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Simulation analysis of thermal stress of RCC dams using 3-D finite element relocating mesh method

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Abstract

The 3-D finite element relocating mesh method is developed for simulation analysis of temperature and thermal stress distribution in a roller compacted concrete dam during the construction period. According to the relation between specific properties and age of concrete, some meshes are merged into a larger mesh or a few larger meshes when the age of the concrete is appropriate. Using this method, the total number of elements and nodes were remarkably reduced when the dam height was increased. When the change in elastic modulus, creeps and hydration heat is within the limits permitted by design criteria, the relocating of mesh will start. Using this method, a 3 D simulation analysis of thermal stress in a roller compacted concrete (RCC) high dam can be realized by microcomputer and appeared at the construction site. On the basis of real factors during the construction period, an engineer can predict the distribution of temperature and thermal stress in the RCC dam. Therefore, engineers can take appropriate measures to control the concrete temperature to reduce the thermal stress and avoid crack development within the dam. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Roller compacted concrete gravity dam; Simulation analysis; 3-D FEM; Thermal stress; Relocating mesh method

1. Introduction

During the construction period of a roller compacted concrete (RCC) dam, the thickness of each layer is usually 0.3–0.5 m. Hence, an RCC dam with a height of 200–300 m may consists of several hundreds up to thousand layers. The heat will be exchanged between the top surface of a new placement layer and the circumference, and between the bottom surface and the old layer or base rock. Since the gradient of temperature and the stress in an RCC dam is great in the vertical direction, when calculating thermal stress in the dam during construction period, the mesh sizes of the region has to be 0.3–0.5 m in order to reduce the calculation error. The size of the mesh is usually same as the thickness of the layer. After generating the mesh, it is very difficult to carry out a 3 D finite element simulation analysis by a microcomputer due to the great number of elements and nodes [1].

When the thermal stresses in the Three Gorges Project (TGP) concrete gravity dam were studied in 1989, a kind of element having two layers or several layers was developed [2]. On the basis of this principle, the relocating mesh method is developed in this paper. Using the relocating mesh method, the 3 D simulation analysis of the thermal stress in a high RCC dam can be completed by microcomputer and performed at the construction site.

2. Time for starting relocation of the mesh

According to the relationship between properties and age of concrete, when the age of concrete is appropriate, some meshes are merged into a larger mesh or a few larger meshes. This method is called relocating mesh method. Using this method, the total number of elements and nodes were remarkably reduced when the dam height was increased. The calculation time and the storage space of the computer were greatly reduced.

The time for starting relocation of the mesh must be established. It should assure that the error of relocating mesh was controlled within the limits permitted by the design criteria. The properties of concrete, such as elastic modulus, creep and hydration heat depend on the age of concrete. The influence of these factors should be taken into account.

In the upper concrete layers of RCC dam, the elastic modulus, creeps and hydration heat change with respect to time; each thin concrete layer is meshed as one layer of element. In the lower concrete layers of RCC dam, the

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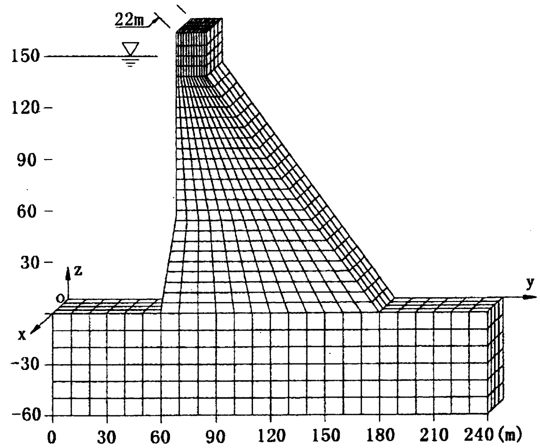

Fig. 1. Finite element mesh for the calculating model and the discretized model for RCC dam.

difference of elastic modulus, creeps and hydration heat between each thin layer is very small; these thin layers can be merged into a larger mesh. The calculating model and discretized model of an RCC dam are shown in Fig. 1. The relocating mesh model is shown in Fig. 2.

2.1. The elastic modulus effect

The elastic modulus of RCC at time τ can be written as

$$E(\tau) = E_0(1 - e^{-\lambda\tau}), \tag{1}$$

where E_0 is the final elastic modulus, λ is a coefficient of placement temperature [3].

If τ_i, τ_j are the age of layers i and j of RCC, we obtain

$$\frac{E(\tau_i) - E(\tau_j)}{E(\tau_j)} \le \varepsilon_1, \tag{2}$$

where ε_1 is the acceptable error; $E(\tau_i)$, $E(\tau_j)$ are the elastic modulus of layers i and j of RCC, respectively.

If the layers from layer i to j were merged into a larger layer, the average elastic modulus of these layers is used as elastic modulus of the larger layer. The error of elastic modulus of the relocating meshes is smaller than $\varepsilon_{1/2}$.

Substituting Eq. (1) into Eq. (2) yields Eq. (3).

$$\tau_i = -\frac{1}{\lambda}\ln[(1 + \varepsilon_1)e^{-\lambda\tau_j} - \varepsilon_1]. \tag{3}$$

After ageing of RCC, the increment of elastic modulus of RCC is very small. When the age of RCC is τ_{p1}, the difference of elastic modulus between layers is smaller than ε_1, and the layers whose ages are greater than τ_{p1} are merged into a larger mesh.

The average elastic modulus of the layers is used as the elastic modulus of the larger layer [8].

From Eq. (2) and let $\tau \to \infty$, yields $[(1 + \varepsilon_1)e^{-\lambda\tau_j} - \varepsilon_1] \to 0$, and for $\tau_j = \tau_{p1}$, we get Eq. (4)

$$\tau_{p1} = -\frac{1}{\lambda}\ln\left(\frac{\varepsilon_1}{1 + \varepsilon_1}\right). \tag{4}$$

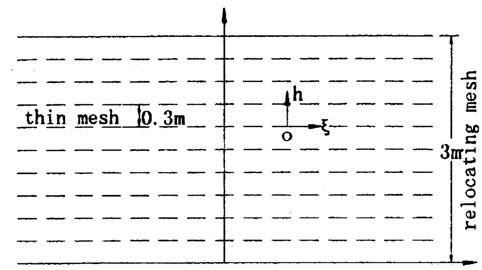

Fig. 2. Finite element mesh for the relocating model.

The layers whose age is greater than τ_{p1} are merged into a larger mesh by relocating.

2.2. Thermal insulation temperature rise effect

The thermal insulation temperature rise $\theta(\tau)$ of RCC can be written as

$$\theta(\tau) = \theta_0(1 - e^{-m\tau}), \tag{5}$$

where θ_0 is the final thermal insulation temperature rise, m is the hydration heat coefficient of cement.

If τ_i, τ_j are the ages of layers i and j of RCC, respectively, we can obtain

$$\frac{\theta(\tau_i) - \theta(\tau_j)}{\theta(\tau_j)} \le \varepsilon_2, \tag{6}$$

where ε_2 is the acceptable error; $\theta(\tau_i)$, $\theta(\tau_j)$ are the final thermal insulation temperature rise of layers i and j of RCC, respectively.

Again, we obtain

$$\tau_{p2} = -\frac{1}{m}\ln\left(\frac{\varepsilon_2}{1 + \varepsilon_2}\right). \tag{7}$$

It means that the layers whose age is greater than τ_{p2} are merged into a larger mesh by relocating, and the error is smaller than ε_2.

2.3. The creep effect

The creep of RCC can be written as

$$C(t, \tau) = (A + B\tau^{-s})(1 - e^{-\gamma(t-\tau)}), \tag{8}$$

where t is the time, τ is the age of concrete; A, B, s, γ are the experimental coefficients in concrete creep.

In Eq. (8), let $t \to \infty$, then the creeps whose age is greater than τ are

$$C(\infty, \tau) = A + B\tau^{-s}. \tag{9}$$

If τ_i, τ_j are the ages of layers i and j of RCC, respectively, we can obtain

$$\frac{C(\tau_i) - C(\tau_j)}{C(\tau_J)} \le \varepsilon_3, \tag{10}$$

where ε_3 is the acceptable error.