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Research Article

Thermal Analysis of Roller Compacted Concrete Dam Utilizing a Probabilistic Model

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Roller compacted concrete (RCC) dam safety evaluation requires a realistic definition of thermal condition during construction and operation. Seasonal variations of temperature induce significant tensile stress. Therefore, the required preparations should be made to control and limit the thermal stresses. In this study, the effect of thermal and mechanical parameters on RCC dam behavior is evaluated using a probabilistic model. ANSYS Workbench software based on the finite element method has been utilized. The Latin hypercube sampling (LHS) method was used for probabilistic and sensitivity analysis, in which the density of concrete, Young's modulus, Poisson ratio, thermal conductivity, and specific heat have been selected as input variables. Dam body temperature, total deformation, and maximum principal stress in the body were considered as output variables. To evaluate the structural performance of the case model of the RCC dam under thermal loading, the model sensitivity to selected input variables is investigated. Considering to obtained curves, it can be concluded that the mechanical and thermal parameters have different effects on the performance of the RCC dam under variation of body temperature. Also, the results show that the sensitivity curves of output parameters are linear or bilinear relative to input variables.

1. Introduction

Concrete is a material with low tensile strength. The changes in the concrete volume are caused by temperature variations, and it exhibits tensile stresses and cracking in critical points. Therefore, studying the behavior of the dam against thermal changes is of special importance.

The high temperature induced in cement hydration and the effect of environmental factors and structural volume changes produces tensile stresses in concrete in large structures. Temperature variations of concrete during the construction and operation of RCC dams are significant in the study of thermal stress because of tensile stress and cracks. The most essential factor in the development of tensile stress and cracks in dams is the constraint that resists against the reduction of concrete volume due to contraction. Due to the importance of the thermal analysis of the dam, many studies have been carried out in simulating the thermal behavior of the dam during construction and operation by adopting a set of mathematical and numerical models.

Ishikawa [1] conducted a thermal analysis of the concrete gravity dam utilizing Adina software. Due to the increase in Young's modulus of concrete over time, he evaluated the process of temperature distribution and thermal stress, using the finite element method. He utilized a time-dependent exponential function to measure the heat generated by hydration and measured the rate of increase of the adiabatic temperature. One of the practical factors in the cracking of concrete dams is environmental factors. Hinks and Copley [2] investigated the effect of solar radiation and concluded that if the speed of construction was lower than the predicted speed in hot seasons, the concrete temperature would increase more than the expected temperature.

Agullo and Aguado [3] presented an analytical solution for the investigation of the thermal behavior of dams subjected to environmental temperature during operation. Obtained results showed the effect of the annual mean ambient temperature, the water temperature, and the annual mean of total daily solar radiation on the mean temperature of the layer.

Agullo et al. [4] proposed an explicit finite difference model to simulate the behavior of dams exposed to environmental conditions. In this study, factors such as the effect of solar radiation, river water temperature, and coefficients of heat transfer on the heat generated in the concrete dam have been examined. Obtained results have been compared with the laboratory results of various dams.

Luna and Wu [5] considered concrete properties to be time-dependent and showed that if the concreting of the dam occurred in cold weather, the produced maximum temperature in the dam body would be reduced.

According to Cervera research [6–8], the precooling of the concrete before concreting operation apparently reduces the temperature, but the efficiency of this method is minimal and just about 20% for the selected dam model. The worst possible scenario is the start of the construction in the summer. In the following, the thermal analysis for the roller-compacted concrete dam (RCC) was conducted by [9], using the ANSYS finite element software. This study aimed to provide the contour distribution of temperature in the gravity dam body to evaluate the thermal response of the dam using the ANSYS software [10]. Reh et al. [11] described the problems that can be addressed, the underlying algorithms, and methodologies implemented using ANSYS software. They illustrated the application of the ANSYS software using various industrial example problems. Also, Lackner and Mang [12] used a perfect formulation based on the thermodynamics of chemically reactive porous media.

Kuzmanovic et al. [13] presented a 3D numerical model for unsteady thermal stress analysis of a Platanovryssi dam. At first, the temperature field was computed using a nonlinear viscoelastic model for stress-strain analysis. The initial and boundary conditions were applied for the model considering appropriate material properties and the experimental concrete placement schedule. The results of a long-term analysis had good agreement with the observed conditions for the case model of the dam. Kuzmanovic et al. [14] evaluated the crack propagation in RCC dams and suggested that the critical situation of the crack extension is along the dam axis. Santillan et al. [15] presented a new analytical 1-D model of the heat diffusion equation assuming specific boundary conditions. The solved model is the heat distribution in 1-D solid whose ends are in mediums at prescribed temperatures. The solution can be extended to other temperatures of the domains through the discrete Fourier transformation. The proposed model results are obtained exceptionally quickly and are similar to other 3D models. Khanzaei et al. [16] studied the changes in thermal stresses and crack fields of the Kinta RCC dam at the end of the construction and its service life, considering water temperature variation at different levels of the reservoir. The finite element model has been used for modeling and analysis. Obtained results illustrated that there is an increase in the thermal stresses after some years of dam construction, while the location and distribution are similar. Ezzeldin Yazeed et al. [17] studied the thermal-stress response of Muzdalifa dam considering the stages of construction to investigate the effect of changing the time intervals in concrete placing schedule on the thermal behavior of the dam. Also, they investigated the effect of environmental and mechanical factors such as concrete casting construction schedule, the cement content, and the ambient temperature of thermal response. Yazeed et al. concluded the effect of the water pipe cooling system on the induced temperature and stresses distribution and recommended the optimal design for pipe cooling.

Hovde et al. [18] studied the capability of a probabilistic and deterministic method to evaluate the safety of existing concrete dams in Norway.

Pouraminian et al. [19] investigated the safety of the Pacoima arch dam using a load-resistance method for evaluation of the risk of failure. They used the ANSYS finite element software and Monte Carlo method to evaluate the probability of failure of the dam body system.

Pouraminian et al. [20] studied the application of sensitivity analysis for the safety assessment of the Pine Flat concrete gravity dam. They performed the structural analysis to evaluate the uncertainties in the physical and mechanical properties of the dam body materials and the reservoir water level.

Following the research, Pouraminian and Ekranezhad. [21] illustrated the reliability analysis of Pacoima concrete arch dam considering the construction stage and evaluated the failure probability of the model.

Because of the dependence of mechanical parameters of concrete to change of temperature, it is necessary to investigate the effect of mechanical behavior variation on the thermal behavior of RCC dams.

The evaluation of the effect of variation of mechanical properties on the thermal behavior of concrete dams is one of the cases that have not been studied in researches.

In this research, the probabilistic method is used to evaluate the effect of change of some parameters such as Young's modulus, thermal conductivity, and specific heat on the response of an RCC dam model. For thermal and sensitivity analysis, dam body temperature, total deformation, and maximum principal stresses in the body are selected as the output variables. Considering to results and sensitivity curves, it is possible to evaluate the thermal behavior of the model and select the optimum values of parameters to reduce the tensile stresses in the dam body.

2. Thermal Conductivity

A 3D solid thermal conductivity relative to time can be described mathematically in the Cartesian coordinates for a transient, orthotropic, and nonlinear state using the following equation:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right)+Q=\rho C\frac{\partial T}{\partial t}. \tag{1}$$

Here, T : area temperature (K); ρ : density (kg/m^3); C : specific heat (J/kgK); K_x, K_y, K_z: thermal conductivity coefficient of the object (w/m^{2}K); and Q: the internal heating rate for the unit volume (w/m^3).

Equation (1) must be solved under the initial and boundary conditions. The boundary conditions for this equation are in the form of the following equations:

$$T = \overline{T}\mathrm{On}\Gamma T,$$

$$-\left(K_x\frac{\partial T}{\partial x}n_x + K_y\frac{\partial T}{\partial y}n_y + K_z\frac{\partial T}{\partial z}n_z\right) = -q_a + q_c + q_r. \tag{2}$$

On Γ_q

Here, Q, Γ_T, Γ_q, $\overline{T}$, and q_a, in sequence, represent the rate of hydration production, the common boundary of the dam and concrete, the concrete open-air boundary, the foundation temperature, and the input thermal flow density generated from the solar radiation, respectively. n_x, n_y, and n_z are normal area vectors, and q_c and q_r are convective and radiation flow intensity presented in the following sections.

3. Heat Transfer through Convection

The heat exchanged caused by convection induced with the temperature difference between Γ_q and ambient air temperature by Newton's cooling law is as follows:

$$\mathrm{qc} = \mathrm{hc}\left(T - T_a\right), \tag{3}$$

where hc: convection coefficient (w/m^{2}K); T: the temperature of the Γq boundaries (K); and T_a: ambient temperature (K).

In this analysis, T_a is the representative temperature of the air, and T represents the surface temperature of the concrete in the vicinity of the heat. Heat transfer through convection is a complex phenomenon and affects many variables in the numerical analysis such as shape, fineness and roughness of the surface, viscosity, and fluid velocity with common boundary in the body. However, the following proposed formulas can be utilized in heat transfer through convection with the proper precision [22]:

$$\begin{aligned} \mathrm{hc} &= 5.7 + 3.8V, \\ \mathrm{hc} &= 2.8 + 3V. \end{aligned} \tag{4}$$

Here, V is the air velocity in the environment.

4. A Case Study

The Javeh RCC dam located on the Javeh river in Iran has been selected as a case model for thermal analysis. The dam crest width is 12.7 m with 300 m length and 86.5 m height. The construction of the dam began in 2007 and was operated in 2013. The 2-dimensional numerical model for thermal analysis consists of a finite element meshing, and the dam body consists of 173 layers consisting of 50 cm of the thickness of the concrete layer. The cross-section of the dam is presented in Figure 1 [23].

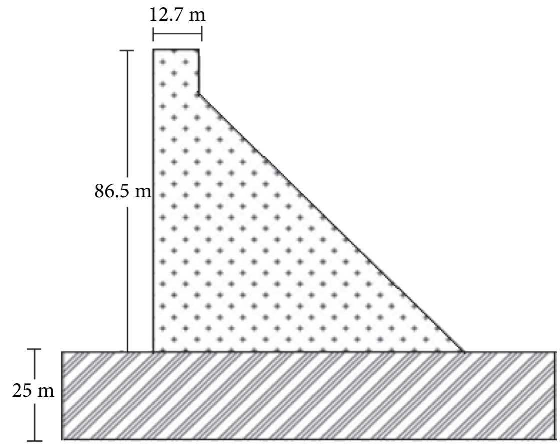

Figure 1: Cross-section of the Javeh RCC dam.

4.1. Thermal Properties. In the Javeh RCC mixture, Urmia cement has been utilized. The diagram of the rise of adiabatic temperature of the mixture of Javeh dam with 25% pozzolan has been presented in Figure 2.

Figure 3 presents the air temperature of the dam site according to reports of the Moshanir Water Resources Department.

In this research, the initial temperature of the concrete is 15°C, and the average annual temperature is 13.8°*C*. The interval between constructions of two consecutive layers is considered as three days.

4.2. Mechanical Properties. In order to analyze the intended model, concrete dam and foundation materials are assumed to have homogeneous, linear, and isotropic behavior. All dimensions are based on the SI system. The parameters required to define the thermal behavior of materials are summarized in Table 1.

5. Thermal Analysis Results

The ANSYS Workbench software, based on the finite element method, is utilized for modeling and analysis. This software has the required capabilities for thermal and probabilistic analysis during dam construction and operation.

One of the methods for controlling the quality of meshing is to utilize the error contour, which indicates the rapid changes in the energy of adjacent elements. So, the error statement is able to identify the areas of the model that have a high error in the stress calculation and which parts require a finer meshing of the elements in order to get an accurate response. Meshing optimization reduces rapid energy changes in adjacent elements. The energy changes in the adjacent elements are reduced to a satisfactory level by shrinking the elements resulting in optimized surface meshes. For this purpose, different meshing has been studied for the model to obtain the most optimal model for meshing.

In Figure 4, the achievement of a suitable criterion in terms of the meshing for the energy transferred between the elements in the maximum energy state has been presented.

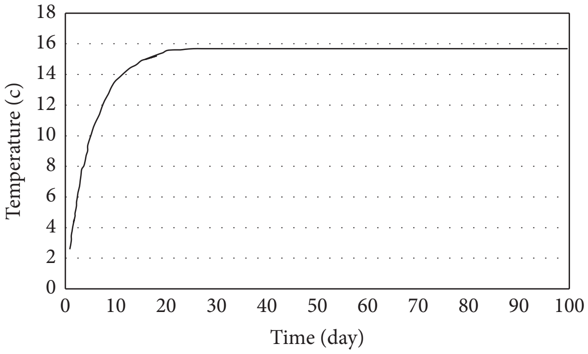

Figure 2: Adiabatic temperature rise of the mixture for Javeh dam.

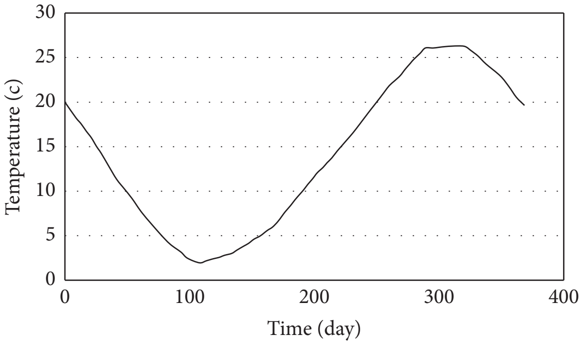

Figure 3: The curve of variation of environment temperature in the Javeh dam site [23].

Table 1: The thermal properties of the mixture used in the analysis

Property	Value	Unit
Young's modulus	25	GPa
Unit weight	2450	Kg/m^3
Poisson's ratio	0.25	—
Thermal conductivity	2.96	W/m°C
Specific heat	970	J/kg°C
Convection coefficient	1500000	J/m^{2}day°C

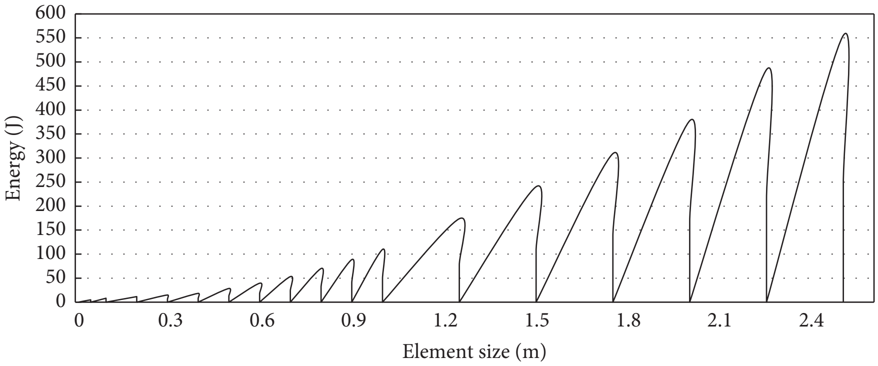

Figure 4: Diagram of changes in the amount of exchanged energy relative to the element size.

Considering the abovementioned for the meshing of the model, 0.3 m is considered for the size of the elements, because in this case, the critical analysis responses are stable. In the present model, each layer is divided into a horizontal direction between 40 parts in the upper layers to 280 parts in the lower layers and in the vertical direction to 3 parts. Therefore, the model has 241912 nodes and 63092 elements. The time step for the thermal analysis of each layer is considered 72 hours.

Considering the optimal mess size of the system, the thermal analysis of the model is conducted according to the timing of the construction of the dam and foundation system and the construction time of each concrete layer. The contour of induced heat distribution of the dam body at the end of analysis has been illustrated in Figure 5.

In order to evaluate the stress results, the principal stress contour at the dam body is presented for different times and various conditions. Figure 6 shows the contour of maximum principal stress distribution in the dam body. Regarding the figure, it can be found that, during the different times of the dam construction, tensile stresses occur in the body surface and the bed because of the thermal changes in the environment at boundaries. As the temperature decreases, the stresses in the dam body turn from compressive to tensile. This phenomenon occurs more quickly at levels that have been constructed in the hot season.

6. Probabilistic Analysis

In this research, the Monte Carlo simulation with the Latin hypercube sampling method has been used for probabilistic and sensitivity analysis. Monte Carlo simulation is an instrumental and robust method for probabilistic and sensitivity analysis. The error associated with these techniques is completely controlled through the number of simulations. This confirmed that once the number of samples reaches infinity, the results converge to an accurate value. The uncertainty in analysis decreases with the increasing number of samples.

For sensitivity analysis, essential parameters variations such as Young's modulus, specific heat, and thermal conductivity of concrete mixture are analyzed in a probabilistic way, using the Latin hypercube sampling technique.

To describe the scatter of the data, the lognormal distribution has been used. The lognormal distribution is particularly suitable for phenomena that arise from the multiplication of a large number of error effects. It is also appropriate to use the lognormal distribution for a random variable that is the result of multiplying two or more random effects.

In probabilistic analysis, the number of required simulations should be such that the average value of the output variable reaches the appropriate convergence according to the number of simulations.

Also, the variation of the number of samples of input parameters with selected distribution function can be investigated with the mean value of parameters. The most basic form of postprocessing of results is direct observation of the results of the simulation loops as a function of the number of loops for all parameters. In this research, variations in the average value of the input parameters are investigated in terms of the number of samples. According to the results, it is seen that, in order to modify the average value of the output parameters, the number of loops implemented for convergence is sufficient. The end parts of the presented curves are almost horizontal which confirms the adequacy sample number in the probabilistic analysis for all variables.

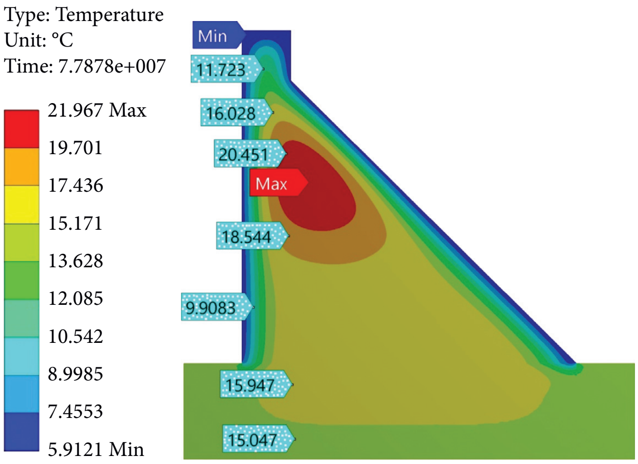

Figure 5: The contour of generated heat distribution of dam body at the end of analysis time.

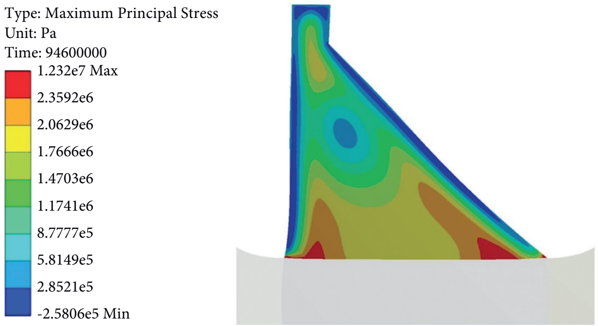

Figure 6: The contour of distribution of maximum principal stresses in the dam body.

Therefore, in this study the ANSYS software settings with the specifications of the parameters used in this sampling for the Monte Carlo probabilistic method are presented in Table 2:

6.1. Effect of Young's Modulus. The sensitivity of maximum principal stress to variation of Young's modulus has been shown in Figure 7. According to the figure, the induced maximum tensile stress variations in the dam body and critical areas are directly related to Young's modulus of RCC mixture. As can be seen in the graph, the variation of tensile principal stress relative to Young's modulus is a bilinear curve. Increasing Young's modulus increases the tensile stresses in the dam body.

According to Figure 8, it can be found that the variations of Young's modulus of the RCC mixture do not affect the

Table 2: Monte Carlo probabilistic analysis settings in ANSYS software and specifications of the parameters.

Parameter	The standard deviation	Lower bound	Main value	Upper bound	Number of simulation loops	Number of iteration
Young's modulus	7	3.36	25	46.6	16	2
Thermal conductivity	0.5	1.41	2.96	4.5	10	2
Specific heat	80	723	970	1218	10	2

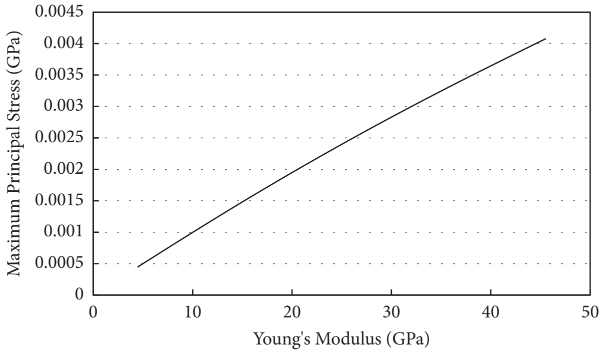

Figure 7: Variation of maximum principal stress in dam body relative to Young's modulus changes.

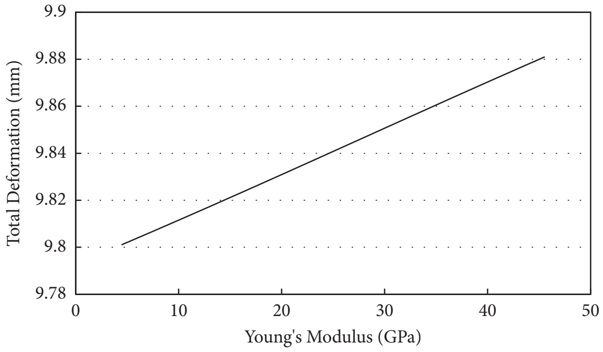

Figure 8: Variation of maximum total deformation relative to Young's modulus changes.

maximum deformation, considerably. The variation of general deformation relative to Young's modulus is linear.

6.2. Effect of Thermal Conductivity. The thermal conductivity coefficient shows the amount of heat flow passing through the surface unit under the thermal gradient. It is dependent on the rock material, moisture content, specific gravity, and temperature. In this section, the probabilistic critical responses of the dam body relative to the thermal conductivity changes of the mixture are discussed. The effect of thermal conductivity as a random input parameter on responses is evaluated in Figures 9and 10.

According to Figure 8, the maximum tensile stresses of the structure, with the increase in thermal conductivity, initially have a linear gradient diagram with a steep slope. That is, with an increase in thermal conductivity, the maximum tensile stress increases at a high rate. This direct

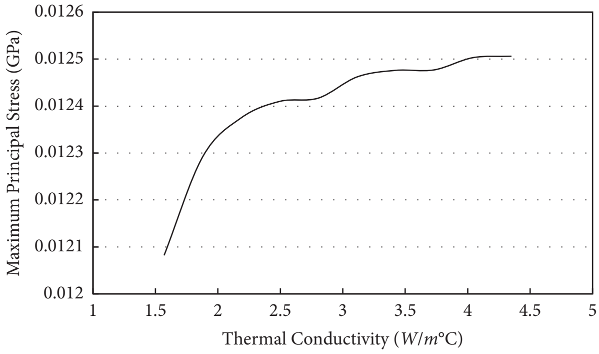

Figure 9: Sensitivity of maximum principal stress of the dam body relative to the changes of thermal conductivity coefficient.

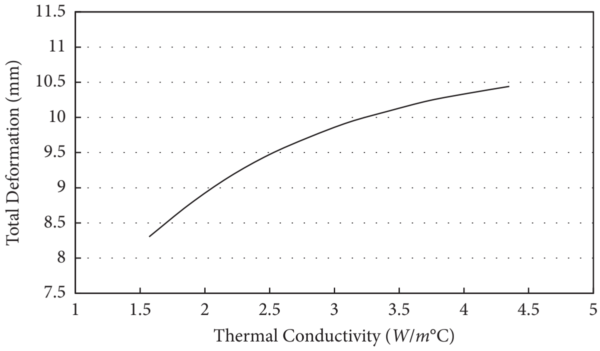

Figure 10: Variation of total deformation of dam body relative to the thermal conductivity coefficient changes.

relationship continues to the thermal conductivity value equal to 2.5 W/m ℃, but after this amount, the variation of maximum tensile stress relative to thermal conductivity will be insignificant.

According to Figure 10, it can be found that changes in the maximum deformation of the dam are directly related to thermal conductivity with bilinear curves, and increasing thermal conductivity will increase the structural deformation of the dam.

6.3. Effect of Specific Heat. Specific heat of material indicates the amount of heat necessary to increase or decrease the concrete temperature to a degree and depends on the type of material. In this section, the probabilistic analysis of critical structural responses relative to specific heat changes is conducted in Figures 11and 12.

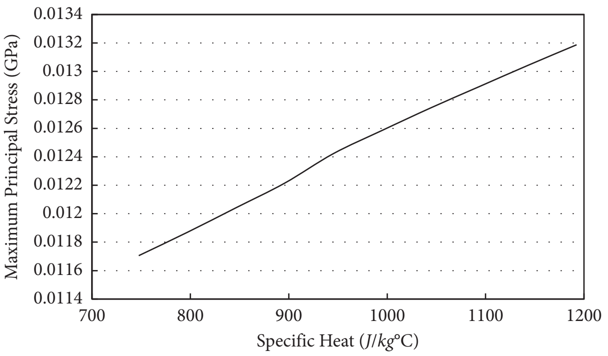

Figure 11: Variation of maximum principal stresses of dam body relative to specific heat changes.

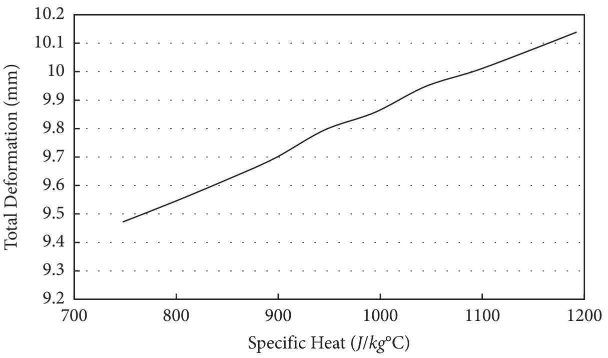

Figure 12: Variation of total deformation of dam body relative to the specific heat changes.

Figure 10 illustrates that increasing the specific heat as an essential thermal property increases the maximum tensile stress in the dam body with a linear ratio.

According to Figure 11, it can be concluded that the specific heat variations of the mixture are directly related to the maximum deformation changes with a linear ratio. The increase in the specific heat also increases the values of the deformation, but this increase is more significant in the general deformation of the structure.

7. Conclusion

In this paper, the thermal analysis of the RCC dam model was investigated using the probabilistic method. A probabilistic analysis with the Latin hypercube sampling was used to identify the effect of the parameters that have a significant effect on the thermal behavior of RCC dams. Based on the developed finite element model with ANSYS Workbench software, the following conclusions can be drawn:

(i) As the temperature decreases, the stresses in the dam body turn from compressive to tensile, mainly when the RCC dam is constructed in the warm season.

(ii) Increasing Young's modulus increases the tensile stresses in the dam body under thermal loading, while the variations of Young's modulus of the RCC mixture do not affect the maximum deformation, considerably.

(iii) With increasing thermal conductivity, the maximum tensile stress increases with a high rate, directly to the thermal conductivity value equal to 2.5 W/m ℃. After this amount, the variation will be insignificant. Changes in the maximum deformation of the dam are directly related to thermal conductivity with a bilinear curve.

(iv) Increasing the specific heat increases the maximum tensile stress and total deformation of the dam body with a linear ratio.

(v) Induced maximum principal stresses because of thermal loading are very impressive to Young's modulus variation compared with other parameters. While the influence and sensitivity of the general structure deformation relative to the thermal properties are considerable.

Data Availability

No data were used to support the findings of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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