Thermal and Structural Analysis of Roller Compacted Concrete (R.C.C) Dams by Finite Element Code

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Abstract: The present investigation deals with the finite element formulation of the field problem with respect to evaluation of the heat generated in the body of the dam during and after construction of the roller compacted concrete dams. So, a two – dimensional finite element code has been developed for predicting the temperature and stresses in roller compacted, concrete dam. Finally the application of this software has been illustrated by thermal and structural analysis of a roller compact concrete dam.

Key words: Roller compacted concrete dam, Thermal modeling, Finite element formulation.

INTRODUCTION

The largest volumetric change in roller compacted concrete dams results from the change in temperature. The rate of change in temperature is due to cement hydration, which introduces temperature gradients in the roller compacted concrete dam body. In the stress analysis of a roller compacted concrete dam, the evaluation of stress is considered to be more complex than normal gravity dam. This is due to fact that in the roller compacted concrete dam there is a tendency to construct the dam without joints and mostly continuously. Hence, thermal loading is of major concern since the dam must carry the induced stress caused by a constantly changing temperature during the construction phase and the following cooling period. The two- dimensional analysis of concrete gravity dams during its construction phase was analyzed Araujo et al., (1998) by using the finite element method. Saetta et al. (1995) presented the stress-strain analysis of concrete structures exposed to time and space variable thermal loads by using the finite element technique. Also, for the thermal analysis of mass concrete with finite element method, Ishikawa, (1991) suggest the consideration of the following two conditions:
1. The value of the elastic modulus of concrete should time dependent.
2. Finite elements should be added according the casting schedule of concrete. The aim of this research was to evaluation of application and development of finite (limitations) element software for temperature distribution in roller compacted concrete dams.

Finite Element Formulation Time Dependent Heat Problems:

The bi dimensional heat transfer problem is governed by the differential equation (Fourier’s law):

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

(1)

Where:
T=Temperature at time “t” and “x, y” coordinates
k_x & k_y = Thermal conductivity for the x and y directions
c=Specific heat coefficient,
\rho = Specific mass
Q=Heat source (rate of internal heat generation due to hydration reaction of cement)

In the finite element method the temperature values at the nodes are expressed as:

$$T = [N]\{T\}$$

(2)

Where:
[N] = Shape functions
{T} = Temperature vectors

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The general procedure for analyzing Eq. (1) is to evaluate the Galerkin residual integral with respect to the space coordinates for a fixed instant of time. The Galerkin residual integral is in the form of Segerlind (1984):

\[ \int_\Omega \left[ \frac{\partial T}{\partial t} + [k_f^e] [T] - \{ F_f^e \} \right] d\Omega = 0 \]  

(3)

Integrating by parts the first term of Eq. (3) using Fourier’s law for heat transfer by conduction and using Eq. (2), the following system of linear differential equations are obtained:

\[ \{ e^e \} \frac{\partial T}{\partial t} + [k_f^e] [T] - \{ F_f^e \} = 0 \]  

(4)

Where \( \{ e^e \} \) is usually called the capacitance matrix which is expressed as:

\[ \{ e^e \} = \int_\Omega \rho c [N]^T [N] d\Omega \]  

(4-a)

and

\[ [k_f^e] = [k_f^e] + \{ k_m^e \} \]  

(4-b)

Where \([k_f^e]\) is stiffness matrix for field problems and \([k_m^e]\) is boundary stiffness matrix for field problems.

\[ [k_f^e] = \int_\Omega [B] [D] [B]^T \{ N \} d\Omega \]  

(4-c)

Where:

\[ [D] = \begin{bmatrix} k_x & 0 \\ 0 & k_y \end{bmatrix} \quad \quad [B] = \begin{bmatrix} \frac{\partial N}{\partial x} \quad \frac{\partial N}{\partial y} \end{bmatrix}^T \]

\[ [k_m^e] = \int_a h [N]^T [N] du \]  

(4-d)

Where:

(h) is thermal convection, and

\[ \{ F_f^e \} = \{ F^e \} + \{ F_f^e \} \]  

(4-e)

\( \{ F^e \} \) is the element force vector and \( \{ F_f^e \} \) is the element force vector in boundary condition

Where:

\[ \{ F^e \} = \int_\Omega N Q [N]^T \ d\Omega \]  

(4-f)

\[ \{ F_f^e \} = \int_a T_{env} h [N]^T \ du \]  

(4-g)

\( T_{env} \) is the temperature of the surrounding environment.

Equation (4) can be integrated in time by using and algorithm in generalize finite difference method which leads to Segerlind (1984):

\[
\begin{align*}
\{ c \} + \theta \Delta t \{ k_f^e \} [T]_b &= \{ c \} - (1 - \theta) \Delta t \ [k] [T]_a \\
&+ \Delta t ((1 - \theta) \{ F_f^e \}_a + \theta \{ F_f^e \}_b)
\end{align*}
\]  

(5)

Where:

\( \{ T \}_b \) and \( \{ F_f^e \}_b \) are \( \{ T \} \) and \( \{ F_f^e \} \) at time \( b \)

\( \{ T \}_a \), \( \{ F_f^e \}_a \) are \( \{ T \} \)

\( \{ F_f^e \} \) at time \( a \). \( 0 \leq \theta \leq 1 \) and

\( \theta \) is a scalar
Araujo (1998) indicates that it is convenient to take $\theta \approx 1$ in order to avoid spurious oscillations. Then it takes following form:

\[
([c] + \Delta t[k_t])\{T\}_b = [c]\{T\}_a + \Delta t\{F_t\}_b
\]

(6)

3. Thermal Transient and Stress – Strain Analysis:

To evaluate the stress - strain state and the displacement field due to any distribution loads, some hypotheses can be assumed Zinkiewicz and Taylor, (1991):

- Uncoupled temperature and stress field.
- Infinitesimal strains and displacements.
- Linear elastic behavior of material.

The first assumption allows solving at a fixed time the thermal transient, then once the temperature field is known, the stress-strain state can be estimated. As soon as the temperature associative distribution $T$ in concrete mass is known at every time $t$, the resulting tension $\sigma_{ij}$ within concrete can be easily obtained through the hypothesis of the material’s linear elastic behavior $\sigma_{ij}$ is converted into equivalent nodal thermal forces Owen and Hinton (1984).

The temperature that appears rapidly in each lifts about 30 days after concrete casting has been assumed to be the initial temperature value Saetta et al., (1995). Also a simulation formula is expressed by Zhu, et al. (1999):

\[
\Delta T = T_p + T_r - T_f
\]

(7)

Where:

- $T_p$ is placing temperature of concrete,
- $T_r$ is temperature rise due to heat of hydration
- $T_f$ is the final stable temperature of the dam $T_p + T_r$ represents the maximum temperature of concrete, which the stress level is zero.

The linear elastic behavior of material can be described as:

\[
\{\sigma\} = [D]\{\epsilon\}
\]

(8)

\[
\{\epsilon\} \text{ is strain due to thermal expansion, expressed by Saetta et al., (1995):}
\]

\[\{\epsilon\} = (1 - \alpha) \left(\{T\} - \{T_0\}\right)\]

(9)

Where:

- $\alpha_0$ is temperature in correspondence with thermal strain level zero and $\alpha$ is coefficient of thermal expansion.
- $[D]$ is elasticity matrix which depends up type of problems (Zienkiewicz, O.C., 1983). However, while generating the $[D]$, the elasticity young’s modulus of concrete at age $t$ ($E_t$) is expressed as time dependent (Dungar, R. and Kahir, 1988):

\[E_t = E_{\max} \left(\frac{t}{t_{100}}\right)^{0.404} \text{ for the } t < t_{100} \text{ and } 100 \text{ days (i.e. } 100 \text{ when } t \text{ is days).}
\]

(10)

\[E_t = E_{\max} \text{ for the } t \geq t_{100} \]

4. Development Of Finite Element Software For Temperature Analysis:

Based on the above temperature formulation, a two dimensional finite element code has been written and its validity has been verified against some standard bench mark problems, Noorzaei et al. (2001). The software consists of two main blocks namely:

Hmaster Block:

This block evaluates the temperature distribution at different stage of construction. The detail computational strategies are presented else where, Noorzaei, (2001).
**Strmaster Block:**

In this block, the thermal distribution in the body of the dam converted in to equivalent nodal force. Then usual stress-strain analysis of the problems has been worked out. These two blocks along with major subroutine are shown in Fig1.

![Flow Chart of Finite Element Code for Thermal and Structural Analysis in R.C.C Dams.](image)

**Fig. 1:** Flow Chart of Finite Element Code for Thermal and Structural Analysis in R.C.C Dams.

**Analyzed R.C.C Dam:**

**Problem Definition:**

This dam is supposed to be constructed in the province of Baluchistan, southern east part of Iran, while the material properties are presented in Table1.

**Table 1: Temperature and material properties of R.C.C, mass concrete and rock ground.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Conduction Coeff. Kcal/marc</th>
<th>Heat Convection Coeff. Kcal/m²/hr °C</th>
<th>Specific Heat Kcal/Kg</th>
<th>Elasticity Modulus T/m²</th>
<th>Poisson Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Ground</td>
<td>2.30</td>
<td>10.00</td>
<td>.30</td>
<td>.6E+6</td>
<td>.30</td>
</tr>
<tr>
<td>Mass Concrete</td>
<td>2.40</td>
<td>10.00</td>
<td>.30</td>
<td>2.3E+6</td>
<td>.30</td>
</tr>
<tr>
<td>R.C.C Concrete</td>
<td>2.40</td>
<td>10.00</td>
<td>.30</td>
<td>1.65E+6</td>
<td>.30</td>
</tr>
</tbody>
</table>

The concrete is cast in 50 cm thick horizontal lifts, each layer being placed in 3 days. In the Fig 2 was showed that the finite element model of the complete dam section under plane strain condition, four nodes isoperimetric type, with one degree freedom at each node for temperature analysis and two degree freedom per node for thermal stress-strain analysis has been considered.

![Finite Element Modeling of the Dam - Foundation System Total number of elements = 2372; Total number of nodes = 2546.](image)

**Fig. 2:** Finite Element Modeling of the Dam - Foundation System Total number of elements = 2372; Total number of nodes = 2546.

**Parameters Involved:**

**Clarification Property of Concrete:**

The clarification property of concrete (hydration) can be described as the following equation of Ishikawa, (1991):

\[ T = T_{\text{max}} \left(1 - \exp(-\beta t)\right) \]  

(11)

Where \( T \) is the temperature of concrete under an adiabatic condition, \( T_{\text{max}} \) is the maximum temperature of concrete under an adiabatic condition, \( \beta \) is a parameter which presents a heat generation rate and \( t \) is time (hr) in the present study, \( T_{\text{max}} = 17 \degree \text{C} \), and \( \beta = 0.0138 \) is adopted for this simulation purpose (Dungar, et al., 1988).
**Fig. 3:** Temperature distribution at lift no.11.

**Initial Temperature Of Rock Ground:**

Before calculating the temperature of concrete, we must know the temperature distribution in the rock ground just before the start of the casting of the concrete. It may be difficult to measure the temperature within the rock media. Usually the temperature distribution within rock is obtained through calculation. As a method to calculate, it is assumed that the initial temperature of all nodes corresponding to the rock ground is the same (27.6 °C). Changing the atmospheric temperature for two years with increment of 48 hours (total 365 increments) observed data, then the heat transfer is analyzed between the atmospheric temperature and the rock ground.

**RESULTS AND DISCUSSION**

**Temperature Prediction:**

To study temperature distribution in the dam body, 15 stages of construction have been considered. The schedule of construction phase of the dam with respect to No. of lifts, height of the dam, thickness of each lift and time (in days) planned by the consultant for the construction of each lift is presented in Fig. 4.

The response of the dam is evaluated for 15 stage of construction. Due to space limitation only final stage of construction are discussed here. Figure 3 illustrate the temperature variation at different height at lift No. 11 of the dam. It is obvious from these plots that there is drop in temperature at both D/S and U/S faces of the dam due to effect of atmospheric temperature, while the interior portion cooled at lower rate. Moreover the effect of gallery in reducing the temperature is clearly shown in the above plot (h=4m).
Structural Analysis:
In present study, mainly the behavior of the R.C.C dams during construction stage has been considered. The structural response of the dam for the lift No. 15 of construction stage has been discussed by applying the dead weight plus thermal loads. The temperature of all the nodal points with respect to time \( t \) has been determined for a particular lift. Now, based on the work presented by Zhu et al., (1999), the \( \Delta T \) determined by using equation (7). The variation of the principal stresses at the end of every lift is evaluated and only for the 15th stage of construction, in the section of the dam is plotted in Fig5. These plots are made for \( h=7.60 \) and \( 42.606 \) meters respectively. It can be seen from these plots that in the conventional concrete mostly there is tensile stress appears while the core undergoes compressive stresses. But the compressive stresses are with in their limit.

Conclusion:
Finite element software for the thermal and structural analysis in R.C.C dams exposed to time variables parameters has been developed. This software is a generalized two dimensional finite element code can predict the temperature distribution in the problems of plane stress, plan strain simulation usual calculated the stress in the dam body. Disassociating the variation of the thermal characteristics of concrete with respect to stress-strain state of the material allows the study of the problem in a simplified uncoupled way. The proposed numerical procedure for thermal transient analysis and thermal stress analysis in the R.C.C gravity dam was shown to be effective and practical in prediction of the temperature level by thermal transients in dam body. Moreover, it is possible to consider environmental conditions variability in time, internal heat generation (hydration) and the variability of the geometry during the analysis. Tensile stress appears in the skin of the dam, which is at a lower temperature, while the core undergoes compressive stresses.

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