Earthquakes and Structures, *Vol. 14, No. 1 (2018) 85-94*
DOI: https://doi.org/10.12989/eas.2018.14.1.085

Soil-structure interaction effects on seismic behavior of a hyperbolic cooling tower using three-parameter Vlasov foundation model

Ali I. Karakas[a], Korhan Ozgan* and Ayse T. Daloglu[b]

Department of Civil Engineering, Karadeniz Technical University, Trabzon, 61080, Turkey

(Received July 25, 2016, Revised January 17, 2018, Accepted January 31, 2018)

Abstract. The paper focuses on the seismic responses of a hyperbolic cooling tower resting on soil foundation represented by the three-parameter Vlasov elastic soil model. The three-parameter soil model eliminates the necessity of field testing to determine soil parameters such as reaction modulus and shear parameter. These parameters are calculated using an iterative procedure depending on the soil surface vertical deformation profile in the model. The soil and tower system are modeled in SAP2000 structural analysis program using a computing tool coded in MATLAB. The tool provides a two-way data transfer between SAP2000 and MATLAB with the help of Open Application Programming Interface (OAPI) feature of SAP2000. The response spectrum analyses of the tower system with circular V-shaped supporting columns and annular raft foundation on elastic soil are conducted thanks to the coded tool. The shell and column forces and displacements are presented for different soil conditions and fixed raft base condition to investigate the effects of soil-structure interaction. Numerical results indicate that the flexibility of soil foundation leads to an increase in displacements but a decrease in shell membrane and column forces. Therefore, it can be stated that the consideration of soil-structure interaction in the seismic response analysis of the cooling tower system provides an economical design process.

Keywords: hyperbolic cooling tower; response spectrum analysis; open application programming interface; finite element analysis; three-parameter foundation model

1. Introduction

Hyperbolic cooling towers are thin-walled slender structures utilized to cool the circulating water used in thermal and nuclear power stations. These structures can be exposed to various loading conditions directly such as wind or indirectly such as earthquake, temperature change, and support settlements. However, the earthquake load can be considered as the main load for the cooling towers located in high seismic zones. Therefore, it is essential to recognize the seismic behaviors of huge cooling towers under severe earthquake attacks in the design process. The loads applied by a design earthquake to the components of a cooling tower can be determined by the response spectrum or time history analyses. The response spectrum method is the most efficient but a time history analysis may be more appropriate if nonlinearities are to be included in the analysis (Gould and Krätzig 2005).

Cooling towers should be modeled in appropriate detail as a system including all structural components such as shell wall, supporting columns, annular raft and soil foundation for a robust seismic design. However, in most of the previous studies in the literature at least one of these components is ignored or extremely simplified. For instance, a number of researchers assumed in their studies that the cooling towers are fully or partially restrained at shell wall base (Jia 2013, Krivoshapko 2002, Kulkarni and Kulkarni 2014, Kulkarni and Kulkarni 2014, Lang *et al*. 2002, Murali *et al*. 2012, Nasir *et al*. 2002, Prashanth and Sayeed 2013), at column bases (Aksu 1996, Esmaeil *et al*. 2012, Karisiddappa *et al*. 1998, Tande and Snehal 2013) or at raft base (Weng *et al*. 2013) without involving the effect of the soil medium. In all of studies above the effects of relatively soft columns or soil foundation are ignored. Therefore, these models can be considered as preliminary tower models.

Considering previous studies, soil-structure introduction is incorporated either using the mechanics of springs by Winkler model (Christian 2011a, b, Sabouri-Ghomi *et al*. 2006), or applying elastic half-space model with boundary element method (Wolf 1986, Yang and Lu 1992, Yang and Lu 1994), or considering it as elastic continuum with finite element method (Noorzaei *et al*. 2006, Viladkar, Karisiddappa *et al*. 2006). In Winkler model, the soil is assumed as linear, independent, discrete, and closely spaced springs ignoring the interaction between adjacent springs. And thus, the vertical shearing stress that occurs within the soil medium and the effect of surrounding soil to the structure are neglected in the model. However, in reality the soil is a continuous medium which transfers shear stresses. Therefore, the Winkler soil model does not represent the soil-structure interaction truly. Similarly, studies utilizing boundary element method to model elastic half-space

*Corresponding author, Associate Professor
E-mail: kozgan@ktu.edu.tr
[a]Assistant Professor
E-mail: aliihsanka@yahoo.com
[b]Professor
E-mail: aysed@ktu.edu.tr

http://www.techno-press.com/journals/eas&subpage=7
ISSN: 2092-7614 (Print), 2092-7622 (Online)

cannot reflect the non-homogeneity of the soil through the depth. On the other hand, the elastic continuum model can consider the non-homogeneity in soil properties with depth using idealized three-dimensional linear elastic isotropic solid finite elements. However, the shortcoming of the continuum model is to require a large number of elements to represent three-dimensional elastic continuum under and surrounding the structure. The abovementioned studies including soil-structure interaction using elastic continuum model focus on the responses of cooling towers subjected to static wind loadings.

It is realized that there has been little work dealing with soil-structure interaction including non-homogeneity in the elasticity modulus with soil depth and shear deformation of soil. Also, the previous studies focus on the wind responses of the soil interacted cooling towers. Therefore, this paper emphasizes the seismic responses of a cooling tower with all structural components such as supporting columns and annular raft as well as soil foundation. The soil foundation is represented by the three-parameter Vlasov or three-parameter elastic soil foundation model. The soil model transfer shear deformations using a layer of incompressible shell elements and incorporates the effect of soil surrounding and underneath the raft foundation considering the non-homogeneity in modulus of elasticity with depth. This model is integrated into existing structural analysis software SAP2000 (2011) with the help of a computing tool coded in MATLAB. The computing tool utilizes Open Application Programing Interface (OAPI) functions of SAP2000 which enable two-way data transfer between MATLAB and SAP2000. In the following sections, the details of the three-parameter Vlasov model and seismic responses of a cooling tower are presented.

2. Open application programming interface

The Open Application Programming Interface (OAPI) feature of SAP2000 allows the researchers to transfer model information to and from SAP2000, to start the SAP2000 execution and to obtain design and analysis information from SAP2000 via computer programming languages including MATLAB.

In this study, OAPI feature of SAP2000 is used interactively with a computing tool coded in MATLAB to perform seismic analyses of a hyperbolic cooling tower on three-parameter elastic soil foundation.

3. Three-parameter Vlasov foundation model

The soil reaction exerted to a structure resting on a two-parameter elastic soil is expressed in Eq. (1).

$$q_z = kw - 2t\nabla^2 w \tag{1}$$

The reaction depends on the soil surface vertical displacement w, soil reaction modulus k, and soil shear parameter $2t$. These two soil parameters, k and $2t$, can be defined by Eq. (2) and (3).

$$k = \int_0^H \frac{E_s(1-\upsilon_s)}{(1+\upsilon_s)(1-2\upsilon_s)}\left(\frac{\partial\varphi(z)}{\partial z}\right)^2 dz \tag{2}$$

$$2t = \int_0^H G_s\phi(z)^2\, dz \tag{3}$$

in which H, ν_s and G_s are the depth, Poisson’s ratio and shear modulus of the soil, respectively. In most of the classical two-parameter soil foundation models such as Pasternak, Hetenyi, and Vlasov models the soil parameters are constants obtained by experimental tests or arbitrarily defined. However, it is highly difficult to determine these parameters experimentally. Therefore, Vallabhan *et al*. (1991) developed an additional parameter γ to characterize vertical displacement profile within subsoil. They called this model including the third parameter γ as three-parameter Vlasov model. This model eliminates the necessity of experimental tests to determine soil parameters since these values are determined iteratively in terms of the new parameter, γ. The vertical deformation profile of the subsoil is described via a mode shape function as given in Eq. (4)

$$\phi(z) = \frac{\sinh\gamma\left(1-\frac{z}{H}\right)}{\sinh\gamma} \tag{4}$$

The boundary values of $\phi(z)$ are assumed to be $\phi(0)=1$ and $\phi(H)=0$ as shown in Fig. 1. The γ parameter can be calculated using Eq. (5).

$$\left(\frac{\gamma}{H}\right)^2 = \frac{(1-2\nu_s)}{2(1-\nu_s)}\frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}(\nabla w)^2\, dxdy}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} w^2 dxdy} \tag{5}$$

Eqs. (2) and (3) indicate that the soil parameters (k and $2t$) are calculated based on the material properties and mode shape function ($\phi(z)$). Also, it is necessary to compute the γ

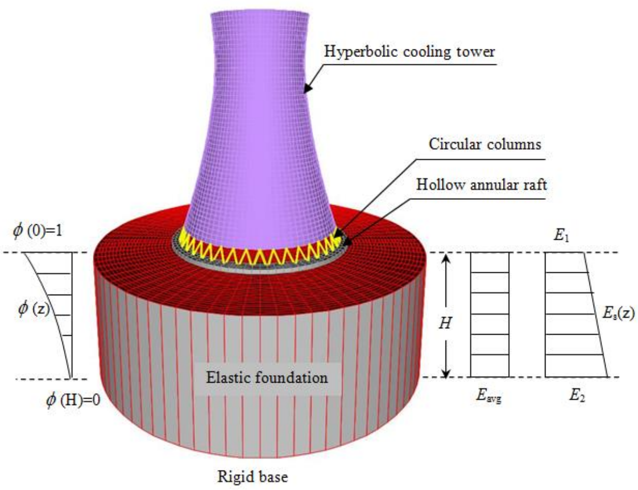

Fig. 1 All structural components of a cooling tower on elastic foundation

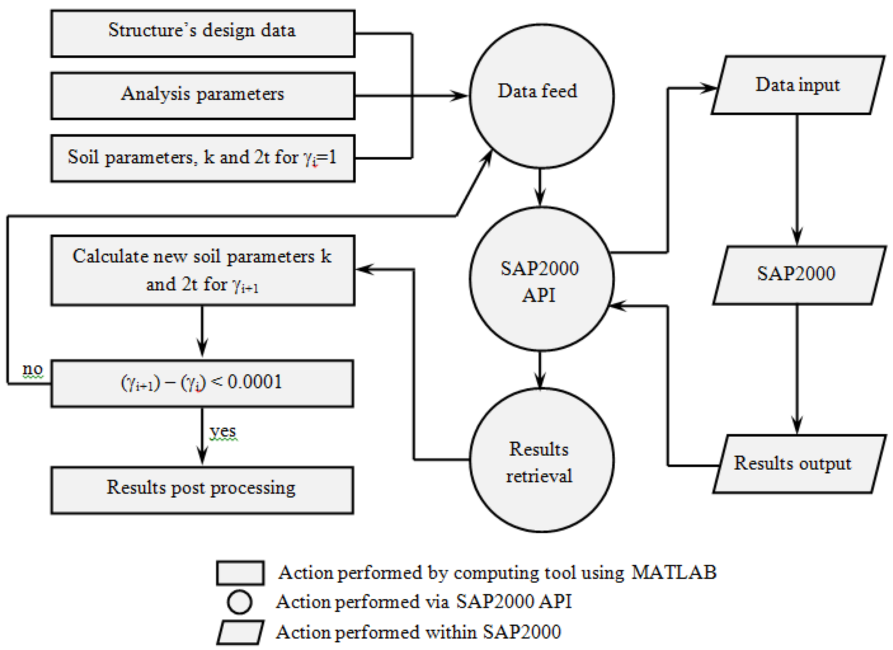

Fig. 2 Flowchart of the solution procedure

parameter to calculate the mode shape function. It is necessary to know the soil vertical surface displacements obtained from the structural analysis to calculate the γ parameter. So, it can be stated that k, $2t$, ϕ, γ and w are interdependent. That's why the analysis requires an iterative procedure. For this purpose, a computer program is coded in MATLAB interacting with SAP2000 structural analysis program via OAPI to perform this iterative procedure in three parameter foundation model.

Using the coded program, a soil model is generated such that the soil reaction modulus k is represented by elastic area springs. The interaction between springs is taken into account using shell elements connecting the top of springs. The soil shell element with one degree of freedom at each node reflects only shear behaviour of the soil. The γ parameter is computed numerically in the coded program using the vertical displacements of soil shell elements. To determine the soil parameters iteratively γ=1 is assumed initially and k and $2t$ values are calculated. Then the structural model is analysed using SAP2000 and the soil surface vertical displacements are retrieved to compute new γ value. The difference between successive values of γ are calculated and checked whether it is within a prescribed tolerance or not. If it is smaller than the tolerance the iteration is terminated. Otherwise, the next iteration is performed and the procedure is repeated until the convergence is fulfilled. The solution flowchart is given in Fig. 2.

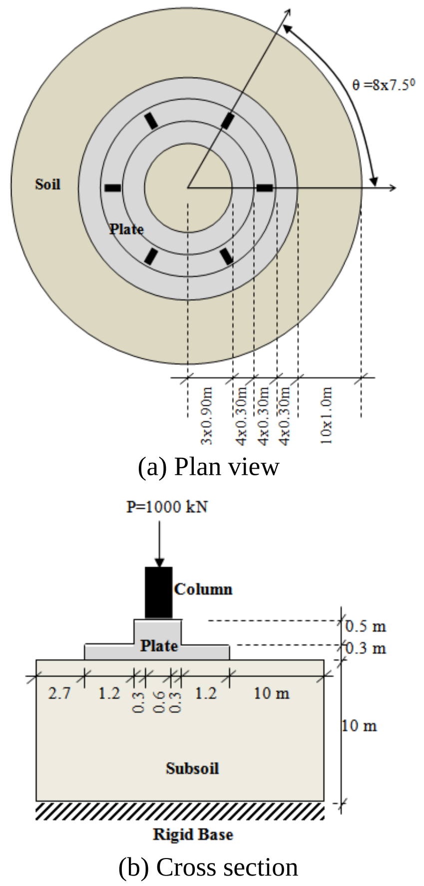

Fig. 3 A circular hollow plate on elastic foundation

4. Numerical verification

The three-parameter Vlasov model is verified by solving hollow circular plate example which is previously studied by Saygun and Çelik (2003) as shown in Fig. 3. They used full compatible ring sector finite element to generate the stiffness matrices of the plate and subsoil. Modulus of elasticity of the plate is 2.107 kN/m^2, Poisson's ratio of the plate is 0.16, modulus of elasticity of the subsoil is 80000 kN/m^2, Poisson's ratio of the subsoil is 0.25 and depth of the subsoil is 10 m. The analysis has been carried out with

Table 1 Soil parameters, central soil displacement and plate moments at θ=0°

	Saygun and Çelik (2003)	Present study
γ	1.323	1.313
k (kN/m^3)	10081.85	10068.92
$2t$ (kN/m)	86809.74	87057.94
w (mm)	2.40	2.42
M_r (kNm)	180	153
M_θ (kNm)	368	372

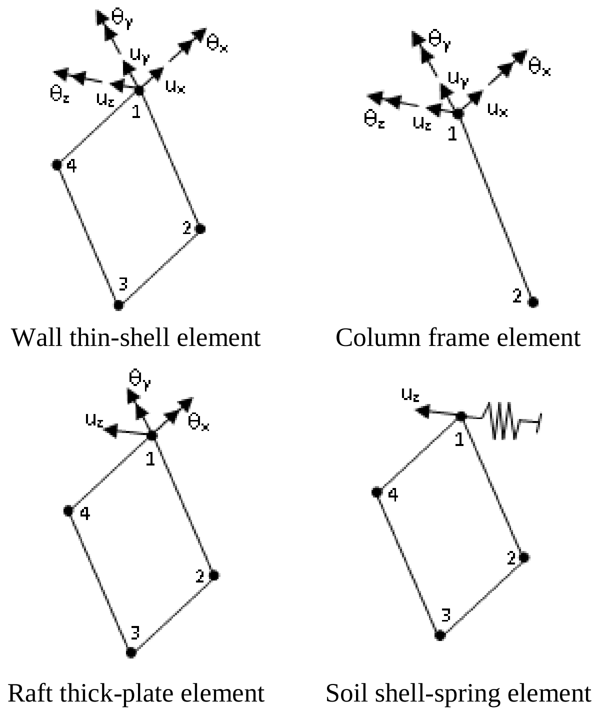

Fig. 4 Element types used for discretization of structural components

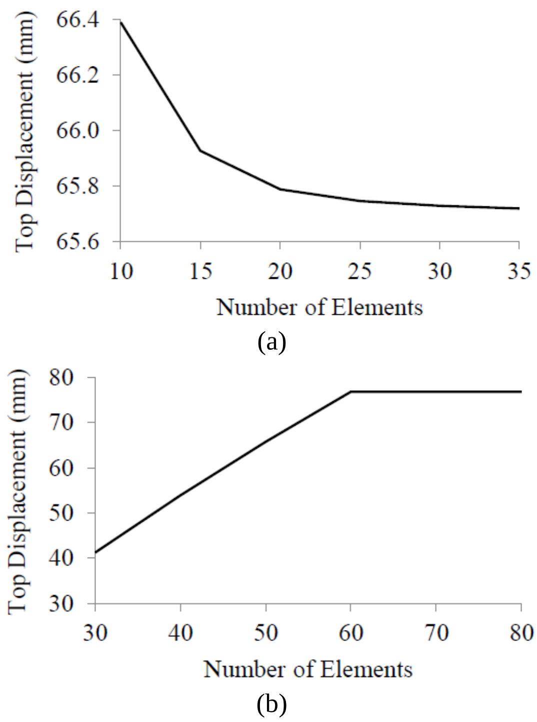

Fig. 5 Convergence studies for the number of (a) axial shell wall elements (b) radial soil shell elements

the same finite element mesh used by Saygun and Çelik (2003), and results are presented in Table 1.

Soil parameters, k, $2t$ and γ, vertical displacement of soil at the center of the plate and maximum bending moments of the plate are very close to each other as seen in Table 1. So, it can be stated that the approach presented in this study is reliable and the model can be effectively used for soil-structure interaction problems.

5. Finite element model

A hyperbolic cooling tower example with supporting columns and annular raft foundation studied previously (Viladkar *et al*. 2006) is investigated for the soil-structure interaction under earthquake loading. The tower wall is modelled using four-node thin-shell elements with six degrees of freedoms (dofs) at each node as shown in Fig. 4. Each shell element may have variable thickness through the meridian in accordance with thicknesses given in Fig. 6. Two-node frame elements and four-node thick-plate elements are used for supporting column and annular raft foundation discretization, respectively. The frame element activates all six dofs at joint connecting shell wall and columns while it activates two rotations and one displacement dofs at joint connecting raft foundation and columns. Soil foundation is modeled using shell-spring elements as shown in Fig. 4. This shell element which provides the shear interaction between springs has only vertical dof at each node and can be deformed only by transverse shearing. The values of soil parameters k and $2t$ calculated as explained in Three-parameter foundation model section are used as spring stiffness and shear modulus in the soil element formulation, respectively.

Prior to structural analyses various convergence studies are conducted to decide the sufficient number of elements to be used in the finite element model. For instance, the top radial displacement of the cooling tower is plotted in Fig. 5 for different number of elements in axial and radial directions for tower wall and soil foundation, respectively. In the convergence and for the following studies C40 class of concrete is used for all cooling tower structural components with modulus of elasticity E=35000 MPa, Poisson's ratio ν=0.2 and unit weight of 25 kN/m^3. Also, soil parameter γ is assumed to be 1 for the convergence studies.

As far as convergence studies are considered, the tower wall is discretized into 88 and 35 thin shell elements in circumferential and meridional directions, respectively. The raft foundation is modeled by using 88 elements in circumferential and 4 thick plate elements in radial directions. The diameter of surrounding soil is taken as the three times larger than that of raft foundation. And the soil foundation is discretized into 88 elements in circumferential and 60 elements in radial directions. The following sections

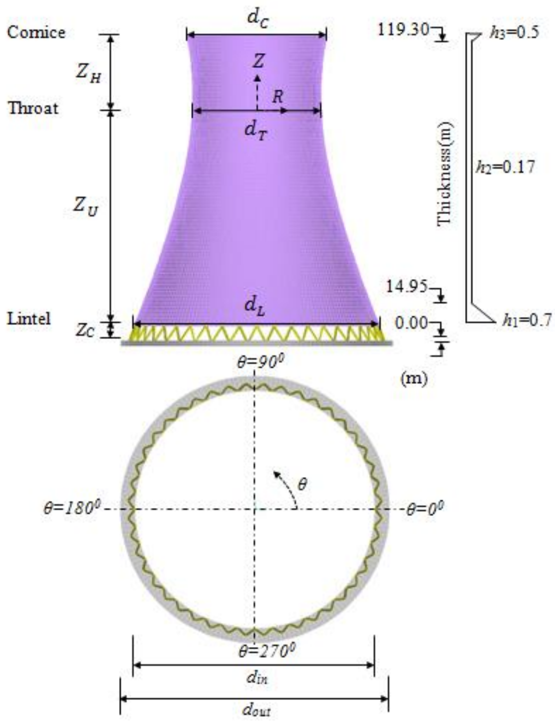

Fig. 6 The geometry of the hyperbolic cooling tower

describe the geometry of the cooling tower, earthquake loading, and soil properties to be considered in three-parameter Vlasov foundation model.

5.1 Cooling tower geometry

A hyperbolic equation as given in Eq. (6) describes the geometry of cooling tower wall. In this equation, axial Z coordinate is measured from the throat level of the cooling tower as shown in Fig. 6. And radial R coordinate is specified on the middle surface of the tower wall.

$$4R^2/d_T^2 - Z^2/b^2 = 1 \tag{6}$$

where b is a characteristic dimension of the wall that is evaluated for upper curve by

$$b = d_T Z_H / \sqrt{(d_H^2 - d_T^2)} \tag{7}$$

and for the lower curve by

$$b = d_T Z_U / \sqrt{(d_U^2 - d_T^2)} \tag{8}$$

The geometrical details of the hyperbolic cooling tower are presented in Table 2 and the shape of the tower is depicted in Fig. 6.

The shell wall is supported by 44 pairs of equally spaced V-type columns having circular cross sections. And, the adjacent top and bottom of the columns are connected. The wall has variable thickness and the transition is assumed to be linear as shown in Fig.6.

5.2 Seismic loading

The earthquake load effects on the behavior of the hyperbolic cooling tower considering soil-structure interaction are investigated using linear response spectrum method. The design response spectrum functions for horizontal and vertical directions are obtained in accordance with Eurocode 8 (2004) with the seismic parameters as given in Table 3.

Fig. 7 shows the design response spectrums for horizontal and vertical directions. The response spectrum analysis is conducted with a modal analysis producing 300 mode shapes and frequencies of the cooling tower. A constant damping value of 5% is considered for all modes. Also, the complete quadratic combination (CQC) and square root of the sum of the squares (SRSS) methods are used in response spectrum analysis for modal and directional combinations, respectively.

Table 2 Geometric details of hyperbolic cooling tower

Description	Symbol	Value (m)
Height above throat level	Z_H	24.090
Height below throat level	Z_U	91.260
Top diameter	d_H	55.070
Throat diameter	d_T	50.608
Shell base diameter	d_U	96.582
Column diameter	-	0.7
Number of column pairs	-	44
Column height	H	6.95
Inner diameter of raft	d_{in}	96.216
Outer diameter of raft	d_{out}	107.616
Depth of ring raft	-	2

Table 3 Seismic parameters for horizontal and vertical design response spectrums

Seismic parameters	Direction	
	Horizontal	Vertical
PGA (g)	0.4	0.4
Importance factor, I	1.5	1.5
Spectrum type	Type 1	Type 1
Ground type	C	-
Soil factor, S	1.15	-
Spectrum period (s), T_b	0.2	0.05
Spectrum period (s), T_c	0.6	0.15
Spectrum period (s), T_d	2.0	1.0
Lower bound factor, β	0.2	0.2
Behavior factor, q	3	3

5.3 Soil properties

The cooling tower-raft foundation system is assumed to be resting on a soil stratum having variable modulus of elasticity with depth as shown in Fig. 8. The soil data is obtained from the literature (Hammam and Eliwa 2013). A total of three boreholes (BH) at different locations of the soil are prepared to measure modulus of elasticity E_s via pressure-meter test for every 5.0 m from the ground surface down to 60.0 m. It can be realized from Fig. 8 that the results of E_s are scattered and there is no clear trend. Therefore, a constant and linear variation functions are

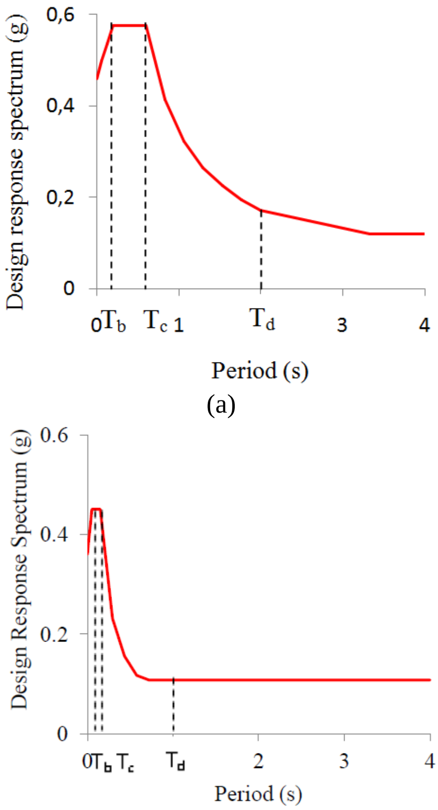

Fig. 7 Design response spectrums for (a) horizontal (b) vertical directions

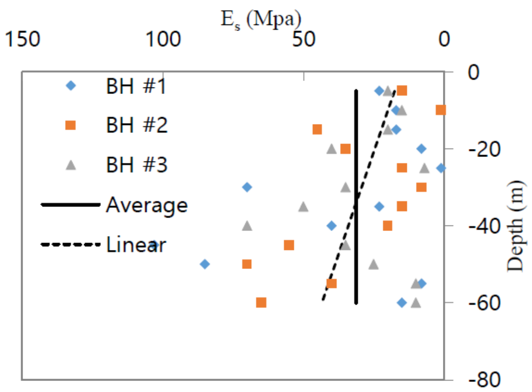

Fig. 8 Variation of E_s through soil depth

assumed to be used in the three-parameter Vlasov foundation model. The constant function is obtained by taking the average of all E_s values. And, the linear approximation function of E_s (MPa)=15.3+0.47*depth is obtained as a best-fit linear trend function. As a result, two soil models can be used for the following analyses with different E_s variations. One of them has a constant variation with the value of E_{avg}=31477 kPa and the other one has a linear variation with the values of E_1=15300 kPa at the top and E_2=43500 kPa at the bottom of the soil layer as shown in Fig. 1.

5.3.1 Soil-structure interaction

In this section, the seismic responses of the cooling tower-column-raft system having fixed raft base instead of soil foundation are compared with the responses obtained using three-parameter Vlasov models with constant and linear modulus of elasticity variations through soil depth to investigate soil-structure interaction. The soil models with *constant* and *linearly* varying modulus of elasticity are called as Constant and Linear, respectively. Also, the cooling tower with fixed raft at the base is called as Fixed throughout the text.

Table 4 Periods of effective modes and modal participating mass ratios

Soil condition	Mode shape periods (s)			
	1st Bending	2nd Bending	3rd Bending	Axial
Constant	0.649 (13,14)	0.173 (153,154)	0.145 (193,194)	0.421 (33)
Linear	0.757 (11,12)	0.173 (153,154)	0.148 (191,192)	0.498 (23)
Fixed	0.303 (59,60)	0.173 (151,152)	0.111 (295,296)	0.129 (230)
Mode number	Modal participating mass ratios for constant soil condition (%)			
	X-direction	Y-direction	Z-direction	
13	25.08	24.08	0	
14	24.08	25.08	0	
153	23.43	9.37	0	
154	9.37	23.43	0	
193	6.97	6.73	0	
194	6.73	6.97	0	
33	0	0	99.73	
Total	95.66	95.66	99.73	

Numbers in parenthesis indicate the mode numbers

The periods and modal participating mass ratios of critical modes in determining the total maximum seismic response of the cooling tower are presented in Table 4. It can be seen that the sum of modal participating mass ratios is over 90% in each direction. Therefore, the required number of modes to be considered in the response spectrum analysis is fulfilled. As far as modal periods are considered, it can be stated that the first bending and axial mode periods of fixed based cooling tower lie within the critical range of seismic periods (T_b, T_c) for this particular soil. Thus, it may result in resonance with one of the seismic periods. Also, the critical bending modes of fixed based cooling tower occur much later compared to those of cooling tower resting on soil foundation. In other words, the soil foundation reduces the overall stiffness of the structural system and the critical modes appear earlier with larger periods as compared to fixed case.

Fig. 9 depicts the shapes of the first eight modes, the critical bending and axial modes for fixed base condition. The subsequent mode numbers indicate that the mode shape appears with the same shape and period in perpendicular directions. Also, it can be seen that the early modes are circumferential which do not produce net translational displacement. Therefore, such fluctuating circumferential modes do not influence the seismic response of the cooling tower. However, the beam-like behaviors of bending modes are effective for horizontal response and the axial mode is

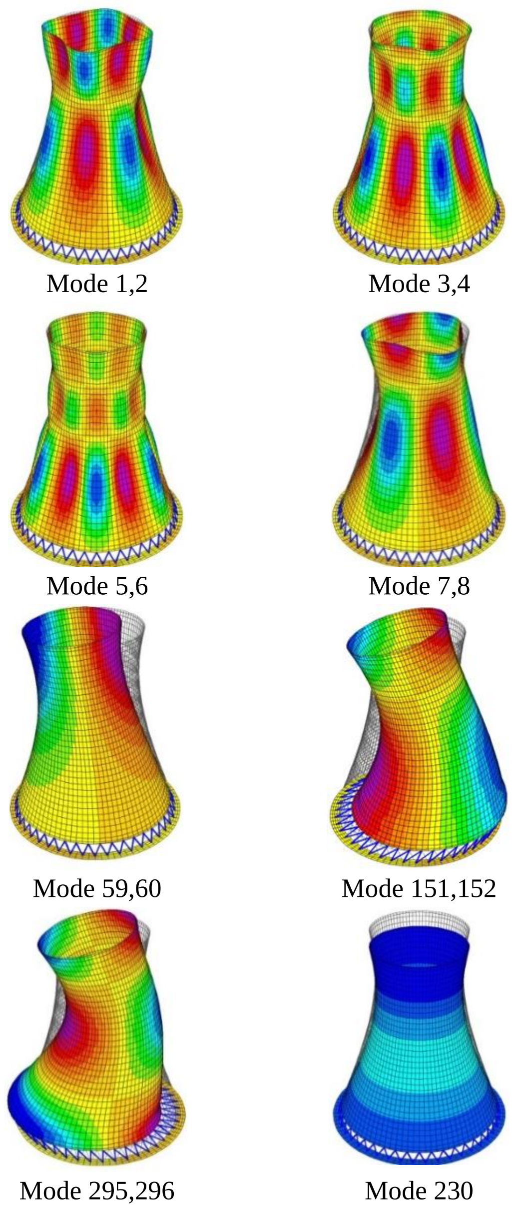

Fig. 9 Particular mode shapes of the cooling tower with fixed raft base

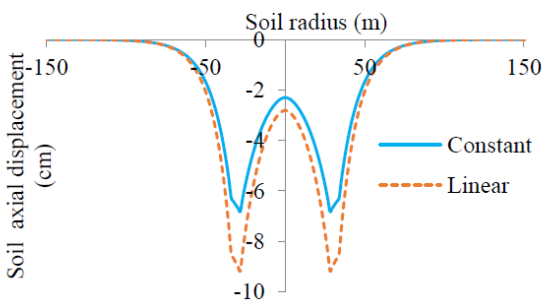

Fig. 10 Soil surface vertical displacement profiles

critical for vertical response of the cooling tower. The importance of the mode shapes can also be understood by exploring the modal participating mass ratios in Table 4.

The vertical soil displacements for constant and linear variation of elasticity modulus through the depth under both

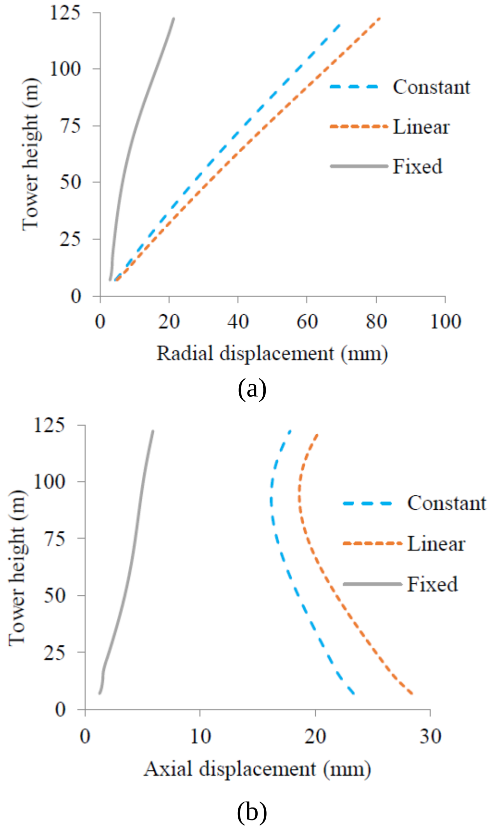

Fig. 11 (a) Radial and (b) axial displacements along the height of the cooling tower at θ=0

self-weight and seismic loading are shown in Fig. 10. It can be seen that soil diameter considered is sufficient since vertical displacements become zero at the outer region of the soil. Constant variation of E_s produces smaller vertical soil displacement than linear variation of E_s. It can be stated that the constant variation generates stiffer foundation.

Fig. 11 displays the responses in terms of radial and axial displacements along the height of the cooling tower at the meridional line at $\theta=0^{\circ}$ for elastic soil foundations and fixed base condition. Maximum radial displacement of 81 mm occurs at the top of the cooling tower having soil foundation with linear variation of E_s. As the soil becomes stiffer the radial displacement decreases and it takes a minimum value of 21 mm for the fixed base condition which is four times smaller than the value obtained considering soil-structure interaction.

As far as axial displacement is considered it can be seen that the location of the maximum displacement is lintel level when the soil-structure effect is considered. However, the maximum axial displacement occurs at the cornice or top level of the cooling tower for the fixed base condition. Similar to the radial displacement, the maximum axial displacement of the fixed case is smaller. So, it can be resulted that the shell displacements increase remarkably when the soil-structure interaction is considered in the analysis.

The longitudinal distributions of the circumferential and meridional forces and moments at $\theta=0^{\circ}$ meridian are depicted in Fig. 12 for different base conditions. It can be

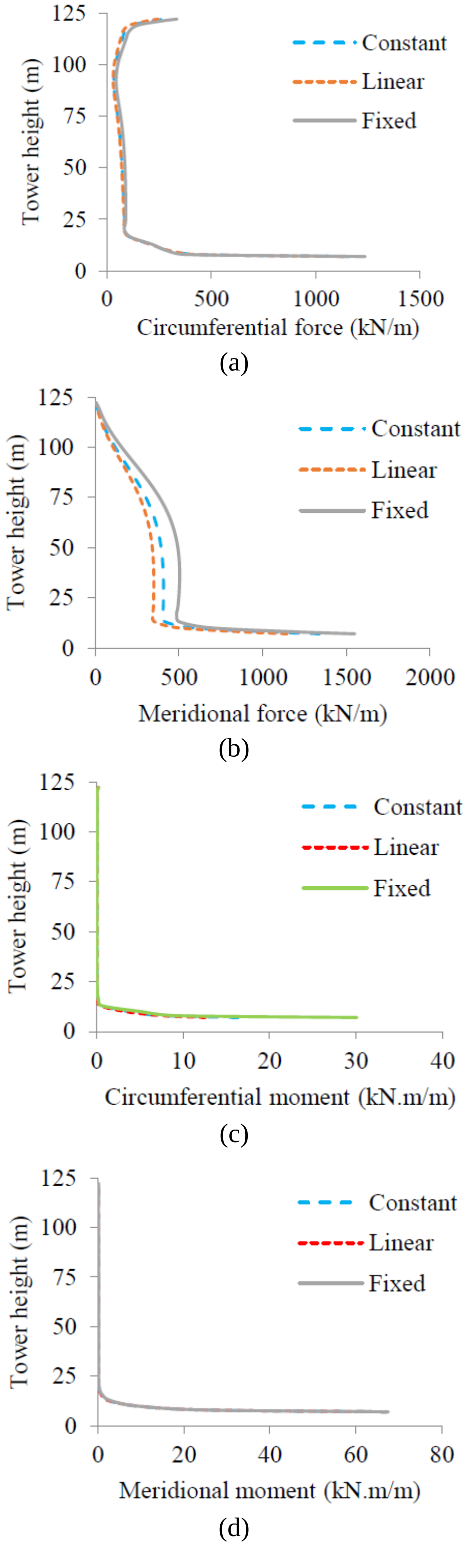

Fig. 12 Forces and moments along the height of the cooling tower at θ=0

seen form Fig. 12(a) that the tensile circumferential force is affected at the lintel and cornice levels of the cooling tower due to the soil-structure interaction. The meridional force along the height of the tower becomes smaller as the soil foundation gets looser. In other words, the fixed base condition produces the largest circumferential and meridional forces. As far as circumferential and meridional moments are concerned, it can be seen that the bending effects are restricted to a region at the shell base with less than 10% of the shell wall height. Therefore, it can be stated that the shell wall response is characterized by membrane behavior.

In order to investigate the soil-structure interaction effects numerically Table 5 presents the maximum circumferential and meridional forces and moments at the shell-column junction of the cooling tower at θ=0°. Significant reductions are observed in the related forces and moments when the three-parameter Vlasov elastic soil foundation is considered. For example, the meridional forces in constant and linear cases are appeared to be smaller by a percent of 13.4% and 26% when compared to fixed based condition, respectively. Similarly, constant and linear elastic cases produce nearly half of the circumferential moment of the fixed base condition. On the other hand, the change in meridional moment can be ignored since the difference is too small. As a result, it can be concluded that the soil-structure interaction reduces crucial membrane tensile forces significantly as well as circumferential bending moment at the lintel level of the cooling tower.

Finally, the column forces are presented in Table 6 for different tower base conditions. Column axial forces in particular appear to be most critical. There is at least 11.9% decrease in tensile axial force when the soil-structure interaction is considered. On the contrary, there is at least 20.4% increase in shear force. And, the differences in moment are small enough to be ignored. As a result, it can be concluded that the soil-structure interaction may influence the column design fairly due to considerable reduction in tensile axial force.

Table 5 Forces and moments at lintel level of the cooling tower at θ=0

Forces (kN/m) and moments (kN.m/m) at lintel	*Constant*[1]	*Linear*[2]	*Fixed*[3]	Difference (%)	
				1-3	2-3
Circumferential force	1161	1132	1237	6.1	8.5
Meridional force	1342	1147	1550	13.4	26.0
Circumferential moment	16.37	12.55	30.08	45.6	58.3
Meridional moment	67.07	67.16	67.52	0.7	0.5

Table 6 Maximum column forces for different boundary conditions

Column forces	*Constant*[1]	*Linear*[2]	*Fixed*[3]	Difference (%)	
				1-3	2-3
Axial (kN)	2176	1986	2470	11.9	19.6
Shear (kN)	25.10	25.64	20.85	-20.4	-23.0
Moment(kNm)	74.43	74.06	73.90	-0.7	-0.2

6. Conclusions

The seismic responses of a hyperbolic cooling tower resting on elastic soil foundation are studied in the present work. The three-parameter Vlasov foundation model is used to represent the elastic soil below the raft foundation. This model applies an iterative method to determine the soil elastic parameters such as reaction modulus and shear parameter without requiring field tests. The soil model and the geometry of the cooling tower with all structural components such as supporting columns and raft foundation are implemented into the structural analysis program SAP2000 using a computer program coded in MATLAB. The program enables two-way data flow between MATLAB and SAP2000 via open application programming interface (OAPI) functions of SAP2000. The coded program is verified for the three-parameter Vlasov model by solving the previously studied circular hollow plate example in the literature. After the verification, the tower system is analyzed using response spectrum method considering constant and linear variations of modulus of elasticity through the depth of soil as well as fixed raft base condition. The following conclusions can be drawn from the study:

- The three-parameter Vlasov foundation model can be implemented into SAP2000 using OAPI feature of SAP2000 with the help of MATLAB.
- The complex geometry of a cooling tower can be defined using OAPI feature of SAP2000.
- Linear variation of modulus of elasticity through the depth of soil generates softer soil condition as compared to constant variation in the three-parameter Vlasov model.
- The number of modes to be considered in seismic response analysis is smaller when the soil-structure interaction is considered since the effective bending modes appear earlier due to the flexibility of soil.
- The circumferential modes with undulating shell behavior do not influence the seismic behavior of the tower because modal participating mass ratios of these modes are too small.
- The shell axial and radial displacements increase remarkably when the soil-structure interaction is considered.
- The maximum tensile circumferential and meridional shell forces decreases as the soil foundation gets looser. In other words, the fixed raft base condition produces the largest membrane forces.
- The bending moments over the shell wall are restricted to a region at the shell base with less than 10% of the wall height.
- The maximum tensile axial column force decreases while shear force increases when the soil effects are included in the analysis.

Acknowledgments

The first author has been supported by TUBITAK (Turkish Scientific and Technological Research Council) with a scholarship which is gratefully acknowledged.

References

Aksu, T. (1996), "A finite element formulation for column-supported hyperboloid cooling towers", *Comput. Struct.*, **59**(5), 965-974.

Christian, L. (2011a), "Earthquake behavior of natural draft cooling towers-Determination of behavior factors with special regard to different types of supporting column systems", *Proceedings of the Proceedings of the 8th International Conference on Structural Dynamics*, Leuven, Belgium.

Christian, L. (2011b), "Free vibration and earthquake behavior of solar power plant chimneys", *Proceedings of the III ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Corfu, Greece.

Esmaeil, A., Rajan, A., Mrudula, S.K. and Sahebali, A. (2012), "Finite element analysis for structural response of rcc cooling tower shell considering alternative supporting systems", *Int. J. Civil Eng. Technol.*, **3**, 82-98.

Eurocode 8 (2004), Design of Structures for Earthquake Resistance.

Gould, P.L. and Kràtzig, W.B. (2005), *Handbook of Structural Engineering*, CRC Press, Germany.

Hammam, A.H. and Eliwa, M. (2013), "Comparison between results of dynamic & static moduli of soil determined by different methods", *HBRC J.*, **9**, 144-149.

Jia, X. (2013), "Revisiting the failure mode of a RC hyperbolic cooling tower, considering changes of material and geometric properties", *Eng. Struct.*, **47**, 148-154.

Karisiddappa, Viladkar, M.N., Godbole, P.N. and Krishna, P. (1998), "Finite element analysis of column supported hyperbolic cooling towers using semi-loof shell and beam elements", *Eng. Struct.*, **20**(1-2), 75-85.

Krivoshapko, S.N. (2002), "Static, vibration, and buckling analyses and applications to one-sheet hyperboloidal shells of revolution", *Appl. Mech. Rev.*, **55**(3), 241-270.

Kulkarni, S. and Kulkarni, A.V. (2014), "Case study of seismic effect on hyperbolic cooling towers", *Civil Environ. Res.*, **6**(11), 85-94.

Kulkarni, S. and Kulkarni, A.V. (2014), "Static and dynamic analysis of hyperbolic cooling tower", *J. Civil Eng. Technol. Res.*, **2**, 39-61.

Lang, C., Meiswinkel, R. and Filippou, F.C. (2002), "Non-linear analysis of shells of revolution with ring elements", *Eng. Struct.*, **24**(2), 163-177.

Murali, G., Vivek Vardhan, C.M. and PKRB, V. (2012), "Response of cooling towers to wind loads", *ARPN J. Eng. Appl. Sci.*, **7**(1), 114-120.

Nasir, A.M., Thambiratnam, D.P., Butler, D. and Austin, P. (2002), "Dynamics of axisymmetric hyperbolic shell structures", *Thin Wall. Struct*., **40**(7-8), 665-690.

Noorzaei, J., Naghshineh, A., Kadir, M.R.A., Thanoon, W.A. and Jaafar, M.S. (2006), "Nonlinear interactive analysis of cooling tower-foundation-soil interaction under unsymmetrical wind load", *Thin Wall. Struct.*, **44**(9), 997-1005.

Prashanth, N. and Sayeed, S. (2013), "To study the effect of seismic loads and wind load on hyperbolic cooling tower of varying dimensions and RCC shell thickness", *Int. J. Emerg. Trend. Eng. Develop.*, **4**, 260-269.

Sabouri-Ghomi, S., Nik, F.A., Roufegarinejad, A. and Bradford, M.A. (2006), "Numerical study of the nonlinear dynamic behaviour of reinforced concrete cooling towers under earthquake excitation", *Adv. Struct. Eng.*, **9**(3), 433-442.

SAP2000 (2011), Analyses Reference Manual.

Saygun, A. and Celik, M. (2003), "Analysis of circular plates on two-parameter elastic foundation", *Struct. Eng. Mech.*, **15**(2), 249-267.

Tande, S.N. and Snehal, S.C. (2013), "Linear and nonlinear behavior of rc cooling tower under earthquake loading", *Int. J. Lat. Trend. Eng. Technol.*, **2**, 370-379.

Vallabhan, C.V.G., Straughan, W.T. and Das, Y.C. (1991), "Refined model for analysis of plates on elastic foundations", *J. Eng. Mech.*, ASCE, **117**(12), 2830-2844.

Viladkar, M.N., Bhargava, P. and Godbole, P.N. (2006), "Static soil-structure interaction response of hyperbolic cooling towers to symmetrical wind loads", *Eng. Struct.*, **28**(9), 1236-1251.

Weng, X.R., Dai, J.W. and Wu, J.X. (2013), "Nonlinear seismic responses analysis for a super cooling tower", *Int. Effort. Lifeline Earthq. Eng.*, 105-112.

Wolf, J.P. (1986), "Seismic analysis of cooling towers", *Eng. Struct.*, **8**(3), 191-198.

Yang, Z.W. and Lu, W.D. (1992), "Static soil-structure interaction analysis by Fe-Be coupling method", *Appl. Math. Model.*, **16**(7), 384-389.

Yang, Z.W. and Lu, W.D. (1994), "Dynamic soil-structure interaction analysis by a hybrid method", *Mech. Struct. Mach.*, **22**(1), 21-36.

CC