DISASTER SCIENCE AND ENGINEERING p. 25-30, 1(2), 2015

The Effect of Water Level on the Earthquake Behavior of Roller Compacted Concrete Dams

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Received: 11.12.2015 Accepted: 29.12.2015

Abstract: This study aims to fill the lack of the studies related to the seismic response of RCC dams. Therefore, earthquake response is investigated using the finite element method. Two-dimensional earthquake response of Cine RCC dam is presented considering geometrical non-linearity. Besides, material nonlinearity is also taken into consideration in time-history analyses. Bilinear kinematic hardening and multi linear-hardening model are used in the materially non-linear analyses for concrete and foundation rock, respectively. The dam–foundation–reservoir interaction is modeled by the contact elements. Different water levels of reservoir are considered in numerical analyses. The hydrodynamic pressure of the reservoir water is modeled with the fluid finite elements based on the Lagrangian approach. In the earthquake analyses, viscous dampers are defined in the finite element model to represent infinite boundary conditions. Comparing of principle stresses with respect to different water levels of the reservoir are carried out. Numerical solutions indicate that the principle stress components increase by the hydrodynamic pressure effect of the reservoir water, however those decrease in the materially non-linear time-history analyses. Larger displacements are obtained for nonlinear analyses compared with linear analyses.

***Index Terms*— Bilinear kinematic hardening, dam–foundation–reservoir interaction, Lagrangian approach, multi linear-hardening model, roller compacted concrete dam.**

I. INTRODUCTION

Roller compacted concrete (RCC) dams are designed as conventional concrete structures. But, the construction methods, concrete mix design and details of the appurtenant structures are different in these structures. The construction techniques utilized in RCC dams are analogous to those used for embankment dams. These techniques provide rapid placement and economically advantages for construction. RCC dams are relatively dry, lean, zero slump concrete material containing coarse and fine aggregate that is consolidated by external vibration using vibratory rollers, dozer and other heavy equipment. Construction procedures associated with RCC require particular attention to be given in the layout and design to watertightness and seepage control, horizontal and transverse joints, facing elements, and appurtenant structures. In the hardened condition, mechanical properties of RCC dams take after those of conventional concrete dams (USACE, 1995).

The researchers usually focused on the thermal analysis of RCC dams because thermal cracking may create a leakage path to the downstream face that is aesthetically undesirable. Noorzaei et al. (2006) performed thermal and structural analysis of Kinta RCC gravity dam, which is the first RCC dam in Malaysia, using the developed two-dimensional finite element code. Then the authors compared predicted temperatures obtained from the finite element code with actual temperatures measured in the field using thermocouples installed within the dam body and they found them to be in good agreement. Jaafar et al. (2007) developed a finite element based computer code to determine the

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temperatures within the dam body. According to performed thermal analysis of a RCC dam changing the placing schedule can optimize the locations of maximum temperature zones. Abdulrazeg et al. (2010) performed three dimensional coupled thermal and structural analysis of roller compacted concrete dams. They assessed crack development within the dam body using the proposed crack index. This method remarkably reduces the total number of elements and nodes when the dam height was increased. Zhang et al. (2011) simulated and analyzed the temperature field and thermal stress of certain RCC gravity dams in cold regions using the material properties of roller-compacted concrete dam by three-dimensional finite element relocating mesh method. As a result, the authors indicated that superficial insulation prevented surface crack forming.

In this study, two dimensional earthquake response is investigated using the finite element method. Cine RCC dam is considered in the numerical solutions. Geometrically and materially nonlinear analyses are also performed in addition to linear analyses. Different levels of reservoir water are taken into consideration. Viscous dampers are defined in the finite element model boundaries to represent infinite boundary condition. In the earthquake analyses, north-south and vertical components of the 1999 Kocaeli earthquake record are utilized. According to linear and nonlinear seismic analyses, hydrodynamic pressure increases the horizontal displacements and principle stress components. Besides, while the horizontal displacements increase with materially non-linear analyses, principle stress components decrease as compared to linear analysis.

II. FORMULATION OF DAM-FOUNDATION-RESERVOIR INTERACTION BY THE LAGRANGIAN APPROACH

The formulation of the fluid system based on the Lagrangian approach is presented as following (Wilson and Khalvati, 1983; Calayır 1994). 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,

$$\begin{Bmatrix} P \\ P_z \end{Bmatrix} = \begin{bmatrix} C_{11} & 0 \\ 0 & C_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_v \\ w_z \end{Bmatrix} \qquad (1)$$

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; Bathe, 1996), 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,

$$\Pi_e = \frac{1}{2}\mathbf{U}_f^T \mathbf{K}_f \mathbf{U}_f \qquad (2)$$

where $\mathbf{U}_f$ and $\mathbf{K}_f$ 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,

$$\mathbf{K}_f = \sum \mathbf{K}_f^e \qquad \mathbf{K}_f^e = \int_V B_f^{e^T} C_f B_f^e dV^e \qquad (3)$$

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

An important behavior 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,

$$\Pi_s = \frac{1}{2}\mathbf{U}_{sf}^T \mathbf{S}_f \mathbf{U}_{sf} \qquad (4)$$

where $\mathbf{U}_{sf}$ and $\mathbf{S}_f$ are the vertical nodal displacement vector and the stiffness matrix of the free surface of the fluid system, respectively. $\mathbf{S}_f$ is obtained by the sum of the stiffness matrices of the free surface fluid elements as follows,

$$\left.\begin{aligned} \mathbf{S}_f &= \sum S_f^e \\ \mathbf{S}_f^e &= \rho_f g \int_A h_s^T h_s dA^e \end{aligned}\right\} \qquad (5)$$

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,

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

Where $\dot{\mathbf{U}}_f$ and $\mathbf{M}_f$ are the nodal velocity vector and the mass matrix of the fluid system, respectively. $\mathbf{M}_f$ is also obtained by the sum of the mass matrices of the fluid elements as follows,

$$\left.\begin{aligned} \mathbf{M}_f &= \sum M_f^e \\ \mathbf{M}_f^e &= \rho_f \int_V H^T H dV^e \end{aligned}\right\} \qquad (7)$$

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,

$$\mathbf{M}_f \ddot{\mathbf{U}}_f + \mathbf{K}_f^* \mathbf{U}_f = \mathbf{R}_f \qquad (8)$$

where, $\ddot{\mathbf{U}}_f$, $\mathbf{U}_f$ and $\mathbf{R}_f$ 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 (Wilson and Khalvati, 1983).

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,

$$U_n^- = U_n^+ \tag{9}$$

where U_n is the normal component of the interface displacement (Akkas et al., 1979). Using the interface condition, the equation of motion of the coupled system to ground motion including damping effects are given by,

$$\mathbf{M}_C\ddot{\mathbf{U}}_C + \mathbf{C}_C\dot{\mathbf{U}}_C + \mathbf{K}_C\mathbf{U}_C = \mathbf{R}_C \tag{10}$$

in which Mc, Cc, and Kc are the mass, damping and stiffness matrices for the coupled system, respectively. $\mathbf{U}_C, \dot{\mathbf{U}}_C, \ddot{\mathbf{U}}_C$ and $\mathbf{R}_c$ are the vectors of the displacements, velocities, accelerations and external loads of the coupled system, respectively.

III. NONLINEAR MATERIAL MODELS

There are two basic hardening rules which are isotropic and kinematic rules (Fig. 1). These rules require uniaxial stress-strain relationships that are easier for practical applications. The uniaxial stress-strain relationship includes three regions such that (i) stress-strain relationship prior to yield, (ii) yield criteria and (iii) stress-strain relationships for the post-yield range. The yield surfaces in two and three dimensional cases are shown in (Fig. 2.) for kinematic hardening model.

The isotropic hardening model deals satisfactory with respect to monotonic loadings, stress level confined to a limited sub-domain of the loading surface and material with negligible hardening. However, these assumptions do not apply strictly to many real situations, especially the last one. The kinematic hardening is often and more successfully employed, thanks to its capability of representing cyclic loads with acceptable approximation. Even though it can accommodate to some extent the Bauschinger effect, still it underestimate the real cyclic response, as opposed to the isotropic case.

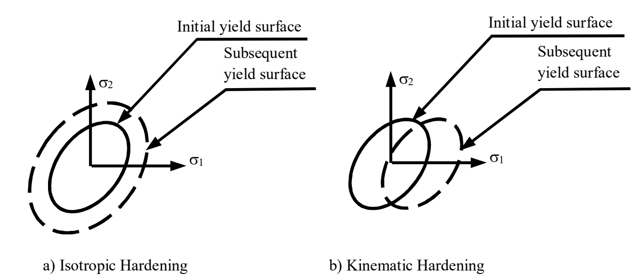


Fig. 1. Isotropic and kinematic hardening rules

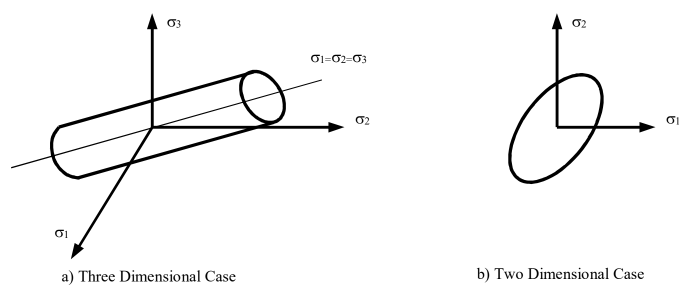


Fig. 2. Yield surfaces for kinematic hardening model

A. Bilinear Kinematic Hardening Model

The bilinear kinematic hardening model is the simplest and widely used mode as shown in Fig. 3. This model uses von Mises yield criterion with the associated flow rule. The elastic range remains constant throughout the various loading stages, while the kinematic hardening rule for the yield surface is assumed to be a linear function of the increment of plastic strain. The tangent modulus, required for updating the element stiffness matrix is the Young's modulus E for stresses lower than the yield stress f_y and μE for stresses of value higher than.

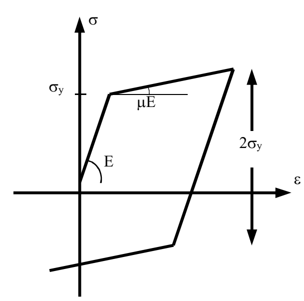


Fig. 3. Stress-Strain behavior of bilinear kinematic hardening model for Bauschinger effect.

B. Multilinear Kinematic Hardening Model

The multilinear kinematic hardening model can be used to model plasticity behavior under cycling loading. This model uses the Besseling model to characterize the perfectly plastic material behavior. The material behavior is assumed to be composed of various sections, all subjected to the same total strain, but each subsection having a different yield strength. Each subvolume has a simple stress-strain response but when combined the model can represent complex behavior. This allows a multilinear stress-strain curve that exhibits the Bauschinger (kinematic hardening) effect (Fig. 4).

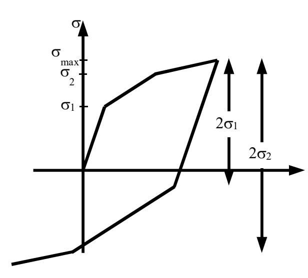


Fig. 4. Stress-Strain behavior of multilinear kinematic hardening model for Bauschinger effect.

IV. NUMERICAL MODEL OF CINE RCC DAM

Cine dam, located approximately 16km southeast of Cine, Aydın, was constructed in 2010 by General Directorate of State Hydraulic Works (Fig. 5) (DSI, 2015). It was established on Cine River. This dam was projected as a roller compacted concrete dam. The reservoir is used for irrigation and energy purposes. The dam crest is 372.5m in length and 9m wide. The maximum height and base width of the dam are 136.5 m and 142.5 m, respectively. The maximum height of the reservoir water is considered as 98.77 m. The annual total power generation capacity is 118 GW.

Fig. 5. Cine RCC Dam (DSI 2015)

A. Material Properties of Cine RCC Dam

The two-dimensional finite element model of Cine dam is modeled considering two layered foundation rock. One of this begins from crest level to base of the dam body. The other begins from the base of the dam body to bottom of the foundation. The material properties of Cine roller compacted concrete dam body and foundation are given in Table 1.

TABLE I
THE MATERIAL PROPERTIES OF CINE RCC DAM (DSI, 2015)

	Material Properties		
	Modulus of Elasticity (GPa)	Poisson's Ratio	Mass Density (kg/m³)
Concrete (Dam)	30	0.20	2530
Rock (Upper Foundation Soil)	28	0.19	2900
Rock (Lower Foundation Soil)	25	0.18	2800

B. Finite Element Model of Cine Dam

This study considers two dimensional finite element model of Cine RCC dam (Fig. 6). In this model, if the height of the dam is indicated as 'H', the foundation soil is extended as 'H' in the transverse river direction, downstream direction and gravity direction. Besides, foundation soil and reservoir water model is extended as "3H" in the upstream direction. Fluid and solid element matrices are computed using the Gauss numerical integration technique (Wilson and Khalvati, 1983). In addition, viscous dampers are defined in the finite element model boundaries to consider infinite boundary condition. Zero length damper elements (Combin14) are used in two directions in solid boundaries and one direction in fluid boundaries. Totally 208 viscos damper elements are defined in the foundation soil boundaries in 'X', 'Y' directions. There are 560 elements in the fluid finite element model, 160 elements in the upper soil finite element model, 896 elements in the below soil finite element model and 180 elements in the dam body finite element model.

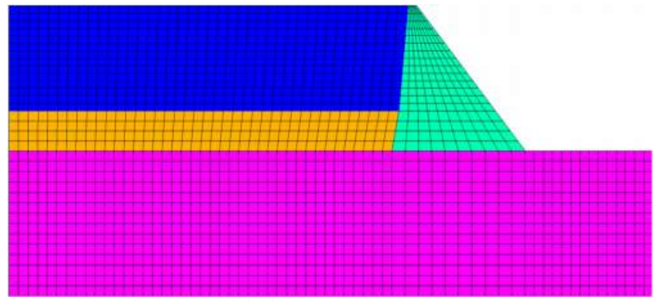
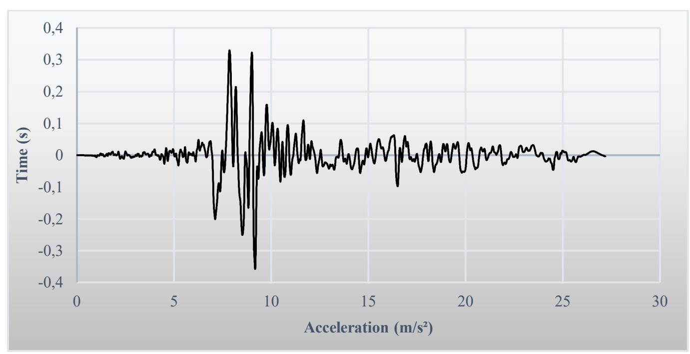


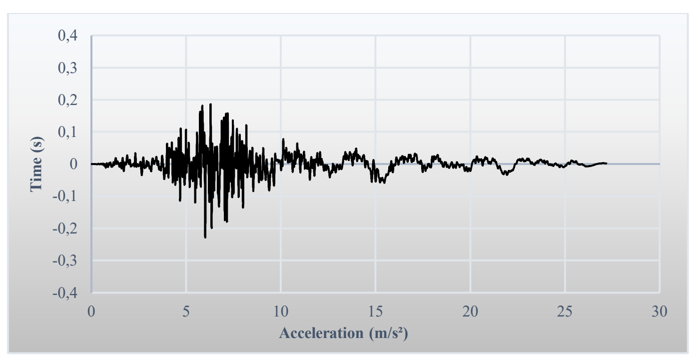
Fig 6. Finite Element Model of RCC Dam

C. Ground Motion Effects

This study investigates the earthquake response of Cine RCC Dam subjected to strong ground motion. Different water level cases are taken into account in the numerical solutions. The north-south and vertical components of the 1999 Kocaeli earthquake (Fig. 7a,b) are utilized in analyses. Earthquake analyses are performed during 27.185 second. Linear and nonlinear time-history analyses were performed using Ansys (2015). Rayleigh damping is used in time-history analysis. Therefore, first six vibration frequencies are considered to calculate Rayleigh damping constants (Rayleigh and Lindsay, 1945; Chopra, 1996). Besides, Newmark algorithm was employed in numerical solutions.



a) North-South component



b) Vertical component
Fig 7. 1999 Kocaeli Earthquake accelerograms

V. NUMERICAL RESULTS

A. Displacements

The effect of the reservoir water level on the earthquake response of the roller compacted dam is investigated for 3 different cases. For this purpose, 36, 64 and 98 meters of reservoir water levels were investigated for linear and nonlinear analyses. As a result of these analyses, the horizontal displacements are shown in Figs. 8-11.

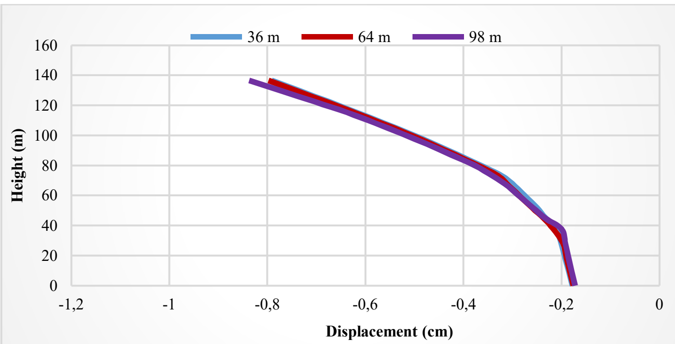


Fig 8. Minimum horizontal displacements for linear analyses

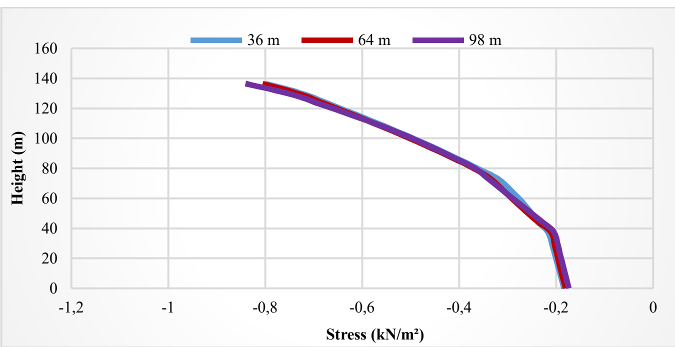


Fig 9. Minimum horizontal displacements for nonlinear analyses

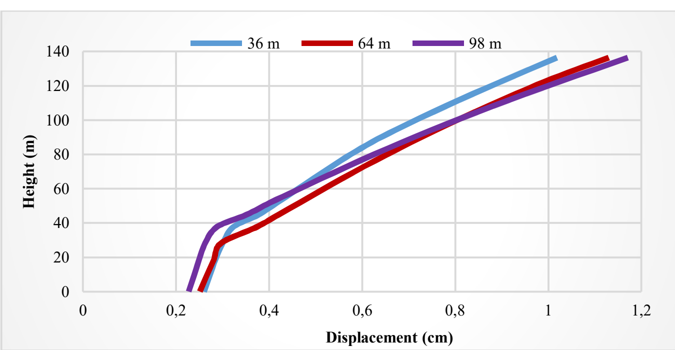


Fig 10. Maximum horizontal displacements for linear analyses

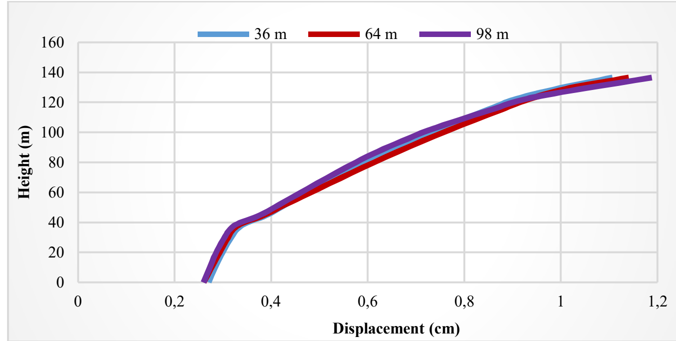


Fig 11. Maximum horizontal displacement for nonlinear analyses

Horizontal displacements are given in Figs. 8-11. The bottom movement is about 0.2 cm for the dam. The maximum horizontal displacements at crest are between 0.8 cm and 1.2 cm in these figures. These figures also show that the horizontal displacements increase by dam height with the increasing the level of reservoir water. The minimum horizontal displacements were obtained at 36 meter of reservoir water for linear and nonlinear analyses. Full reservoir water has the largest displacements. If linear analyses and nonlinear analyses are compared, non-linear analyses have larger displacements than linear analyses.

B. Stresses

The principle stresses for different level of the reservoir water level of the roller compacted dam are also investigated. For this purpose, three different reservoir water levels were considered in linear and nonlinear analyses. As a result of these analyses, the principle tensile and compressive stresses are shown in Figs. 12-15.

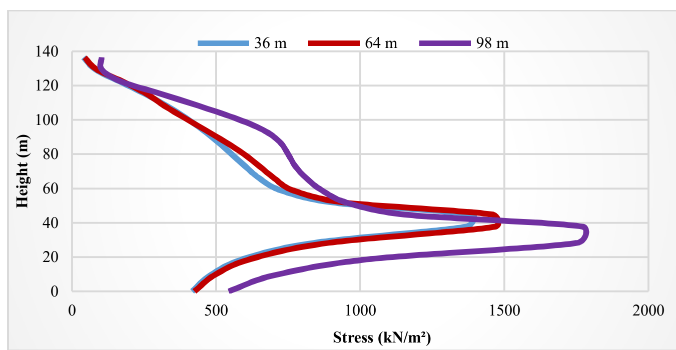


Fig 12. Principle tensile stresses for linear analyses

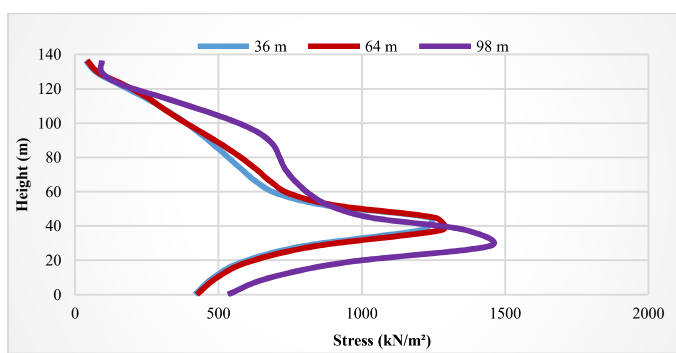


Fig 13. Principle tensile stresses for nonlinear analyses

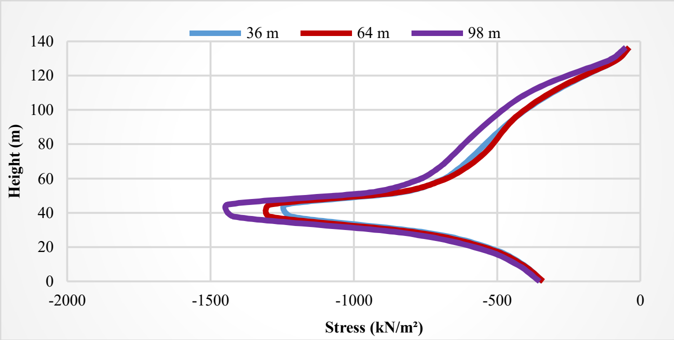


Fig 14. Principle compressive stresses for linear analyses

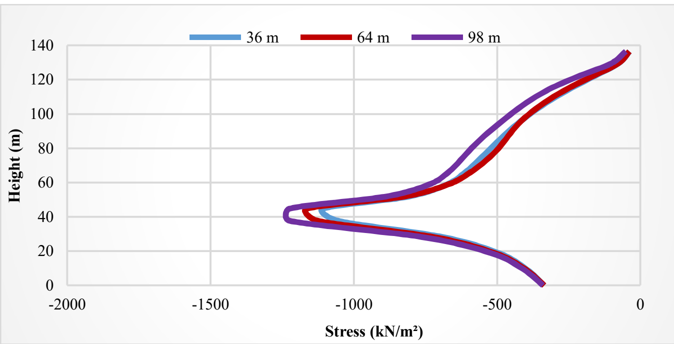


Fig 15. Principle compressive stresses for nonlinear analyses

Figures 12-15 indicate that maximum and minimum stresses increase with the rising level of reservoir water. 98-meter level of reservoir water has the largest stresses than the other reservoir levels. The dam of 98-meter level of reservoir water has 1770kN/m² and 1450kN/m² principle tensile stresses according to linear and nonlinear analyses, respectively. According to these results, linear analyses have greater stresses than the nonlinear ones. The resemble results are also obtained for principle compressive stresses. The maximum principle compressive stresses of the dam were also obtained for 98-meter level of reservoir water between 1225kN/m² and 1440kN/m² according to linear and nonlinear analyses, respectively. The principle compressive stresses obtained from linear analyses are larger than nonlinear ones for increasing reservoir water levels.

VI. Conclusion

The linear and nonlinear analyses of RCC dam were carried out considering ground motion effects. In nonlinear analyses, bilinear kinematic hardening model was used for concrete dam and multi linear kinematic hardening model was used for rock foundation. Dam-foundation-reservoir interaction was considered in numerical analysis. The contact elements were used between reservoir-dam and reservoir-foundation interactions. So, horizontal and vertical component of 1999 Kocaeli earthquake accelerations were used in dynamic analyses. Viscous dampers were utilized in the boundary of the finite element model to represent infinite boundary condition.

According to performed analyses, the followings are deducted from this study;

- Linear analyses indicated that principal stress components and displacements increases with hydrodynamic pressure at raising water levels.
- Principal stress components obtained from non-linear analyses diminished and however horizontal displacements increased when compared to linear analyses.

Acknowledgement

This study is improved and developed from the conference paper named presented in the International Science and Technology Conference, Russia.

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