods of the dam deformation.

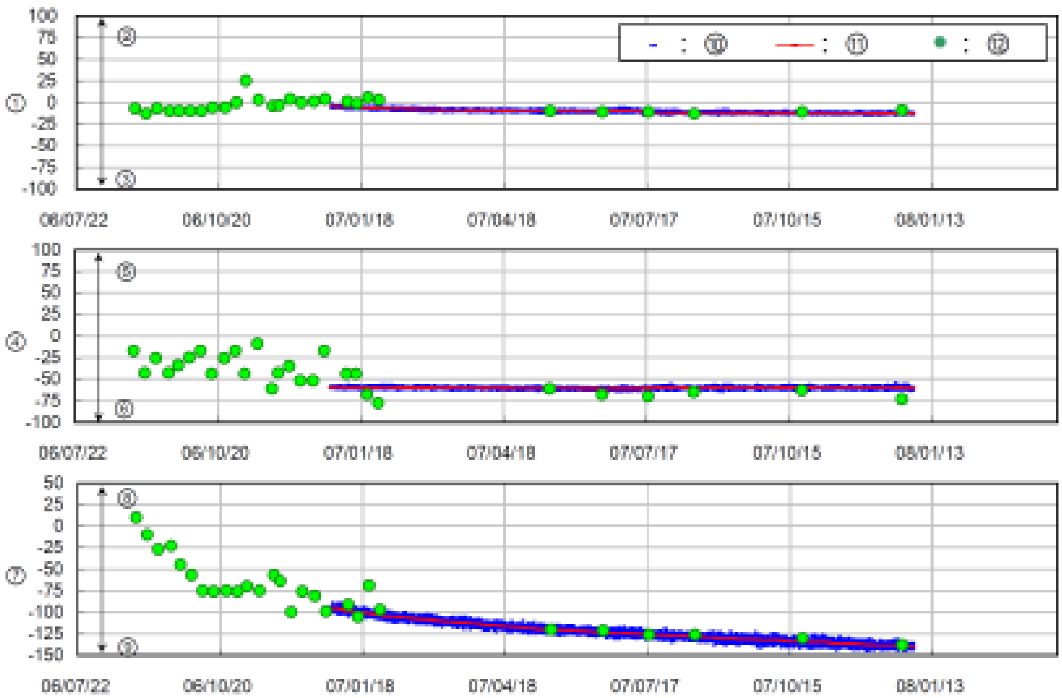


Fig.6

Results of GPS measurement with results of geodimeter and leveling surveys (G-19)

Résultats des measures GPS avec les résultats du géodimètre
et les études de nivellement (G-19)

1	D/S - U/S (mm)	*1*	*D/S(Aval) - U/S(Amont) (mm)*
2	Upstream	*2*	*En amont*
3	Downstream	*3*	*En aval*
4	Dam axis (mm)	*4*	*Axe du barrage (mm)*
5	Right bank	*5*	*Rive droite*
6	Left bank	*6*	*Rive gauche*
7	Vertical (mm)	*7*	*Vertical (mm)*
8	Upward	*8*	*Vers le haut*
9	Downward	*9*	*Vers le bas*
10	GPS	*10*	*GPS*
11	After data processing	*11*	*Après traitement de la donnée*
12	Conventional survey	*12*	*Etude conventionnelle*

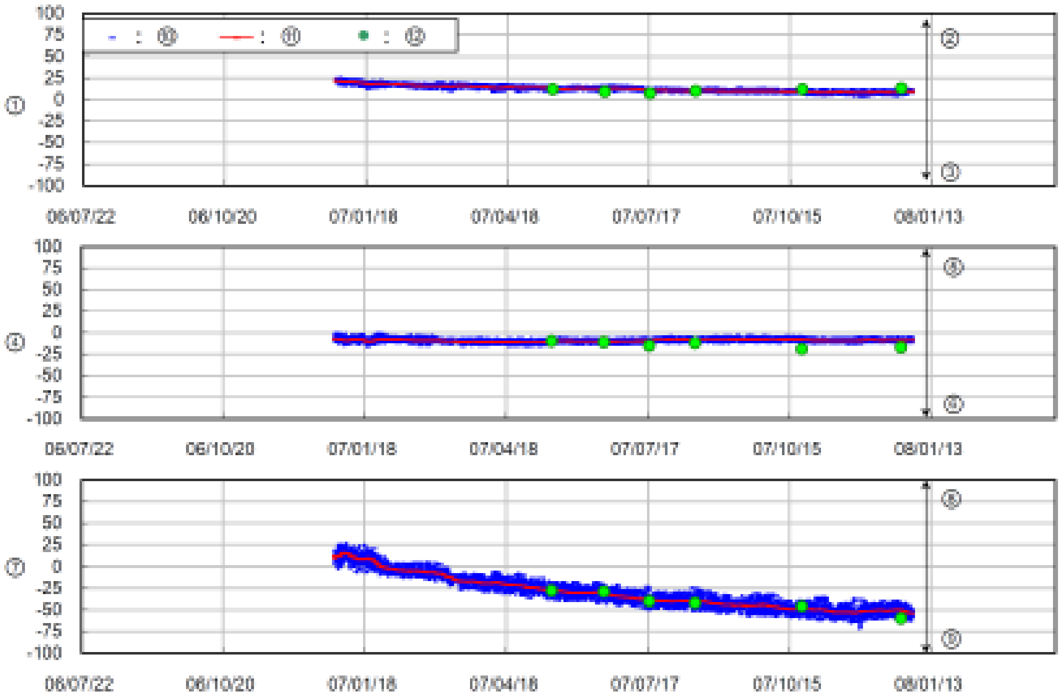


Fig.7

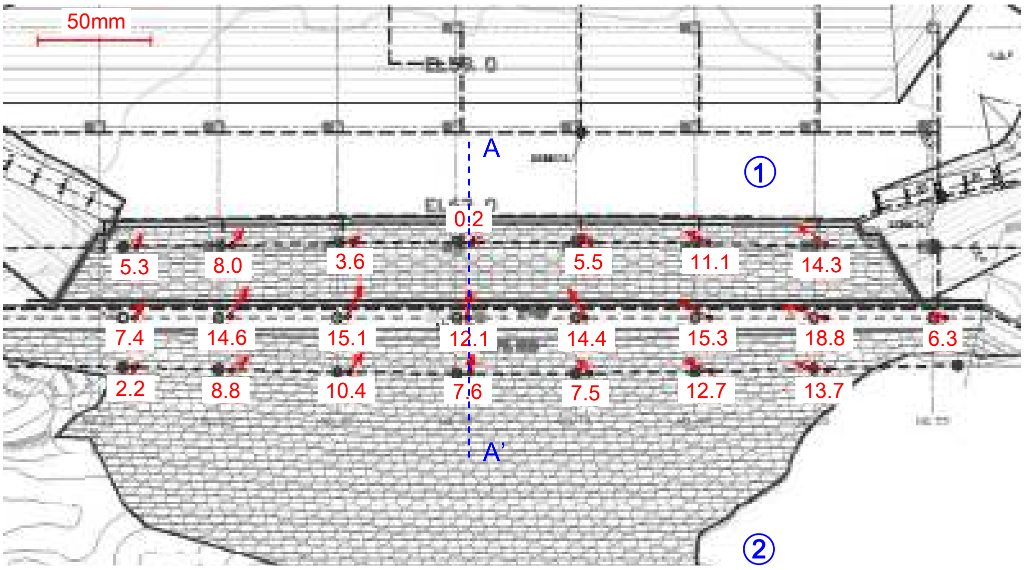
Results of GPS measurement with results of geodimeter and leveling surveys (G-11)

Résultats des measures GPS avec les résultats du géodimètre et les études de nivellement (G-11)

1	D/S - U/S (mm)	*1*	*D/S(Aval) - U/S(Amont) (mm)*
2	Upstream	*2*	*En amont*
3	Downstream	*3*	*En aval*
4	Dam axis (mm)	*4*	*Axe du barrage (mm)*
5	Right bank	*5*	*Rive droite*
6	Left bank	*6*	*Rive gauche*
7	Vertical (mm)	*7*	*Vertical (mm)*
8	Upward	*8*	*Vers le haut*
9	Downward	*9*	*Vers le bas*
10	GPS	*10*	*GPS*
11	After data processing	*11*	*Après traitement de la donnée*
12	Conventional survey	*12*	*Etude conventionnelle*

Vector representations of the results of deformation behavior measured by GPS are illustrated in Fig. 8 and Fig. 9. Fig. 8 shows the horizontal direction displacement vector and Fig.9 shows the vector in the A-A' section shown in the plane diagram. It shows the displacement vector in the period from Dec. 29, 2006, when the GPS sensors were installed, to March 1, 2008.

The measurement results before the reservoir impounding show that in the plane direction the dam body was deformed towards the downstream side in the center of the river on both the right and left banks. In the section A-A' in Fig.9, the settlement was downstream direction one at measurement point (G-19) on the upstream slope surface and at measurement point (G-11) on the crest, but at measurement point (G-4) on the downstream side, it was almost vertical direction settlement. This presumably occurred because the counterweight on the downstream side provided resistance to displacement on the downstream side.

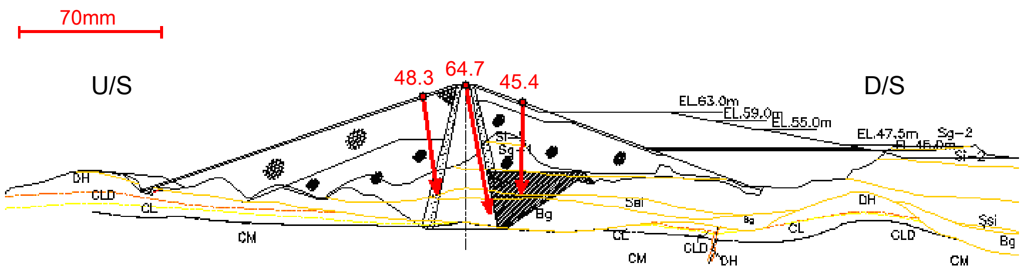


Displacement vector representation from December 29, 2006 to March 1, 2008

Fig. 8
Horizontal direction displacement vector
Vecteur de déplacement en direction horizontale

1 Downstream side
2 Upstream side

1 Côté en aval
2 Côté en amont



Displacement vector representation from December 29, 2006 to March 1, 2008

Fig. 9
Displacement vector in A-A' section
Vecteur de déplacement pour la section A-A'

4.3. Method of Changing to GPS Measurements

At the Taiho Dam, the main dam, a concrete gravity dam, with a height of 77.5m, is under construction. The trial impounding of the reservoir is scheduled to begin in April 2009.

At the Taiho Subdam, embankment work was completed in November 2006, and during the period from completion of dam body construction until the start of impounding (approx. 2 years), GPS measurements and conventional surveys are jointly used to measure exterior deformation to verify that GPS measurement can ensure adequate precision. The measured results at the Taiho Subdam have confirmed that the GPS measurement can ensure precision equal or superior to that obtained by conventional surveying. So a safety management method during trial impounding is being planned: using GPS as the principle measurement method while sharply reducing the frequency of conventional surveys.

In response to the results, a scenario to embankment dam exterior deformation by a hybrid method with GPS used for the principal measurements or to the exclusive use of GPS measurement has been proposed in Fig.10.

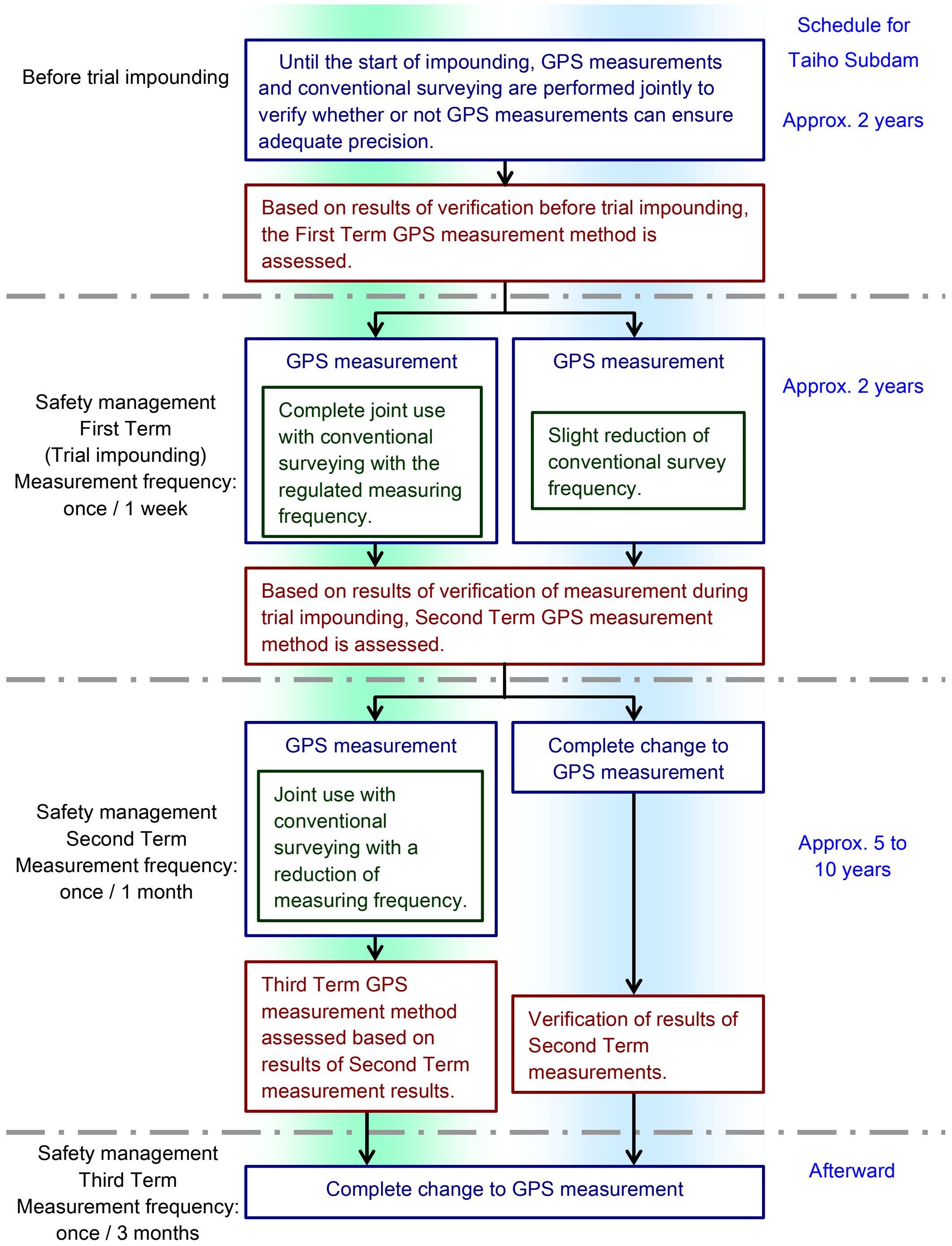


Fig. 10

Scenarios to Hybrid Measurements with GPS as Principal Method or to Exclusive GPS Measurements of Exterior Deformation of an Embankment Dam

Scénarios de changement pour passer aux mesures hybrides avec l'utilisation du système GPS comme méthode principale ou aux mesures utilisant exclusivement le système GPS des déformations extérieures d'un barrage en remblai

CONCLUSIONS

It is possible to measure exterior deformation of embankment dams with high precision at short intervals almost approximating real time by using GPS technology. And its capacity to perform almost real-time displacement measurements is an even more effective benefit during emergencies such as a large earthquake or an abrupt rise of reservoir water level during a large flood.

This paper outlines the introduction of GPS measurement to the Taiho Subdam and its precision. And it introduces scenarios for the replacement of the existing exterior deformation measurement method, that is conventional surveying, with a combined measurement system with GPS as the principal method or to an exclusively GPS based method. Based on the measurement results at the Taiho Subdam, it is considered that safety management based on exterior deformation during impounding of the reservoir will be done with GPS as the principal measurement method.

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SUMMARY

A Global Positioning System (GPS) can be used for the real-time measurement of the exterior deformation of an embankment dam. This is, therefore, an extremely effective method during emergencies: when the reservoir water level is abruptly increased by a large flood or when a large earthquake occurs.

A study is now being carried out to prepare to replace safety management based on measuring exterior deformation by conventional surveying with safety management using GPS at the Taiho Subdam constructed by the Okinawa General Bureau of the Cabinet Office, the Government of Japan. At the Taiho Subdam, GPS sensors are installed at all the exterior deformation measurement targets for conventional surveys.

This paper outlines the introduction of GPS to the Taiho Subdam and its precision. And it introduces scenarios for the replacement of the existing exterior deformation measurement method, that is conventional surveying, with a combined measurement system with GPS as the principal method or to an exclusively GPS based method.

RÉSUMÉ

Un système de positionnement global de type GPS peut être utilisé pour les mesures en temps réel des déformations extérieures d'un barrage en remblai. Ceci est par conséquent une méthode extrêmement efficace dans les cas d'urgence lorsque le niveau d'eau dans le réservoir augmente soudainement à cause d'une crue importante ou bien encore dans le cas de la survenue d'un séisme grave.

Une étude est menée actuellement en vue de la préparation du remplacement d'une gestion de la sécurité basée sur la mesure des déformations extérieures par études conventionnelles, par une gestion de la sécurité utilisant un système de positionnement global (GPS) sur le site du barrage subsidiaire de Taiho, construit par le Bureau général d'Okinawa du Cabinet , le gouvernement du Japon. Au barrage subsidiaire de Taiho, des capteurs GPS ont été installés à tous les points ciblés pour la mesure des déformations extérieures pour les études conventionnelles.

Cette étude décrit la mise en place du système de positionnement global sur le site du barrage subsidiaire de Taiho et sa précision. En outre, elle présente des scénarios en vue de remplacer la méthode existante de mesure des déformations extérieures, c'est-à-dire la méthode par étude conventionnelle, par

un système de mesure combinée utilisant comme méthode principale le système de positionnement global (GPS), ou encore par une méthode basée exclusivement sur le système de positionnement global.