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Dynamic response property of cooling tower structures

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A B S T R A C T

Reinforced concrete (R/C) cooling tower structures have been used for cooling down the hot water produced by power or chemical plants. These structures are designed to prevent against the failure under a self-weight and a wind loading, as well as an earthquake loading. In this paper, the numerical scheme under parallel processing is introduced and the dynamic evaluation of the cooling tower under an earthquake loading is examined. In numerical analyses, the cooling tower is assumed to have two types of conventional column system, i.e., V-column and I-column systems. Both R/C shell portion and column system are modeled by use of solid elements. From the numerical analyses, the higher stress concentrations are arisen between the junctions of R/C shell and columns for I-column than those for V-column. Also, it is concluded that the additional reinforcements should be placed around the junction considering the seismic effects.

A R T I C L E I N F O

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1. Introduction

Reinforced concrete (R/C) cooling tower structures have been used for cooling down the hot water produced by power or chemical plants. These structures are designed to prevent against the failure under a self-weight and a wind loading, as well as an earthquake loading. To grow up the economy of developing countries, these structures may be built around the strong seismic regions due to supply the electric energy. Therefore, engineers must examine the safety of a cooling tower under earthquake loading. However, these structures are constructed with a large surface of R/C shell and columns and the numerical analyses are laborious and difficult based on the conventional numerical analyses.

To overcome these problems, several numerical schemes have been proposed combining the axisymmetric analyses or modal analyses (Hara and Gould, 2002; Lang et al., 2003). However, it is difficult to represent the local behavior of these structures by such numerical scheme. Although the finite element method (FEM) is one of the useful schemes, there must be a numerical effort to apply FEM to such problems, especially under a dynamic loading.

In this paper, the numerical scheme under parallel processing is introduced (Adeli and Soegiarso, 1999) and the dynamic evaluation of the cooling tower under an earthquake loading is performed. The parallel processing to compute the behavior of the cooling tower structure was proposed by Hara and the numerical efficiency was presented (Hara, 2004a). In this paper, the cooling tower is assumed to have two types of conventional column system, i.e., V-column and I-column systems. Examples of the column supported cooling towers are shown in Fig. 1.

In numerical analyses, R/C shell portion and column system are modeled by use of solid elements because the smooth combination of the deformations and the stresses between columns and R/C shell portion. Also, the EBE approach to the huge R/C structures is applied. Then the deformation characteristics of R/C shell with supporting columns are examined.

2. Numerical Scheme

2.1. Definition of the solid element

The 20 noded solid elements are adopted to model both shell and column portions. R/C shell elements are composed of the concrete and the reinforcing materials. To define the concrete nonlinearity, Drucker-Prager

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yield criterion and Madrid parabola is used to trace the nonlinear stress strain relation of concrete. Also, the maximum principal tensile crack criterion is used to define the occurrence of the initial cracks. Tension stiffening and the stress degradation after cracks of concrete are adopted. In addition, reinforcing steels are modeled as the equivalent sheet with stiffness only of bar direction. The detailed definition is represented in the previous paper (Hara, 1988; Hara, 2004a; Hara, 2006).


I-column V-column

Fig. 1. Cooling tower column systems.

2.2. Dynamic response analysis

During the time increment, the dynamic equilibrium equation is represented as follows:

$$M\Delta\ddot{y} + C\Delta\dot{y} + K\Delta y = -MI\Delta\ddot{y}_0 \, , \tag{1}$$

where M is the mass matrix, C is the damping matrix, K is the stiffness matrix. Δy, $\Delta\dot{y}$ and $\Delta\ddot{y}$ are the response displacement, the response velocity and the response acceleration vector, respectively. $\Delta\ddot{y}_0$ is the ground motion acceleration and Δ denotes the increment. In this analysis, Raileigh damping is adopted to define the damping matrix. To solve Eq. (1), the Newmark method is adopted in this paper. Then, the dynamic equiliburium equation systems, Eq. (1), is transformed as follows:

$$\widetilde{K} y = \tilde{f} \, , \tag{2}$$

where

$$\widetilde{K} = \frac{M}{\beta\Delta t^2} + \frac{C}{2\beta\Delta t} + K \quad \text{and}$$

$$\tilde{f} = -MI\Delta\ddot{y}_0 + M\left(\frac{\Delta\dot{y}}{\beta\Delta t} + \frac{\Delta\ddot{y}}{2\beta}\right) + C\left\{\frac{\Delta\dot{y}}{2\beta} + \left(\frac{1}{4\beta} - 1\right)\Delta y \Delta t\right\} \tag{3}$$

are the effective stiffness matrix and the modified load vectors, respectively.

In this paper, the dynamic response is evaluated with a time step of Δt=0.001sec. The damping factor is considered 3% proportional to the mass by Rayleigh damping. The convergence rule of equation of motion is defined by Newton-Raphson method

2.3. EBE procedure

To solve the dynamic response of structure, element-by-element (EBE) solution techniques (Hughes et al., 1983) are applied to Eq. (2). Each term of Eq. (2) is assembled by each element equilibrium equations. Then the equation is solved by use of the conjugate gradient method (Adeli and Soegiarso, 1999). PC cluster is applied to solve Eq. (2). In this analysis, PC cluster is composed of eight personal computers and a switching hub to connect each other. The data communication of each computer is governed by MPI.

In conjugate gradient scheme, the solution vector y_{k+1} and the gradient vector r_{k+1} are represented as follows:

$$y_{k+1} = y_k - \alpha_k p_k \;\; , \;\; r_{k+1} = r_k - \alpha_k \widetilde{K} p_k \, , \tag{4}$$

where

$$\alpha_k = \frac{r_k^T r_k}{p_k^T \widetilde{K} p_k} \;\; , \;\; p_{k+1} = r_k + \beta_{k+1} p_k \;\; , \;\; \beta_{k+1} = \frac{r_{k+1}^T r_{k+1}}{r_k^T r_k} \, . \tag{5}$$

In Eq. (5), $\widetilde{K} p_k$ is calculated by element by element. Therefore, these are easy to parallelize.

3. Numerical Model

Fig. 2 shows the numerical models of the R/C cooling tower. The model is a half of R/C shell considering the symmetry of the configuration, the loading and supporting conditions. Both models are divided into 32 elements in hoop direction and into 30 elements in meridional direction. The height is about 175 m. The thickness of the shell changes 105 cm at the lintel through 20 cm at the top. In R/C shell structure, reinforcements are doubly placed in both hoop and meridional direction. The reinforcing ratio is 0.2%. On the other hand, reinforcements are placed 2% in the columns. R/C hyperbolic shell is supported on the 16 columns. Each column has 90 cm square cross section and 9.17 m length. In I-column model, the supporting columns are placed equidistance. In V-column model, the supporting columns are placed equidistance and the adjacent top of the columns are connected. Each column is divided into four elements to represent the flexural deformation of the columns. The material properties are shown in Table 1. The geometric properties are shown in the previous papers in detail (Hara, 2004a; Hara, 2006).

4. Dynamic Response of Cooling Tower with Column

4.1. Deformation behavior of R/C cooling tower shell

To evaluate the basic dynamic response properties of R/C cooling tower, the step load of 0.1g (g: gravity acceleration 980 cm/s^2) is applied. From the numerical analysis, the natural frequencies of the shell response with I-columns are 1.05 Hz and 2.70 Hz from the lintel and the top response, respectively. They show different responses. In the case of the shell without columns, the natural frequency of this model shows 3.5 Hz (Hara, 2004b).

In the case of the shell with V-columns shows the natural frequency of 2.66 Hz. The amplitudes of the displacements on both lintel and the top are different. But the natural frequencies of them are the same.

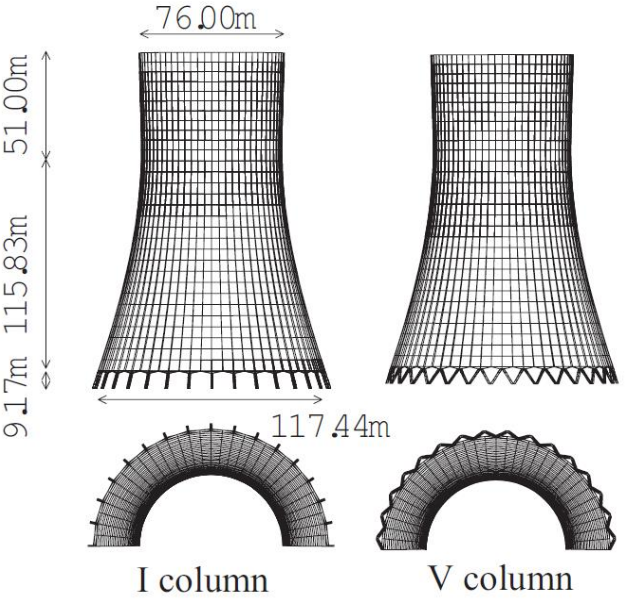

Fig. 2. Numerical models.

Table 1. Material properties.

Concrete	
Elastic Modulus	34 GPa
Poisson's Ratio	0.167
Density	0.0023 kg/cm^3
Compressive Strength	36 MPa
Tensile Strength	2.7 MPa
Reinforcing steel	
Elastic Modulus	206 GPa
Tangent Modulus	2.1 GPa
Yield Stress	500 MPa

Figs. 3 and 4 show the deformation patterns of R/C cooling tower with I-columns and V-columns, respectively. The deformation of the shell with I-column represents the kink at the connection between the shell and the columns and the shell shows the rigid body rotation. On the other hand, the response of R/C cooling tower with V-column deforms like as the cantilevered column.

4.2. *R/C cooling tower under harmonic loading*

Figs. 5 and 6 show the responses of the cooling tower with I-columns and V-columns under the harmonic loading, respectively. The dotted and the solid line denote the response at the top and the lintel, respectively. In this analysis, the intensity of the load is 0.1g.

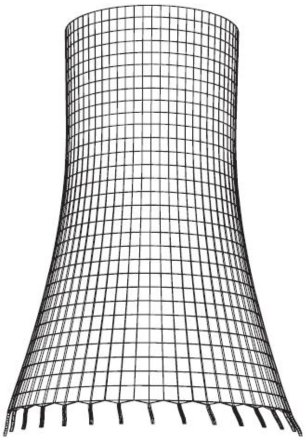

Fig. 3. Deformation under step load (I-column).

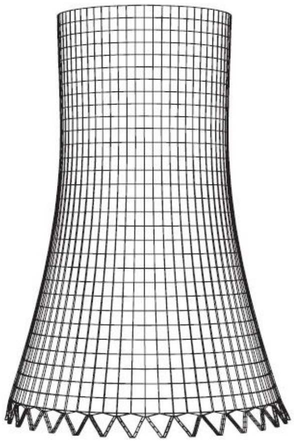

Fig. 4. Deformation under step load (V-column).

Frequencies of an external harmonic load are 1.05 Hz for the shell with I-columns and 2.66 Hz for the shell with V-columns, respectively. Fig. 5 shows the resonance response of the structure. In the case of I-columns, the large deformation is detected around the conjunction between the lintel and columns. Fig. 6 does not show the resonance response of the structure within 3 seconds. The cooling tower shell with V-columns shows the same deformation mode as that shown under step loading.

4.3. *Effectiveness of parallel computing*

Fig. 7 shows the relation between the numbers of processors and computing time. The calculation example is the response of the shell with I-columns under step loading. The greater the numbers of processors is, the fewer the computation time. However, these relations are not proportional because the computation time includes the process of the message passing.

5. Conclusions

This paper presented the numerical analysis of R/C cooling tower with column support under dynamic loading. To apply the general finite element to solve the huge R/C structure, the parallel computing technique is adopted.

From the numerical investigations, following conclusions are obtained.

- R/C cooling tower with I-column supports under dynamic loading shows local deformation around the junction between the lintel and columns but shows small deformation or distortion on the shell.
- R/C cooling tower with V-column supports under dynamic loading shows the cantilever type global deformation but the deformation is small.
- Total structural responses of the shell with supporting columns are different from the conventional pin-supported ideal shell (Hara, 2004b). Therefore, the precise total analyses must be considered.
- The numerical scheme presented here will be applicable to the practical one such as the earthquake response of the structure or the response of the dynamic wind loading considering the local deviations such as supporting columns and the hole on the shell surface.

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