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Dynamic Analysis of Seismic Behavior of Raised Concrete Gravity Dam during Large Earthquake

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ABSTRACT:

Raising the height of existing dams can be one of the most effective solutions to meeting the changing needs of flood control and water use in river basins. Meanwhile, evaluating the structural safety of dams against large scale earthquakes is one of the most important issues in the construction of new dams and the sustenance of existing dams.

In this paper, the seismic behavior of raised concrete gravity dams during large scale earthquakes is investigated through the use of numerical simulations, including a linear analysis and a non-linear dynamic analysis that considers the crack propagation accompanied by tension softening of dam concrete.

The analyses revealed that the damage caused to a raised concrete gravity dam resulting from a large earthquake is not the same as that of a newly constructed dam with the same shape. Further, it was determined that the damage depends on the height of dam raising and the water level of the reservoir during the raising work. Based on these results, it was pointed out that when evaluating the effect of seismic motion on a raised concrete gravity dam through the use of dynamic analysis, the process of raising work, including the placement of new concrete, and the actual water level of the reservoir during the raising work should be properly taken into consideration.

Keywords: upgrading, raising, concrete gravity dam, earthquake, dynamic analysis

1. INTRODUCTION

Dams are required to maintain their functions for very long periods. As a result, dams are sometimes required to adapt their functions to the changing situations of river basins, such as changes in rainfall characteristics and water demand. Under such circumstances, a dam upgrade project to enhance the functions of an existing dam may be more favorable to constructing a new dam. Raising an existing dam to increase its reservoir capacity is one of the most common methods to upgrade a dam. In Japan, among the options for upgrading existing dams, raising an existing concrete gravity dam, which is the subject of this paper, is most commonly selected.

At the same time, in Japan, ensuring structural safety against large earthquakes is a very important issue. Therefore, for both new and existing dams, including those which were designed in accordance with present structural design standards, efforts have been made to conduct seismic performance evaluations that, based on the most recent findings of surrounding active faults and plate boundaries, consider earthquake scenarios that would cause the strongest ground motion at each dam site. With regard to concrete gravity dams, Japanese draft guidelines for seismic performance evaluations of dams (MLIT, 2005), hereinafter called *the Guidelines*, require an estimation of earthquake induced damage, including crack propagation of a dam's body, by using non-linear dynamic analysis that considers tension-softening of dam concrete. Further, judgment of whether the expected damage would cause an uncontrolled release of reservoir water is also required.

Nevertheless, the seismic behavior of raised concrete dams during large earthquakes is yet to be fully understood. To evaluate the seismic safety of a raised dam appropriately, it is necessary to consider several characteristics that are unique to dams of this type. Among them is the stress distribution characteristics on the inside of a dam body under usual (non-earthquake) conditions. In the case of a raised dam, the self-weight of the dam body as well as the hydraulic loading increase after the raising work completes. Such changes in loading condition produce stress redistribution within the dam body. In order to appropriately evaluate the structural safety of a raised dam against large earthquakes, it is necessary to consider these processes which determine the initial stress state, a factor which affects the stress state during an earthquake.

In this research, the seismic behavior of a raised concrete gravity dam during a large earthquake is simulated by considering the above-mentioned matters and by using linear and non-linear dynamic analyses. Based on the results of the numerical simulations, the stress distribution calculated by linear analysis and the damage region expected by non-linear analysis which considers crack propagation under large seismic of a raised dam are compared with that of a newly constructed dam with the same cross sectional shape and to cases of different height raises.
In addition, the effect of differences in reservoir water levels during the raising work is investigated. The water level condition is often subject to the function of the dam required even during the raising work as well as the condition of the raising work, and also possibly affects the stress state of a raised dam.

2. OUTLINE OF NUMERICAL ANALYSES

Assuming that a concrete gravity dam is raised directly on the same axis as the existing dam by increasing its width on the downstream face side, both the stress state under usual (non-earthquake) conditions and the seismic behavior during a large earthquake were analytically investigated using the numerical simulations. The stress state under usual (non-earthquake) conditions was simulated by using linear analysis with a two-dimensional finite element model, consisting of a dam body, foundation and reservoir water. The dynamic behavior of the raised dam under large earthquakes was simulated by using the linear and non-linear dynamic analyses. The non-linear dynamic analysis was performed using the smeared crack model by considering crack propagation caused by tension softening of dam concrete. An analysis code of ISCEF was used for these simulations.

The analysis was performed for a total of 7 cases, as shown in Table 1. The height of the model dam (new or raised) in each case was equal to 90 m. Case 1 is a model of a newly constructed dam with the same height and cross section shape as the basic model of a dam that is raised from 70m to 90m (Case 3). The Case 2 and 4 are models of a raised dam with different raised heights from Case 3. Another three cases (Cases 3a, 3b and 3c) are models with different water levels during the raising works. The heights of the existing dam in these cases are the same as Case 3.

As an example, the analysis model of Case 3 is illustrated in Fig. 1. For each case, the slope of the upstream face is vertical. The slope of the downstream face of the existing dam was set to the steepest ratio, a ratio at which tensile stress was not generated at the heel of the dam body when applying a static analysis based on the beam theory by assuming a horizontal seismic coefficient of 0.10 and an uplift coefficient of 0.33. The slope of the downstream face for the raised part of each of the raised dam models and the newly constructed dam model (Case 1) was set to 1:0.86. This ratio was equivalent to the steepest slope at which the tensile stress was not generated at the heel of the dam body in the basic model of a raised dam (Case 3), when the traditional static analysis to determine the basic sectional shape of a raised dam by considering the increased weight of the dam body and hydraulic loading. With these conditions, the value of the safety factor for shear sliding along the dam base was not less than the value required by the Japanese design standard (=4.0) when the pure shear strength of foundation rock (τ_0) was greater than or equal to 1.6 N/mm^2 and the internal friction angle ϕ = 45°. This level of shear strength is generally required for foundation rock of concrete gravity dams.

Table 1 Analysis cases

Case (Model)		Dam height (m)		Reservoir water level (m)		Downstream surface slope	
		Existing dam	After raised	During raising works	After raised	Existing dam	After raised
1	Newly constructed	90		85		1:0.86	
2	Raised	50	90	40(80%)	85	1:0.71	1:0.86
3	Raised	70	90	56(80%)	85	1:0.74	1:0.86
3a	Raised			42(60%)			
3b	Raised			21(30%)			
3c	Raised			0(empty)			
4	Raised	80	90	64(80%)	85	1:0.75	1:0.86

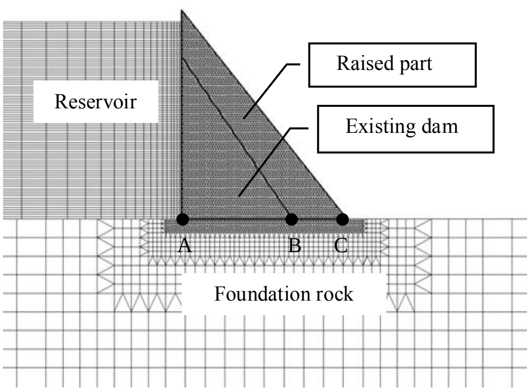


Fig. 1 An example of finite element model of raised dam (Enlarged view around dam body)

The physical properties of dam concrete and foundation rock used in analyses are shown in Table 2. The tension-softening characteristic of dam concrete that were assumed for the non-linear dynamic analysis is shown in Fig. 2. The stress at the start of the tension softening was assumed to be equivalent to the tensile strength of the concrete in Table 2, and the value for fracture energy G_f was set to 300N/m, considering the experimental formula for dam concrete proposed by Horii, et al.(2000);

$$G_f = (0.79G_{max} + 80) \times (f'_{ck}/10)^{0.7}$$

where f'_{ck} (N/mm^2) is the compressive strength of dam concrete and G_{max} (mm) is the maximum aggregate size. The value of G_f shown above was set by assuming f'_{ck}= 24N/mm2 and G_{max}=150mm. The joint between existing dam body and raised part was assumed to be well integrated and modeled by using linear joint elements with a stiffness equivalent to dam concrete.

The horizontal and vertical components of input earthquake motion that were used for the dynamic analysis are shown in Fig. 3. This earthquake motion was generated from a wave form observed during the Southern Hyogo Prefecture (Kobe) Earthquake in 1995 (Mw* 6.9, *moment magnitude) at the base of a concrete gravity dam near the epicenter by modifying its amplitude to meet the minimal acceleration response spectrum for the seismic performance evaluation shown in *the Guidelines* (MLIT, 2005). Moreover, in order to clearly understand the differences in damage (cracks) generation under the different analysis conditions, the non-linear analysis was also performed for the earthquake motion with twice the amplitude of the earthquake motion shown in Fig. 3.

Table 2 Physical properties used for the analysis.

	Density (kg/m^3)	Modulus of elasticity (N/mm^2)	Poisson ratio	Tensile strength (N/mm^2)	Fracture energy (N/m)
Dam body	2,300	25,000	0.2	2.0	300
Foundation rock	2,300	25,000	0.3		

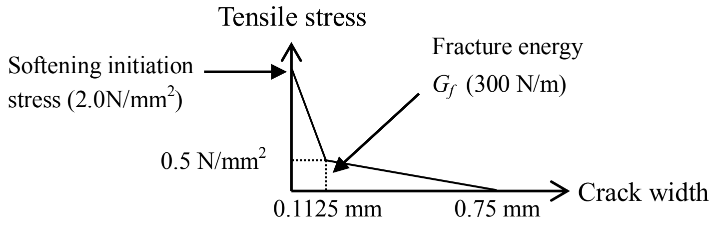


Fig. 2 Tension softening diagram of dam concrete assumed for non-linear analysis

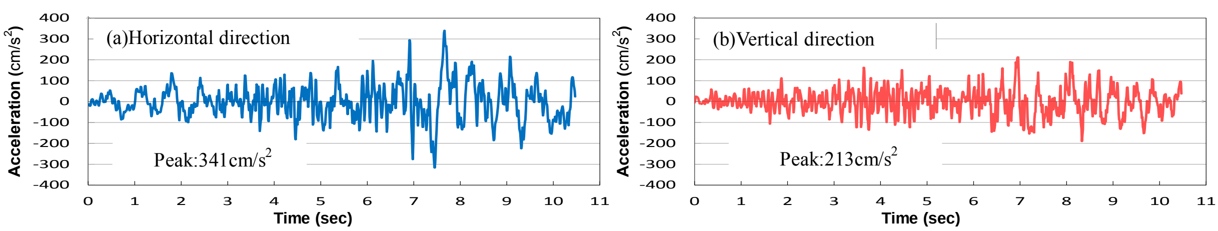
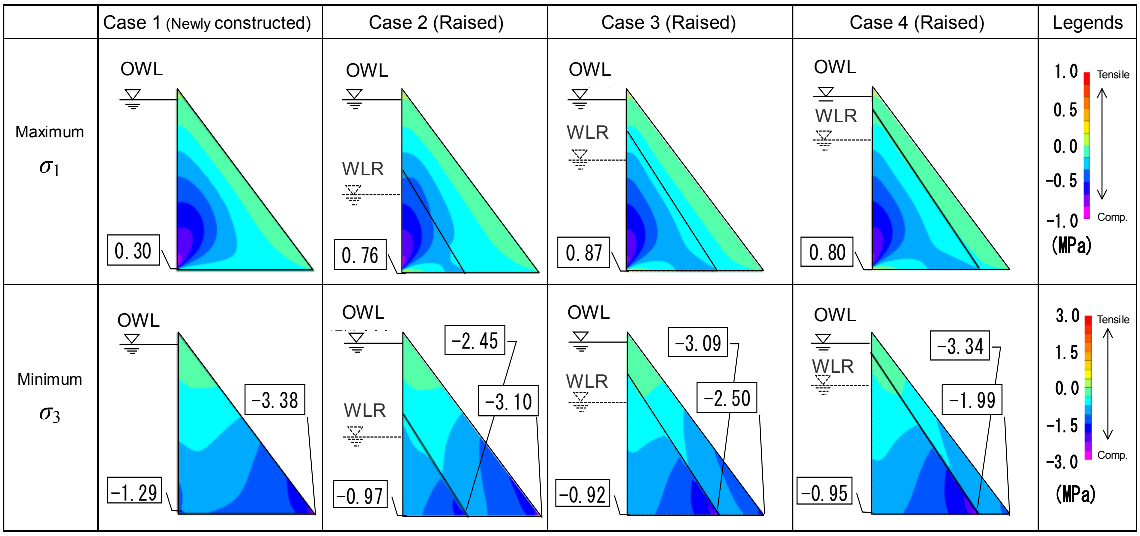


Fig. 3 Earthquake motion for dynamic analysis

3. ANALYSES RESULTS AND DISCUSSIONS

3.1. Stress distribution calculated from linear analysis

The initial stress distribution inside the dam under usual (non-earthquake) conditions that was obtained by linear analysis is shown in Fig. 4. The maximum tensile stress is generated at the heel of the dam (indicated as point A in Fig.1) in each case, while the maximum compressive stress is generated at the downstream face of the existing dam part (point B in Fig.1) or at the toe of the raised dam (point C in Fig.1). However, in each case, the maximum value of these stresses is much less than the assumed strengths of dam concrete (24 N/mm^2 in compression, 2.0 N/mm^2 in tension). For the raised dam models (Cases 2, 3 and 4), it was also found that compressive stress is maximized at point C if the height of raising (and increment in width) is large, but the compressive stress at point B becomes relatively larger if the height of raising is low.



OWL: Operational Water Level after raised, WLR: Water Level during Raising works

Fig. 4 Stress distribution in the usual (non-earthquake) condition

Next, the linear dynamic analysis was performed to understand the characteristics of stress distribution inside the dam body during a large earthquake. The obtained distribution of the maximum and minimum principal stress (σ_1, σ_3) is shown in Fig. 5. In each case, the maximum value of the compressive stress is smaller than the compressive strength of dam concrete, but the value of the tensile stress locally exceeds the tensile strength of dam concrete around the heel of the dam. In addition, the maximum value of the tensile stress at this point is higher for the raised dam models (Case 2, 3 and 4) than the newly constructed dam model (Case 1). Moreover, for each case, the tensile stress turns out to also be generated around the toe of the dam, even though it is smaller than that calculated around the heel of the dam. Its magnitude is larger in the raised dam models than the newly constructed dam model, and almost reaches the assumed tensile strength of dam concrete if the height of raising (and increment in width) is small (Case 4). The maximum stresses at the points of interest (Points A, B and C in Fig.1) that were calculated under the linear dynamic analysis are compared with values under usual conditions in Fig. 6. The increment of maximum tensile stress during earthquakes from the usual condition becomes larger when the height of raising becomes low. These results mean that careful attention needs to be paid, more in the case of raised dams than newly constructed dams to the tensile stress, especially in the case of relatively low (or thin) raising.

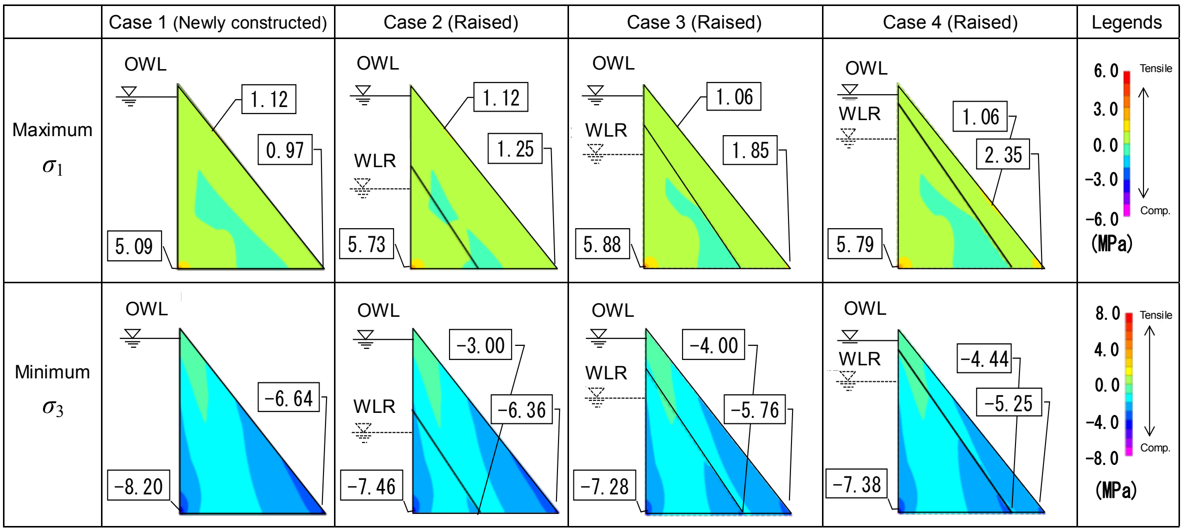


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Fig. 5 Maximum stress distribution during large earthquake (341 cm/s^2, linear analysis)

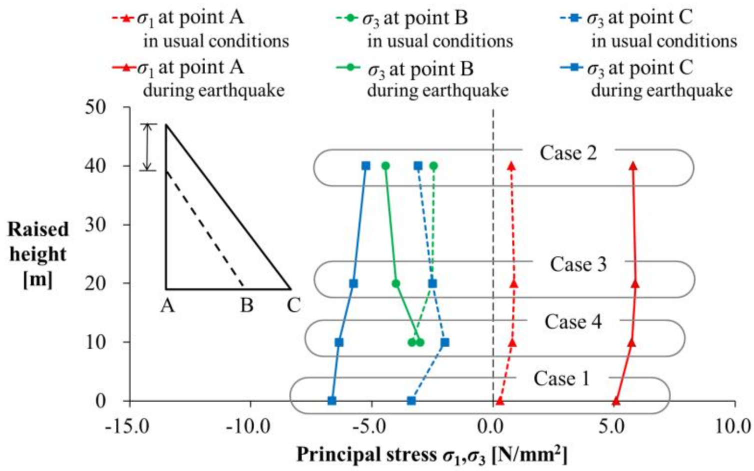
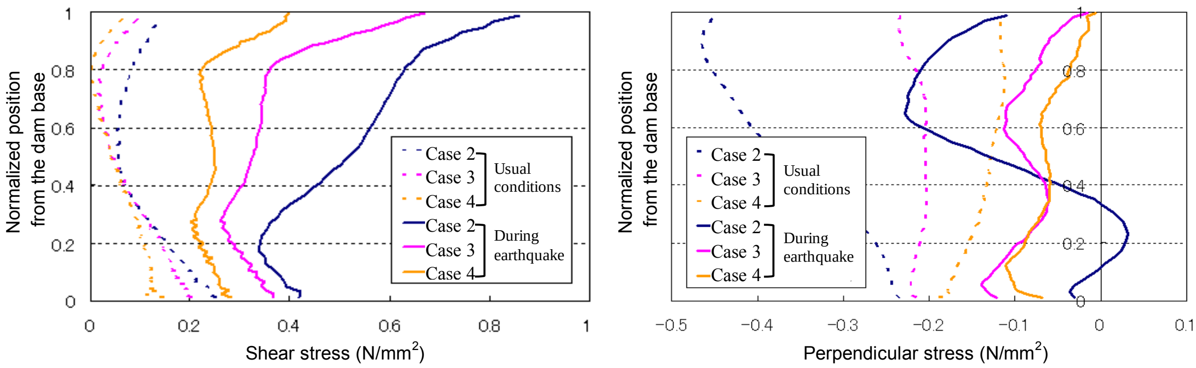


Fig. 6 Comparison of the maximum principal stresses at selected points (Case 1,2,3,4)

Meanwhile, one of the most significant structural characteristics of the raised dams is the existence of a joint surface between the existing and raised part of the bodies. As to this joint surface, in order to avoid making a weak plane, careful precautions are usually taken, such as chipping the surface of the existing dam and then laying rich mortar before placing the concrete of the raised part. In addition, for the sake of preventing cracks, rabers are often inserted. In order to confirm that these design and construction procedures are enough to integrate the joint surface well, it is considered important to investigate the effects of large earthquake motions by focusing on this joint surface. For this purpose, the distributions of the maximum shear stress along the joint surface and the maximum stress perpendicular to the joint surface during a large earthquake, which are derived from the result of the linear dynamic analysis are shown in Fig. 7. If the height of the raised dam is the same, the shear stress along the joint surface is increased as the height of rising becomes high, both in the usual condition and during the earthquake, although the maximum value of the shear stress is less than 1.0 N/mm^2. This value is quite less than the shear strength of dam concrete if it is assumed to be 20% of the compressive strength (24N/mm^2). The stress perpendicular to the joint surface is compressive in the whole region on the joint surface in the usual condition, and in almost all regions during the earthquake, although the tensile stress, which is quite less than the tensile strength, is calculated at low positions only in Case 2. These results indicate that, under the conditions assumed in this analysis, neither the shear failures nor tensile fractures along the joint surface between the existing dam and the raised part is likely to occur, if appropriate procedures are taken to make the joint surface well integrated.



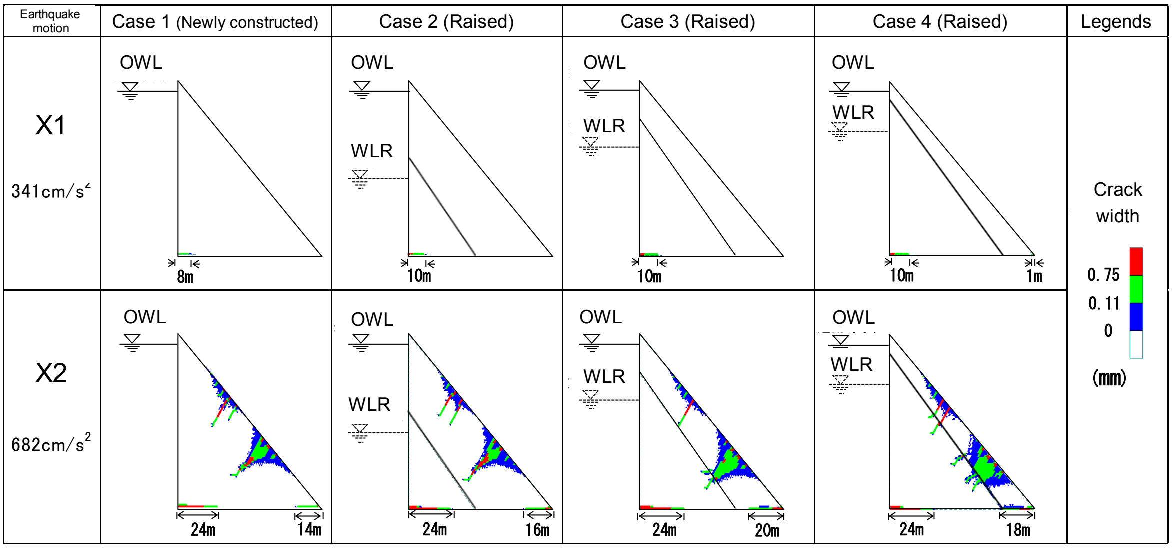
(a) Maximum shear stress (b) Maximum vertical stress

Fig. 7 Stress distribution on the joint surface between existing dam and raised part

3.2. Simulated damage by using non-linear dynamic analysis

In the linear dynamic analysis, as shown in Fig. 5, the calculated tensile stress exceeded the tensile strength of dam concrete, although locally around the heel of dam. This result means there is the possibility of damage (cracks into dam body) resulting from tension softening. Thus, a non-linear dynamic analysis accounting for crack propagation caused by the tension softening of dam concrete as shown in Fig.2 was performed. In order to make the differences in damage region clear between the different conditions, non-linear analysis was performed for both the earthquake motion shown in Fig.3 (the maximum acceleration of 341cm/s^2 in the horizontal direction, hereinafter called “X1”) and also for the motion with twice the amplitude (682cm/s^2, ”X2”).

As the analysis result, the region of tension softening generation of dam concrete, together with the distribution of the crack width for each case is shown in Fig.8. In the case of the earthquake motion X1, it was found that a horizontal crack is generated from the heel of the dam, where the maximum tensile stress has been calculated in the linear analysis, and extending along the dam base. In the case of the earthquake motion X2, the crack along the dam base form the heel of the dam extends further toward the downstream side, and new cracks are generated in the downstream side of the dam, which includes the horizontal one from the toe of the dam and the diagonal ones spreading in relative large area from the downstream face.



OWL: Operational Water Level after raised, WLR: Water Level during Raising works

Fig. 8 Damage region due to tension softening of concrete during large earthquake (Case 1,2,3,4)

Comparing the crack propagation area in the newly constructed dam model (Case 1) and the raised dam models (Cases 2, 3 and 4), there are no major differences between these models. To have a detailed view, however, for the case of earthquake motion X1, the horizontal crack from the heel of the dam, a factor which is likely to affect the stability of the dam by triggering the increment of uplift, is slightly longer in the cases of raised dam (Case 2, 3 and 4) than was simulated in the cases of the newly constructed dam (Case 1). Additionally, the downstream side damage regions, simulated in the case of earthquake motion X2, reach the joint surface between the existing dam part and the raised part when the raising height is small.

If the dam body is not completely separated as a result of the cracks penetrating from upstream face to the downstream face, the uncontrolled release of reservoir water caused by damage to the dam body will not occur. According to this concept which is commonly adopted in many guidelines for seismic safety of dams, including Japanese ones, if the joint surface is not the potentially weak plane as a result of various precautions taken in the raising works mentioned above, the requirement for seismic safety should be ensured even if the cracks simulated in the analysis are actually generated. This also means if the actual joint surface is not in good condition, the effect of the damage on the stability of the raised dam should be considered carefully.

3.3. Effect of differences in water level conditions during raising works

In order to investigate the effect of differences in water level conditions during the raising works, stress distribution, both in the usual condition and during the large earthquake (X1) that was calculated from the linear analysis for cases in which only the condition of temporary water level during the raising works is different (Cases 3, 3a, 3b, and 3c), were compared together in Fig.9.

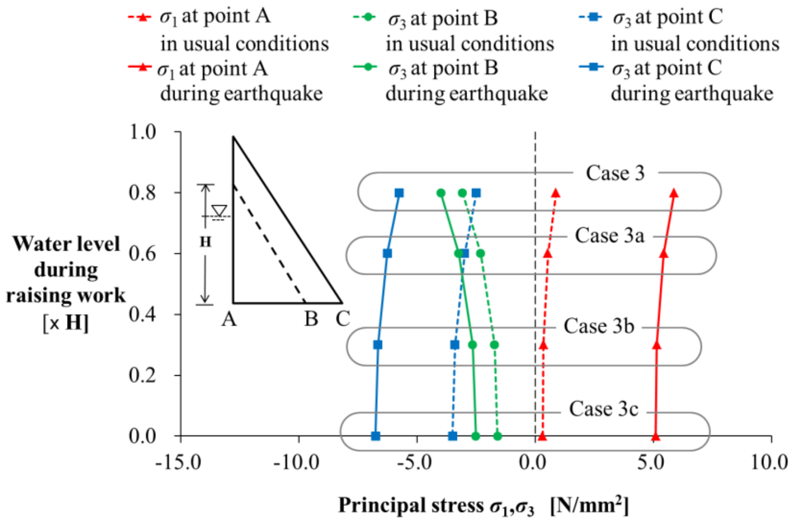
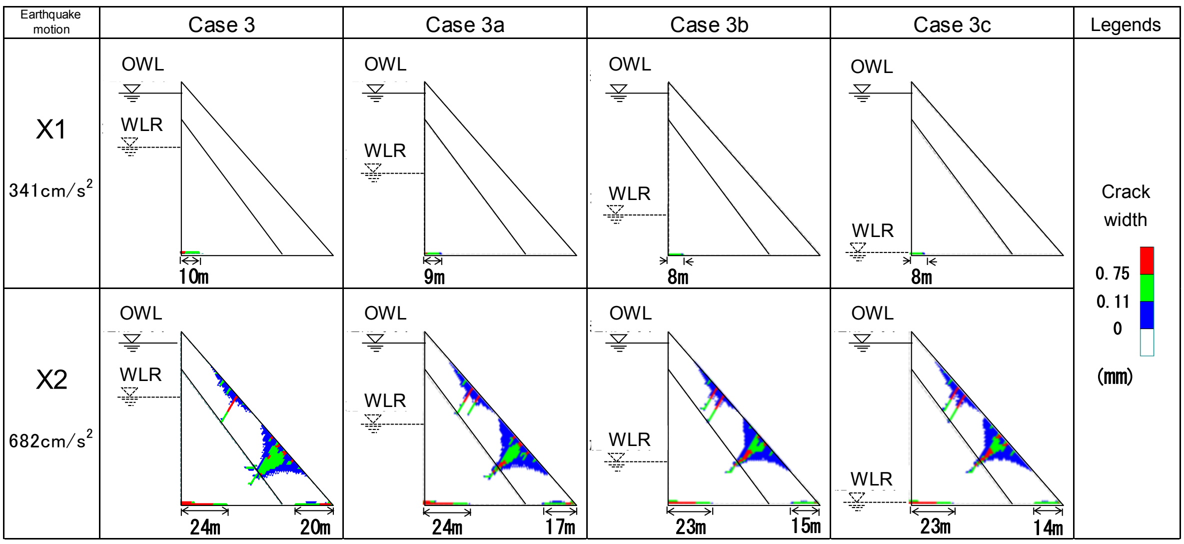


Fig. 9 Comparison of the maximum principal stresses at selected points (Case 3,3a-c)

It was found that, both under usual conditions and during the earthquake, the maximum tensile stresses calculated form linear analyses at the heel of dam (point A in Fig.1), which affects the stability of the dam the most, and the maximum compressive stress at the surface of the existing dam part (point B), are increased as the water level during the raising works becomes high, while the compressive stress at the toe of the dam (Point C) is decreased.

In Fig.10, an estimation of damage regions, where tensile cracks may propagate during the large earthquake (X1, X2), are indicated as results of the non-linear dynamic analysis for the same cases. The result shows that the horizontal cracks generated from the heel and toe of the dam become slightly deeper with increasing water levels during raising works.



OWL: Operational Water Level after raised, WLR: Water Level during Raising works

Fig. 10 Damage region due to tension softening of concrete during large earthquake (Case 3,3a-c)

Based on these results, in estimating the seismic behavior during large earthquakes to evaluate the seismic safety of a raised dam, it would be preferable to consider the actual water level during the raising work. In addition, if the sectional shape of a raised dam has to be checked before the actual reservoir operation rule to be effected during raising works is determined, it would basically be a safe-side condition to perform the analysis assuming the operational water level of the existing dam.

4. CONCLUSION

The stress state of the raised concrete gravity dam in the usual (non-earthquake) condition and the seismic behavior during large earthquakes were investigated by linear and non-linear analyses. Through the study based on these analyses, several important characteristics which should be considered when designing or conducting seismic safety evaluation of a raised concrete gravity dam were pointed out, as shown below:

1) The stress state inside a raised dam is different from a newly constructed dam with the same cross section shape, both under usual conditions and during earthquakes. Careful attention needs to be paid to the tensile stress generated during large earthquakes more in the case of raised dams than newly constructed dams.
2) The stress state inside a raised dam also varies depending on the raising height, even the cross sectional shape of the raised dam is same. Careful attention to tensile stress needs to be paid, especially in the case of a relatively small (or thin) raising project.
3) The water level condition during the raising works also affects the stress state inside a raised dam. When estimating the seismic behavior during large earthquakes to evaluate the seismic safety of a raised dam, it would be preferable to consider the actual water level under the construction, or assume the operational water level of the existing dam.

Finally, though not considered in the analyses, the seismic behavior of a raised dam would be affected by differences in physical properties of the dam concrete and foundation rock of the existing part and raised part. The thermal stress of dam concrete would also have an affect on it. The actual design or seismic safety evaluation of a raised dam should be conducted by considering these aspects as much as possible.

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Seismic Analysis of Concrete Gravity Dam Installing New Outlet Conduit into Existing Dam Body

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ABSTRACT

To meet changing needs for flood control or water supply in river basin with effective use of existing stock, installing new or additional outlet works into existing dam body by drilling can be one of the most effective solutions in terms of both cost and impact on natural environment. Meanwhile, seismic safety of existing dam against large earthquakes has become to be required more strongly in Japan.

In this paper, seismic behavior of a concrete gravity dam during large earthquakes is investigated focusing on damage to dam body around new or additional outlet conduit which is installed into existing dam body by using numerical simulations including non-linear dynamic analysis considering crack propagation accompanied with tension softening of dam concrete.

The analyses revealed that the estimated damage into dam body around the new or additional conduit is not the same as the case of newly constructed dam with conduits. It means that when evaluating the seismic safety of dams installing conduit into existing dam body by using numerical analyses, construction process that includes drilling and lining, as well as reservoir water level during and after construction works should be taken into consideration. From the analyses, it was also revealed that rebars around the new conduit are effective in reducing crack opening and extension into existing dam body.

Keywords: upgrade, drilling, outlet conduit, earthquake, dynamic analysis.

1. INTRODUCTION

In Japan, there are some existing dams upgraded by installing a new or additional outlet conduit into the dam body instead of constructing a new dam to meet changing needs for flood control or water supply in river basin with effective use of existing stock. When designing an upgrade dam by drilling its dam body, structural stability equal to that of a new dam is ensured by methods such as a theoretical solution based on a perforated infinite plate, 2-dimensional finite element model (hereafter called “FE model”) analysis (method based on combining two types of 2-dimensional analysis; for the cross-section and for longitudinal section) or 3-dimensional FE model analysis for the conduit drilled block.

On the other hand, in response to growing public concern regarding the safety of civil engineering structures against large-scale earthquakes, trials of seismic the performance evaluation of dams hypothesizing the maximum class of earthquake that can be predicted at the site of each dam have begun in Japan. In the case of concrete gravity dams, the Japanese draft guidelines for seismic performance evaluation of dams (MLIT, 2005, called "the Guidelines" hereafter and introduced by Shimamoto, et al. 2007), require to estimate damage processes of dams and judge whether the expected damage will not cause the uncontrolled release of reservoir water. The Guidelines are intended for both existing and newly constructed dams. However, the evaluation method which considers structural characteristics unique to dams with added or newly installed conduit by drilling has not been fully established. The stress state inside dam body, especially inside the monolith which is drilled to install the new conduit will differ from that of a newly constructed dam. This is because the stress around a new conduit is redistributed when infilled concrete is placed after drilling to install a new conduit. The reservoir water level during drilling works would also affect the stress state around the new conduit. Therefore, to evaluate seismic safety of dams installed a new conduit, it is necessary to estimate the stress state in the usual condition (non-earthquake) considering the actual process of dam upgrading works by drilling an existing concrete dam.

In this research, stress analyses are conducted by using the FE model of a monolith in which a new conduit is installed considering the actual process of upgrading works by drilling. And seismic response analyses hypothesizing a large-scale earthquake are also conducted in order to help establish a seismic performance evaluation method for dams upgraded by drilling their dam bodies and installing an additional conduit. From these analyses, the characteristics of the stress state in the usual (non-earthquake) condition and during a large-scale earthquake are investigated. The possibility of damage to a dam installed a new conduit are also investigated.

2. ANALYSIS METHOD AND ANALYSIS CONDITIONS

The stress state in an upgraded concrete gravity dam drilled through its dam body from the downstream side to the upstream side to install an additional conduit (hereafter called "a drilled dam") in usual condition, differs from that in a newly constructed dam (hereafter called "a newly constructed dam") when considering its construction process including drilling the dam body, lining, and raising the water level to the operating water level after installing the new conduit. Therefore, static analyses were first conducted to calculate the initial stress state. Next, dynamic analyses considering large earthquakes were conducted to investigate the stress state and damage area around new conduits. In the dynamic analyses, the effect of rebars which are often installed around the conduit of actual upgraded dams in order to reduce the damage to concrete around the conduit caused by tension cracking was also investigated.

2.1. Analysis method

In order to investigate behavior in a drilled dam during a large-scale earthquake, numerical analysis using a 3-dimensional FE model consisting of dam body, foundation and reservoir was conducted. Firstly, static analysis considering the actual process of upgrading works which includes drilling, lining and raising the reservoir water level was conducted to simulate stress in the usual condition. After that, linear dynamic analysis was conducted to simulate stress when a large-scale earthquake has struck after operation of the dam has restarted. The stress calculated from this static analysis was used for the following dynamic analysis as the initial stress. Next, linear dynamic analysis was conducted to calculate the stress distribution around the conduit. And non-linear dynamic analysis considering the tension cracking of concrete was also conducted to investigate the state of damage around the conduit by using the smeared crack model which can simulate a state of crack generation and extension, without setting positions of crack beforehand. An analysis code, "ISCEF" was used for these simulations.

2.2. Analysis model and material properties values

Fig. 1 and Fig. 2 show the shape and meshing of the analysis model. Half of the monolith in which a new conduit was installed by drilling was modeled considering the symmetry of model shape. The diameter of the hole drilled for the conduit and the internal diameter of conduit in this model were set considering past works on actual dams in Japan. Reservoir was modeled using incompressible fluid elements. Hydrostatic and hydrodynamic pressures acting on the dam body from reservoir were considered. Those in the conduit were not considered.

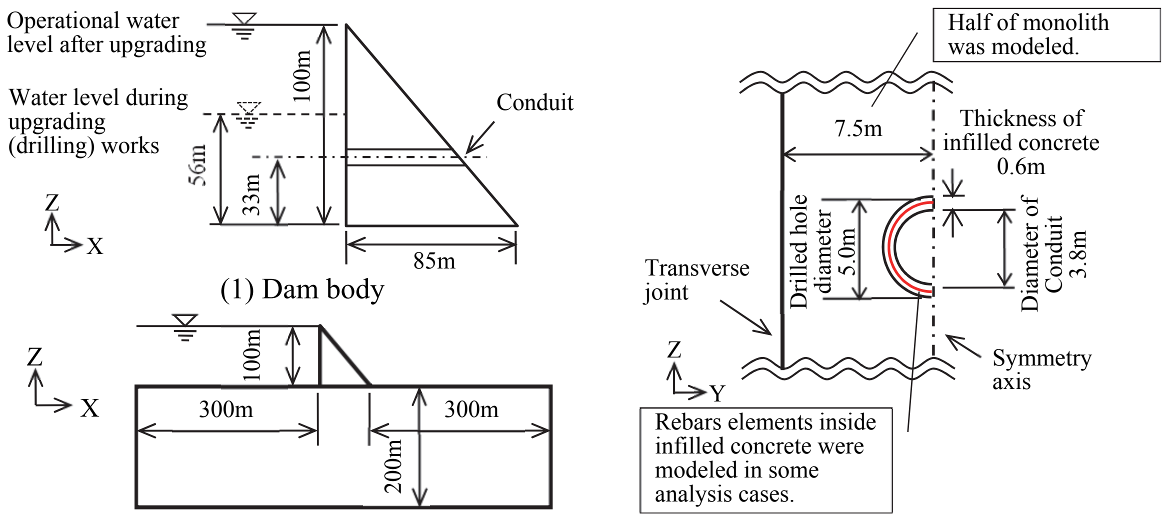


Figure 1. Shape of the analysis Model

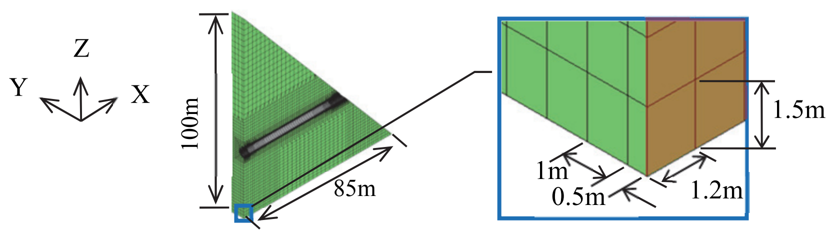


Figure 2. Meshing of the Analysis Model (dam body)

In the analysis cases of drilled dams, for the usual condition, a series of steps upgrading works process which consists of drilling a hole slightly larger than the diameter of the conduit that will be installed, installing rebars, then lining by concrete were set, while the analysis case for comparison, hypothesizing a new dam with an installed conduit of which diameter equal to that of a drilled dam.

In some drilled dam cases, the rebars were modeled by rod elements and were arranged longitudinally along the full length of the conduit. The required quantity of rebars was set by the traditional design method based on the condition that rebars bear the tensile force generated when a void with conduit diameter is formed, assuming the horizontal seismic coefficient of 0.15. The total section area of rebars per unit length (upstream-downstream direction) in this analysis model is constant. The steel conduit pipe is not modeled.

Table 1 shows the material property values for the analysis. When conducting non-linear dynamic analysis, the material property values in Table 2 and the tensile softening model shown in Fig. 3 were also used. The stress at the start of the tension softening was assumed to be equivalent to the tensile strength of the concrete (2.0N/mm^2). The value for fracture energy G_f was set as 300N/m considering Eq. 1, the experimental formula for dam concrete proposed by Horii, et al. (2000);

$$G_f = (0.79G_{max} + 80) \times (f'_{ck}/10)^{0.7} \qquad (1)$$

Where f'_{ck} (N/mm^2) is the compressive strength of dam concrete and G_{max} (mm) is the maximum aggregate size. The value of G_f shown above was set by assuming f'_{ck}= 24N/mm^2 and G_{max}=150mm. For infilled concrete, G_f was set as 90N/m based on Eq. 2, formula for ordinary concrete which is shown in the Japanese standard (JSCE, 2012) under the condition that d_{max}(=G_{max} in Eq. 1) is 40mm and f'_{ck} =2.0N/mm^2.

$$G_f = 10(d_{max})^{1/3} \cdot {f'_{ck}}^{1/3} \qquad (2)$$

For tensile softening properties, bi-linear type diagram (JSCE, 2012) was assumed.

Table 1. Physical Property Values

Model	Density (kg/m^3)	Modulus of elasticity (N/mm^2)	Poisson ratio
Dam body concrete	2,300	25,000	0.2
Infilled concrete	2,300	25,000	0.2
Rock foundation	2,300	25,000	0.3
Rebars	-	200,000	0.3

Table 2. Material Property Values for Non-linear Dynamic Analysis

Model	Tensile strength (N/mm^2)	Fracture energy G_f (N/m)	Tensile softening properties
Dam body concrete	2.0	300	Fig. 3
Infilled concrete	2.0	90	Fig. 3
Rebars	345(*Yield stress)	-	-

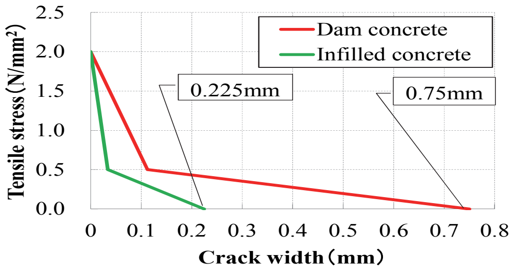


Figure 3. Tensile Softening model in Non-linear Dynamic Analysis

2.3. Input earthquake motion

The horizontal and vertical components of input earthquake motion basically used for the dynamic analysis are shown in Fig. 4. This earthquake motion was generated from a wave form observed during Southern Hyogo Prefecture (Kobe) Earthquake in 1995 (Mw* 6.9, *Moment magnitude) at the base of a concrete gravity dam near the epicenter by modifying its amplitude to meet the minimal acceleration response spectrum for the seismic performance evaluation shown in the Guidelines (Fig . 5, MLIT, 2005).

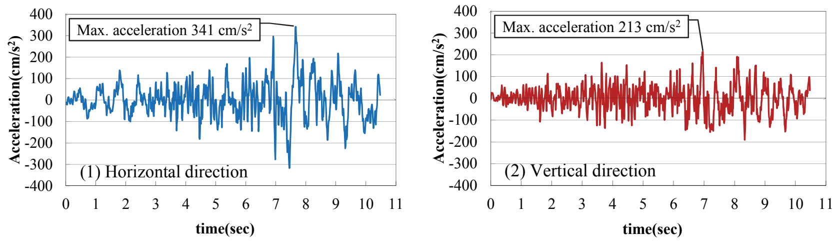


Figure 4. Input Earthquake Motion

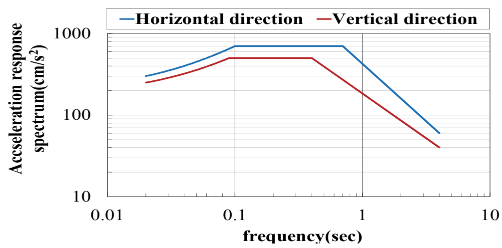


Figure 5. The minimal acceleration response spectrum in the Guidelines

2.4. Analysis cases

Table 3 shows analysis cases in this investigation. Five analysis cases were performed for different combinations of quantities of rebars for a drilled dam model and a newly constructed dam model.

Table 3. Analysis case

Case		Rebars quantity*	Remarks
1a 1b	Drilled dam	0 (none)	1a:Linear dynamic analysis 1b:Non-linear dynamic analysis
2a 2b	Newly constructed dam		2a:Linear dynamic analysis 2b:Non-linear dynamic analysis
3a 3b	Drilled dam	100%	3a:Linear dynamic analysis 3b:Non-linear dynamic analysis
4	Newly constructed dam		Linear dynamic analysis
5	Drilled dam	50%	Non-linear dynamic analysis

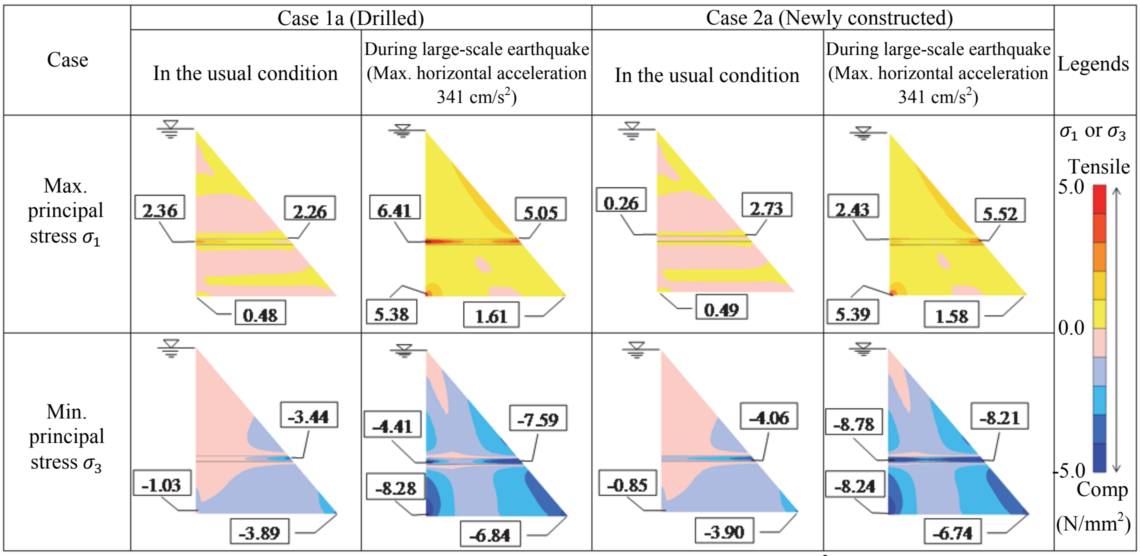
*Percentage of quantity of rebars to required one in newly constructed dam (quantity of rebars based on condition that rebars bear the entire tensile force generated when a void with conduit diameter is formed).

3. ANALYSIS RESULTS

3.1. Comparison between drilled dam and newly constructed dam

Based on the results of the linear dynamic analysis, Fig. 6 shows the distribution of values of principal stress inside the dam body (center section of drilled monolith) in the usual condition and during a large-scale earthquake in a drilled dam (Case 1a) and a newly constructed dam (Case 2a). The values in the figure are the simulated local maximum or minimum principal stress values and their locations.

Looking at the stress distribution in the usual condition, in the drilled dam (Case 1a), the tensile stress of infilled concrete near the upstream surface is higher than that in the newly constructed dam (Case 2a) and its value is almost comes near the assumed tensile strength of dam concrete. And the stress distribution during a large-scale earthquake shows that the tensile stress around the conduit in the drilled dam (Case 1a) becomes larger than the tensile strength of dam concrete both around upstream face and downstream face side, while in the newly constructed dam (Case 2a), the tensile stress during a large-scale earthquake is larger than the tensile strength only near the downstream face side.



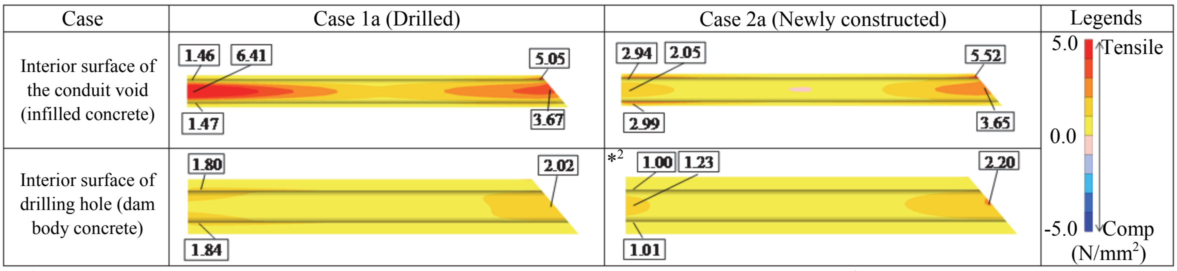
*The values in the figure are the simulated local maximum or minimum principal values (N/mm²) and their locations.

Figure 6. Maximum and Minimum Principal Stress inside Dam Body (Linear Dynamic Analysis)

The simulated compressive stress inside the dam body is sufficiently small under the assumed compressive strength of dam concrete even during a large-scale earthquake in both Case 1a and Case 2a. Therefore, the following discussion focuses on tensile stress. Fig. 7 enlarges the maximum principal stress σ_1 around the conduit based on the same analysis results shown in Fig. 6.

In the drilled dam (Case 1a), the tensile stress value is highest on the upstream side of the dam body concrete, and also tends to be concentrated at the top edge and the lateral side of the conduit void on the downstream side. And at these locations, the tensile stress value exceeds the assumed tensile strength of the dam concrete over a wide range. On the interior surface of the drilling hole (dam body concrete), the tensile stress is also concentrated near the downstream surface of the dam body. And its value almost nears the tensile strength of the dam concrete.

In contrast, in the newly constructed dam (Case 2a), the tensile stress is highest at the top edge of the conduit void near the downstream surface, and its value exceeds the assumed tensile strength of the dam concrete. In addition, the tensile stress is also a little high at the top of the conduit void on the upstream side and the lateral side of the conduit void on the downstream side. These tensile stress values exceed the tensile strength of the dam concrete.



*1 The values in the figure are the simulated local maximum or minimum principal values (N/mm^2) and their locations.
*2 Stress distribution on the cylindrical cross section with the diameter equivalent to that of drilling hole in the drilled dam (Case 1a).

Figure 7. Maximum Principal Stress σ_1 around Conduit during Large-scale Earthquake (Linear Dynamic Analysis)

Judging from above mentioned results, in evaluating the seismic safety of dams against a large-scale earthquake, it would be preferable to conduct a static analysis to simulate the initial stress state, for not only a drilled dam, but also the monolith with a conduit in a newly constructed dam.

As a result of linear dynamic analysis, the simulated tensile stress value exceeds the assumed tensile strength of the concrete locally, so non-linear dynamic analysis was conducted considering tension softening of the concrete. Fig. 8 shows the estimated damage areas around the conduit according to the analysis results. The length of tension softening areas from the upstream or downstream face along the conduit into the dam body were longer in the drilled dam (Case 1b) than in the newly constructed dam (Case 2b). The tension softening areas of the dam concrete were also wider in the drilled dam (Case 1b) than in the newly constructed dam (Case 2b). The tension softening from the upstream surface occurred at the lateral side of the conduit in the drilled dam (Case 1b), while above and below the conduit in the newly constructed dam (Case 2b). From the downstream face around the conduit, the tension softening areas occurred in both cases.

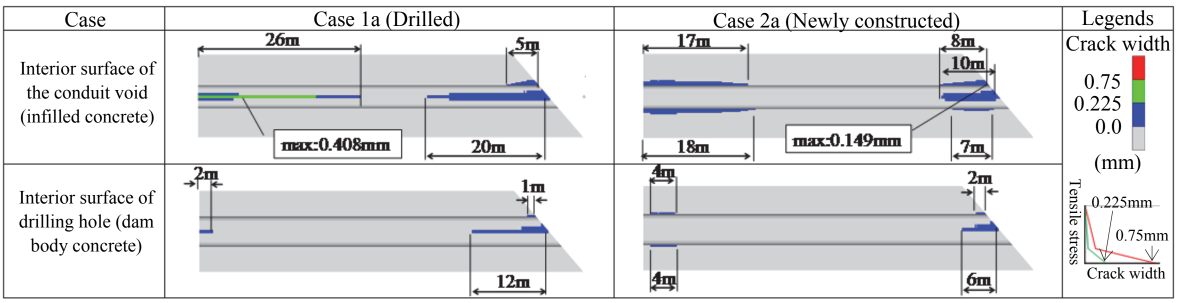
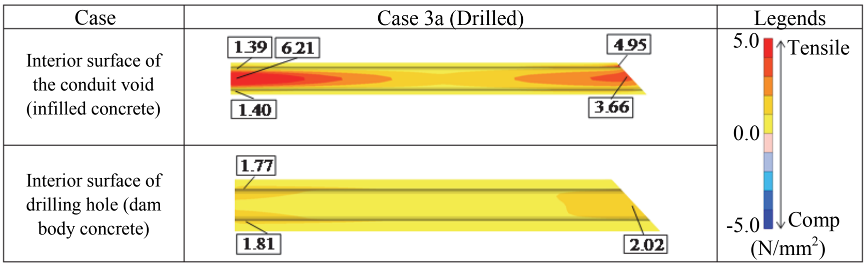


Figure 8. Estimated Damage areas around the Conduit during a Large-scale Earthquake (Non-linear Dynamic Analysis)

The above mentioned results show that it is necessary to pay attention to the fact that tension cracking of concrete around a conduit occurs more easily in case of an existing drilled dam than a newly constructed dam with a conduit.

3.2. Effects of rebar installation

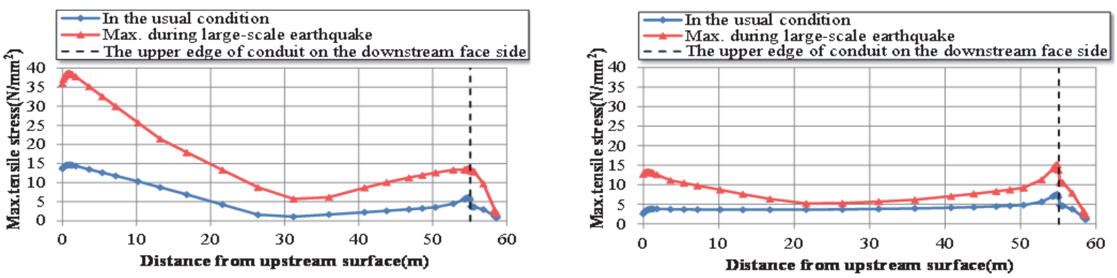
Fig. 9 shows the maximum principal stress of concrete around the conduit calculated from linear dynamic analysis for the case of the drilled dam with modeling rebars around the conduit (Case 3a). Almost no difference can be seen in the maximum principal stress of concrete around a conduit compared with the case without rebars (Case 1a). This is presumably a result of the fact that the effect of rebar installation around the conduit to reduce the tensile stress generated around conduit is not very high.



*The values in the figure are the simulated local maximum or minimum principal values (N/mm^2) and their locations.

Figure 9. Maximum Principal Stress σ_1 around Conduit during Large-scale Earthquake (Case 3a, Linear Dynamic Analysis)

Fig. 10(1) shows the tensile stress which act on rebars around the conduit calculated from the same analysis. The result of the case of a newly constructed dam modeling rebars (Case 4) is showed in Fig. 10(2) for comparison. When comparing with the analysis results for both cases, the tensile stress of the rebars in the drilled dam (Case 3a) is higher than the newly constructed dam (Case 4) on the upstream side, although the value of tensile stress is much smaller than the assumed yield stress (345N/mm^2) of the rebars.



(1) Case 3a (A drilled dam) (2) Case 4 (A newly constructed dam)

Figure 10. Tensile Stress acting on Rebars around the Conduit during Large-scale Earthquake (Linear Dynamic Analysis)

Additionally, in order to investigate the possibility of damage around the conduit caused by a large-scale earthquake and the effect of rebars in reducing the opening of tension cracks, non-linear dynamic analysis considering tension softening of concrete and yield of reinforcing rebars was conducted. Fig. 11 shows the estimated damage areas around a conduit in the case of drilled dam without rebars (Case 1a), with rebars (Case 3b) and with half rebars (Case 5).

Looking at Fig. 11, the estimated areas of damage accompanied with tension softening of concrete are almost unchanged by differences in the quantity of rebars. This is presumably a result of the fact that rebars have a greatly effect of reducing the opening of tension cracks into concrete although the effects of having tension stress before cracking is limited as mentioned above. When focusing on the width of tension crack openings in the upstream-downstream direction section, the maximum opening of the simulated tension cracking around the conduit was reduced. In addition, by considering the rebars in the analysis model, the increase of the quantity of rebars reduced the opening and propagation of tensile cracks into the existing dam body. This means that it is necessary to consider the effect of rebars installed around the conduit when estimating the damage to dam concrete around the conduit for the purpose of seismic safety evaluation against large-scale earthquakes.

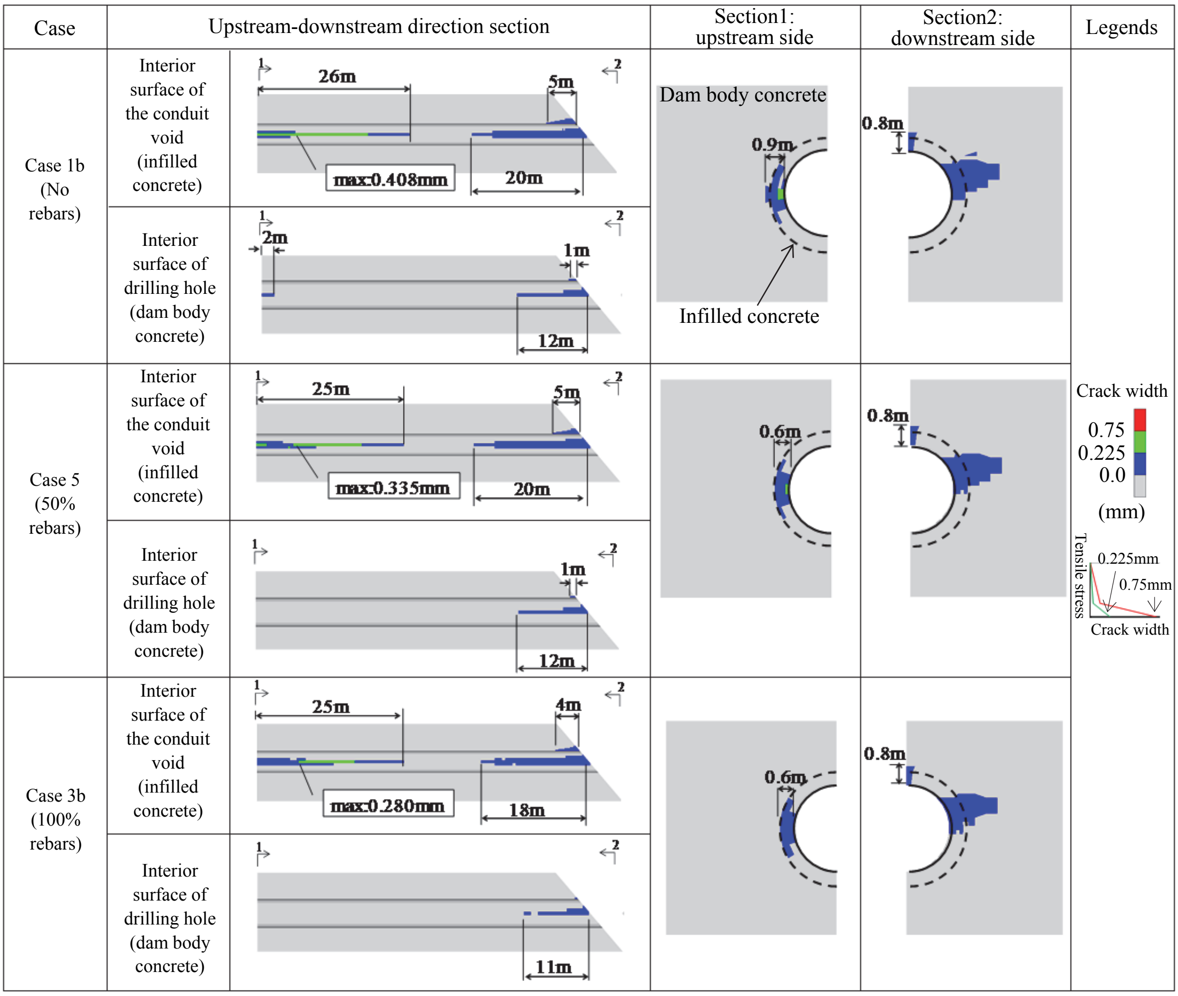
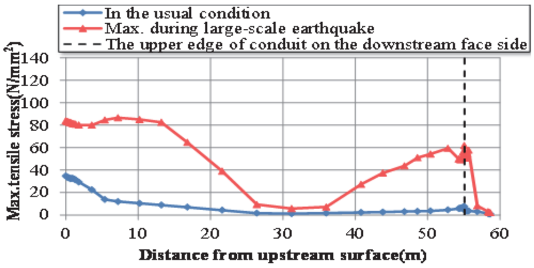
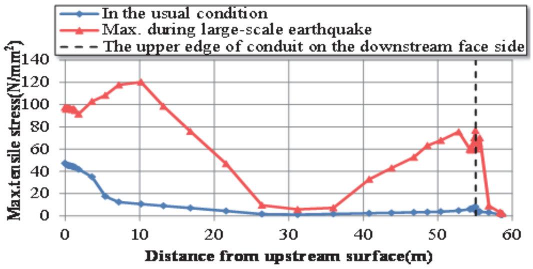


Figure 11. Estimated Damage areas around the Conduit caused by a Large-scale Earthquake and Effect of Rebars (Non-linear Dynamic Analysis)

Fig. 12 shows the simulated tensile stress acting on the rebars around the conduit from the same analysis. The value of tensile stress acting on the rebars is much smaller than the assumed yield stress of rebars in each case. In designing an upgrading project by drilling an existing dam body, it would be preferable to consider the above mentioned effect of the rebars and make their arrangement a rational one to reduce the damage to concrete around the conduit caused by tension cracking even if a maximum-class earthquake motion strikes the dam.



(1) Case 5 (50%rebars)



(2) Case 3b (100%rebars)

Figure 12. Tensile stress acting on Rebars around the Conduit during Large-scale Earthquake (Non-linear Dynamic Analysis)

4. CONCLUSION

Linear and non-linear dynamic analyses for an upgrading project by drilling an existing concrete gravity dam were conducted by FE model considering the upgrading works process. The following is a summarization of findings from the analyses.

(1) When a new conduit is installed by drilling an existing dam body, the tensile stress concentrated in the concrete around the conduit becomes larger than in a case of newly constructed dam with a conduit. It is necessary to pay attention to the fact that tension cracking of concrete around a conduit occurs more easily in the case of a drilled dam than a newly constructed dam with a conduit.
(2)When the analysis model considers rebars installed around the conduit, the estimated crack damage areas are almost unchanged by differences in the quantity of rebars. This is presumably a result of the fact that while rebars have a greatly effect of reducing the opening of tension cracks into concrete, although the effects of having tension stress before cracking in concrete is limited.
(3) By considering the rebars in the analysis model, the maximum opening of the simulated tension cracking around the conduitis reduced. The increase of the quantity of rebars reduces the opening and propagation of tensile cracks into dam body.

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