A Spatial FEM Model of Thermal and Mechanical Action in RCC dam

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Abstract: Specific features of the thermal stress fields in roller compacted concrete (RCC) dam are always their spatial character and completely dependent on the maturity functions such as deformations properties (elastic, creep). The thermal changes in the material affect the elastic, creep properties of the material, and in turn, the stress fields within the structure. Therefore, the effects of temperature on the properties of RCC materials(elastic, creep) has to be taken into account in order to determine the risk of the thermally induced cracking in these dams. In this study, a viscoelastic model, including ageing effects and thermal dependent properties is presented. The different isothermal temperature influence on creep and elastic modulus is taken into account using the maturity concept. The result of analysis on an RCC dam has shown that, the increase of the elastic modulus has been accelerated duo to the high temperature of hydration at the initial stage, and consequently stresses are increased. The elastic modulus increased by 42% in the initial stage.

Keywords: FEM; Roller Compacted Concrete Dam; Thermal Stress; Creep

1 Introduction

The temperature rising in RCC dams is due to hydration of cement and climatic changes on the convective boundaries. In addition, the quick construction process can induce a high thermal gradient in interior mass and exterior surface of the dam [Noorzaei et al. (2006)]. Temperature does not only influence the properties of concrete such as elastic modulus and creep properties, but also induces thermal stresses [Wu and Luna (2001)]. If these thermal stresses, in addition to the tensile stresses resulting from other loads, exceed the tensile strength of RCC, crack will develop in the dam body.

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Details steps for performing a complete thermal study for a simple mass concrete dam structure was discussed by Tarto [Tatro and Schrader (1985)]. In the presented work the incremental construction concept was incorporated into the model by assigning material placement times relative to a common time of origin to each defined mode element. However, approximated air temperature was used in the work. Later on, Saetta presented a finite element procedure for the stress-strain analysis in concrete structures exposed to time-variable environmental conditions. In this study, the authors ignored the effect of the variation of the elastic modulus with time [Saetta et al. (1995)].

Noorzaei focused on the development, verification and application of a three-dimensional finite element code for coupled thermal and structural analysis of roller compacted concrete dams. The actual climatic conditions and thermal properties of the materials were considered in the analysis. The structural stress analysis was performed using the elasto-plastic stress analysis. However, the time dependent deformations such as; creep and shrinkage have not been reported in their study [Noorzaei et al. (2009)].

In the previous work, the authors [Abdulrazeg et al. (2010)] a viscoelastic model, including ageing effects and thermal dependent properties was developed for the RCC material. Based on this model a tow dimensional finite element program was developed to simulate the construction processes of the RCC dams. The result shown that, the increase of the elastic modulus has been accelerated duo to the high temperature of hydration at the initial stage, and consequently stresses were increased.

The present investigation is continuation of authors' previous work [Abdulrazeg et al. (2010)]. The primary objective of the present research work is to propose the methodology of simulation of RCC dam under construction. In this work, the different isothermal temperature influence on creep and elastic modulus is taken into account using the maturity concept.

2 Constitutive Relationships

2.1 Heat Diffusion

The general partial differential equation governing heat flow in a two-dimensional solid medium is expressed as [Incropera and De Witt (1985)]:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \dot{Q} = \rho c \frac{\partial T}{\partial t}$$
(1)

where T is the solid temperature (°C); k_x , and k_y are the concrete conductivity coefficients in x, and y directions respectively (W/m °C); \dot{Q} is the rate of the heat

introduced per volume (W/m³); ρ is the material density (kg/m³), and; *c* is the solid specific heat (J/kg °C).

2.2 Creep of Concrete

The exponential model has been attractive from the computation point of view, because it can avoid storing the whole stress history and made the implementation feasible comparing with other models [Abdulrazeg (2011)].

The creep functions may be expressed with Dirichlet [Bazant and Wu (1973)] series as

$$J(t,\tau) = \sum_{\gamma:\gamma=1}^{M} \frac{1}{\mu_{\gamma}(\tau)} [1 - e^{y_{\gamma}(t) - y_{\lambda}(t)}]$$
(2)

where is $J(t, \tau)$ creep functions, $\mu_{\gamma}(\tau)$ is function of one variable, called the reduced times, τ is the loading age in days, $y_{\gamma}(\tau)$ is experimental function.

Neglecting temperature effects, a specific form of the compliance function is often used [Zhu et al. (1976)]

$$J(t,\tau) = C(t,\tau) + \frac{1}{E(t)}$$
(3)

where $C(t, \tau)$ is creep compliance, it can be expressed as,

$$C(t,\tau) = \sum_{\gamma=1}^{3} \phi_{\gamma}(\tau) [1 - e^{-S_{\gamma}(t-\tau)}]$$
(4)

$$\phi_1 = \alpha_1 + \beta_1 \tau^{-\delta_1}, \quad \phi_2 = \alpha_2 + \beta_2 \tau^{-\delta_2}, \quad \phi_3 = De^{-S_3 \tau}$$

where α_{γ} , β_{γ} , δ_{γ} , D, S_{γ} are constants determined from the experimental data. This model expresses the variation of the elastic modulus of RCC material with time

$$E(t) = E_c e^{a\tau^b} \tag{5}$$

where E_c is the final elastic modulus, a and b are model parameters.

Bazant introduced the concept of the degree of hydration to include the temperature influence [Bazant et al. (2004)]. Term equivalent age (τ_e), which represents the hydration period for which the same degree of hydration is reached at a current temperature as that one reached during the actual time (*t*) at a reference temperature. The concrete age, τ , will be replaced by equivalent age (τ_e) in the exponential model (Eq. 5) [Wu and Luna (2001)].

$$\tau_e = \int_0^\tau \beta_\tau(t) dt \tag{6}$$

Where $\beta(t)$ is a function of current temperature and expressed as

$$\beta_{\tau}(t) = e^{\Pi_{h}(\frac{1}{T_{r}} + \frac{1}{T(t)})}$$
(7)

where T(t) is a current temperature, $T_r = 20^0 C$, Π_h is function of hydration degree =2700 K.

3 Modeling Application

A brief description of the Sg. Kinta RCC dam project is given in previous work of authors..[Noorzaei et al. (2009)]. The reader may refer to it for details about the progress of the dam construction with respect to time and the geometry of the dam as well as the material properties of the different types of concrete used in the foundation, body, and faces. The creep experimental data which reported in the literature..[Zhang (1995)] for RCC and CVC materials has been used in present study, these data tabulated in the Table 1. The 2D finite element model of the deepest block is shown in Fig.1. Eight noded isoparametric elements are used in the analysis. The mesh of the dam body is generated in such a way to simulate the construction phase.

Material	α_i		β_i	δ_i	D _i
CVC	1	0.35494	0.48368	0.35361	
	2	3.7335	-0.186	0.012486	
	3	-2.5644	0.13786	0.032642	0.83509
RCC	1	0.058864	0.38362	1.356	
	2	7.4729	-11.115	0.08919	
	3	-5.2079	7.9619	0.078675	4.2808

Table 1: Creep data for RCC and CVC materials [Zhang (1995)]



Figure 1: 2-D Finite Element mesh

4 Result and Discussion

4.1 Temperature Distribution During Construction

From the two-dimensional analysis, plots for temperature contour distribution in the body of the dam for the different constructed lifts are shown in Fig. 2. The temperature distributions within the dam's body after completion of the 10th stage was shown in Fig.2-a. The maximum temperature observed was 43 0 C, it was formed at the bottom of the dam. This is attributed to the use of higher RCC placing temperatures combined with the higher insulating property of this region due its massive volume compared with the other locations. Isothermal contour plot at the end of the dam construction is shown in Fig.2-b. The plot shows that, the higher temperature zone is at the center of the dam body with maximum predicted temperature of 41 0 C, which gradually decreased to reach approximately the air temperature at the boundaries.

In order to illustrate the effect of the temperature on the variation of the elastic modulus, Fig. 3 has been plotted to show the temperature at the particular point (a). The temperature increases due to the heat produced by hydration, then reaches a maximum point at about 5 days after casting. It is obvious from the plot there is a significant difference between the two curves of the elastic modulus during the



Figure 2: Temperature distribution for different lifts: (a) temperature distribution at Lift 10; (b)temperature distribution at the end of construction

initial stage due to the high temperature of hydration. If the temperature effect was considered the elastic modulus is increased by 43% and 20% in the first two and four weeks respectively. The ultimate elastic modulus is not significantly effect, where there is increase in the elastic modulus by 4% after 300 days from casting if the temperature was considered.

4.2 Stress Simulation during Construction

In this section, the results from thermally induced stress analysis preformed on a numerical model of Kinta RCC dam are presented. Results from the reference case study, simulating the real construction process of RCC dams are discussed.

Fig.4 shows the maximum principle stress path along the dam width after completion of fifth stage. It demonstrated that, the stress has been increased. When the temperature effects are considered, the maximum principle stresses increased from 0.91 MPa to 1.7 MPa. This is because the temperature at the initial stage is high due to hydration the elastic modulus is high also which increased the stress during this stage. However, the ultimate elastic modulus is not significantly affected by the temperature and higher elastic modulus reduces the creep rate. Therefore, the stresses will not be much effected comparing with initial stage.

Fig. 5 shows the principle stress contours developed in the dam body for different constructed lifts. The result indicate that, the tensile stress developed at different levels with the dam body during construction the presence of high tensile stresses at the dam bottom with maximum value at the heel and increasing with constriction sequence to reach 3.5 MPa at the end of construction. Generally, it is observed that most of the dam body under compressive stresses.



Figure 3: Temperature and the variation of the elastic modulus at the central point



Figure 4: The principal stress path along the dam width after the casting at 13.5 m from the base

5 Conclusions

Early results from these analyses have shown the following conclusion:

(i) A viscoelastic model which includes ageing and temperature effects on properties of RCC materials was developed.

(ii) The Conrad's model which expresses the variation of the elastic modulus of RCC material with time has been further modified to account for temperature effect.



Figure 5: Stress distribution in body of the dam

(iii) The result has shown that, If the temperature effects are considered, the maximum principle stresses increased by 42% in the initial stage. This is because the temperature at the initial stage is high due to hydration the elastic modulus is high also which increased the stress during this stage.

(v) The exposed dam boundaries posses the same air temperature at the end of each stage of analysis. Higher temperature zones are formed at the thicker places near the abutments at lower elevation levels. The requirements of strength and crack resistance are greater in high Zone, because of the adiabatic temperature is high in this zone.

References

Abdulrazeg, A.; Noorzaei, J.; Khanehzaei, P.; Jaafar, M.; Mohammed, T. (2010): Effect of Temperature and Creep on Roller Compacted Concrete Dam During the Construction Stages. *CMES: Computer Modeling in Engineering & Sciences*, 68, 239-268.

Abdulrazeg, A. A. (2011). Analysis of Roller Compacted Concrete Dam. In Civil

Engineering. UPM-Serdang, Malaysia: Universiti Putra.

Bazant, Z. P.; Cusatis, G.; Cedolin, L.(2004): Temperature effect on concrete creep modeled by microprestress-solidification theory. *Journal of Engineering Mechanics-Proceedings of the ASCE,* 130, 691-699.

Bazant, Z. P.; Wu, S. T.(1973): Dirichlet series creep function for aging concrete. *Journal of the Engineering Mechanics Division*, 99, 367-387.

Incropera, F. P.; De Witt, D. P.(1985): Fundamentals of heat and mass transfer New York: John Wiley & Sons. p. 289–96 [chapter 5].

Noorzaei, J.; Bayagoob, K.; Abdulrazeg, A.; Jaafar, M.; Mohammed, T. (2009): Three Dimensional Nonlinear Temperature and Structural Analysis of Roller compacted Concrete Dam. *CMES: Computer Modeling in Engineering & Sciences*, 47, 43-60.

Noorzaei, J.; Bayagoob, K.; Thanoon, W.; Jaafar, M. (2006): Thermal and stress analysis of Kinta RCC dam. *Journal of Engineering Structures*, 28, 1795-1802.

Saetta, A.; Scotta, R.; Vitaliani, R.(1995): Stress analysis of concrete structures subjected to variable thermal loads. *Journal of Structural Engineering*, 121, 446.

Tatro, S. B.; Schrader, E. K. (1985). Thermal considerations for roller-compacted concrete. ACI.

Wu, Y.; Luna, R. (2001): Numerical implementation of temperature and creep in mass concrete. *Journal Finite elements in analysis and design*, 37, 97-106.

Zhang, M. L. (1995). Study on structural treatment, stress and stability of roller compacted concrete gravity dam. In *Department of Hydraulic and Hydropower Engineering*. Beijing, China: Tsinghua University.

Zhu, B. F.; Wang, T. S.; Ding, B. Y. (1976): Thermal Stresses and Temperature Control in Hydraulic Concrete Structures. *Water Power Press*.