# SEISMIC PERFORMANCE EVALUATION METHOD FOR MULTIPLE ARCH DAM CONSIDERING MUTUAL INFLUENCE

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## *Abstract*

Multiple arch dam is a composite structure with complex shape, in which two or more arch dams are connected. When verifying the seismic performance of multiple arch dam, roughly two evaluation methods can be supposed. One is an individual evaluation method by setting a single dam model which treats each arch dam as a single arch dam individually. Another is a coupled evaluation method by setting a coupled dam model taking the mutual influence between plural dams into account.

During the 2011 off the Pacific coast of Tohoku Earthquake, the strong earthquake motions were observed at existing dual arch dam. And, we made 3-D reproduction analysis for the actual dynamic behavior of the dual arch dam by utilizing the observed motions, and quantitatively evaluated nonlinearity, or the strain dependence of dynamic shear modulus of dam. On the basis of these results, we studied on the evaluation method for seismic performance of multiple arch dam. Furthermore, we examined the effect of strain dependence of dynamic shear modulus on the seismic tensile stress caused by earthquake motion.

In this study, we set two analysis models. One is a single dam model composed of one arch dam. Another is a dual dam model composed of two arch dams. And we examined which method is appropriate. In the single dam model, one arch dam with dam height of 100 m and crest length of 310 m was set. In the dual dam model, two arch dams with dam height of 100 m and crest length of 310 m and 246 m were set. Both the dam and the foundation were modeled with 8-nodes solid elements. The lateral boundary of FEM model was a viscous boundary and the bottom boundary was a rigid base. As for reservoir water, an empty condition was assumed. The analysis program ISCEF was used for the 3-D FEM dynamic analysis.

As the results, the seismic tensile stress in the dam evaluated by the single dam model became smaller than by the dual dam model. The evaluation by the single dam model tends to underestimate the seismic stress compared with the dual dam model. So, there is a risk of overestimating the seismic safety by the single dam model. This tendency will increase as the dynamic shear modulus of dam decreases.

From the above, in order to accurately check the seismic performance of multiple arch dams, it is necessary to execute the coupled evaluation by setting the coupled dam model taking the dynamic mutual influence between plural dams into account.

The effect of dynamic shear modulus on the seismic tensile stress was relatively small in the evaluation by the single dam model, but relatively large by the coupled dam model. The seismic tensile stress in the dam body is affected by the seismic interaction between dams and foundation rock.

The more complex the shape and seismic response of dam becomes, the larger the mutual influence between dams and foundation rock becomes. As for the structure with complex shape and complicated constitution, it is necessary to evaluate the seismic performance by taking the mutual influence into consideration.

*Keywords: multiple arch dam, seismic performance evaluation, 3-D dynamic analysis, tensile stress, non-linearity*

## 1. Introduction

Multiple dam is a compound structure composed of two or more dams. There are several construction cases of multiple dam. As for dual arch dam, the Hongrin Dam (dam height: 123m, crest length: 600m, completion: 1969, Switzerland) [1] and the Okura Dam (dam height: 82m, total crest length: 323m, completion: 1961, Japan, Sendai city) [2] have been reported. Both were built in the 1960s, and more than 50 years have already passed since their completions. Numerical analysis technology and design method at that time were significantly different from the current technical level. So, it is necessary to verify the seismic safety for the aging dams baed on the present technical standard if they are located in the earthquake regions.

In regard to the evaluation method for multiple arch dam, two analysis methods can be supposed. One is "an individual evaluation", and another is "a coupled evaluation". The individual evaluation is a method to analyze each dam one by one individually without considering mutual effects between plural dams. The coupled evaluation is a method to analyze the multiple dam as one structure with considering mutual effects between plural dams. Should the mutual effects between plural dams be considered? Is it not necessary to consider mutual effects between plural dams? There are such problems with respect to the seismic safety evaluation of multiple arch dams.

Because of its complexity of geometrical shape and seismic response, the seismic safety of the multiple arch dam should be accurately evaluated. From such necessity, in order to realize an accurate and reliable evaluation method, we studied on the method for seismic safety evaluation of multiple arch dam based on the comparative analyses by 3-D FEM dynamic analysis.

## 2. Method of 3-D dynamic analysis

### 2.1 Overview

Dual arch dam is set as an analysis object. The shape and size of analysis object was set with reference to the existing dams, and two analysis models were set. The comparative analyses were made based on 3-D FEM dynamic analysis by inputting same earthquake motion. In seismic safety evaluation of concrete dams, the tensile stress is an important indicator. So, we examined by focusing on the tensile stress caused by earthquake motion. In addition, in order to make clear the effect of dynamic non-linearity, or strain dependence of dynamic shear modulus, we made the comparative study when the dynamic shear modulus of dam was changed.

### 2.2 Analysis models

Two analysis models were set by taking the construction cases of the Hongrin Dam [1] and the Okura Dam [2] into account. The single dam model shown in Fig.1, and the dual dam model is shown in Fig.2. The height of dam is 100 m for both the single dam model and the dual dam model. The crest length is 310 m for the single dam model. For the dual dam model, the crest length of the right-side dam is 310 m, and 246 m of the left-side dam. The shape of the single dam model and the right-side dam of dual dam model are the same. The comparison of analysis results was made with the single dam model and the right-side dam of dual dam model. The dam and the foundation rock were both modeled by using solid elements. The lateral boundary was a viscous boundary, and the bottom boundary was a rigid base.

Regarding the reservoir water, if there is full water, the water pressure acts on the dam, so the dam is in a compressive stress condition. If there is no water, the water pressure does not act on the dam, so the dam is not restrained by water pressure. And the dam can easily behave when subjected to strong earthquake motion. Consequently, the tensile stress is easily generated in the dam when the reservoir is empty. For this reason, from the viewpoint of the seismic safety evaluation, the analysis condition is severer when the reservoir is empty than full. Therefore, it was assumed that the reservoir is empty. The analysis program ISCEF [3] was used for the 3-D dynamic analysis [3].



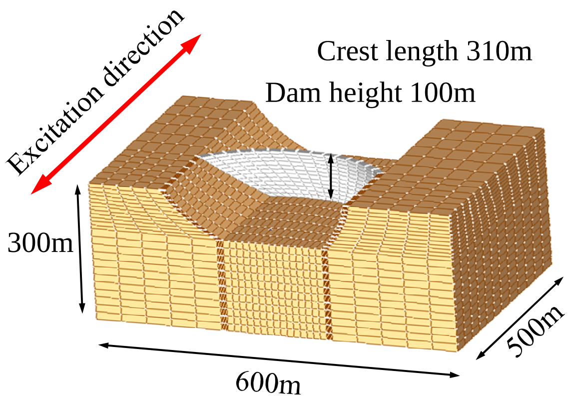



Fig. 1 – Single dam model

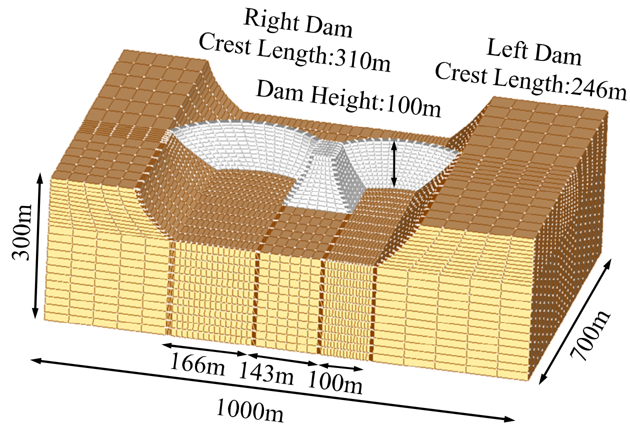



Fig. 2 – Dual dam model

### 2.3 Dynamic property values

The dynamic property values of the dam were set as shown in Table 1 based on the results of previous studies [4]. The dynamic property values of foundation rock were set as shown in Table 2 [4]. Table 3 shows the values of dynamic shear modulus of existing dual arch dam identified based on the seismic behavior during the 2011 off the Pacific coast of Tohoku Earthquake [5], [6], [7].

Table 1 – Dynamic property values of dam

| **Dynamic shear modulus $N/mm^2$** | **Density $t/m^3$** | **Poison's ratio** | **Damping factor** | **Note (Decline ratio)** |
|---|---|---|---|---|
| 6000 | 2.4 | 0.20 | 0.05 | G/Go=0.65 |

(Go: Dynamic shear modulus for minute strain)

Table 2 – Dynamic property values of foundation rock

| **Dynamic shear modulus $N/mm^2$** | **Density $t/m^3$** | **Poison's ratio** | **Dampimg factor** |
|---|---|---|---|
| 4500 | 2.6 | 0.25 | 0.05 |

Table 3 – Dynamic shear modulus of existing daul arch dam identified by 3-D reproduction analysis of earthquake behavior during the 2011 off the Pacific coast of Tohoku Earthquake

| **Situation** | **Dynamic shear modulus identified by reproduction analysis** | **Observed maximum acceleration** |
|---|---|---|
| Main shock (2011.3/11) | $G_{dam}$=6000 $N/mm^2$ (Vs 1580 m/s) | Amax =626 Gal |
| After shock (2011.4/7) | $G_{dam}$=7310 $N/mm^2$ (Vs 1730 m/s) | Amax = 430 Gal |
| Tremor | $G_{dam}$=9250 $N/mm^2$ (Vs 1960 m/s) | Few Gal |

($G_{dam}$: Dynamic shear modulus of dam body, Vs: Shear wave velocity)



The values shown in Table 4 were set for examining the effect of strain dependence of dynamic shear modulus on the seismic tensile stress in the dam. Dynamic strain was supposed to be around 1~2×$10^{-4}$. Then, two cases of G/Go =0.65 and G/Go =1.00 were set by referring the dynamic strain dependence of dam concrete as shown in Fig.3 [8], [9]. The values of density, Poisson's ratio, and damping factor were set with reference to the previous studies [10], [11], [12]. The values of dynamic shear modulus were set by taking non-linearity into account, and the dynamic analyses were executed as linear analysis.

Table 4 – Values of dymanic shear modulus for examining effect of dynamic non-linearity on seismic tensile stress generated by earthquake motion

| Case | Decline ratio | Dynamic shear modulus $N/mm^2$ | Density $t/m^3$ | Pison's ratio | Damping factor | Strain level |
|---|---|---|---|---|---|---|
| 1 | G/Go=0.65 | 6000 | 2.4 | 0.20 | 0.05 | Large strain |
| 2 | G/Go=1.00 | 9250 | 2.4 | 0.20 | 0.05 | Minute strain |

(Go: Dynamic shear modulus for minute strain)

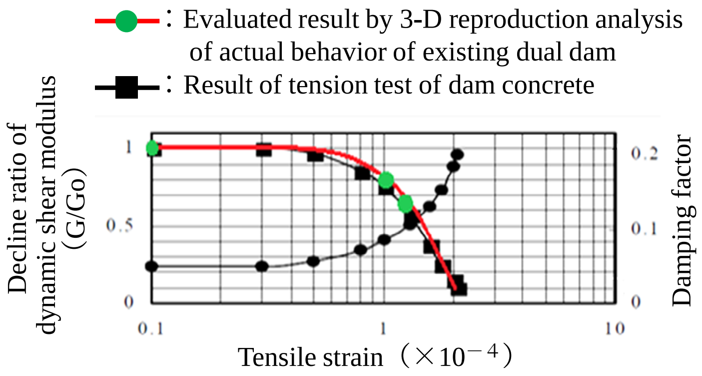



Fig. 3 – Dynamic non-linearity of deformation property of dam concrete

## 2.4 Input earthquake motion

Input earthquake motion is shown in Fig.4 [13]. The maximum acceleration is 749.64 Gal, and the duration time is 12.0 second. The motion was input from the bottom boundary in the upstream-downstream direction.

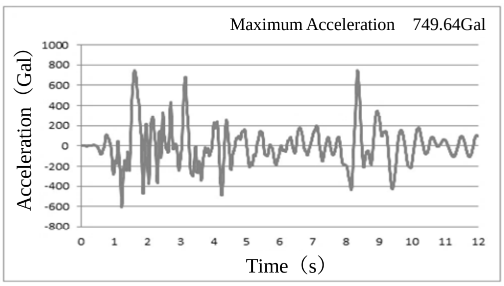



Fig. 4 – Input earthquake motion



## 3. Results of 3-D dynamic analysis

### 3.1 Comparison of results evaluated by the single dam model and by the dual dam model

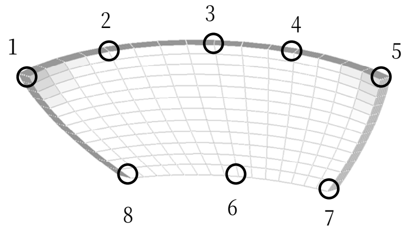
#### 3.1.1 Displacement caused by earthquake motion

The comparison of maximum displacement evaluated by the single dam model and by the dual dam model is shown in Table 5. The representative output position is shown in Fig.5. The values of displacement at the dam crest were properly larger than at the dam bottom. At the dam crest, the maximum displacement by the dual dam model was slightly larger than by the single dam model. At the dam bottom, the maximum displacement by the dual dam model was slightly smaller than by the single dam model. The maximum displacement at the crest center was 63.5 cm by the single dam model and 68.6 cm by the dual dam model.

Table 5 – Maximum displacement at representative position caused by earthquake motion

| Representative position | | $G_{dam}$=6000 N/mm$^2$ | |
|---|---|---|---|
| | | **Single dam model** | **Dual dam model** |
| 1 | Crest・right abutment | 29.9 cm | 28.9 cm |
| 2 | Crest・right side | 41.8 | 42.4 |
| 3 | Crest・center | 63.5 | 68.6 |
| 4 | Crest・left side | 47.4 | 50.5 |
| 5 | Crest・left abutment | 30.3 | 24.0 |
| 6 | Bottom・left | 17.5 | 15.1 |
| 7 | Bottom・center | 21.0 | 15.6 |
| 8 | Bottom・right | 19.4 | 18.1 |

($G_{dam}$: Dynamic shear modulus of dam body)




Representative output nodes

Fig. 5 – Representative output position for displacement

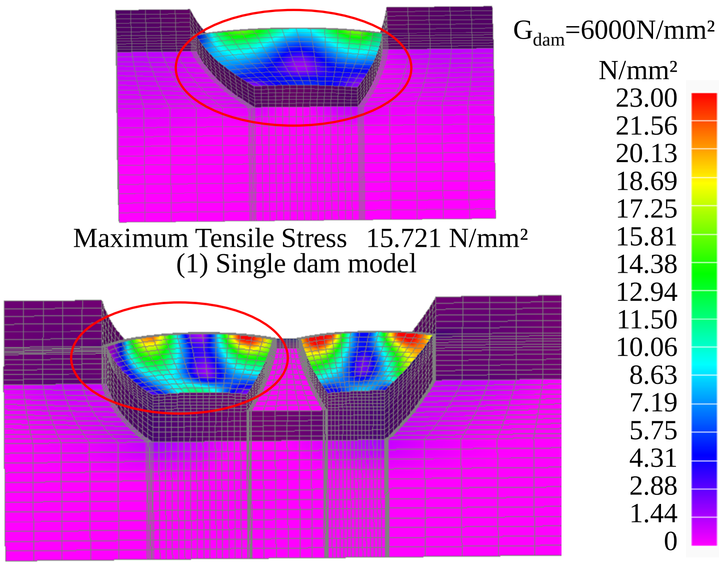
#### 3.1.2 Tensile stress at dam body caused by earthquake motion

The distribution of tensile stress at the dam body caused by earthquake motion is shown in Fig.6. Table 6 shows the comparison of tensile stress caused by earthquake motion. The representative output position is shown in Fig.7. The tensile stress generated in the dam body by the dual dam model was generally larger than by the single dam model. The maximum tensile stress at the dam crest was 15.72 N/mm$^2$ by the single dam model and 22.38 N/mm$^2$ by the dual dam model. As it is clear from Fig.6, the maximum tensile stress showed large difference between the single dam model and the dual dam model. From this result, it is considered that the evaluation by single dam model (the individual evaluation) will be a dangerous side evaluation, consequently the evaluation by dual dam model (the coupled evaluation) shall be necessary.



The mutual effects between plural dams should be considered in order to realize an accurate and reliable evaluation for the multiple arch dam.




Maximum Tensile Stress 15.721 N/mm²
(1) Single dam model

Maximum Tensile Stress 22.383 N/mm²
(2) Dual dam model

Fig. 6 – Comparison of distribution of tensile stress at dam caused by earthquake motion

Table 6 – Maximum tensile stress at representative position caused by earthquake motion

| **Representative position** | | **$G_{dam}$=6000 N/mm$^2$** | |
|---|---|---|---|
| | | **Single dam model** | **Dual dam model** |
| 1 | Crest・right abutment | 5.96 N/mm$^2$ | 11.20 N/mm$^2$ |
| 2 | Crest・right side | 15.72 | 22.38 |
| 3 | Crest・center | 10.40 | 14.65 |
| 4 | Crest・left side | 12.49 | 13.32 |
| 5 | Crest・left abutment | 11.94 | 19.26 |
| 6 | Bottom・left | 12.72 | 12.80 |
| 7 | Bottom・center | 8.23 | 5.39 |
| 8 | Bottom・right | 6.96 | 7.59 |

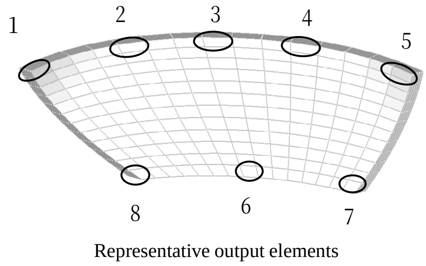



Fig. 7 – Representative output position for stress



### 3.1.3 Tensile stress at foundation rock by earthquake motion

The distribution of tensile stress at the foundation rock generated by earthquake motion is shown in Fig.8. The maximum tensile stress at the right abutment is 5.43 N/mm$^2$ by the single dam model and 10.76 N/mm$^2$ by the dual dam model. The tensile stress by the dual dam model was approximately twice as that by the single dam model. This result suggests that the individual evaluation by using the single dam model will be the risk side evaluation, so that the coupled evaluation by using the dual dam model should be executed.

The seismic safety of arch dam is governed by the soundness of foundation rock, therefore careful attention shall be payed to the occurrence of tensile stress in the foundation rock. As mentioned above, the dynamic analysis using a single dam model will be a risk side evaluation. It is necessary to make a coupled evaluation which can take the seismic interaction between plural dams into account in order to conduct a proper evaluation.

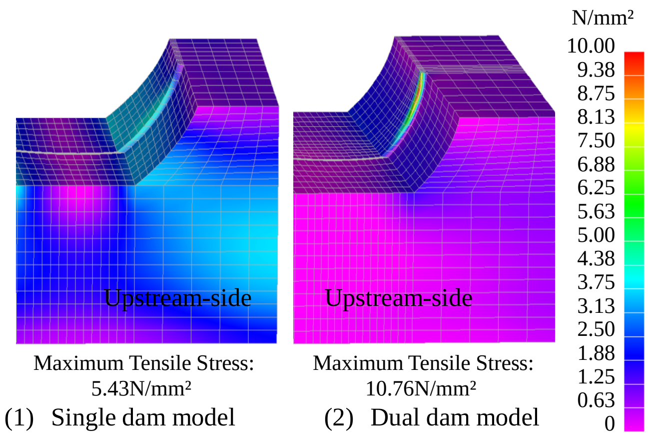



Fig. 8 – Comparison of distribution of seismic tensile stress at foundation rock

### 3.2 Result about effect of non-linearity of dynamic shear modulus

Fig.9 shows the distribution of the maximum tensile stresses when the dynamic shear modulus ($G_{dam}$) was 6000 N/mm$^2$ and 9250 N/mm$^2$. Table 7 shows the values of the maximum tensile stresses at the representative output position which is shown in Fig.10. As can be seen from Table 7, the tensile stresses generally decreased as the dynamic shear modulus decreased. At 19 positions of 22 positions, the tensile stresses decreased due to the decrease of dynamic shear modulus. At position 12, when $G_{dam}$ = 9250 N/mm$^2$, the tensile stress was 32.59 N/mm$^2$, and when $G_{dam}$ = 6000 N/mm$^2$, it became 29.66 N/mm$^2$. At position 15, when $G_{dam}$ = 9250 N/mm$^2$, it was 32.07 N/mm$^2$, and when $G_{dam}$ = 6000 N/mm$^2$, it became 26.62 N/mm$^2$. But, at position 13, 6 and 18, the tensile stresses increased due to the decrease in dynamic shear modulus. At position 13, when $G_{dam}$ = 9250 N/mm$^2$, the tensile stress was 18.78 N/mm$^2$, and when $G_{dam}$ = 6000 N/mm$^2$, it became 23.97 N/mm$^2$.

When the dynamic shear modulus of dam changes, there appear positions where the tensile stresses increase and where they decrease. It is considered that this result is due to the seismic response of the coupled dam and foundation rock system. The tensile stress in the dam tends to decrease as the dynamic shear modulus decreased. As a result, it can be thought that the non-linearity of dynamic shear modulus of dam will have advantageous effect on the seismic safety of arch dam.



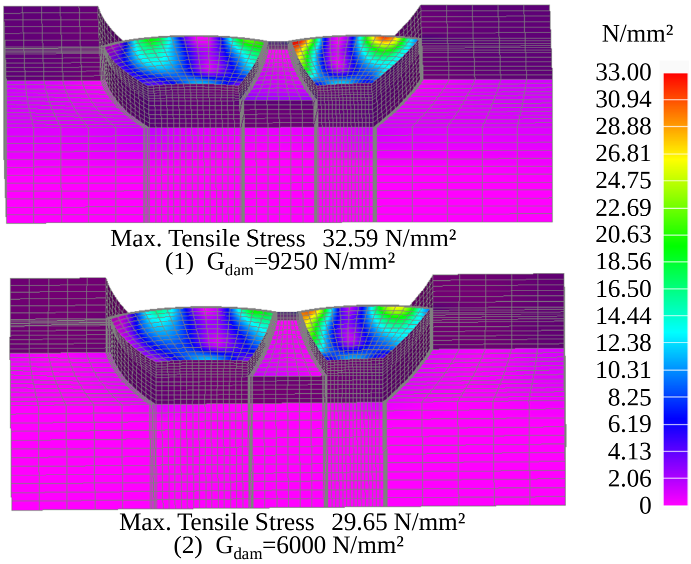



Fig. 9 – Distribution of the maximum tensile stress when $G_{dam}$= 6000 N/mm$^2$ and 9250 N/mm$^2$.

Table 7 – Influence of decrease of dynamic shear modulus of dam on dynamic tensile stress

| **Representative position** | | | | **Gd＝9250 N/mm$^2$** | **Gd＝6000 N/mm$^2$** |
|---|---|---|---|---|---|
| Right dam | Crest | 1 | Right abutment | 11.35 N/mm$^2$ | 11.20 N/mm$^2$ |
| | | 2 | Right side | 24.79 | 22.38 |
| | | 3 | Center | 20.13 | 14.64 |
| | | 4 | Left side | 13.68 | 13.32 |
| | | 5 | Left abutment | 29.75 | 9.27 |
| | Middle | 6 | Right abutment | 10.53 | 11.42 |
| | | 7 | Center | 10.24 | 6.61 |
| | | 8 | Left abutment | 22.48 | 13.68 |
| | Botoom | 9 | Right abutment | 8.85 | 7.59 |
| | | 10 | Center | 15.46 | 12.80 |
| | | 11 | Left abutment | 6.32 | 5.39 |
| Left dam | Crest | 12 | Right abutment | 32.59 | 29.66 |
| | | 13 | Right side | 18.78 | 23.97 |
| | | 14 | Center | 7.23 | 7.07 |
| | | 15 | Left side | 32.07 | 26.62 |
| | | 16 | Left abutment | 19.58 | 17.71 |
| | Middle | 17 | Right abutment | 25.44 | 22.85 |
| | | 18 | Center | 4.27 | 4.81 |
| | | 19 | Left abutment | 21.16 | 19.98 |
| | Bottom | 20 | Right abutment | 7.59 | 5.79 |
| | | 21 | Center | 14.62 | 11.42 |
| | | 22 | Left abutment | 8.24 | 6.42 |



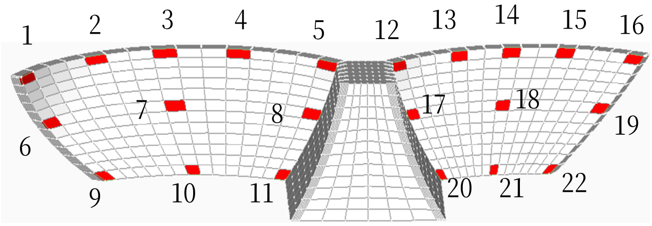



Fig. 10 – Representative output position for tensile stress

## 4. Conclusions

◆In order to develop accurate and reliable evaluation method, the seismic safety evaluation method for multiple arch dam was studied based on the 3-D dynamic analysis. And the effect of non-linearity of dynamic shear modulus on the tensile stress was also studied.

◆As a result, seismic tensile stress evaluated by the single dam model became smaller than by the dual dam model. The individual evaluation by setting the single dam model will be a dangerous side evaluation, and there is a risk for over-estimating the safety. Therefore, regarding the dual arch dam, the coupled evaluation by setting the dual dam model should be made. Mutual effect between plural dams should be considered in order to realize an accurate and reliable evaluation for the multiple arch dam.

◆Seismic safety of arch dam is governed by the soundness of foundation rock, so careful attention should be payed to the occurrence of tensile stress not only in the dam doby but also in the foundation rock.

◆Seismic tensile stress in the dam body showed the decreasing tendency with decreasing of the dynamic shear modulus. But, seismic tensile stress in the foundation rock showed increasing tendency as the dynamic shear modulus decreased. From these results, it is considered that the non-linearity of dynamic shear modulus has an advantageous effect on the dam body, however a disanvantageous effect on the foundation rock. This tendency will increase as the dynamic shear modulus of dam decreases.

◆The effect of dynamic shear modulus on the seismic tensile stress was relatively small in the evaluation by the single dam model, but relatively large by the coupled dam model. The seismic tensile stress in the dam body is affected by the seismic interaction between dams and foundation rock.

◆The more complex the shape and seismic response of dam becomes, the larger the mutual influence between dams and foundation rock becomes. As for the structure with complex shape and complicated constitution, it is necessary to evaluate the seismic performance by taking the mutual influence into consideration.

◆As for the further study, the effect of thrust block, the effect of dynamic nonlinearity of foundation rock, the effect of reservoir water, the effect of contraction joint and peripheral joint, and so forth can be mentioned.

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