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Trends in the Annual Behavior of Concrete Dams

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ABSTRACT:

This paper delineates the general trends in concrete dam bodies' annual behavioral changes based on a large amount of measurement data of dams owned by Japan Water Agency. The outline of the paper is as follows:

Deformation of Dam Body: Relationship between dam heights and the amount of annual variations in dam body displacements is shown in diagrams based on the measurement data at sixteen dams. As for gravity dams, these diagrams show that the higher the dam height the greater the deformation and the closer the upstream water level to the dam crest the greater the deformation toward the downstream direction.

Leakage Amount: Many dams showed the decreasing trends in leakage amount during the initial operation period of 10 years. When looking at the leakage amount variations in one year, there are many cases that showed the increasing trends in leakage amount during a certain season.

Uplift Pressures: As for uplift force measuring method, uplift pressures were measured by two different methods; one method by closing alternate drain holes and the other by closing all drain holes. These two methods were compared with each other. Uplift pressures measured by closing all drain holes showed higher values than those measured by closing alternate drain holes because no pressure reducing effect was achieved when all drain holes were closed.

Keywords: Plumb line, Drain hole, Bourdon pressure gauge, Annual variation

1. INTRODUCTION

This paper delineates the comparative analyses of concrete dam bodies' deformation, water leakage and uplift pressures acting on dam bodies by focusing on the annual variations in the past observation data and general trends in behavioral changes of dam bodies. Japan Water Agency owns 20 concrete dams whose heights range from 24m to 156m and operation periods from one year to 56 years (see Fig. 1).

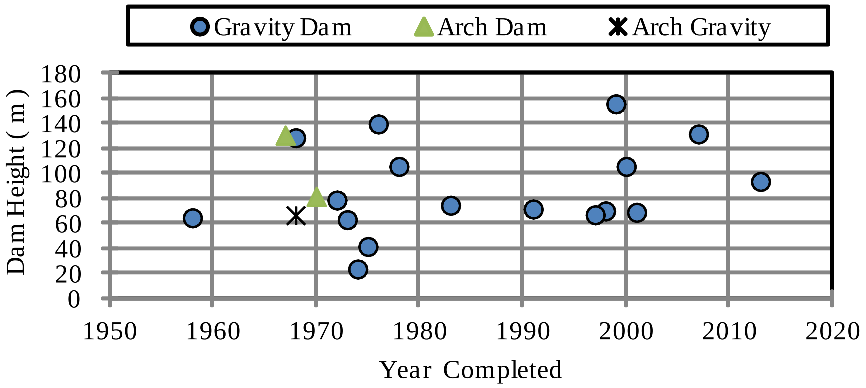


Figure 1. Heights and Completion Years of Concrete Dams under the Management of Japan Water Agency

2. DEFORMATION OF CONCRETE DAMS

Deformation of a concrete dam is usually measured by separating it into two; deformation of the dam body and displacement of the foundation. Deformations of the dam bodies of 17 dams out of 20 are measured by plumb lines. Under normal conditions, dam body deformation is measured by suspending plumbs with wire from the dam top (normal plumb-line). Displacement of dam foundation is measured by tensioning a plumb line fixed on the deepest point of the shaft in the foundation rock with a float (reverse plumb-line; see Fig. 2). Analyses of the measurement data were made by separating the dam body deformation and the foundation displacement; The analyzed dam body deformation, that is consisted of the deflection caused by the annual variations in hydrostatic pressures and the expansion and contraction caused by seasonal temperature changes, is described in Section 2.1; The analyzed foundation displacement caused by the annual variations in hydrostatic pressures is described in Section 2.2.

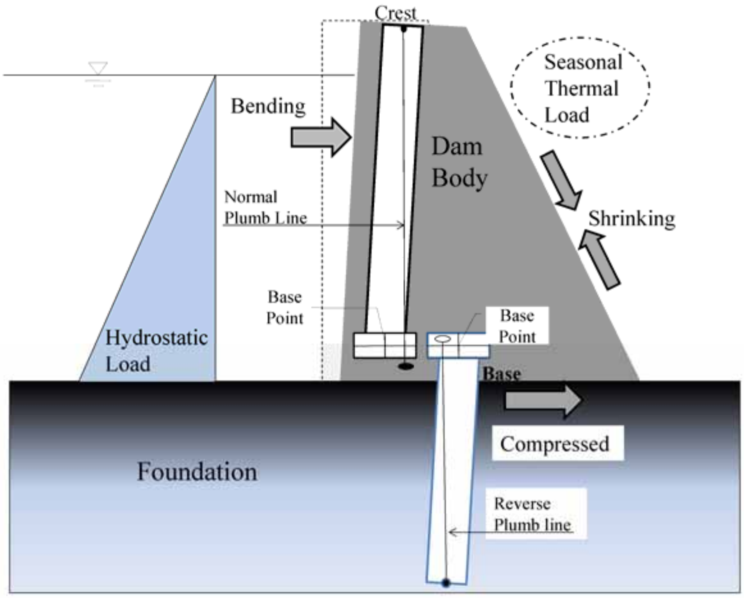


Figure 2. Image of the Deformation of a Concrete Gravity Dam

2.1. Displacement of Dam Crest

In general, top of a concrete dam is displaced toward the downstream direction in proportion to the dam height by hydrostatic pressure. In addition, when temperature decreases it is displaced toward the downstream direction by the effect of the contraction of the dam body's downstream-side surface. On the other hand, lower the reservoir level and higher the temperature, the top of a dam tends to be displaced toward the upstream direction. The trends in the annual variation of the displacement obtained from measurement data are described below:

2.1.1. Displacement of Dam Crest

As an example of dam crest displacement toward the upstream and downstream directions, measurement result of "A" Dam (132.0 m high, completed in 2007) is shown in Fig. 3. The dam crest displacement toward the upstream and downstream directions is associated with reservoir water level (hereinafter reservoir level) variations and seasonal changes. By focusing on a period of almost the constant reservoir level in Fig. 3 and comparing the winter (February) when temperature is lowest in a year to the summer (August) when temperature is the highest, the figure shows the displacements of 2.7 mm when the reservoir level was low (W.L. 485.5 m) in 2006, 10.0 mm when the reservoir level was high (W.L. 546.0 m) in 2007, and 7.8 mm when the reservoir was at an intermediate level (W.L. 533.7 m) in 2009, that is, higher the reservoir level larger the displacement toward the upstream and downstream directions, and the lower the winter temperature the largest displacement toward the downstream direction.

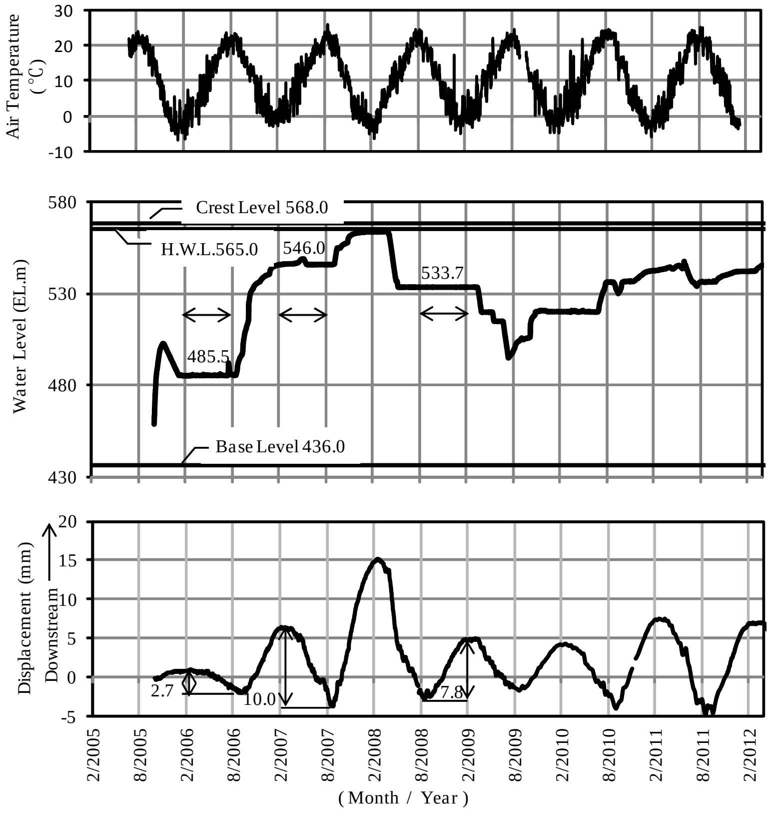
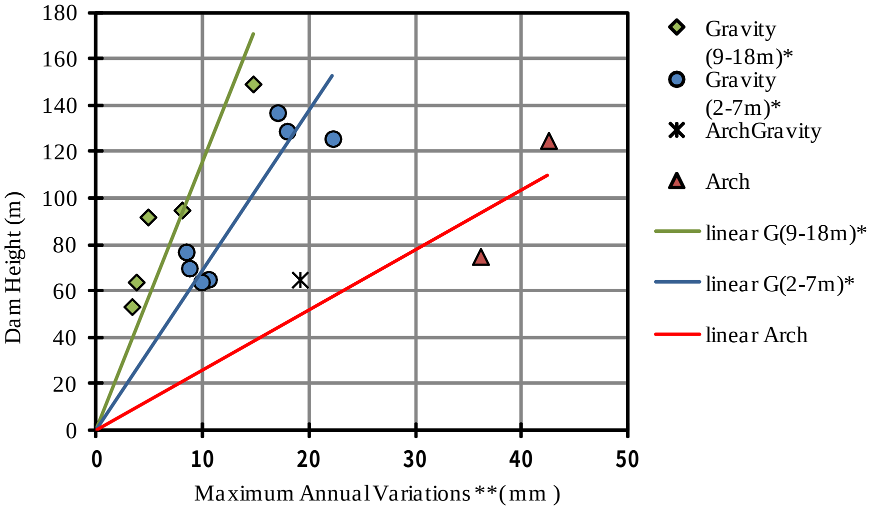


Figure 3. "A" Dam's Reservoir Level Variation and Crest Displacement

In view of above, dam crest displacement toward the upstream and downstream directions may be explained as the superposition of the deflection caused by the hydrostatic pressures due to the variations of reservoir level and the deflection caused by the deformation due to temperature changes on the upstream-side and downstream-side surfaces of the dam body in accordance with the change of seasons.

2.1.2. Displacement of Dam Crest of 16 Dams

Normal plumb lines are installed to measure dam body displacements. For those 16 dams that have been managed for more than five years, the dam crests' annual amount of displacements toward the upstream and downstream directions were analyzed for the most recent five-year period when the effects of the early impoundment periods were small. The correlation diagrams of the maximum values and the dam heights were prepared and shown in Fig. 4.



* Difference between Crest and Maxmum Water Level

**In Crest Displacement during 2006 - 2011 , Upstream-Downstream Direction

Figure 4. Relationship between Dam Height and Annual Variations (Five Year Maximum)

It is clear from Fig. 4 that the higher the dam height the greater the annual displacement. In order to show that the amount of annual displacement of the crest of a gravity dam becomes larger when the reservoir level rises closer to the crest, correlation of the amount of annual displacement and the distance between the reservoir level and the dam crest was plotted in Fig. 4 by separating the distance into two groups, i.e., less than 7 m and above 9 m. As a result, it became easier to recognize the nearly linear correlation. Upper part of a gravity dam has almost a right triangle shape with the downstream side slope of about 1 on 0.8. As the rigidity of a dam body becomes smaller when the height becomes higher, the deflection becomes comparatively large. Thus, it is considered that the difference in the distance between the highest reservoir level and dam crest makes a large difference in the amount of annual displacement of the crest even for dams having the same height. As for the deflection of a dam crest during the low water level, there are no large annual variations every year because water pressure acts on the area of the dam-body having relatively high rigidity and the temperature difference between the upstream-side and the downstream-side of the dam is small.

In addition, it is clear that such types of dams as arch-gravity and arch have larger amount of annual displacement of their crests.

2.2. Displacement of Foundation

As not many dams' foundation displacements are measured, the foundation displacement data of "B" Dam (156m high, completed in 1999) measured with reverse-plumb lines for more than 5 years are used here in order to show the trends in the foundation displacement for the most recent 5 year period when the effects of the consolidation process of the base ground compressed by the impoundment were small (see Figs. 5 and 6).

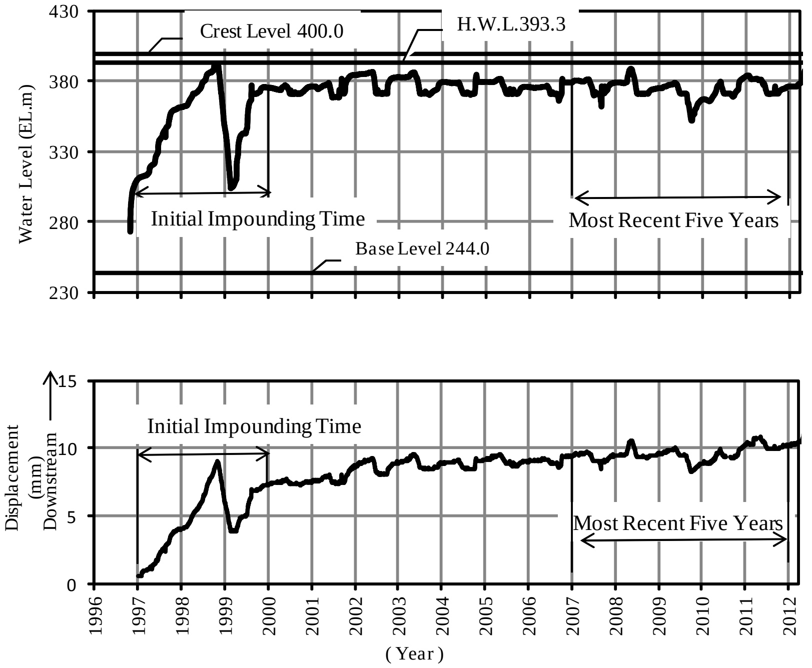


Figure 5. "B" Dam's Reservoir Level Changes and the History of Foundation Displacement

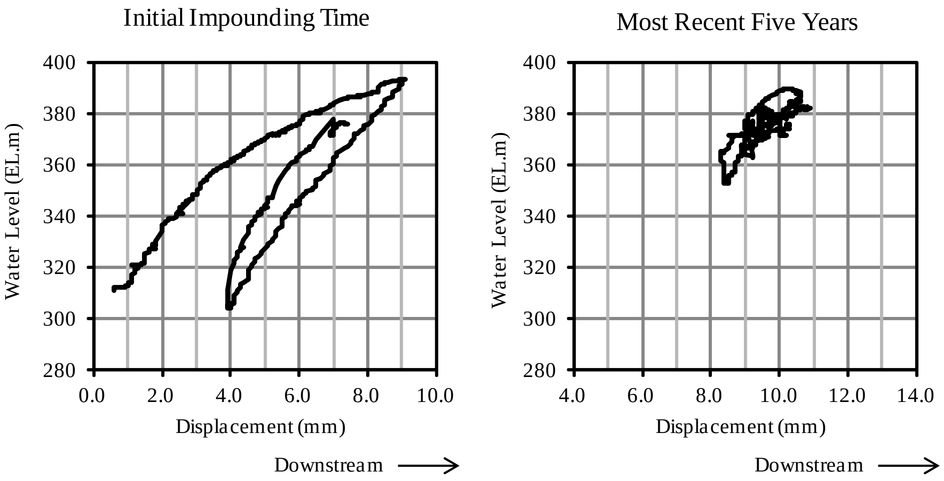


Figure 6. Correlation between the Variation in Reservoir Level and Foundation's Displacement during the Initial Impounding Time and Most Recent 5 Year Period

These figures show the constant slope correlation of the foundation displacement toward the downstream direction in accordance with the reservoir level rise during the initial impoundment period of 2 years from 1997 through 1998. After that period, when the reservoir level started to lower, the foundation started to displace toward the upstream direction and the correlation changed creating the residual displacement of 4 mm. When the reservoir level started to rise again, the foundation displaced toward the downstream direction with the same degree of the correlation that appeared during the reservoir level lowering time. Furthermore, it is understandable that the correlation between the reservoir level rise and the foundation displacement during the most recent 5-year period became elastic and maintained almost the same slope correlation.

As mentioned above, the foundation displacement has a high correlation with the reservoir level variation. When the variations in the reservoir level changes are largest during the initial impoundment period, inelastic behavior of the foundation is recognized then the correlation gradually becomes elastic.

When equipment of a plumb-line measuring system is replaced or maintained, the zero point tends to be changed. As a result, reading of the long-term trends in displacement becomes difficult. Thus, it is important to give special consideration to the continuity of data.

3. LEAKAGE OF CONCRETE DAMS

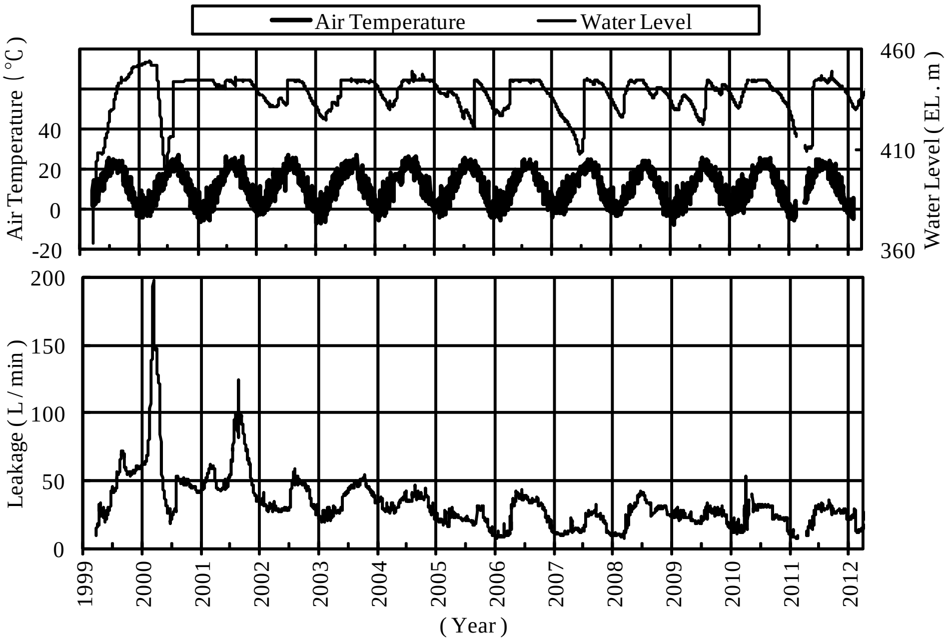
As for leakage from a concrete dam, inspection gallery is provided in the dam body. Seepage water through the dam foundation flowing from the cut-off line toward the downstream direction and leakage water from the reservoir through the joints in the dam body are led into the drain holes then into the side ditches in the gallery. The leakage water is usually measured using a triangular weir installed at the deepest point in the dam body. Amount of leakage water measured with a triangular weir was analyzed in this paper.

3.1. Trends in Leakage since Initial Impounding

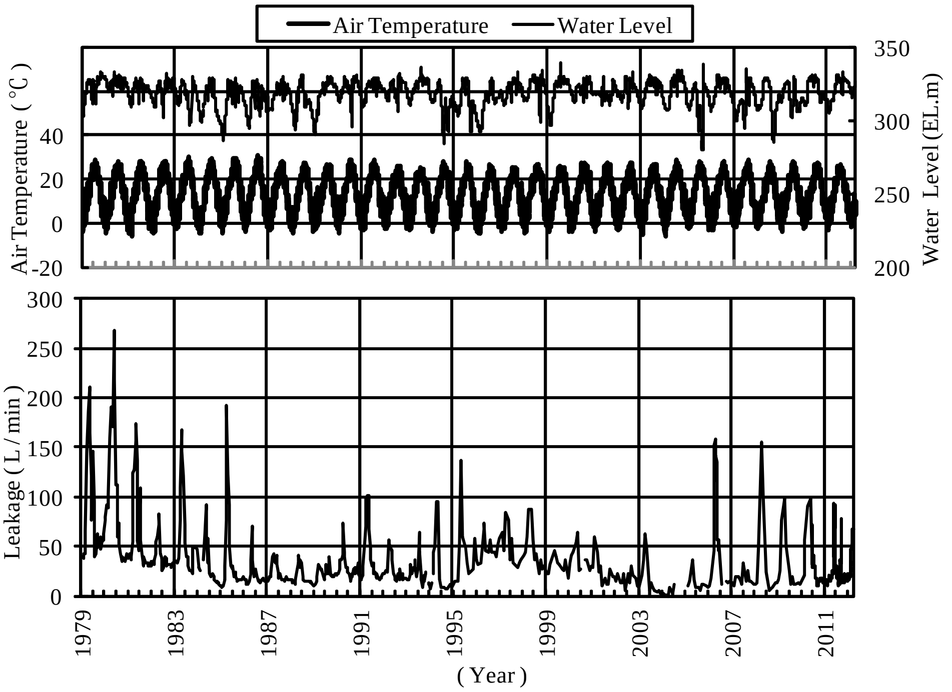
In accordance with the long-term trends in leakage amount during a ten-year period starting from reservoirs' test impounding time, the trends at 16 dams were clarified from data. As a result, 12 out of those 16 dams showed decreasing trends in leakage amount from the initial impounding time. As for other 4 dams that did not show decreasing trends, one dam had almost no leakage from the initial impounding time and 3 dams had variable leakage through joints depending upon reservoir levels and seasons.

As examples of decreasing trends in leakage amounts, the long-term changes in leakage amounts of "C" Dam (106m high, completed in 2000) and "D" Dam (106m high, completed in 1978) are shown in Fig. 7.

Fig. 7 (a) shows an example of the decrease in the maximum leakage amount after ten years comparing to that at the initial impounding time in 1999 and the variation in the leakage amount corresponding to reservoir level changes. On the other hand, Fig.7 (b) shows the decrease in the maximum leakage amount after 10 years comparing to the maximum leakage amount at the starting time of dam management in 1979. The annual variation in leakage amount shows seasonally increasing trends. The leakage amount after 20 years became larger than that of 10 years ago. This phenomenon indicates the examples that all dams not necessarily have decreasing trends in leakage amount.



(a) "C" Dam's Long-term Changes in Reservoir Level, Air Temperature and Leakage Amount



(b) "D" Dam's Long-term Changes in Reservoir Level, Air Temperature and Leakage Amount

Figure 7. Long-term Changes in Leakage Amount at Dams having Decreasing Trends in Leakage Amount

3.2. Trends in Annual Leakage

As a result of clarification of the trends in leakage amounts of 19 dams at where leakage measurements have been recorded, seasonal changes in leakage amounts in one-year period were recognized at 13 dams as seen in Fig. 7(b). Other dams having seasonal changes had a small leakage amounts throughout a year.

Seasonal changes in leakage amount are mainly attributed to opening of the horizontal joints in dam body. When the seasonal changes in leakage amount are reversible behavior to open or close of seepage paths due to the dam body's expansion and contraction, the phenomenon does not lead to progressive failure of the ground. Thus, it is considered that the phenomenon does not immediately affect the stability of the dam body.

Extraneous materials gradually accumulate on the edge of a triangular weir. When these materials gradually develop larger, apparent leakage amount seems to increase. For this reason, it is important to conduct periodical maintenance of weir to record accurate leakage amount.

4. UPLIFT OF CONCRETE DAMS

Uplift pressures are kind of buoyant forces exerting on the base of a concrete dam caused by seepage water flowing through the base ground. For a concrete gravity dam, many foundation drain holes are installed in the gallery that is provided close to the dam base. All drain holes are always kept open to reduce uplift pressures.

However, it is necessary to close the openings of drain holes to measure uplift pressures. A problem arises as how many drain holes should be closed at once in order to reduce measuring time. In order to consider this problem, uplift pressures were measured by two different methods; one method by closing all drain holes and the other by closing alternate drain holes (neighboring holes of each closed hole are kept open) then compared measured values.

Uplift pressure measurement results are shown in Fig. 8 and significant differences in measured values are listed in Fig. 9. Uplift forces are values measured at locations of Bourdon pressure gauges.

As seen in Fig. 8, uplift pressures measured by closing alternative drain holes are smaller than those measured by closing all drain holes. The difference is conspicuous at the left side where leakage amount was comparatively large. Fig. 9 comprehensibly shows uplift-pressure reducing effect caused by draining adjacent drain holes. When all drain holes were closed, uplift pressure at drain hole D-9-1, which had the largest amount of leakage, had the highest value of 0.18MPa and the neighboring holes showed gradually decreasing uplift pressures in proportion to the distance. Measurement of uplift pressures by closing alternative drain holes was conducted in two steps. When alternate drain holes were closed first time, D-9-1 and D-9-3 were drained and, as a result, the highest uplift pressures at the closed drain holes dropped maximum 0.02MPa, which was almost the same to the drain-hole height. When alternate drain holes were closed second time, the uplift pressure at D-9-3 dropped almost to the same level as the drain pipe height and the uplift pressure at D-9-1 dropped 0.06MPa. As mentioned here, effect of draining neighboring holes on uplift pressure measurement is quite large. It is clear that draining a hole having a large amount of leakage and a high uplift pressure, such as D-9-1, gives a great effect to the decrease in the uplift pressures in the neighboring holes.

Therefore, it is important to maintain draining function of foundation drain holes in order to maintain uplift pressure reducing effect. In particular, it is required to pay a special attention whether concerned drain holes and neighboring drain holes performing or not performing draining function may greatly change the uplift pressures exerting on the dam foundation in an area where uplift pressures are especially high.

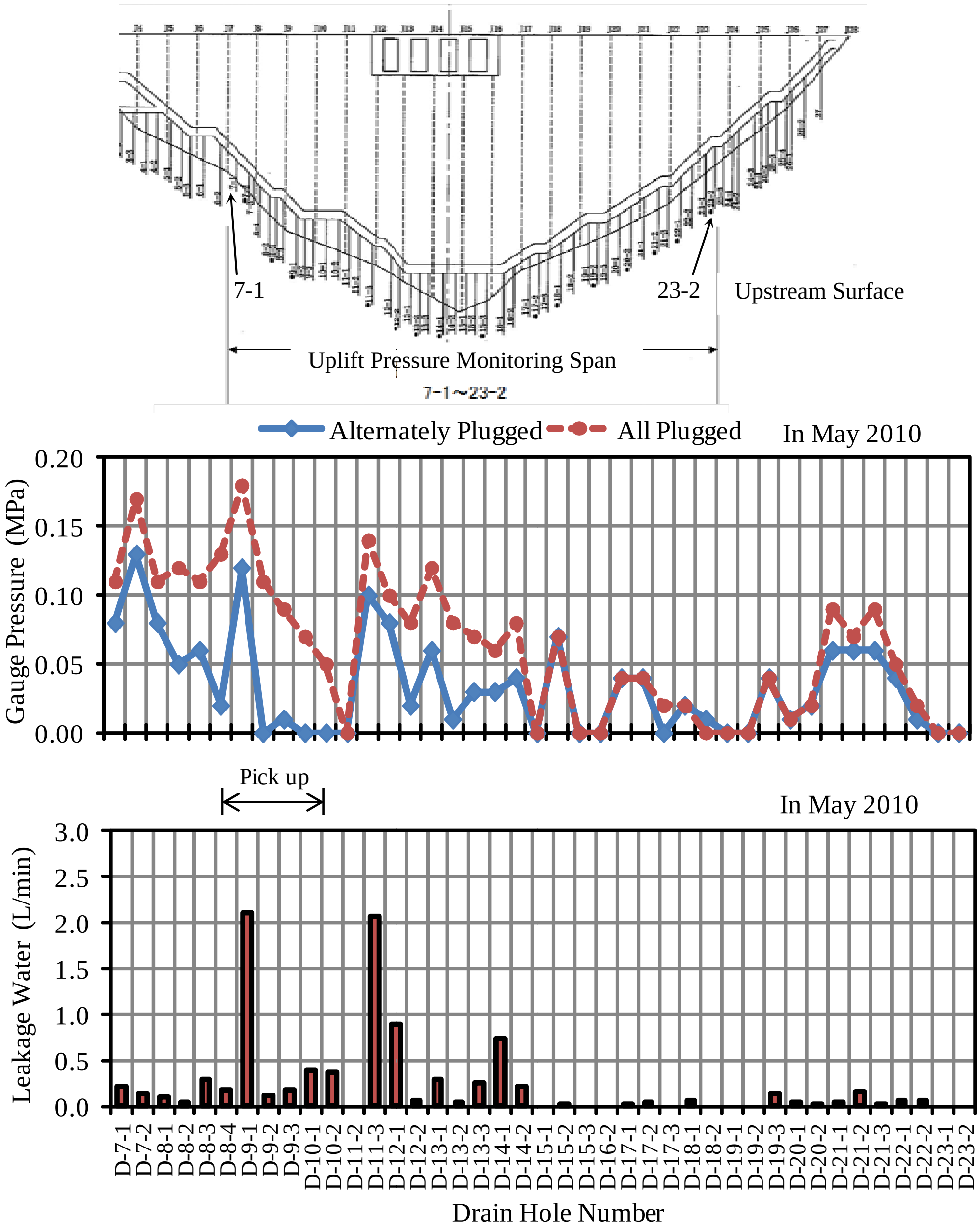


Figure 8. Comparison of Uplift Pressures when Alternate Dain Holes were Closed and when All Drain Holes were Closed at “E” Dam

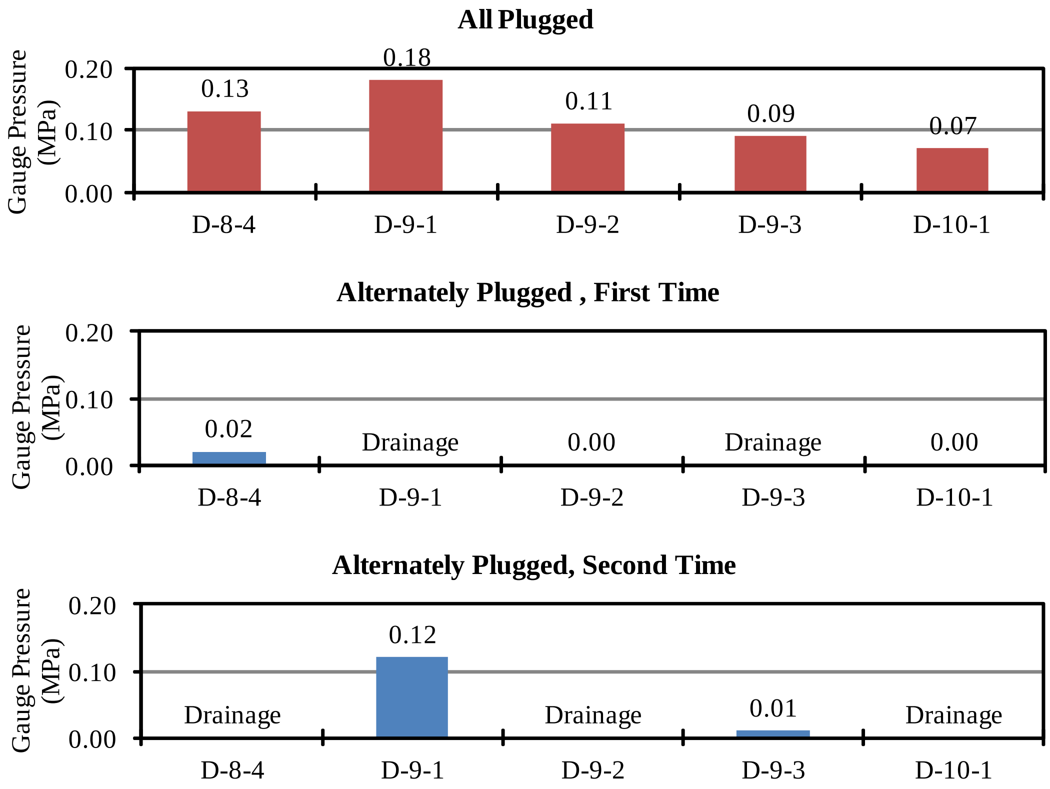


Figure 9. Comparison of Measuring Conditions when Alternate Drain Holes were Closed and when All Drain Holes were Closed.

5. CLOSING REMARKS

This paper described the analyses of measurement data related to the dam bodies' behavior of 20 concrete dams that Japan Water Agency owns and operates and showed the general trends in those dams' deformation, leakage, and uplift pressures. It is considered that the knowledge acquired through the study will be useful for conducting safe dam management and evaluating the safety of dam bodies during earthquakes and large floods. In addition, trends in long-term dam behaviors will also contribute to the preparation of various plans, such as measurement methods for safe dam operation and management, and examination of measurement frequency. Furthermore, for safe management of dam body behaviors, it is necessary to conduct comparative analysis of data observed for a long period of time. Thus, it is important to periodically inspect and maintain observation instrument units, such as plumb lines, triangular weirs, and foundation drain holes.