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THE STATIC BEHAVIORS AND NUMERICAL PREDICTION ON DISPLACEMENT OF AN EXISTING ARCH DAM

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In order to estimate the seismic safety of existing arch dams, it is essential to assess the static behavior and the mechanical resistance of arch dam. Numerical analysis model for transverse joints (contraction joints) of the arch dam is developed considering the separation, sliding and re-contact behaviors of contraction joints. The static behaviors of an arch dam under annual change of temperature and water level were calculated by using non-linear three-dimensional finite element analysis method that incorporated the developed numerical analysis model of contraction joints. The displacement of the dam body was compared both in analysis and in measured data. At a result, the calculated results can give a good estimation for dam deformation of an existing arch dam caused by those loads. In addition, the effective arch zone was formed under consecutive contraction joints. Thus, the nature of load capacity mechanism was identified. Using these calculated results, the numerical prediction on the displacement of an existing arch dam was proposed for daily management.

Keywords: Contraction joint, Finite element analysis, Numerical prediction.

1 INTRODUCTION

Arch dams are usually constructed as cantilever monoliths separated by transverse joints (contraction joints). From our numerical and experimental study (Nishiuchi and Sakata 2006), it is found that some of the contraction joints open near the surface of an existing arch dam. Therefore, it is expected that the contraction joints may open (separation), slide and close (re-contact) through an annual thermal load (expansion and shrinkage), several cycles of vibration during an earthquake, affecting the transfer of internal forces between the arches and cantilevers. Despite the possibility of contraction joint's behavior, it is impossible to simulate the non-linearity on joint by standard linear analysis procedures, which assume that a dam is a monolithic structure and the behavior is linearly elastic. This makes it indispensable to develop a newly analysis procedure for computing an annual static and the dynamic response of arch dams including the non-linear effects of contraction joint opening, sliding and closing. The non-linear analysis procedure specifically addresses the redistribution of forces that occur in arch dams, when the contraction joints open and slide, close in response to annual static loads and earthquake ground motion.

2 OBJECTIVES

The objectives of this study are as follows:

(1) To examine the effects of contraction joint's behavior and load capacity mechanism on annual static loads in arch dams.

(2) To validate the applicability of the newly developed analysis procedure to predict the displacement in a typical arch dam.

3 METHOD OF THE ANALYSIS PROCEDURE

3.1 Finite Element Model of an Arch Dam

The finite element model of an existing arch dam has a 133m high and crest length of 276m, almost perfectly symmetric doubly curved arch. The dam consists of 20 monolith cantilevers separated by contraction joints.

Figure 1 shows the finite element mesh pattern. The region of dam-foundation rock was modeled by 8 node isoparametric solid elements. The fine mesh pattern through the thickness in the stream direction was used near the surface of the dam body, while coarse mesh pattern was used in the internal portion of the dam body. The contraction joints were modeled by three-dimensional non-linear elements. Specifying appropriate properties for the joint elements controlled the non-linearity of the contraction joints in the model. More details about the joint elements are given in the next section.

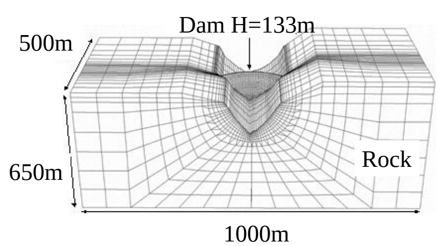


Figure 1. Finite element model of an existing arch dam.

3.2 Numerical Modeling of Contraction Joint

Figure 2 shows the basic concept of contraction joint's numerical modeling in an arch dam. The technical ground of contraction joint's numerical modeling is presented other thesis (Nishiuchi and Sakata 2006). To clarify the failure criterion at the joint element, the shear-slipping test was carried out. Based on the test results, the failure criterion at the joint element was decided as shown in Figure 2. The stress-strain relationship at the joint element is shown in Figure 3.

3.3 Conditions of the Numerical Simulation

Using three-dimensional finite element mesh, non-linear static analysis (FEM) was carried out. In FEM analysis, the structural analysis code "ABAQUS" was used and non-linear behaviors at contraction joints were considered.

The static loads are self-weight, hydrostatic pressure, thermal load and uplift pressure. The water level of hydrostatic pressure is from low water level to high water level as about 45m heights. The thermal load is an annual change of air temperature and reservoir temperature (Figure 4). The uplift is triangular distribution according to water level (zero to one-third).

The material properties for the analyses are shown in Table 1. For analyses, the concrete and rock elements were assumed to be linearly elastic.

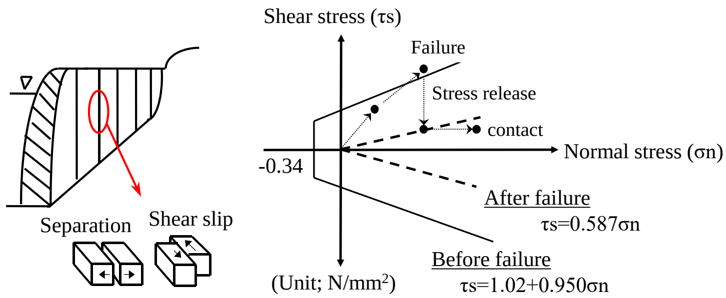
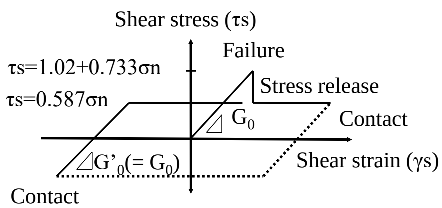
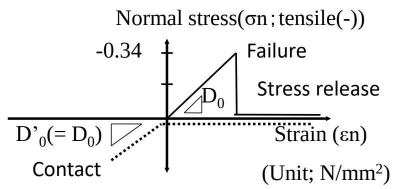


Figure 2. Characteristics of contraction joints behaviors in an arch dam.

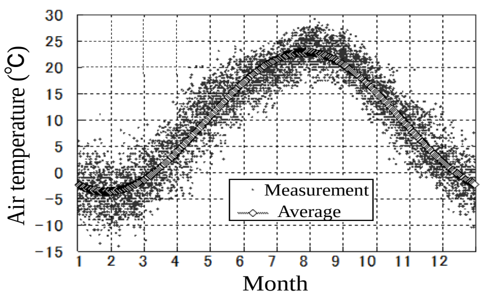


(a) Shear stress-strain relationship.

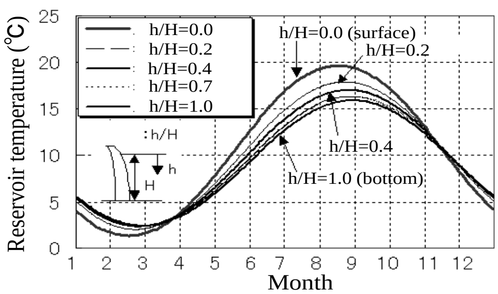


(b) Normal stress-strain relationship.

Figure 3. Stress-strain relationship at joint element in an arch dam.



(a) Air temperature.



(b) Reservoir temperature.

Figure 4. The annual change of air temperature and reservoir temperature in analysis.

Table 1. Material properties.

	Concrete	Joint	Rock
Young's modulus (MPa)	30000	9000	7000
Poisson’s ratio	0.2	0.2	0.2

4 STATIC BEHAVIORS OF AN EXISTING ARCH DAM

4.1 In-situ Measurement of an Arch Dam

To verify the performance of non-linear joint model, we carried out analytical estimation of an existing arch dam. On this dam, the displacement of crown cantilever was measured in every week. The location of measurement instruments (plumb line) is showed in Figure 5.

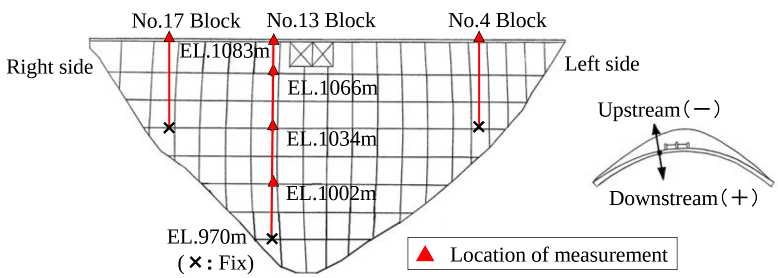


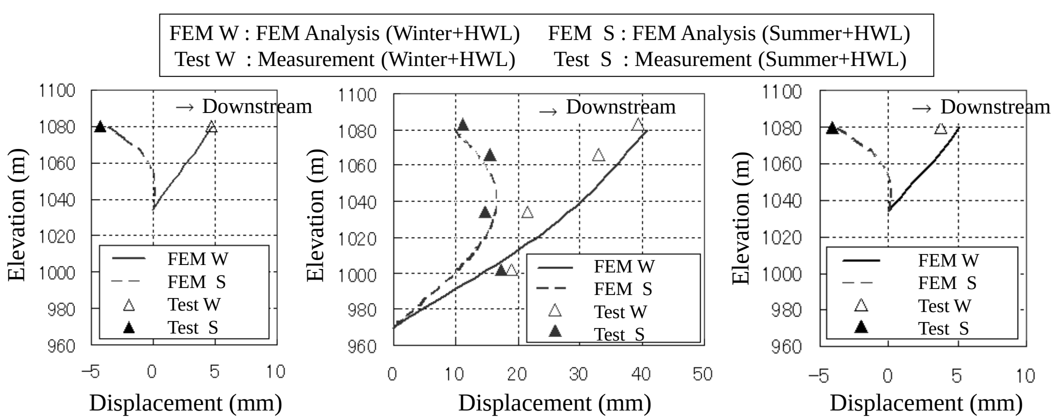
Figure 5. The measurement instruments (plumb line) of displacement.

4.2 Numerical Predict Method on Displacement of Crown Cantilever

At the point of annual maintenance and management, it is important to know the actual condition of the arch dam, for example, stress, displacement, and deformation etc. In these conditions, the displacement is easy to measure as daily or weekly use. To measure the displacement is one of the duties on the high arch dam in Japan, so it is done in actual.

To develop the prediction method of displacement, first step, the validity of non-linear analysis is estimated, through as compared to measurement data. After that, the prediction method of displacement was developed, combined several calculated results of load conditions.

Figure 6 shows the effect of the thermal load at cantilever displacement between calculated result and measurement data. The condition of water level is high and thermal loads are winter (20 Feb.) and summer (20 Aug.).



(a) No.17 Block. (b) No.13 Block. (c) No.4 Block.

Figure 6. The cantilever displacement between analysis and measurement (effect of thermal load).

The top of crown cantilever moves to downstream in winter and moves to upstream in summer, relatively. These movements are affected by thermal stress. In winter, the temperature of inner dam becomes cool, so thermal stress as arch compression decreases. The effect of decreasing arch compression, dam moves to downstream.

Figure 7 shows the effect of the water level at cantilever displacement between calculated result and measurement data. The condition of thermal load is in winter (20 Feb.) and the water level is high (HWL) and low (LWL). The displacement of No.4 and No.17 are smaller than that of No.13. The data of No.13 seems to move sensitive. On the annual management of displacement, this measure point is good as typical location.

The typical location of measurement was decided as the crown cantilever at No.13. For example, Figure 8 shows the prediction of displacement at No.13 (EL.1066m). In this figure, both the predicted result and the actual measurement data are showed.

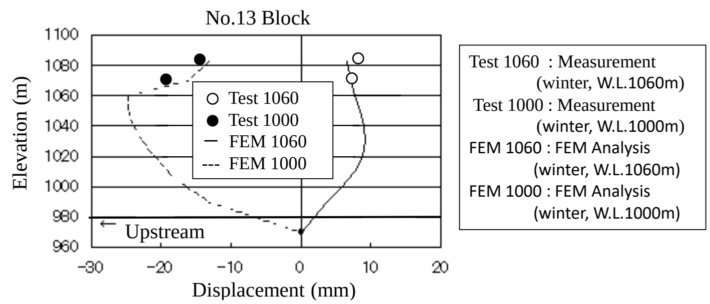


Figure 7. The cantilever displacement between analysis and measurement (effect of water level).

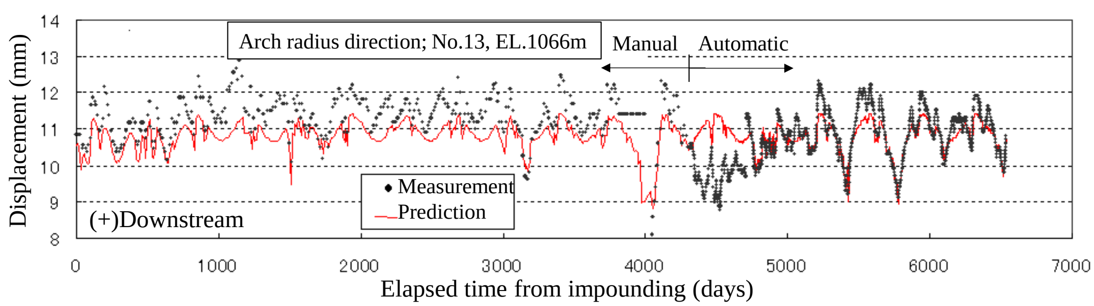


Figure 8. The comparison of crown cantilever displacement between analysis and measurement.

Eq. (1) shows the prediction curve of displacement at No.13 (EL.1066m). To make the prediction curve, several functions toward the response of load fluctuation, the hydrostatic pressure (water level) and the thermal load, are used. The response of displacement, which affected the water level and thermal load, are already calculated in FEM analysis. The effect of thermal load is shown in Figure 6 and the effect of water level is shown in Figure 7. These effects are combined in Eq. (1).

$$Disp = A \cdot \sin\frac{2\pi T}{365} + B \cdot \cos\frac{2\pi T}{365} + C \cdot H^3 + D \cdot H^2 + E \cdot H + F \tag{1}$$

where, $Disp$: Displacement at No.13.EL.1066m (mm), T : Elapsed time from impounding (days), H : Water level of difference from LWL 1035m (m), $A \sim F$: Regression coefficient, and $A = 0.34$, $B = -0.12$, $C = -2.52\times10^{-5}$, $D = 7.51\times10^{-4}$, $E = 5.47\times10^{-2}$, $F = 9.28$.

In Figure 8, for the most part, the trend curve of prediction results agrees with the measurement data. The past 4,000 days, the measurement instruments were manually operated, so the human error may be happening.

4.3 Contraction Joints Behaviors and Load Capacity Mechanism

Figure 9 shows the conditions of contraction joints. In winter, many joints of downstream surface separate which are affected by cool temperature. In summer, many joints close. Affecting the joint's conditions, the consecutive zone in cross-section of the dam body changes depending on annual temperature and water level. This consecutive zone transfers the arch compressive stress effectively. The formation of effective arch stress transfer zone is the load capacity mechanism of the arch dam.

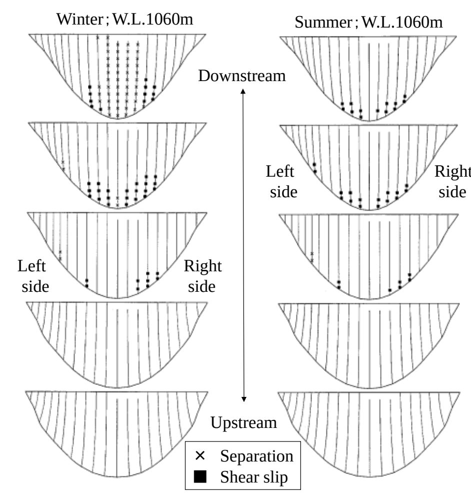


Figure 9. The conditions of contraction joints and the arch resistance zone.

5 CONCLUSION

In order to estimate the load capacity mechanism on annual static loads in the arch dam and validate the applicability of prediction method of deformation of the arch dam, the non-linear FEM analysis was carried out. The conclusions obtained from this study are as follows:

(1) Effect on the contraction joint's behavior: the consecutive zone which transfer the arch compressive stress is formed. The formation of effective arch stress transfer zone is the load capacity mechanism of the arch dam.

(2) The prediction method of arch dam's deformation is suitable and agrees with the measurement data according as the change of an annual temperature and water level.

References

Nishiuchi, T., and Sakata, K., Investigation on Static Behavior of Existing Arch Dams Using Finite Element Method Considering Nonlinear Behavior of Transverse Joints, *Journal of JSCE, Division E,* Vol.62, No.4, pp.672-688, October, 2006.