Static and dynamic soil–structure interaction response of Kazeroon cooling towers

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Abstract

To get a better insight about the soil properties and their effects on the structural behavior of Kazeroon cooling towers, a finite element model has been prepared by considering the structure and a huge amount of its underneath soil. Nonlinear static analysis for the dead load and nonlinear dynamic analysis for the earthquake load are done because of the importance of these loads in the design of cooling towers. Analysis results of this model are compared with the results obtained from the model used for the design of the cooling tower. Comparison showed that the effects of soil-structure interaction should be noticed carefully for cooling towers.

Keywords: Cooling tower, Finite element method, Soil-structure interaction, nonlinear dynamic analysis.

1. INTORDUCTION

Natural draft cooling towers are reinforced concrete shell structures used in thermal and nuclear power plants as cooling devices. These structures are one of the largest shell structures being constructed nowadays. These are the hyperbolic shells of revolution in form. The largeness and slenderness of these shells makes them vulnerable to earthquake and wind disturbances [1-6]. This was evident in the spectacular failure of the cooling towers at Ferrybridge, England in 1965 during a gust storm, the collapse of another cooling tower at Ardeer, Scotland in 1973 and a cooling tower at Fiddlers Ferry in 1984 and failure of a cooling tower at Bouchain in Northern France in 1979. These failures have attracted the attention of many investigators for an improved and robust analysis of cooling towers [2].

Soil–structure interaction states the mechanics of interaction between soil, foundation, and the superstructure. In most of the Civil Engineering analyses, structure is assumed to be fixed at the base. Thus, the flexibility of foundation and the compressibility of the supporting soil medium are neglected. Consequently, the effect of uneven foundation settlements on redistribution of forces and moments in the superstructure is neglected too [2]. Lots of work is available in the literature on analysis of fixed base hyperbolic cooling towers [3-6]. However, a more realistic analysis would be the one in which the influence of the soil–structure interaction is also included. Lu et al. studied the effect of unequal settlement of foundation on stress resultants in the tower shell using finite element representation of column supported cooling towers [7]. Tilak et al. considered a soil–structure interaction effect in which the supporting compressible soil was treated as a Winkler medium [8]. However, due to limitations of the Winkler model, this analysis does not reflect the true interactive response of cooling towers. Kato et al. introduced a modified thin-layered far field soil element for considering soil–structure interaction analysis of axisymmetric structure [9]. Kato et al. presented an analysis of cooling towers on a soft soil layer subjected to the horizontal incident earthquake motions from the base rock [10]. In addition, based on the complex spectral element method and the theory of fractional calculus, a hybrid complex decoupled spectral method has been developed by Horr and Safi for studying the dynamic soil–structure interaction of cooling towers [11].

Kazeroon Combined cycle power plant is located near city of Kazeroon in Fars province with capital Shiraz. The nearest city to the plant is Kazeroon with 14km distance. The three cooling towers are located in the east part of the plant in a triangular arrangement with approximately 150m distance to each other. The cooling towers are natural draft heller type with indirect dry cooling system and forgo T60 heat exchanger. To get a better insight about the soil properties and their effects on the structural behavior of Kazeroon cooling towers, a model has been prepared by considering the structure and a huge amount of its underneath soil. In this analysis the real behavior of structure, soil and interaction of them can be evaluated. The finite element program Ansys 8 is used to prepare the three dimensional model of the cooling tower, its foundation and the soil. The static analysis for the dead load and the dynamic analysis for the earthquake load are done because of the importance of these loads in the design of cooling towers. Nonlinear time history analysis is chosen for the seismic analysis of the structure. The results of the analysis of this model are compared with the results of the analysis of the model used for the design of the cooling tower. In the design model the effects of the soil on the behavior of the structure is considered by using springs at the base of the cooling tower. The results of this analysis showed that the effects of soil-structure interaction should be investigated in future projects.

2. Cooling Tower Geometry

Structural parts of Kazeroon cooling towers are: ring foundation, 36 pairs of X-leg columns at the bottom, reinforced concrete shell from the top of X-leg columns up to level +125m and a ring beam at level +123.5m. The geometrical information of cooling towers is shown in Table 1.

Table 1- Cooling tower geometry.

Cooling tower geometry	Dimensions
Height of cooling tower	125 m
Axe to axe throat diameter(D_T)	62.18 m
Height of throat (H_T)	105 m
Top level of X-legs (H_X)	24.6 m
Diameter at the top of X-legs (D_X)	81.331 m
R.C. Concrete shell thickness (from bottom to top)	120cm ≈ 18cm
X-leg columns angle to horizon	78°23′59″

The mathematical formulation of radius (R(h)) and shell thickness (t(h)) of tower in any height (h) is:

$$R(h) = \sqrt{\left(\frac{D_T}{2}\right)^2 + \left(\frac{H_T - h}{b}\right)^2} \quad (1)$$

$$b = \frac{2\times(H_T - H_X)}{\sqrt{(D_X)^2 - (D_T)^2}} = 3.0672 \quad (2)$$

$$t(h) = \begin{cases} 300 + 900\times\left(\dfrac{35-h}{10.4}\right)^2 & , \quad 24.6\text{ m} < h < 35\text{ m} \\ 180 + 120\times\left(\dfrac{80-h}{45}\right) & , \quad 35\text{ m} < h < 80\text{ m} \\ 180 & , \quad 80\text{ m} < h < 125\text{ m} \end{cases} \quad (3)$$

All of the variables in the above equations are in metric units except for t(h) which its unit is in millimeter. Figure 1 shows the schematic view of the cooling tower. The material properties of the cooling tower are listed in Table 2.

Table 2- Material properties of Kazeroon cooling tower.

Material properties	
Young's modulus (Concrete)	E_c=34000 N/mm^2
Poisson's ratio (Concrete)	ν=0.2
Compression strength of X-leg columns (Concrete)	f_{cm}=35.00 N/mm^2
Compression strength of other parts (Concrete)	f_{cm}=28.00 N/mm^2
Specific weight (Concrete)	γ=2400 Kg/m^3
Young's modulus (Steel)	E_s=210000 N/mm^2
Yield strength (Steel)	F_{ym}=400.00 N/mm^2

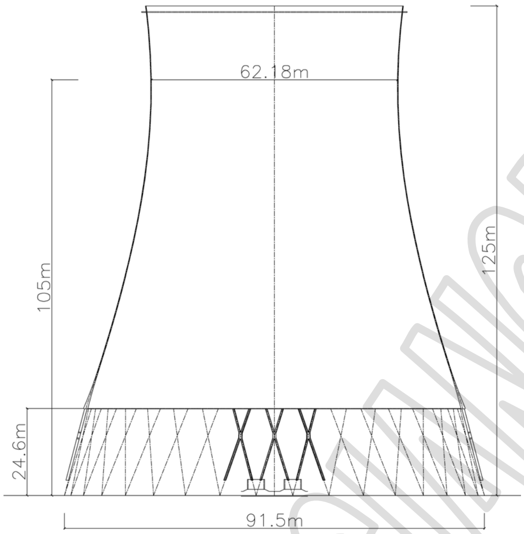

Figure 1. Kazeroon cooling tower geometry.

The geotechnical investigations of the site were done by Mandro consulting engineers [12]. By drilling 12 boreholes the soil profile for design purposes was specified. The recommended soil parameters are shown in Table 3. Dynamic parameters of soil are as follows:

Depth: 0-10 m $E_{dynamic} = 2500$ kg/cm^2

Depth: 10-30 m $E_{dynamic} = 4000$ kg/cm^2

Depth: 30-40 m $E_{dynamic} = 7000$ kg/cm^2

Table 3- Physical and mechanical specifications of the soil.

Different properties	Type of soil		Units
	Clay stiff to hard (0-25 m)	Clay stiff to hard (25-40 m)	
Drained angle of friction (φ_d)	26-28	27-29	Degree
Undrained angle of friction (φ_u)	5-10	8-12	Degree
Drained cohesion coefficient (C_d)	0-0.1	0-0.1	Kg/cm^2
Undrained cohesion coefficient (C_u)	0.7-0.9	0.8-1.2	Kg/cm^2
Density (γ)	2-2.1	2.0-2.15	gr/cm^3
Modulus of elasticity (E)	300-350	400-450	Kg/cm^2
Poisson's ratio (μ)	0.4	0.4	-
Swell index (C_s)	0.01	0.01	-
Compression index (C_c)	0.13	0.12	-
Void ratio (e)	0.5-0.7	0.5-0.7	-
Over Consolidation Ratio (OCR)	1.5	1.5	-

The foundation is a ring with the width of 5.3m and variable thickness between 2 and 1.3 meters. The axis diameter of the foundation is 93.28m just like the base of X-legs of the cooling tower.

3. STRUCTURAL MODELING IN THE DESIGN STAGE

The structural model used for the design of Kazeroon cooling tower was prepared in SAP2000 software [13]. The effects of soil structure interaction for the design model were considered by using springs under the foundation of the cooling tower. The spring coefficients were suggested by Mandro consulting engineers. Springs stiffness in vertical and horizontal directions for static and dynamic loadings were: $K_{static} = 0.55$ kg/cm^3 and $K_{dynamic} = 3.0$ kg/cm^3. For seismic analysis of the cooling tower, spectral analysis was used. The fundamental period of the tower calculated by SAP2000 software was 0.74 second. Dimension of the X-leg columns obtained in the design process was 1.1×0.75 m^2.

4. STRUCTURAL MODELING IN THIS STUDY

To get a better insight about the soil properties and their effects on the structural behavior of Kazeroon cooling towers, a model has been prepared by considering the structure and a huge amount of its underneath soil. The results of this analysis can be checked with the results of analysis of the design model. The finite element software Ansys 8 is used to prepare the three dimensional model of the cooling tower, foundation and the soil. For modeling the shell of cooling tower shell63 element is used. The specification of the element is just like previous analysis done by Sap2000. For modeling of X-legs and other beam like elements, beam4 element is used. The specification is just like the beam element in SAP2000. Foundation was first modeled with the beam44 element that is suitable for variable section beams. But for the purpose of calculating the different settlements of the edges of foundation, it is modeled with the shell63 element also. In this case there are two nodes outward and inward of each foundation element and calculating the different settlements is possible (Figure 2).

For modeling the soil, solid45 element is used according to the soil specification table. For layers of soil at specified depths, elements with different properties for static and dynamic analysis are defined. The effects of soil mass on the results of the analysis are investigated by considering it in one analysis and neglecting it in others. Nonlinearity of the soil is modeled with the well known drucker-pruger material. Different coefficient for defining drucker-pruger material is calculated from the soil specification table. Diameter and depth of the soil block that is modeled under the cooling tower are 486.4m and 111.15m respectively. The depth of the soil block is about 1.5D and the diameter of the soil is about 5D (D: diameter of the axe of foundation). These values were suggested by the geotechnical experts. Because depth of the boreholes is 40m, for the soil under the level of -40m the specification is assumed to be just like the soil between level -25m to -40m (Figure 3).

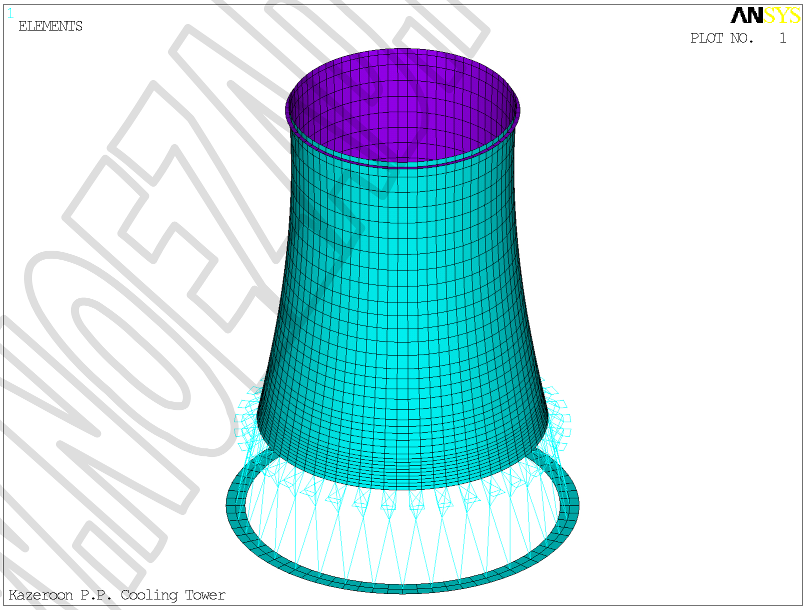

Figure 2. Structural model of Kazeroon cooling tower.

The boundary condition of the soil block is as follow:

1- At the bottom of the block the displacement in three directions are restrained.

2- The interactions between soil elements of the underneath block and outside soil in all around are modeled by Combin14 element.

The Combin14 element is used to model the damping at the end of radius of the soil block [14]. In other words these elements try to model the infinite boundary condition for the soil block. The damping coefficients are calculated from shear wave velocity (V_s) of the soil and its density (ρ). Because the area of the soil element that is covered by a combin14 element is not the same at different levels (because the dimensions of the elements are larger in lower levels), the damping coefficients are not the same at different levels. Damping coefficient per area of the soil is calculated as follows:

$$\text{Damping coefficient / area} = \rho \times V_s = 2000 \times 230 = 460000\ \text{Kg / m}^2\text{s} \qquad (4)$$

The damping coefficients of the Combin14 elements are calculated by multiplying the above value in the area of the soil elements that are covered by the Combin14 elements.

To prevent generating ill shaped elements, soil elements are modeled in cubic form at the center of the soil block. Foundation of the cooling tower is in circular form and therefore the cubic form of the elements is changed to a circular form at the outer parts of the soil block (Figure 4). By using this method, just a few number of soil elements have 6 nodes and most of the elements have good shapes. To reduce the amount of elements, it was decided to increase the size of soil elements at the lower parts of the soil (Figure 5). Total number of elements and degrees of freedom in this model are 16860 and 54966 respectively. Of curse analysis of such a huge model is significantly time-consuming.

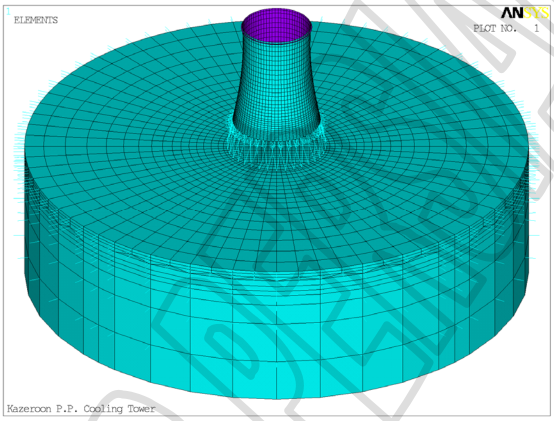

Figure 3. Structural model of Kazeroon cooling tower with its underneath soil.

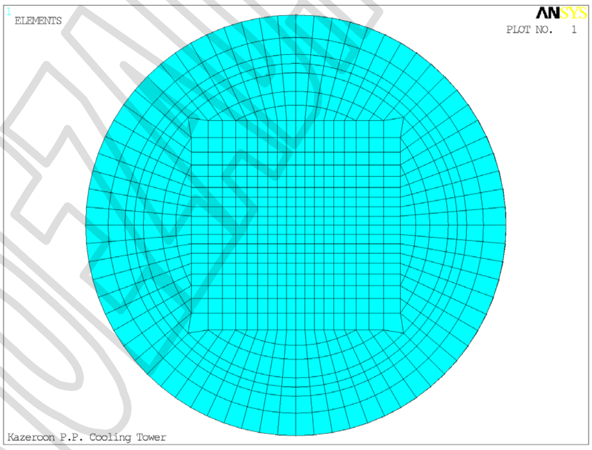

Figure 4. Distribution of the elements at the center of soil block.

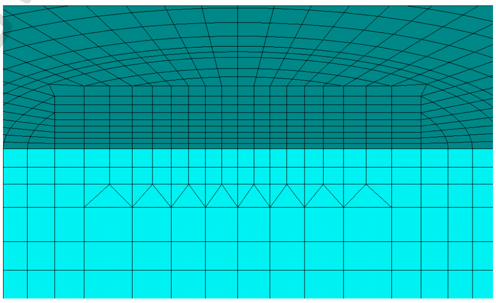

Figure 5. Distribution of the elements in the depth of soil block.

5. LOADING

The static analysis for the dead load and the dynamic analysis for the earthquake load are done because of the importance of these loads in the design of cooling towers. Dead load includes weight of x-leg columns, RC shell and foundation (as main structural members) and widening roof, mechanical cooling systems, top ring , stairs , ladders and walkways (as secondary members) and soil embankment. Based on seismic risk study that is carried out for the power plant site, two intensities of seismic forces is recommended to be considered in design of cooling tower: Earthquake with return period of 50 years and Earthquake with return period of 475 years. Two individual seismic risk studies were done for the project by MAPNA consulting engineers and Zare [15]. In this research both of these studies are used.

Maximum ground horizontal accelerations are 0.158g and 0.23g according to MAPNA civil technical data and Zare report respectively for 50 years return period earthquake. Maximum ground horizontal accelerations are 0.313g and 0.45g according to MAPNA civil technical data and Zare report respectively for 475 years return period earthquake. According to MAPNA seismic data, the seismic design of all major structures, including cooling towers, shall be based on the concept of normalized response spectra to appropriate maximum ground acceleration level in the case of 50 or 475 years return period earthquake (critical one), the proposed spectra in this regard is the spectra presented in third edition of IS-2800 for soil TYPE III [16]. The energy dissipation (damping ratio) in cooling tower structure to be considered in dynamic response analysis for design based on overall safety factor is %5 of critical damping value, as per VGB Guidelines.

In this research three accelerograms are used for performing the nonlinear time history analysis. Two simulated accelerograms that are compatible with earthquakes with return period of 50 and 475 years, based on Zare study, are used. The third accelerogram is Tabas accelerogram. As explained by the IS-2800 code the accelerogram should be compatible with the code spectrum. For this purpose the spectrum of the Tabas accelerogram is constructed and changed to be compatible with the code spectrum [14]. For this accelerogram the maximum ground horizontal accelerations is considered to be 0.313g. If the spectrum of the accelerogram is changed to be the same as the code spectrum, the shape of the original accelerogram will be modified completely. To prevent this matter the compatibility procedure is restricted to a level which both goals (compatibility and not changing the characteristics of the accelerogram completely) are reached. The compatibility procedure is done through the described range of periods that is desirable in IS-2800. Modified acceleration response spectrum of Tabas record is shown in Figure 6.

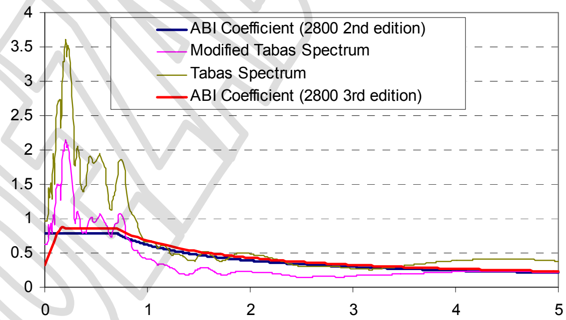

Figure 6. Modified acceleration response spectrum of Tabas record.

6. ANALYSIS RESULTS

Figure 7 shows the distribution of vertical stress in the soil for static analysis. It can be seen that the distribution of the stresses in the depth of the soil is realistic. There are some virtual maximum points in the figure that are produced because of some ill shaped elements. Table 4 compares the results of ANSYS model and SAP2000 model obtained by static analysis. Maximum vertical displacement of the soil obtained by ANSYS model is about 0.085 m and the residual vertical displacement in soil is about 0.02 m. Maximum vertical stress in soil is about 150000 N/m^2. Maximum vertical displacement of the soil and maximum rotation of foundation are larger in ANSYS model. It means that the spring properties in SAP2000 model can not represent the real property of the soil. Another source for these differences is the method of modeling the foundation. In ANSYS model that the shell elements are used to represent the foundation, the displacements at the edges of foundation are larger than the displacements in the middle of it. But in SAP2000 model this phenomenon is ignored. Maximum vertical stress in soil is smaller in ANSYS model because the real deformations of the soil such as shear deformation are modeled in ANSYS that SAP2000 can not represent them with simple springs.

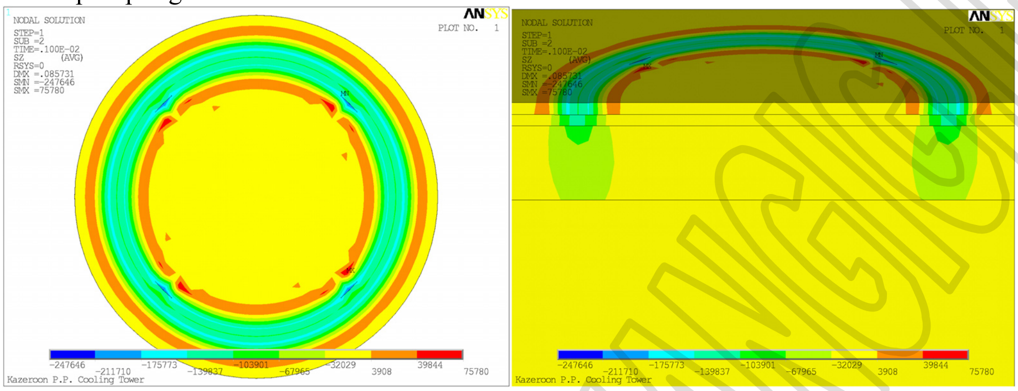

Figure 7. Distribution of vertical stress in the soil for static analysis.

Table 4- Comparison the results of SAP2000 model and ANSYS model for static analysis.

SAP2000 results	ANSYS results
Maximum displacements of the soil in vertical direction (m)	
-0.043915	-0.084942
Maximum rotations of the foundation (rad)	
0.000246	0.000341
Maximum soil pressure under the x-leg (N/m^2)	
-236862	-149909

Figure 8 shows the distribution of vertical stress in the soil for dynamic analysis. This figure is obtained at the moment that the maximum stress is experienced. Table 5 compares the results of ANSYS model and SAP2000 model obtained by dynamic analysis. The results of SAP2000 model are obtained using response spectra of earthquake with 475 years return period. Forces and stresses obtained from SAP2000 model are more than what is obtained for dynamic analysis of simulated accelerograms and less than the results of Tabas record. It can be said that the results of SAP2000 model is somehow conservative. The main reason for the differences of the results for Tabas record is its scaling method.

7. CONCLUSIONS

Comparison showed that the effects of soil-structure interaction should be noticed carefully for cooling towers especially for the sites with complicated geotechnical specifications. If equivalent springs are preferred to be used instead of modeling the huge amount of soil, their stiffness properties for static and dynamic analysis should be calculated with special care.

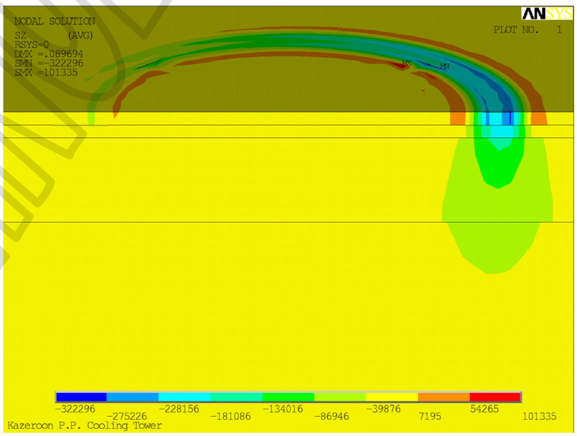

Figure 8. Distribution of vertical stress in the soil for dynamic analysis.

Table 5- Comparison the results of SAP2000 model and ANSYS model for dynamic analysis.

SAP2000 spectral analysis results	ANSYS results of Tabas record	ANSYS results of simulated accelerogram with 50 years return period	ANSYS results of simulated accelerogram with 475 years return period
Maximum displacements of the soil in vertical direction (m)			
-0.0038	-0.0047	-0.0012	-0.0021
Maximum rotations of the foundation (rad)			
0.000181	0.000105	0.000027	0.000056
Maximum soil pressure under the x-leg (N/m^2)			
-111956	-124667	-31504	-62614

8. ACKNOWLEDGMENT

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