

INVESTIGATION OF CONCRETE GRAVITY DAM BEHAVIOUR CONSIDERING DAM–FOUNDATION–RESERVOIR INTERACTION

Muhammet KARABULUT¹, Murat Emre KARTAL², Murat CAVUSLI³, Seda COSKAN⁴, Oguzhan DURSUN⁵

1 Bulent Ecevit University, Department of Civil Engineering, Zonguldak/TURKEY, karabulut@beun.edu.tr

2 Bulent Ecevit University, Department of Civil Engineering, Zonguldak/TURKEY kartal@beun.edu.tr

3 Bulent Ecevit University, Department of Civil Engineering, Zonguldak/TURKEY murat.cavusli@beun.edu.tr

4 Vocational School, Bulent Ecevit University, Kilimli, Zonguldak/TURKEY,

sedacoskan@gmail.com

5 Bulent Ecevit University, Department of Civil Engineering, Zonguldak/TURKEY, oguzhan-dursun@hotmail.com

Abstract: Ground motion effects on a concrete gravity (CG) dam in the earthquake zone should be taken into account for design conditions. Boyabat CG dam constructed in Sinop, Turkey, is selected as an application. This study presents two-dimensional earthquake response of Boyabat CG dam including friction between dam and foundation. The two-dimensional finite element model of Boyabat CG dam is obtained using ANSYS finite element software. The unfavorable section of the dam is selected for two-dimensional numerical analyses. The contact-target element pairs are used in the dam–foundation–reservoir interaction. In this case, friction contact is considered in the numerical solutions. Empty and full reservoir cases are also considered in these solutions. The hydrodynamic pressure of the reservoir water is modeled with two dimensional fluid finite elements based on the Lagrangian approach. In the earthquake analyses, the finite element model has fixed boundary conditions. According to linear dynamic analyses, maximum horizontal displacements and maximum principle stress components are presented by dam height in the largest section. These results are evaluated considering empty and full reservoir conditions.

Keywords: Concrete gravity dam, Contact-target elements, Dam-foundation-reservoir interaction, Lagrangian approach.

Introduction

Water has been one of the most important things in human life from first era to now. People always try to live in around water resources. Because water is necessary for the continuing of life, so people had to learn how water was stored and how water usage was done. In many area, water has vital importance for instance, consumption, irrigation, climate and power.

Dam is one of the most difficult structural construction in civil engineering field because dam has huge potential risk in active seismic zones especially. A gravity dam is a massive sized dam fabricated from concrete and designed to hold back large volumes of water (Cracking Dams, 2008). By using concrete, the weight of the dam is actually able to resist the horizontal thrust of water pushing against it. This is why it is called a gravity dam. Gravity essentially holds the dam down to the ground, stopping water from toppling it over. Gravity dams are well suited for blocking rivers in wide valleys or narrow gorge ways. Since gravity dams must rely on their own weight to hold back water, it is key that they are built on a solid foundation of bedrock. The one advantage of a gravity dam is its rather simple design, with most dams being a straight vertical wall across a valley or gorge way. However, gravity dams can also be designed curved, as in the Hoover dam. Gravity dams are very durable and still highly preferred over buttress dams and arch dams (About Dams, 2008). The one drawback is that gravity dams require a large amount of material and construction to build are therefore relatively expensive (Gravity Dams, 2008). Therefore, each project should be evaluated on its own. When the conditions allow consideration of a concrete gravity dam alternative, the following points can be a plus. The method or scheme of diverting flows around or through the dam site during construction is an important consideration to the economy of the dam. A concrete gravity dam offers major advantages and potential cost savings by providing the option of diversion through alternate construction blocks, and lowers risk and delay if overtopping should occur (USACE, 1995).

This study showed that linear behavior of the concrete gravity Boyabat dam under Kocaeli earthquake. The change of maximum principal stresses and horizontal displacements by dam height were investigated. Numerical analyses were performed for empty and full reservoir cases considering fixed boundary conditions. ANSYS software was used for dam modeling and all dynamic analysis. The contact-target element pairs are used in the dam–foundation– reservoir interaction. Besides, friction is considered in the numerical solutions. It is provided by no separation



friction case.

Mathematical Model of Boyabat CG Dam

Boyabat dam, located approximately 10km south-east of Duragan county center, Sinop, was constructed in 2012 by General Directorate of State Hydraulic Works. It was established on K121lrmak River. The reservoir is used for irrigation and energy purposes. The dam crest is 262 m in length and 8 m wide. The maximum height of the dam from base to top crest point is 195 m, respectively. The annual total power generation capacity is 1.500×10^6 kWh/year.



Figure 1. Boyabat Dam.

Boyabat concrete gravity dam was modeled in ANSYS software. Finite element model of concrete gravity dam was divided to convenient finite element sizes. Finite element mesh was carried out approximately resemble measurements for dam model. Finite element model of the dam was given in given Fig. 2.



a) Empty reservoir condition





Figure 2. Finite element model of Boyabat Dam

Firstly, contact-target elements were identified between dam body and foundation. Dam model includes two cases. One of these situations is empty reservoir conditions and second one is full reservoir conditions. Linear dynamic analysis was done for the both situations.

Material Properties

The material properties of dam-foundation-reservoir interaction model used in linear analyses given in Table 1.

Table 1: Material	properties of Boyabat dam
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	Elastic modulus (kN/m ²)	Poisson ratio (v)	Density (γ) (kN/m ³)
concrete	2.8×10^{7}	0.2	2.3955
foundation	$10.5E^{6}$	0.17	2.73293
water	$2.07E^{6}$	0	0.99918

Lagrangian Approach for Dam -Reservoir -Foundation Interaction

The formulation of the fluid system based on the Lagrangian approach is presented as following (Wilson and Khalvati, 1983). In this approach, fluid is assumed to be linearly compressible, inviscid and irrotational. For a general two-dimensional fluid, pressure-volumetric strain relationships can be written in matrix form as follows,

$$\begin{cases} P \\ P_Z \end{cases} = \begin{bmatrix} C_{11} & 0 \\ 0 & C_{22} \end{bmatrix} \begin{cases} \varepsilon_V \\ w_Z \end{cases}$$
 (1)

where P, C_{11} , and ε_v are the pressures which are equal to mean stresses, the bulk modulus and the volumetric strains of the fluid, respectively. Since irrotationality of the fluid is considered like penalty methods (Zienkiewicz and Taylor, 1989) rotations and constraint parameters are included in the pressure-volumetric strain equation (Eq. (1)) of the fluid. In this equation P_z , is the rotational stress; C_{22} is the constraint parameter and w_z is the rotation about the Cartesian axis y and z.

In this study, the equations of motion of the fluid system are obtained using energy principles. Using the finite element approximation, the total strain energy of the fluid system may be written as,

$$\pi_{e} = \frac{1}{2} \mathbf{U}_{f}^{T} \mathbf{K}_{f} \mathbf{U}_{f}$$
(2)



where U_f and K_f are the nodal displacement vector and the stiffness matrix of the fluid system, respectively. K_f is obtained by the sum of the stiffness matrices of the fluid elements as follows,

$$\mathbf{K}_{f}^{e} = \int_{V} \mathbf{B}_{f}^{e^{T}} \mathbf{C}_{f} \mathbf{B}_{f}^{e} dV^{e}$$
(3)

where C_f is the elasticity matrix consisting of diagonal terms in Eq. (1) is the strain-displacement matrix of the fluid element.

An important behaviour of fluid systems is the ability to displace without a change in volume. For reservoir and storage tanks, this movement is known as sloshing waves in which the displacement is in the vertical direction. The increase in the potential energy of the system because of the free surface motion can be written as,

$$\pi_{s} = \frac{1}{2} \mathbf{U}_{sf}^{T} \mathbf{S}_{f} \mathbf{U}_{sf}$$
(4)

where U_{sf} and S_f are the vertical nodal displacement vector and the stiffness matrix of the free surface of the fluid g_{sf} are the vertical nodal displacement vector and the stiffness matrix of the free surface fluid elements as follows,

$$\mathbf{S}_{\mathbf{f}}^{\mathbf{e}} = \rho_{\mathbf{f}} \mathbf{g}_{\mathbf{A}}^{\mathsf{T}} \mathbf{h}_{\mathbf{S}} \mathbf{d} \mathbf{A}^{\mathbf{e}}$$
(5)

where h_s is the vector consisting of interpolation functions of the free surface fluid element. ρ_f and g are the mass density of the fluid and the acceleration due to gravity, respectively. Besides, kinetic energy of the system can be written as,

$$T = \frac{1}{2} \dot{\mathbf{U}}_{f}^{T} \mathbf{M}_{f} \dot{\mathbf{U}}_{f}$$
(6)

where U and M_f are the nodal velocity vector and the mass matrix of the fluid system, respectively. M_f is also oMained M_f the sum of the mass matrices of the fluid elements as follows,

$$\mathbf{M}_{f}^{e} = \rho_{f} \bigvee_{V}^{\int \mathbf{H}^{T} \mathbf{H} dV^{e}}$$
(7)

where H is the matrix consisting of interpolation functions of the fluid element. If (Eq. (2), (4) and (6)) are combined using the Lagrange's equation (Clough and Penzien, 1993); the following set of equations is obtained, $\mathbf{M}_{\mathbf{f}}\ddot{\mathbf{U}}_{\mathbf{f}} + \mathbf{K}_{\mathbf{f}}^{*}\mathbf{U}_{\mathbf{f}} = \mathbf{R}_{\mathbf{f}}$ (8)

where \dot{U}_{f} , \dot{U}_{f} , U_{f} and R_{f} are the system stiffness matrix including the free surface stiffness, the nodal acceleration and displacement vectors and time-varying nodal force vector for the fluid system, respectively. In the formation of the fluid element matrices, reduced integration orders are used.

The equations of motion of the fluid system, (Eq. (8)), have a similar form with those of the structure system. To obtain the coupled equations of the fluid-structure system, the determination of the interface condition is required. Since the fluid is assumed to be inviscid, only the displacement in the normal direction to the interface is continuous at the interface of the system. Assuming that the structure has the positive face and the fluid has the negative face, the boundary condition at the fluid-structure interface is,

$$\mathbf{U}_{\mathbf{n}}^{-} = \mathbf{U}_{\mathbf{n}}^{+} \tag{9}$$



where U_n is the normal component of the interface displacement. Using the interface condition, the equation of motion of the coupled system to ground motion including damping effects are given by,

$$\mathbf{M}_{c}\ddot{\mathbf{U}}_{c} + \mathbf{C}_{c}\dot{\mathbf{U}}_{c} + \mathbf{K}_{c}\mathbf{U}_{c} = \mathbf{R}_{c}$$
⁽¹⁰⁾

in which M_c , C_c , and K_c are the mass, damping and stiffness matrices for the coupled system, respectively. ${}^{\dot{U}c}$, U_c and R_c are the vectors of the displacements, velocities, accelerations and external loads of the coupled system, respectively (Kartal, 2012).

Kocaeli Earthquake

In this study, 1999 Kocaeli earthquake records were used in all linear dynamic analysis. The earthquake duration is 27.185 seconds. The earthquake accelerogram was given in Fig .4.



Figure 3. 1999 Kocaeli Earthquake records

Results

The displacements of upstream site of dam were calculated for empty and full reservoir cases. It is clearly seen that full reservoir case has higher displacements than empty reservoir case in linear dynamic analysis due to hydrodynamic pressure. The maximum displacement in full reservoir case is 3.2 cm and the maximum displacement in empty reservoir case is 2.7 cm for the dam. The change of displacements by dam height is given in Fig. 4 and 5.





Figure 4. Maximum displacements changing



Figure 5. Minimum displacements changing

We investigated the principal stress changing by dam height under Kocaeli earthquake for linear dynamic analysis. It was expected that full reservoir case had higher principal stresses than empty reservoir case because of hydrodynamic pressure effect. According to linear dynamic analysis, it was observed that full reservoir case has higher principal stresses. The maximum principal stress is 2206.96 kN/m² in empty reservoir condition and 2904.08 kN/m² in full reservoir condition for the dam. Besides, the maximum compressive stress is 2622.44 kN/m² in empty reservoir condition and 2324.98 kN/m² in full reservoir condition for the dam. The change of maximum principal stresses and compressive stresses by dam height are given in Fig. 6 and 7.





Figure 6. Maximum tensile stresses changing



Figure 7. Maximum compressive stresses changing

Conclusion

Boyabat CG Dam geometry and the unfavorable section of the dam was examined using finite element model. Boyabat dam was modeled as two-dimensional and the material and foundation soil mechanical properties were obtained from the experimental data of the dam. After that these materials were identified to dam model by ANSYS software. Fixed boundary conditions were defined around dam and foundation. Finally, 1999 Kocaeli earthquake was selected for this application due to similar earthquake seismic zones.

In this study, we investigated the effect of strong ground motion on stresses and displacements. In addition to this, it was examined that friction, which was identified between dam body-foundation soil, effect on stress for empty and full reservoir conditions. It is clearly seen that full reservoir model has larger tensile-compressive stresses and displacements than empty reservoir model.



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