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SEISMIC SAFETY OF CONCRETE GRAVITY DAMS WITH TRANSVERSE JOINTS BASED ON DYNAMIC CRACKING PROPAGATION ANALYSIS

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Abstract

It is important to be secured a function of the water-storage in reservior for dam body throughout large-scale earthquake. Although, concrete gravity dam is only plain concrete structure, failure pattern would be crack progressive failure. Therefore, three-dimensional dynamic cracking propagation analysis was conducted to investigate dynamic performance and to evaluate seismic safety of concrete gravity dam with transverse joints. Three-dimensional analysis model, as shown in Fig. 1, was based on finite element and was constituted of water-storage of reservoir, foundation rock and dam body. The model size of the dam body was 100m high and 230m wide at crest level, and dam body was divided 14 blocks by transverse joints at dam-axial direction. Dam body was tetrahedron element applied smeared crack model considering concrete softening constitutive model and transverse joints based on Mohr-Coulomb's failure criterion for non-linear behavior. Horizontal and vertical simulated earthquake applied the analysis were made from target spectrum which is defined a lower limit acceleration spectrum for the dam in Japan. Phase characteristics of simulated wave was applied the acceleration wave observed at corridor of Hitokura dam through Southern Hyogo Earthquake (1995). In the analyses, the input horizontal angles θ of input seismic motion, as shown in Fig. 1, were given as parameter from 0° (dam axis orthogonality direction) to 90° (dam axial direction) with 15° pace. According to the dynamic analysis result, crack pattern and crack progress of dam body with transverse joints were discussed by the analysis results based on the angles. Maximum relative displacement between blocks at dam body generated at the angle of 60°, as shown in Fig. 2. At first, cracks occurred at dam bottom of upstream side on riverbed part and abutment part, after that, crack sequentially progressed from the upstream side to the downstream side along the transverse joints. If crack penetrated from upstream side to downstream side at dam bottom part, water-storage of reservoir would almost disappear. From the above point of view, the authors introduced new index of seismic safety factor, which was ratio γ (=1-L/T) that was obtained from residual ligament length (L) and the block thickness (T) of dam body. When γ was equal to 0.0, crack penetrateed from the upstream side to the downstream side at dam body and function of water-storage was not maintained. Furthermore, relationship between γ and θ was discussed in this paper. Safety factor γ increased at the angle from 0° to 60°, however, it was almost constant at the angle from 60° to 90°. From the present work, it was realized that proposal index considering crack progress would be one of methods to evaluate seismic safety of the dam body with transverse joints.

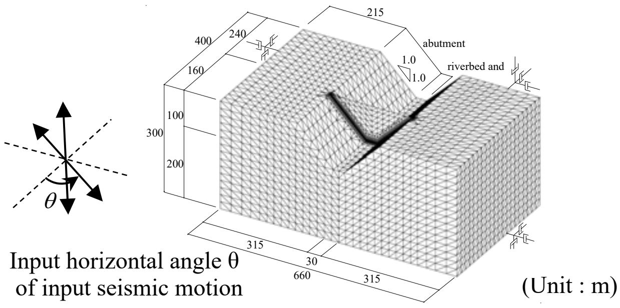


Fig. 1. Three-dimensional analysis model and seismic motion

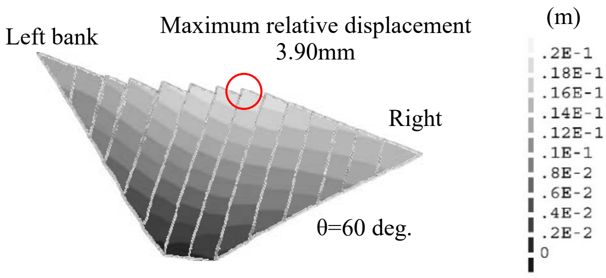


Fig. 2. Relative displacement of dynamic analysis at 7.85

Keywords: Keywords: concrete gravity dam, seismic safety, three-dimensional dynamic cracking propagation analysis

1. Introduction

Large-scale earthquakes have recently occurred on each area in Japan, so that earthquake response analyses have been carried out to evaluate the seismic resistance of socially important infrastructure facilities. The seismic design of dams had been applied only seismic force of dam body based on seismic intensity method [1], however, dynamic analysis in large-scale earthquakes has been also introduced after the 1995 Hyogo-ken Nanbu Earthquake. The main failure of concrete gravity dams, which are subject to seismic safety evaluation for large-scale earthquakes, are considered to be crack penetration failure [2-8] due to crack progress of the dam body. In order to precisely evaluate the cracks occurred and progressed in the dam body, authors proposed an evaluation technique [12] using concrete model of smeared crack model [10,11] considering constitutive model of concrete tension softening [9] and using tangent stiffness proportional damping. In addition, the evaluation technique was confirmed the validity in the comparison with the results of simulation analysis and results of shaking table experiments [13], and seismic safety evaluation and dam reinforcing methods [14, 15] of actual dams were investigated.

However, the authors pointed out that the seismic safety of concrete gravity dams cannot be appropriately evaluated, when two-dimensional dynamic cracking propagation analysis is carried out for the dam whose crest length is relatively short compared with dam height. Because two-dimensional analysis model was not included abutment part, dam response was not considered effects accompanying with dam body restraint and wave dissipation due to the foundation rock. Then, three-dimensional dynamic cracking propagation analysis [16] had been carried out to evaluate the seismic safety considering crack propagation and water storage function. In the study, the dam body was modeled as a three-dimensional continuum, but the actual concrete gravity dams has been norlmally divided by transverse joints at intervals of about 15 to 20m. The authors carried out three-dimensional dynamic cracking propagation analysis by using the model with/without transverse joints and compared the crack progress length of the dam body. As the analysis result, the length of crack progress of the dam body was reduced with transverse joints, and the improvement of earthquake resistant safety margin was clarified by considering transverse joints. The three-dimensional analytical model used here were a half model considering the reduction of analysis time, and the direction of seismic input was limited to the one of upstream and downstream [17].

By the way, the studies on the response effect of the transverse joint of the arch dam in the earthquake has been actively carried out, however, the study on the concrete gravity dam with the transverse joint has not been almost carried out. Among them, Ariga [18] carried out three-dimensional FEM dynamic nonlinear analysis for Ikehara dam which was a concrete gravity dam with the transverse joints. That dam had been also taken observation records of dam representative positions in Southern Hyogo Earthquake. Analysis model with contact elements which were substituted for transverse joints was carried out, and the element was given not only peeling behavior but also slipping behavior based on shear properties applying Mohl-Coulomb's fracture criterion. The observed maximum acceleration in upstream-downstream directions at crest level of dam body was 89.7 Gal. Because the acceleration was relatively small, the response of the dam became in elastic state and it was difficult to discuss performance of the transverse joints. Shiojiri and Ueda [19] suggested that it was necessary to precisely evaluate seismic safety of an actual concrete gravity dam using three-dimensional models including the foundation rock and transverse joints. In the studies about crack progress of concrete gravity dam with transverse joint until now, the horizontal direction of input motion of earthquake has been only targeted in upstream-downstream direction. However, the actual earthquake direction became normally the oblique one, it was sufficiently considered that crack occurrence and progress would be different according to the direction of input horizontal motion.

In this paper, therefore, the authors carried out three-dimensional dynamic cracking propagation analysis considering the input motion in the oblique horizontal direction by using a model of concrete gravity dam with transverse joints. From the results, it clarified that the direction of input horizontal motion was affected the crack occurrence and progress in the dam body with transverse joints. Moreover, quantitative seismic safety evaluation of concrete gravity dam with transverse joint was tried from the viewpoint of water storage function based on crack progress considering the difference of input horizontal direction.

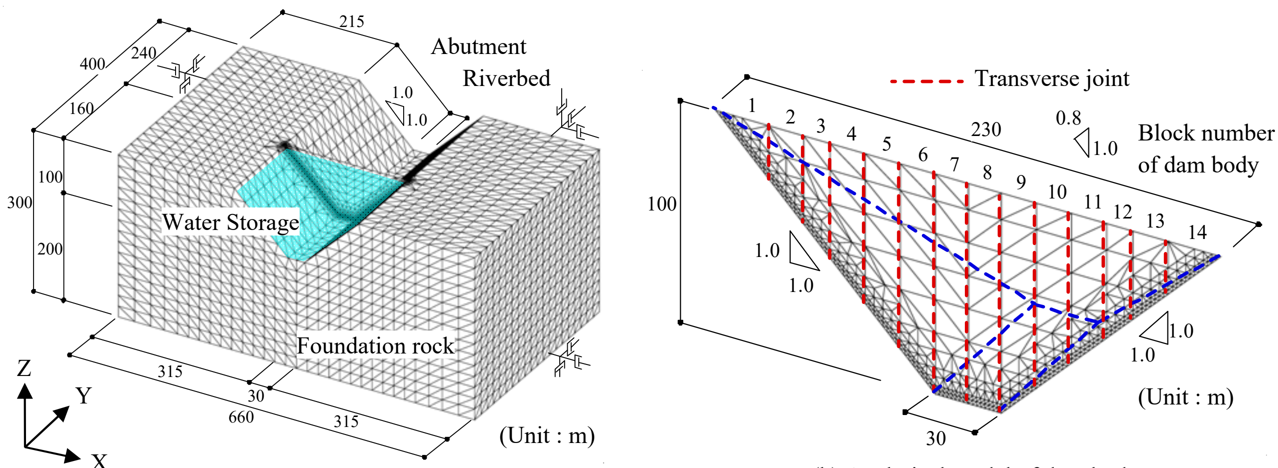
2. Concrete gravity dam evaluated seismic safety

2.1 Analysis conditions

2.1.1 Analysis model

The model dam is concrete gravity dam with transverse joints, with a dam height of 100m and a crest length of 230m. The slope of the abutment part at dam axial direction is 1:1, the slope of dam downstream side is 1:0.8, and the height of the reservoir is 97.0m. To evaluate seismic safety of the dam, authors prepared three-dimensional FEM model of dam body-foundation rock-reservoir coupled system shown in Fig. 1. The dam body is divided 14 blocks, which are 12 blocks at abutment part and two blocks at riverbed part. Each block is connected in transverse joint in the dam body. The transverse joints are arranged every 15m to 20m to the dam axial direction, which simulates the transverse joint of the actual dam. In the previous study [16] on the seismic safety evaluation of the dam body, it was considered that the crack occurred the upstream side in the bottom of dam body, and it spreaded over the whole bottom of the dam body (when there is a fillet in the dam body, the crack also arised from the fillet position). Also, in order to eliminate the effect of model mesh dependency, mesh at bottom of the dam body is divided by regular tetrahedron element which one side of the element is about 2.0m basis. Each concrete element is given a smeared crack model with tensile softening characteristics to consider the crack progress behavior. The model size of the foundation rock is 660m (x) ×400m (y) × 300m (z), and side surface on foundation rock is provided dashpot, which indicates energy transfer function between the side surface of foundation rock and free ground. In addition, bottom surface of the foundation rock is provided dashpot for semi-infinite boundary, which indicates energy dissipation function between the bottom surface of foundation rock and free ground. The water storage replaces additional mass calculated from Westergaard equation [20].

Furthermore, it is assumed that the boundary between the bottom of the dam body and the foundation rock is filled with sufficient grouting, so that it shall not cause crack occurrence in the grouting part.



(a) Analytical model of bird-eye-view

(b) Analytical model of dam body

Fig. 1 – Three-dimensional FEM model of dam-reservoir-foundation rock interaction

2.1.2 Material properties and non-linear characteristics

The dam material properties applied dynamic cracking propagation analysis are shown Table 1. Those are set by referring to the previous studies [12, 21]. Constitutive model of concrete tension softening is adopted the two-line tension softening type model (1/4 model) [9], which features relationship between the tensile stress and crack opening displacements of the concrete, as shown in Fig. 2. In the crack propagation analysis, the equivalent length of the each tetrahedron element in the three-dimensional model is obtained from mean length of the perpendicular lines at the apex 4 points, because the crack opening displacement is necessary to replace the crack strain for the analysis. If the tensile stress is unloading, the hysteretic behavior are performed as the origin-oriented type. The performance of the concrete compression is assumed to be elastic. Shear stiffness retention factor after the crack occurring is adopted 0.005 as the one does not affect the crack propagation of dam body.

Table 1 – Properties of model material

Property	Dam body	Foundation rock
Young's modulus E (GPa)	28 (28)	10 (10)
Poisson's ratio ν	0.20(0.20)	0.25(0.25)
Density γ(kg/m³)	2300 (2300)	2500 (2500)
Compressive stress f_c (MPa)	30.0	-
Tensile stress f_t (MPa)	3.9	-
Fracture energy G_F (N/m)	400	-
Damping factor h (%)	5.0	2.0

Note:( ) is properties by using initial stress analysis

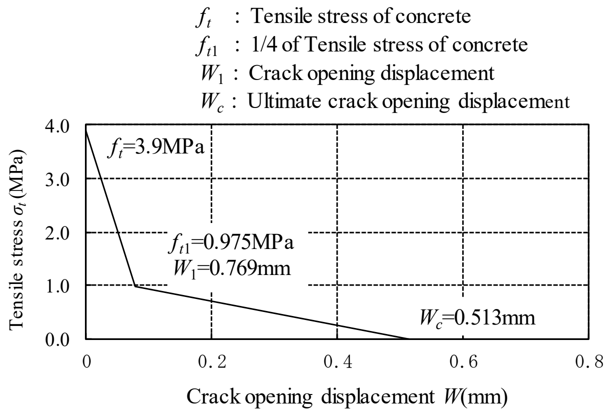


Fig. 2 – Relationship between concrete tensile stress and crack opening displacement for the analysis

The transverse joint modeled by using joint element has functions of slipping and peeling behavior. The slipping behavior is applied bi-linear hysteretic characteristics as shear stress-shear strain relationship, and peeling behavior is applied non-linear characteristics as actual stress-axial strain relationship. When the tensile stress generates in the joint element, the shear stress is not transmitted. However, when the compressive stress is generated, the shear stress is transmitted. Mohl-Coulomb's failure criterion is applied to the non-linear shear stresses-share strain relationship. In the coulomb friction evaluation as the fracture criterion of the joint element, the adhesive force (C) is neglected, and the friction coefficient is assumed to be 0.6 based on the previous study [18]. Since this paper focuses on the occurrence and progress of crack in dam body, the foundation rock is evaluated as elasticity.

In the dynamic cracking propagation analysis, the Newton-Raphson method is adopted for the convergence calculation, and the Newmark-β method (β=1/4) is used for the time integration.

2.1.3 Damping characteristic

Rayleigh damping is often used in three-dimensional FEM models. However, the concrete gravity dam which is unreinforced by steel bars, it is difficult to be occurred crack localization appropriately in dam body. Therefore, the tangent stiffness proportional damping is adopted as the damping type on the studies [12, 16] which has been carried out by the authors. In the dynamic analysis, the damping matrix can be indicated by equation (1).

$$[C(t)] = b[K(t)] \tag{1}$$

where [C(t)] is the damping matrix at time t, [K(t)] is the stiffness matrix at time t, and b is the coefficient determined from the first natural frequency of the model. The damping matrix [C(t)] is proportional to the stiffness matrix [K(t)], and if the stiffness of the dam body becomes non-linear, the damping is similarly non-linear. For example, when the crack is fully opened, the damping becomes zero in the crack orthogonal plane at the same time, so that damping force does not occur at the crack occurring plane. As a result, the tensile stress transfer at the crack occurring plane can be matched to the actual performance. In addition, the damping constants adopted in the three-dimensional FEM models are applied 5% for the dam body and 2% for foundation rock, referring to the results [22] of the past studies based on the observed records.

2.2 Input seismic motion

The dynamic analysis is applied simulated earthquake made by the lower limit acceleration response spectrum [23, 24] as a target spectrum. This spectrum prescribes minimum earthquake to be considered the dam seismic safety during a large-scale earthquake, assuming invisible fault. The phase characteristics of the simulated earthquake are applied horizontal and vertical acceleration wave observed in the corridor of Hitokura dam in the Southern Hyogo-ken earthquake in 1995.

The acceleration wave and the acceleration response spectrum created for the simulated earthquake are shown in Fig. 3(a)-(c). The definition level of the simulated earthquake in the three-dimensional FEM model is the bottom level of the dam body. Maximum acceleration is 352Gal at horizontal direction and 243Gal at vertical direction. The input sismic motion at the bottom of foundation rock, that means the bottom of three-dimensional FEM model, is calculated by the one-dimensional wave theory. The input seismic motion used for the analyses are in two directions, horizontal (H) and vertical (V).The input seismic motion is taken input horizontal angle θ into account shown in Fig. 3(d), but the waves of horizontal seismic motion are the same regardless of θ for the dynamic analyses. There are six angles of 0° (upstream-downstream direction), 15°, 30°, 45°, 60° and 90° (dam axis direction) prepared for the analyses.

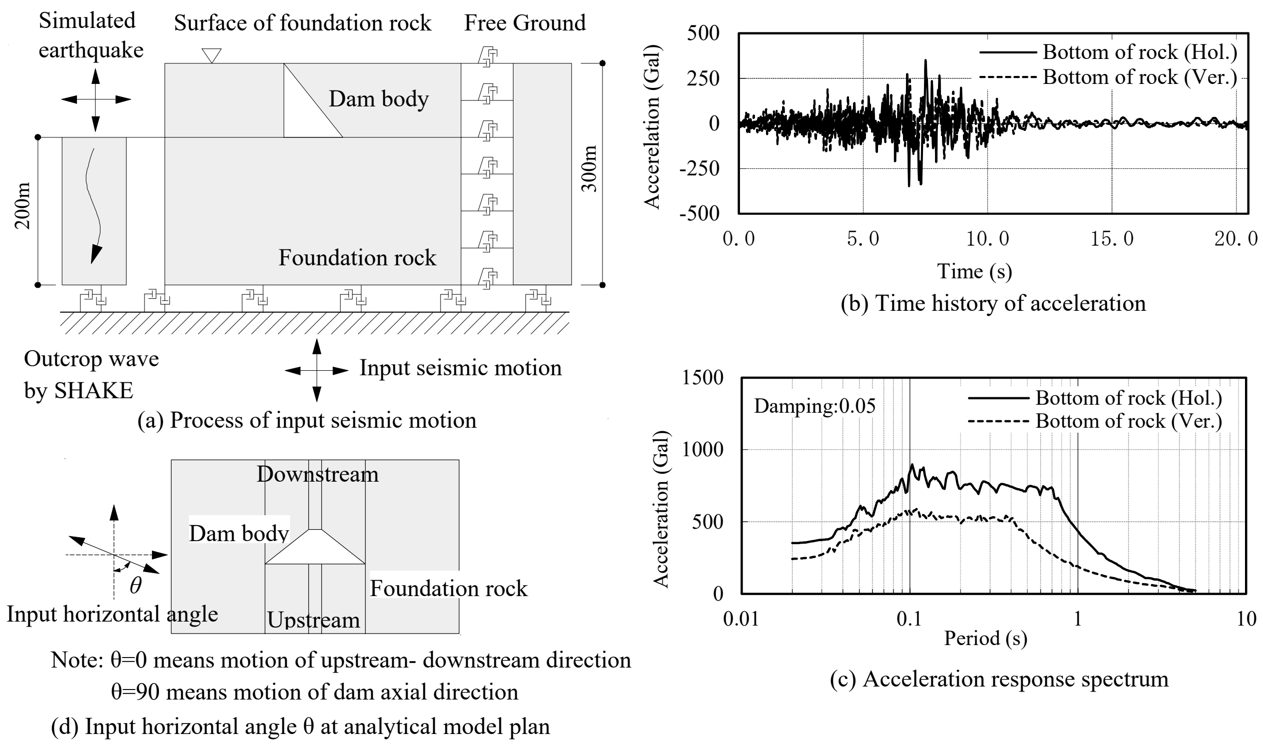


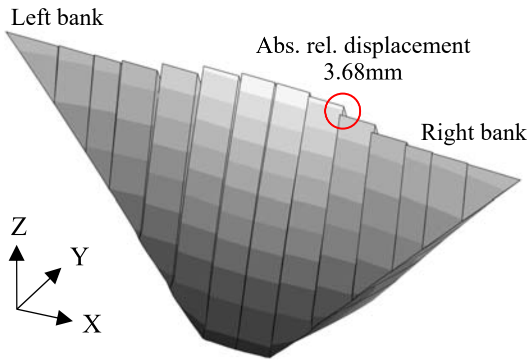
Fig. 3 – Input seismic motion and Input horizontal angle θ

3. Relative displacement and crack progress behavior from the analysis

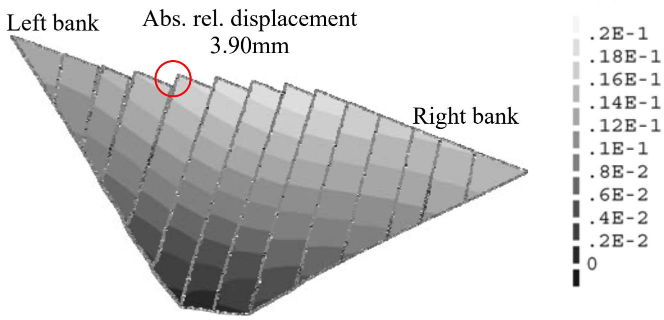
3.1 Relative displacement of dam body

Maximum relative displacement distribution with respect to the displacement at bottom of foundation rock obtained from the analyses are shown in Fig. 4, in which there are two distributions of the input horizontal angle of 0° and 60 ° at the time of 7.58 seconds. The relative displacement occurring at the transverse joint between blocks at dam body becomes stepwise due to slippage during input seismic motion simulated an earthquake. The slipping and peeling size between blocks also differ by the difference of the input horizontal angle. At input horizontal angle of 0°, the block in the central part shows a large relative displacement, while the relative displacement is smaller in the blocks near the left and right bank. This is probably because the dam height of the blocks near the left and right bank is low, and the cracks are less likely to occur on the bottom of the block. Further, at input horizontal angle of 60°, the displacement in the dam axial direction is increased, a large relative displacement occurs not only in the blocks between riverbed and abutment at right side but also in the blocks of the abutment at left bank side.

Time history of relative displacements in the three directions of top of the dam block with respect to the bottom and the absolute values (square root of sum of squares) of the relative displacements in each direction are shown in Fig. 5. The relative displacement in X direction (upstream-downstream direction) tends to decrease with the increase of input horizontal angle, the relative displacement in Y direction (dam axis direction) tends to increase with the increase of the angle. Although, the relative displacement in Z direction (vertical direction) is small regardless of the input horizontal angle, because the behavior of Z direction is close to the rigid body motion. The maximum value of the absolute value of the relative displacement increases slightly as the input horizontal angle increases.



(a) Input horizontal angle 0 deg. (Time=7.58s)



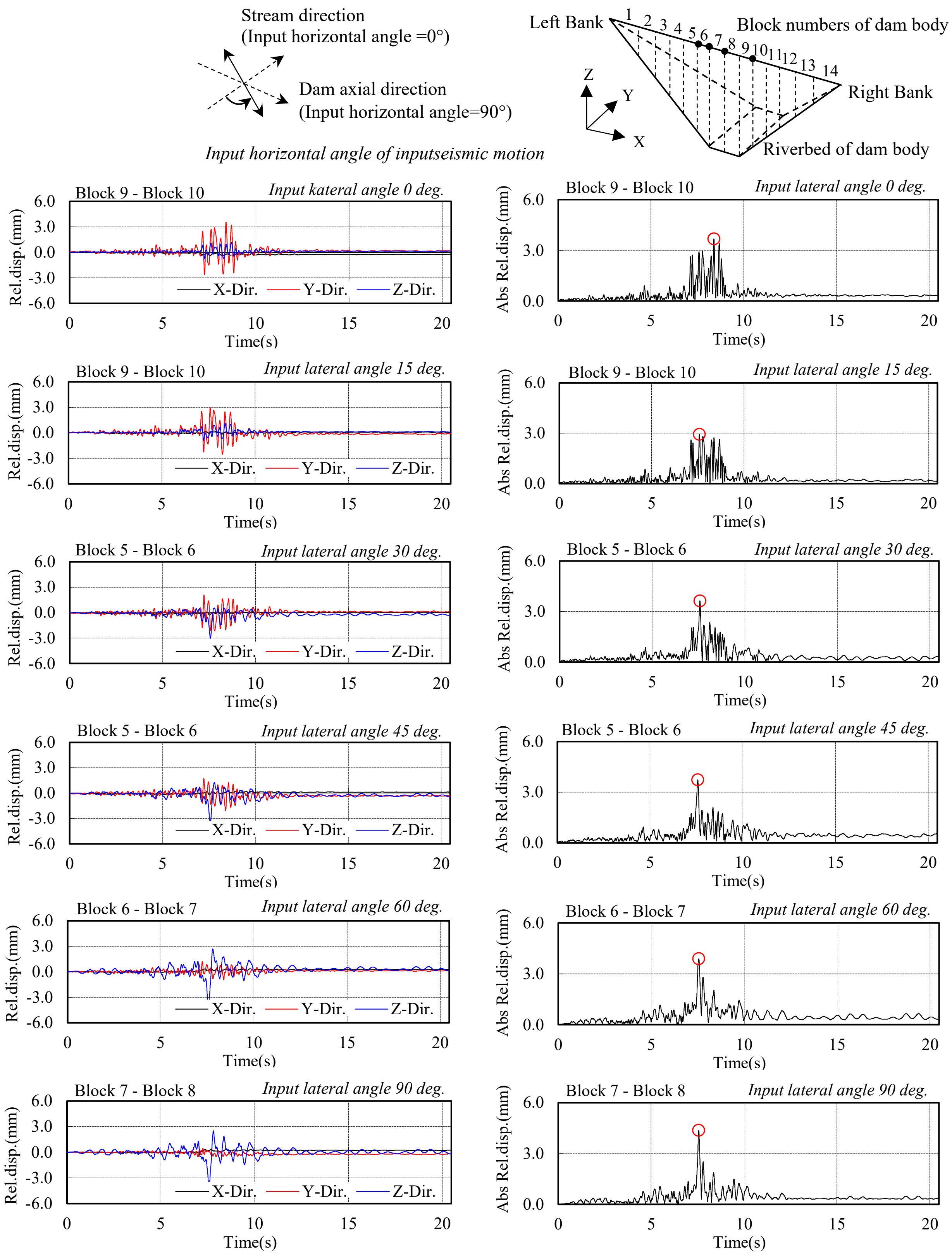
(b) Input horizontal angle 60 deg. (Time=7.58s)

Fig. 4 – Relative displacement distribution of dam body

3.2 Behavior of crack occurrence and progress

Crack strain of the dam body is shown in Fig. 6. The cracks occurring at the bottom of dam body propagate from the upstream side to the downstream side along the transverse joint of the riverbed part and the abutment part near riverbed, although the cracks do not occur at the bottom of three blocks around the left bank side and four blocks around the right bank side. This crack behavior depends upon the dam body shape. The block height of dam body around the left and right bank is low, so that the rigidity is larger than that of other blocks, and the relative displacement between blocks hardly occurs. In addition, the crack progress greatly differs depending on the input horizontal angle. Although the crack progress along the transverse joint is not so remarkable until the input horizontal angle is 45°, it develops rapidly when the angle is 60° or more. This indicates that the crack progress is significantly influenced by the input seismic motion of dam axial direction compared with the input seismic motion of the upstream-downstream direction. However, since the ultimate opening crack strain ε_c (red range in Fig. 6) occurred along the transverse joint has not reached the downstream side, it can be considered that the water storage function of the concrete gravity dam can be retained.

On the other hand, according to the previous study [25], the transverse joint had not been considered, since the dynamic behavior of the dam body had been almost thought rigid mode in the dam axial direction.



(a) Relative displacement for three directions (b) Absolute rel. displacement for three directions

Fig. 5 – Time history of relative displacement between the blocks next each other of dam body

The cracks were unlikely to occur in the riverbed part and vicinity part. So that, it was considered that water storage function of the dam was unlikely to be affected, the seismic safety of concrete gravity dams had been mainly discussed based on the input seismic motion of the upstream-downstream direction. For the dams with transverse joints, in this paper, it becomes important to evaluate seismic safety with sufficient attention in relation to the input horizontal angle of earthquake motion and water storage function.

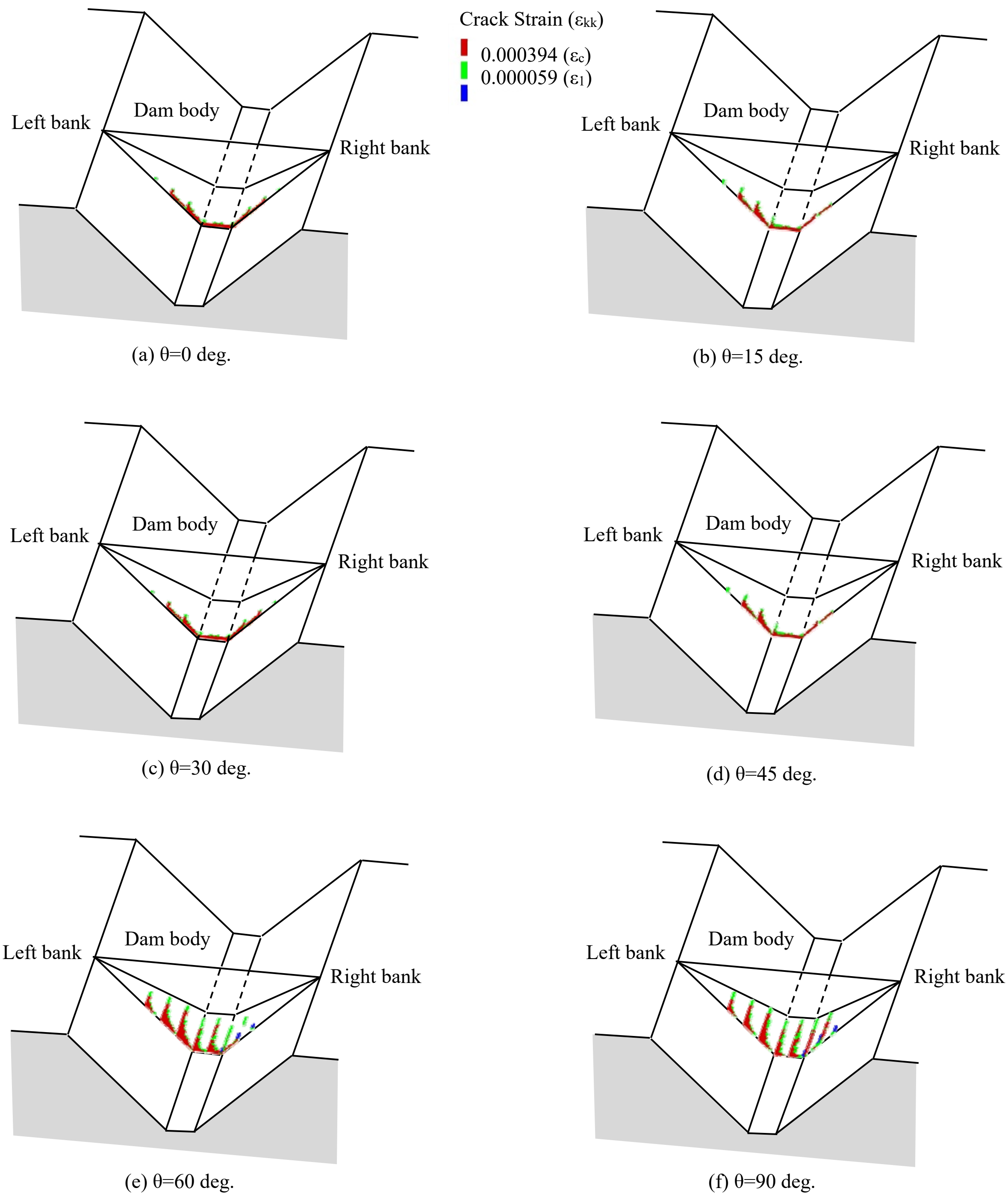


Fig. 6 – Crack strain of bottom of dam body at each input horizontal angle (θ) (t=7.58s)

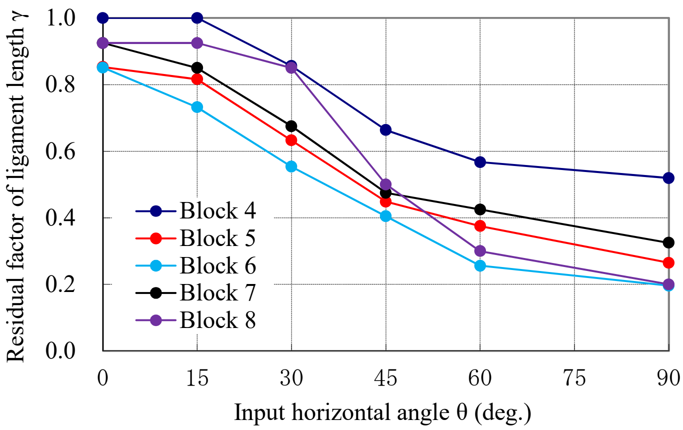
4. Seismic safety evaluation of concrete gravity dam

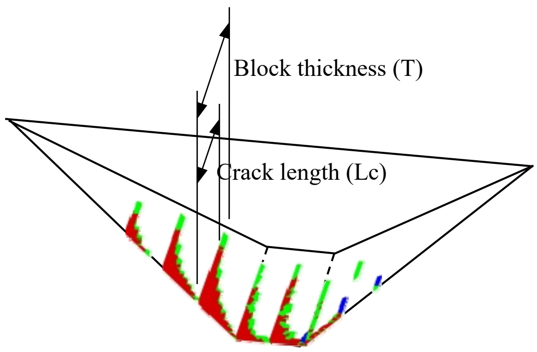
Seismic safety of the dam body focusing on the water storage function could be evaluated based on the crack progress obtained from the three-dimensional dynamic cracking propagation analysis. Cracks had occurred bottom of dam body at the riverbed part and the abutment part along the transverse joint. As results of the development of this crack, even if the crack penetrated from the upstream side to the downstream side in some blocks at the bottom of the dam, it was considered that the dam body did not collapse. But in case of the crack penetration partially, the dam could not be surely expected to maintain the water storage function. Therefore, from the viewpoint of seismic safety including the water storage function of the dam, authors introduced new index, that was the residual factor of ligament length based on crack progress as indicated in Equation (2).

$$\gamma = 1.0 - L_c/T \tag{2}$$

Where, γ is residual factor of ligament length, L_c is the length of crack propagation, and T is the thickness of dam blocks. If γ is equal 0.0, it means that the crack penetrates from the upstream side to the downstream side through the bottom of the dam body block. The relationship between γ and θ is shown in Fig. 7. The residual factor γ decreases significantlly as θ increases untile the angle of 60°, but the decrease of γ becomes gradual at the angles larger than 60°. The analysis results of concrete gravity dams conventionally carried out by two-dimensional crack propagation analysis corresponds to the analysis result of the angle of 0° by three-dimensional analysis. In case of seismic safety evaluation using two-dimensional cracking propagation analysis, it is nessesary to be aware of caution that the crack progress and length are underestimated.

From the above, it is reasonable to evaluate the seismic safety including crack progress and water storage function by conducting three-dimensional dynamic cracking propagation analysis of dam body with the transverse joints. Also, introducing new index, that is residual factor of ligament length, can be useful for quantitative seismic safety evaluation of concrete gravity dam.





Note: Definition of block thickness (T) and crack length (Lc) based on the dynamic analyses results

Fig. 7 – Relationship between residual factor of ligament length and input horizontal angle

On the other hand, an evaluation method of seismic safety based on crack progress is presented by using only model dam with transverse joints, however, effects on seismic safety due to differences in dam body shapes (dam height, dam length, etc.) and effects on seismic safety including the crack of grouting parts which become contact surfaces of the dam body and foundation rock are future subjects.

5. Conclusion

Three-dimensional dynamic cracking propagation analysis was carried out for the concrete gravity dam with the transverse joint using input seimic motion considering input horizontal angle as a parameter. From analysis result, quantitative seismic safety evaluation was tried based on the crack progress length in the dam body. The following conclusions in this paper have been drawn from present work.

(i) According to the relative displacement distribution of the dam body for the foundation rock bottom obtained from the three-dimensional cracking propagation analyses, relative displacement occurring at the transverse joint between blocks at dam body became stepwise due to slippage during an earthquake. From the time history of relative displacement response waves, the relative displacement in X direction (upstream-downstream direction) tends to decrease with the increase of input horizontal angle, the relative displacement in Y direction (dam axis direction) tended to increase with the increase of the angle. Although, the relative displacement in Z direction (vertical direction) was small regardless of the input horizontal angle.

(ii) Cracks occurring on the dam body bottom progressed from the upstream side to the downstream side along the transverse joint of abutment part near riverbed and riverbed part, although cracks did not occur at the bottom of three blocks around the left bank side and four blocks around the right bank side. This crack behavior depended upon the dam body shape and the input horizontal angle. In particular, the crack progress greatly differed depending on the angle, and is deeply related to dam's water storage function, so that the seismic safety of concrete gravity dams would be discussed to take the angle into account.

(iii) Seismic safety of the dam body focusing on the water storage function could be evaluated based on the crack progress obtained from the three-dimensional dynamic cracking propagation analysis. From crack progress of the analysis, authors introduced new index of seismic safety of the dam, which was the residual factor of ligament length (γ) based on crack progress. The factor γ decreased significantlly as θ increased untile the angle of 60°, but the decrease of γ became gradual at the angles larger than 60°. From that reason, it is found that the seismic safety of the dam with the transverse joint can not be evaluated by using two-dimensional cracking propagation analysis.

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