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DEFORMATIONAL BEHAVIOR OF CONCRETE ARCH DAM DUE TO SOLAR HEAT IN A DAY

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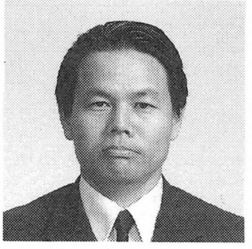
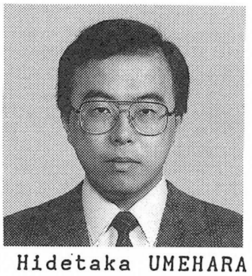
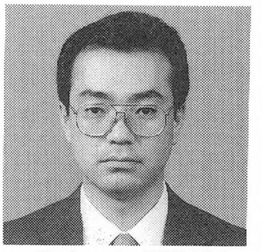

Hirotomo YOSHIDA Tada-aki TANABE Hidetaka UMEHARA Takumi UEHARA

SYNOPSIS

Three dimensional deflections of a concrete arch dam due to solar heat in a daytime on March,July,and November were measured by system consisting of two sets of theodolite with the launcher of a laser and the device which receives the laser. The thermal analysis using finite element method has been conducted to compare the measured deflections and estimate the behavior of arch dam by solar heat. It has been cleared that the obtained results from the thermal analysis estimate the behavior of all over the concrete arch dam with enough accuracy.

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1. INTRODUCTION

It is the most directly method to measure the deformational behavior of large concrete structures such as a dam and so on, for the maintenance of structures. Furthermore, it is very useful and important to return the obtained informations from measurements to designs for rationalizing design methods. The defect in concrete such as cracks decreases the stiffness of structures and causes the change of the deformational behavior in structures. Therefore, it is an effective method for the maintenance of structures to pay attention to the deformational behavior. Authors have studied in order to clarify the behavior of structures by comparing the measured results of deflections in structures due to solar heat with the analyzed results of them [1] .

The measuring system using a laser beam has been developed so as to measure the behavior with great accuracy and simply, and the deformational behaviors of a concrete arch dam due to solar heat in a daytime in November 1985 and 1988 were measured using this system [2] . The deflections were analyzed by using the thermal data such as the surface temperature at the concrete dam and the atmospheric temperature measured in November 1988 [3] . As the result, it is clear that the crest of dam moves several mm under the influence of a difference of the surface temperature between upstream and downstream. It is also clear that the obtained results from the deformational analysis agree with the measured deflections along radial direction of dam and the deflection along radial direction can be estimated from the measurement of the surface temperature at the concrete dam.

Last two measurements were conducted in a clear day in November. However, in this time the mesurement was conducted in Mach 1989, in July 1989 to investigate the deformational behavior of concrete dam in the different weather condition. Futhormore, the influence of different weather condition to the deformational behavior of the dam in a day was analyzed using finite element method and compared with the measured data. Besides, it was tried to estimate the deformational behavior of all over the dam from the analyzed results, because the measurements were conducted at a place of the crest of dam in half a day from sunrise to sunset.

2. RESULTS OF MEASUREMENT OF THE DEFORMATIONAL BEHAVIOR IN A CONCRETE ARCH DAM

2.1 Outline of measuring system

As a measuring apparatus and a measuring system used in this study have been explained in detail in the reference [2] , the outline of the system to measure three-dimensional deflection is briefly explained here. Two sets of theodolite with the launcher of a laser are set in the distance of 50m to 150m away from the structure and the devices which receive the laser are set close to the structure. When the deflection occurs at the structure, the amount of laser beam coming into an object lens in the receiver changes. Therefore, the deflection of the receiver which equals to the deflection of the structure is shown in the indicator as the change of the amount of laser beam. It becomes possible to measure three-dimensional deflection of the structure with 0.5 mm accuracy using two sets of theodolite and receiver. Furthermore, it can measure with 0.1mm accuracy in the best environmental condition.

2.2 Outline of measurement

The three-dimensional deflection of the concrete arch dam was measured to

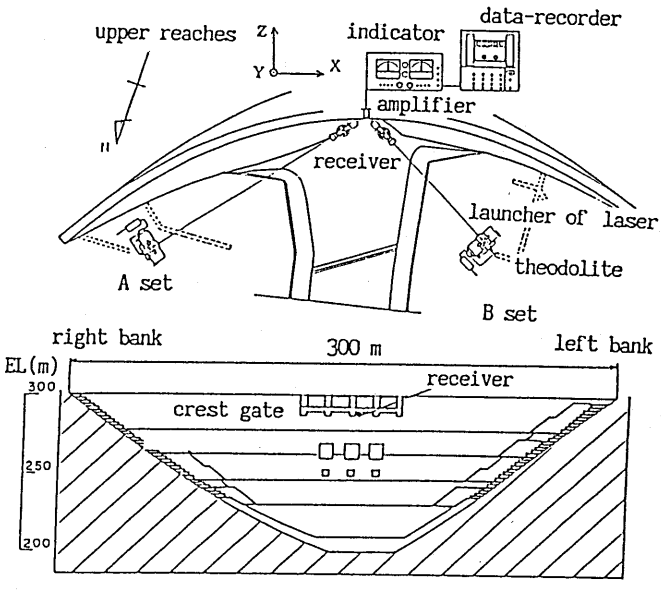

Fig.1 Outline of measurement

clarify the effect of a quantity of solar heat to the deformational behavior of the dam in a daytime, in November 1985 and 1988 in the same season, in March and July 1989 in the different season.

The dam to measure a deflection is a concrete arch dam built in 1971 which is 100m high, has 321.1m crest length and is 300m above sea level. A measuring point is the downstream wall under a gate of dam,and an outline of measuring point is shown in Fig.1. The gate is 16m away from the crest center of the dam to the left river bank and directions of deflection at the measuring point is shown in Fig.1. The deformational behavior, atmospheric temperatures and the surface temperatures of the upstream and downstream concrete, were measured at 30 minutes interval from sunrise to sunset, at one point in 1985, and at 9 points in 1988 and 1989. The surface temperatures of concrete were measured by touching the surface of concrete with the contact type thermometer(a minimal unit is 0.1 ℃).

2.3 Results of mesurement

The water level of the dam lake was about 82m and it was fine in Novenber 1985, about 90m and fine in Novenber 1988, about 79m and fine then cloudy and after then rainy at 3:00p.m. in March 1989, about 87m and cloudy then rainy at 11:30a.m. in July 1989.

The deflections along X, Y, and Z axes at the measuring point in a daytime were obtained by transforming the coordinate of data shown in the indicator. The deflections along X, Y, and Z axes in every measuring time are shown in Fig.2 ～ Fig.5, when the deflection at the beginning of measurement equals to 0. The deformational behavior of the dam in a daytime is discussed by especially considering the influence of solar heat, and the change of solar heat is replaced by the change of surface temperature at the concrete dam. The changes of surface temperature at upstream and downstream concrete in every measuring

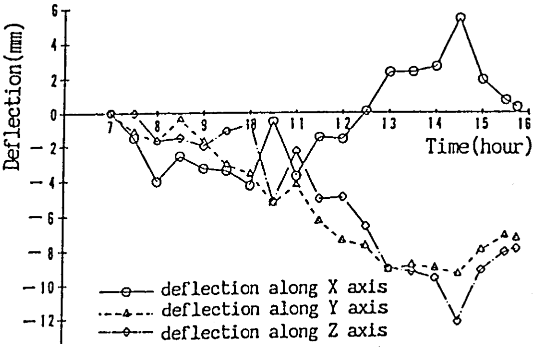

Fig.2 Results of measurement in Nov. 1985

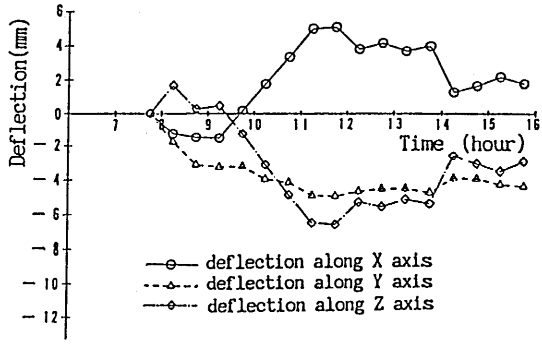

Fig.3 Results of measurement in Nov. 1988

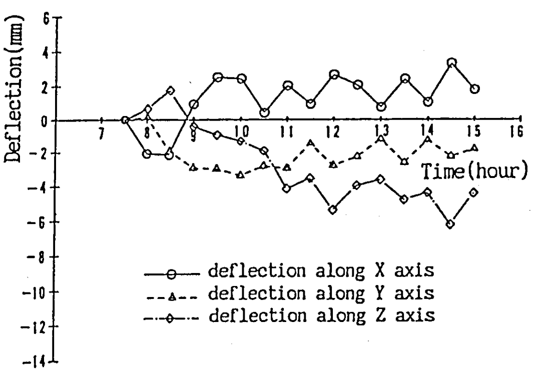

Fig.4 Results of measurement in Mar. 1989

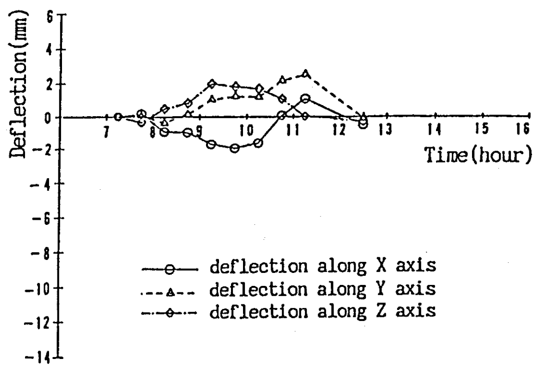

Fig.5 Results of measurement in Jul. 1989

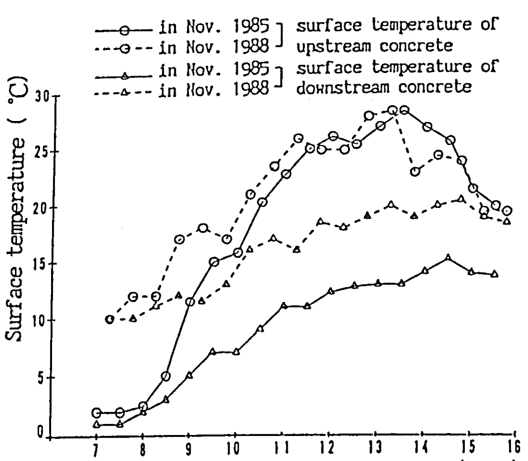

Fig.6 Surface temperature 1

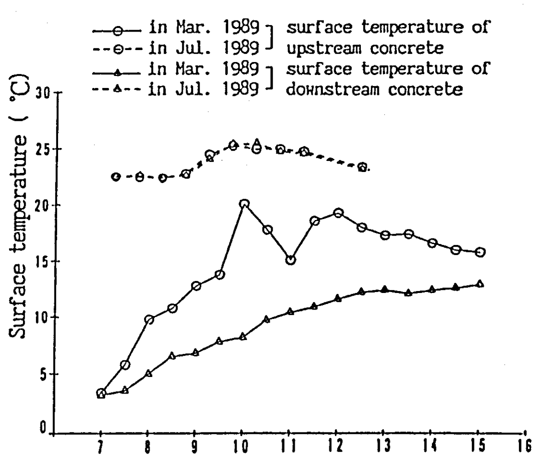

Fig.7 Surface temperature 2

time are shown in Fig.6 and Fig.7. The atmospheric temperature in every measuring time is almost equal to the surface temperature at downstream concrete and the water temperature in the dam lake does not chang due to the weather and solar heat in a daytime, namely constant, which is about 12℃ in November, about 7 ℃ in March, and about 17 ℃ in July.

(a) Tendency of measured results

In November 1985, the deflection along X axis at the crest center of the dam from sunrise to sunset changed about 4mm to the right bank, then turned to the left bank at 0:30p.m., and after then the maximum deflection of 5mm occured. The maximum deflection along Y axis was downward about 9mm, and that along Z axis was downstream about 12mm. All of the deflections along X, Y and Z axes had the maximum at around 2:30p.m..

The deflection in November 1988 had the same tendency as 1985. The deflection along X axis changed about 2mm to the right bank, then turned to the left bank at 9:45a.m., and after then the maximum deflection was about 5mm at 11:30a.m.. The deflection along Y axis was downward about 4mm at 8:45a.m. then kept it. The deflection along Z axis was upstream about 2mm, then turned downstream at 9:30a.m., after then the maximum deflection was about 7mm at 11:45a.m..

The tendency of the deflection in March 1989 was almost same as November 1988. The deflection along X axis changed about 2mm to the right bank, then turned to the left bank at 9:00a.m., and swung from 0.2mm to 2.5mm toward the left bank as time went on. The deflection along Y axis kept to downward about 3mm from 9:00a.m. to 11:00a.m., then the deflection decreased and returned to 0 as time went on. The deflection along Z axis was upstream about 2mm, turned downstream at 9:00a.m., and swung downward from 4mm to 6mm.

There was no solar heat at the measurement in July 1989. The measurement finished at 0:30p.m. caused by rain starting at 11:30a.m.. The deflection along X axis had the same result as other measurements. First, the deflection changed to the right bank, and the maximum deflection was 2mm at 9:45a.m.. Then it turned to the left bank at 10:45a.m., and it became 0 at 0:30p.m.. The deflection along Y axis occured upward, and the maximum was 2.5mm at 11:15a.m.. Then it became 0 at 0:30p.m.. The deflection along Z axis occured upstream and kept constant about 2mm from 9:00a.m. to 10:30a.m.. Then it became 0 at 11:15p.m. and kept constant to 0:30p.m..

The deflections of the dam have been measured 4 times. The deflections along X axis have the same tendency to occur to the right bank and then turn to the left bank. The deflection along Y axis occured downward in March and November, but occured upward in July when there was no solar heat. The deflection along Z axis occured downstream in November and March, but occured upstream in July when there was no solar heat. The tendency of the deflection along each axis is discussed in detail, because it is affected by the weather condition in each measurement.

(b) Deflection along X axis

The deflection along X axis at the crest center of the dam caused by solar heat during a daytime was assumed to be little, because both banks of the dam are fixed by the bedrock. However, the results measured 4 times indicate that the deflection along X axis occured a great deal, as shown in Fig.2~5. There are two reasons as follows; the conditions of sunny place in the left bank concrete or the right bank concrete of the dam are different as time goes on, because the upperstream face of the dam is in the direction of the southeast. Young's modulus of the bedrock in both banks of the dam are different, namely the modulus of the solid rock in the right bank is 2942MPa and that of the solid rock in the left bank is 4903MPa. It is considered that the crest center of the dam moved along the horizontal direction by the influence of the weather condition, such as solar heat, atmospheric temperature, and so on.

The deflections, in November 1985 and 1988, and in March 1989, are influenced by solar heat and atmospheric temperature. First, as the atmospheric temperature went up, the whole dam moved to the right bank whose Young's modulus is smaller. As time went on, sunny places at upper reaches of the dam spread from the left bank to the right bank. Then as the temperature at all over the dam rose, the deflections changed to the left bank. In the afternoon, the deflections returned since solar heat decreased.

The deflection along X axis in July 1989 changed to the right bank with the rise of the atmospheric temperature in the same tendency as last 3 times. However, as there was no solar heat, it turned to the left bank with the drop of the atmospheric temperature from 9:45p.m., and the deflection along X axis was influenced by the change of the atmospheric temperature.

It is considered that the crest center of the concrete arch dam moves to the right bank with the rise of the atmospheric temperature at first, then turns to the left bank with the drop of the atmospheric temperature, because the deflection occurs along the horizontal direction regardless of the solar heat. Furthermore, it is considered that when there is solar heat, the deflection toward the left bank becomes large.

(c) Deflection along Y axis

As shown in Fig.2 ~Fig.5, the deflections along Y axis occured downward in a fine day in November 1985 and 1988, and in March 1989. However, the deflection occured upward in a cloudy day in July 1989. This concrete arch dam has a convex cross section to upper reaches and it seems to be a shape of cantilever fixed at the solid rock on the bottom of the dam. Besides the measuring point is at the downstream surface of the dam. Therefore, it is supposed that the deflection along Y axis was influenced by the deflection along Z axis due to the weather condition more greatly than the change of the weather condition. Namely, the deflection along Y axis changed upward when the deflection along Z axis changed upstream, and it changed downward when the deflection along Z axis changed downstream. It is concluded from the results measured 4 times that the deflection along Y axis is connected with the deflection along Z axis, and is influenced by the deflection along Z axis more greatly than the weather condition.

(d) Deflection along Z axis

When the sun shone on the surface of the upstream concrete, the deflection along Z axis occured downstream in proportion to the difference of surface temperature between the upper reaches and the lower reaches, as shown in Fig.2~ Fig.4. While, it was predicted that few deflection occured when there was no solar heat. However, it was clear from the results of measurement in July 1989 as shown in Fig.5 that when there was no solar heat, the deflection along Z axis occured upstream.

The deflection along Z axis due to the change of the weather condition is discussed by separating the upper layer from all over the dam at the surface of water in the dam lake. When there is solar heat at the upper layer of the dam in a daytime, the deflection at the crest center of the dam occurs downstream, because the increasing rate of surface temperature at the upstream face is larger than that at the downstream face. Incidentally, the surface temperature of upstream concrete at the lower layer is constant, because the lower layer of the dam is under the surface of water. While, the surface temperature at the downstream concrete goes up with the rise of the atmospheric temperature, and the downstream face at the lower layer expands contrary to the behavior of the upper layer, then the lower layer pushes up the upper layer. In this case, the lower layer influences the deflection at the crest center of the dam indirectly. Namely, the change of the surface temperature at the upper reaches is different from that at the lower reaches whether the surface of the upstream concrete is over the surface of water or not. Accordingly, the reverse deflection occurs in a daytime at the upper layer and the lower layer. It is considered that the deflection is influenced by both layers when there is solar heat, and it is influenced by only the lower layer when there is no solar heat.

The difference of the surface temperature between the upstream face and the downstream face is shown in Fig.8, and Fig.9, when the difference at the beginning of measurement equals to 0. The value of temperature is plus when the increasing rate of the upstream surface temperature is higher than that of the downstream. In November 1985 and 1988, and in March 1989, the differences of temperature between the upper layer and the lower layer were large, and the quantity of the difference was nearly equal in every measuring time. However, the obtained results of the deflection along Z axis indicated in proportion to the difference of surface temperature at the upper layer. In the other hand, there was no difference of surface temperature at the upper layer in July, but there was a little difference at the lower layer which was smaller than the differences in other measurements. Comparing with them, the difference of surface temperature at the lower layer was larger than that at the upper layer in July. In this case, the deflection along Z axis indicated in proportion to the difference of the surface temperature at the lower layer. Namely, it is concluded that the deflection along Z axis at the crest center of the dam occured in proportion to the difference of surface temperature at the upper layer concrete when there is solar heat, and in proportion to it at the lower layer when there is no solar heat. The persentage of the influence at the both layers is supposed to be different because of the solar heat, the water level, the thickness of the dam, the internal temperature of the dam, the increasing

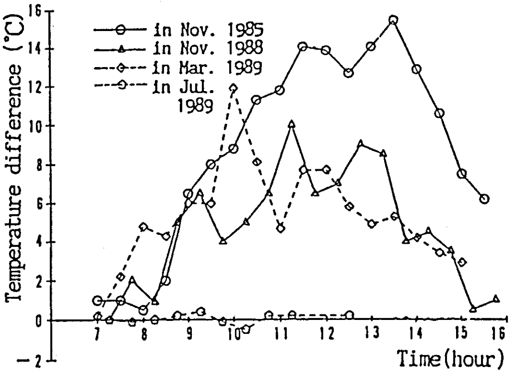

Fig.8 Difference of surface temperature at upper layer

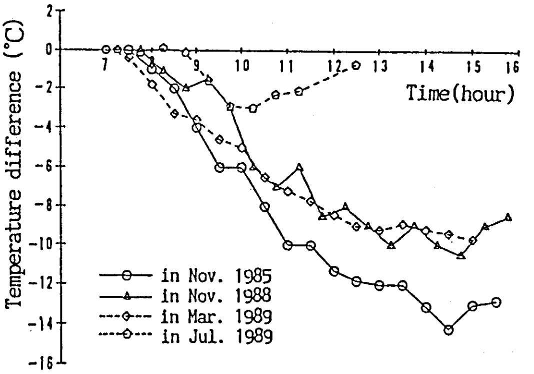

Fig.9 Difference of surface temperature at lower layer

velocity of surface temperature, etc. However, the persentage is not estimated from these mesured results.

From the results measured 4 times, it is clear that the deflection along X axis occurs to the left bank, the deflection along Y axis occurs downward and the deflection along Z axis occurs downstream when there is solar heat,and on the other hand, the deflection along X axis occurs to the right bank, the deflection along Y axis occurs upward and the deflection along Z axis occurs upstream when there is no solar heat. Furthermore, it is clear that the crest center of the concrete arch dam in a daytime moves along the line which connects the right bank at the upper reaches to the left bank at the lawer reaches, and moves upward to the right bank at the upper reaches when there is solar heat, and moves downward to the left bank at the lawer reaches when there is no solar heat.

3. OUTLINE OF ANALYSIS

The deformational behavior of the concrete arch dam was measured 4 times. However, the measuring point was only one and the measuring term was from sunrise to sunnset. It is necessary to measure some points in the dam in order to investigate the deformational behavior of all over the dam, but the investigation has some troubles because of the method and the expense. Therefore, it was attempted to analyze in order to estimate the deformational behavior of all over the dam in a daytime.

The tendency of the analyzed results of the deflection along the z axis in November 1988 nearly agreed with that of the measured results. Thus it may be said that the deformational behavior of all over the dam is estimated by using the deformational analysis based on the data of surface temperature of concrete [3] . In this study, the deformational analysis was improved by considering the vartical slope of the dam. Therefore, the obtained data of surface temperature in March and July 1989 were analyzed, then the analyzed results were compared with the measured results at the measuring point. Furthermore, it was attempted to estimate the deformational behavior of all over the dam.

This analysis is composed of the thermal analysis to calculate the temperature of all over the dam in a daytime, and the deformational analysis to estimate the deflection of the dam using obtained results in the thermal analysis.

3.1 Thermal analysis

In 1988 and 1989, the atmospheric temperature and the surface temperatures at nine points of each upper and lower reaches at the crest of the dam were measured in each mesuring time. However, the distribution of internal temperature of the dam can be obtained to calculate the flow rate of heat from the concrete surface. Therefore, the distribution of internal temperature is estimated by using Schmit's method with one dimensional model which has the measured temperatures at both ends. As the layer thickness of the dam is different with height, the height of the dam is divided into 5 parts as shown in Fig.10. The measured surface temperatures are given for initial data at the 1st. layer. As the downstream surface from the 2nd. layer to the 5th. layer was in the shade, the temperature of it is supposed to be nearly equal to the atmospheric temperature. As the upstream surface from the 2nd. layer to the 5th. layer are under the surface of water, the temperature of it is supposed to be equal to the temperature of water. In this study, the thermal analysis is conducted at 9 points in the 1st. layer and each one point from the 2nd. layer

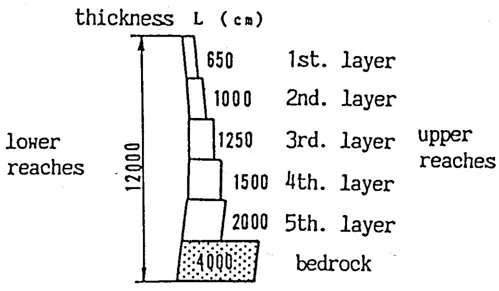

Fig.10 Model for thermal analysis

to the 5th. layer. Considering the thickness of the dam, the internal temperature is controled by the surface temperature for a certain period influenced by the season. Therefore, the initial temperature of internal concrete of the dam is given by considering the average of atomospheric temperature and the water temperature at the measuring time. The distribution of internal temperature of the dam is estimated by the thermal analysis, assuming that the measured surface temperature is constant for several days. Here, the heat conductivity of concrete is assumed to be 2.917W/(m°C).

3.2 The deformational analysis

The laminate model method which is generaly used to analyze concrete floor slabs and shell sturactures is adopted for the deformational analysis. This method is developed from the finite element method and the change of characteristics of material along the deep direction can be considered by dividing a concrete floor slab and a shell sturacture into a small plane-element. Pecknold's element, a quadrilateral shell element with 20 degrees of freedam, was adopted [4]. A node in this element has 5 degrees of freedam; u, v, and w are the deflection along X, Y, and Z axis, respectively. θ_X and θ_Y are the rotation along X and Y axis, respectively. A strain $\{\varepsilon\}$ at the distance z from the middle plane of element is represented as follows,

$$\{\varepsilon\} = \{\varepsilon_0\} + z\{\eta\} \tag{1}$$

Where, $\{\varepsilon_0\}$ is a strain at the middle plane of element and $\{\eta\}$ is a curvature at that place expressed as follows,

$$\{\varepsilon_0\} = [B_1]\{V_1\} \quad (2) \qquad \{\eta\} = [B_2]\{V_2\} \quad (3)$$

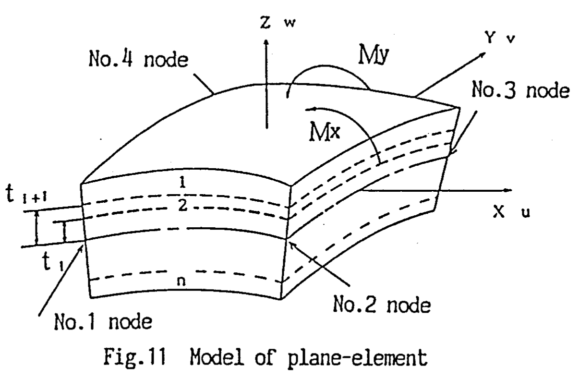

Fig.11 Model of plane-element

Where, $[B_1]$ and $[B_2]$ are matrices which show the relation between deflection and strain, $\{V_1\}$ indicates deflections along X and Y axes at each node, and $\{V_2\}$ indicates a deflection along Z axis and rotations along X and Y axes.

A problem of thermal stress is regarded as a problem of initial strain. The distribution of temperature estimated by the thermal analysis is separated into the increment of temperature at the center of gravity in a element shown by ΔT and the increment of slope along deep direction shown by $\Delta T'$. The increment of initial strain coused by solar heat is written as follows,

$$\{\Delta \varepsilon_0\} = \begin{Bmatrix} \alpha \Delta T \\ \alpha \Delta T \\ 0 \end{Bmatrix} = [B_1] \quad \{V_1\} \tag{4}$$

$$\{\Delta \eta\} = \begin{Bmatrix} \alpha \Delta T' \\ \alpha \Delta T' \\ 0 \end{Bmatrix} = [B_2] \quad \{V_2\} \tag{5}$$

$\{\Delta F_0\}$, which is an increment of nodal force caused by the increment of initial strain in each element, is rewritten as follows, applying the virtual work method,

$$\{\Delta F_0\} = \begin{Bmatrix} \sum_{i=1}^{n} (t_{i+1} - t_i) \int_s [B_1]^T [D] \{\Delta \varepsilon_0\} \, dS \\ + \sum_{i=1}^{n} \frac{1}{2} (t_{i+1}^2 - t_i^2) \int_s [B_1]^T [D] \{\Delta \eta_0\} \, dS \\ \sum_{i=1}^{n} \frac{1}{2} (t_{i+1}^2 - t_i^2) \int_s [B_2]^T [D] \{\Delta \varepsilon_0\} \, dS \\ + \sum_{i=1}^{n} \frac{1}{3} (t_{i+1}^3 - t_i^3) \int_s [B_2]^T [D] \{\Delta \eta_0\} \, dS \end{Bmatrix} \tag{6}$$

$$[D] = \frac{E}{1 - \nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & (1-\nu)/2 \end{bmatrix} \tag{7}$$

Where, [D] is a material matrix, E is Young's modulus of material, and ν is Poisson's ratio. The concrete arch dam is regarded elastic in this method. As shown in Fig.11, t_i is a distance from the middle plane to the top of layer with number i, and the thickness of layer can be changed in each element. The increment of nodal force $\{\Delta F_0\}$ is obtained at all nodal points, this increment is superposed at each node in the whole structure, and finially $\{\Delta U\}$, which is an increment of deflection caused by the temperature, is obtained as follows,

$$\{\Delta U\} = [D]^{-1} \{\Delta F_0\} \tag{8}$$

Where, [K] is a stiffness matrix of the whole structure. The deformational behavior caused by the solar heat is estimated as mentioned above.

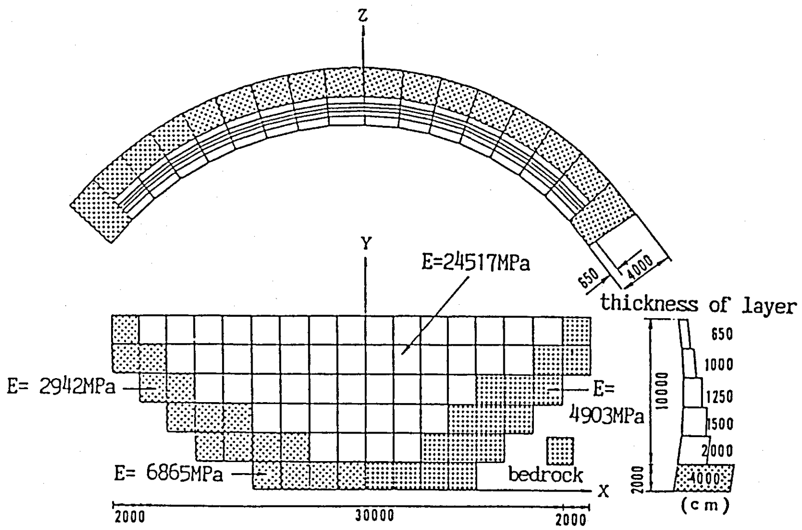

Fig.12 Model for deformational analysis

4. COMPARISION OF ANALYZED RESULTS AND MEASURED RESULTS

4.1 Analytical model and condition

The analytical model is decided considering a shape of the concrete arch dam as shown in Fig.12. This model includes bedrocks considering the influence of them and is a shell model with 105 nodes and 81 elements. It was concluded by the results of thermal analysis that although the internal temperature of concrete in the distance 20cm away from the surface was influenced by the change of surface temperature as time went on, that of concrete in the distance more than 20cm away from the surface was almost constant [3] . Therefore, the increment of internal temperature of each element in every measuring time,(ΔT), and the increment of slope of temperature, (ΔT'), are introduced into the laminate mode method to estimate the deformational behavior in a daytime. Young's modulus of bedrocks and the dam body are obtained from the results of the test at constructing period as follows: the bedrock at the left bank is 4903MPa, the bedrock at the right bank is 2942MPa, the bedrock of the bottom is 6865MPa, and the dam body is 24517MPa. It is assumed that the thermal expansion coefficient is 1×10^{-5}/ ℃ and edges of bedrocks are fixed.

4.2 Comparison of analyzed results and mesured results

The analysis is conducted using the difference of surface temperature shown in Fig.8, and 9. Analyzed results and measured results in March and July 1989, and in November 1988 are shown in Fig.13,14, and 15, respectively. The analyzed values shown in these figures signify the deflections along X, Y, and Z axes at the measuring point.

As Young's modulus of bedrocks at the left bank is different from that at the right bank, the model is unsymmentrical along Y axis. However, very few deflection is developed at the measuring point, as shown in Fig.13～Fig.15. Furthermore, the analyzed deflection along X axis at the place 80m away from the

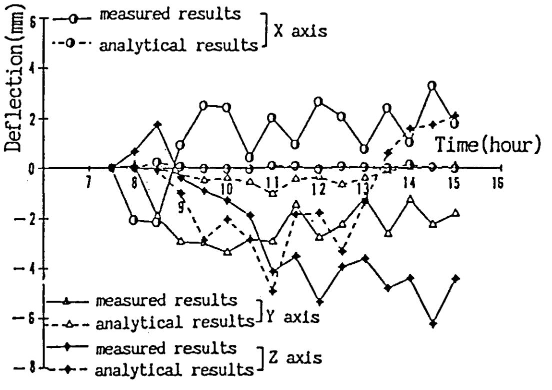

Fig.13 Comparison of measured results with analytical results (in Mar. 1989)

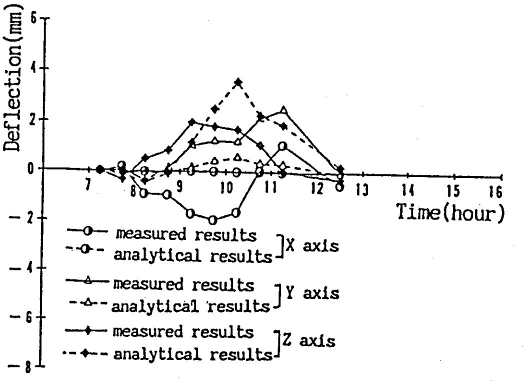

Fig.14 Comparison of measured results with analytical results (in Jul. 1989)

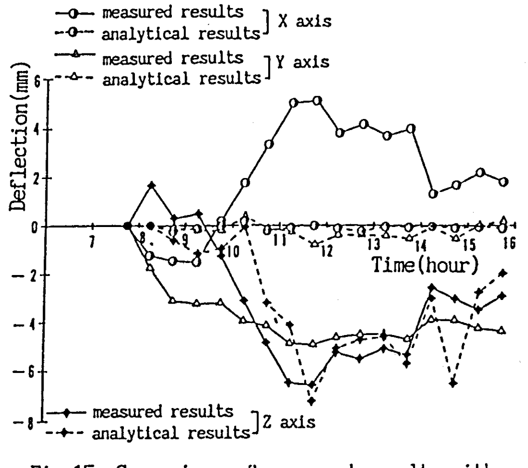

Fig.15 Comparison of measured results with analytical results (in Nov. 1988)

center to the left bank occurs to the positive direction along X axis when the center of dam moves downstream, and it changes to the negative direction when the center moves upstream. While, the deflection at the place 80m away from the center to the right bank occurs to the negative direction along X axis when the center moves downstream, and it changes to the positive direction when it moves upstream. Therefore, the whole dam moves to the center when the deflection of the center occurs downstream, and it moves to both banks when the deflection of the center changes upstream. As the boundary conditions at the banks of dam are unknown, the edges of bedrocks are assumed to be fixed in this analysis. It is considered that the force along X axis is balanced in the vicinity of the measuring point, and the deflection along X axis is few in this case. Therefore, it was attempted to estimate the deflection along X axis at the measuring point by changing boundary conditions. However, it was found that the analyzed deflections along each direction could hardly follow measurement results. In this study, the future problem is to analyze the deflection along X axis at the measuring point, because the boundary conditions at banks of the dam are unknown.

In the case of the deflection along Y axis, the measured maximum values are about -3.5mm in March and about -4.8mm in November, while the analytical values are about -1mm and -0.8mm, respectively. The measured maximum value is about 2.5mm in July, while the analytical value is about 0.5mm. As shown in Fig.13, and 15, the deflection occurs downward when the deflection along Z axis occurs downstream. On the other hand, as shown in Fig.14, it changes upward when the deflection along Z axis changes upstream. It means that the deflection along Y axis is influenced by the deflection along Z axis, as mentioned before. However, it is considered that the analytical value makes a difference from the measured value, because the influence of deflection along Z axis is a little in this analysis. The tendency of the obtained deflection along Y axis in this analysis agrees with that of the measured deflection whether there is solar heat or not. Consequently, it is concluded that the tendency of deflection along Y axis at the crest of dam in a daytime can be estimated using this analysis.

In the case of deflection along Z axis, the values of obtained deflection in this analysis are almost same as those of measured except that the analytical value is different from the measured value from the afternoon in March. The deflection in March and November when there is solar heat shows a tendency in proportion to the difference of surface temperature is at the upper layer, as shown in Fig.8, while it shows a tendency in proportion to the difference of surface temperature at the lower layer in July when there is no solar heat, as shown in Fig.9. As mentioned before, the deflection along Z axis is affected by the upper layer when there is solar heat and affected by the lower layer when there is no solar heat.

The deflections along Z axis at the crest center of dam in March when there is solar heat and in July when there is no solar heat, are analyzed and examined in following three cases; the difference of surface temperature at the upper layer is only used, that at the lower layer is only used, and both of them are used. As shown in Fig.16, when there is solar heat, the crest center of dam moves downstream using only the difference of surface temperature at the upper layer and it moves upstream using only the difference of surface temperature at the lower layer. Namely, the effects of the difference of surface temperature to the deflection at the crest center of dam are different at the upper layer and lower layer when there is solar heat. As shown in Fig.16, it is clear that the deflection along Z axis at the crest center of dam is affected by the difference of surface temperature at the upper layer, since the tendency of

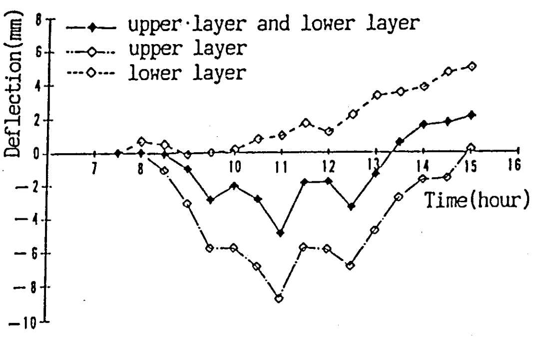

Fig.16 Analyzed deflection along radial direction (in Mar. 1989)

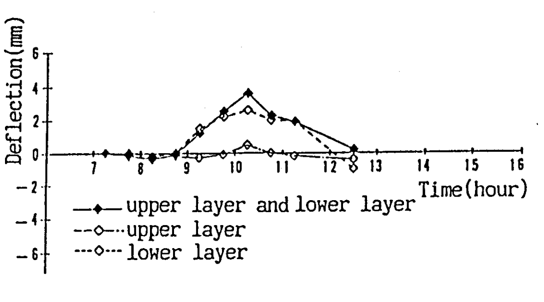

Fig.17 Analyzed deflection along radial direction (in Jul. 1989)

analyzed deflection using both layers is similar to that using only upper layer. The quantity of deflection is almost equal to the total of deflection at the upper layer and the lower layer. It means that the deflection along Z axis at the crest center of dam agrees with the tendency of measured results as mentioned before. Besides, the analyzed results in November indicate similar results in March. On the other hand, in July when there is no solar heat as shown in Fig.17, the crest center of dam does not move using only the difference of surface temperature at the upper layer. However, it moves upward using only the difference of surface temperature at the lower layer. It means that the deflection along Z axis at the crest center of dam is affected by the difference of the surface temperature at the lower layer, when there is no solar heat. The tendency of analyzed deflection using both layers is similar to that using only lower layer. It agrees with the tendency of measured results as mentioned before. Consequently, it becomes possible to estimate the tendency of the deformational behavior of dam, whether there is solar heat or not, in the analysis using the difference of surface temperature between the upper layer and the lower layer.

From the analyzed results above, it may say that the deflection along Z axis and the tendency of the deflection along Y axis can be estimated by measuring the surface temperature at the upstream and downstream of the dam, the water level in the dam lake, the temperature of water, and the atmospheric temperature, and analyzing the internal temperature of dam. Furthermore, it may be possible to predict the deformational behavior of all over the dam by combining the measurement and the analysis.

The deflections on the same level at the crest of dam and the deflections of the cross section at the center of dam containing measering point are shown in Fig.18. The bold lines in the figure express a form of the dam at beginning time

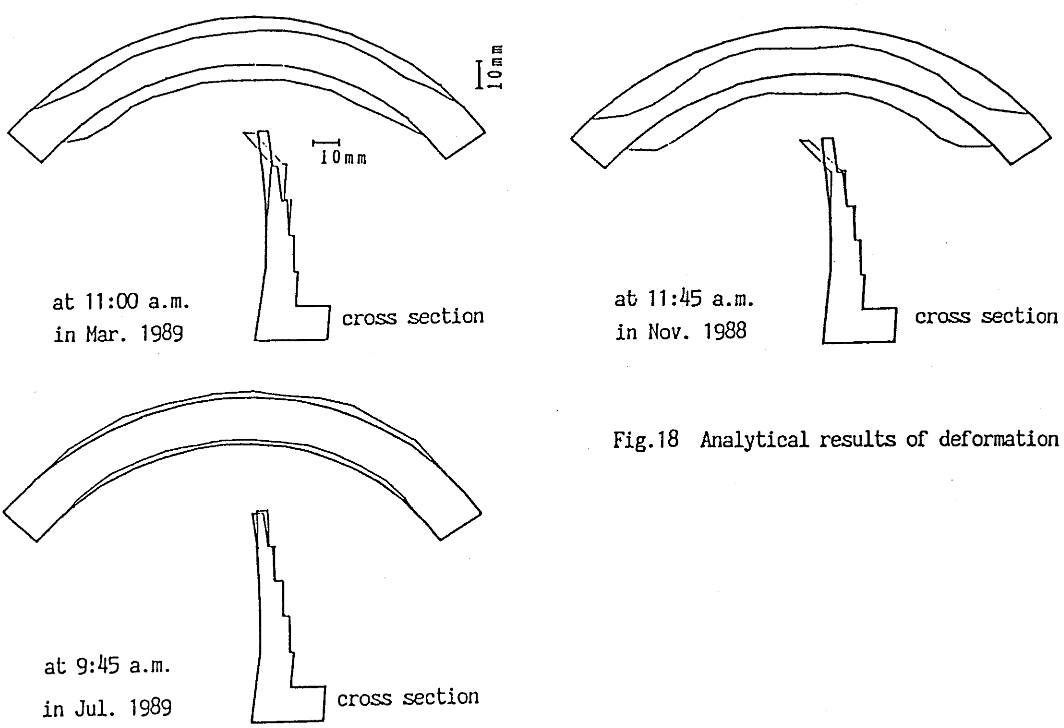

Fig.18 Analytical results of deformation

of measurement, and the fine lines express a deformation. When there is solar heat in March and in November, the crest of dam moves downstream. The deflection at the place near both banks is larger than that at the crest center of dam, because the shape of dam is convex and both banks are fixed. Furthermore, it is found that the upper layer moves in the opposite direction to the deflection occured at the lower layer, when there is solar heat, from the obtained deflection of the cross section at the center of dam. While, in July when there is no solar heat, all over the dam push out upstream, and it is observed that the deflection occurs at the upper layer, and does not occur at the lower layer.

5. CONCLUSIONS

Deformational behaviors at the crest center of the concrete arch dam in a daytime in March, in July, and in November, were measured by the system using laser beams, and it was discussed on the influence of weather condition to the deflections of dam. Furthermore, the measured results were composed with the analytical results using the laminate model method. Then, it was attemped to estimate deformational behaviors of all over the dam in a daytime. From the foregoing study, the following conclusions are obtained.

(1) The deflection along X axis at the crest center of the concrete arch dam occured to the right bank with the rise of atmospheric temperature, then turened to the left bank with the drop of atmospheric temperature, and the maximum deflection was about 6mm to the right bank.
(2) It is found that the deflection along Y axis at the crest center of the concrete arch dam is influenced by the deflection along Z axis. Namely, the deflection along Y axis changed downwared when the deflection along Z axis changed downstream, and the maximum deflection was about 8mm. In the other hand, it changed upwared when the deflection along Z axis changed upstream, and the maximum deflection was about 2mm.
(3) It is found that the deflection along Z axis at the crest center of the concrete arch dam occurred in proportion to the difference of surface temperature at the upper layer when there is solar heat, and in proportion to it at the lower layer when there is no solar heat. Namely, the deflection along Z axis occured downstream and the maximum deflection was about 12mm when there was solar heat. It occured upstream and the maximum was about 2mm when there was no solar heat.
(4) The analytical results of the deflection along Z axis at the crest center of dam are almost same as the measured results, and the tendency of analyzed deflection along Y axis agrees with that of the measured deflection. From the analyzed results above, it is concluded that the deflection at the crest center of dam is affected by the difference of surface temperature at the upper layer when there is solar heat, and by the difference of surface temperature at the lower layer when there is no solar heat. Consequently, it may be possible to estimate deformational behaviors of all over the dam by using the analysis based on the data of surface temperature of dam in the measurement, whether there is solar heat or not.

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