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DYNAMIC ANALYSIS OF AN EXISTING ARCH DAM INCLUDING JOINT NON-LINEARITY AND DAM-WATER-FOUNDATION ROCK INTERACTION

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SUMMARY

This paper presents the experimental and finite element studies on the effects of reservoir water level on the dynamic response of the existing arch dam. The measured dynamic properties are compared to predictions from finite element models, for which the discontinuities due to the nonlinear behavior of the vertical contraction joints are both included and neglected. The computed results demonstrate that the observed variation of the frequencies was attributed to a modification in the arch stiffness due to the nonlinear effect of the joints. Furthermore, the joint opening effects on dynamic response of the arch dam will be discussed.

INTRODUCTION

Although concrete dams are regarded as safe structures during earthquakes, it is necessary to evaluate the seismic performance of designed and existing dams. Arch dams are typically constructed as cantilever monoliths separated by vertical contraction joints, and the opening of contraction joints affects the seismic response of arch dams in several ways (Dowling et al.[1]; Hall[2]). The monolith joint opening causes reduction in the arch action forces and the internal forces are redistributed to the cantilever bending. The loss of arch stiffness lengthens the vibration periods of the dam, possibly shifting them into different parts of the ground-motion spectrum and changing the maximum response. Therefore, in order to evaluate the earthquake safety of arch dams, it is essential to develop reliable analytical procedures for computing earthquake response of arch dams including the nonlinear effects of the contraction joint opening.

The importance of the joint-opening mechanism has motivated several experimental research efforts. Niwa and Clough[3] conducted a shaking-table study on the monolith joint mechanism in arch dams by using a segmented arch rib model. They showed that the mechanism limits the development of tensile

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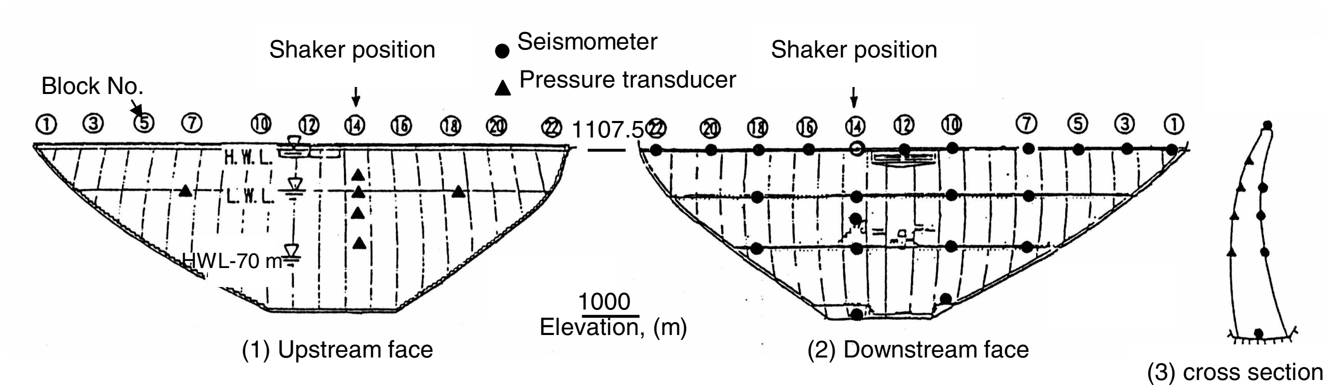

Figure 1 Experimental set-up and reservoir water level during vibration

stress in the arch direction, and greatly influences the dynamic response behavior, mainly due to changing the period of vibration of the structure. Darbre et al.[4] carried out ambient vibration tests of the 250m-high arch dam, with particular attention paid to the variation of the resonant frequencies with changes in the water level. They observed that the resonance frequencies initially increase with rising water level and then decrease with a further rise. The explanation offered for the observed variation was that the combined effects of increasing added mass of water and closing of the vertical contraction joints. The similar experimental results were also obtained from forced vibration tests on two arch dams located in the European Alps (Proulx et al.[5]).

Analytical studies on the effects of contraction joint opening have been conducted in recent years. These studies are still in the research and development phase and are not yet ready for practical application. In the most sophisticated work to date, an efficient analytical procedure, including joint opening effects, was developed by implementation of a nonlinear joint element in the computer program ADAP-88 (Fenves et al.[6]). The seismic response analysis of Pacoima Dam subjected 1994 Northridge Earthquake was conducted by using the computer program, and the computed results corresponded with the recorded time histories of the dam with sufficient accuracy (Mojtahedi and Fenves[7]). However, because of the employment of the simplified representation of the foundation rock and the reservoir water, a very high value was assigned for the damping ratio of their model. Though a considerable amount of research on dynamic response of arch dams has been conducted, only a limited number of well-documented correlation studies with particular reference to the joint nonlinearities are available.

The objectives of this study are (1) to validate the applicability of a newly developed computer program for the earthquake response of arch dams, including both the effects of dam-water-foundation rock interaction and the nonlinear behavior of the contraction joints; (2) to examine the effects of the contraction joint opening on the dynamic response of an existing arch dam.

DESCRIPTION OF THE EXISTING ARCH DAM

The existing arch dam selected for this study has a relatively thick, triple-curvature body. It is located on a narrow canyon in the seismically active mountain range in the middle part of Japan, and completed in October 1992. Figure 1 shows upstream and down stream view of the dam with the experimental set-up, together with the cross section at block 14. The dam consists of 22 monolith cantilevers separated by vertical contraction joints. The first reservoir filling took place after completion of the dam, and it had a full reservoir condition in December 1994. This large variation in the water level is an important feature of this study as it permits a clear identification of the influence of the water level on the dynamic properties of the dam.

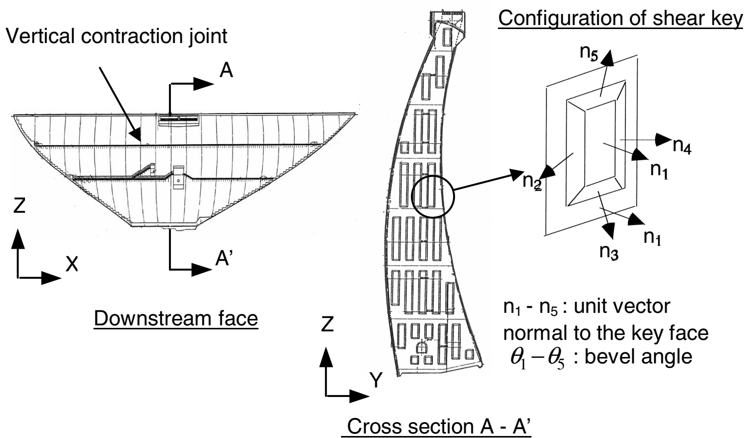

Figure 2 Plane of vertical contraction joint and Configuration of shear key

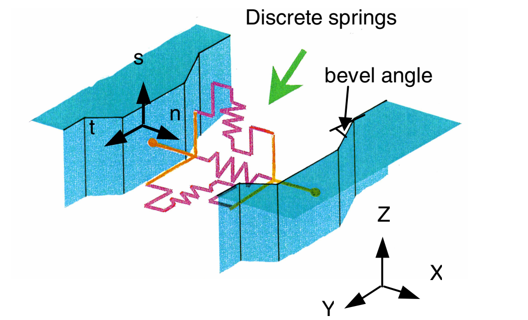

Figure 3 Representation of joint behavior by discrete springs

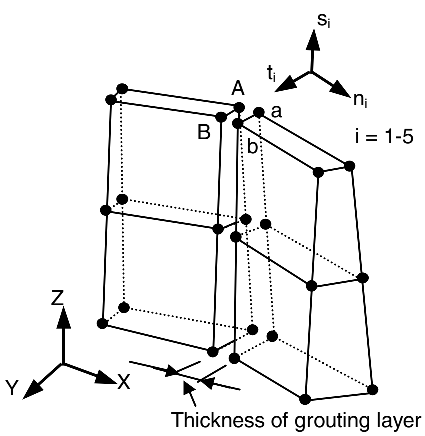

Figure 4 Joint plane at solid element intersection

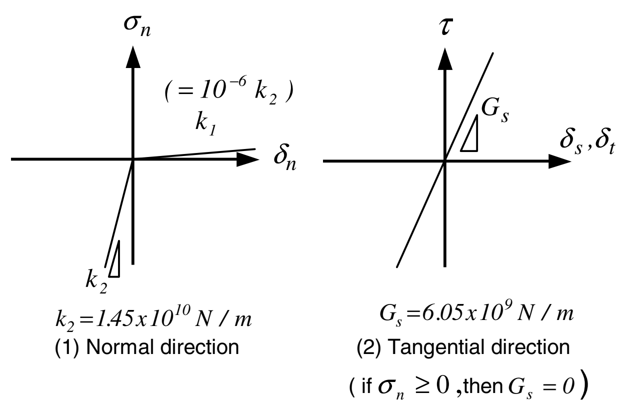

Figure 5 Resistance force – Relative displacement relationship of discrete spring

DESCRIPTION OF IN-SITE TESTS

A series of forced vibration tests were conducted during 1993-1994; the data were obtained at first in November 1993 when the water level was 70m below the crest and two times during October-December 1994 for water levels 26.5m below the crest and full reservoir. During the forced vibration tests, the responses of the horizontal displacement and hydrodynamic pressure were recorded while the dam was subjected to a harmonic load, generated by two eccentric mass shakers mounted on the dam crest at block 14 (see Figure 1). In addition to the experimental program of the forced-vibrations, the ambient vibration tests were also carried out with the instruments already in place. Both test results will be presented in the later section, together with the computed results.

FINITE ELEMENT MODEL OF THE ARCH DAM

Nonlinear Joint Element

Each of all the contraction joint faces has build-in shear keys with beveled geometry, as shown in Figure 2. In this study, the discontinuous behavior at the contraction joints has been modeled by connecting

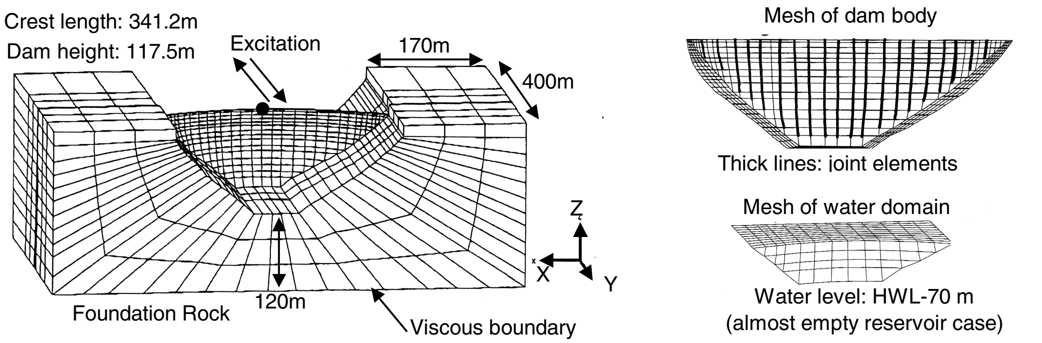

Figure 6 Finite element model of the dam-water-foundation rock system

Table 1 Material properties for analyses

	Elastic wave speed (m/sec)	Dynamic modulus of elasticity (GPa)	Poisson's ratio	Density (kg/m^3)	Damping factor (%)
Dam	2.46 x 10^3	37.24	0.20	2.5x10^3	1.0
Foundation rock	1.70 x 10^3	18.03	0.25	2.5x10^3	1.0
Reservoir	Pressure wave speed (m/sec)		1.4 x 10^3		
	Impedance ratio		5.3 (bottom and sides), 1.0 (upstream end)		

finite element nodes with each other by discrete spring elements, which consists of a pair of nonlinear spring elements normal and tangential to the key face (see Figure 3). The element develops resisting forces due to relative displacement, but it does not develop inertial or damping forces. The relative nodal displacement "δ" can be expressed as differences between the double nodes, that is, point "A" and point "a"(see Figure 4).

To account for interlocking effects due to presence of the shear keys, the specific local coordinate system (n, s, t) for defining orientation of the translational dof normal and tangential to each plane of the keys is employed (see Figure 4). An additional rotation is specified by identifying s or t-direction of the coordinate system as a rotation axis and giving a rotation corresponding to each bevel angle, $\theta_i\,(i=1-5)$, about that axis, and then the direction of the resistance force fields can be specified by giving orientation of the normal vector, $n_i\,(i=1-5)$, to each key plane. The constitutive relation of the spring element can be expressed by two parameter $k_n(n=1,2)$ and G_s, as shown in Figure 5. In the current application, sliding between the two surfaces is not considered. The stiffness matrix of each spring element $[K]_e^i$ is given by

$$[K]_e^i = A_i \begin{bmatrix} K_n & & 0 \\ & G_s & \\ 0 & & G_s \end{bmatrix}$$

where $A_i\,(i=1-5)$ is a weighted factor related to area of the specific influence domain for each node. The values of the stiffness are determined by using the relevant properties of layer of the grouting material between the joint faces. The stiffness matrix should be transformed to the general coordinate system in actual use.

System analyzed

The complete 3-D model prepared for analyses is shown in Figure 6. The material properties for the analytical model are shown in Table 1. Discretization of the dam body employs 8-node linearly-interpolated solid elements. The dam body in the thickness direction was divided into four layers. The vertical joint planes represented by the nonlinear joint elements, drawn with thick lines in Figure 6, are the same location as the actual contraction joints in the dam.

An appropriate portion of the foundation region extending a distance away from the dam body beyond 1.5-2 times the dam height is discretized by using 8-node linearly-interpolated solid elements. The viscous boundary derived by virtual work is applied at the far end of foundation rock in order to minimize the reflection of elastic wave energy back into the interior finite element domain. Material properties for the foundation were obtained from field and laboratory tests.The material properties used for concrete and foundation rock were obtained from the previous extensive study(Sato et al. [8], [9]) on dynamic elastic modulus of dam concrete and rock under earthquake motion.

The model of the impounded water can include compressibility, and uses a special boundary condition along the reservoir bottom and sides which absorb a portion of an incident pressure wave according to one-dimensional wave propagation theory. The far end of the reservoir water is assumed to be a transmission plane with the radiation condition for a region that extends to infinity along the upstream direction. Several meshes were prepared for the reservoir, for comparison with the results of in-site tests conducted different water levels. For all the computations, Rayleigh damping parameters was set to yield 1.0 per cent at 2Hz and 6Hz, base on the previous correlation study (Ueda et al. [10]).

Numerical Procedure

In this study, step-by-step integration procedure in time domain was adopted. To account for effects of static stresses on opening of the joints, the dynamic analysis was preceded by the static analyses for hydrostatic loads. The hydrostatic loads were also applied to the entire model, including all of the joint elements, corresponding to conditions of the water level. Both temperature and gravity loads are disregarded in the current study, though their effects should be considered in a complete safety evaluation. Other static effects due to silt, uplift, and tailwater loads are also neglected. Newmark beta method was used for time integration of the equations of motion with a time step of 0.01 sec, and the Newton-Raphson procedure was used to achieve equilibrium in each time step.

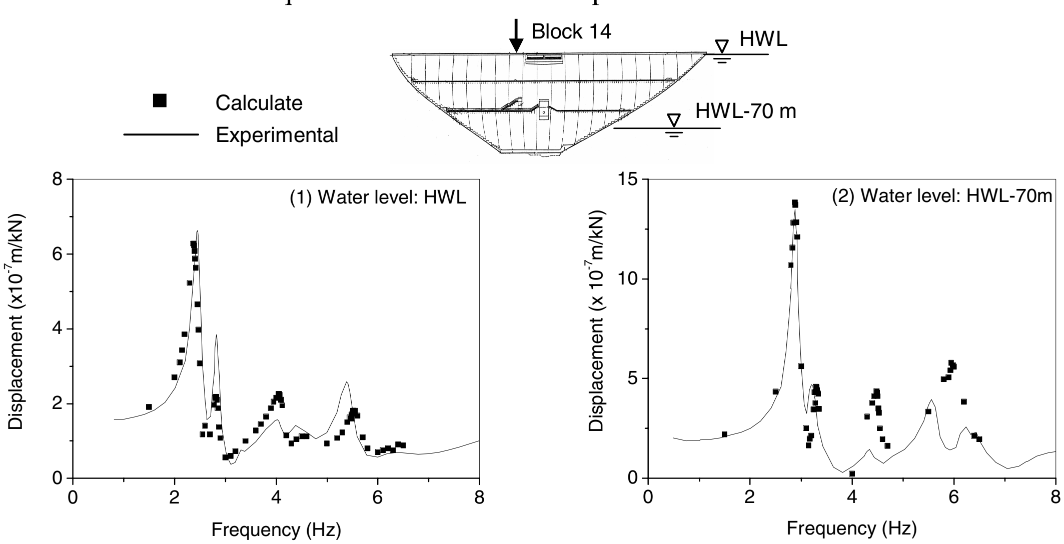

Figure 7 Frequency responses for displacement (crest – block 14)

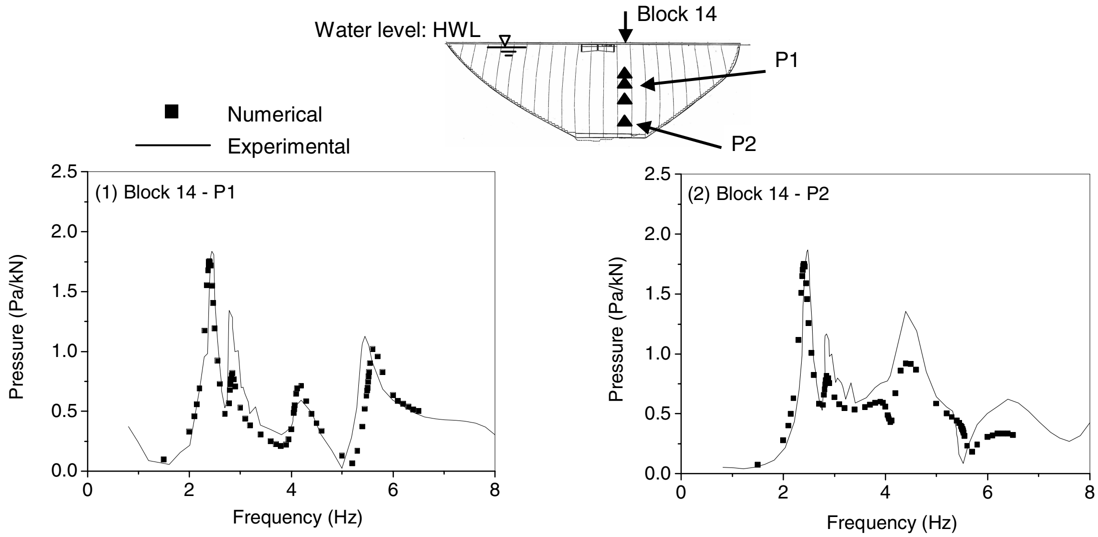

Figure 8 Frequency responses for hydrodynamic pressure (water level: HWL)

Case analyzed

Frequency response curves were obtained for the two dam-water-foundation rock systems: one with the joint nonlinearity and the other without that. For each case, full reservoir as well as almost empty reservoir cases are considered, in order to investigate the variation of resonant frequencies as a function of the water level.

COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

Dynamic Properties

Figure 7 shows a comparison of the measured and computed frequency response curves of the radial displacement on the dam crest for partially-full reservoir cases. In addition, frequency responses of the water pressures on the upstream face of the dam are shown in Figure 8. All the frequency responses are normalized with respect to the exciting force used during the tests, and the phase information is omitted. As shown in both figures, overall the agreement between the computed and measured responses is sufficient accuracy. Regarding the peak amplitude of the displacement response at the higher resonances above 4Hz, the computed values for almost empty reservoir case (HWL-70m) are slightly larger than the measured ones. The lower peak amplitudes in the experimental data, however, suggest that much higher damping is present. If 1.0 per cent is a reasonable value for the dam and foundation contributions, then the presence of another damping mechanism is suggested. One possibility may be that associated with joint nonlinearities due to slippage in contraction joint region.

A comparison between the computed and measured mode shapes at the first two resonances is indicated in Figure 9, where the mode shapes of the radial component of displacement on the crest and hydrodynamic pressure at Block 14 are plotted. The resonating shapes of the dam displacement and water pressure show sufficient agreement between the measured and computed results.

Reservoir Level Effects

Natural Frequencies

Figure 10 shows the variation of the frequencies as a function of the water level for the first resonating mode. All of the resonant frequencies, identified from the vibration tests, are plotted, together with those

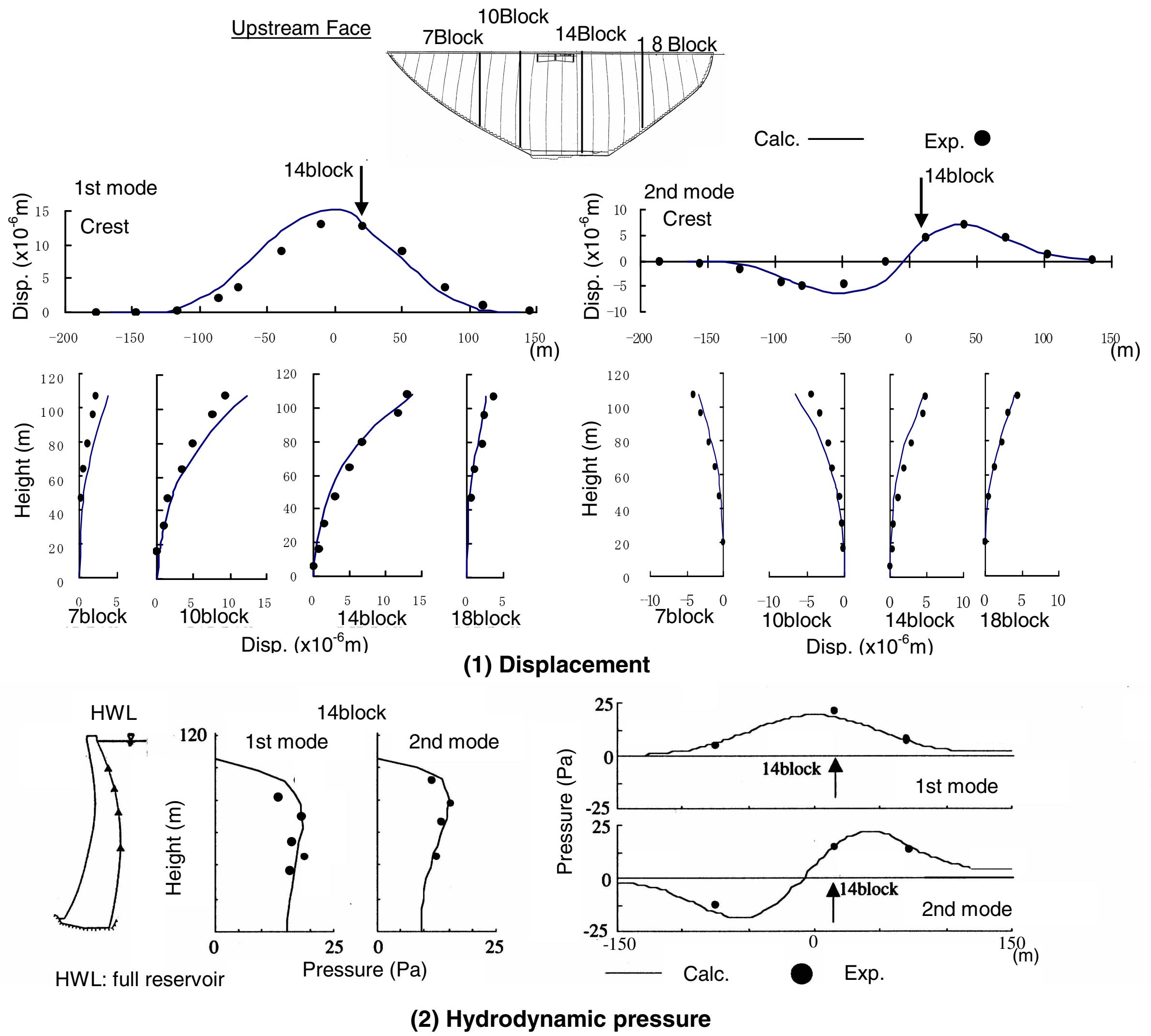

Figure 9 Experimental and calculated resonant shapes

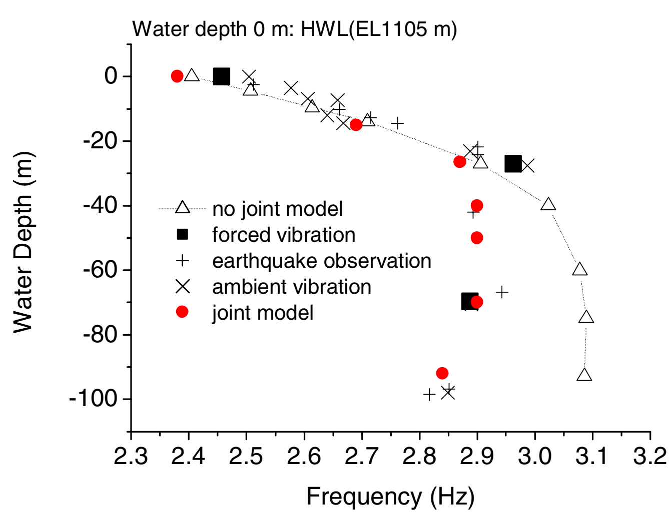

Figure 10 Effect of reservoir water level: measured and computed results.

from earthquake observations. The numerical results, obtained for the cases of the dam with joint nonlinearity or with no joint, are also plotted against the measured frequencies. The observed trend for higher water levels is well reproduced by both numerical models. However, as is shown in Figure 10, only the numerical model with the joint nonlinearity reproduced the observed trend for lower water levels, whereas the no joint model does not reproduced the trend.

The explanation offered for this correlation is as follows. A rise in water level is associated with an increasing of the mass of entrained water. Without the presence of any further effect, this would in turn be associated with a monotonic reduction of the resonance frequencies. This not being the case at the lower water levels is attributed to the vertical contraction joints closing under increasing hydrostatic pressure, and thus to the dam becoming stiffer. This latter effect is associated with an increasing of the resonance frequencies. These two effects compete with one another, the former prevailing at higher water levels and the latter at lower ones. In this case of the arch dam analyzed, after the water standard level is reached at three-fourths full reservoir condition, the latter phenomenon is overcome by the added mass of the reservoir, and thus the resonant frequencies begin to decrease. It should be noted that the opening and closing of the joints can occur, even if at moderate levels of excitations. Similar trend was also observed from vibration tests on another arch dam (Darbre et al.[4]; Proulx et al.[5]). The variations in concrete temperature that occur in a dam in a mountain region also affect closure of the vertical joints to an extent that might be perceptible in the resonance frequencies. However, since the series of our vibration tests were carried out in almost same season, the variation of mean temperatures could be considered to be not so large.

Opening of Contraction Joints

Figure 11 shows the computed time histories of relative joint and resistant force acting normal to the joint face for the two reservoir cases. One is a one-third full reservoir case (HWL-70m), the other is a three-fourths reservoir case (HWL-26.5m). As with the case of the one-third full reservoir, the joint periodically open to relieve arch tensile stresses. Based on the computed result, the maximum joint opening is approximately 2 x 10^{-6}m. On the other hand, for the latter case, no relative joint motion does not occur due to the large compressive stresses in arch direction.

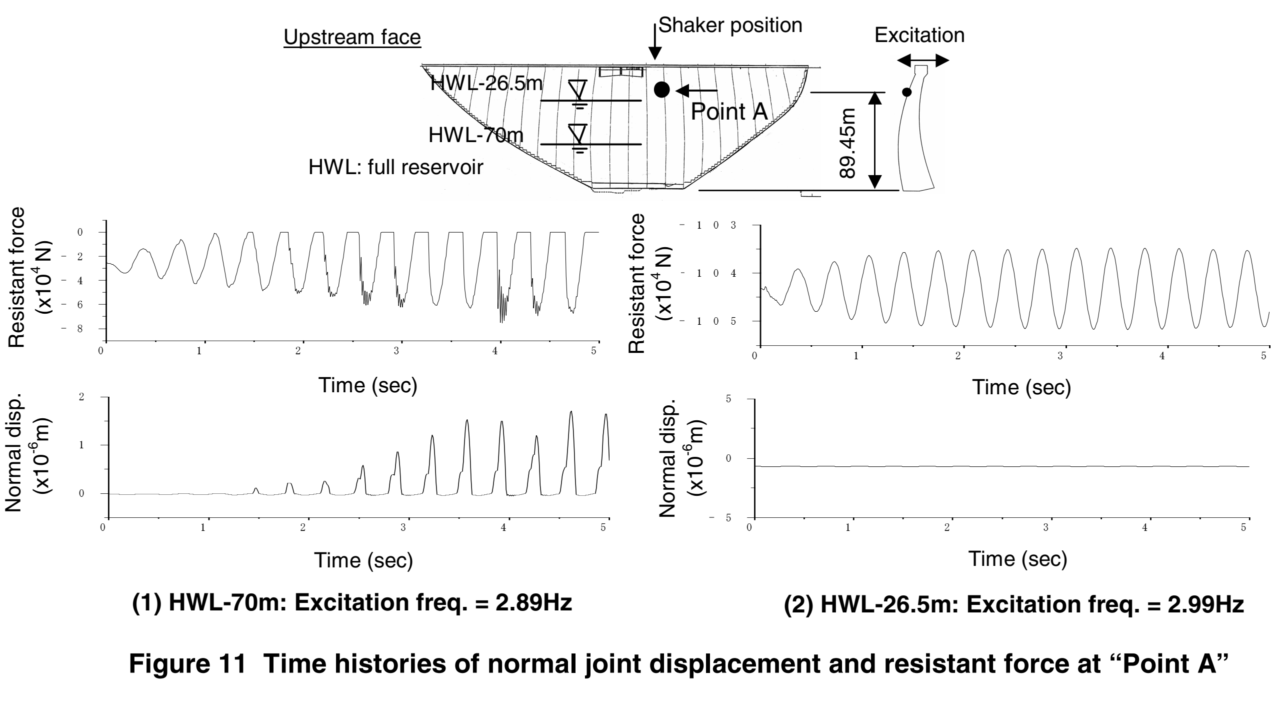

Figure 11 Time histories of normal joint displacement and resistant force at "Point A"

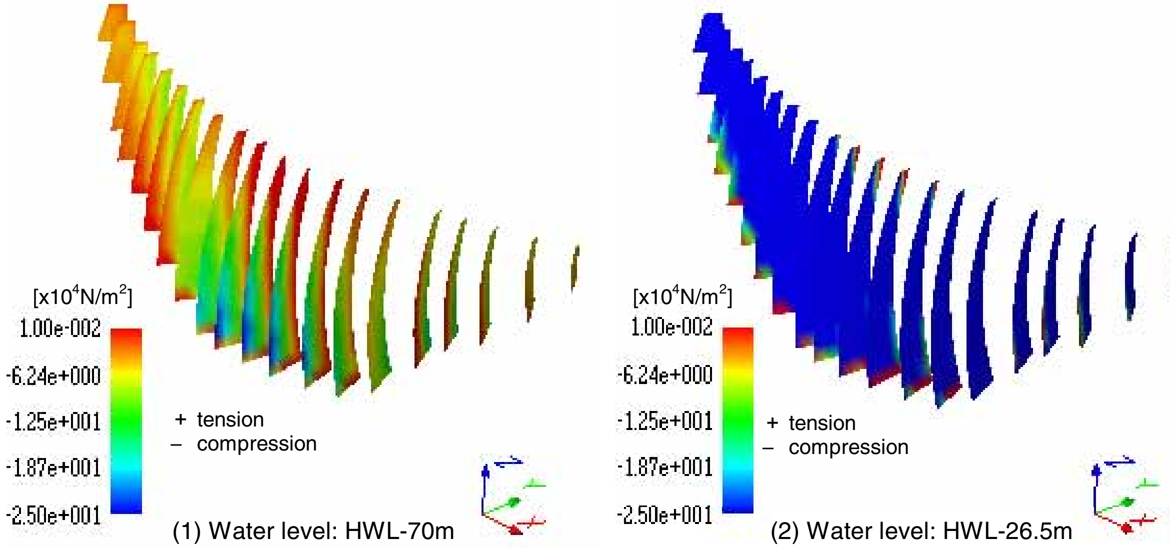

Figure 10 Distribution of resistant forces normal to joint faces

In order to illustrate the distribution of the resistant force acting normal to the joint face at particular instants of time, Figure 12 shows computed snapshots of each of all the joint faces at the time of maximum upstream excursion for the above-mentioned cases. For "HWL-70m" case, the joint opening clearly occurs on most of the joint faces in the model. In particular, it can be found that the complete separation between the monoliths occurs near the crest at the crown cantilever. For "HWL-26.5m" case, each of all the joint faces is tightened due to the compressive forces. This implies that the hydrodynamic pressure provides a substantial restraint against joint opening and the arch action due to the higher pressure causes the dam to behave the entire dam body to behave like as a continuous structure.

CONCLUSIONS

An efficient procedure for the dynamic response analysis of arch dams considering the discontinuous behavior at the vertical contraction joints is newly developed. The analytical method is based on the application of the special joint element, which consists of nonlinear discrete springs. The dynamic response characteristics of the existing arch dam are computed in order to illustrate the applicability of the method to the actual dam-reservoir water-foundation rock system and to clarify the effects of opening and closing phenomena on the dynamic response of the system.

The presented finite element procedure would be a valuable tool for understanding the seismic response of arch dams, however, it must be appreciated that the above conclusions only apply to low levels of response that are not representative of those encountered during strong earthquakes. Although the analytical results presented herein have shown realistic behavior for the coupled system including discontinuous phenomena at the vertical joints, there are many problems in performing the more rigorous response analysis. For instance, further research is needed on the yielding criteria and constitutive relation of the joint, and on the effect of nonlinearity of foundation rock behavior.

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