Improvement of Deformation Prediction of Rock-fill Dam with GPS Measurement

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ABSTRACT:
Accurate and continuous data accumulation of deformation measurement of dam body is important for proper dam safety management. Regarding the improvement of the accuracy of rock-fill dam deformation survey, there are problems that the measurement frequency is low and the accuracy may be affected by slight differences in measurement techniques and by observer. In recent years, Global Positioning System (GPS) measurement system which enables us to measure the exterior deformation of rock-fill dam bodies continuously, accurately and three-dimensionally have been developed and is experimentally introduced in about 20 dams in Japan.
The authors, based on the approximate expressions corresponding to the long-term settlement of the embankment, have proposed approximate expressions of settlement and the horizontal displacement by using the GPS measurement data in Tokuyama Dam. As a result, predicted deformation by using the approximate expressions well matched to the value measured by GPS measurement system. Based on the research results in Tokuyama dam, it is possible to monitor other dams by proposing approximate expressions using the same method that utilizes the features of the GPS of high precision and continuous observation data.

Keywords: fill dams, GPS measurement, exterior deformation, approximate expressions

1. INTRODUCTION

Aging of structures constructed during the rapid growth period of Japan has recently been much talked about, and implementation or review of reinforcement or reconstruction of social infrastructures is conducted in response to such apparent situation. It is important to understand the current condition of the structures in order to properly maintain those facilities and conduct appropriate reinforcement or reconstruction work. The Japan Water Agency (JWA) has been operating many dams, include over 50 years old. Authors has accumulated measuring result of eight rock-fill dams JWA manages, and regularly conducts cross-sectional safety checks and evaluation of dam body behavior of all of them.

In safety management of an embankment dam, measurement of external deformation of dam body is one of the most important items along with seepage measurement. To check those items, it is necessary to keep monitoring the dam body during its service years.

In addition, immediately after such a catastrophe as an earthquake and a large-scale flood, Dam owners will promptly need to ensure that the safety of the dam body and the prerequisite functions of the dam are properly maintained together with other regular inspections and observations.

So, the measurement of external deformation requires the long-term monitoring, appropriate level of precision, incessant and correct measurement, and easy maintenance. And furthermore, it has to be carried out as promptly as possible even under unfavorable conditions like the disasters.

Conducting the external deformation measurement continuously with high level of precision, involving three achievement should be payed:

1) Comprehension of dam body deformation behavior in detail;
2) High precision forecast of the possible deformation in the future;
3) Evaluation based on the forecast;

There are increasing number of cases where GPS measurement, which is often used to measure slopes, is also used for deformation measurement as part of the policy to refine dam body measurement. GPS measurement is capable of making continuous, highly accurate and three-dimensional measurement. When it is applied to dam body measurement, it is expected to produce various positive effects, including the capability of making measurement more accurate than the conventional methods and early detection of displacement caused by, for example, an earthquake.

With this concept, JWA has been developing a new high-precision deformation measurement method with the use of GPS at a few dams. The authors wanted to make an index for safety management by using the reliable measurement result using the GPS measurement.

The authors, based on the approximate expressions corresponding to the long-term settlement of the embankment, have proposed approximate expressions of settlement and the horizontal displacement by using the GPS measurement data of Tokuyama Dam. As a result, predicted deformation by using the approximate expressions well matched to the value measured by GPS measurement system. Based on the research results in Tokuyama dam, it is possible to monitor other dams by proposing approximate expressions using the same method that utilizes the features of the GPS of high precision and continuous observation data.

2. SETTLEMENT AND THE HORIZONTAL DISPLACEMENT OF ROCK-FILL DAM

2.1. Settlement and the horizontal displacement of Rock-fill Dam

Causes of behavior of rock-fill dams are analyzed as in Table 1. Although rainfall, one of the identified causes, affects the amount of water permeation, such influence does not indicate dam behavior. Therefore it is necessary to appropriately remove rainfall factor as a causal factor in question. Hence, it is not included in the table.

Table 1. Causes of behavior of rock-fill dams

		Behavior of the Dam			
		deformation	Settlement	Pressure of foundation	Seepage
Causes of behavior	Temperature	-	-	-	-
	Water level	L, E	S, P	L, E	M, VE
	Rainfall	-	-	-	L
	Consoridation	M, VP	L, VP	-	L,VP
	Clogging			M, VP	
	Earthquake	P	P	P	P

L,M,S: Amount of infuluence. Large, Medium, Small
V,P,E: Type of behavior V: visco, P: plastic, E: elastic

The relationship between the number of days and deformation of the dam is analyzed on the basis of those causes as in Fig. 1 and 2. The decimal logarithm is taken for horizontal axes. 13 rock-fill dams over 100m height are plotted in these figures.

Fig.1 shows relationship between the number of days after their completion and settlement of 13 dams at crest. It is generally understood that the amount of settlement varies depending on dam height, materials, compaction method, and dam shape. In after the lapse of 200 to 300 days after completion of the dam, settlement at the crest has a linear relationship with the logarithm of number of days. As Matsumoto N., et al. 1991 showed.
Fig. 2 shows relationship between the number of days after their initial filling and the amount of horizontal displacement at the crest. As in the case of the settlement, the amount of horizontal displacement greatly varies depending on dam height, materials and compaction method. Although changes occur depending on water level changes, it is presumed that the behavior after the lapse of 300 days has an almost linear relationship with the logarithm of the number of days.

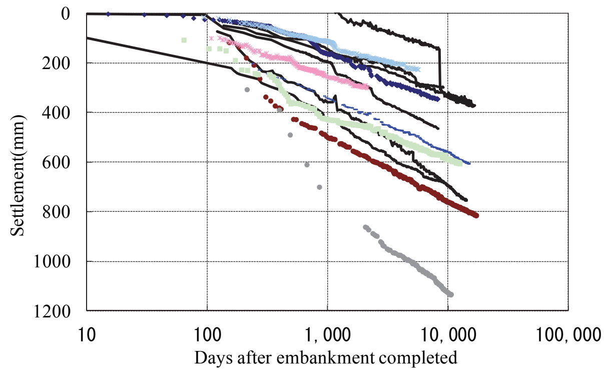

Figure 1. Settlement of rock-fill dams

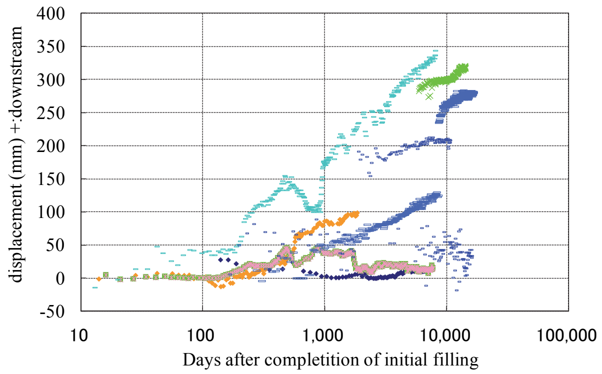

Figure 2. Horizontal displacement of rock-fill dam

2.2 Analysis of Settlement and the Horizontal Displacement of a Rock-fill Dam

According to large-scale testing of rock-fill materials by Marsal, etc., the relationship between the number of days and the amount of settlement when rock materials are compacted shows a time and compression relationship similar to primary and secondary consolidation of cohesive soil. In the experiment results, no fracture occurred in secondary compression, and a linear settlement due to compression is shown relative to the logarithms of the number of days.
Settlement of the rock-fill dam body is characterized by the amount of settlement having a linear relationship with the logarithms of the number of elapsed days. Since this behavior agrees with the test result of Marsal, 1967. etc., it is presumed that the behavior of secondary compression unique to the rock-fill materials comes to emerge in the process of settlement of the dam body. Since it is impossible to list any external force imposed on the dam body other than its dead weight, the amount of settlement of the dam body is logically judged to be caused by creep of the materials.

The components of horizontal deformation of the rock-fill dam, corresponding to temporal changes, are discussed here. Horizontal displacement shows an almost linear relationship with the logarithms of the number of elapsed days. Assuming that part of horizontal displacement is caused by creep that resists hydraulic pressure or by the horizontal components of settlement by the weight, it is considered reasonable that horizontal displacement has a linear relationship with the logarithms of the number of elapsed days as in the case of settlement.

Now deformation in response to horizontal displacement is discussed. Since the allowable range of water level changes is mostly limited at many dams, the influence of water level changes on hydraulic pressure always applied to the dam is considered small. It is also understood that water level changes that occur in ordinary operation will not greatly exceed the range of external force that was experienced in the past. As discussed above, it is logically feasible to think that occurrence of horizontal displacement relative to water level changes has a linear relationship with water level changes.

3. REVIEW ON APPROXIMATE EXPRESSIONS OF SETTLEMENT AND THE HORIZONTAL DISPLACEMENT

3.1.Review on Approximate Expressions for Settlement and the Horizontal Displacement of A Rock-fill Dam

As discussed in 2.1, long-term settlement shows a linear behavior relative to the logarithms of the number of days. This suggests it is feasible to develop an empirical approximation equation. However, the conventional practice of dam body observation with electro-optical measurement had been less frequent. A long period of time was therefore necessary to develop the appropriate approximation equation.

When horizontal displacement occurs, it generally occurs in three mixed ways: 1) the deformation caused by creep as in the case of settlement, 2) the elastic behavior relative to hydraulic pressure changes, and 3) settlement by impoundment in the upstream side rock zone. However, since measurement with electro-optical surveying had been generally conducted once a week even during initial filling and the dam's water level changed much greater while tracking horizontal displacement appropriately by such measurement, it was difficult to conduct future prediction or evaluation. This was the reason why qualitative evaluation had been a primary method of behavior evaluation.

If such viscous and elastic behavior can be separated, it should be able to add a quantitative index to future dam behavior evaluation. The authors attempted to separate viscous behavior from elastic behavior by making detailed observation of the settlement behavior and horizontal displacement behavior of the dam using the results of accurate continuous measurement based on GPS measurement.

3.2. Subject Dam of Evaluation

The Tokuyama Dam owned by the JWA was chosen as the subject of analysis. Fig. 3 shows plan of this dam. More than 5 years passed since completion of initial filling of the Tokuyama Dam in 2008, GPS measurement has been conducted since the beginning of the initial filling, it is reasonable to consider that the dam behavior has entered into a stabilized state.

Initial elastic deformation and its subsequent change to elastic deformation have been observed by GPS measurement system (Yamaguchi Y., et al. (2005)), (J.S.D.E(2014)). This system uses “Trend-model” as error-correction method to correct random noise (Shimizu N., et al. (2014)) and fixed-point observation method to correct tropospheric delay (Nakashima S., et al. (2014)).
Fig. 4 and 5 shows changes in horizontal displacement and settlement of the Tokuyama Dam over time. Correlation between the reservoir level and horizontal displacement of the Tokuyama Dam are shown in Fig. 6.

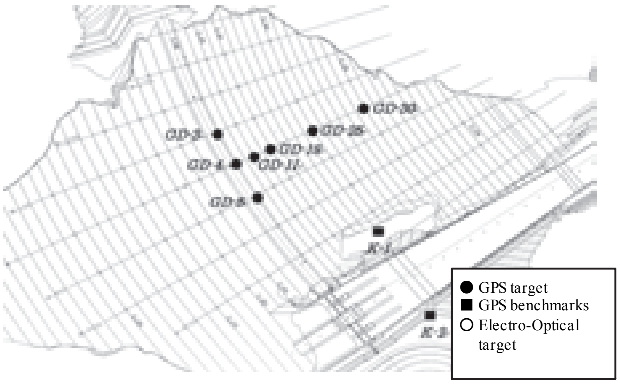

Figure 3. The plan of The Tokuyama Dam

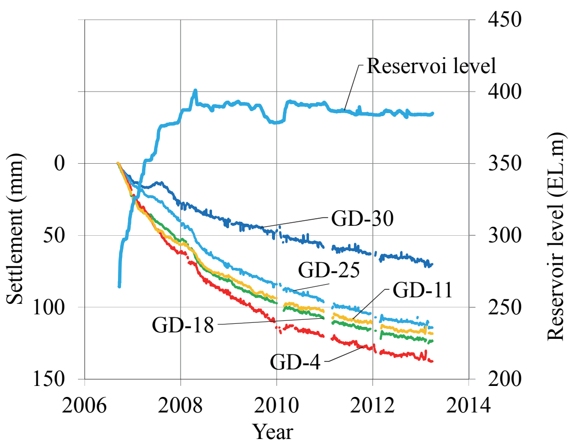

Figure 4. Changes in settlement of the Tokuyama Dam

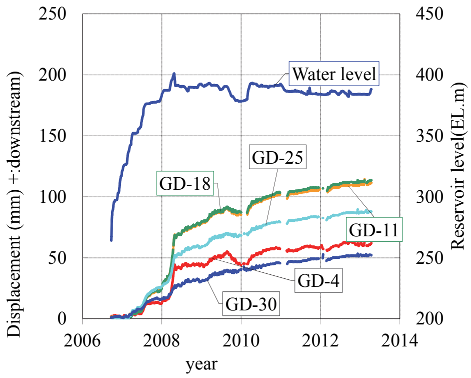

Figure 5. Changes in the horizontal displacement of the Tokuyama Dam

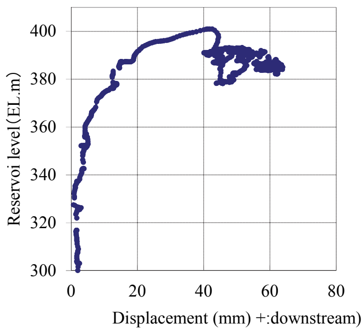

Figure 6. Correlation between the reservoir level and the horizontal displacement of the Tokuyama Dam

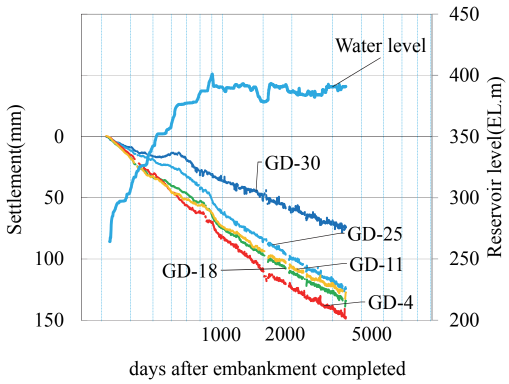

Figure 7. Relationship between settlement and logarithms of number of days

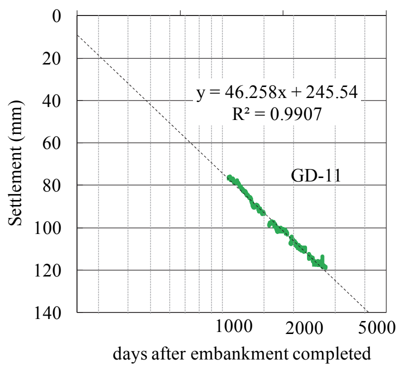

Figure 8. Approximation equation for GD-11

3.3. Evaluation Method of Settlement

Considering the fact that settlement shows linear behavior in its relation to the logarithms of the number of days, a linear approximation equation should be created for the logarithms of the number of days. Fig. 7 shows relationship between settlement and logarithms of number of days after embankment completed, settlement change linear relationship.

The behavior in 1,000 days after the change occurred to the water level showed a linear behavior relative to the logarithms of the number of days.

Fig. 8 shows the approximation equation for GD-11 based on the above review. The calculation result of the approximation equation almost agrees with the actual measurement of settlement, shows Eq.1

$$\delta v = 46.258 \ln(t) + 245.54 \quad [1]$$

Where

δv: settlement (mm) , t: days after completion

3.4. Evaluation Method of Horizontal Displacement

The authors assumed that horizontal displacement would be expressed as the superposition of the compressive deformation in the horizontal direction caused by hydraulic pressure and the elastic deformation caused by water level changes. The evaluation procedure is shown as follows:

(a) Fig.9 shows relationship between days since completion of initial filling and the horizontal displacement. In order to get an entire picture of horizontal displacement, a period that is considered to have linearity was set with the logarithmic of date as in case of settlement. In setting the period, the range that allows evaluation of long-term behavior, which is the purpose of review, was taken into consideration.

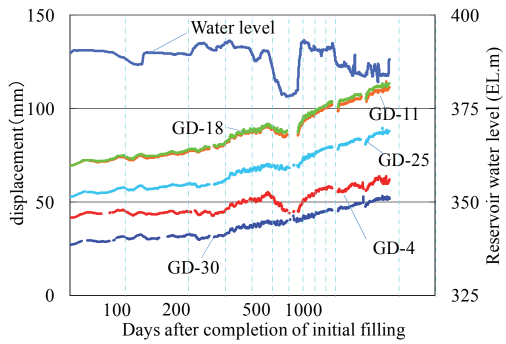

Figure. 9 Relationship between days since completion of initial filling and the horizontal displacement

(b) In the period selected in (a), the amount of horizontal displacement at the time of the same water level was selected and logarithmically approximated to the time axis, as in Fig. 10.

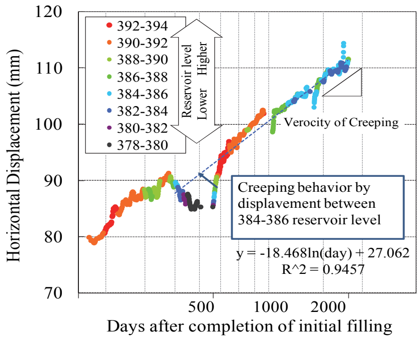

Figure 10. Change of the horizontal displacement with time under the same water level condition (GD-11)

(c) Deformation calculated from the logarithmic approximation equation determined in (b) was deducted from the actual deformation, and the relation with the water level was clarified as in Fig. 11.

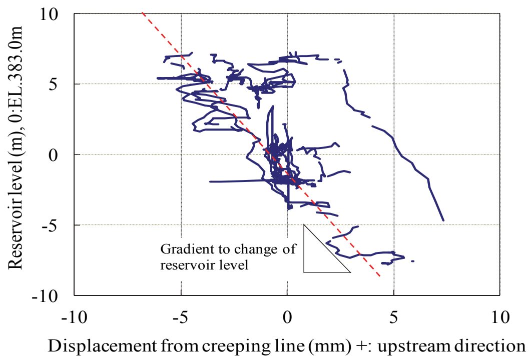

Figure 11. Relationship between the horizontal displacement with temporal change deducted and the water level (GD-11)

1) Setting of the period for assumption of horizontal displacement

The relationship between the number of days since completion of initial filling and the amount of deformation is plotted as in Fig. 9 in order to determine long-term deformation. As indicated by this figure, the amount of horizontal displacement seems to have a linear relationship with the logarithms of the number of days around after the lapse of 200 days.

As shown in Fig. 11, a linear relationship is established for the amount of settlement after the lapse of 100 days. It is therefore presumed that the amount of horizontal displacement would come to have a linear relationship with the time logarithm after the lapse of a certain length of time after experiencing the maximum value of stress as in the case of settlement.

Based on these results, the data obtained after the lapse of 200 days since completion of initial filling were organized for a better understanding.

2) Selection of horizontal displacement at the time of the same water level and logarithmic approximation

The amount of deformation at GD-11 in the period selected in 1) is arranged by the water level, and those values are plotted in different colors as in Fig. 10. Among the water levels shown in Fig. 10, logarithmic approximation was conducted for EL. 382 m to EL. 384 m, which is the range of water levels where the data of the longest period were obtained. The determination coefficient in this case (R^2) is 0.945, which indicates a good correlation.

3) Deduction of deformation speed calculated from logarithmic approximation

The deformation speed obtained from the logarithmic approximation conducted in 2) was deducted from the actually measured deformation to clarify the relationship with the water level as shown in Fig. 11. The reference water level is set to EL. 383.0 m. As shown by Fig. 11, as a result of deduction of the deformation speed, the water level and deformation seem to always draw a locus with a constant gradient. Based on this relationship, displacement of 12 mm is assumed relative to a water level difference of 18 m, and the relationship of 0.67 x 10^{-3} was obtained.

Based on the above relationship, the approximation equation determined for GD-11 of the Tokuyama Dam is Eq. 2.

$$\delta_h = -18.468 \ln(t) + 27.062 + 0.67 (h_w - 383) \qquad [2]$$

Where
δh: horizontal displacement (mm; the downstream side is negative)
t: number of days since completion of initial filling (EL. m)
hw: reservoir level at the prediction date (EL. m)

These empirical approximation equations were computed at other GPS measurement points installed at the Tokuyama Dam, and the results did not suggest any points where approximation was impossible.

The superimposition of the measured value of horizontal displacement of the dam body at GD-11 with the predicted value by Eq. 1 is plotted in Fig. 12. This graph shows a good agreement between measurement and prediction.

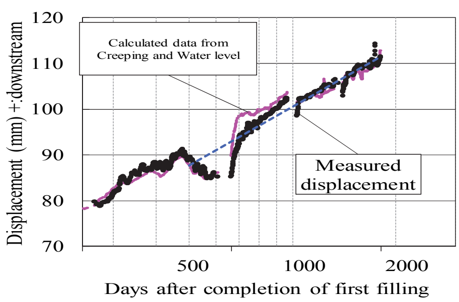

Figure 12. Measurement and prediction of the horizontal displacement (GD-11)

3.5. Applicability of Approximation Equations

It is considered that comparison with the current condition based on the approximation equations prepared based on the range of past data could lead to determine how the present condition has changed from the past. It was assumed that the elapsed time and the water level condition being input to the approximation equations obtained up to 3.4 would enable us to make a simple health check of the dam.

Fig.13 and 14 shows calculated values by approximation equation on 3.3.Eq. 1. and 3.4. Eq. 2. Figures compare values of the calculated and the measured. The data of either settlement or horizontal displacement show a good agreement between the measurement and approximation equations calculation results. When these approximation equations are established in advance and the present and past data are compared, we should be able to establish a simple judgment criterion for the dam stability.

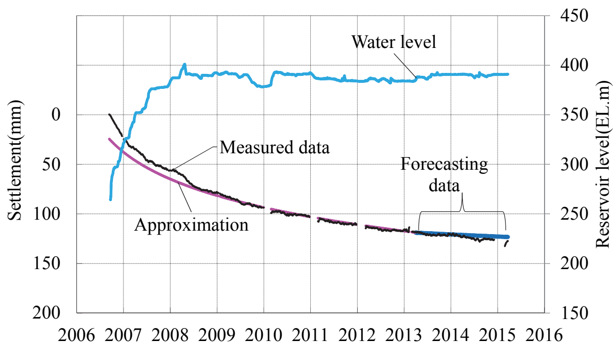

Figure 13. Measurement and approximation of settlement (GD-11)

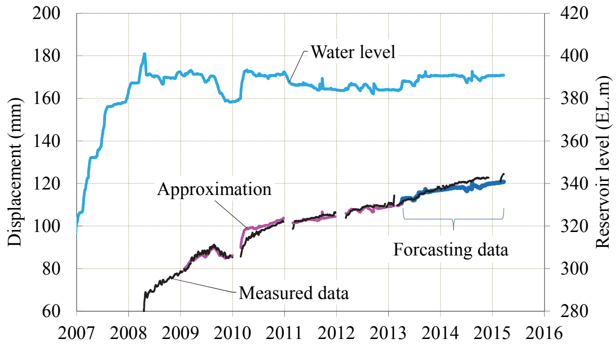

Figure 14. Measurement and approximation of the horizontal displacement (GD-11)

4. CONCLUSION

The authors proposed techniques to measure and evaluate deformation behavior using GPS measurement as part of the process of quantification of behavior evaluation of a rock-fill dam, which had been empirically conducted, based on the existing data. The authors focused on settlement and upstream and downstream deformation and studied a technique to develop approximate equations based on the past data.

The authors attempted to decompose the data into elastic behavior associated with water level changes and viscous behavior relative to the time lapse as a preliminary review for prediction of the amounts of settlement and horizontal displacement of dam body based on the data obtained with GPS measurement. The approximation equations established based on the results of those operations was extrapolated for comparison with the present data. As a result, continuous and highly accurate survey data obtained with GPS measurement should lead to appropriately express the amount of settlement and horizontal displacement. The authors hope to propose a quantitative safety management method based on these research results.

Use of these methods should enable us to ensure appropriate management and future prediction of dam body deformation. The authors intend to work on applicability of the proposed techniques and verify their practicality through analysis of measurement results at other dams.

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