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STUDY ON EVALUATION METHOD FOR SEISMIC SAFETY OF MULTIPLE ARCH DAM

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Abstract

Multiple arch dam is complex structure composed of more than two arch dams. There are several construction cases of multiple arch dam in the world, which were constructed about several decades ago. As for such aged dams with peculiar figures, earthquake resistant design based on dynamic analysis was not executed from the limitation of technical levels at the time of construction, so re-evaluation of seismic safety shall be necessary based on the latest technical standards.

In this study, I made comparative analyses by three-dimensional dynamic analysis for the purpose of improving accuracy and reliability of seismic safety evaluation of multiple arch dam. I set two kinds of analysis model. One is individual dam model, or single dam model. Another is compound dam model, or double dam model.

As a result of comparative analyses, dynamic tensile stress evaluated by the single dam model became smaller than that evaluated by the double dam model. So, it is considered that the evaluation by the single dam model will be dangerous side compared with that by the double dam model. This tendency increased as values of dynamic shear modulus of dam decreased.

Finally, it was concluded that the mutual dynamic effects among plural arch dams should be taken into account in order to realize an accurate and reliable evaluation for seismic safety of multiple arch dam.

Keywords: multiple arch dam, seismic safety evaluation, 3D dynamic analysis, dynamic tensile stress, mutual effect

1. Introduction

Multiple arch dam is composed of more than two arch dams. Several multiple arch dams have been constructed in the world thus far. There are two construction cases of double (dual) arch dam. These are the Ohkura Dam (dam height: right dam 42m, left dam 82m, total crest length: 323m, completion: 1961, Japan) and the Hongrin Dam (dam height: 123m, total crest length: 600m, completion: 1969, Switzerland). Both were completed in the 1960s. About 50 years ago, it was impossible to execute earthquake resistant design by dynamic analysis because of the technical standard. Therefore, seismic performance of such aged dams should be re-evaluated and verified based on the present technical standard. Fig.1 shows the panoramic view the Ohkura Dam [1].

In regard to complex structure such as multiple arch dam composed of plural dams, it will be necessary to judge whether individual evaluation should be made or whole evaluation should be made. In other words, two analysis methods can be thought for seismic safety evaluation of multiple arch dam. One is an individual analysis method, in which each of plural dams is considered as a separate and individual structure one by one. Another is a compound analysis method, in which plural dams are considered as one structure as a whole. Which method is appropriate and accurate? This is a problem at the time of seismic safety evaluation of multiple arch dam.

From such background, I made comparative study on the analysis method for seismic safety of multiple arch dam by the three-dimensional dynamic analysis for the purpose of improving the accuracy of seismic safety evaluation. Based on the result, I considered about a method for seismic safety evaluation of multiple arch dam.

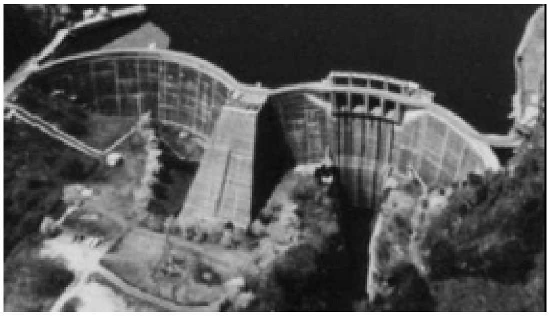


Fig.1 – Existing multiple arch dam (Construction case of double arch dam)

2. Three-dimensional dynamic analyses

2.1 Outline

I set two kinds of analysis models by taking existing construction cases of multiple arch dam into account. One is single dam model as partial evaluation method, and another is double dam model as total evaluation method. I paid my attention to tensile stress induced by earthquake motion, because the earthquake damage of concrete dam such as cracks is caused by the tensile stress.

By the comparative analyses, I examined the influence of dynamic shear modulus of dam on the dynamic tensile stress within dam body. The value of dynamic shear modulus of dam was set based on the results of reproduction analyses of actual behavior of the Ohkura dam during the 2011 off the Pacific Coast of Tohoku Earthquake.

2.2 Three-dimensional Analysis model

Fig.2 and Fig.3 show the single dam model and the double dam model, respectively. The dam height and crest length of a dam was set to be 50m and 145m. The shape and size of dam is same in the single dam model and the double dam model. The shape of river channel is same as dam base.

The dam and foundation rock were modelled by using the solid elements. The lateral boundary was set to be viscous boundary and the bottom boundary was rigid boundary. The analyses were made by the linear dynamic analysis in the time domain. The analysis program used is ISCEF.

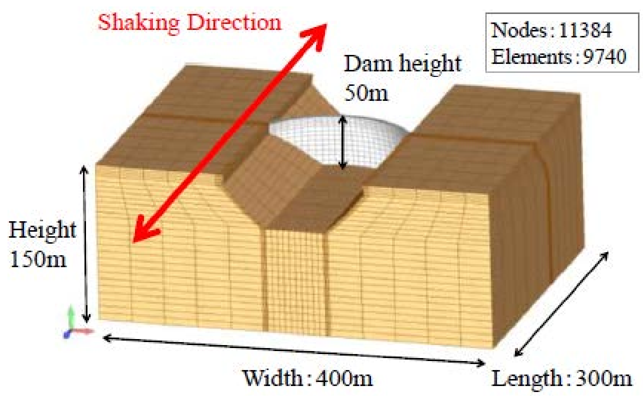


Fig.2 – Single dam model

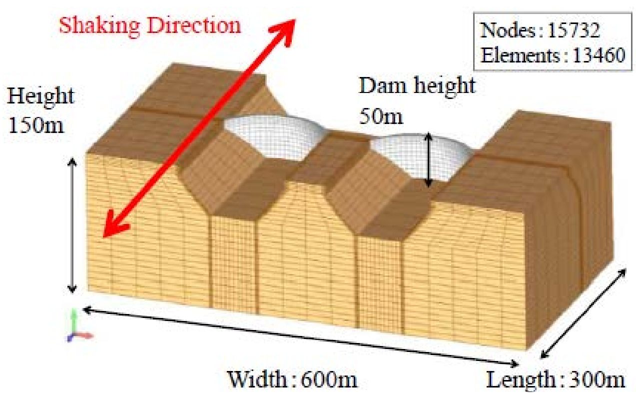


Fig.3 – Double dam model

2.3 Dynamic property values

The dynamic property values of the dam and the foundation are shown in Table 1 and Table 2, respectively. Nonlinear property of dynamic shear modulus of dam was assumed as shown in Fig.4. Three cases of values of dynamic shear modulus were set in order to examine the influence of dynamic shear modulus on the dynamic tensile stress.

The reduction rate of dynamic shear modulus of dam was set to be $G_{dam}/Go=1$, $G_{dam}/Go=0.79$, $G_{dam}/Go=0.65$, as shown in Table 3. The mark of ■ in Fig.4 is the results of tensile test of dam concrete [2, 3], and ● is the results of reproduction analyses of actual behavior of the Ohkura dam during the 2011 off the Pacific Coast of Tohoku Earthquake [4].

Table 1 – Dynamic property values of dam

Item	**Dynamic shear modulus (N/mm^2)**	**Density (t/m^3)**	**Dynamic Poisson's ratio**	**Damping factor**	**Reduction ratio of shear modulus**
Case-1	G_{dam}=9250	2.4	0.20	0.05	G_{dam}/G_0=1.00
Case-2	G_{dam}=7310	2.4	0.20	0.05	G_{dam}/G_0=0.79
Case-3	G_{dam}=6000	2.4	0.20	0.05	G_{dam}/G_0=0.65

Table 2 – Dynamic property values of foundation rock

Item	**Dynamic shear modulus (N/mm^2)**	**Density (t/m^3)**	**Dynamic Poisson's ratio**	**Damping factor**	**Shear wave velocity (m/s)**
Rock	G_{rock}=4500	2.6	0.25	0.05	1315

Table 3 – Dynamic shear modulus of dam identified by reproduction analysis of actual behavior of the Ohkura Dam during the 2011 off the Pacific coast of Tohoku Earthquake [4]

Condition (Date of occurrence)	**Dynamic shear modulus of dam (Shear wave velocity)**	**Observed maximum acceleration at dam crest**
Main shock (11th March 2011)	G_{dam}=6000 N/mm^2 (Vs=1580 m/s)	626 Gal
After shock (7th April 2011)	G_{dam}=7310 N/mm^2 (Vs=1730 m/s)	430 Gal
Small earthquake motion	G_{dam}=9250 N/mm^2 (Vs=1960 m/s)	Several Gal

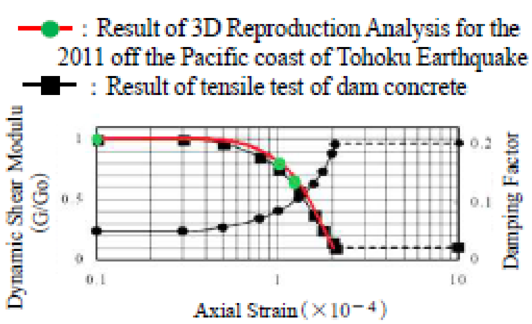


Fig.4 – Non-linear characteristics of dam concrete

2.4 Input earthquake motion

Acceleration time history shown in Fig.5 was used as input earthquake motion. The motion was input in the up-downstream direction from the bottom boundary. Maximum acceleration is 438.7 Gal.

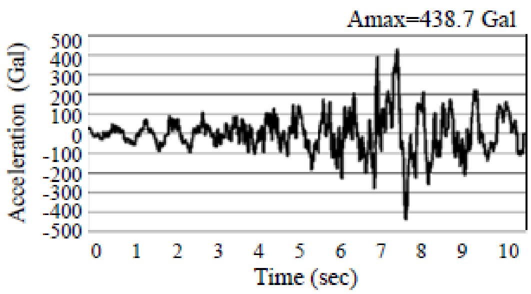


Fig.5 – Input earthquake motion

2.5 Analysis results

2.5.1 Outline

Table 4 shows the results of maximum tensile stresses at the representative positions of single dam model. Similarly, maximum tensile stresses at the representative positions of double dam model are shown in Table 5.

Table 4 – Maximum tensile stress evaluated by single dam model

Representative position			**Maximum tensile stress (N/mm^2)**		
Position		**No.**	**G_{dam}=9250**	**G_{dam}=7310**	**G_{dam}=6000**
Downstream face	Right abutment	1	1.55	1.57	1.37
	Dam crest by right bank	2	2.47	3.78	4.32
	Dam crest center	3	3.16	3.36	2.89
	Dam base center	4	1.49	2.57	2.62
	Dam crest by left bank	5	2.47	3.78	4.32
	Left abutment	6	1.54	1.56	1.36
Upstream face	Right abutment	7	1.60	1.97	1.80
	Dam crest by right bank	8	3.08	3.17	3.82
	Dam crest center	9	3.34	4.95	5.85
	Dam base center	10	5.28	4.89	4.47
	Dam crest by left bank	11	3.08	3.18	3.82
	Left abutment	12	1.60	1.97	1.80

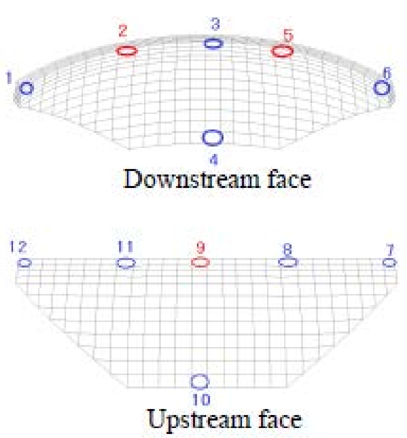


Fig.6 – Representative position of single dam model

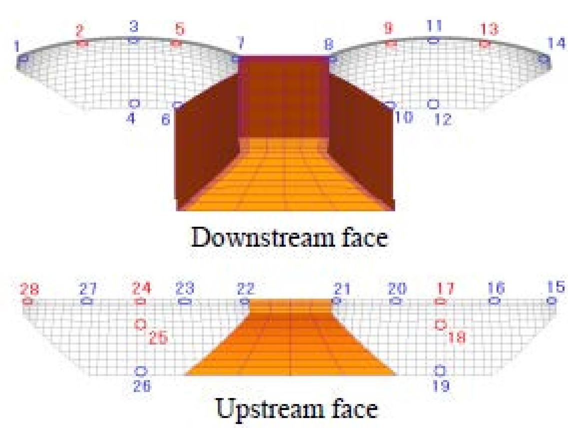


Fig.7 – Representative position of double dam model

Table 5 – Maximum tensile stress evaluated by double dam model

Representative position				**Maximum tensile stress (N/mm^2)**		
Position			**No.**	**G_{dam}=9250**	**G_{dam}=7310**	**G_{dam}=6000**
Down -stream face	Right dam	Right abutment	1	3.03	3.02	2.02
		Dam crest by right bank	2	5.25	6.29	7.28
		Dam crest center	3	3.64	3.78	3.04
		Dam base center	4	2.63	3.50	3.86
		Dam crest by left bank	5	2.88	4.77	6.35
		Left bank base	6	2.28	2.67	2.68
		Left abutment	7	2.57	2.96	2.27
Up -stream face	Left dam	Right abutment	15	2.95	2.93	3.30
		Dam crest by right bank	16	3.26	3.68	3.61
		Dam crest center	17	5.07	7.96	9.58
		Dam center	18	3.77	4.54	5.71
		Dam base center	19	4.51	4.74	4.61
		Dam crest by left bank	20	5.32	6.76	6.54
		Left abutment	21	1.69	2.64	3.28

The representative position of the single dam model and the double dam model are shown in Fig.6 and Fig.7. The distributions of tensile stress in the single dam model are shown in Fig.8 (G_{dam}=9250N/mm^2), Fig.9 (G_{dam}=7310N/mm^2) and Fig.10 (G_{dam}=6000N/mm^2). Similarly, the distributions of tensile stress in the double dam model are shown in Fig.11 (G_{dam}=9250N/mm^2), Fig.12 (G_{dam}=7310N/mm^2) and Fig.13 (G_{dam}=6000N/mm^2). As the results of three-dimensional dynamic analysis, the tensile stress induced by earthquake motion became larger at dam crest.

2.5.2 Analysis result of single dam model

The positions where the dynamic tensile stress increased with the reduction of the value of dynamic shear modulus were the dam crest (position 2 and 5) and the center of dam base (position 4) on the downstream face, and the dam crest (position 8, 9 and 11) on the upstream surface. But at the right and left abutment (position 1 and 6) on the downstream surface, and the dam base center (position 10) on the upstream surface, the dynamic tensile stress reduced as the values of dynamic shear modulus reduced.

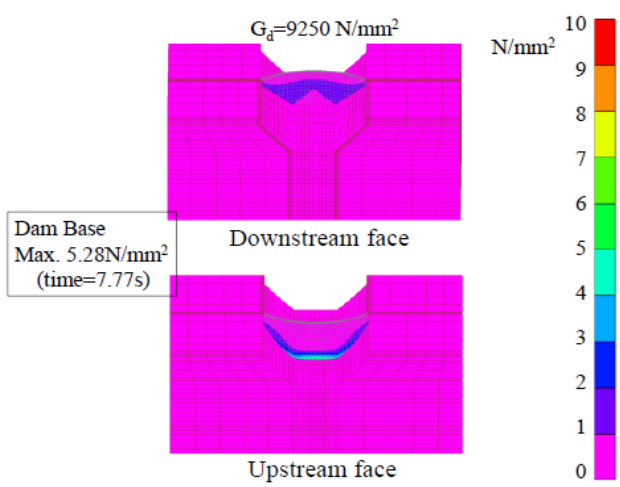


Fig.8 – Distribution of dynamic tensile stress evaluated by single dam model when G_{dam}=9250N/mm^2

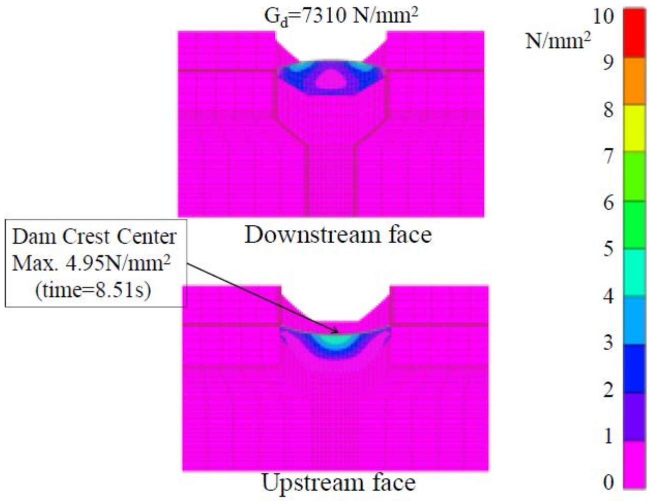


Fig.9 – Distribution of dynamic tensile stress evaluated by single dam model when G_{dam}=7310N/mm^2

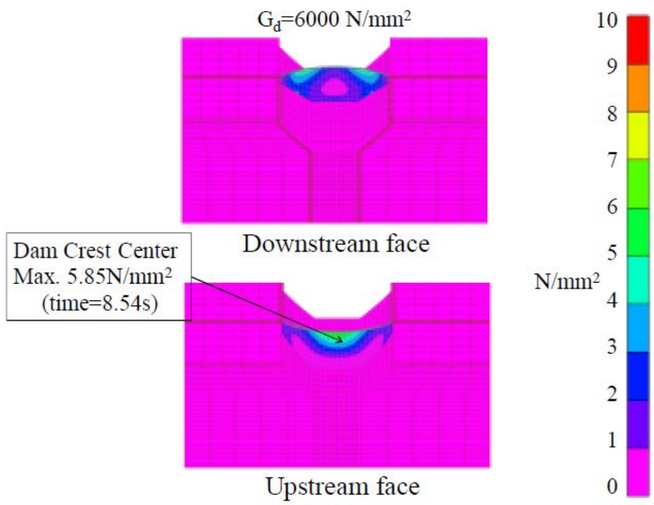


Fig.10 – Distribution of dynamic tensile stress evaluated by single dam model when G_{dam}=6000N/mm^2

The influence of dynamic shear modulus on dynamic tensile stress changed according to the position. From Fig.8, Fig.9 and Fig.10, it can be understood that the dynamic tensile stress increased mainly at the dam crest and the abutment. As for the left and right abutment, the maximum values of dynamic tensile stress were 1.36N/mm² - 1.97N/mm², and the influence of dynamic shear modulus was small. As for the dam crest, the dynamic tensile stress showed a tendency to increase with the reduction of dynamic shear modulus, and the maximum values of dynamic tensile stress were 2.47N/mm² - 5.58N/mm². In addition, the distribution of the dynamic tensile stress was symmetric because the shape of the dam and the foundation was set to be symmetric.

2.5.3 Analysis result of double dam model

As shown in Table 5, the positions where the dynamic tensile stress largely increased with the decline of the value of dynamic shear modulus were the dam crest (position 2 and 5) on the downstream face. And, as for the upstream face, the positions where the dynamic tensile stress largely increased were the dam crest (position 17 and 20), and the dam center (position 18) on the upstream face. But at the right and left abutment (position 1 and 7), the dynamic tensile stresses did not vary largely when the values of dynamic shear modulus of dam reduced. Thus, the influence of dynamic shear modulus on dynamic tensile stress varied according to the position, or the vibration mode of dam. From Fig.9, it can be understood that the dynamic tensile stress became large mainly at the dam crest center on the upstream face and the dam crest on the downstream face. As for the left and right abutment, the values of dynamic tensile stresses were 1.69N/mm² - 3.30N/mm², and the influence was small. As for the dam crest, the dynamic tensile stress showed a tendency to increase with the drop of dynamic shear modulus, and the dynamic tensile stress distributed from 2.88N/mm² to 9.58N/mm².

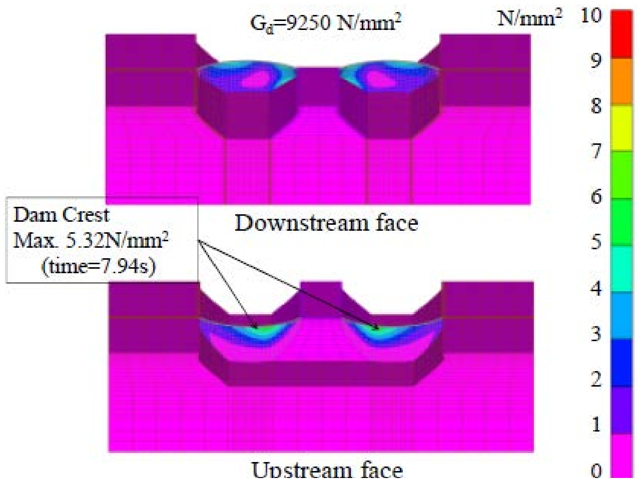


Fig.11 – Distribution of dynamic tensile stress evaluated by double dam model when G_{dam}=9250N/mm^2

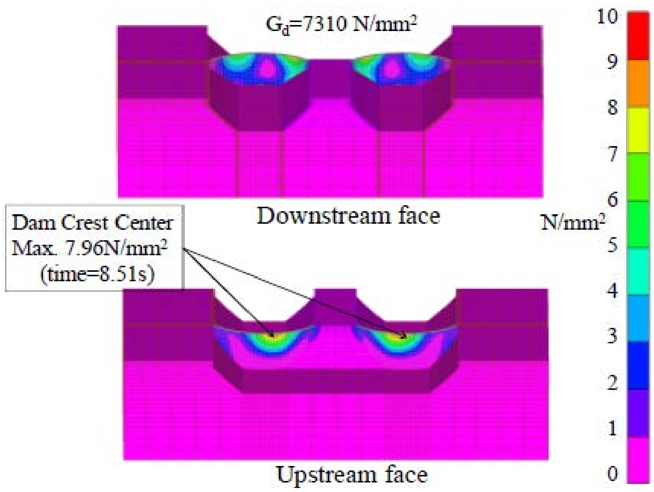


Fig.12 – Distribution of dynamic tensile stress evaluated by double dam model when G_{dam}=7310N/mm^2

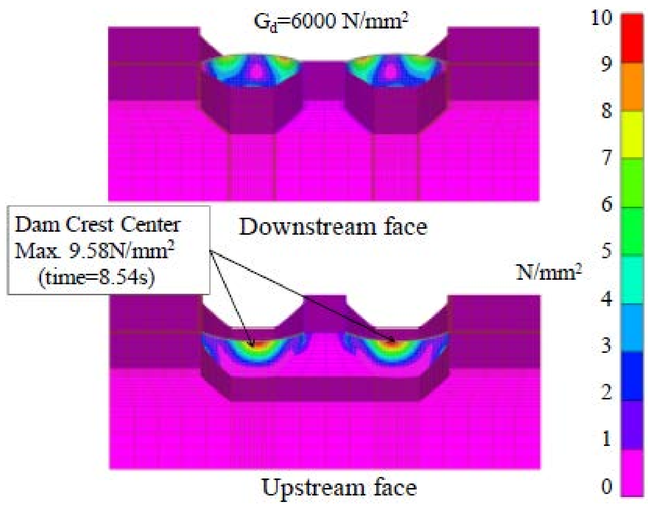


Fig.13 – Distribution of dynamic tensile stress evaluated by double dam model when G_{dam}=6000N/mm^2

In regard to the double dam model, the distribution of dynamic tensile stress also became symmetric because the shape of analysis model was set to be symmetric. As for the double dam model, even when the dynamic shear modulus of dam is high, the displacement behavior of dam becomes large, and the dam behaves with a symmetrical second mode. The influence of dynamic shear modulus of dam on the dynamic tensile stress became larger in the double dam model compared with the single dam model.

2.5.4 Comparison between single dam model and double dam model

About the influence of reduction of dynamic shear modulus on the dynamic tensile stress, the dynamic tensile stress at the abutment became small, and the variable range for increase or decrease became relatively narrow. This tendency is common to both models. The maximum dynamic tensile stress at the dam crest was 5.85N/mm² by the single dam model, but 9.58N/mm² by the double dam model.

The dynamic tensile stress evaluated by the double dam model became generally greater than that evaluated by the single dam model. From this result, it is thought that the evaluation method by using the single dam model becomes more dangerous than the method by the double dam model. Consequently, it is considered that the evaluation method by using the double dam model, namely the whole evaluation method by using coupled whole system model shall be made in order to execute an accurate and reliable verification for seismic safety of multiple arch dam composed of more than two dams.

3. Conclusions

The dynamic tensile stress is an important index for evaluating the damage of concrete dam by strong earthquake motion. So the analysis results were sum up about the dynamic tensile stress induced by strong earthquake motion. Table 6 shows the comparison of maximum tensile stress between the single dam model and the double dam model when the dynamic shear modulus of dam is 6,000N/mm^2. The distribution of dynamic tensile stress evaluated by the double dam model was symmetric, so the results regarding the right dam were summarized in Table 6. The comparison of dynamic tensile stresses between the single dam model and the double dam model were shown in Fig.14.

Table 6 – Comparison between single dam model and double dam model regarding dynamic tensile stress when dynamic shear modulus of dam is 6000 N/mm^2

Representative position		**Single dam model**		**Double dam model**	
Position		**No.***	**Maximum tensile stress**	**No.****	**Maximum tensile stress**
Downstream face of right dam	Right abutment	1	1.37	1	2.02
	Dam crest by right bank	2	4.32	2	7.28
	Dam crest center	3	2.89	3	3.04
	Dam base center	4	2.62	4	3.86
	Dam crest by left bank	5	4.32	5	6.35
	Left abutment	6	1.36	7	2.27
Upstream face of right dam	Right abutment	7	1.80	15	3.30
	Dam crest by right bank	8	3.82	16	3.61
	Dam crest center	9	5.85	17	9.58
	Dam base center	10	4.47	19	4.61
	Dam crest by left bank	11	3.82	20	6.54
	Left abutment	12	1.80	21	3.28

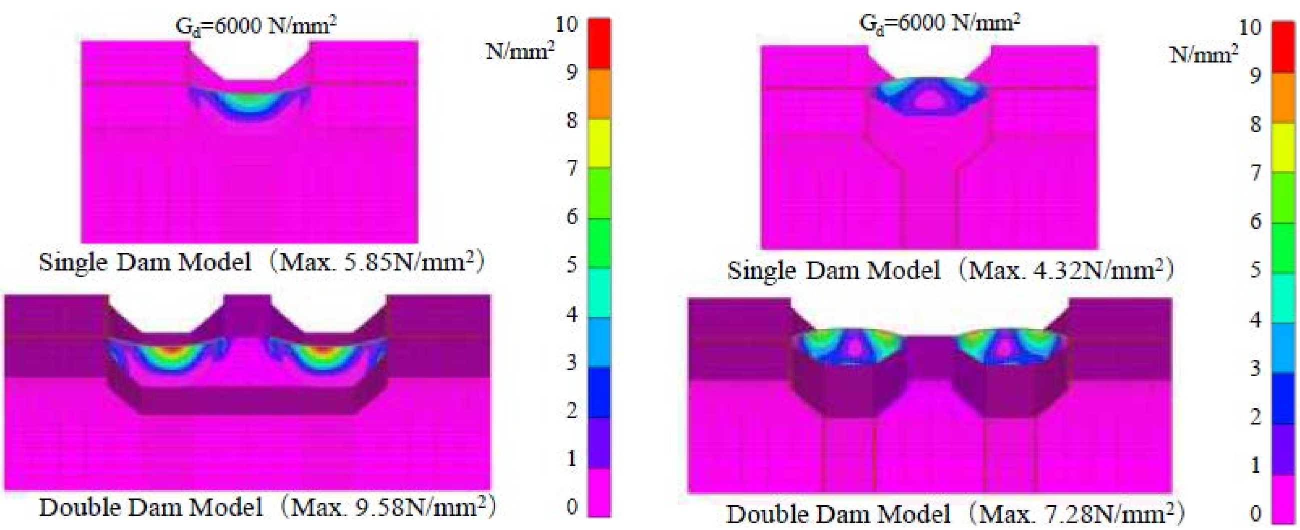
【Note】*,**: Position Number, Refer Fig.6(*) and Fig.7(**)

Table 7 shows the analysis results of maximum acceleration, maximum displacement, and maximum dynamic tensile stresses when the dynamic shear modulus of dam body is 6,000N/mm^2.

The influence of reduction of dynamic shear modulus on dynamic tensile stress become larger in the double dam model compared with in the single dam model. Therefore, the seismic safety of multiple arch dam should be evaluated by using the double dam model, or the whole evaluation by using whole model should be executed. When the value of dynamic shear modulus decreases, the dynamic tensile stress varies according to the position of the dam body, and the dynamic tensile stress largely increases at the dam crest.

Table 7 – Comparison between single dam model and double dam model regarding maximum acceleration, maximum displacement and maximum tensile stress when dynamic shear modulus of dam is 6000 N/mm^2

Analysis model	Maximum acceleration	Maximum displacement	Maximum tensile stress
Single Dam Model	2888 Gal	9.8 cm	5.85 N/mm^2
Double Dam Model	4646 Gal	11.5 cm	9.58 N/mm^2



(1) Upstream face (2) Downstream face

Fig.14 – Comparison of distribution of dynamic shear stress between single dam model and double dam model when dynamic shear modulus of dam is 6000 N/mm^2

From these results, in regard to the evaluation method for seismic safety of multiple arch dam, the partial evaluation (the individual evaluation) will be the dangerous evaluation. This tendency will increase as the dynamic shear modulus of dam decreases. Therefore, the whole evaluation that can take the dynamic interaction among plural arch dams into account is necessary to realize an accurate and reliable evaluation for the seismic safety of multiple arch dam.

As a conclusion, mutual effect among plural arch dams during large earthquake should be considered in order to make appropriate evaluation for multiple arch dam, or the complex structure of high importance.

The necessity of re-evaluation for seismic safety of existing aged dam increases more and more as the time passes from now on. I regard the three-dimensional dynamic analysis as a three-dimensional shaking table test in the computer. Accurate and reliable three-dimensional analysis is very useful for the verification of seismic damage of complex structure such as multiple arch dam, connected and complex structure.

4. Afterword

The followings are the subject for future study.

Influence of the distance between two dams, influence of the long-period earthquake motion, influence of thrust block between two dams, influence of dynamic property of rock foundation, influence of reservoir water, influence of temperature stress, influence of joint of the dam body.

5. Acknowledgement

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