THE MEASURED BEHAVIOR OF LARGE ROCKFILL DAMS AND STABILITY EVALUATION OF THE MISOGAWA DAM

Fumio Yonezaki[1], Mitsuhiro Oie[2]

INTRODUCTION

Since there is a close relationship between deformation and stress, a proper evaluation of deformation behavior can be considered to be a useful judgment factor in evaluating stress behavior inside the dam body.

Deformation behavior of rockfill dams is generally affected by the height and shape of the dam, fill material and construction. However, with central earth core rockfill dams, common phenomena can be seen between the behavior characteristics of the core zone and rock zone, and in the behavior characteristics during banking and filling.

Therefore, we made a comparative analysis between all five of the JWA's dams using the measured data. From this we identified what appears to be typical deformation behavior common to all the dams, and behavior which is characteristic of each individual dam. In addition, we made a comparative analysis of the measured behavior of four of the JWA's dams during banking and filling with regard to stress distribution, deformation distribution, and stress deflection paths within the dam body, arranging the data in the same way. JWA will use the data in its examinations of the details of the Misogawa Dam as examples of taking decisions about phased designation in the management of facilities.

OVERVIEW OF THE RELEVANT DAMS

The JWA manages four dams completed within the last 20 years, the Naramata dam, the Misogawa dam, the Agigawa dam, and the Yamaguchi dam, as well as the Terauchi dam completed 29 years ago. The dimensions of these five dams are shown in Table 1 and the standard sections are shown in Figure 1. All of the dams are the central earth core rockfill type.

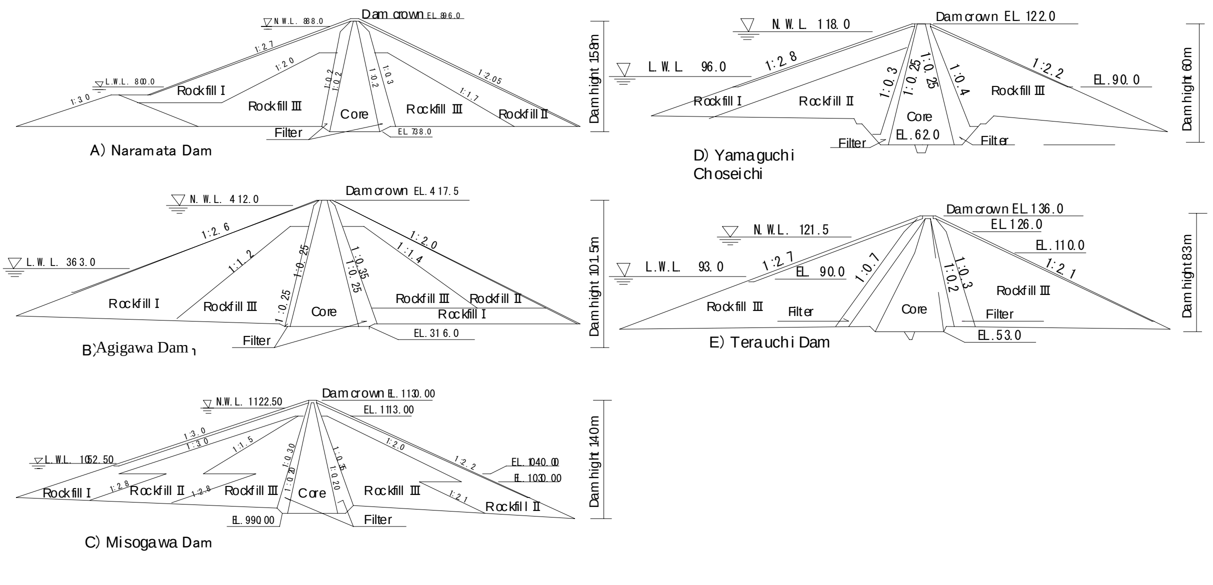


Figure 1 Standard sections

Name		Naramata Dam	Agigawa Dam	Misogawa Dam	Yamaguchi Chouseichi	Terauchi Dam
Dam height	m	158	101.5	140	60	83
Length of dam	m	520	362	447	326	420
Dam volume	m^3	13,100,000	4,900,000	8,900,000	1,060,000	3,000,000
Length of dam/dam height		3.3	3.6	3.2	5.4	5.1
Embankment period (days)		1696	701	2492	492	703
Completion of banking/initiation of controlled filling		120	595	190	558	59
Initial filling period		991	582	967	455	426
Completion of banking to current time		4196	4648	2755	1718	7925
Start of initial filling to current time		4076	4053	2565	1160	7866
Current time		1999/12/2	2000/11/6	2000/12/18	2001/1/9	1998/10/14

Table 1 Dimensions of the rock-fill dams

DEFORMATION BEHAVIOR OF THE DAM BODY

Settlement behavior

Figure 2 shows the amount of settlement of the core at the crest and the rock at upstream in the maximum cross section of the five dams. The tendency in the rate of settlement differs between the Naramata and Misogawa dams on the one hand, and the Agigawa, Yamaguchi and Terauchi dams on the other. The settlement ratio of the Agigawa dam is the greatest at 0.4%, with settlement of about 40 cm. Although there are significant differences up to around 1,000 days, thereafter the settlement trend shows similar speed of settlement. This trend is shown in Figure 3, including the upstream and downstream rockfill with the relationship between the settlement ratio of the core of the crest and the speed of the embankment work (the average of the whole embankment construction period). From this it can be inferred that the settlement ratio is significantly influenced by the speed of embankment work. However, there appears to be no correlation with the height of dam. Furthermore, initial filling of all five dams was finished by around the 1,500th day, and the settlement thereafter is attributed to secondary consolidation and drawdown.

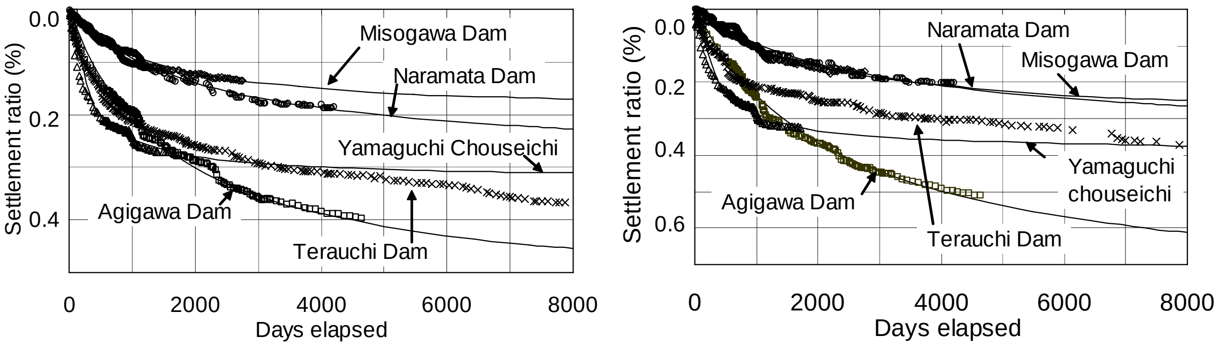


Figure 2 Secular change in the settlement ratio of the core at the crest

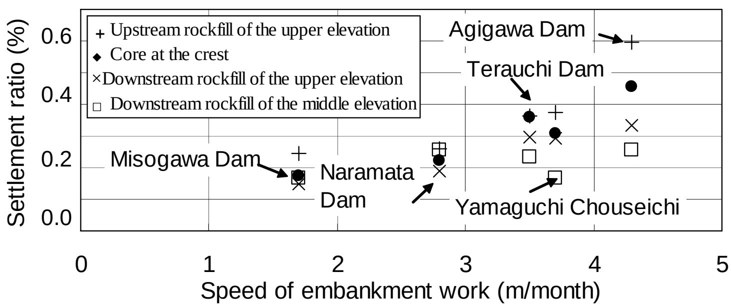


Figure 3 Settlement ratio and speed of embankment work in each zone

Settlement behavior within the dam body

In the Misogawa dam, differential settlement gauges with settlement plates attached at each 10 m elevation are installed in three places, in the upstream and downstream rock zones and the core zone. Figure 4 shows the cumulative settlement recorded by each gauge. The cumulative settlement at the initiation of controlled filling is about the same in the core at the crest and in the upstream and downstream rockfill. After filling, settlement of the core at the crest and the upstream rockfill is more advanced than in the downstream rockfill. Figure 5 shows the compression. The compression amount of the core at the crest is bigger after filling in the upper elevation and lower elevation. The range in the upper elevation where the compression amount was larger corresponds to the range where the reservoir level fluctuated. The compression amount of the upstream and downstream rockfill becomes larger from the middle elevation to the lower elevation. After filling, settlement of the upstream rockfill is more advanced than in the downstream rockfill, however the tendency towards increase in the direction of depth is similar. [Yoshikoshi et al (1997)] cite five reasons for settlement of the core, according to which settlement of the upper elevation is significantly influenced by fluctuation in reservoir level, while the lower elevation is significantly affected by the weight of filling. As for the reason for settlement of the rockfill, it can be inferred that since the compression amount between layers in the direction of depth shows an increasing tendency, the amount is affected by confining pressure inside the dam body, and this influence gets stronger with water-logging.

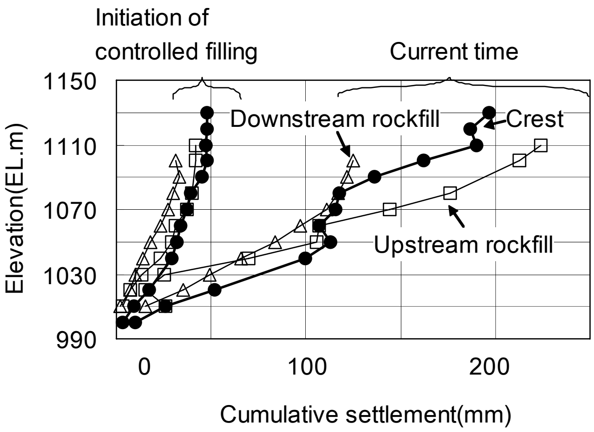


Figure 4 Cumulative settlement of the Misogawa dam differential settlement gauges

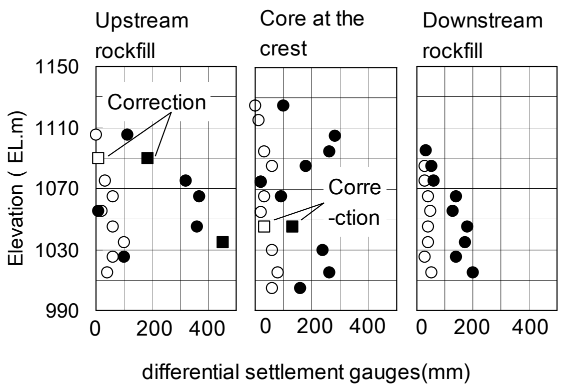


Figure 5 Compression amount between the settlement plates of the Misogawa dam

Horizontal displacement behavior

Figure 6 shows the horizontal displacement of the core at the crest and of the upper elevation of the upstream and downstream rockfill of the five dams. In the Naramata dam, the amount of horizontal displacement of the downstream rockfill of the upper elevation is especially large at 285 mm. In addition, the downstream rockfill of the upper elevation shows a tendency towards greater horizontal displacement towards the downstream side than the core at the crest[Nakamura et al (1994)]. The core at the crest of the Agigawa dam is displaced -31 mm on the upstream side. The reason for this is inferred to be related to the water-logging behavior associated with flooding of the upstream rockfill.

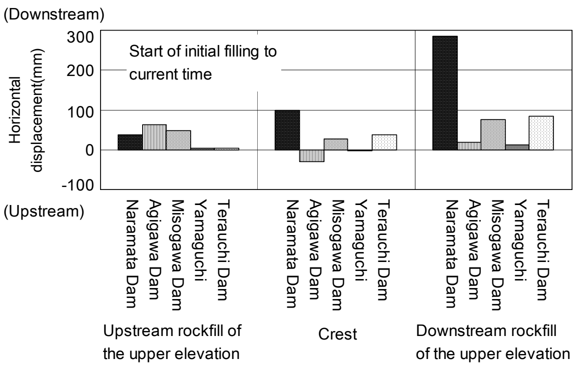


Figure 6 Horizontal displacement in the crest and rockfill

STRESS AND STRAIN BEHAVIOR OF THE DAM BODY

Stress behavior

Figure 7 shows the vertical stress from the earth pressure gauges installed at each elevation of the core and filter of the Agigawa dam, and the secular change in the covering thickness above the earth pressure gauges. During the latter stages of embankment, the vertical stress at each elevation shows a tendency to fall markedly in relation to the line of soil weight. The fact that the vertical stress of both filters rises significantly above the line of soil weight when the covering thickness is still low indicates that concentration of stress on the filters occurs when the covering thickness is still low.

The earth pressure gauges at the base measure vertical stress, while the amount and direction of the maximum and minimum principal stress can be found from the gauges installed at 45º and 135º on the upstream and downstream sides. The stress paths for minimum and maximum principal stress during banking are shown in Figure 8. The principal stress ratio in the core is about σ_3/σ_1 = 0.4 to 1.0 and there is variation between dams. However, in general, stress increases at a constant principal stress ratio. The principal stress ratio in rockfill for each dam varies between σ_3/σ_1 = 0.2 to 0.6, but in general, stress increases at a constant rate. The principal stress ratio in the filters for each dam varies between σ_3/σ_1 = 0.2 to 0.6, and there is a slight downward tendency but in general, stress increases at a constant principal stress ratio. These results show a similar trend to earlier research findings [Harada et al (1997)],[Mori et al (1984)], [Sasakawa et al (1984)].

Figure 9 is a comparison of the vertical stress and soil weight of each dam showing the differences in vertical stress in the filters and core of each dam. Since earth pressure gauges are installed in each dam at between two and four elevations, and in the core they are also installed on the upstream and downstream sides at the same elevation outside the central part, a horizontal axis is also shown to allow comparison between them.

There is variability between dams with regard to vertical stress but in general, it is 0.8 to 1.5 times and 0.4 to 0.7 times relative to the soil load for the filters and the core, respectively. The vertical stress ratio for the filters and core is about double. This is about the same as the measured data for other rockfill dams in Japan [Sakamoto et al (1994)]. The reason for the earth load of the upstream filter being bigger than that of the downstream side is probably that the width of the upstream filter is narrower and this bears part of the weight of rockfill and core.

Figure 9 above is a comparison of the vertical stress and soil weight of the four dams excluding the Terauchi dam, regarding the up and downstream filters and core at the start of initial filling and when the first highest reservoir level was reached. Vertical stress of the upstream filter shows an overall downward tendency when the first highest reservoir level was reached compared with the start of initial filling. Vertical stress of the upstream filter shows an overall downward tendency in line with the rise in water level after filling. Since the measured value is for total stress, in theory the dam body should become saturated due to filling and the vertical stress of the upstream filter should increase, but contrary to expectation it decreases. One of the factors in decreasing vertical stress in the upstream filter in conjunction with rising reservoir level may be attributed to buoyancy due to filling affecting the upstream rockfill, relaxing concentration of stress on the filter, thereby reducing vertical stress in the filter.

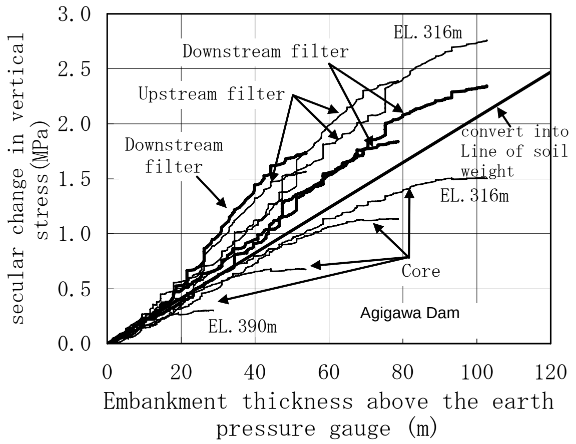


Figure 7 Relationship between covering thickness and vertical stress

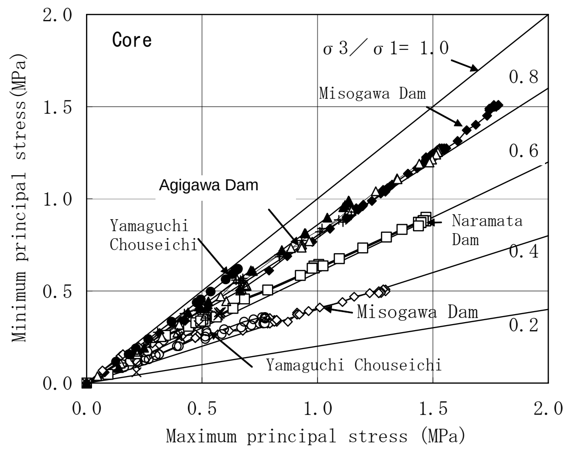


Figure 8(1) Stress paths in the core during banking

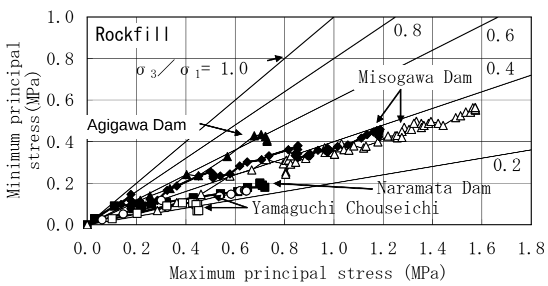


Figure 8(2) Stress paths in the rockfill during banking

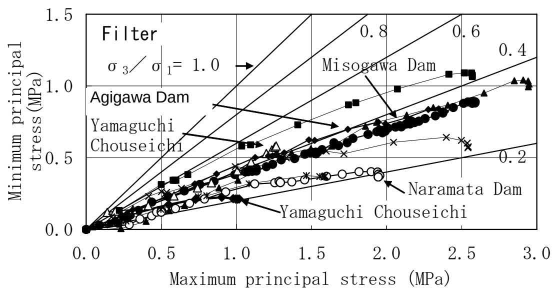


Figure 8(3) Stress paths in the filter during banking

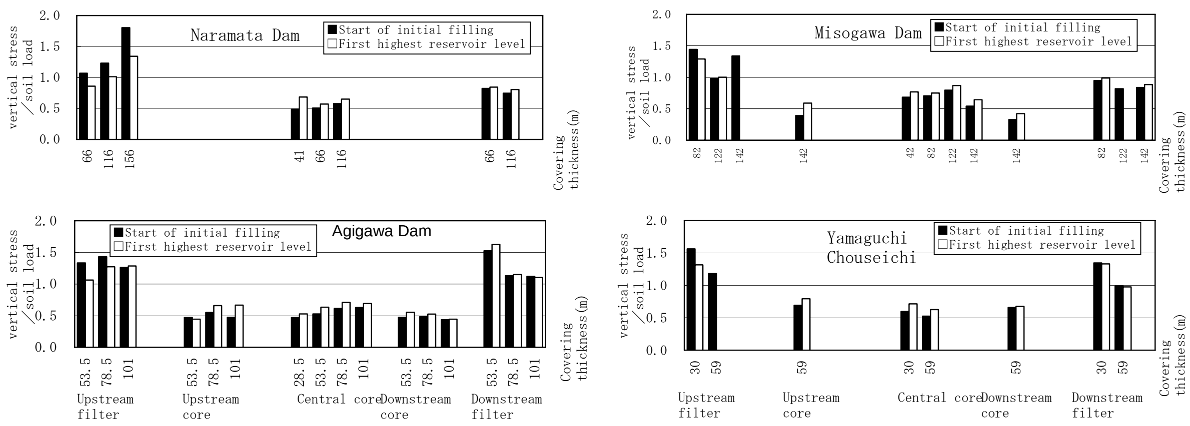


Figure 9 Comparison of the vertical stress and soil load of each dam

Strain behavior

Figure 10 shows the vertical strain distribution of the core and upstream and downstream rockfill obtained from the settlement data from the differential settlement gauges. The vertical axis is the depth from the top of the differential settlement gauge to each settlement plate, and the horizontal axis is the vertical deformation. The value for sinkage of the settlement plates at one location fluctuates due to measuring and other errors so that the vertical deformation above and below it changes significantly. Therefore we reduced the error for vertical deformation using Kuno's method (1991). Vertical deformation of the core shows a tendency to increase with depth. Furthermore, the tendency towards increase in vertical deformation is greater in the shallow parts and decreases in the deeper parts. In some of the dams, vertical deformation of the rockfill increases rectilinearly in the direction of depth, while in others, the tendency towards increase drops off in the deep parts in the same way as in the core.

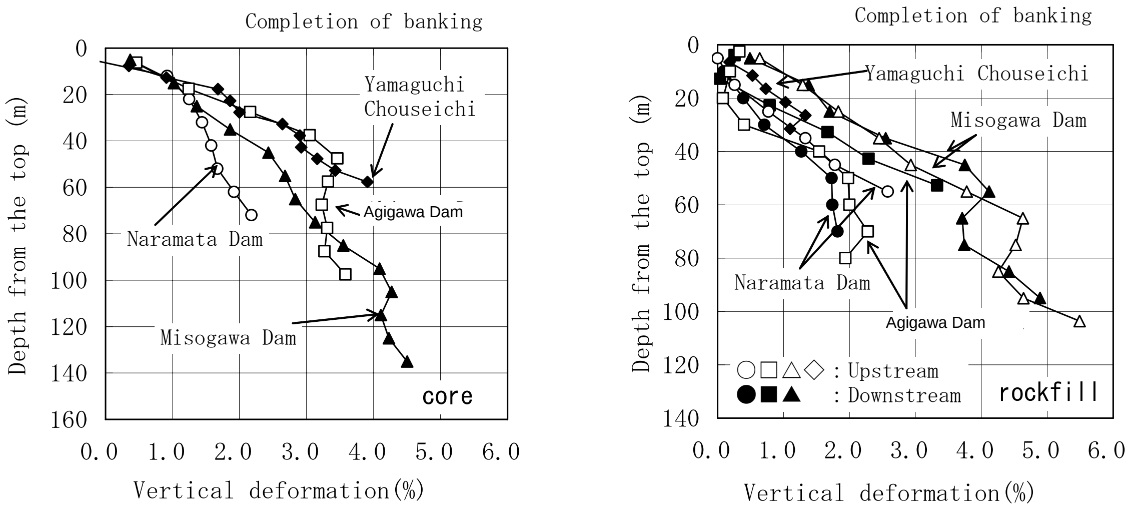


Figure 10 Vertical deformation in the core measured with differential settlement gauges

Stress and Strain behavior

In this study we summarized the relationship between vertical deformation and vertical stress based on the vertical stress measured by earth pressure gauges installed alongside the differential settlement gauges in the core of the four dams, and the vertical deformation obtained from the differential settlement gauges. The relationship between vertical deformation and vertical stress during banking is shown in Figure 11. The figure also shows the numbers of the earth pressure gauges and the covering thickness at each gauge. The apparent characteristics of the deformation coefficients obtained from the measured vertical stress and vertical deformation in the Agigawa and Misogawa dams are shown below. In terms of the overall tendency in stress deformation during banking, the apparent deformation coefficient is a low 0~50 MPa while the vertical stress is low at about 0.5 MPa. However, it increases between 40~80 MPa above that, and if consolidation settlement during rest periods is discounted, an even greater tendency is observed. The vertical stress component of stress deformation of the top of the dam is small, but the apparent deformation coefficient shows a close to constant tendency.

The tendency towards increase in stress deformation of each dam is linear, and there are slight differences in the apparent deformation coefficient, with about 50 MPa for the Naramata dam, about 40 MPa for the Agigawa dam, and about 60 Mpa for the Yamaguchi Chouseichi. As regards the relationship with the stress deformation of the core, while the apparent deformation coefficient differs in the period when the vertical stress is big and when it is small, in general the rockfill shows a linear tendency. One of the reasons may be that while the core is located in the center of the dam body and is constrained on both sides by the filter and rockfill restricting lateral displacement, the rockfill is being displaced laterally during banking as [Sato et al (2003)] have shown.

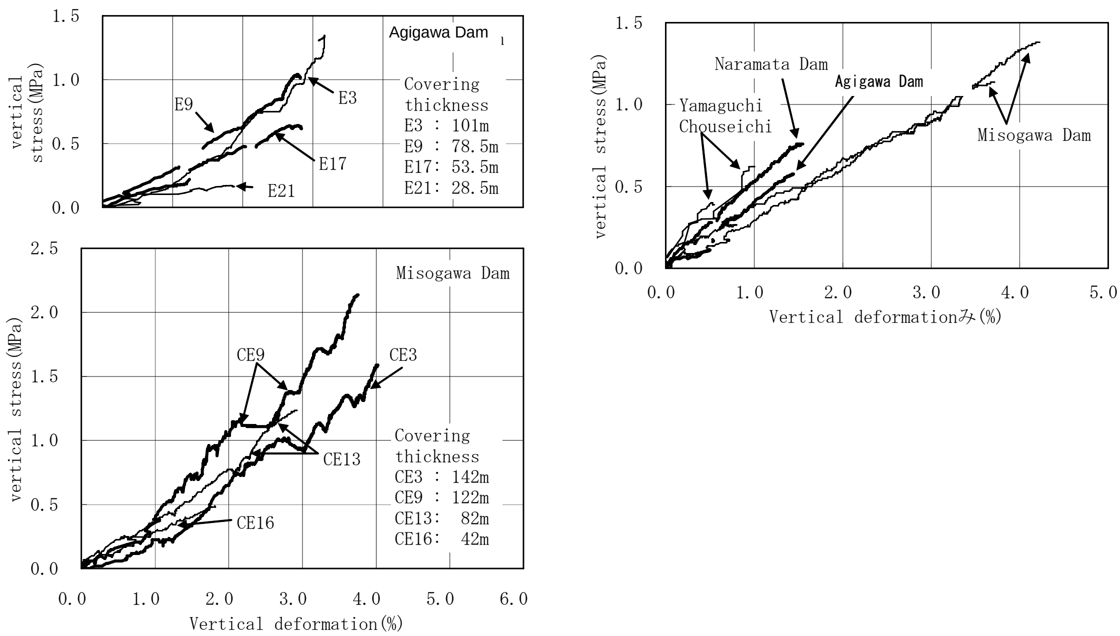


Figure 11 Vertical deformation and vertical stress in the core of each dam

STABILITY EVALUATION OF THE MISOGAWA DAM

In 2002, six years after completion of initial filling, JWA decided to assign the Misogawa dam to Stage III based on the various data. Here we report on the principle data behind the decision.

Regulations and standards concerning safety control for dams

Japan’s Cabinet Order Concerning Structural Standards for River Management Facilities stipulates that devices must be provided for measuring leakage and deformation in central earth core fill dams. Furthermore, the Revised Dam Construction and Management Standards (Japan Commission on Large Dams, 1986) stipulates the following concerning the stages for dam management.

Stage I. The time from the initiation of controlled filling to complete filling plus a specified time period after complete filling

Stage II. The time required until the behavior of the dam reaches a steady state after the completion of Stage I

Stage III: The stage following the completion of Stage II

Furthermore, the Commentary on the Structural Ordinance states that in Stage I it is necessary to continue the same monitoring at full water level as that preceding it, and that this stage should be two months or more. It also states that Stage II is the period from when Stage I is completed until the behavior of the dam is confirmed to be stable. For a dam higher than 100 m, this stage is three years or more.

Stage I is the initial impoundment phase when it is confirmed that the dam can be impounded safely, and additional measures are taken if necessary. For dams that will operate reservoirs, the various phenomena arising from the dam are measured. This is the most important stage because the values that form the standard for judging the safety of the dam are collected in this period.

The transition between Stage II and Stage III is only made after checking overall phenomena focused on the amount of leakage and deformation. The criteria for judgment are a stationary state for safety levels linked to the reservoir level, reduction tendency and so on. The criterion for Stage II is about three to five years after initial impoundment.

Since Stage III is the result of confirming the safety of the dam in Stage II, it is acceptable to adopt a management system with a reduced frequency of measurements. The focus of safety control can be changed to monitoring for signs of deterioration with inspection patrols.

Stability of the percolation system

<u>Amount of percolation</u>

In the percolation system of the Misogawa dam, catchment walls are installed in each of the five blocks inside the dam (PW-1 to 5). Here the amount of leakage is termed “amount of percolation”. Figure 12 is a plan of the locations of percolation observation facilities, while Figure 13 shows the secular change in percolation, rainfall, and reservoir level.

The amount of percolation from the dam body (total of PW-1 to PW-5) is affected by precipitation in this system too, sometimes causing it to break out temporarily. However, in general, it shows a tendency to follow the reservoir level. The amount of percolation during about one year after initiation of controlled filling was low at about 100 l/min since the water level was low. However, after the reservoir level reached an elevation of 1,075 m, it increased suddenly from 200 l/min to 400 l/min. Thereafter when the reservoir level reached an elevation of 1,105 m, when the effect of precipitation is discounted, no increase in the amount of percolation was apparent, and it remained steady or declined slightly. In addition, after initial filling to the present, the system is maintaining a comparatively stable flow, and over the years there has been a downward trend in the amount of percolation.

Figure 14 shows the correlation between reservoir level and percolation. If the effect of rainfall is discounted, percolation tends to change rectilinearly in step with fluctuations in the reservoir level, remaining quite stable. Furthermore, the amount of percolation shows a tendency to decline in a loop pattern over time in relation to the same reservoir level. In recent years, when the amount of percolation in the whole dam body is observed at close to a full supply level, it is found that percolation that was at 300 to 400 l/min at the time of initial impoundment is declining to as little as 100 to 150 l/min.

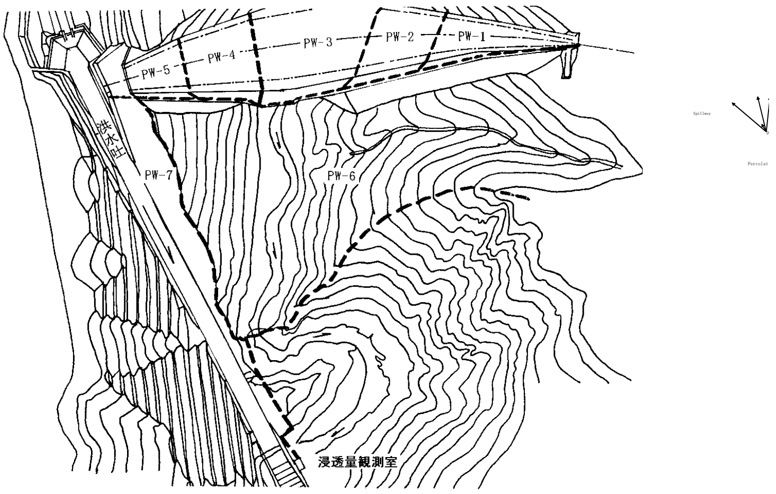
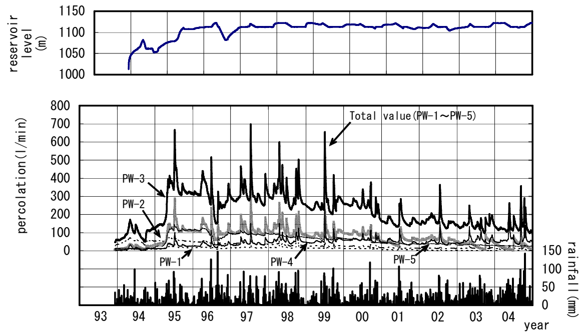


Figure 12 Plan of observation facilities for percolation



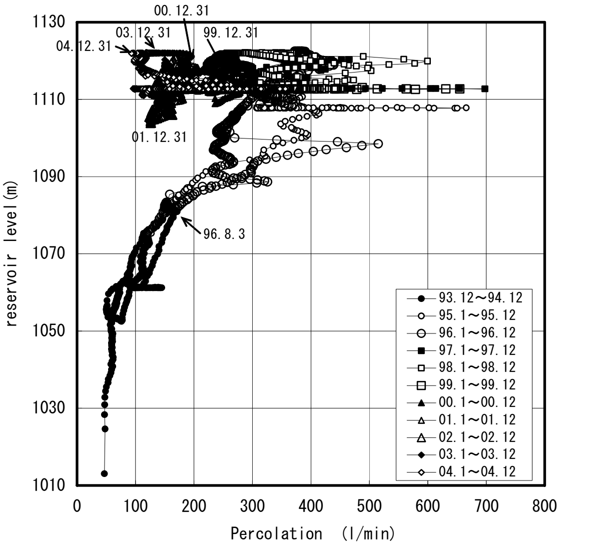


Figure 13 Secular change in percolation, rainfall, and reservoir level

Figure 14 Correlation diagram of reservoir level and percolation (total for PW-1~5)

<u>Pore water pressure</u>

Figure 15 shows pore water pressure distribution. Pore water pressure that was generated during construction dissipated during the winter break in work, and the residual pore water pressure during banking is relatively small. This pressure has been dissipating gradually from initial filling to the present. The pressure distribution in the core zone when the water level fell in August 1996 was high in relation to the reservoir level since the core zone has low permeability, causing a lag in tracking drawdown. If we focus on distribution of pore water pressure that is higher than the rise in reservoir level, when the highest reservoir level from initial impoundment was experienced, a rise in pore water pressure in the lower elevation was observed. However, thereafter it gradually dissipated in line with the fluctuations of the water level.

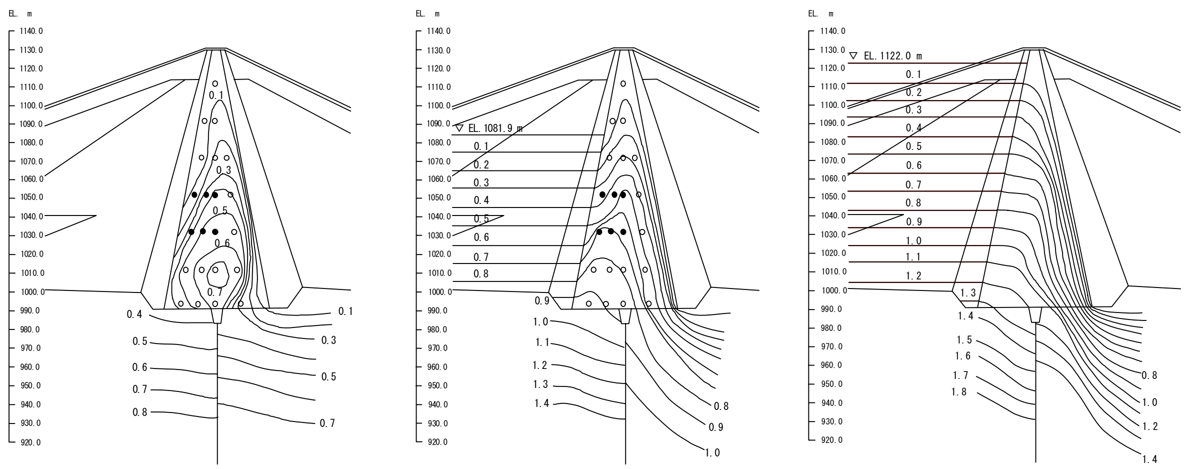


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Figure 15 Secular change in the pore-water pressure distribution in the principle observed section

Stability of the dynamical system

Figure 16 shows the settlement at the crown along the dam axis, and on the surface of the principal section of the dam body respectively. Settlement of the dam crown is distributed correspondingly with the fill height. Secular change in settlement was significant between

December 1993 and August 1996 during initial impoundment. However throughout 2001 it was low at 1 cm or less near the middle of the dam axis, showing stable behavior.

Figure 17 is a profile of horizontal displacement along f survey line for the dam crown, and g survey line for the downstream upper elevation. The amount of displacement for each line is greatest near the maximum cross-section (F7, G6, H5), with a tendency to decline towards the left and right banks centered on the maximum cross-section, and showing displacement in accordance with fill height and the topography of the foundation.

Furthermore, in the last two years, it has been confirmed that no uneven settlement has been observed over the whole surface of the dam body.

Concerning vertical displacement measured by the differential settlement gauges, Figure 18 shows the settlement distribution when banking was completed where 0 represents the time of installation (June 17, '93), before initiation of filling (December 8, '93), and once a year since November '94. Also since the completion of initial impoundment, no advances in settlement have been confirmed. This tendency was also confirmed from the data of differential settlement gauges located separately in two other places in the core zone.

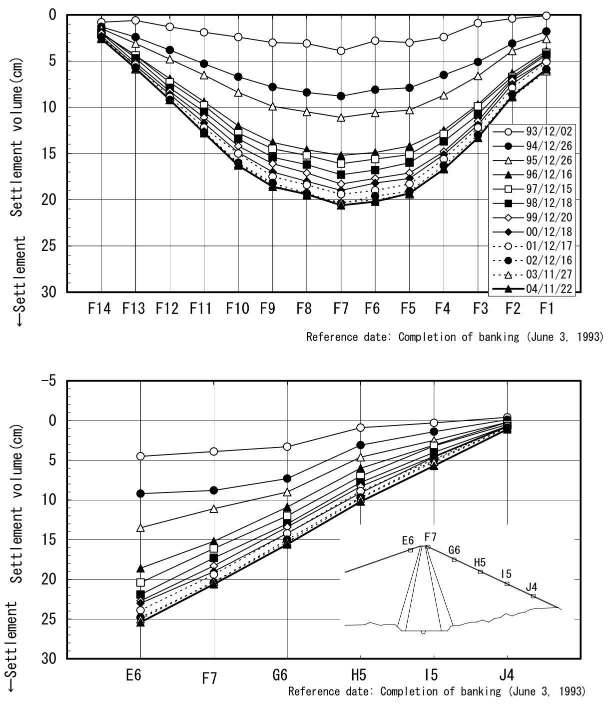

Figure 16 Settlement of the dam axis

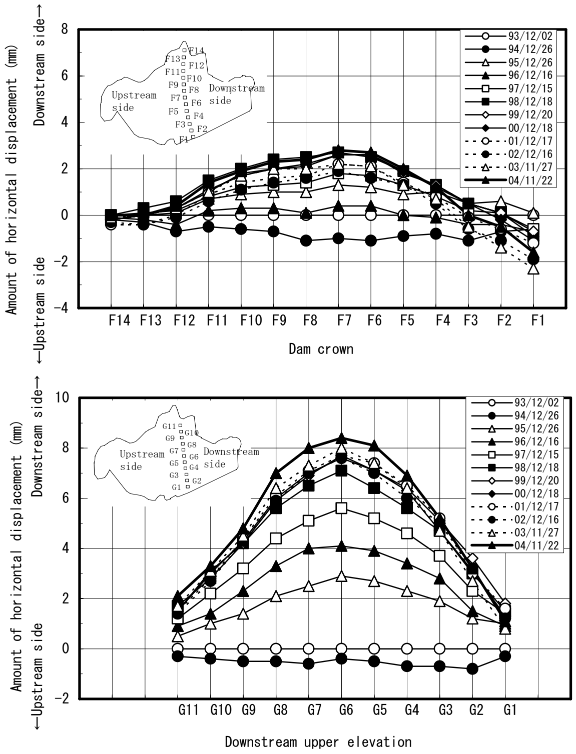

Figure 17 Horizontal displacement section

The decision to assign the dam to Stage III

The results of the stability evaluation of the percolation system of the Misogawa dam show that although the percolation from the five blocks in the dam body (PW-1 to PW-5) is affected by precipitation and sometimes breaks out temporarily, in general, the percolation shows a tendency to follow the reservoir level. In addition, the amount of percolation shows a tendency to decline in a loop pattern over time in relation to the same reservoir level. No change has been seen in the distribution characteristics of pore water pressure in the dam body.

In addition, the results of the stability evaluation of the dynamical system show that settlement of the maximum cross-section of the crown was 19.4 cm from the start of observation to December 2001. Settlement of the maximum cross-section of the crown as a

percentage of dam height was 0.14% and settlement of the maximum cross-section of the crown was sufficiently small compared with the designed extra banking. Anticipated settlement after 100 years using hyperbolic approximation is 27 cm, which is sufficiently small compared with the designed extra banking. In addition, as Figure 2 above shows in the form of settlement ratio (settlement/fill height), annual settlement is 0.003% of dam height, which is below the criterion for steady state of 0.02%.
Since stable and safe dam behavior was confirmed from these results, it was determined that the dam has reached a steady state suitable for transition to Stage III.

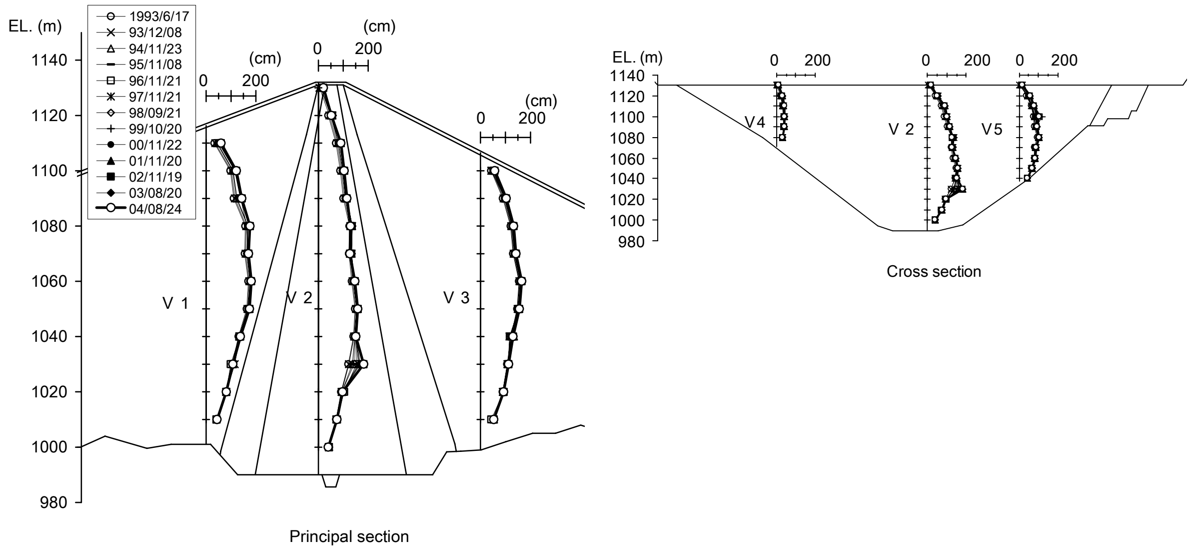

Figure 18 Vertical displacement measured with differential settlement gauges

CONCLUSION

We carried out a comparative analysis of the five rockfill dams belonging to JWA concerning the behavior characteristics of the core zone and rock zone, and their behavior characteristics during the banking and filling processes. From this we identified what appears to be typical deformation behavior common to all the dams, and behavior which is characteristic of each individual dam. Identifying these tendencies was useful in evaluating the stability of rockfill dams. Based on these comparative analyses, we carried out comprehensive stability evaluations of the Misogawa dam using data from the percolation and dynamical systems. This resulted in the decision to assign the dam to Stage III.
In actual management of dams, it is important to carry out periodical visual inspection in addition to checking the data from monitoring devices. In Stage III, since new problems associated with aging may occur, visual inspection after earthquakes, floods and other similar events becomes increasingly important.

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1. Water Resources Engineering Department, Japan Water Agency
936 Jinde, Sakura-ku, Saitama-shi, Saitama-ken 338-0812,Japan
Telephone: 048-853-1785 Fax: 048-855-8099 E-Mail: fumio_yonezaki@water.go.jp

2. Water Resources Engineering Department, Japan Water Agency
936 Jinde, Sakura-ku, Saitama-shi, Saitama-ken 338-0812, Japan
Telephone: 048-853-1785 Fax: 048-855-8099 E-Mail: mitsuhiro_oie@water.go.jp