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INFLUENCE OF SEDIMENT ON SEISMIC STRESS OF ARCH DAM WITHOUT RESERVOIR WATER

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Abstract

Due to ground disasters and surface modification around river, sediment flows into the river during rainfall, and sedimentation occurs at dam site. In this study, the influence of sediment on the seismic response of dam and foundation rock was evaluated by 3-D dynamic analysis from the viewpoint of structural engineering and earthquake engineering. Arch dam is a structure that maintains structural stability by arch action, so the safety of arch dam largely depends on the soundness of foundation rock. Therefore, the influence of sediment was examined focusing on the foundation rock as well as the dam body.

When the reservoir is full, the reservoir water pressure acts on the dam, and the dam becomes in a compressive stress state. When the reservoir is empty, the water pressure does not act, consequently the tensile stress will be easily generated by strong earthquake motion. In the seismic safety evaluation, the condition is more severe when the reservoir is empty than full. So, we studied the case when the reservoir was empty, here.

The analysis object is arch dam with dam height of 100m and crest length of 300m. 4 analysis models were set up for the sedimentation rate of 0%, 25%, 50%, and 75%, or sediment thickness of 0m, 25m, 50m, and 75m. The dam, the sediment and the foundation rock were modeled by using solid elements. Viscous boundary was set for the lateral and bottom boundary. 3-D dynamic analysis was made as linear analysis. The dynamic shear modulus of dam was set with reference to the results of reproduction analyses for actual behaviors of existing dams during actual earthquakes, such as the 2011 off the Pacific coast of Tohoku Earthquake, and so forth. The analysis program ISCEF was used for 3-D dynamic analysis.

As a result, the maximum displacement of dam body decreased with the increase of sediment. When there is no sediment, the dam can displace individually and easily. When the sediment is thick, the dam will behave as a coupled system with sediment, and the displacement becomes difficult to occur as the sediment increases.

As for the seismic stress, the maximum tensile stress at dam body generally decreased with the increase of sediment. This suggests that the sediment may have a beneficial effect on the seismic safety of dam. However, around the abutment and the foundation rock, there appeared the places where the maximum tensile stress increased with the increase of sediment. It is thought that this was due to the displacement behavior of the coupled sediment-dam-foundation rock system. Especially, when the seismic tensile stress increases in the foundation rock, the seismic safety of dam may be reduced. In such cases, it becomes necessary to accurately verify the safety of foundation rock.

As future study, it is important to examine the effect of dynamic deformation properties against strong earthquake motion and the effect of discontinuous behavior (opening, sliding) of contact plane between dam and sediment and foundation rock.

Keywords: sedimentation, arch dam, seismic safety, tensile stress, 3D dynamic analysis

1. Introduction

When ground disaster or surface alteration occurs around the river, sediment flows into the river during and after rainfall, and sedimentation occurs at dam site. As sedimentation progresses, flood control function and power generation function will decrease. So, for these functions, countermeasures against sedimentation such as sand removal and dredge have been taken thus far. However, regarding seismic safety of dam, it is not clear how sedimentation affects the seismic safety of dam. Is sediment advantageous or disadvantageous to the seismic safety of dam? In this study, in order to develop a method for verifying seismic performance of dam taking effects of sediment into consideration, the effects of sediment on seismic response of arch dam were examined by 3-D dynamic analysis.

2. Necessity and purpose of study

In the guideline for verifying seismic performance of dam against large-scale earthquake [1], there is no description on the effects of sedimentation during earthquakes and evaluation method for sedimentation.

As a domestic study on the relationship between the seismic safety of dam and the sedimentation, the study by shaking table test of concrete gravity dam using 1m-high scale model was published. It was reported that the hydrodynamic pressure acting on the dam model decreased and the dynamic earth pressure increased as the sediment increased [2].

As the foreign studies, in the case of concrete gravity dam, the following studies were published, such as the study on analysis method of interaction between dam, reservoir water and sediment by two-dimensional boundary element method [3], the study on method for evaluating interaction between dam, reservoir water and sediment by modeling sediment as porous medium [4, 5], the study on the effect of sediment on the hydrodynamic pressure and seismic stress [6], the study on two-dimensional dynamic analysis for horizontal and vertical motion when sedimentation is modeled as a porous medium [7], and the studies based on the pressure wave formula of a saturated porous medium for the sediments derived from the consolidation theory [8, 9].

As for the arch dam, the following studies were published, such as the study on numerical model for analyzing sediment reflection behavior based on the dynamic theory of saturated porous media based on Biot's theory [10], the study on evaluation of seismic response by 3-D boundary element method by modeling water as compressible fluid, dam and foundation rock as viscoelastic solid, and sediment as two layered porosity region [11] , the study on evaluation of sediment effect on dynamic response of dam by 3-D boundary element method by modeling of sediment as a porous medium [12], the study on seismic response analysis using a compressible fluid as a reservoir, an elastic solid as a dam and foundation rock, and a solid-liquid two-layer porous medium as sediment [13]. In many studies, the sediment in reservoir is treated as a porous media.

In addition, the dynamic analysis in these studies focused on the evaluation of the hydrodynamic pressure acting on dam and the acceleration response of dam. Few cases focused on the evaluation of the seismic stress generated in the dam and foundation rock. From the viewpoints of water engineering and soil engineering, it becomes important to make clear the distribution and magnitude of hydrodynamic pressure and dynamic earth pressure acting on the dam. However, from the viewpoints of structural engineering and earthquake engineering, it becomes important how the presence of sediment affects the seismic stress generated in the dam and foundation rock. It is very important and necessary to clarify these matters in order to realize accurate verification of seismic safety of arch dam.

This study targets arch dam. Since the arch dam is a thin and easily deformable structure, and the shape of upstream surface is a complicated curved surface, the effects of sediment on arch dam during earthquakes are still unknown. Therefore, in order to achieve accurate and reliable seismic performance verification of arch dam, it is necessary to quantitatively clarify how sediment affects the seismic stress generated in the dam and foundation rock. So, we studied the effects of sediment on the seismic stress generated in the dam and foundation rock by three-dimensional dynamic analysis using coupled dam-sediment-foundation rock system model.

3. 3D dynamic analysis method for dam-sediment-foundation rock system

3.1 Outline

When the reservoir is full of water, the compressive pressure by reservoir water acts on the surface of arch dam, and the dam becomes in a compressive stress condition. But, if there is no water, the compressive pressure by reservoir water does not act on the dam, so the dam is likely to generate tensile stress when subjected to strong earthquake motion. Therefore, from the viewpoint of seismic performance verification of arch dam, the condition becomes more severe in the empty state than in the full state. So, we examined the effects of sediment on arch dam when the reservoir was empty.

3.2 Analysis method

Three dimensional dynamic analysis model of a coupled dam-foundation rock-sediment system was set up, and comparative analyses were made by changing the sedimentation rate. The effects of sediment on the seismic response of arch dam was evaluated quantitatively. FEM analysis program "ISCEF" [14] was used in this study.

3.3 Three dimensional dynamic analysis model

The analysis object was arch dam with dam height of 100 m and crest length of 300 m, as shown in Fig. 1. The foundation rock was modeled in the area of 920 m wide, 740 m long and 250 m deep. As shown in Fig. 2, sedimentation rate 0% (sediment thickness 0 m), 25% (sediment thickness 25 m), 50% (sediment thickness 50 m) and 75% (sediment thickness 75 m) were set. The arch dam, foundation rock and sediment were all modeled with solid elements, and the lateral boundary and bottom boundary were set as viscous boundary.

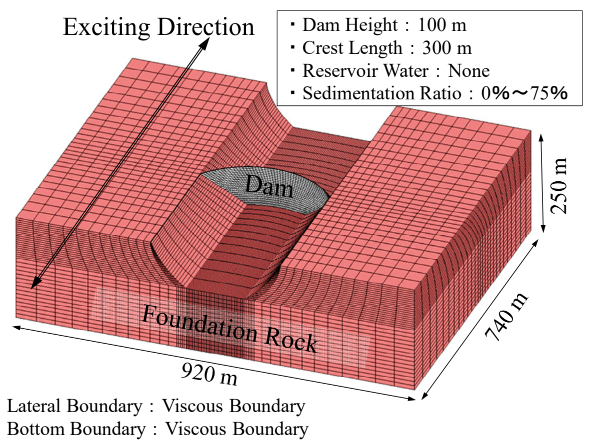


Fig. 1 – 3D dynamic analysis model of coupled dam and foundation system

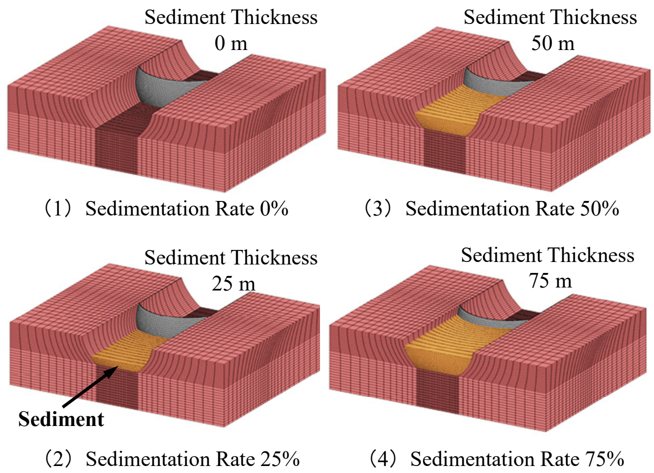


Fig. 2 – Analysis models for examining influence of sediment

3.4 Dynamic property values

Table 1 shows the dynamic property values of dam, foundation rock and sediment.

3.4.1 Dynamic property values of dam

The dynamic property values of the arch dam were set based on the result of reproduction analysis of actual behaviors of existing arch dam during the 2011 off the Pacific coast of Tohoku Earthquake [15, 16].

3.4.2 Dynamic property values of foundation rock

The dynamic property values of foundation rock were also supposed according to the results of study on the quantitative evaluation of property values by the reproduction analysis for actual behavior of existing dams during actual earthquakes [17, 18, 19]. Here, the foundation rock is supposed to be a hard rock composed of late Miocene to Pliocene andesite and basalts.

3.4.3 Dynamic property values of sediment

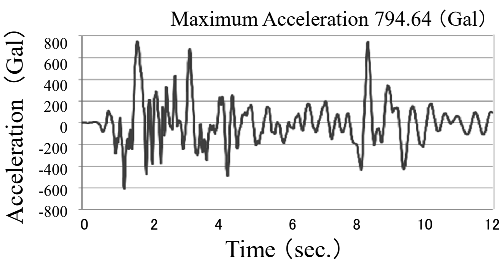
Against strong earthquake motion, the dynamic shear modulus of sediment may decrease due to the non-linearity, or dynamic strain dependence. And, the density and dynamic shear modulus of sediment may be changed with the progress of sedimentation or sand discharge. Here, we assumed that the sediment was loosely deposited, and the density of sediment is about 1.6 g/cm^3, which was smaller than natural soil (1.7 to 1.9 g/cm^3). In regard to the dynamic shear modulus, the shear wave velocity (Vs) was assumed to be 80 m/s by applying the empirical formula $80N^{1/3}$ (m/s), assuming N value is 1. The damping factor of loose soil is estimated to be larger than 0.05. However, since there is no specific measured data, the damping factor of sediment was assumed to be 0.05, here.

Table 1 – Dynamic property values of dam, foundation rock and sediment

Item	Density (g/cm³)	Poison's ratio	Shear modulus (N/mm²)	Shear wave velocity (m/s)	Damping factor
Dam	2.4	0.2	6000	1580	0.05
Foundation rock	2.6	0.25	4500	1315	0.05
Sediment	1.6	0.4	10.25	80	0.05

3.5 Input earthquake motion

The simulated motion by JSCE [20] (Level 2 earthquake motion) shown in Fig. 3 was used as input motion. This motion was defined on the surface of foundation rock at the end of downstream, and transfered from the surface to the bottom boundary using 1-D ground model. Then, the motion was input from the input base of 3-D dynamic analysis model. The excitation direction was the up-downstream directions.



【Note】
◆Reference:
Japan Society of Civil Engineers: Standard Specifications for Concrete Structures -Seismic Performance Verification- 2002.
◆This motion was defined on the foundation rock surface at the end of downstream, and input from the bottom boundary after pulling down to the input base.

Fig. 3 – Time history of input eathquake motion

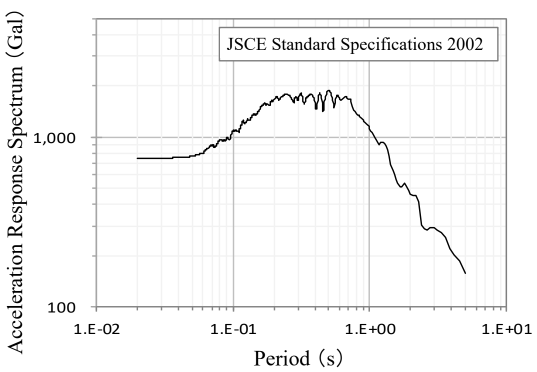


Fig. 4 – Spectrum of input earthquake motion

4. Analysis results regarding influence of sediment on dam and foundation rock

In the seismic performance evaluation of dam, the seismic stress generated by earthquake motion in the dam is important indicator. Here, the analysis results were organized and considered with a focus on the seismic stress caused by earthquake motion. Since the seismic safety of arch dam largely depends on the soundness of foundation rock, we carefully examined the seismic stress generated not only in the dam body but also in the foundation rock. Here, the value of seismic stress is a stress generated by earthquake motion, and is a value that is not super-imposed with normal stress.

4.1 Displacement response of dam

The distribution of displacement of dam at the time when the maximum displacement occurs is shown in Fig. 5. The maximum displacement of dam for the sedimentation rates of 0%, 25%, 50%, and 75% was 305 mm, 300 mm, 271 mm, and 213 mm, respectively. The displacement of dam decreased as the sedimentation rate increased. In the absence of sediment, the dam can behave independently by itself, whereas in the case of thick sediment, the dam will behave as a coupled system with sediment.

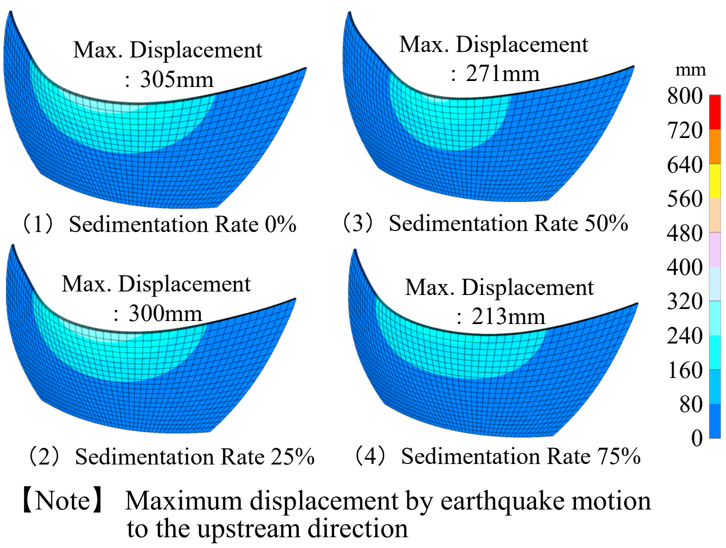


Fig. 5 – Distribution of maximum displecement of dam caused by earthuake motion

4.2 Tensile stress of dam caused by earthquake motion

The distribution of seismic tensile stress generated by earthquake motion is shown in Fig. 6. Table 2 shows the maximum tensile stress at the representative output position shown in Fig. 7.

The maximum tensile stress at position A (upstream-side of crest center) was 13.78 N/mm^2, 13.47 N/mm^2, 11.71 N/mm^2 and 9.30 N/mm^2 for sedimentation rates of 0%, 25%, 50%, and 75%, respectively. Thus, the maximum tensile stress at position A during earthquake decreased as the sedimentation rate increased.

On the other hand, the maximum tensile stress at position B (downstream of the left abutment) was 7.03 N/mm^2, 7.09 N/mm^2, 7.59 N/mm^2, 8.93 N/mm^2 for the sedimentation rates of 0%, 25%, 50%, and 75%, respectively. Thus, the maximum tensile stress at position B during earthquake increased as the sedimentation rate increased.

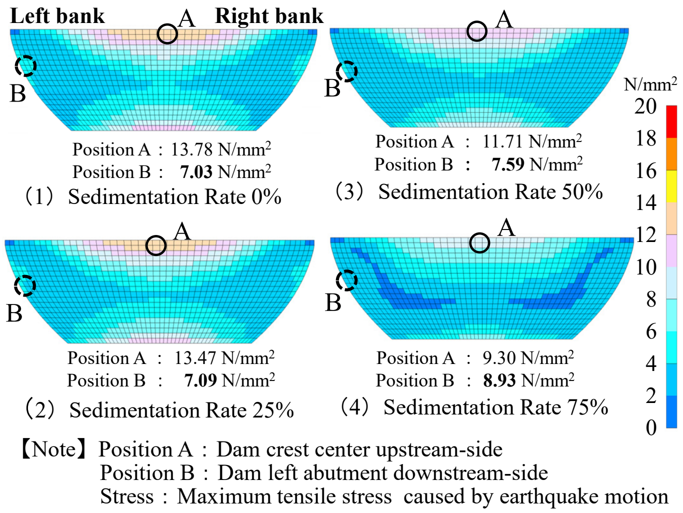


Fig. 6 – Distribution of maximum tensile stress at dam body caused by earthquake motion

Table 2 – Comparison of maximum tensile stress at dam body caused by earthuake motion

Position at dam body		**Maximum tansile stress (N/mm²)**				**Note**
		Sedimentation rate				
		0 %	**25 %**	**50 %**	**75 %**	**(Tendency)**
Upstream-side	Dam Crest center	13.78	13.47	11.71	9.30	Decrease
	Dam bottom center	11.22	11.19	10.00	6.42	Decrease
	Dam Right abutment	5.06	4.94	4.05	3.48	Decrease
Downstream-side	Dam Crest center	12.62	12.33	11.19	9.24	Decrease
	Dam Crest left-side	11.27	11.02	9.59	7.68	Decrease
	Dam bottom center	6.59	6.67	7.35	7.63	Increase
	Dam Left abutment	7.03	7.09	7.59	8.93	Increase

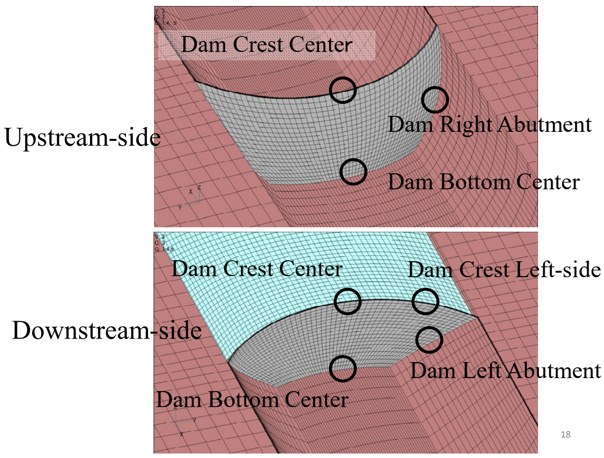


Fig. 7 – Representative position for output of tensile stress at dam

4.3 Seismic tensile stress in foundation rock

The distribution of tensile stress in the foundation rock generated by earthquake motion is shown in Fig. 8. Table 3 shows the values of maximum tensile stress at the representative output positions shown in Fig. 9.

At position D (upstream side of foundation rock below dam bottom), the values of maximum tensile stress became 3.98 N/mm^2, 3.99 N/mm^2, 3.54 N/mm^2, and 2.27 N/mm^2 for the sedimentation rates of 0%, 25%, 50%, and 75%, respectively. Thus, the maximum tensile stress at the position D decreased with the increase of sediment.

But, the maximum tensile stress at the position C (downstream side of right abutment of foundation rock) became 3.09 N/mm^2, 3.12 N/mm^2, 3.41N/mm^2, and 3.77 N/mm^2 for the sedimentation rates of 0%, 25%, 50%, and 75%, respectively. The maximum tensile stress by earthquake motion increased with the increase of sediment at position C.

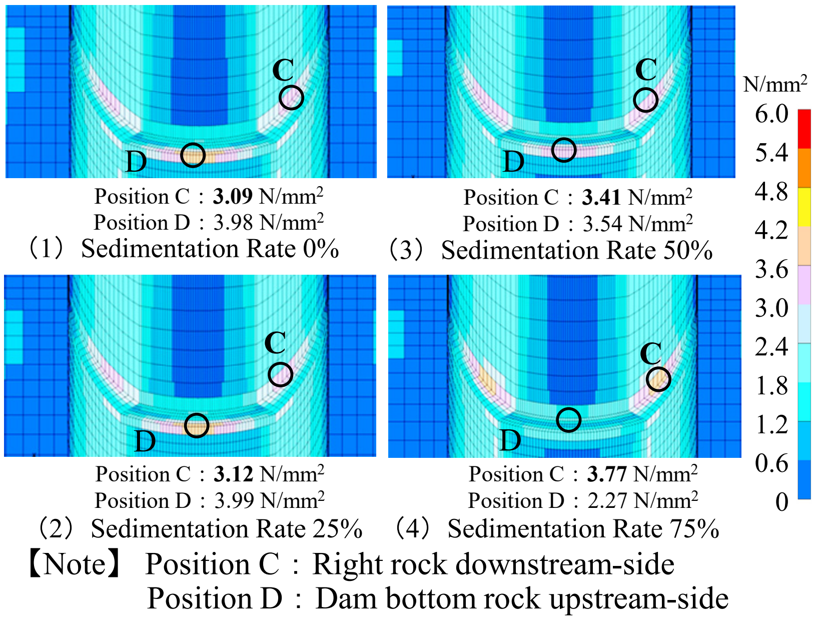


Fig. 8 – Distribution of maximum tensile stresses at foundation rock caused by earthuake motion

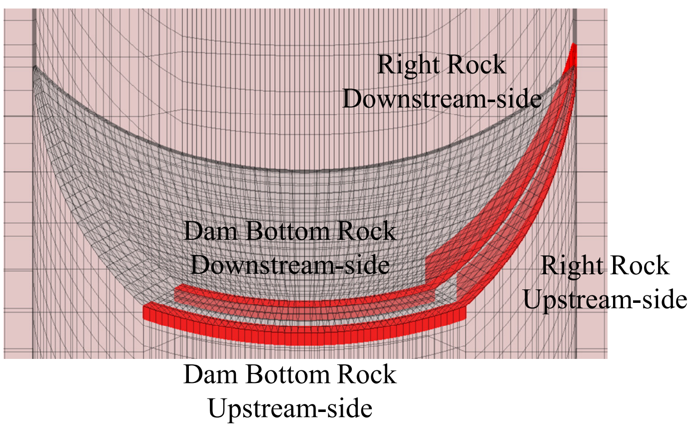


Fig. 9 – Representative position for output of tensile stress at foundation rock

Table 3 – Comparison of maximum tensile stress at foundtion rock

Position at foundation rock		**Maximum tansile stress (N/mm^2)**				**Note**
		Sedimentation rate				
		0 %	**25 %**	**50 %**	**75 %**	**(Tendency)**
Dam bottom Rock	Up-stream side *(D)	3.98	3.99	3.54	2.27	Decrease
	Down-stream side	1.80	1.83	2.04	2.20	Increase
Right abutment Rock	Up-stream side	1.52	1.51	1.48	1.46	Decrease
	Down-stream side *(C)	3.09	3.12	3.41	3.77	Increase

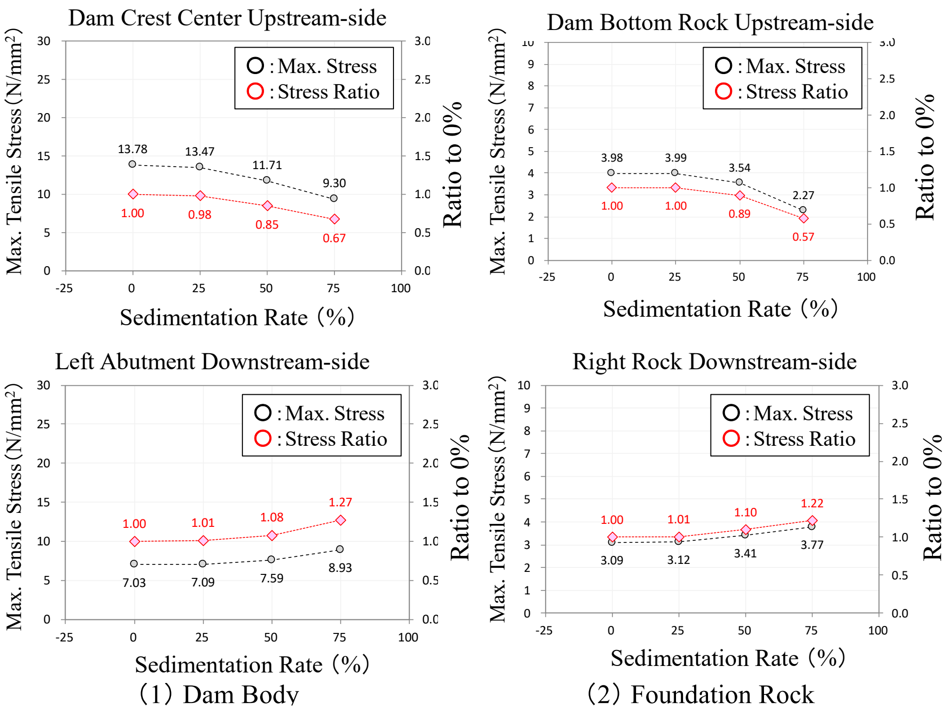
【Note】 *(C), *(D) : Position C and D shown in Fig. 8

4.4 Influence of sediment on maximum tensile stress at dan and foundtion rock

Analysis results regarding the influence of sediment on maximum tensile stress at dam and foundtion rock are summarized in Fig.10.

In regard to the dam body, as can be seen from Fig. 10, the maximum tensile stress by earthquake motion decreased on the upstream-side of crest center with the increase of sedimentat. But, the maximum tensile stress on the downstream-side of left abutment increased.

In regard to the foundation rock, the maximum tensile stress on the downstream-side of right rock increased with the increase of sediment. On the other hand, on the upstream-side of dam bottom rock, the maximum tensile stress decreased as the sediment increased.



【Note】 Ratio to 10% : Ratio of max. Tensile stress to Sedimentation Rate 0%.

Fig. 10 – Influence of sediment on maximum tensile stress at dan and foundation rock

5. Conclusions

◆In order to realize an accurate reliable evaluation for seismic safety of dam, infuluence of sediment on seismic response of dam was studied examined by 3-D dynamic analysis.

◆As a result, displacement of dam decreased as the sediment increased. If there is no sediment, the dam can behave alone. But, if the sediment is thick, the dam must behave as a coupled system with sediment.

◆It is considered that the sediment may have reduction effect on thr displacement behavior of dam.

◆In regard to the dam body, maximum seismic tensile stress on the upstream-side of dam crest center decreased with the increase of sediment. On the other hand, the maximum seismic tensile stress on the downstream-side of dam abutment increased as the sediment increased.

◆In regard to the foundation rock, maximum seismic tensile stress on the upstream-side of foundation rock decreased as the sedimentat increased. But, maximum seismic tensile stress on the downstream-side of foundation rock increased as the sediment increased.

◆It is considered that there appears two kinds of place as the result of the mutual effects among dam, sediment and foundation rock. One is the place where the seismic tensile stresses decrease, and the other is where they increase.

◆ If the seismic tensile stress decreases with the increase of sediment, the sediment will have an advantageous effect on the seismic safety of dam. However, if the stress increases, the effect of sediment will be disadvantageous. Therefore, it is necessary to carefully and precisely evaluate the seismic safety of dam when the seismic tensile stress increses with the progress of sedimentation.

◆Special attention should be paid when the seismic tensile stress increases in the foundation rock, because the seismic safety of arch dam largly depends on the stability of foundation rock.

◆Consideration should be given to future issues such as the effects of dynamic deformation property (dynamic shear modulus, damping factor) of sediment, the effects of discontinuous behaviour (opening, sliding) at the contact plane between sediment and dam, the effect of reservoir water.

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