SEISMIC PERFORMANCE EVALUATION OF DAM GATE PIERS FOCUSED ON LOADING CAPACITY AND DEFORMATION

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Abstract

In Japan, seismic design of dams is carried out by the "Seismic Intensity Method". In this method, it is possible to perform structural calculations that take into account the inertial force and dynamic water pressure due to earthquakes by applying a horizontal seismic intensity determined by the type of dam and regional classification to a dam that is assumed to be a rigid body. However, when large-scale earthquakes are targeted, there is a problem that dam response and material nonlinearity cannot be considered. Therefore, after the 1995 Hyogoken-Nanbu Earthquake, a method of modeling the dam body and dam-related facilities with FEM, calculating the response by dynamic analysis, and evaluating the seismic performance based on the result is being tested. This paper describes a case where the seismic performance of the dam gate piers constructed at the top of a gravity concrete dam was evaluated based on the results of dynamic analysis using 3D and 2D FEM models. The characteristic of the dam gate pier is that it supports both superstructure of bridge and dam gate, and the ratio of reinforcing bars to cross section is low. Therefore, in this study, the bending and shear strengths of reinforced concrete section were appropriately evaluated, and the structural stability was examined. In addition, the deformation amount of the dam gate pier was also checked from the viewpoint of maintenance of the function to open and close the dam gate. The remarkable point of this study is that the elastic modulus of concrete was identified based on the natural period of the dam gate pier obtained by microtremor observation, and the analysis accuracy was improved.

Keywords: dam gate pier, seismic performance evaluation, finite element method, dynamic analysis, deformation

1. Introduction

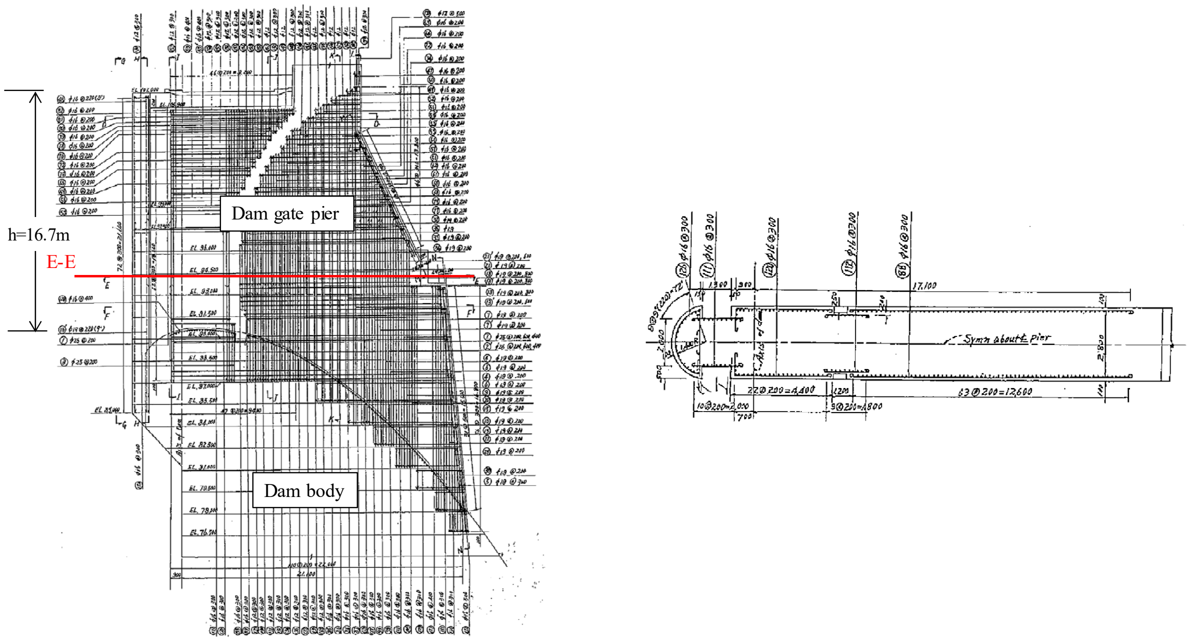
The seismic design of Japanese dams is traditionally carried out by the "Seismic Intensity Method". In this method, it is possible to perform structural calculations that take into account the inertial force and dynamic water pressure due to earthquakes by applying a horizontal seismic intensity determined by the type of dam and regional classification to a dam that is assumed to be a rigid body. Thus, the effects of earthquakes can be easily considered, but there is a problem that the response of dams and the nonlinearity of materials cannot be considered when large-scale earthquakes are targeted. To solve this problem, after the 1995 Hyogoken-Nanbu Earthquake, a method of modeling the dam body and dam-related facilities with FEM, calculating the response by dynamic analysis, and evaluating the seismic performance based on the results is being tested [1]. However, there have been reports of large-scale earthquakes, such as the collapse of the Fujinuma Dam caused by the 2011 off the Pacific coast of Tohoku Earthquake, that caused the dam to lose its storage function and cause serious damage to downstream areas [2]. Therefore, there is a social demand for evaluate the safety of dams and related facilities against large-scale earthquakes, regardless of whether they are new or existing, and taking measures if the safety is not satisfactory.

This paper describes an example of evaluating the seismic performance of a dam gate pier built on the top of a gravity concrete dam against large-scale earthquakes. In this case, the possibility of damage is determined by a linear dynamic analysis using a 3D FEM model, and if damage occurs, the degree of damage is obtained by a nonlinear dynamic analysis using a 2D FEM model. The dam gate pier features both support of the bridge superstructure and the dam gate, and a low ratio of reinforcing bars to cross section. This is different from the general bridge pier. Therefore, in this study, the bending and shear strengths of reinforced concrete section were appropriately evaluated, and the structural stability was examined. In addition, the deformation amount of the dam gate pier was also checked from the viewpoint of maintenance of the function to open and close the dam gate.

2. Overview of Target Facilities

The dam examined in this study is a gravity concrete dam with a height of 40 m and a crest length of 453 m. It is a dam for power generation about 55 years after its construction in 1964. Also, as shown in Photo 1, the dam gate piers are located on both sides of the crest radial gate. The height of the dam gate pier at the dam axis is 16.7 m, and the rebar arrangement diagram is as shown in Fig. 1. The superstructure of the bridge and the operation facility of the radial gate are located at the top of the dam gate pier, and the radial gate is fixed on the side. In addition, the dam gate pier is characterized by the fact that there are few reinforcing bars in the cross section, and the elevation of the base changes in the upstream and downstream directions.

Photo 1 – Panoramic photo of the target facility



(a) Side view (b) Sectional view (E-E)

Fig. 1 – Bar arrangement of the dam gate pier

3. Evaluation of Seismic Performance of Dam Gate Pier against Large-Scale Earthquake

3.1 Overview of seismic performance evaluation

Fig. 2 shows the flow chart of the seismic performance evaluation of the dam gate pier carried out in this study. Firstly, the seismic performance required of the dam gate pier in the event of a large-scale earthquake and the limit state for it were set. Next, based on the design and construction information, the structural specifications were arranged and the physical properties used for analysis were set. After that, the entire dam and foundation rock were modeled by 3D FEM, and the seismic response of the dam gate pier was confirmed by linear dynamic analysis to determine the possibility of damage. In order to improve the accuracy of the analysis, the elastic modulus of concrete was identified based on the natural period of the dam gate pier obtained by microtremor observation. As a result of the linear dynamic analysis, the tensile stress at the base of the dam gate pier exceeded the allowable value. Therefore, one block of the dam was modeled by 2D FEM, and the degree of damage to the dam gate pier was confirmed by dynamic analysis considering the nonlinearity of the material using the model. At that time, the loading capacity of the dam gate pier was examined in detail, and the deformation amount was checked from the viewpoint of maintaining the opening and closing function of the dam gate. Fig. 3 shows the acceleration response spectrum and time history waveform of the input seismic motion used in this study. These are simulated seismic motions that conform to the lower-limit acceleration response spectrum for reference shown in Reference 1. The details of each study are described below. Note, the analysis program used in this study is ISCEF (manufactured by Century Techno, Inc.).

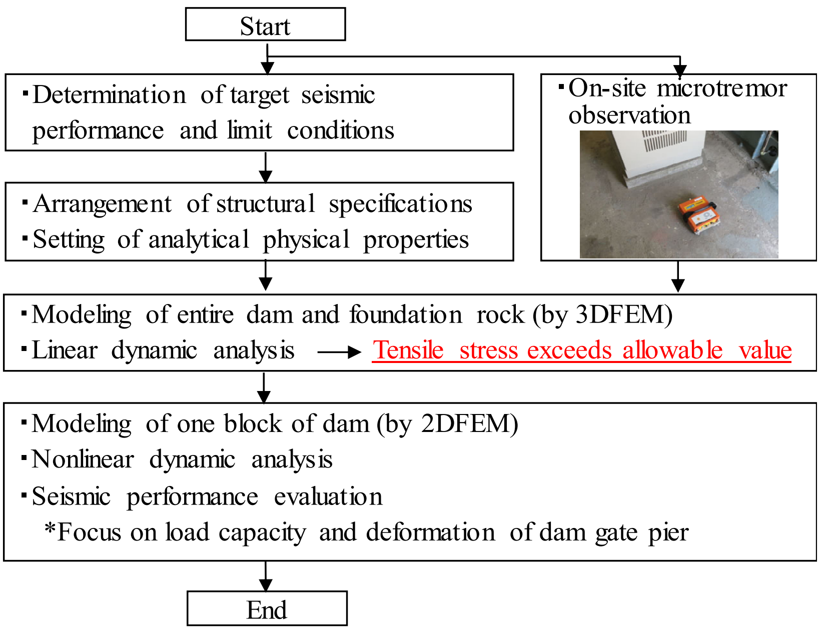
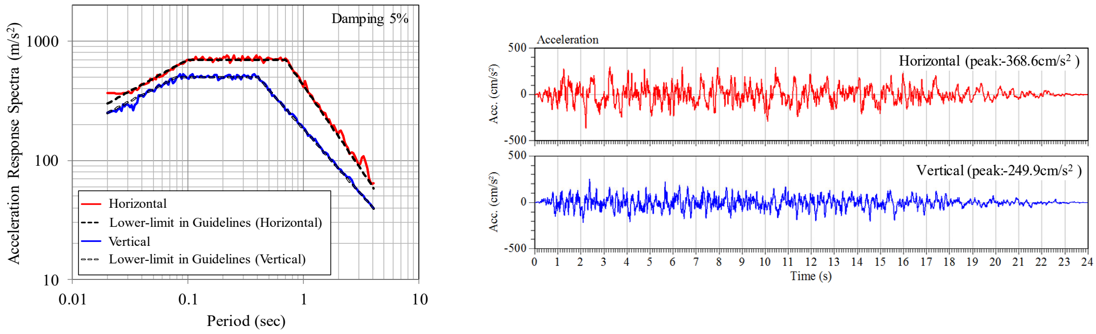


Fig. 2 – Flow chart of seismic performance evaluation in this study



(a) Acceleration response spectrum (b) Time history waveform of Acceleration

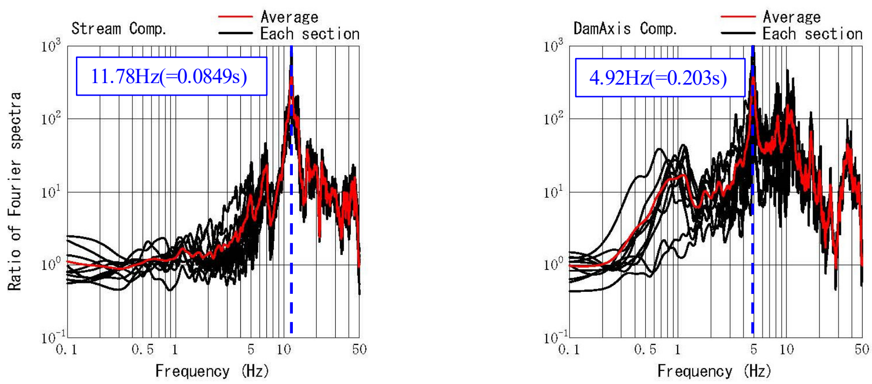
Fig. 3 – Acceleration response spectrum and time history waveform of the input seismic motion

3.2 Determination of target seismic performance and limit conditions

The seismic performance and limit conditions required for dam gate piers during a large-scale earthquake were set based on Reference 3. First, in order to maintain the water storage function, it was decided that the dam gate pier should stay within the range of response that can hold the load capacity. Second, in order to maintain the opening and closing function of the gate, the amount of deformation of the dam gate pier caused by the earthquake should not exceed the play length with the gate.

3.3 Estimation of natural period of dam gate pier by microtremor observation

Microtremor observation using an accelerometer was carried out on site to determine the natural period of the dam gate pier. The observation positions were on the top of the dam gate pier and on the bedrock downstream of the dam. The two points were observed at the same time, with 100Hz sampling for 15 minutes. From the observation results, ten sections of about 40 seconds were selected, and the Fourier spectrum of each point and the ratio of the Fourier spectrum of the top of the dam gate pier to the downstream rock shown in Fig. 4 were calculated. As a result, it was found that the dominant frequency in the upstream and downstream directions was 11.78 Hz (= 0.0849 s), and the dominant frequency in the dam axis direction was 4.92 Hz (= 0.203 s) on the average of ten sections. Therefore, the value in the dam axis direction was set as the target value in the eigenvalue analysis of the dam gate pier.



(a) Upstream and downstream direction (b) Dam axis direction

Fig. 4 – Fourier spectrum ratio (Dam gate pier / downstream bedrock)

3.4 Linear dynamic analysis by 3D FEM model

As shown in Fig. 5, the analysis model used in the linear dynamic analysis was a 3D FEM model in which the entire dam and foundation rock were modeled using solid elements. In this model, all concrete parts including dam gate piers were modeled as plain concrete. Table 1 shows the material properties of concrete. The elastic modulus in the table was identified by eigenvalue analysis using 3D FEM for one block of the dam body (maximum cross section, 15 m width in the dam axis direction) based on the target value of the natural period described above. Before the linear dynamic analysis, a static linear analysis was performed to determine the stress state during non-earthquake. The loads considered in the static linear analysis are dam weight, hydrostatic pressure at full water level, sedimentation pressure, and ice pressure. In the linear dynamic analysis, the seismic motion shown in Fig. 3 was input after being pulled back to the bottom of the foundation rock. At that time, three directions (upstream and downstream, dam axis, vertical) were simultaneously excited. The dynamic water pressure during an earthquake was calculated based on Westergaard's equation and considered as additional mass [4].

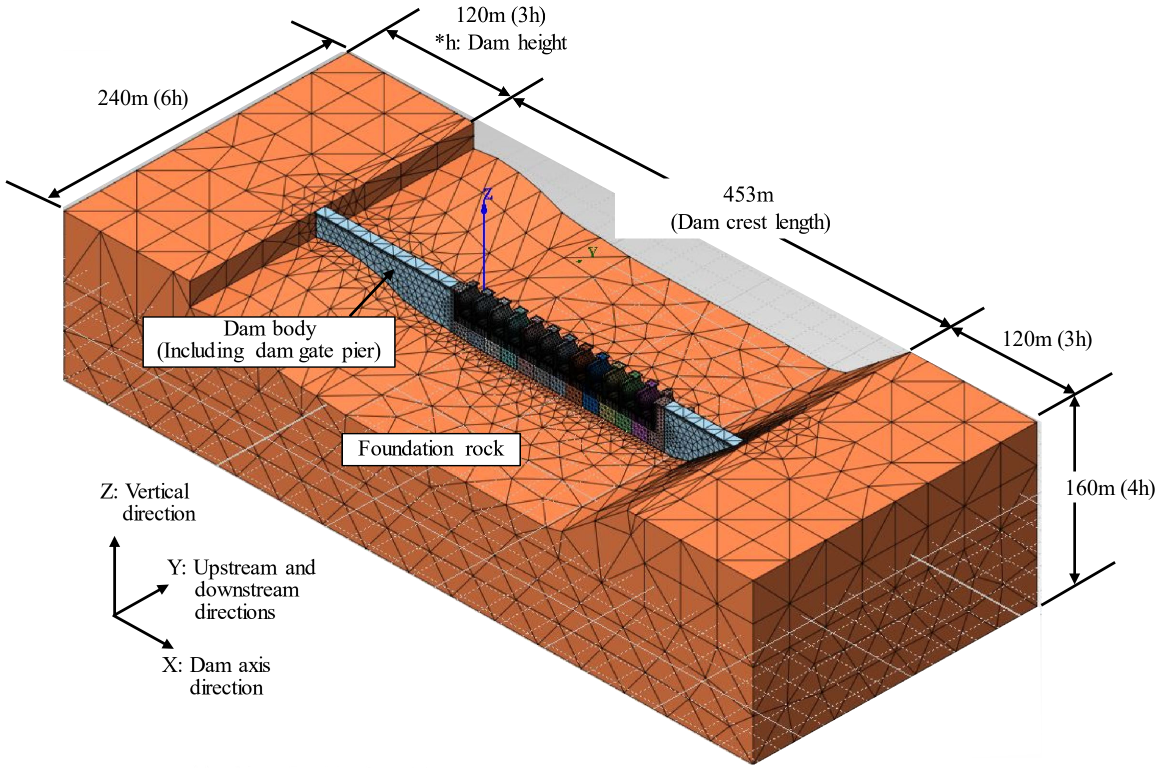


Fig. 5 – 3D FEM model used for linear dynamic analysis (Bird view from upstream)

Table 1 – Physical properties of concrete

Unit weight γ (kN/m^3)	Compressive strength σ_c (N/mm^2)	Tensile strength σ_t (N/mm^2)	Elastic modulus E (N/mm^2)	Poisson's ratio ν (-)	Damping ratio h (%)
22.9	19.4	2.33	23000	0.126	10

Fig. 6 shows the response displacement diagram obtained by linear dynamic analysis. Similarly, Fig. 7 shows the maximum principal stress distribution diagram. The response displacement of the dam gate pier is predominant in the direction of the dam axis, where the rigidity of the cross section is small, and the effect tends to increase the maximum principal stress at the base. In addition, the maximum value was 8.05 N/mm^2, which resulted in greatly exceeding the tensile strength. Thus, dam gate piers can be damaged by tensile stress at the base. Therefore, the degree of damage was confirmed by dynamic analysis considering the nonlinearity of the material.

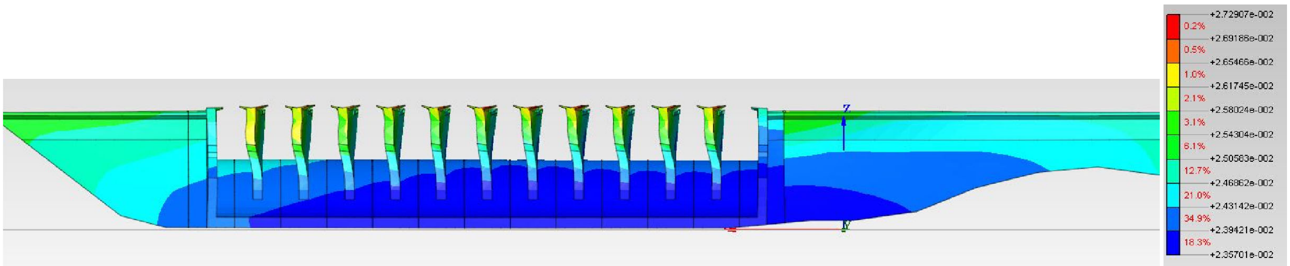
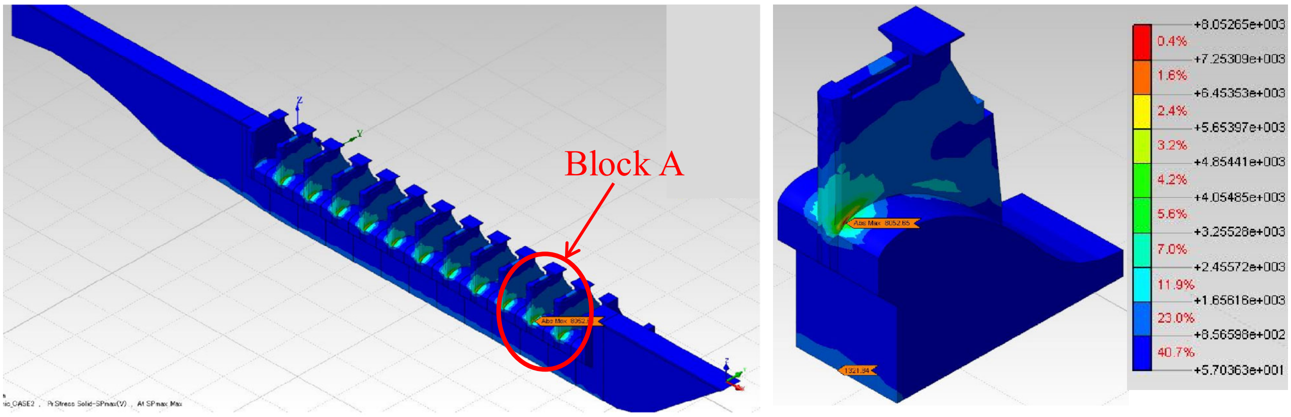


Fig. 6 – Response displacement diagram by linear dynamic analysis
(View from downstream side, Unit of displacement: m)



(a) Entire dam body (b) Block A

Fig. 7 – Maximum principal stress distribution diagram by linear dynamic analysis
(Bird view from upstream, Unit of principal stress: N/mm^2)

3.5 Nonlinear dynamic analysis by 2D FEM model

The analysis model of the nonlinear dynamic analysis was a 2D FEM model for one block (maximum section) of the dam body as shown in Fig. 8 from the viewpoint of analysis accuracy and cost. In this model, the dam body was modeled with elastic elements. In addition, the dam gate pier is modeled by superimposing the RC element (Reinforcing bar: round steel, yield point: 235 N/mm^2) and the unreinforced element, and the depth of the section and the bias of the reinforcing steel can be considered. The material properties of concrete were based on the values shown in Table 1, and the damping constant was 5% for plain concrete elements and 2% for RC elements [5]. The Maekawa model was used for nonlinear characteristics of reinforced concrete [6]. In the nonlinear dynamic analysis, the seismic motion shown in Fig. 3 was input to the bottom of the 2D FEM model. The dynamic water pressure during an earthquake was considered as an additional mass, as in the linear dynamic analysis. Damage of dam gate pier in nonlinear dynamic analysis was determined based on the strain generated in the element. Specifically, the strains that are determined to be in the final state are 3% for tensile strain, 1% for compressive strain, and 2% for shear strain.

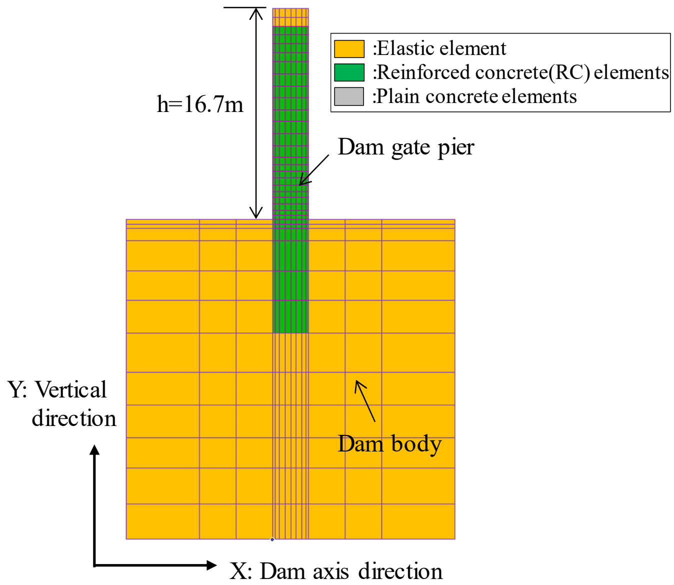


Fig. 8 – 2D FEM model used for nonlinear dynamic analysis (View from downstream side)

Fig. 9 shows the relationship between the load and displacement at the base of the dam gate pier obtained by pushover analysis (displacement control) using the 2D FEM model. In this analysis, a forced displacement was applied to the top of the dam gate pier at a rate of 0.1 cm/STEP in the axial direction of the dam. As a result, the horizontal force showed the maximum value (7270kN) when the horizontal displacement was about 1.8cm, and then decreased to about 78%(5700kN) of the maximum value. The relationship between the load and displacement at which such shear failure occurs first is a characteristic behavior of RC concrete with few reinforcing bars, and occurs when the yield load is smaller than the crack load. When a load such as seismic motion is applied to such RC concrete, it is difficult to express the softening behavior when the load capacity is reduced by analysis. Therefore, as shown in Fig. 9, the tensile strength of concrete was reduced by about half so that the relationship between the load and the displacement in the pushover analysis by the load control became the same as the relationship after the load capacity was reduced by the displacement control.

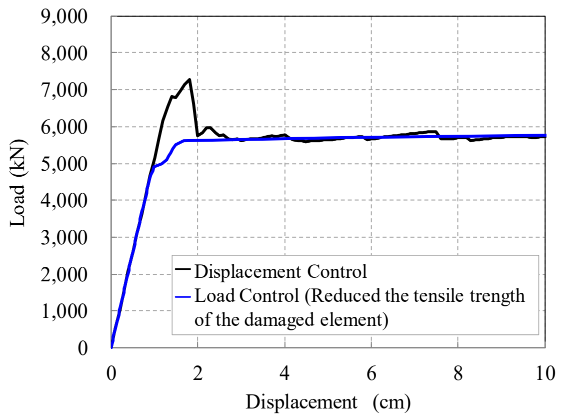
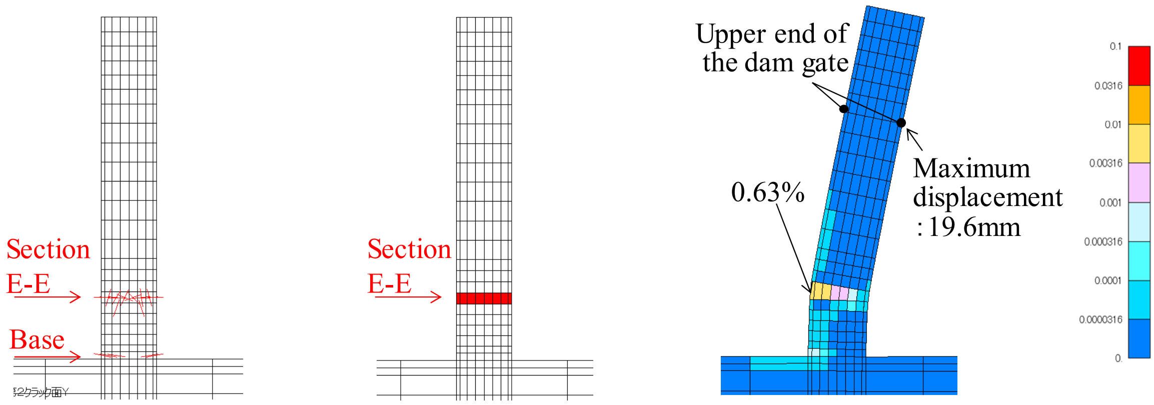


Fig. 9 – Relationship between load and displacement by pushover analysis using 2D FEM model

Fig. 10 shows the crack distribution, the yield distribution of the reinforcing bar, and the tensile strain distribution obtained by nonlinear dynamic analysis. In the dam gate pier, cracks and yielding of the reinforcing bars occur at the Cutting point (E-E section) due to tensile stress. However, the maximum value of the tensile strain is 0.63%, and it does not reach the final state. Therefore, it was determined that the load capacity of the dam gate pier was maintained even during a large-scale earthquake. On the other hand, the amount of deformation of the dam gate pier was 19.6 mm at the upper end of the gate, which exceeded the gap length of the gate of 10 mm. From this result, there is a possibility that the dam gate pier and the gate will collide during the earthquake. However, since the residual displacement at the same position was 0.6 mm, the gate opening and closing function was maintained even after the earthquake, and it was determined that the gate could be operated. Based on the above results, it was determined that the dam gate piers targeted in this study had seismic performance because both the water storage function and the gate opening and closing function could be maintained during a large-scale earthquake.



(a) Crack distribution (b) Yield distribution (c) Tensile strain distribution

Fig. 10 – Results of nonlinear dynamic analysis

4. Conclusions

This paper describes a case where the seismic performance of the dam gate piers constructed at the top of a gravity concrete dam was evaluated based on the results of dynamic analysis using 3D and 2D FEM models. The findings obtained in this paper are summarized below.

Microtremor observation is an effective method to determine the natural period of a dam gate pier. In addition, identifying the elastic modulus of concrete by eigenvalue analysis based on the results will lead to improvement of the analysis accuracy.

The linear dynamic analysis using the 3D FEM model can determine the deformation of the dam gate pier in the axial direction of the dam, the tendency of the maximum principal stress to increase at the base due to the effect, and the possibility of damage due to tensile stress.

The nonlinear dynamic analysis using the 2D FEM model can evaluate the seismic performance focusing on the load capacity and deformation of the dam gate pier. However, since the dam gate pier is an RC concrete structure with few reinforcing bars, the relationship between the load and the displacement at which the failure due to shear occurs first. Therefore, when setting the load capacity, it is necessary to adjust the tensile strength of concrete so that the softening behavior after the load capacity is reduced can be expressed.

5. References

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