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# Nonlinear interactive analysis of cooling tower–foundation–soil interaction under unsymmetrical wind load

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**Abstract**

This paper deals with physical and material modelling of a cooling tower–foundation–soil system. The physical modelling has been carried out using solid 20-noded isoparametric element to model the cooling tower, annular raft foundation and soil media. The cooling tower–foundation–soil system was analysed under vertical and lateral load generated due to self-weight and wind loads. The soil nonlinearity has been taken into consideration using hyperbolic nonlinear elastic constitutive law. The response of the structure has been investigated with respect to displacement and stresses. Moreover, an attempt has been made to study the effect of the linear and nonlinear interactive analyses compared with conventional analysis. It was seen that the interactive analysis of the cooling tower–foundation–soil media plays a major role in releasing the stresses in the cooling tower, particularly at the bottom ring beam.


*Keywords:* Cooling tower; Wind load; Soil–structure interaction; Linear analysis; Nonlinear analysis

## 1. Introduction

The natural draught cooling tower is a very important and essential component in the thermal nuclear power stations and industrial power plant. Due to their complexities in geometry, the analysis of such type of structures has attracted attention of many researches throughout the world. In the absence of earthquake loading, wind constitutes the main loading for the natural draught cooling towers.

Due to the failure of cooling towers in the UK in 1965 and 1984, Scotland in 1973, and France in 1979 [1], the analysis of cooling tower attracted the attention of many investigators to account for the proper physical, material, and load modelling of cooling towers. Karisiddappa et al. [1] carried out the analysis of column supported cooling towers for unsymmetrical wind loads. Improved 3D finite element formulation of column supported hyperbolic cooling towers and the realistic circumferential wind pressure distribution, which is unsymmetrical, had been carried out. Consequently, for different wind pressure distribution profiles, meridional membrane forces were shown to exhibit more sensitivity towards the pressure variations.

Abbu-Sitta [2] had presented ring-stiffened hyperbolic cooling towers under static wind loading. Equations for the interaction between a hyperboloid shell of revolution and a top boundary ring beam were derived and solved with the general shell equations for two sample-cooling towers. It was shown that the ring beam effect was local and influences mainly the meridional moment and the circumferential force.

Gran and Yang [3] used a doubly curved membrane quadrilateral shell finite element to obtain the static response of a fixed base-cooling tower under dead load only. This element had been developed with the intention of its application to study the response of the column supported cooling towers. Gupta and Maestrini [4] had an investigation on hyperbolic cooling tower's ultimate behaviour. It was shown that a significant redistribution of meridional stresses occurs after yielding of the reinforcement, thus increasing the ultimate strength beyond that predicted by the elastic analysis.

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Gopalakrishnan et al.[5,6] investigated nonlinear analysis of reinforced concrete hyperbolic cooling tower. A four-noded isoparametric curved shell element had been used in the nonlinear finite element analysis. Consequently, a nonlinear finite element analysis procedure for studying the post-cracking behaviour and ultimate load of reinforced concrete shell structures, having load transfer mechanism predominantly through membrane action, was presented. Niemann and Kopper [7] studied the influence of adjacent buildings on wind effects on cooling tower. The response of the cooling tower was compared with the British Standard 4485 (BS 4485) [8] and it was seen that interference factors to the wind-induced stresses were used. These factors were different over the shell height and individual values were given for the quasi-static stress.

The assessment of wind loads on cooling towers had been carried out by Niemann and Kasperski [9]. In this study, a new approach with individual equivalent static loads for each design situation, the design of the reinforcement in the meridional and circumferential direction and the design against buckling was presented. Rao [10] presented the stress resultants in hyperbolic-cooling tower shell subjected to the foundation settlement. The effect of differential settlement of columns supporting a natural draught hyperboloid-cooling tower on the stress resultants in the tower shell was analysed using discrete finite element modelling of the shell and the supporting base. It is shown that the stress concentration can be severe, up to seven times the average stress resultants due to dead load and up to five times the average stress resultants due to the foundation settlement.

Zenon et al. [11] presented a nonlinear analysis of a reinforced concrete cooling tower with geometrical imperfections and material nonlinearity. The computations were carried out for a cooling tower shell pinned at the bottom contour. The dead load and wind pressure were applied to the shell. The results of computations for a perfect hyperboloid shell were compared with the results obtained using the DIANA finite element package. It was noted that a considerably softer response corresponds to larger deformations and advanced cracking, and the geometrical imperfections only slightly influence the response of the shell. Orlando [12] described wind-induced interference effects on two adjacent cooling towers experimentally and concluded that the wind-induced pressures can be significantly different from those on an isolated tower.

Little attention has been paid on interactive analysis of cooling tower–foundation–soil system by considering them as a single compatible unit. Moreover, the effect of soil nonlinearity on the structural interactive response of the cooling tower–foundation system is not widely reported in the literature.

The present investigation is focused on:

(i) The development of a 3D nonlinear finite element computer code, which is capable of modelling the cooling tower under unsymmetrical wind load by considering the tower shell, annular raft, and soil mass as a single compatible unit.

(ii) Exploring the effect of soil nonlinearity on the overall response of cooling towers by using hyperbolic nonlinear elastic stress–strain law for soil.

## 2. Nonlinear hyperbolic stress–strain relationship

Unlike many engineering materials, the constitutive law of soil is complex and nonlinear in nature. Several nonlinear models such as bi-linear, K-G model, hyperbolic, hypo-elastic, and hyper-elastic model are reported in Ref. [13]. However, the hyperbolic model is attractive from the computational point of view. It is well suited for implementation in finite element program and is applicable virtually to all types of soils. Experiences in applying hyperbolic model in the analysis of dams, excavations, and various types of soil–structure interaction problems have been reported [13]. However, this model is useful for evaluating the movement in stable earth masses and is not suitable for predicting the instability or failure pattern of the soils. The tangent modulus of elasticity defined in this model is stress dependent and is expressed as

$$E_t = \left[1 - \frac{R_f(1-\sin\theta)(\sigma_1-\sigma_3)}{2C\cos\theta + 2\sigma_3\sin\theta}\right]^2 Kp_a\left(\frac{\sigma_3}{P_a}\right)^n, \quad (1)$$

where $R_f$ is the failure ratio, $p_a$ the atmospheric pressure, $n$ the exponent determining the rate of variation of $E_t$ with $\sigma_3$, $K$ a modulus number, $C$ the cohesion, $\theta$ the angle of internal friction (deg), $\sigma_1$ the maximum principal stresses, and $\sigma_3$ the minimum principal stresses.

Expression for nonlinear Poison's ratio was given by Duncan [13] as

$$v_t = \frac{G - F\log(\sigma_3/P_a)}{\left\{1 - \dfrac{(\sigma_1-\sigma_3)d}{Kp_a\left(\dfrac{\sigma_3}{p_a}\right)^n\left[1 - \dfrac{R_f(1-\sin\theta)(\sigma_1-\sigma_3)}{2c\cos\theta+2\sigma_3\sin\theta}\right]}\right\}^2}, \quad (2)$$

where $G$ is the value of $v_t$ at 1 atm pressure, $F$ the rate of change of initial Poison's ratio $v_i$ with confining pressure, $\sigma_3$, $D$ the parameter expressing rate of change of $v_i$ with strain.

## 3. Finite element computer code

The existing finite element program developed by Noorzaei [14] has been modified by adding the following features:

(i) Evaluation of pressure coefficient, pressure distribution under symmetrical and unsymmetrical wind loads had considered several schemes, i.e., Indian standards, British standards, and Fourier sine–cosine series.