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The use of TS498 and TS-EN-1991-1-4 in the Wind Load Calculation of Reinforced Concrete Minarets Considering Soil-Structure Interaction

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Abstract: The minarets are among the most beautiful, meaningful and delicate works of Islamic architecture. At early times, although these slender structures were built short and with masonry stone, as time progressed, the construction of minarets with reinforced concrete and that are thin-walled and long were preferred. This has caused many reinforced concrete minarets to be damaged or destroyed under wind and earthquake forces. With regard to this issue, because of the severe winds, many minaret collapse incident took place in Turkey. Due to this reason, in this study, the wind loads acting on a selected reinforced concrete minaret have been calculated in details according to TS498 and TS-EN-1991-1-4 standards. In the calculations made, the effects of soil structure interaction on the calculated wind loads were also examined. At the end of the study, the wind loads obtained in the calculations were compared. The obtained results show that soil structure interaction is a negative effect on wind loads, this interaction increases them and that the soil structure interaction should be included in wind load calculations.

Betonarme Minarelerin Zemin-Yapı Etkileşimiyle Rüzgâr Yükü Hesaplamasında TS498 ve TS-EN-1991-1-4'ün Kullanılması

Anahtar Kelimeler
Minare,
Rüzgâr yükü,
Zemin-yapı etkileşimi,
Viskoz sınırlar

Özet: Minareler, İslami mimarinin en güzel, anlamlı ve bir o kadar da narin eserleri arasında bulunmaktadır. Bu narin yapılar, ilk zamanlarda, yığma ve kısa bir şekilde yapılmış olmalarına rağmen, zaman ilerledikçe, betonarme, ince cidarlı ve uzun minarelerin yapımı tercih edilmiştir. Bu durum ise birçok betonarme minarenin rüzgâr ve deprem kuvvetleri altında hasar görmesine veya yıkılmasına sebep olmuştur. Bu konu ile ilgili olarak, şiddetli rüzgârlardan dolayı, Türkiye'de de birçok minare yıkılması olayı gerçekleşmiştir. Bu sebepten dolayı, bu çalışmada, TS498 ve TS-EN-1991-1-4 standartlarına göre, seçilen bir betonarme minareye etkiyen rüzgâr yükleri ayrıntılı bir şekilde hesaplanmıştır. Yapılan hesaplamalarda ayrıca, zemin yapı etkileşiminin, hesaplanan rüzgâr yüklerine etkileri de incelenmiştir. Çalışmanın sonunda, yapılan hesaplamalar sonucunda elde edilen rüzgâr yüklerinin karşılaştırılması yapılmıştır. Elde edilen veriler, zemin yapı etkileşiminin rüzgâr yükleri üzerinde olumsuz bir etkisi olduğunu, bunları arttırdığını ve rüzgar yükü hesaplamalarında zemin yapı etkileşiminin de dahil edilmesi gerektiğini göstermektedir.

1. Introduction

The minarets used since ancient times are one of the indispensable structures of Islamic architecture. In the early days, they were used to announce the arrival of prayer times to people that are far from the mosques (*Hodja's reading the azan from the minaret*). With the developed technology, by constructing tall and slender minarets, they were also used for completing the magnificence and impressiveness of the mosques in terms of visuality. For this reason, designers prefer to construct taller and slender minarets. This makes the minarets more vulnerable to earthquake and wind forces.

As in all structures, various types of loads are acting on minarets. Among these, earthquakes and wind loads can be shown as the most important ones.

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Recently, so many minarets have been reported to be severely damaged or destroyed due to wind loads [1, 2, 3, 4]. Researches [5] show that many minarets in Turkey were built without any engineering service, only with the experience of craftsmen and contractors and without considering ground conditions and seismicity. For this reason, it is necessary to examine the minarets in details considering the soil-structure interaction (SSI).

Regarding the structural behavior and SSI of minarets, there are so many studies in the technical literature. Doğangün investigated many buildings that were damaged during the Bingöl Earthquake. Among these structures, the structural damages of minarets were also presented [6]. Temüz investigated the calculations of wind loads of minarets according ACI-307 and TS-498 and performed the structural design of these structures according to results obtained from the cited standards [2]. Sezen *et* al. examined the dynamic behavior of minarets, taking into consideration the structural elements such as balconies, doorways and ladders [5]. Pena *et* al. investigated the seismic behavior of the old masonry tower named as Qutb Minar in India [7]. Livaoğlu examined the dynamic behavior of a steel chimney taking into account SSI and high-temperature effects [8]. Cordero and Fernandez continued the measurement work initiated for the Andalusian minarets by Félix Hernández and Basilio Pavón [9].

In view of the search of the technical literature, although in many studies, the structural behavioral studies of minarets under wind and earthquake loads have been investigated, a few of them dealt with the SSI effect of these stuctures. Because of this reason, this study may be helpful to complete the abscence of the subject in the literature.

In this study, wind loading of reinforced concrete (RC) minarets considering SSI effects was investigated. For this purpose, finite element model of a selected minaret superstructure is constructed and wind loads are calculated for the selected model with and without SSI. Wind load calculations were made according to TS498 and TS-EN-1991-1-4 standards that were adopted in 1997 and 2007, respectively. Also, the obtained results were compared with each other.

2. Research Significance

There are so many constructed RC minarets in Turkey and the construction of many of them are in progress. In their service lives, these tall and slender structures are prone to strong wind and severe ground motions. After these miserable events, many of RC minarets are collapsed or heavily damaged. Therefore, the exact behavior of these slender structures should be determined to prevent the lose of lives and economy. From literature survey, it is apparent that there are a few studies dealing with the wind response of RC minarets that is considering the effect underlying soil. Therefore, it is inevitable to make such a research study about the effect of SSI on wind loading of RC minarets. It is believed by the author that this study will enlighten the ways of designers and theoretician that are studying about the wind responses of RC minarets.

3. Material and Method

In this study, TS-498 [10] and TS-EN-1991-1-4 [11] standards that adopted in 1997 and 2007 were used for the determination of wind forces acting on minarets, respectively. The procedures for these standards are briefly described below.

3.1. TS-498 wind load procedure

Wind load according to TS-498 [10],

$$W = C_f \cdot q \cdot A \tag{1}$$

is calculated with Eq.1. In Eq.1, C_f, q and A is denoting the aerodynamic load factor, suction pressure (kN/m^2) and affected area (m^2), respectively. In TS498, a table is presented to determine the C_f coefficient. In this table, the C_f coefficient for the minaret superstructure used in the study is 1.60. Furthermore, for q (*suction pressure*), the suction pressures specified in TS-498 are shown in Table 1 depending on the height from the ground.

Table 1. Wind speed and suction depending on height [10]

Height from ground (m)	Wind Speed (v) (m/s)	Suction (q) (kN/m^2)
0-8	28	0.5
9-20	36	0.8
21-100	42	1.1
>100	46	1.3

3.2. TS-EN-1991-1-4 wind load procedure

Wind load according to TS-EN-1991-1-4 [11],

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref} \tag{2}$$

is calculated with Eq.2. In Eq.2, $c_s c_d$, c_f, $q_p(z_e)$ and A_{ref} is denoting structural factor, force parameter for structure, peak velocity pressure at reference height z_e and reference area for structure, respectively. In this study, z_e reference height, as already mentioned, is included in the calculations equal to the height of the corresponding minaret superstructure. The structural factor given in Eq.2 can be calculated by using Eq.3 [11].

$$c_s c_d = \frac{1+2\cdot k_p \cdot I_v(z_e)\cdot\sqrt{B^2+R^2}}{1+7\cdot I_v(z_e)} \tag{3}$$

In Eq.(3), k_p is denoting peak factor, B^2 is denoting the background factor (*recommended value of the background factor is 1.0*), R^2 is denoting resonance response factor and $I_v(z_e)$ is denoting the turbulence intensity at reference height z_e. Turbulence intensity $I_v(z)$ can be calculated from Eq.(4) or Eq.(5) which one is suitable for the given condition [11].

$$I_v(z) = \frac{k_I}{c_0(z)\cdot \ln(\frac{z}{z_0})} \quad z_{min} \le z \le z_{max} \tag{4}$$

$$I_v(z) = I_v(z_{min}) \qquad z \le z_{min} \tag{5}$$

Furthermore, the recommended value for the turbulence coefficient, k_I is 1.0. Also, for the orography coefficient $c_0(z)$, it is recommended that 1.0 value be used if there is no turbulence-induced velocity increase on the terrain. In this study, it was assumed that the modeled minaret was located in the sea or coastal area exposed to open sea effect. Because of this reason, in the standard, it is presented that the smallest z value in Eq.4 and 5 is 1.0 m. and the value of z_0 is 0.003 m., respectively. It has been noted that although the various correlations are presented for calculating the background coefficient (B^2), the use of the value 1.0 will be on the more secure side. For this reason, the value of 1.0 is used as the background coefficient in this study. In the calculation of the resonance response coefficient, Eq.6 given in the technical literature has been taken into consideration [12].

$$R^2 = \frac{2\cdot\pi\cdot F\cdot \emptyset_b\cdot \emptyset_h}{\delta_s+\delta_a} \tag{6}$$

In Eq.(5), F is denoting wind energy spectrum, $ø_b$ is denoting size effect (*breadth of the structure*), $ø_h$ is denoting size effect (*height of the structure*), δ_s is denoting structural damping expressed by the logarithmic decrement and δ_a is denoting aerodynamic damping. The parameters forming the Eq.6 are given in Eq.7, Eq.8, Eq.9 and Eq.10 [11].

$$F = \frac{4C}{[1+70.8(C^2)]^{\frac{5}{6}}} \tag{7}$$

$$\emptyset_b = \frac{1}{1+\left[\frac{3.2\cdot n_{1,x}\cdot b}{V_m(z_e)}\right]} \tag{8}$$

$$\emptyset_h = \frac{1}{1+\left[\frac{2\cdot n_{1,x}\cdot h}{V_m(z_e)}\right]} \tag{9}$$

$$\delta_a = \frac{\rho\cdot C_f\cdot b\cdot V_m(z_e)}{n_{1,x}\cdot m_e} \tag{10}$$

In Eq.(7), Eq.(8), Eq. (9) and Eq.(10), C, $n_{1,x}$, h, b, $V_m(z_e)$, ρ, c_f and m_e are denoting the non-dimensional frequency, the vibration frequency of minaret at 1st mod(Hz), total height of the minaret, the outer diameter of the section considered, the mean wind velocity at the top of the minaret, density of air (taken as 1,25 kg/m^3) [11], force coefficient and equivalent mass per unit length, respectively. Further, approximate values of the logarithmic decrement of structural damping, δ_s, are presented in Table 2.

Table 2. Approximate values of logarithmic decrement of structural damping [11]

Structural Type	Structural Damping, δs
Reinforced Concrete	0.1
Steel Structures	0.05
Composite Structures (Reinforced Concrete+Steel)	0.08
Reinforced Concrete Towers and Chimneys	0.03

The non-dimensional frequency given in Eq.(7) can be calculated by using Eq.(11) [11].

$$C = \frac{L_c\cdot n_{1,x}}{V_m(z)} \tag{11}$$

In Eq.(11), L_c denotes the turbulence length scale that is recommended as 150 m [12]. The mean wind velocity $V_m(z)$ at a height z above the terrain can be determined using Eq.(12) [11].

$$V_m(z) = c_r(z)\cdot c_0(z)\cdot V_b \tag{12}$$

In Eq.(12), V_b is denoting basic wind velocity given in Eq.(13), $c_r(z)$ is denoting the roughness factor and $c_o(z)$ is denoting the orography factor. The calculation procedure for the basic wind velocity V_b is shown in Eq.(13) [11].

$$V_b = c_{dir}\cdot c_{season}\cdot V_{b,0} \tag{13}$$

In Eq.(13), c_{dir} is denoting the directional factor, $V_{b,0}$ is denoting the fundamental value of the basic wind velocity and lastly c_{season} is denoting the season factor. It is stated in Eurocode 1 that the values of both the directional factor c_{dir} and the season factor c_{season} can be taken as 1.00. Therefore, in this study, the values of both the directional factor c_{dir} and the season factor c_{season} is taken as 1.00. Moreover, the fundamental value of the basic wind velocity $V_{b,0}$ is calculated based on logarithmic velocity profile described with Eq.(14) [13].

$$\frac{V}{V_0} = \frac{\mathrm{Ln}(H/z_0)}{\mathrm{Ln}(H_0/z_0)} \tag{14}$$

In Eq.(14), V is denoting the speed of wind at height H and V_0 is denoting the wind speed at height H_0 from the ground. H_0 is generally is taken as 10.00 meters. It is stated in Eurocode 1 that the value of the orography factor $c_o(z)$ that is given in Eq.(12) can be taken as 1.00 unless otherwise specified in different sources. Therefore, for this study the value of the orography factor is taken as 1.00. The recommended procedure for the determination of the roughness factor for Eq.(12) at height *z* is given by Eq.(15) and

Eq.(16) which one is suitable for the given condition [11].

$$c_r(z) = k_r \cdot ln\left(\frac{z}{z_0}\right) \quad z_{min} \le z \le z_{max} \tag{15}$$

$$c_r(z) = c_r(z_{min}) \qquad z \le z_{min} \tag{16}$$

In Eq.(15), k_r is denoting the terrain factor that can be determined by using Eq.(17) [11].

$$k_r = 0.19 \cdot \left(\frac{z_0}{z_{0,11}}\right)^{0.07} \tag{17}$$

In this study, it is assumed that the minaret is constructed to the sea or coastal area exposed to the open sea effect. Therefore, from a table provided in TS-EN-1991-1-4, the values of z_{min}, z_0 and z_{max} are selected as 1.00 m, 0.003 m and 200 m, respectively.

In order to calculate the aerodynamic damping, the second parameter is the force coefficient whose symbol is c_f. For a finite circular cylinder, the force coefficient can be calculated from Eq.(18) [11].

$$c_f = c_{f,0} \cdot \varphi_\gamma \tag{18}$$

In Eq.(18), $C_{f,0}$ is denoting the force coefficient of cylinders without free-end flow and ψ_λ is denoting end-effect factor. In order to calculate the force coefficient given by Eq.(18), the first parameter that should be determined is the force coefficient of cylinders without free-end flow whose symbol is $c_{f,0}$. The parameter $c_{f,0}$ can be found by using graph shown in Fig.1 [11].

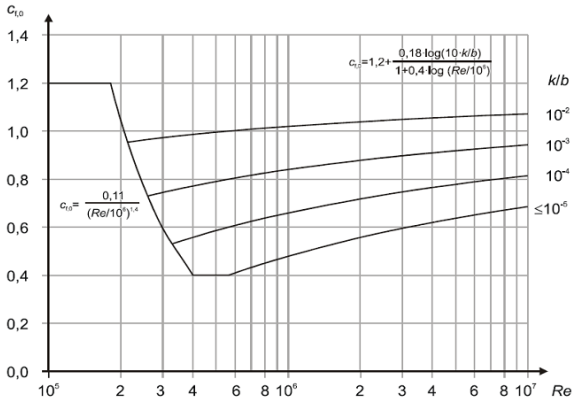


Figure 1. Different Values of Parameter $C_{f,0}$ For Different Values of *Reynolds Number* and *k/b* ratios [11]

The graph shown in Fig.1 is constructed by using Eq.(19) and Eq.(20) that belong to *Reynolds Number* and *k/b* ratios for the sections considered. The equations used in the construction of the graph shown in Fig.1 are as follows [11]:

$$c_{f,0} = \frac{0.11}{(Re/10^6)^{1.4}} \tag{19}$$

$$c_{f,0} = 1.2 + \frac{0.18 \cdot \log(10 \cdot k/b)}{1 + 0.4 \cdot \log(Re/10^6)} \tag{20}$$

In Eq.(19) and Eq.(20), *Re* is denoting Reynolds Number, k is denoting the equivalent surface roughness and b is denoting the diameter of the section considered. In this study, equivalent roughness for rough concrete is selected as 1.00 mm for the calculations.

End-effect factor ψ_λ can be determined from the graph shown in Fig.2 as a function of solidity ratio and slenderness [11].

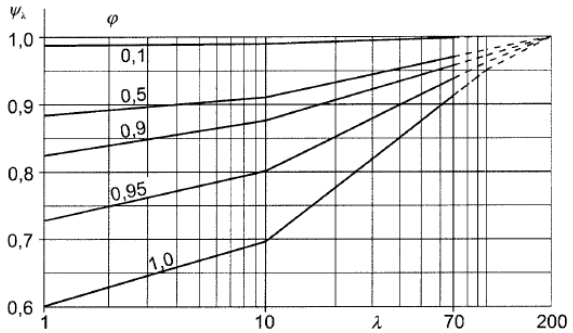


Figure 2. Values of End-Effect Factor ($\psi\lambda$) As a Function of Solidity Ratio (φ) Versus Effective Slenderness (λ) [11]

The solidity ratio can be calculated from Eq.(21) [11].

$$\varphi = \frac{A}{A_c} \tag{21}$$

A rectangular structural element is shown in Fig.3 that is used for showing these two types of areas.

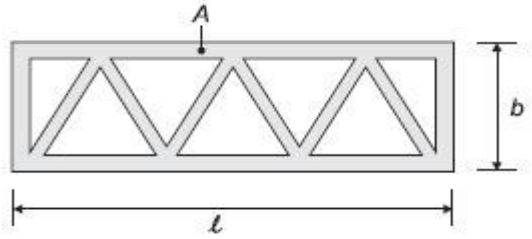


Figure 3. The Graphical Representation of Solidity Ratio (φ) [11]

In Fig.3, A is denoting the projection areas of the structural elements and A_c is denoting the total area.

Effective slenderness λ can be found from the table provided in the standard showing the recommended values of effective slenderness. According to the table given in TS-EN-1991-1-4, for circular cylinders whose height is above or equal to 50 meters, effective slenderness can be calculated from Eq.(22) or Eq.(23) which gives smaller values than the other [11].

$$\lambda = 0.7\, l/b \tag{22}$$

$$\lambda = 70 \tag{23}$$

Peak factor, which is defined as the ratio of the maximum value of the fluctuating part of the response to its standard deviation, can be calculated from Eq.(24) or Eq.(25) which gives higher values than the other [11].

$$k_p = \sqrt{2\ln(\nu T)} + \frac{0.6}{\sqrt{2\ln(\nu T)}} \quad (24)$$

$$k_p = 3 \quad (25)$$

The up-crossing frequency (should be equal or less than 0.08 Hz.) in Eq.(24) can be calculated from Eq.(26) [11].

$$\nu = n_{1,x}\sqrt{\frac{R^2}{B^2+R^2}} \quad (26)$$

In Eq.(24), T is denoting the average time which is T=600 sec [11].

Peak velocity pressure $q_p(z)$ can be calculated by using Eq.(27) [11].

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot V_m^2(z) \quad (27)$$

The reference area for the sections of the structure is calculated by assuming that the area swept by the wind is the projection of the cylinder that is considered. In this study, ρ is denoting the density of air which is 1.25 kg/m^3 [11].

4. Finite Element Model of Soil and Minaret

The finite element model of the minaret and the soil was produced in SAP2000 structural analysis program [14]. The upper structure of the minaret is modeled using shell elements. Also, the foundation and the soil under the foundation is modelled using solid elements (Fig.4).

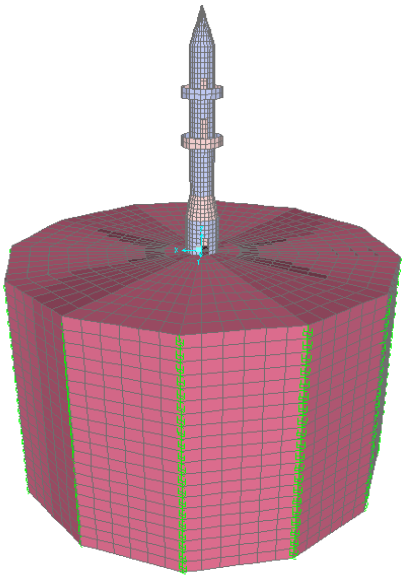


Figure 4. The finite element model of minaret, foundation, soil and viscous boundaries

The minaret is constructed from RC whose unit weight, elasticity module and Poisson's ratio is 23.5 kN/m^3, 30.000.000 kN/m^2 and 0.2, respectively [18]. The geometrical features of the minaret are given in Fig.5. There are a total of three door openings in the minaret, one at the ground level and the other at the level of the balconies. The height of the door openings is 1.50 m. and they are considered to draw an arc of approximately 30 °. The wall thickness of the minaret is 0.18 m. Furthermore, the height and the diameter of the foundation is 1.0 m and 6.0 m, respectively. The characteristic compressive strength of the concrete is preferred to be used as 16 MPa which is often utilized in practice. In addition, the interaction effect between minaret and the mosque superstructure have not been examined in this study since this interference can change the analysis results. Furthermore, the earthquake analysis of the minaret considered is not included in the scope of this study.

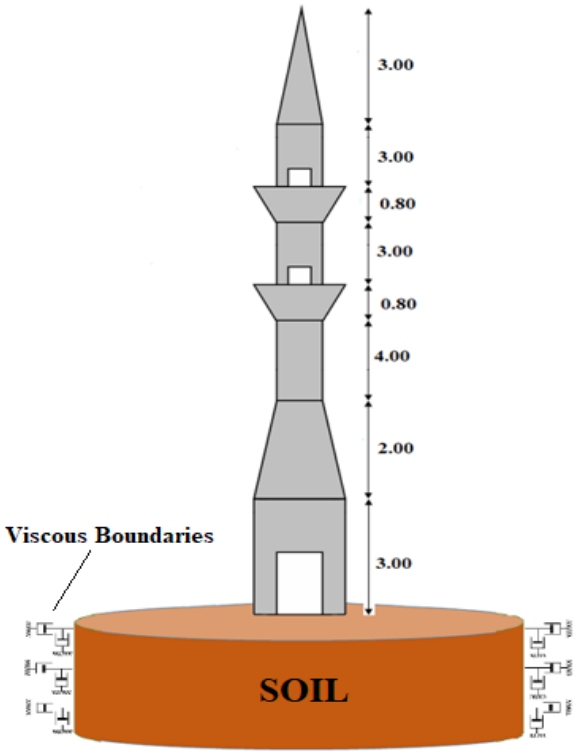


Figure 5. Geometrical features of the minaret

The mechanical properties of the underlying soil is selected from the technical literature whose type, Elasticity Module, Poisson's ratio and density are soft, 35000 kN/m^2, 0.4 and 1800 kg/m^3, respectively [15]. By using a general acceptance, it is assumed that the length of soil under the minaret is 2.50 times the diameter of the foundation. Furthermore, viscous dampers were added to the boundaries of the soil to examine the effect of SSI (Fig.4-5). It is assumed that the thickness of the soil is 20 m. and after this height the soil is anchored to the main rock that it can be accepted as rigid. Also, it is assumed that the soil is homogeneous in itself. Viscous dampers at the boundaries were modeled using the method proposed by Lysmer and Kuhlemeyer [16]. According

to this method, the boundary condition is a pair of stresses expressed as follows [17],

$$\sigma = a \cdot \rho \cdot V_p \cdot \vartheta_n \quad (28)$$

$$\tau = b \cdot \rho \cdot V_s \cdot \vartheta_t \quad (29)$$

In Eq.(28) and Eq.(29), σ and τ are the normal and shear stress on the boundary, respectively. Also, v_n and v_t are the normal and tangential particle velocities of the boundary. The other parameters in the cited equations are, ρ, Vp, Vs, a and b which are denoting the unit mass, velocities of P and S waves in the boundary material, dimensionless parameters, respectively. Also, the damping coefficients of the dashpots are for normal and shear directions [17]:

$$c_n = a \cdot \rho \cdot l_0 \cdot V_p \quad (30)$$

$$c_t = b \cdot \rho \cdot l_0 \cdot V_s \quad (31)$$

where, l_0, is the length of the boundary to which the dashpots are attached. The solid and shell structural elements (Fig.4) that forms the chimney, foundation and soil are divided into the appropriate number of finite elements for the purpose of structural analysis and imaging. As a result of this process, 1412 shell elements and 12720 solid elements were utilized in the structural analysis. Although the minarets are tall and slender structures, it can be said that the first mode mass participation ratios obtained from the analyses are generally higher than the other modes. Because of this reason, in order to obtain the effect of SSI on the wind load of RC minarets, the first mode periods of RC minarets with and without soil are compared with each other. After the structural analyses, the first mode of RC minaret without soil and without foundation is obtained as 0.24622 s (*Upper structure is directly anchoraged to the ground*). Also, the first mode of RC minaret with soil and foundation (Fig.4) is obtained as 0.55204 s. This shows that SSI is very effective on the dynamic response of RC minarets. The first mode period of RC minaret with soil and foundation increased approximately 124 % compared with the first mode of RC minaret without soil and foundation.

5. Results of Wind Load Calculations

In this section of the study, the wind loads acting on RC minaret given in section 3 is calculated according to TS498 and TS-EN-1991-1-4.

5.1. According to TS 498

In the wind load calculations according to TS498, as can be seen from Eq.(1), there is no parameter related to the vibration or structural behavior of the considered structure. Therefore, the wind load values calculated according to TS 498 are independent of the effect of SSI.

Table 3. Wind loads according to TS498

No	Height from ground (m)	Cf	q (kN/m²)	A (m²)	***W (kN)***
0	0-3	1.6	0.5	7.5	***6.00***
1	3-5	1.6	0.5	4.3	***3.44***
2	5-8	1.6	0.5	5.4	***4.32***
3	8-11	1.6	0.8	5.4	***6.91***
4	11-14	1.6	0.8	5.4	***6.91***
5	14-16.6	1.6	0.8	4.68	***5.99***
6	16.6-19.6	1.6	0.8	1.8	***2.30***

As can be seen from Table 3, the wind load values calculated according to TS498 do not include the effects due to the dynamic behavior of the structure and the effects due to SSI. Therefore, for TS498, there is no difference in the wind load values acting on the minaret with and without soil flexibility. The values in Table 3 is valid for the minarets with and without the effect of SSI. Moreover, in wind load calculations using TS 498, no wind speed value is used, but only the relation of the suction force due to the height is emphasized.

5.2. According to TS-EN-1991-1-4

According to TS-EN-1991-1-4, wind speed V_0 at the height H_0 (*generally taken at 10 m*) is the first variable to be considered in the wind load calculation. In this study, calculations were carried out assuming that V_0 wind speed is 45 m/s (*approximately 162 km/h*). This value is equivalent to the speed of the storms. The procedure given TS-EN-1991-1-4 for wind loading calculation includes the dynamic behavior of the considered structure as the first mode natural frequency (depending on the first mode period of the structure) is an important parameter in the calculations. Therefore, for the purpose of comparison, the wind loading for RC minaret with and without soil flexibility is given seperately.

5.2.1. Calculations without ssı effect

The fundamental value of basic wind velocity depending on V_0 can be calculated as given in Table 4. In this calculation, logaritmic velocity profile is utilized as described in Eq.(14).

Table 4. Fundamental value of basic wind velocity

No	Height from ground (m)	H_0 (m)	z_0 (m)	V_0 (m/s)	$V_{b,0}$ (m/s)
0	0-3	10	0.003	45	38.321
1	3-5	10	0.003	45	41.155
2	5-8	10	0.003	45	43.762
3	8-11	10	0.003	45	45.529
4	11-14	10	0.003	45	46.867
5	14-16.6	10	0.003	45	47.812
6	16.6-19.6	10	0.003	45	48.733

Also, basic wind velocity is given in Table 5.

Table 5. Basic wind velocity

No	Height From Ground (m)	$V_{b.0}$ (m/s)	C_{dir}	C_{season}	V_b (m/s)
0	0-3.00	38.321	1.000	1.000	38.321
1	3.00-5.00	41.155	1.000	1.000	41.155
2	5.00-8.00	43.762	1.000	1.000	43.762
3	8.00-11.00	45.529	1.000	1.000	45.529
4	11.00-14.00	46.867	1.000	1.000	46.867
5	14.00-16.60	47.812	1.000	1.000	47.812
6	16.60-19.60	48.733	1.000	1.000	48.733

Then the values of roughness factor for different sections is calculated as given in Table 6.

Table 6. Roughness factor for different sections

No	Height From Ground (m)	z_0 (m)	$\ln(z/z_0)$	k_r	$C_r(z)$
0	0-3.00	0.003	6.908	0.190	1.312
1	3.00-5.00	0.003	7.419	0.190	1.410
2	5.00-8.00	0.003	7.889	0.190	1.499
3	8.00-11.00	0.003	8.207	0.190	1.559
4	11.00-14.00	0.003	8.448	0.190	1.605
5	14.00-16.60	0.003	8.619	0.190	1.638
6	16.60-19.60	0.003	8.785	0.190	1.669

By using the values found in Table 4, 5 and 6, the mean wind velocity can be calculated in Table 7.

Table 7. Mean wind velocity for different sections

No	Height From Ground (m)	$C_r(z)$	$C_o(z)$	V_b (m/s)	$V_m(z)$ (m/s)
0	0-3.00	1.312	1.000	38.321	50.295
1	3.00-5.00	1.410	1.000	41.155	58.009
2	5.00-8.00	1.499	1.000	43.762	65.592
3	8.00-11.00	1.559	1.000	45.529	70.995
4	11.00-14.00	1.605	1.000	46.867	75.228
5	14.00-16.60	1.638	1.000	47.812	78.293
6	16.60-19.60	1.669	1.000	48.733	81.340

The size effect parameters are calculated in Table 8.

Table 8. Size effect parameters (height and breadth of the structure)

Outer Diameter At Top of The Tower (m)	First Mode Natural Frequency (Hz)	Mean Wind Speed At Top (m/s)	Height of the Minaret (m)	$Ø_b$	$Ø_h$
1.800	0.246220	81.34	19.60	0.983	0.89

In Table 9, the value of wind energy spectrum calculated by using non-dimensional frequency is given.

Table 9. Wind energy spectrum and non-dimensional frequency

Turbulence Length Scale (m)	First Mode Natural Frequency (Hz)	Mean Wind Speed At Top (m/s)	C	F
150	0.246	81.340	0.454	0.108

Peak velocity pressure is given in Table 10.

Table 10. Peak velocity pressure for different sections

No	Height From Ground (m)	$I_v(z)$	ρ (kg/m³)	$V_m(z)$ (m/s)	$q_p(z)$
0	0-3.00	0.145	1.250	50.295	3183.122
1	3.00-5.00	0.135	1.250	58.009	4087.620
2	5.00-8.00	0.127	1.250	65.592	5075.001
3	8.00-11.00	0.122	1.250	70.995	5836.997
4	11.00-14.00	0.118	1.250	75.228	6467.791
5	14.00-16.60	0.116	1.250	78.293	6942.694
6	16.60-19.60	0.114	1.250	81.340	7430.154

Reynolds Number is calculated and given in Table 11.

Table 11. Reynolds Number calculated for different sections

No	Height From Ground (m)	$V_m(z)$ (m/s)	ν (m²/s)	Re
0	0-3.00	50.295	0.000015	8,382,534.840
1	3.00-5.00	58.009	0.000015	8,314,604.690
2	5.00-8.00	65.592	0.000015	7,871,040.446
3	8.00-11.00	70.995	0.000015	8,519,358.483
4	11.00-14.00	75.228	0.000015	9,027,393.694
5	14.00-16.60	78.293	0.000015	9,395,111.809
6	16.60-19.60	81.340	0.000015	9,760,793.678

Then, force coefficient of cylinders without free-end flow (Table 12) is calculated.

Table 12. Force coefficient of cylinders without free-end flow

No	Height From Ground (m)	k/b	Re	$C_{f.0}$
0	0-3.00	0.0004	8,382,534.840	0.885
1	3.00-5.00	0.0004	8,314,604.690	0.893
2	5.00-8.00	0.0005	7,871,040.446	0.901
3	8.00-11.00	0.0005	8,519,358.483	0.904
4	11.00-14.00	0.0005	9,027,393.694	0.906
5	14.00-16.60	0.0005	9,395,111.809	0.908
6	16.60-19.60	0.0005	9,760,793.678	0.909

After that, the value of end-effect factor depending on solidity ratio and effective slenderness is calculated by using the graph given in Fig.2 and given in Table 13.

Table 13. The end-effect factor

0.7*l/b	λ	φ=A/Ac	ψλ
7.622	70.000	1.000	0.680

Then, the force coefficient is calculated in Table 14.

Table 14. The force coefficient for different sections

No	Height From Ground (m)	$C_{f,0}$	ψ_λ	C_f
0	0-3.00	0.885	0.680	0.602
1	3.00-5.00	0.893	0.680	0.607
2	5.00-8.00	0.901	0.680	0.613
3	8.00-11.00	0.904	0.680	0.615
4	11.00-14.00	0.906	0.680	0.616
5	14.00-16.60	0.908	0.680	0.617
6	16.60-19.60	0.909	0.680	0.618

Aerodynamic damping given with Eq.10 is calculated and shown in Table 15.

Table 15. Aerodynamic damping for different sections

C_f	ρ (kg/m³)	Mean Wind Speed At Top (m/s)	m_e (kg/m)	First Mode Natural Frequency (Hz)	δ_a
0.60	1.250	81.340	2289.060	0.246220	0.195
0.60	1.250	81.340	2289.060	0.246220	0.197
0.61	1.250	81.340	2289.060	0.246220	0.199
0.61	1.250	81.340	2289.060	0.246220	0.200
0.61	1.250	81.340	2289.060	0.246220	0.200
0.61	1.250	81.340	2289.060	0.246220	0.200
0.61	1.250	81.340	2289.060	0.246220	0.201

By using the values calculated in Table 8, Table 9 and Table 15, the resonance response factor is calculated and given in Table 16.

Table 16. Resonance response factor for different sections

F	$Ø_b$	$Ø_h$	δ_s	δ_a	R^2
0.108	0.983	0.894	0.030	0.195	2.643
0.108	0.983	0.894	0.030	0.197	2.622
0.108	0.983	0.894	0.030	0.199	2.602
0.108	0.983	0.894	0.030	0.200	2.594
0.108	0.983	0.894	0.030	0.200	2.589
0.108	0.983	0.894	0.030	0.200	2.585
0.108	0.983	0.894	0.030	0.201	2.582

After calculating resonance response factor, the up-crossing frequency given with Eq.26 is determined and shown in Table 17.

Table 17. Up-crossing frequency

B^2	R^2	ν
1.000	2.643	0.210
1.000	2.622	0.209
1.000	2.602	0.209
1.000	2.594	0.209
1.000	2.589	0.209
1.000	2.585	0.209
1.000	2.582	0.209

Then, the structural factor which is the main parameter of the wind loading provided in TS-EN-1991-1-4 is given in Table 18.

Table 18. Structural factor for different sections

k_p	$I_v(z_e)$	R^2	B^2	$c_s c_d$
3.000	0.114	2.643	1.000	1.282
3.000	0.114	2.622	1.000	1.280
3.000	0.114	2.602	1.000	1.278
3.000	0.114	2.594	1.000	1.277
3.000	0.114	2.589	1.000	1.277
3.000	0.114	2.585	1.000	1.276
3.000	0.114	2.582	1.000	1.276

At last, the wind loading acting on RC minaret without SSI effect is determined and given at the last column of Table 19 in bold and italics.

Table 19. Wind loading of RC minaret without SSI effect

Height From Ground (m)	$c_s c_d$	C_f	$q_p(z)$	A_{ref}	***F_w (kN)***
0-3.00	1.282	0.602	3183.122	7.50	***18.416***
3.00-5.00	1.280	0.607	4087.620	4.30	***13.663***
5.00-8.00	1.278	0.613	5075.001	5.40	***21.461***
8.00-11.00	1.277	0.615	5836.997	5.40	***24.751***
11.00-14.00	1.277	0.616	6467.791	5.40	***27.479***
14.00-16.60	1.276	0.617	6942.694	4.68	***25.598***
16.60-19.60	1.276	0.618	7430.154	1.80	***10.550***

5.2.2. Calculations with ssı effect

In the preceding section, wind loading of considered RC minaret without SSI effect is detailed given in Table 4-19. Therefore, there is no need to give detailed wind load calculation of considered RC with SSI effect. Therefore, only main parameters of wind load acting on the considered RC minaret is given in Table 20.

Table 20. Wind loading of RC minaret with SSI effect

Height From Ground (m)	$c_s c_d$	C_f	$q_p(z)$	A_{ref}	***F_w (kN)***
0-3.00	1.440	0.602	3183.122	7.500	***20.682***
3.00-5.00	1.437	0.607	4087.620	4.300	***15.343***
5.00-8.00	1.435	0.613	5075.001	5.400	***24.098***
8.00-11.00	1.434	0.615	5836.997	5.400	***27.791***
11.00-14.00	1.433	0.616	6467.791	5.400	***30.854***
14.00-16.60	1.433	0.617	6942.694	4.680	***28.742***
16.60-19.60	1.433	0.618	7430.154	1.800	***11.845***

5.2.3. Comparison of wind loadings

In this part of the study, the wind loadings of the considered RC minaret according to TS498 and TS-EN-1991-1-4 are compared with each other.

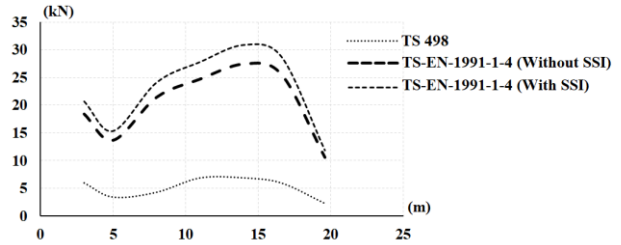


Figure 6. Graph of the wind loads obtained from TS498 and TS-EN-1991-1-4

From Fig.6, it can be clearly seen that the wind loadings obtained for all sections according to TS-EN-1991-1-4 is approximately 200-300 % larger compared to those obtained from TS498. It is because of the reason that the equation provided in TS498 do not include the dynamic behaviour of the structure. However, in the equation provided in TS-EN-1991-1-4, the mode frequency of the structure is included in the calculations. Also, by using TS498, the wind speed is considered in the suction pressure as the only parameter that changed wind speed is the total height from the ground. Although this is the case for TS498, in TS-EN-1991-1-4, logarithmic velocity profile is utilized in determining wind speed that is used in the calculations. Also, from Fig.6 and for both standards considered, it is clearly seen that there are two sudden drops in the wind loads that are calculated (*although the wind speed increases with height*). These are the places where there is a decrease in the reference area that is affected from the wind. The first drop place is the transition segment that is between pulpit (*boot*) and cylindircal body of the considered RC minaret. The second drop place is the spire part which has the conical shape on top of the considered RC minaret. Other than these, for all sections considered, by using TS-EN-1991-1-4, considering SSI has an adverse effect on the wind loading that it increased the wind loading approximately 12 %.

6. Discussion and Conclusion

In this study, the wind loads of a selected RC minaret is calculated according to two Turkish Standards namely TS498 and TS-EN-1991-1-4. Then, some comparisons are performed in order to show the effect of these cited standards on the wind loads acting. Also, the effect of SSI on the wind loads is investigated. In the SSI investigations, the boundaries of the soil is modelled by using viscous boundaries which have a general usage among scientists about this subject. Some of conclusions deducted from the findings of this study are given below:

For all sections considered, the wind loadings obtained from TS-EN-1991-1-4 are approximately 200-300 % higher than the ones obtained from TS498. However, from Fig.6, it can be clearly seen that the general trend of the wind loadings are following the same path along the height of the minaret. Also, the dynamic behavior of the minaret has an importance in the wind loads that are calculated by including the first mode natural frequency of the minaret in the equation of standard TS-EN-1991-1-4. Because of this reason, two different wind loadings are obtained for all sections by considering the effect soil flexibility with the same standard (TS-EN-1991-1-4). By adding soil flexibility to the system (viscous boundaries), the wind loadings increased approximately 12 %. Moreover, only considering SSI in the dynamic analysis, the first mode natural frequency of the minaret changed from 0.24622 s to 0.55204 s. This shows that SSI is very effective on the dynamic response of RC minarets. This should be the case in all real life civil engineering structures.

In conclusion, minarets are tall and slender structures that are very important for Islamic architecture. Therefore, it is very important for us to preserve and herit these structures to the next generations. To do that the wind and other destructive effects should be determined precisely and application projects of these slender structures should be prepared according to the findings of these investigations.

Acknowledgment

This study is dedicated to venerable memory of our light, great scientist and a honorable person Prof. Dr. Ing. Ahmet DURMUŞ whom we lost in 07.03.2017.

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Appendices

A	Affected area (m^2)
A	Projection areas of the structural elements
A_c	Total area
A_{ref}	Reference area for structure
b	Outer diameter of the section considered
B^2	Background factor
C	Non-dimensional frequency
c_{dir}	Directional factor
c_f	Force coefficient
C_f	Aerodynamic load factor
c_f	Force parameter for structure
$C_{f,0}$	Force coefficient of cylinders without free-end flow
$c_0(z)$	Orography coefficient
$c_r(z)$	Roughness factor
$c_s c_d$	Structural factor
c_{season}	Season factor
F	Wind energy spectrum
h	Total height of the minaret
$I_v(z_e)$	Turbulence intensity at reference height z_e
k	Equivalent surface roughness
k_I	Turbulence coefficient
k_p	Peak factor
k_r	Terrain factor
L_c	Turbulence length scale
m_e	Equivalent mass per unit length
$n_{1,x}$	Vibration frequency of minaret at 1^{st} mod(Hz)
q	Suction pressure (kN/m^2)
$q_p(z_e)$	Peak velocity pressure at reference height z_e
R^2	Resonance response factor
Re	Reynolds Number
T	Average time (T=600 sec.)
V	Speed of wind at height H
V_0	Wind speed at height H_0 from the ground
V_b	Basic wind velocity
$V_{b,0}$	Fundamental value of the basic wind velocity
$V_m(z)$	Mean wind velocity at a height z
$V_m(z_e)$	Mean wind velocity at the top of the minaret
$ø_b$	Size effect (*breadth of the structure*)
$ø_h$	Size effect (*height of the structure*)
δ_s	Structural damping expressed by the logarithmic decrement
δ_a	Aerodynamic damping
ρ	Density of air (taken as 1,25 kg/m^3),
ψ_λ	End-effect factor.
λ	Effective slenderness
ν	Up-crossing frequency