# THE EFFECT OF RESERVOIR LENGTH ON THE EARTHQUAKE BEHAVIOR OF ROLLER COMPACTED CONCRETE DAMS

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**Abstract:** Finite element analysis is an effective method for evaluating roller-compacted concrete (RCC) dams in the earthquake zone and investigating earthquake response of RCC dams. The primary aim of this research is to inspect the effect of various reservoir lengths on the earthquake response of a selected RCC dam under strong ground motion effect. This study presents two-dimensional earthquake response of Cine RCC dam considering geometrical and material non-linearity in time-history analyses. The Drucker-Prager material model is used in the materially non-linear analyses for concrete and also foundation rock. The reservoir length of RCC dam is modeled respectively as half, itself, two times, three times, five times and ten times of the dam height. The dam–reservoir-foundation interaction is modeled by the contact-target element couples. The hydrodynamic pressure of the reservoir water is modeled with two dimensional fluid finite elements based on the Lagrangian approach. 1999 Duzce Earthquake acceleration records are considered in all dynamic analysis. According to non-linear time history analyses, the horizontal displacements and principle stress components are compared and evaluated.

**Keywords:** Contact-target element, Hydrodynamic pressure, Lagrangian approach, Roller-compacted concrete dam.

## Introduction

People have always tried to live around water resources from past to present Because water is very important to survive people and other lives. People have needed water for a lot of purpose until humanity. The settlers around water resources have used water for storing, drinking and irrigation in many eras. Furthermore, settlements away from water supplies have always many problems. They were not obtainable water every time and every place. Dams are the most important buildings for storing water, water protection and the buildings play very important role for obtaining of energy and continuing of people's daily lives. Dams can prevent uncontrolled water. Dams can reduce consumption of fossil fuels for electricity production. Roller compacted concrete (RCC) dams have been widely used by all world countries since the 1980s. DSI (state hydraulic works) which is responsible for realization of water resources development projects in Turkey is completed 204 large dams and 339 small dams until today. 111 large dams and 159 small dams are under construction in Turkey.

The investigators 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 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. Bayraktar et al. (2010) investigated the effect of reservoir length on seismic performance of gravity dams to near and far-fault ground motions. 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) simulate and analyze the temperature field and thermal stress of certain RCC gravity dams in cold regions using the material properties of roller-compacted concrete by three-dimensional finite element relocating mesh method. As a result, the authors indicated that superficial insulation prevented surface cracks from forming. Kartal et al. 2012 investigated three-dimensional earthquake analysis of roller-compacted concrete dams.

In this study, two-dimensional earthquake response of Cine RCC dam is investigated for six different cases. The reservoir length of RCC dam is modeled respectively as half, itself, two times, three times, five times and ten times of the dam height. The two dimensional fluid finite elements based on the Lagrangian approach is utilized to obtain the hydrodynamic pressure effect of the reservoir water. Contact-target elements are used in dam-foundation-reservoir interfaces. No separation friction case is considered between dam and foundation. Nonlinear time-history analyses are carried out to obtain earthquake response of the dam. Geometrically and materially nonlinear analysis were made for this purpose. Fixed boundary conditions are considered in the numerical solutions. Numerical solutions indicate that the horizontal displacements increased by increasing reservoir length and hydrodynamic pressure effect. In addition to this, principal tensile and compressive stresses increased by reservoir length. When reservoir length extended, greater displacements and stresses appeared in the upstream side of the dam.

## 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,

$$\begin{Bmatrix} P \\ P_z \end{Bmatrix} = \begin{bmatrix} C_{11} & 0 \\ 0 & C_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_V \\ w_z \end{Bmatrix} \tag{1}$$

Where P, $C_{11}$, and $\varepsilon_v$ 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,

$$\Pi_e = \frac{1}{2}\mathbf{U}_f^{T}\mathbf{K}_f\mathbf{U}_f \tag{2}$$

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,

$$\begin{aligned} \mathbf{K}_f &= \sum \mathbf{K}_f^e \\ \mathbf{K}_f^e &= \int_V B_f^{e\,T} C_f B_f^e dV^e \end{aligned} \tag{3}$$

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,

$$\Pi_S = \frac{1}{2}\mathbf{U}_{sf}^{T}\mathbf{S}_f\mathbf{U}_{sf} \tag{4}$$

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,

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

where $h_s$ is the vector consisting of interpolation functions of the free surface fluid element. $\rho_f$ 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,

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

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,

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

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,

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

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,

$$U_n^- = U_n^+ \quad (9)$$

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,

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

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.

## Numerical Model of Cine Rcc Dam

### The 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. 1) (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. 1**. Cine Roller Compacted Concree Dam

## Material Properties of Cine 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 1**. Material Properties of Cine RCC dam

| | **Material Properties** | | |
|---|---|---|---|
| | Modulus of Elasticity (GPa) | Poisson's Ratio | Mass Density ($kg/m^3$) |
| **Concrete (Dam)** | 30 | 0.20 | 2530 |
| **Rock (Lower Foundation Soil)** | 25 | 0.18 | 2800 |

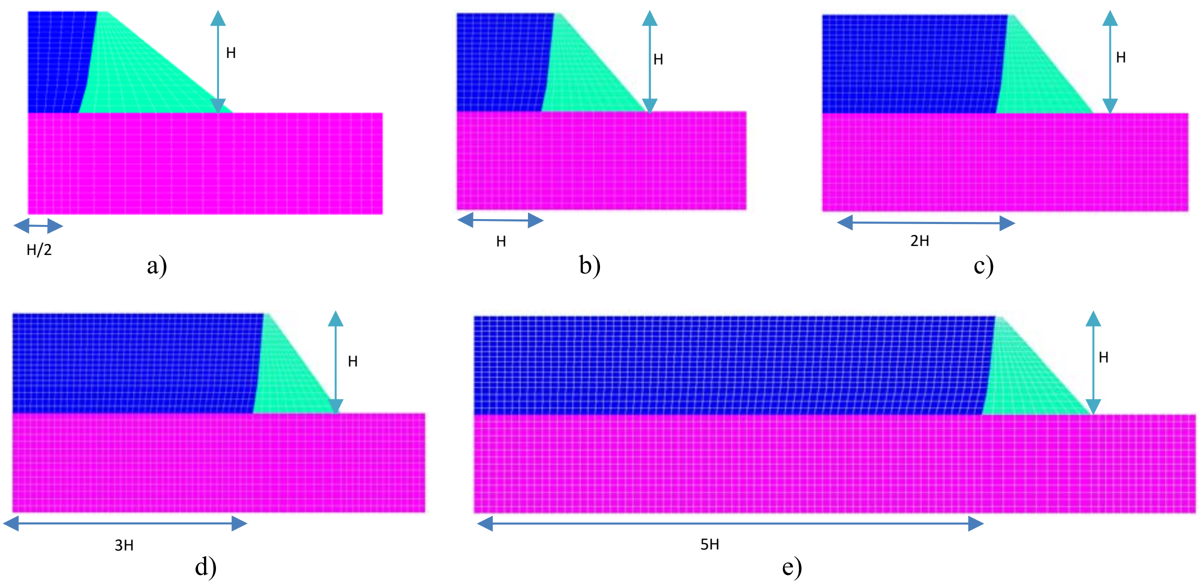
## Finite Element Models of Cine Dam

This study considers two-dimensional finite element models of Cine RCC dam (Fig. 2). 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, reservoir water model is extended as following Table 2. Numerical analysis were performed for these six cases.

**Table 2.** Numerical analysis

| *Cases* | *Reservoir length* |
|---|---|
| Case 1 | H/2 |
| Case 2 | H |
| Case 3 | 2H |
| Case 4 | 3H |
| Case 5 | 5H |
| Case 6 | 10H |

Fluid and solid element matrices are computed using the Gauss numerical integration technique (Wilson and Khalvati, 1983).



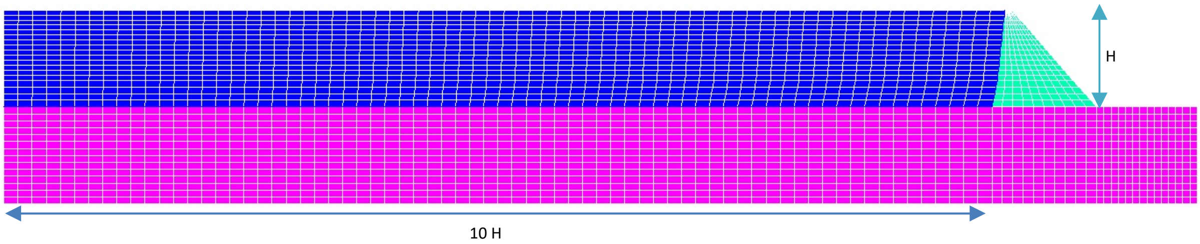



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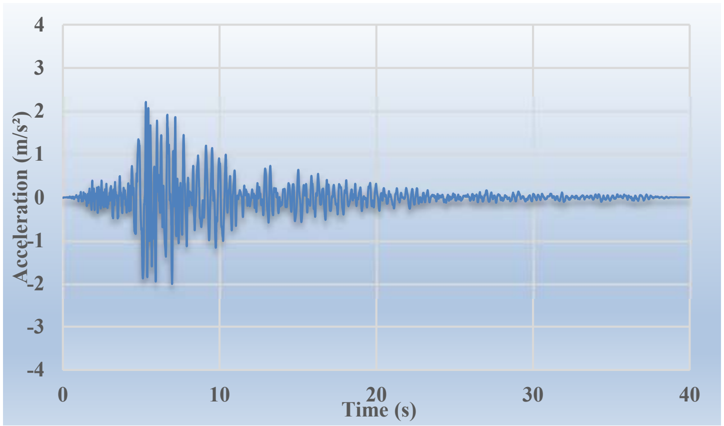
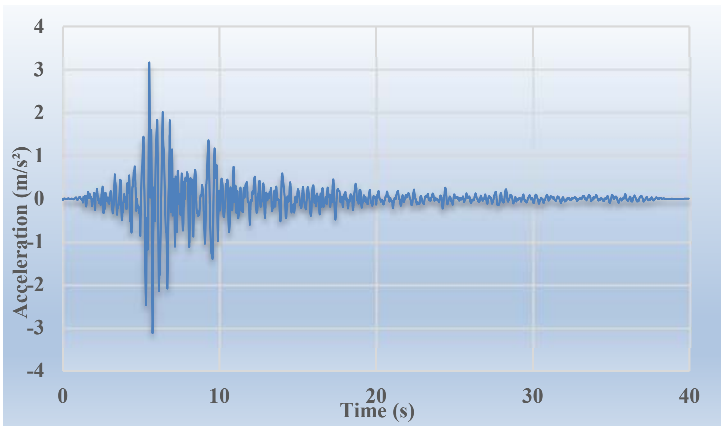
**Fig. 2.** Finite Element Models of Cine RCC dam

## Strong Ground Motion Effects

This study investigates the earthquake response of Cine RCC Dam subjected to strong ground motion. Different reservoir length cases are taken into account in the numerical solutions. The north-south and vertical components of the 1989 Loma Prieta earthquake (Fig. 3) are utilized in analyses. Earthquake analyses are performed during 39.96 second. Nonlinear time-history analyses were performed using Ansys (2016). In the non-linear time history analyses, the time interval is used as 0.01 in different water level case. Rayleigh damping is used in time-history analysis. Therefore, first six vibration frequencies are considered to calculate Rayleigh damping constants using initial boundary conditions (Rayleigh and Lindsay, 1945; Chopra, 1996). Besides, Newmark algorithm was employed in numerical solutions.




a) Vertical component




b) North-South component

**Fig 3.** 1989 Loma Prieta Accelerograms

## Numerical Analysis and Results

This study presents earthquake behavior of Cine RCC dam considering north-south and vertical components of 1989 Loma Prieta earthquake. Earthquake analyses are performed during 39.96 second. Numerical analysis was investigated for six different cases. If dam body height supposes as H, reservoir length is modelled as the following (Table 2). Numerical analysis is performed for each cases.
Solutions are shown in Fig. 4-6. According to these solutions, the smallest displacement is approximately 4.7 cm at dam crest for Case 1. However, the maximum displacement is 7.4 cm at dam crest for Case 6 (Fig. 4). So this solution is clearly shown that when reservoir length extends, higher displacements are obtained.

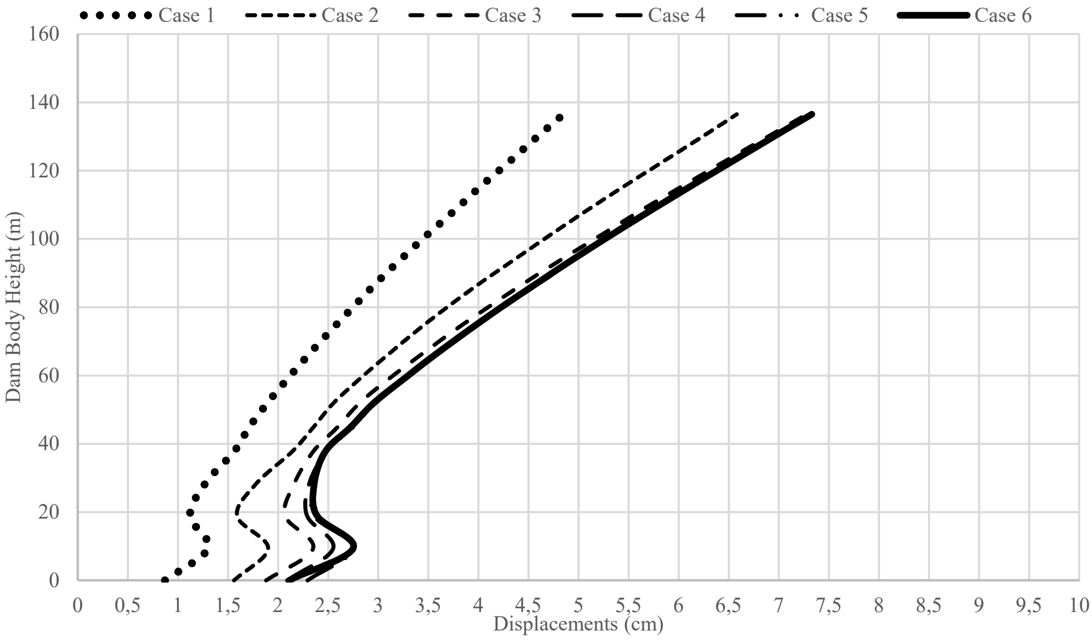



**Fig. 4.** Horizontal Displacements

The principal tensile and compression stresses are shown in Fig. 5-6. The maximum principal compression stress is approximately 9900 kN/m$^2$ at bottom of dam for Case 6. The minimum principal compression stress is 7350 kN/m$^2$ for Case 1 (Fig. 5.). The effect of reservoir length clearly appeared from these solutions.

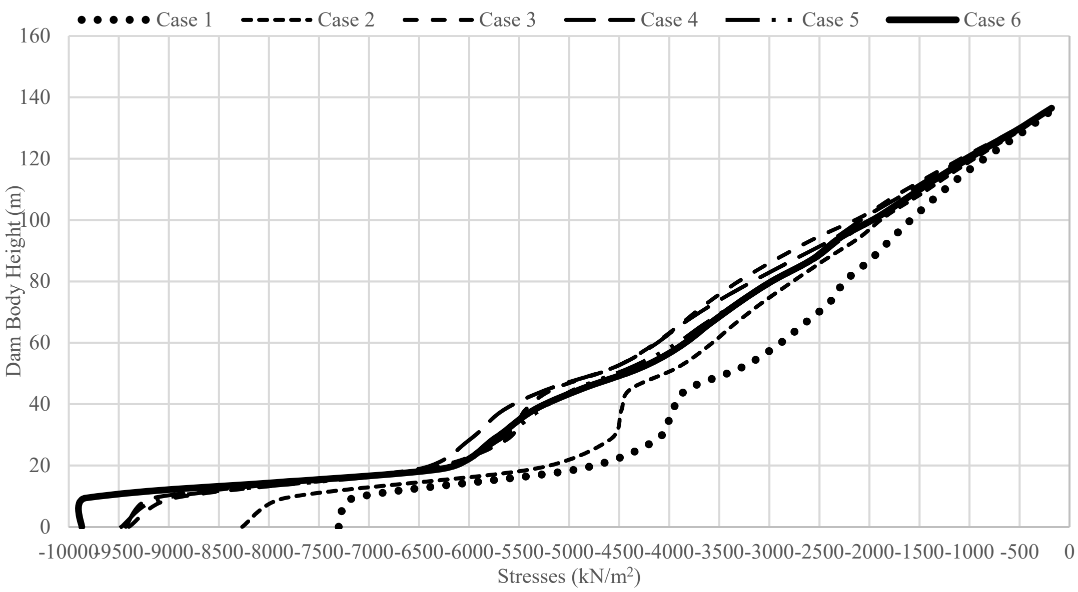



**Fig. 5.** Principal Compression Stresses

The maximum principal tensile stress is approximately 1950 kN/m$^2$ for Case 6 and the minimum principal compression stress is 7350 kN/m$^2$ for Case 1 at bottom of dam body (Fig. 6.). It clearly appears from Fig. 6 that if reservoir length extends, the principal tensile stresses increase by dam height.

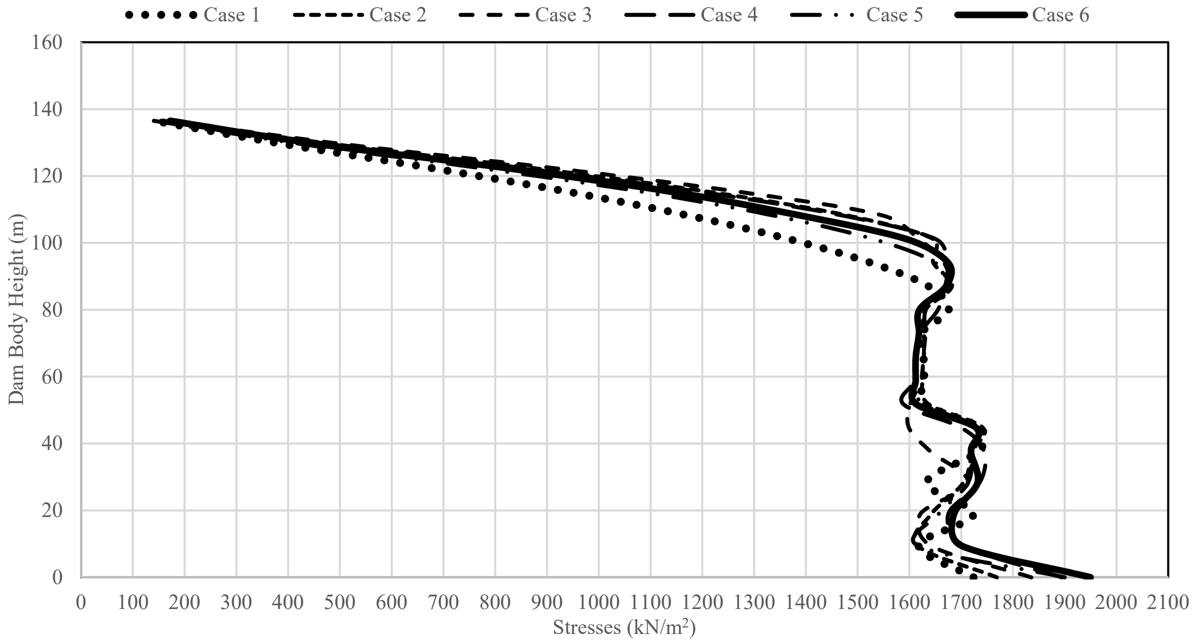



**Fig. 6.** Principal Tensile Stresses

## Conclusion

Investigation of the effect of different reservoir length on the earthquake behavior of RCC dams is very important to observe the response of the dam. According to performed numerical solutions, if reservoir length extends, horizontal displacements increase. In additional this, nonlinear analyses clearly refer that the principle tensile and compressive stresses decrease the upper side of the dam body compared to bottom of the dam body. When reservoir length extended, principal stresses and compression stresses increase. This solution shows that effect of reservoir length on behavior of dam.

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