Study on The Deformation Mechanism of an Ageing Dam Aiming at Future Deformation Prediction

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ABSTRACT:
In evaluation of dam behaviour, deformation monitoring is essential. Although most dams show a stable deformation trend, it is highly important to confirm whether these trends will continue in the future assuming that the lifespan of a dam is more than 100 years. If a unique deformation behaviours have been encountered in a dam, such as monotonic increase toward the stream direction of the dam and variation in the deformation degree corresponding to reservoir water level or the ambient temperature, the current deformation mechanism, future dam behaviour, and also the necessity of correspondence should be addressed considering dam safety in the future.
In this report, we studied the deformation and related data of a 50-year-old concrete gravity dam and interpreted the deformation mechanism with the aid of numerical analysis, and conducted a simulation of dam behaviour in an elastic and steady manner considering the three parameters of reservoir water level, ambient temperature, and sediment depth. The results of the simulation show the consistent dam behaviour against these loads acting on the concrete gravity dam usually.

Keywords: concrete gravity dam, ageing dam, deformation mechanism, stability, measurement

1. OUTLINE

Dam deformation monitoring is essential in evaluation of dam safety because dam deformation shows the comprehensive behaviour of the dam and foundation rock. Recently, consecutive automatic measurement by GPS, in addition to collimation or levelling survey and plumb line measurement have been adopted for more detailed interpretation of dam behaviour.
Around 50 dams owned by J-power (Electric Power Development Co. Ltd.) which is one of the electricity utility companies in Japan, show a stable deformation trend. However, it is very important to confirm whether these trends will continue into the future assuming that these lifespans are more than 100 years. When the deformation behaviours are examined in detail, unique deformation behaviours have been encountered in some dams, such as monotonic increase, even though, slightly toward the upstream direction of the dam and variation in the deformation degree corresponding to the reservoir water level or the ambient temperature, which are cyclic loads on the dam surface. Although these are limited cases under the current condition, the deformation mechanism, future behaviour, and possible correspondence of the dam should be addressed of considering dam safety in the future.
We studied the deformation and related data of a 50-year-old concrete gravity dam and interpreted the deformation mechanism with the aid of numerical analysis. Factors affecting dam behaviour were examined for a prediction of future behaviour of the dam.

2. INTERPRETATION OF DAM DEFORMATION

2.1. Major characteristics of the dam

Monitored deformation of a 50-year-old concrete gravity dam as shown in Fig. 1 is studied. The major parameters and the monitoring schemes are shown in Table 1 and in Table 2 and Fig. 2, respectively.

Table 1. Parameters of the dam

Type	Concrete gravity
Height(m)	155.50
Crest length (m)	293.50
Width of crest (m)	8.10
Volume (m^3)	1,120,000
Crest elevation (EL. m)	270.00
Geology of foundation rock	Granite
Year of completion	1956

Figure 1. Downstream view of the dam

Table 2. Monitoring scheme

Type of monitoring	Frequency of monitorng	Notes
Deformation	1 time/month	Plumb line:1line
Seepage	2 times/month	
Uplift pressure	4 times/year	

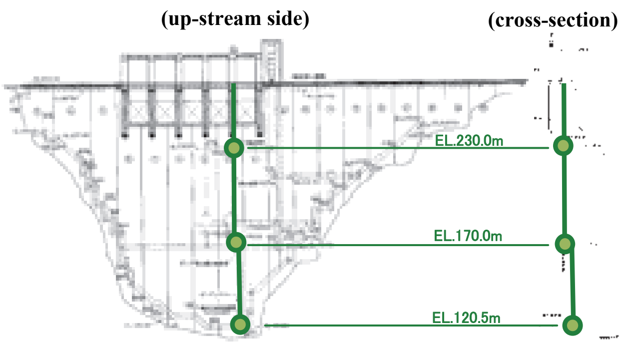

Figure 2. Position of the plumb line

2.2. Deformation of the dam

Deformation of the dam from completion in 1956 is shown in Fig. 3 with related data of the reservoir water level, ambient temperature around the dam, and rainfall. The following can be observed in these data.

1) The dam was deformed upstream at the beginning corresponding to reservoir impoundment at a maximum of 12 mm recorded in 1957. This was followed by downstream deformation up to approximately 30 mm until 1965.

2) After 1965, the dam was continuously deformed gradually upstream with yearly fluctuation. It has moved to almost zero deformation in respect to the initial position of the dam just after its completion in 1956 from the maximum downstream deformation of 18 mm in 1960.

3) In terms of yearly fluctuation, the dam is deformed elastically in the range of 5 mm, which is downstream in the winter season with lower ambient temperature and upstream in the summer season with higher ambient temperature.

The wide range of deformation fluctuation in the initial several years is not consistent with the elastic structural behaviour of concrete gravity dams against loads due to hydrostatic pressure and ambient temperature. It may be supposed that the interaction of the dam and the foundation affected by the initial infiltration into the dam foundation from the reservoir and temperature ageing in the dam body due to hydration of the concrete are the reasons. However, the behaviour after 1965 is the focus of this report to clarify the mechanism of elastic deformation of the concrete gravity dam due to the usual loads that are commonly loaded onto the dam.

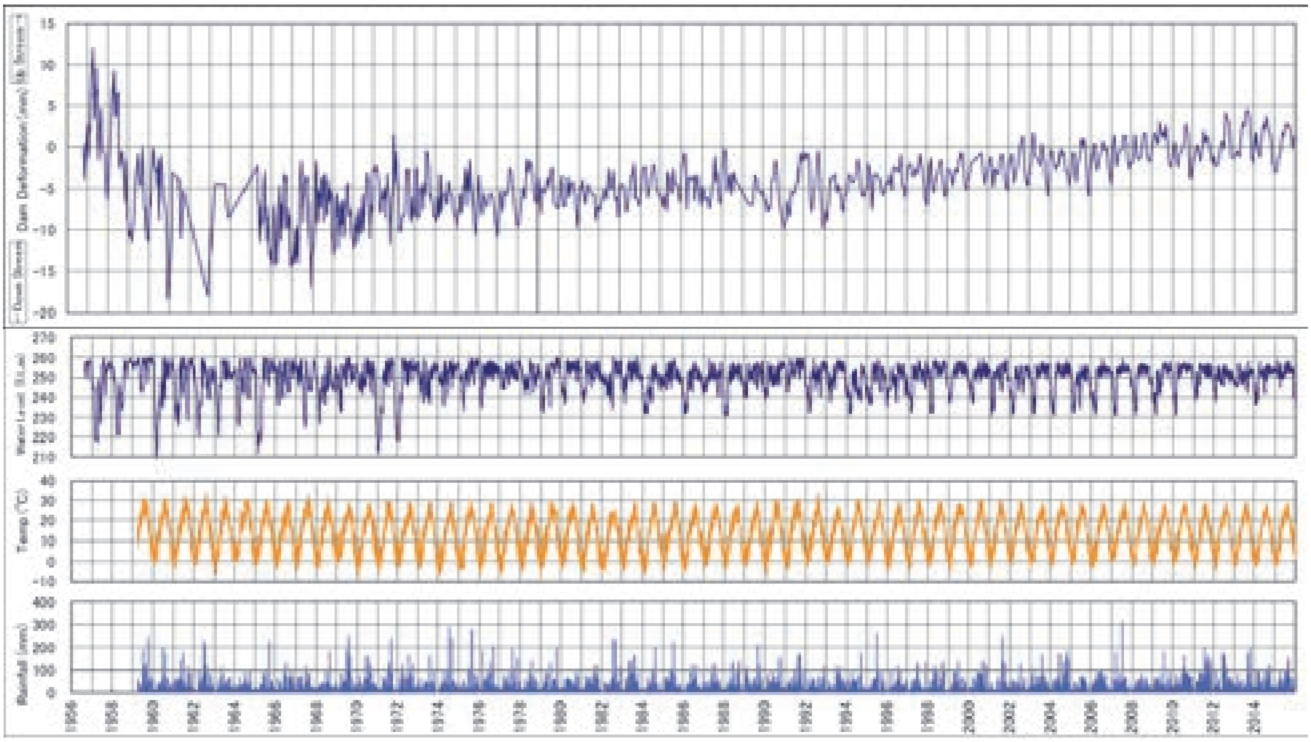

Figure 3. Charts of dam deformation, reservoir water level, temperature, and rainfall

2.3. Study on the factors on dam deformation

Variation in reservoir water level and temperature are major loads incurring the yearly periodical deformation behaviour of the concrete gravity dam. The correlations of dam deformation with reservoir water level and ambient temperature are shown in Fig. 4 and Fig. 5 respectively. Data period is 50 years when the dam is continuously deformed gradually upstream from 1966 through 2015. In these graphs, the influence of the elapsed days is subtracted because the dam was continuously deformed gradually upstream. The rise in reservoir water level causes downstream deformation of the dam when it is under the same temperature. This is reasonable behaviour for the concrete gravity dam subject to hydrostatic pressure. The deformation range is approximately 10 mm by the fluctuation of the 30-m-deep water level or the 0-30 degrees Celsius and the deformation degree corresponding to the reservoir water level or the ambient temperature is not change.

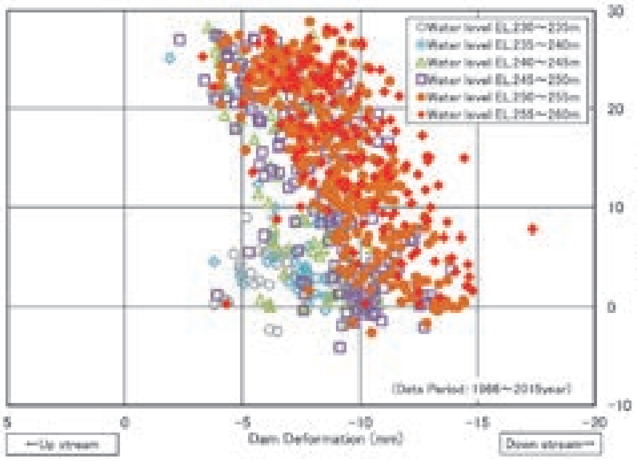

Figure 4. Correlation between dam deformation and water level

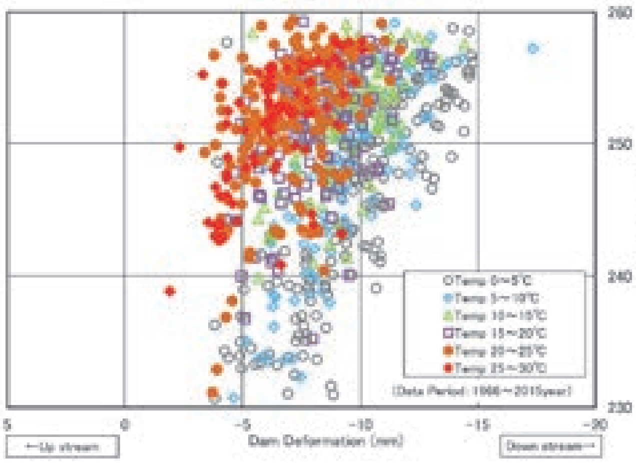

Figure 5. Correlation between dam deformation and temperature

To understand the long-term behaviour of the dam against the usual loads, the annual averaged values of dam deformation, sediment level in front of the dam, reservoir water level and ambient temperature are shown in Fig. 6. The dam shows a clear tendency to deform upstream after 1965, which is shown in Fig. 3, though the reservoir water level and the temperature show a roughly flat tendency. Though property variation of the dam body or the foundation rock might be suspected, the influence of sedimentation in front of dam is supposed to be a major factor in the long-term behaviour of the dam. The increase in sediment height seems to match the dam behaviour even though there is less data on sediment.

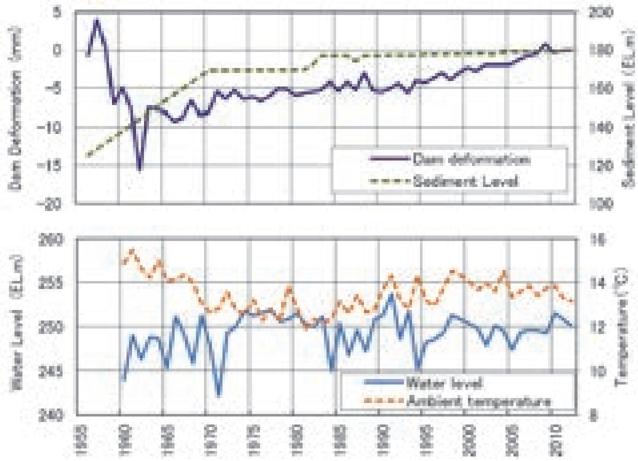

Figure 6. Annual average charts of dam deformation, water level, temperature, and sediment level

The multiple regression analysis on the dam deformation in terms of the reservoir water level, the ambient temperature, and the elapsed days of the operation from 1965 is conducted to examaine the dam behaviour during whole period and each decade of the monitoirng after 1966. The sediment depth is not incorporated in the analaysis due to the unsufficient data number comparing others. The elapsed days are adopted taking the development of the sedimentation into consideration.
The analysis prvides regression coefficient and each constant of $c0$, $c1$, $c2$, $c3$ as shown in Table 3. The dam deformation is fomulated as Eq. 1 usig these parameters.

$$D = c0 + c1 \times H + c2 \times T + c3 \times t \quad (1)$$

Where, D: dam deformation (mm), H: reservoir water level (m, 0m = EL.220m), T: ambient temperature (degrees Celsius), t: elapsed days (0 = 1965/1/1), $c0$: intercept coefficient, $c1$ to $c3$: coefficient of explanatory variables

The good relations are found in all periods of which regression coefficients are approximately 0.8 and more except the period from 1986 to 1995. It is illustrated in Fig.7. Overall both ones of monitoed and esitmated by Eq. 1 shows good correlation. The coefficient ($c1$) of the reservior water level and the coefficient ($c2$) of the temperature are almost consistent during whole monitoring period, showing that the deformation mechanism corresponding to these variables is consistent.

Table 3. Results of the multiple regression analysis

(1)	1966 -2015	1966 -1975	1976 -1985	1986 -1995	1996 -2005	2006 -2015
	50	10	10	10	10	10
(2)	809	356	116	108	110	119
(3)	0.90	0.88	0.78	0.67	0.80	0.89
$c0$	-4.143	-5.371	-1.097	1.776	-6.153	-7.905
$c1$	-0.237	-0.255	-0.222	-0.251	-0.215	-0.242
$c2$	0.192	0.221	0.181	0.136	0.170	0.227
$c3$	0.0005	0.0013	0.0000	-0.0001	0.0006	0.0007
$a1$	-0.47	-0.69	-0.65	-0.72	-0.78	-0.73
$a2$	0.45	0.61	0.82	0.53	0.79	1.04
$a3$	0.75	0.41	0.02	-0.05	0.34	0.41

(1) :data piriod (yaar)
(2): number of data
(3): regression coefficient
$c0$: intercept coefficient
$c1$ to $c3$: coefficient of water level, temperature, time
$a1$ to $a3$: standard partial regression coefficient of water level, temperature, elapsed days

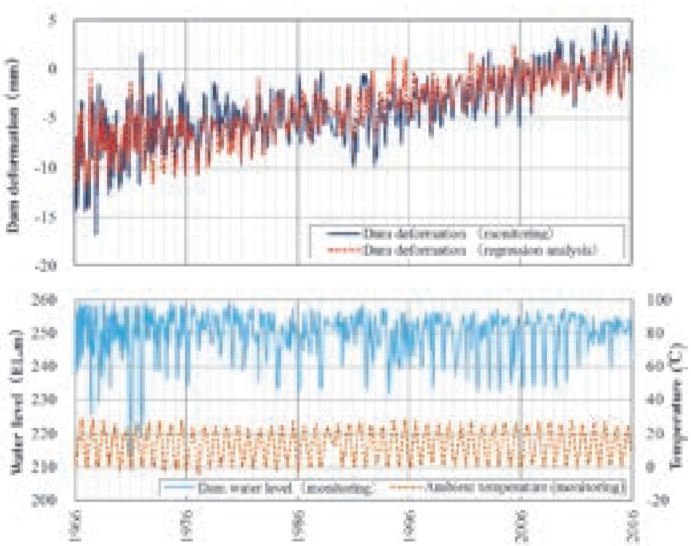

Figure 7. Multiple regression analysis of the dam deformation

The larger standard partial regression coefficients are interpreted that the contirbutions of those are predominant in the dam defromation. From this basis, the larger ones are found in the whole period of $a3$and in the decases periods of $a1$ and $a2$. In addition, $a3$ is estimated in lower and fluctuating figures in decades periods. These are considered that the reservoir water level and the temperature act majorly on the yeraly behavior of the dam. On the other hand, the elapsed days act major role on the longer term behavior of the dam. While the elapsed days does not directly relate to the sediment developement, both are approximately related to affect the dam deformation. It is considered that the unique upstream deformation of the dam is caused by the sediment development.
Therefore the study aided by the numarical simulation is conducted in the following section to quantify the influence of the reservoir water level, the abminet temperature and the sediment on the dam deformation.

3. NUMERICAL SIMULATION OF THE DAM BEHAVIOUR

Numerical simulation using elastic FEM is conducted to examine the dam behaviour against loads due to the reservoir water level, ambient temperature and sediment. The non-linearity of the dam and the foundation and the unsteady fluctuation of the temperature of the air and/or the reservoir are sometimes incorporated into the simulation of dam behaviour. There are difficulties in knowing these parameters and to conducting unsteady calculation.
In this report, we conducted a simulation of dam behaviour in an elastic and steady manner considering the three parameters of reservoir water level, ambient temperature, and sediment depth.

3.1. Conditions of simulation

The highest section of the dam where the plumb lines are arranged is selected for the simulation model. The model consists of the dam and the foundation, as shown in Fig. 8, with the properties shown in Table 4. The side boundary and the bottom boundary of the model are modelled as the roller boundary and the fixed boundary, respectively.
The simulation cases are corresponded to the abovementioned loads, shown in Table 5. Hydrostatic pressure is loaded on the upstream face perpendicularly on the dam surface, not on the foundation, corresponding to the reservoir water level. In terms of temperature loads, the ambient temperature around the dam and the water temperature of the reservoir water are considered. In preliminary examination, both temperatures are strongly related and the water temperature of the reservoir water shows a vertical uniform distribution from the water surface to the bottom of the reservoir. The water temperature is added to the submerged surface of the dam with the value correlated to the ambient temperature and the unique in the vertical direction. The ambient temperature is added to the exposed dam surface.
The sediment pressure is added perpendicularly to the surfaces of both the dam and the foundation. The specific weight and the horizontal earth pressure coefficient of the sediment are assumed to be 1.1 t/m^3 and 0.4 in reference to the design value. Loading images are shown in Fig. 9.

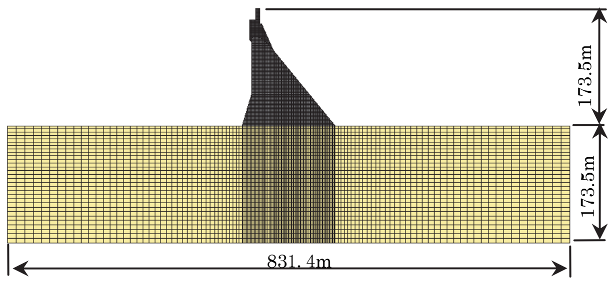

Figure 8. Simulation model

Table 4. Properties for simulation

Item	Dam	Foundation
Elastic coefficient (MPa)	32,000	20,000
Poisson ratio	0.2	0.25
Thermal conductivity (kj/mh°C)	9.2	5.0
Linear coefficient of expansion (1/°C)	1×10^{-5}	0

Table 5. Simulation cases

Case	Condition
Water level (EL. m)	180, 200, 220, 240, 260
Ambient temperature (°C)	0(4), 10(11), 20(18), 30(24) *
Sediment level (EL. m)	120, 140, 160, 180, 190, 200

* The number in the parenthesis is water temperature

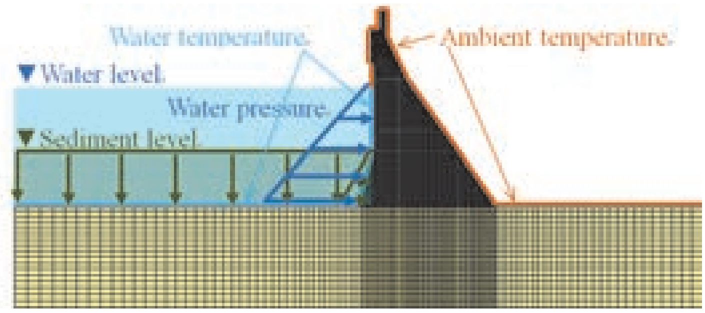

Figure 9. Loading image

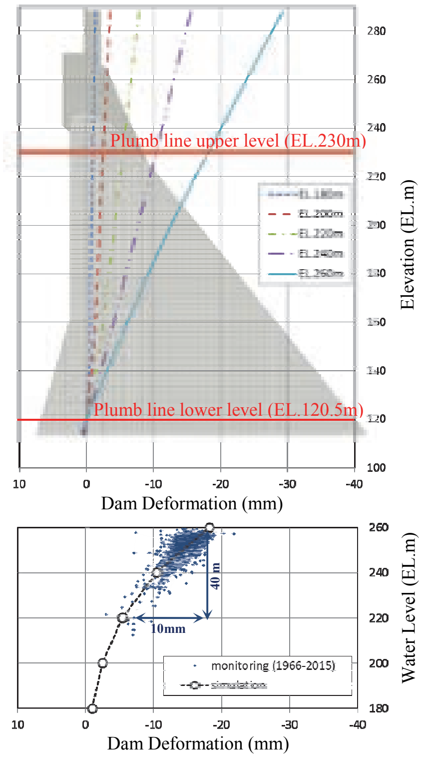

Figure 10. Correlation between dam deformation and water level

3.2. Results of analysis

The relative displacement of the stream direction between each monitoring location respective to the lowest location along the plumb line in the dam is shown in Tables 6 to 8, and Figs. 10 to 12.

Table 6. Dam deformation against reservoir water level

No.	Water level (EL.m)	Dam deformation (mm)
1	180	-0.9
2	200	-2.5
3	220	-5.4
4	240	-10.4
5	260	-18.2

Table 7. Dam deformation against temperature

No.	Temperature (°C)		Dam Deformation (mm)
	Ambient	Water	
6	0	4	-9.9
7	10	11	-2.7
8	20	18	4.6
9	30	24	11.8

Table 8. Dam deformation against sediment depth

No.	Sediment Level(EL.m)	Dam Deformation (mm)
10	120	0.5
11	140	2.2
12	160	3.8
13	180	5.2
14	190	5.8
15	200	6.2

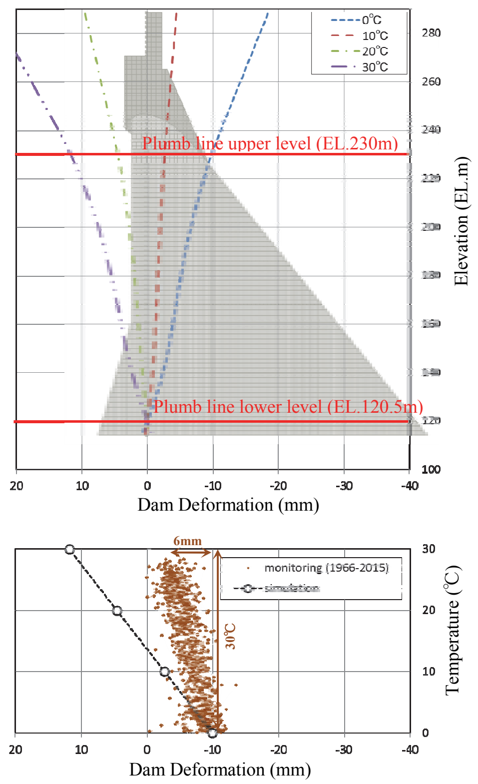

Figure 11. Correlation between dam deformation and temperature

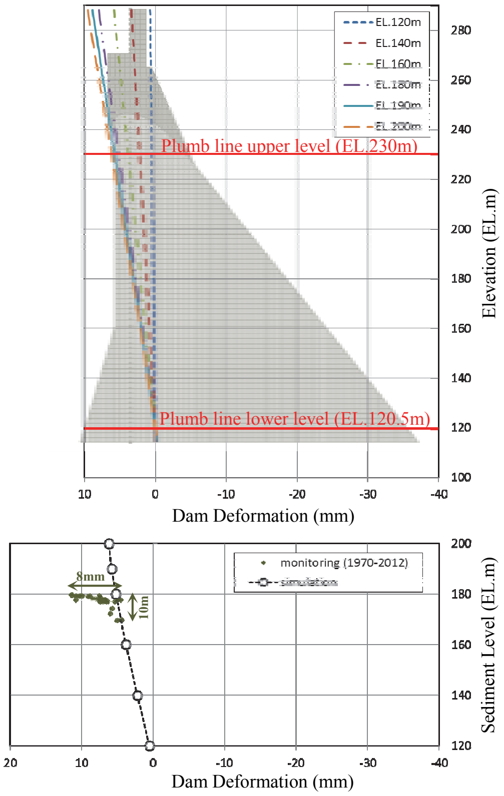

Figure 12. Correlation between dam deformation and sediment level

Each result of the simulation shows a similar tendency to the monitored results. A higher reservoir water level induces downstream deformation, while higher temperature and deeper sediment induce upstream deformation. The consistency between the monitoring and the simulation is preferable in the deformation due to the reservoir water level, while the deformation due to the temperature is simulated in approximately 3 times of the monitored ones. Assumed sediment effect in the simulation does not represent the monitored ones, even though it makes the upstream deformation of the dam, which is monitored as unique behaviour.

The simulated deformation of the dam due to reservoir water level is approximately 10 mm by 40-m-deep variation from a water level of EL. 220 m to EL. 260 m, which is quantitatively consistent with the monitored values as shown in Fig. 10.

When the ambient temperature rises from 0 to 30°C, the simulated dam deformation is approximately 20 mm, while the monitored one is approximately 6 mm as shown in Fig. 11. Due to the steady-state calculation method in the simulation, the dam temperature is considered to be uniform in the whole dam body. In reality, the ambient temperature around the dam fluctuates in certain periods such as day, season, and year. This causes temperature distribution inside the dam, which results in large inconsistency between the simulated and the monitored results.

The long-term behaviour of the dam from 1970 shows 8-mm upstream deformation and sediment level rises from EL. 170 m to EL. 180 m as shown in Fig. 12. The corresponding result of the simulation shows 1-mm upstream deformation by the 10-m-sediment level-variation. Because of the finite depth of the model, the sediment load does not impact deep enough and results in less deformation than monitored one. This should be addressed in the future. The study on the horizontal earth pressure coefficient shows a very slight influence on the simulated deformation. In addition, the simulation result shows that dam deformation converges so that the sediment level becomes higher. It is important to predict the future deformation of the dam.

The results of the abovementioned simulation show consistent dam behaviour against major loads acting on the dam usually. However, it is confirmed that further study is necessary to assess dam behaviour quantitatively. Dam behaviour is the consequence of combined factors including the abovementioned loads. Study of a combination of major loads, which is not considered in this paper, is an issue to be addressed in future.

4. CONCLUSIONS

The conclusions in this report are summarized below.

1) Three major factors on the deformation mechanism of the concrete gravity dam are identified, which are loads due to the reservoir water pressure, the ambient temperature change and the sediment.
2) Based on the multi regression analysis on those parameters, first two act a role on the yearly fluctuation of the dam deformation, while the last one acts a role on the long-term behaviour of the dam. These characteristics are consistently found during whole monitoring period of five decades.
3) The numerical simulation on the dam behaviour due to these loads provides following findings;
   (1) The deformation due to water pressure is quantitatively simulated consistent to the monitored one.
   (2) The deformation due to the temperature change is simulated qualitatively, not quantitatively by the steady state method. A time-dependent simulation is necessary for more preferable representation of the monitoring results.
   (3) The deformation due to the sediment pressure is simulated qualitatively, not quantitatively due to the defectiveness of the numerical model. It is clarified that the sediment pressure can cause the unique deformation of the dam developing upstream continuously.
4) The further study is necessary especially on the effect of the temperature change and the sediment pressure on the simulation of the dam deformation. It is essential to predict the future safety condition of the dam.