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SYNOPSIS The design of embankment is carried out based on several assumptions for the dam body and foundation, and the dam is constructed according to the design conditions. Therefore, it is important to evaluate the conforming of assumptions to the design and construction by the observation of behavior of the dam body and foundation.

In this report, internal vertical movement, pore-water pressure and surface movement are arranged concerning of 21 embankment dams of Japan in order to optimize the measurement method including frequency and proper installation of instrmentation and consequently to present a guidelines for the safety control of dams.

1. INTRODUCTION

Prior to the design of rockfill dams, analyses are made on dams and foundations based on the data obtained by laboratory or in-situ tests, so as to ensure that construction work meets the design requirements. Therefore, it is very important to measure the behaviors of dams and foundations, and to analyze the compatibility of design features and procedures, and to improve design methods. It is expected that methods of measurement, including the layout of monitoring instrumentation and the measuring frequency, will be optimized and the measured data will be referred to as guidelines for safety control.

This report will describe the results of the analyses made, paying attention to the behaviors of dams during and after the first filling of reservoir and long-term operation of dams. Items discussed in this report are the external displacement of dam bodies, internal vertical movement, and the pore-water pressure measured in the core zone of dams. The tendency of readings, causes for movement and pore-water pressure, and their distribution shapes were thoroughly reviewed here.

2. INTERNAL VERTICAL MOVEMENT OF DAM BODIES

Behavior of rockfill dams is monitored mainly for the purpose of verifying the design adequacy and the safety of dams after completion. As Penman (1988) stated in his report , measurement of lateral displacement of dam bodies made during construction will contribute to the management of construction and will warn of potential slides of surface slopes. It is considered that measuring the displacement of dams during construction will give an index for the safety control of dam.

However, external displacement of dams is most often measured during first filling of reservoir. Measurement to be done during construction is normally limited only to internal vertical and lateral movement.

This report will also describe the characteristics of internal vertical movement of dams occurring during construction , based on the summarized readings of settlement sensors installed inside the dam body.

Five rockfill dams with central core under the control of the Ministry of Construction were selected and made available for investigation and analyses.

2.1 Displacement Characteristics

Measuring intervals of internal vertical ovement device are most often set at every 5 meters. Devices were placed in the core zone or in the rock zone of the maximum cross section. At large dams, devices were also placed in the core zone near both abutments . The tendency of settlement, read at various measuring points during construction, is shown in Fig. 1. It can be seen that measuring points tend to settle as the construction proceeds, and settlement continues slowly by creeping while the construction is suspended.

The relationship between the measured settlement rate and locations of measuring points during construction is shown in Fig. 2. The settlement rate means here the value obtained by dividing the settlement (dz) read at measuring points with the final height of embankment (H) where devices were placed. The settlement of both rock and core zone can be shown by polygonal lines. These lines usually indicate the largest settlement rate at the mid-height of rock and core zones. Such a tendency of vertical movement in the dam body was also verified by finite element analyses, taking into consideration the process of the construction (Matsui et al.(1971)).

2.2 Maximum Settlement

Fig. 3 shows the relationship between the maximum readings by internal vertical movement devices and the final height of embankment. Reviewing the data collected from core and rock zones, the relational formula (1) can be obtained. Coefficients are widely distributed, but range from 0.005 to 0.02.

$$dZ_{max}=(0.005\text{-}0.02)H \qquad (1)$$

Where,

dZ_{max} = maximum settlement measured by internal vertical movement devices (in meters)

H = final height of embankment at measuring points (in meters)

If data are separated into the core zone and the rock zone, the correlation of the core zone will improve. As expressed by formula (2), the average of the maximum settlement will be around one percent of the final height of embankment.

$$dZ_{max}C=0.01\cdot H \qquad (2)$$

Where, $dZ_{max}C$ = maximum settlement of the core zone.

Fig. 4 shows the relationship between the locations where maximum settlement occurs and the final height of embankment. Maximum settlement is occurring at the elevation between 40 and 60% of the final height of embankment. When the core zone and the rock zone are compared, maximum settlement is distributed between 40 to 60% in the core zone but 40 to 90% in the rock zone, which is slightly higher than that of core zone. It was noted that maximum settlement tended to occur at higher elevations in the core zone when the final height of embankment was higher.

2.3 Vertical Strain

What is measured by internal vertical movement sensors is the settlement at each measuring point, and the magnitude of compression between measuring points can also be obtained from the differences in each settlement. The vertical strain is the value obtained by dividing the compression (dL) with the distance (L) between measuring points.

Fig. 5 shows vertical strain (ε_v) distributed along settlement sensors when the construction was finished. Vertical strain tended to increase at lower elevations but to decrease in upper elevations. There are a few different types that indicate the distribution of strain, but the most popular type was used to draw these curves. Kuno(1991) states in his report that physical properties (elastic modulus and Poisson's ratio) of dams can be expressed more correctly when vertical curves are used for reviewing the results of static analyses, compared with the settlement curves shown in Fig. 2.

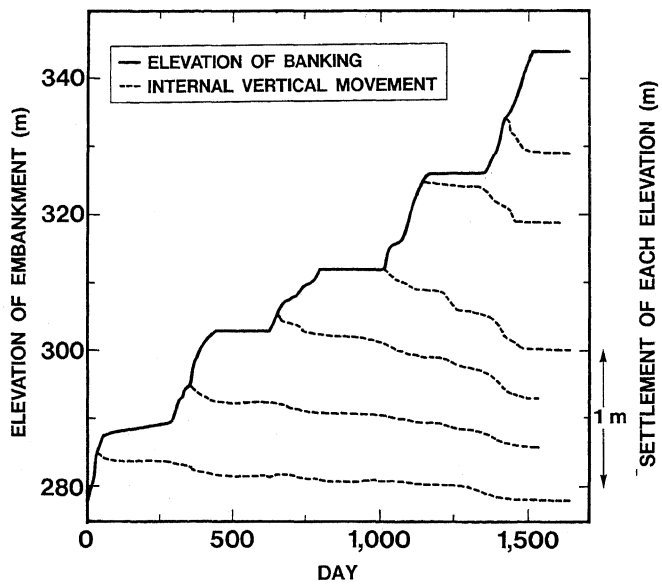

Fig. 1 Example plot of internal vertical movement

The relationship between maximum vertical strain (ε_{vmax}) and the final height of embankment is shown in Fig. 6. Maximum vertical

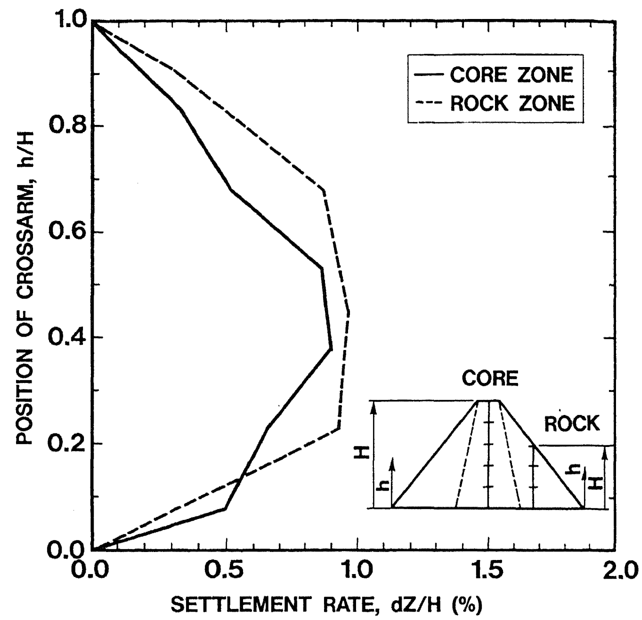

Fig. 2 Settlement rate measured by internal vertical movement devices

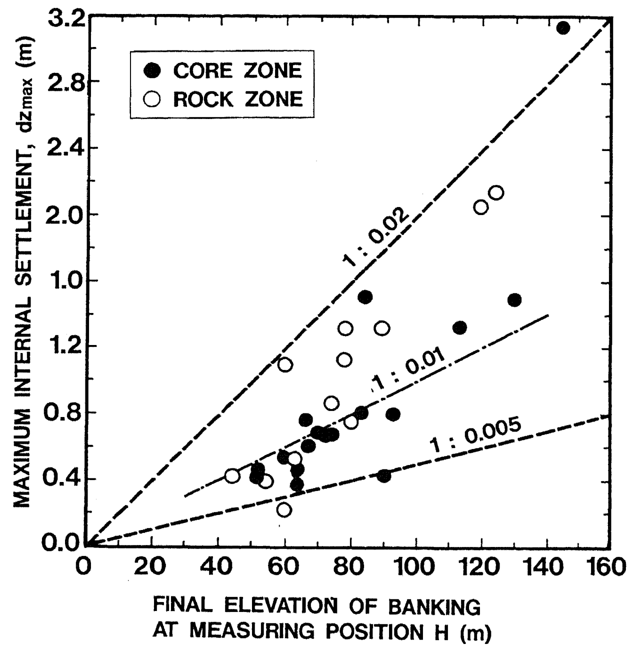

Fig. 3 Relationship between maximum settlements and final heights at the locations of devices

strain is distributed within a range expressed by formula (3) (shown in broken lines) and becomes larger as the final height of embankment increases.

$$\varepsilon_{vmax}=(0.03-0.1)\cdot H \qquad (3)$$

Where, ε_{vmax} = maximum vertical strain .

It can be assumed that the upper limit of maximum vertical strain will be 8% at the core zone and 6% at the rock zone, because measured values at the core zone ranged from 2 to 8% and those at the rock zone from 2 to 6%.

3. PORE-WATER PRESSURE

When impervious wet soil is used for embankment materials , pore-water pressure occurs in the embankment. As the pore-water pressure increases, the effective stress and

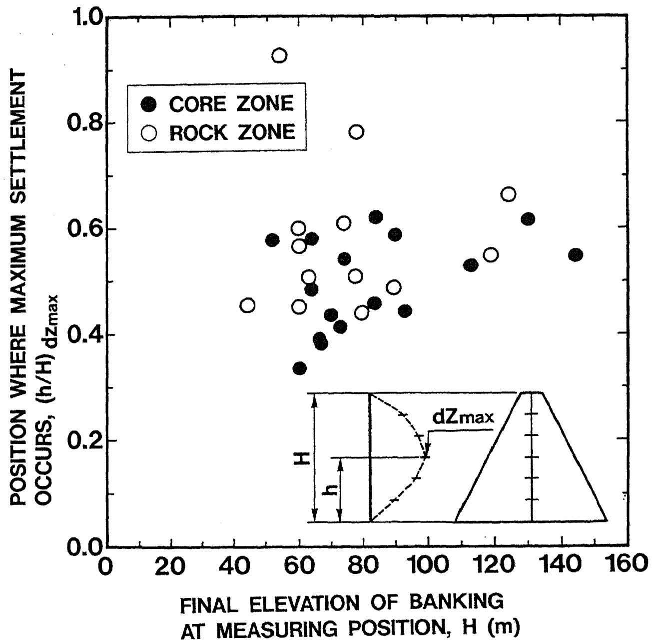

Fig. 4 Relationship between the position of cross arm with maximum settlement and final heights at the location of devices

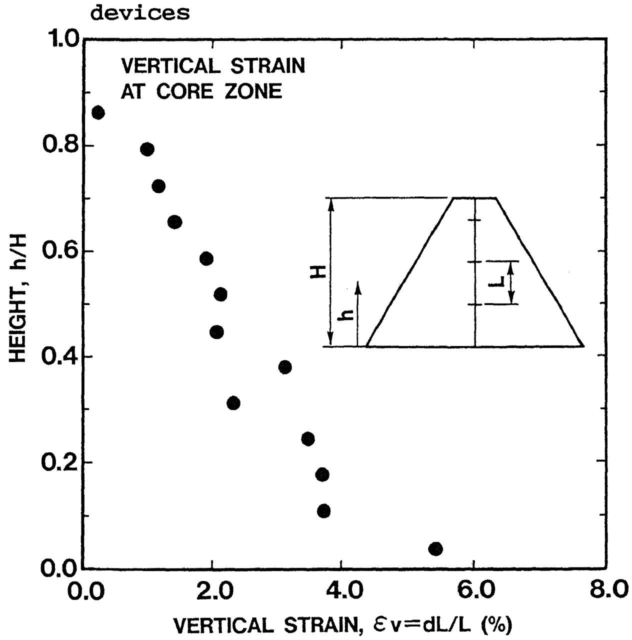

Fig. 5 Vertical strain along the center of core zone

shear strength of the material will decrease. Since it is very important to measure the pore-water pressure to review the safety and to estimate settlement of the structure during construction, measurements are made for most rockfill dams.

Sherard(1963) described the relationship between B/H (B = bottom width of core zone and H = height of dam), construction speed , and soil material properties in his report , referring to dams constructed by the U.S. Bureau of Reclamation. Hunter(1970) stated that high pore-water pressures occurred in soils compacted at the positive (+) side (wet side) but decreased when compacted at the negative (-) side (dry side) of optimum moisture content,

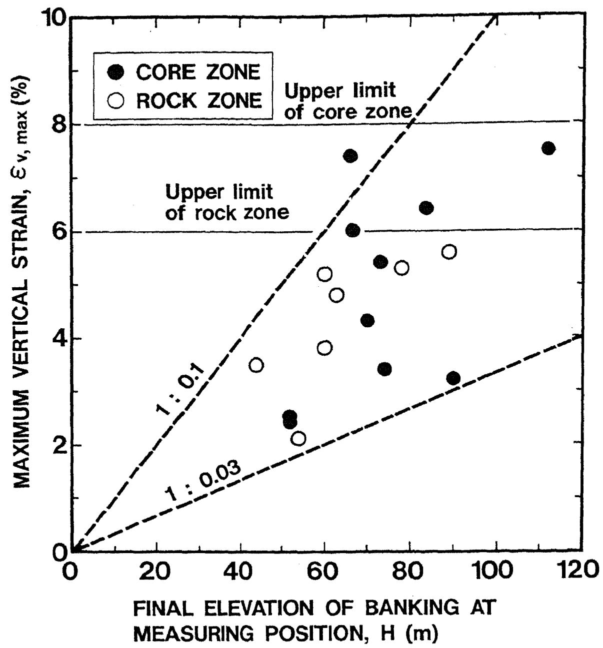

Fig. 6 Relationship between maximum vertical strains and final heights at the location of devices

referring to the data obtained from Blowering Dam. In Japan, Noda (1966) discussed that different tendencies were noted in the variation of pore-water pressure, for the impervious zone and the upstream pervious zone of Motozawa Dam, responding to the changes in the level of reservoir water.

This report will classify the cause of water pressure ,based on the maximum pore-water pressure and their locations when construction was finished completely.

Nineteen rockfill dams with central core under the control of the Ministry of Construction were selected and made available for investigation and analyses.

3.1 Maximum Pore-Water Pressure

Typical uniform pressure distribution diagrams are shown in Fig. 7. The pore-water pressure used here, as a rule, was measured

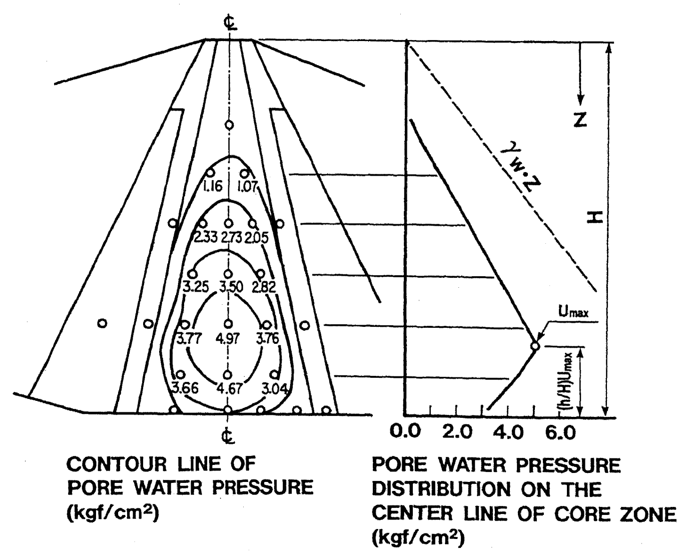

Fig. 7 Distribution of pore-water pressure at core zone

when the construction was finished. However there are some exceptions data of which were measured at start of initial impounding .

The pore-pressure is distributed in a bulb

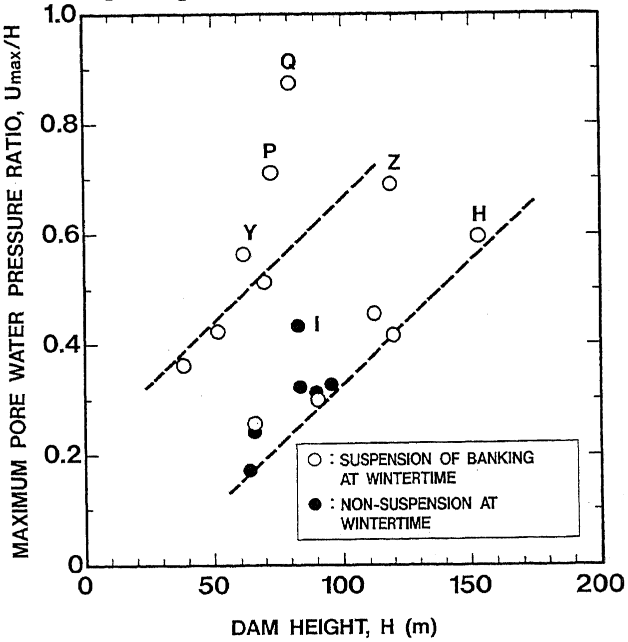

Fig. 8 Relationship between U_{ma}/H and dam height

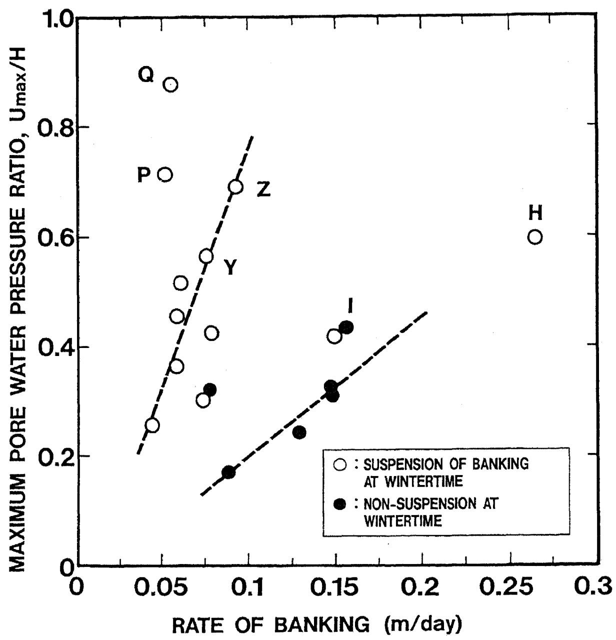

Fig. 9 Relationship between U_{ma} /H and construction speed

form in the core zone. As the pore-water pressure varies at different measuring points, it was considered to be best to pay attention to the maximum value along the center of core zone in this study.

The relationship between maximum pore-water pressure ratio and the height of dams is shown in Fig. 8. The pore-water pressure ratio means here the value of pore-water pressure divided by the height of dam (H) which is expressed by headwater. Different symbols indicate whether the construction is suspended or not during winter season. Symbols also indicate dams, in site of which the ground

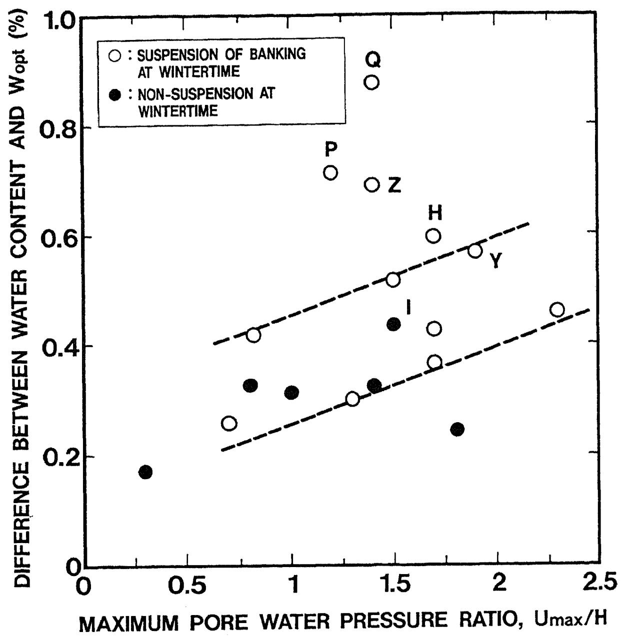

Fig. 10 Relationship of U_{max}/H to difference between actual moisture content

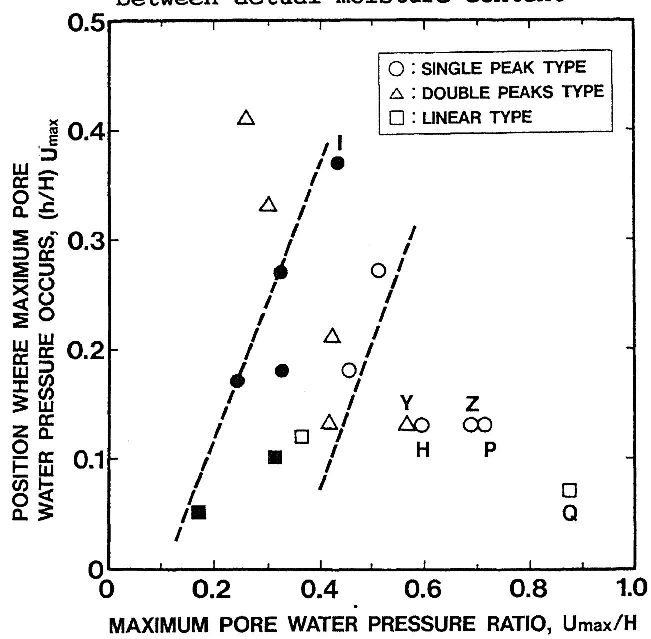

Fig. 11 Relationship between the position of U_{max} and U_{max}/H

water level is high. There was a water pond, the level of which was 40% of the total height of the dam, in an area between the core zone and an upstream coffer dam, before impounding was initiated in "P" Dam. The groundwater level was very high in the sites where "Y", "I", "H", and "Z" Dams were constructed. The most part of core bottoms of "Q", "H", and "Z" Dams were replaced with cement concrete. It can be assumed that the pore-water pressure of these six dams was higher than others, affected by the site conditions described above.

Broken lines roughly show the tendency of pore-water pressure distribution, indicating the situation at six dams where the groundwater level is high, and shows whether or not construction were suspended during winter season. It can be seen from the figure that U_{max}/H tends to become larger as the heights of dams in-

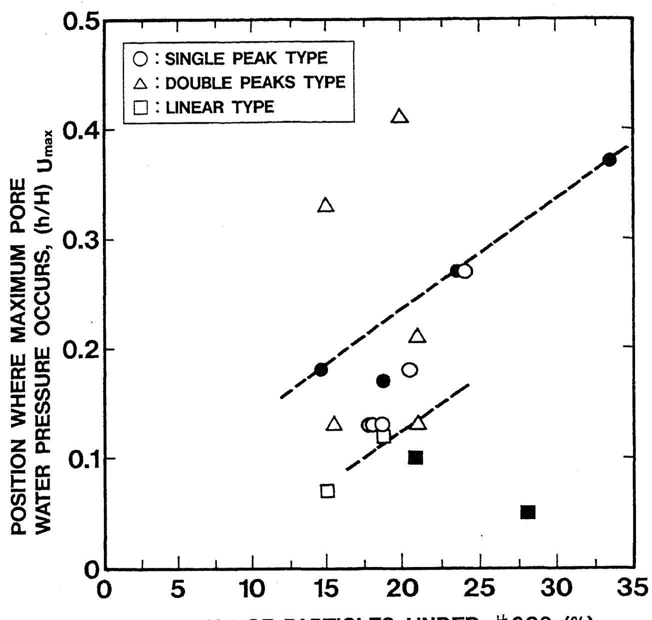

Fig. 12 Relationship between the position of U_{max} and the content of materials passing a #200 sieve

creases. However, the maximum value of U_{max}/H will be approximately 0.5 when such dams with high groundwater level are included.

The relationship between construction speed and U_{max}/H is shown in Fig. 9. The construction speed can be obtained by dividing the height of dam with total calendar days required for the completion of construction. It can be clearly seen from this figure is affected by the suspension of construction in winter season.

Fig. 10 shows the relationship of the differences between actual moisture content during construction and optimum moisture content to U_{max}/H . It appears that U_{max}/H tends to increase as the difference between actual and optimum moisture contents increases, regardless if the construction was suspended or not, except for the six dams ($U_{max}/H > 0.06$) constructed on a sites with high groundwater level.

Analyses were made on various other conditions such as B/H, and the relationship between the content of materials passing a #200 sieve (-#200) and actual moisture content during construction, but there was no significant correlation.

3.2 Maximum Pore-Water Pressure

The relationship between U_{max}/H and locations of maximum pore-water pressure is shown in Fig. 11. The locations of maximum pore-water pressure can be obtained by dividing measured pressure by the height of embankment, in order to indicate it as a proportion of the height. Symbols were selected to show the shape of pore-water pressure distribution, along the center line of the core zone. The shape of distribution can be grouped into three types: a single parabola curve, twin parabola curves, and a straight line. Fig. 7 shows an example of a single parabola curve. The maximum pore-water pressure shown in straight lines is supposed to be caused at the bottom where pore-water pressure gauges were installed. Symbols (○△□) indicate that the constructions were suspended during winter seasons , but symbols (●▲■) indicate that the construction were continuous.

The broken lines in Fig. 11 were drawn to distinguish parabola curves and straight lines, and twin parabola curves for two dams distributed at higher elevation of measuring points. It can be seen from the broken lines that maximum pore-water pressure tends to be distributed at higher measuring points as U_{max}/H increases.

Observing the shape of distribution, the maximum pore-water pressure shown in single parabola curves tends to occur at a point from 0.1 to 0.4 times of the dam height.

The relationship between the locations of maximum pore-water pressure $(h/H)U_{max}$ and the content of -#200 is shown in Fig. 12. The broken lines separately indicate a single parabola curves and straight lines, and two twin parabola curves distributed at higher points. It can be seen that there is a correlation between $(h/H)U_{max}$ and the content of -#200 at dams indicating the single parabola distribution curve , and that maximum pore-water pressure tends to occur at higher points as the content of -200# increases.

As for the height of dam and B/H, maximum pore-water pressure tends to be distributed at higher measuring points as the height of dam decreases and B/H increases.

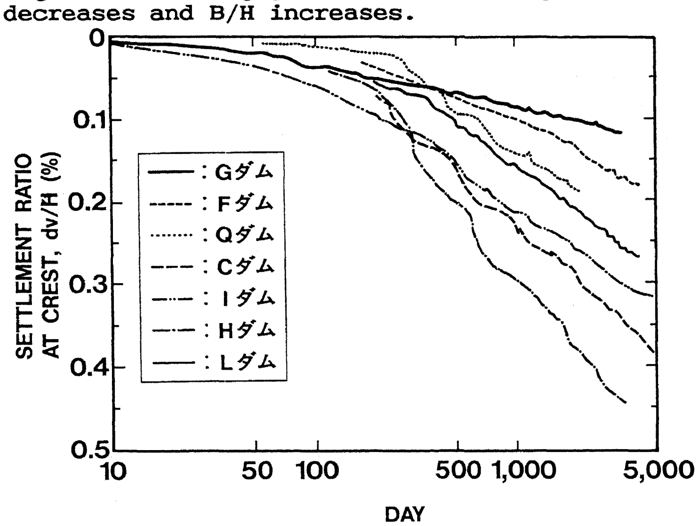

Fig. 13 Secular change of settlement at crest

4. SURFACE MOVEMENT

The settlement of rockfill dams at the crest of the maximum cross section , appearing as most significant surface movement, changes with time as shown in Fig. 13 (Matsumoto et al.(1991)). However, the measurement of settlement is started at most dams when the impounding operation is initiated. Therefore, a few dams have been measured for displacement during the period between the completion of construction and the start of impounding (hereafter "initial time"). This measurement after completion was done for only two, out of the 21 dams investigated in this study. Since settlement is starting at the time of completion, it is necessary to take into consideration the initial settlement to precisely analyze the behaviors of dams.

However, it is not mostly practicable to start measurement at the time of completion, mainly because of the inconveniences of construction at the crest and its vicinity. Even if a non-overflow crest has been completed, the

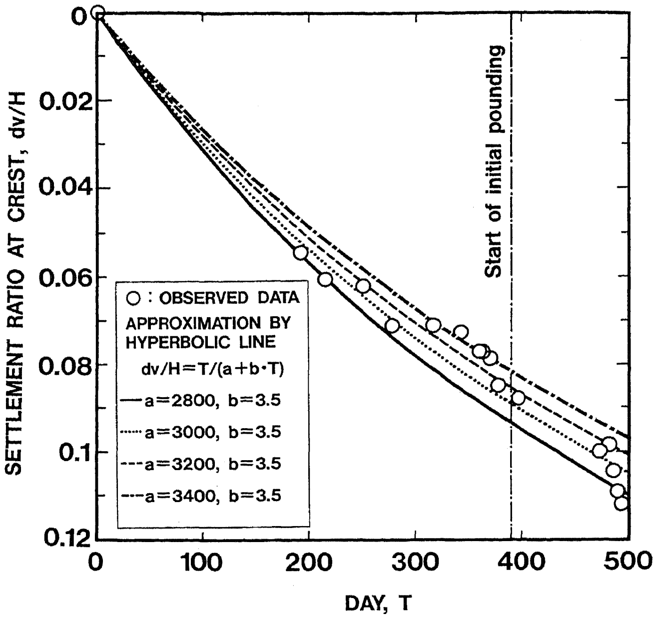

Fig. 14 Hyperbolic approximation of initial settlement

crest surface may have to be paved, or in other cases measurements cannot be made because construction is often suspended in snowy districts during winter seasons.

For this report, the settlement at the crest of the maximum cross section from the time of completion was estimated by correcting the measured settlement.

4.1 Correction of Initial Settlement

Correction of the settlement for the

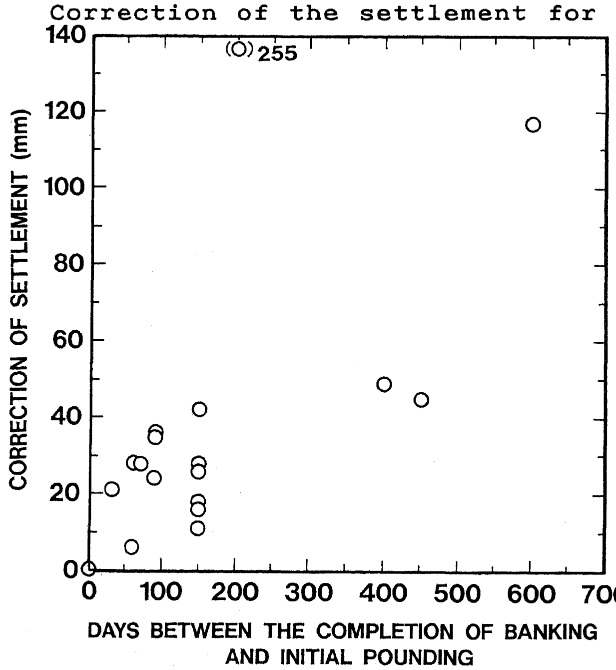

Fig.15 Relationship between initial corrected settlement and initial corrected days

period from the completion of construction to the start of measurement (hereafter "initial settlement") was done referring to observed data of settlement available for the two dams. There are several methods for correcting settlement curves (Matsumoto et al.(1991 b)), however, a hyperbolic curve [dv/H = T/(a + b T)] was used for corrections to simplify the

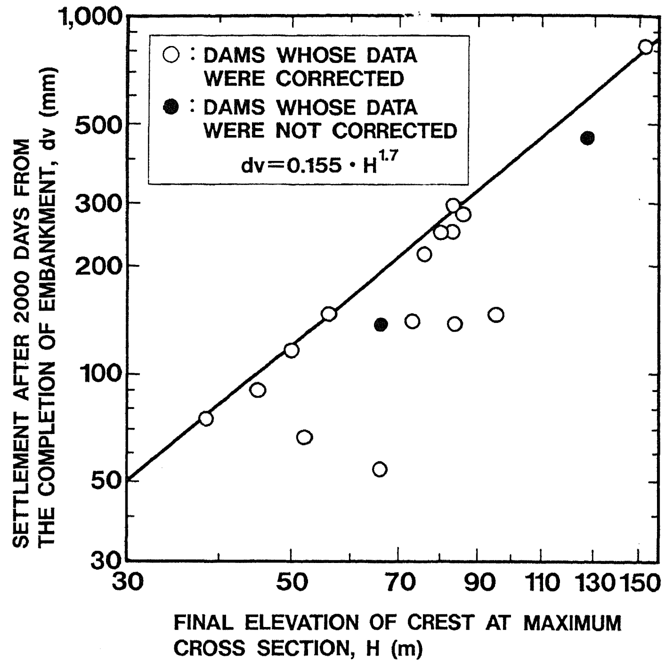

Fig.16 Relationship between settlement after 2,000days from the completion of construction and dam height at the maximum cross section

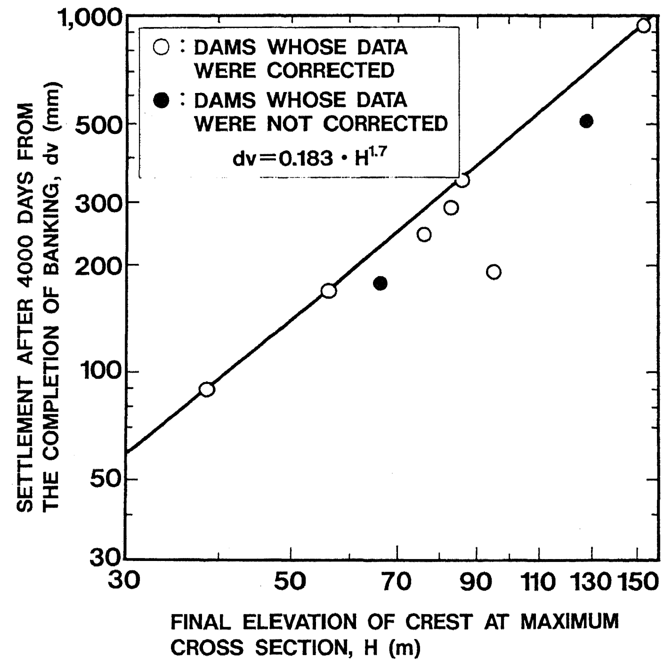

Fig.17 Relationship between settlement after 4,000 days from the completion of construction and dam height at the maximum cross section

processing, because the differences in corrected values of all settlement curves were not so great.

Fig. 14 shows the initial settlement of "L" Dam and the settlement curves approximated to the measured data. The period of approximation shown in the figure is approximately 400 days from the completion of construction to the start of initial impounding. Out of two hyperbolic curve factors, a and b, the common for two dams is factor b and its value is equal to 3.5. Therefore, the factor a which agrees with the measurement was obtained, assuming a with constant b.

Factor a can also be expressed by an exponential function, which correlates closely to the height of dam (H). Initial corrected settlement can be obtained by formula (4).

$$dV_{cr}=\frac{T'\cdot H}{(20{,}130\cdot e^{-0.026H}+3.5\cdot T')} \qquad (4)$$

Where,

dV_{cr} = initial corrected settlement at the crest of maximum cross section

H = final height of dam at the crest of maximum cross section (height of dam in meters)

T' = days required for correction from completion of construction to start of measurement (number of calendar days)

The relationship between the initial settlement corrected by formula (4) and the number of days required for initial correction is shown in Fig. 15. Initial corrected settlement varies widely depending on the final height of dam, but roughly ranges from 10 to 50 mm.

4.2 Estimation of Settlement from the Completion of Construction

Figs. 16 and 17 show the settlement after 2000 and 4000 days from the completion of constructions, corrected by the final height of dams and formula (4). Corrections were not necessary for the dams marked by symbol (●), but corrections were made for the dams marked by symbol
(○).

The formula that estimates the settlement from completion of constructions was obtained in a method similar to our proposed method of estimating the settlement from the starting day of measurement. The relationship between the time lapse from completion and the settlement can be expressed by the exponential power regression formula ($dv = c\ H^d$), factor d was assumed to be 1.7, taken from the average. Factor c of the exponential power regression formula was expressed as a logarithm. The settlement from the completion of construction can be estimated by formula (5).

$$dv=(0.041\cdot l_nT-0.157)H^{1.7} \qquad (5)$$

Where,

dv = settlement at the crest of maximum cross section (mm)

T = day from completion of construction (days)

Bold lines in figures show the settlement obtained by formula (5). It can be seen that the formula envelops the maximum value of all readings.

4.3 Multipliers of H

A simple model is assumed , based on Hooke's law between deflection in the soil and vertical stress. Namely, we obtain the settlement of crest assuming the model is elastic. Two models were assumed, a one-dimensional and a triangle. The elastic coefficient (E) was assumed in two ways, one as a constant, and the other to change with the depth (hereafter "stress function").

Table 1 shows the formulas obtained. As a result, if E is constant, the one-dimensional model is expressed by H^2 and the triangular model is expressed by H^3. If E is stress function, two models are expressed by H^{2-P} and H^{3-P} respectively. The value "P" amounts to nearly 0.7 according to the report by Ogata et al.

Table 1 Equations for presenting settlement

	E=const	$E=K\cdot(\gamma\cdot h)^p$
One dimension	$dv=\frac{\gamma}{2E}\cdot H^2$	$dv=\frac{\gamma^{(1-p)}}{(2-p)\cdot K}\cdot H^{(2-p)}$
Triangle	$dv=\frac{\gamma}{24E}\cdot H^3$	$dv=\frac{\gamma^{(1-p)}}{8\cdot(3-p)\cdot K}\cdot H^{(3-p)}$

(1978). Therefore, it can be assumed that the multiplier of H will be around 1.3 for the one-dimensional model, and 2.3 for the triangular model.

Conversely, the relationship between measured settlement and the height of dams was expressed by H=1.7. It is obvious that deformation and strength of soil material depend on confining stress, and it is understandable that E is expressed by the stress function. Triangular models are considered most suitable for the shape of dams, but the main topic here is the settlement at the crest of the maximum cross section and the core zone. Therefore, it can be assumed that multipliers will descend according to one-dimensional process of consolidation, bounded by the pervious zone, and by the stress transfered by arching action at the core zone. That is, multipliers of H for the settlement at the crest can be expressed by medium values between triangular and one-dimensional models, and it can be determined that the multiplier 1.7 is adequate.

5. CONCLUSION

Surface movement of dams, internal vertical movement, and pore-water pressure in the core zone can be summarized as follows:

Internal vertical movement during construction tends to be as follows.

1 The maximum settlement at measuring points by settlement sensors ranges from 0.5 to 2.0%, but is nearly 1% in the core zone.

2 The ceiling of maximum vertical strain is approximately 8% in the core zone and 6% in the rock zone.

Maximum pore-water pressure at the completion of construction tends to be as shown below:

1 Maximum pore-water pressure, U_{max}/H = 0.5 can be deemed as a yardstick.

2 It was noted that maximum pore-water pressure has correlation with the height of dams, construction speed, and differences between actual moisture content and optimum moisture content (W_{opt}).

3 It was found that maximum pore-water pressure tends to occur at higher measuring points as the content of -#200 increases.

4 Pore-water pressure curves distributed along the center of the core zone can be grouped into the three shapes of a single parabola curve, twin parabola curves and a straight line.

The settlement at the crest after completion of construction can be estimated with the following formula.

$$dv=(0.041\cdot l_nT-0.157)H^{1.7}$$

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