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Effect of Soil Type on Dynamic Behavior of Reinforced Concrete Industry Chimneys

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ABSTRACT

Industrial structures built with different materials and methods play an important role in the sector with the development of industry and the increase in energy needs. Many parameters are considered in the design and application phase of industrial structures to provide service for many years. The aim of this study is to examine the dynamic behavior of reinforced concrete industrial chimneys depending on soil-structure interaction (SSI). For this reason, a reinforced concrete industrial chimney, which was exposed to the 1999 Kocaeli Earthquake, was chosen as a sample. The effect of soils with different properties (hard, medium and soft) on the dynamic behavior of the selected structure was investigated numerically by linear time history analysis in ANSYS finite element program. The horizontal component of the Kocaeli Earthquake (1999) was used in analyses. As a result of the studies, besides the mode shape and frequency of structure, stress, strain and displacements were also obtained. It has been observed that as the hardness of the soil environment decreases (transition from hard soil to soft soil), chimney apex displacements and stresses on the edge of the voids increase.

Keywords: Linear dynamic analysis, Industrial chimneys, Soil-structure interaction, Finite element method

Zemin Tipinin Betonarme Sanayi Bacalarının Dinamik Davranışına Etkisi

ÖZ

Farklı malzeme ve yöntemlerle inşa edilen endüstriyel yapılar, sanayinin gelişmesi ve enerji ihtiyacının artması ile sektörde önemli bir rol oynamaktadır. Endüstriyel yapıların uzun yıllar hizmet verebilmesi için tasarım ve uygulama aşamasında birçok parametre dikkate alınmaktadır. Bu çalışmanın amacı, betonarme endüstriyel bacaların zemin-yapı etkileşimine (SSI) bağlı dinamik davranışını incelemektir. Bu nedenle örnek olarak 1999 Kocaeli Depremi'ne maruz kalan betonarme bir endüstriyel baca seçilmiştir. Farklı özelliklere sahip (sert, orta ve yumuşak) zeminlerin seçilen yapının dinamik davranışına etkisi ANSYS sonlu elemanlar programında lineer zaman alanı analizi ile sayısal olarak incelenmiştir. Analizlerde Kocaeli Depremi'nin (1999) yatay bileşeni kullanılmıştır. Çalışmalar sonucunda yapının mod şekli ve frekansının yanı sıra gerilme, gerinim ve yer değiştirmeler de elde edilmiştir. Zemin ortamının sertliği azaldıkça (sert zeminden yumuşak zemine geçiş), baca tepe yer değiştirmelerinin ve boşluk kenarlarındaki gerilmelerin arttığı gözlemlenmiştir.

Anahtar Kelimeler: Lineer dinamik analiz, Endüstriyel bacalar, Yapı-zemin etkileşimi, Sonlu elemanlar yöntemi

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1. Introduction

Chimneys are structures that release waste gases from the production site into the atmosphere. They are built to raise the polluted air high enough in order not to pollute the environment. Thus, chimneys which used in power plants and industrial factories need to be as tall as possible (Esmail et al., 2022). They have a slender structure due to their altitude. Chimneys are exposed to many load effects during their lifetimes. Dead, wind, temperature and especially earthquake loads are some of these effects and they are of great importance for such structures (Gunaydin et al., 2022). In addition to these factors, the characteristics of soil on which the chimneys are built are also very important on behavior of the structures.

The subject of soil structure interaction (SSI), whose importance and application area has increased recently, is often preferred especially in the construction of important structures (Altunışık et al., 2019). It is a very vital subject that requires extensive research since it considers the behavior of the structure and the soil as well as their interaction with each other. With this method, it is possible to protect the structures from damage and make a safe design (Ahmadi, 2019). Due to the developing technology and numerical methods, soil structure interaction is handled in different ways in engineering applications.

Pinzon et al. (2020) examined the effect of earthquake direction in determining the dynamic SSI in this study and they argued that earthquakes at different angles should be considered with simplified methods. Qaftan et al. (2020) made experimental and numerical studies on a scale model. To examine the soil structure and pile relations in the experiment, flexible soil tanks were created, and dry sand was preferred as the ground. They have shown that studies that will cause high costs with their real dimensions can be done with scale models. Ge et al. (2019) tried to explain the behavior of collective buildings during an earthquake, depending on the SSI, under the group effect. For this purpose, experimental studies were carried out with a shaking table. As a result of the studies, they stated that the natural frequency results of the systems containing the collective building SSI are lower than the normal single SSI and the displacements show differences according to the locations of the structures.

Many studies exist in literature about reinforced concrete chimneys, which have a key role for industrial sector and national economies.
Maj and Ubysz (2017) studied the maintenance and repair of vertical-horizontal cracks in reinforced concrete chimney walls caused by loads such as temperature and wind that reduce the bearing capacity. Remyasree and Megha (2016) examined the effects of earthquake load, wind load and temperature on reinforced concrete chimneys. As a result of the analysis, they found the displacement and stress values depending on the wind loads, and the peak displacement depending on earthquake load and temperature.

In this study, dynamic analysis of a reinforced concrete thermal power plant chimney (which collapsed in Kocaeli Earthquake, 1999) was investigated by considering the soil-structure interaction and different boundary (fixed and viscous) conditions. In the analysis performed using the ANSYS program, three different soils (hard, medium and soft) were selected, and results were presented by comparing them with each other.

2. Description of the Chimney Model

The example of a reinforced concrete chimney considered within the scope of the study is a refinery chimney in Kocaeli, Turkey that was damaged and collapsed during the earthquake that occurred in 1999. This chimney was 115m high and conical. The outer diameter ranged from 10.3m at the base to 6.6m at the top. It had rectangular opening, located about 1/3 of the height above the base and this is also the region where first damage occurred (Gould et al., 2004). The dimension values such as outside slopes, diameters and wall thicknesses of the chimney are shown in Table 1. The general appearance of the 3D solid model is shown in Figure 1.

Table 1. Dimensions of the chimney (Akniyazov, 2016)

Height (m)	Outside slope (%)	Outer diameter (m)	Wall thickness (m)
115	1.00	6.60	0.20
90	1.00	7.10	0.22
60	1.50	8.00	0.28
40	1.75	8.70	0.30
0	2.00	10.30	0.45

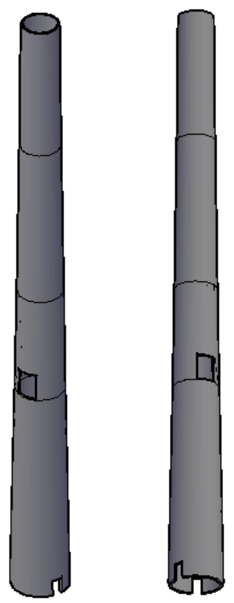


Figure 1. The general appearance of the chimney model

3. FE Model of the Chimney

Finite element (FE) models (Figure 2) of the reinforced concrete chimney with fixed support and SSI were constituted using ANSYS software (2016). SOLID65 and SOLID185 element types were used to represent the chimney and soil, respectively. These element types are defined by eight nodes with three degrees of freedom at each node: translations in the nodal x, y and z directions. SOLID65 is capable of cracking in tension and crushing in compression while SOLID185 has plasticity, stress stiffening, creep, large deflection, and strain capabilities. The material properties used in the chimney models and information about different soil types are given in Tables 2 and 3, respectively.

As shown in Figure 2 the soil media's depth was supposed as 30 m and its width was selected 108 m, with acceptance of about five times the size of foundation width (Hökelekli and Al-Helwani, 2019). Artificial viscous boundaries that can absorb energy in the soil and prevent waves back reflection on the cutting surfaces of the soil were used (Lysmer and Kuhlemeyer, 1969).

Table 2. Material properties of the concrete

Material properties	Concrete
Modulus of elasticity (MPa)	30000
Poisson ratio (-)	0.20
Density (kg/m^3)	2400

Viscous boundaries were modeled by using COMBIN14 element type and placed in each direction at the cartesian coordinate system. For these boundary condition normal and tangential damping coefficients (Cn, Ct) were calculated with the following Equations (1) and (2)

$$C_n = A_1 \rho V_p \qquad (1)$$

$$C_t = A_2 \rho V_s \qquad (2)$$

In these equations given above, Vp and Vs states compression and shear wave velocities, respectively. These values can be determined as,

$$V_p = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}} \qquad (3)$$

$$V_s = \sqrt{\frac{G}{\rho}} \qquad (4)$$

where G, E and ρ is the shear modulus, Young modulus and density, respectively. Also, υ is the Poisson ratio and A coefficients can be determined depending on this value.

Table 3. Material properties of the different soil types (Hökelekli and Al-Helwani, 2019)

Soil	Modulus of elasticity (MPa)	Poisson Ratio (-)	Density (kg/m^3)	Vp (m/s)	Vs (m/s)
Hard	5.68E9	0.30	2064	1924.716	1028.804
Medium	3.61E8	0.35	1864	557.519	267.824
Soft	3.45E7	0.40	1667	210.590	85.973

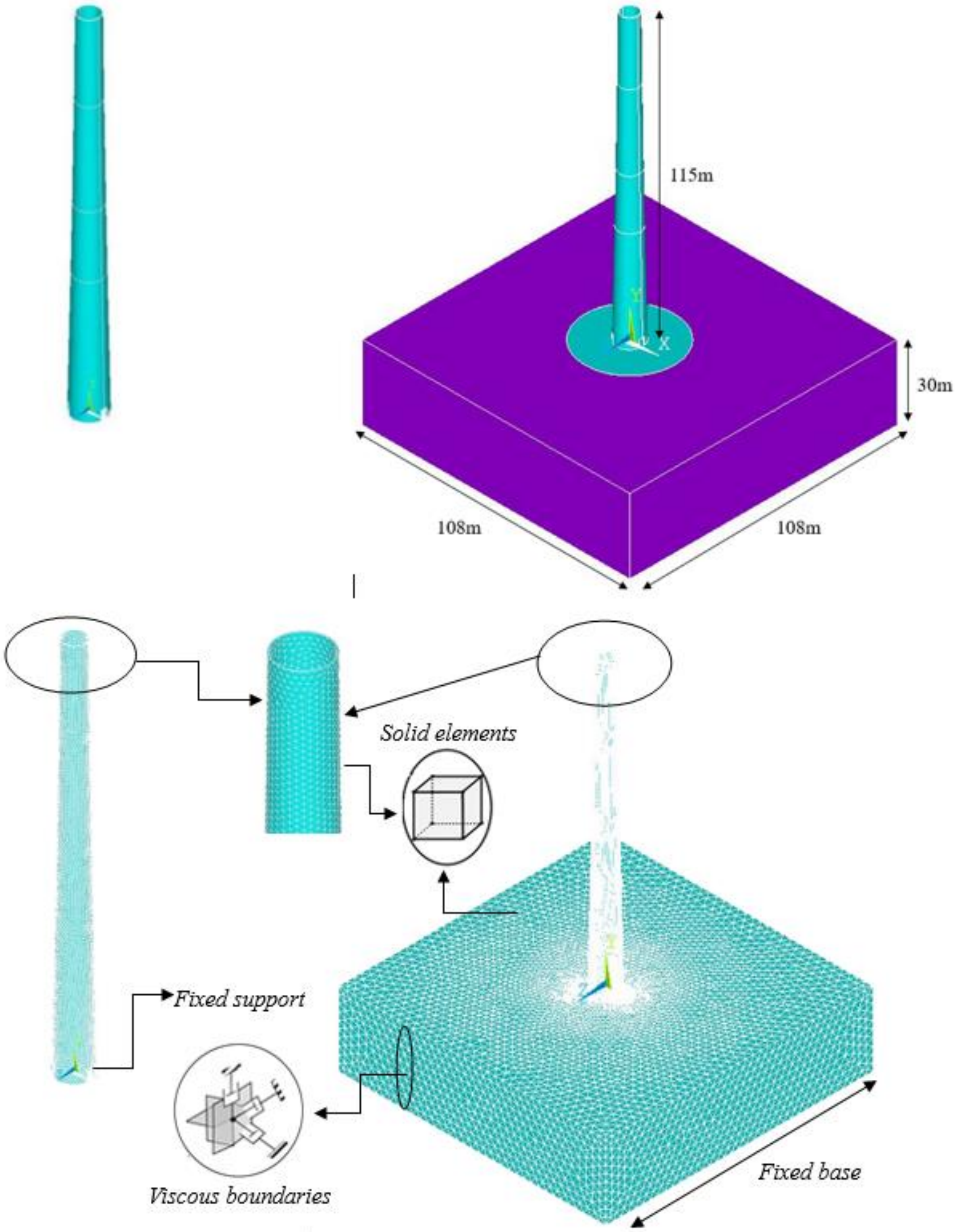


Figure 2. Finite element models of the chimney

4. Linear Time History Analysis

The effect of soil types and boundary conditions on the seismic performance of reinforced concrete chimney was examined by using linear time history analysis. In order to determine the responses of the selected chimney, the horizontal component of Kocaeli (İzmit) Earthquake (1999) was used as ground motion record (Figure 3). The ground motion record was applied on the 1st mode direction. Three different soil types (hard, medium and soft) and fixed boundary condition were taken into account in analyses. Natural frequencies and related mode shapes for fixed support were obtained as seen in Figure 4 and frequencies for different types of soil were also given in Table 4.

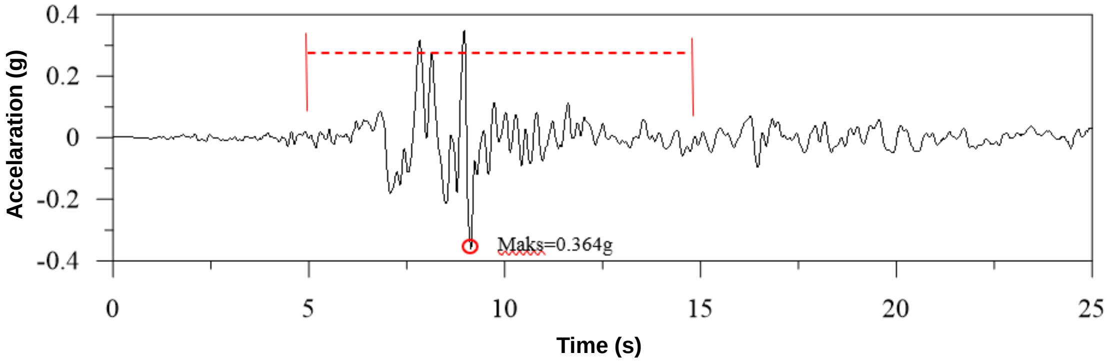
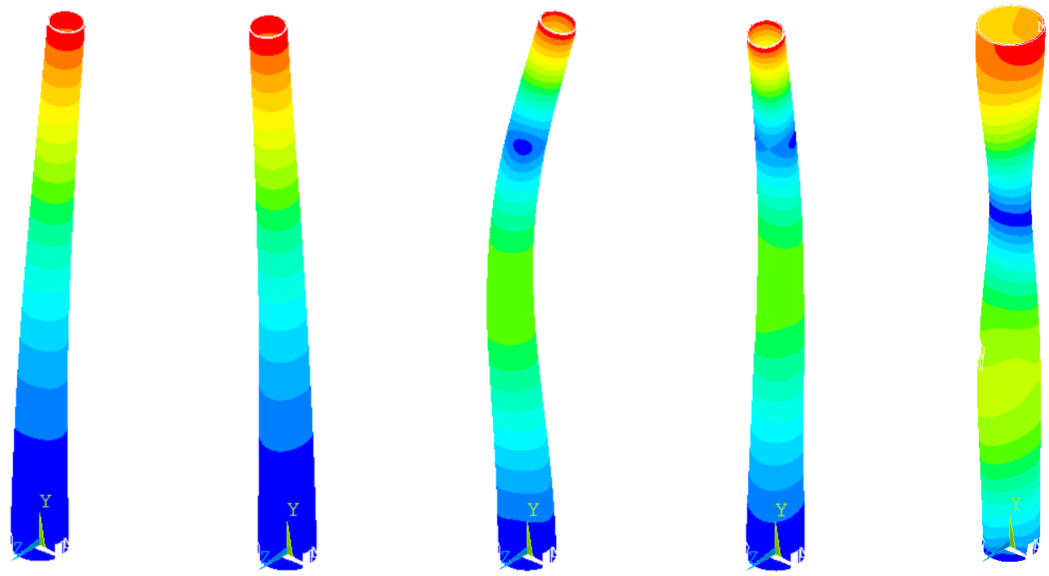


Figure 3. The time-history of ground motion acceleration record (KOCAELI_DZC270)



Mode 1 Freq= 0.646 Hz (X direction) | Mode 2 Freq= 0.668 Hz (Y direction) | Mode 3 Freq= 2.853 Hz (X direction) | Mode 4 Freq= 2.881 Hz (Y direction) | Mode 5 Freq=15.999Hz (Torsional)

Figure 4. Natural frequencies and related mode shapes

Table 4. Frequency values obtained from finite element analysis

Modes	Fixed support	Difference (%)	Hard soil	Difference (%)	Medium soil	Difference (%)	Soft soil
Mode 1	0.646	-1.70	0.635	-3.62	0.612	-9.97	0.551
Mode 2	0.668	-1.80	0.656	-3.81	0.631	-10.78	0.563
Mode 3	2.853	-2.10	2.793	-26.30	2.058	-67.54	0.668
Mode 4	2.881	-2.01	2.823	-27.10	2.058	-67.49	0.669
Mode 5	15.999	-49.02	8.156	-73.90	2.129	-67.78	0.686

The effect of soil type on the seismic performance of reinforced concrete industrial chimney was determined by using linear time history analysis. Displacement contour diagrams obtained from analysis are given in Figure 5. These contour diagrams show the displacement distribution that occurs in the structure when the maximum displacement is reached. In addition, the variation of the maximum displacements obtained from the industrial chimney finite element models with time is given in Figure 6. As seen in Figure 6, the maximum displacement value is 56.1 cm for the fixed support. These values were found to be 58 cm, 62 cm and 177.3 cm from hard soil to soft soil, respectively.

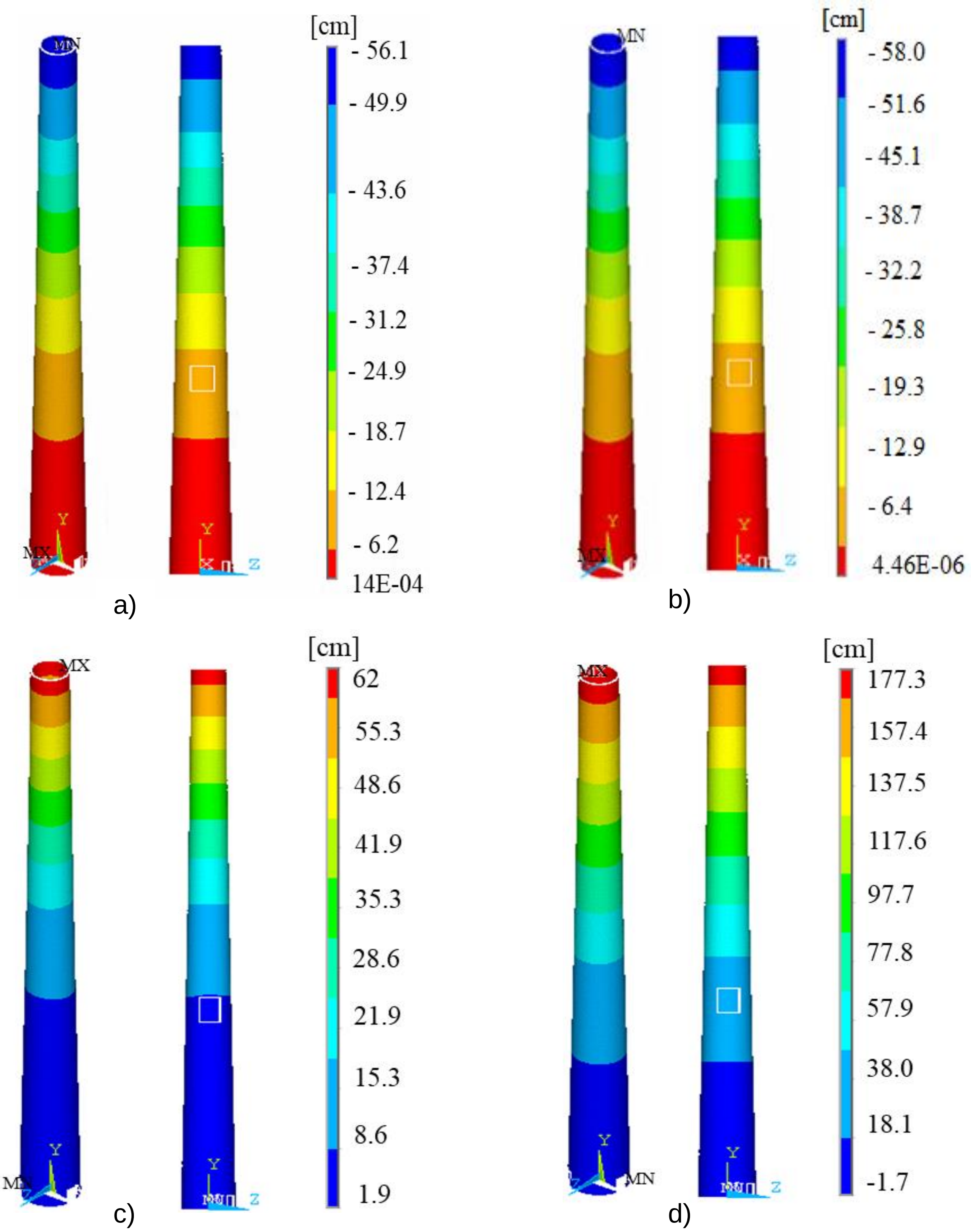


Figure 5. Displacement contour diagrams for a) fixed, b) hard, c) medium and d) soft soil

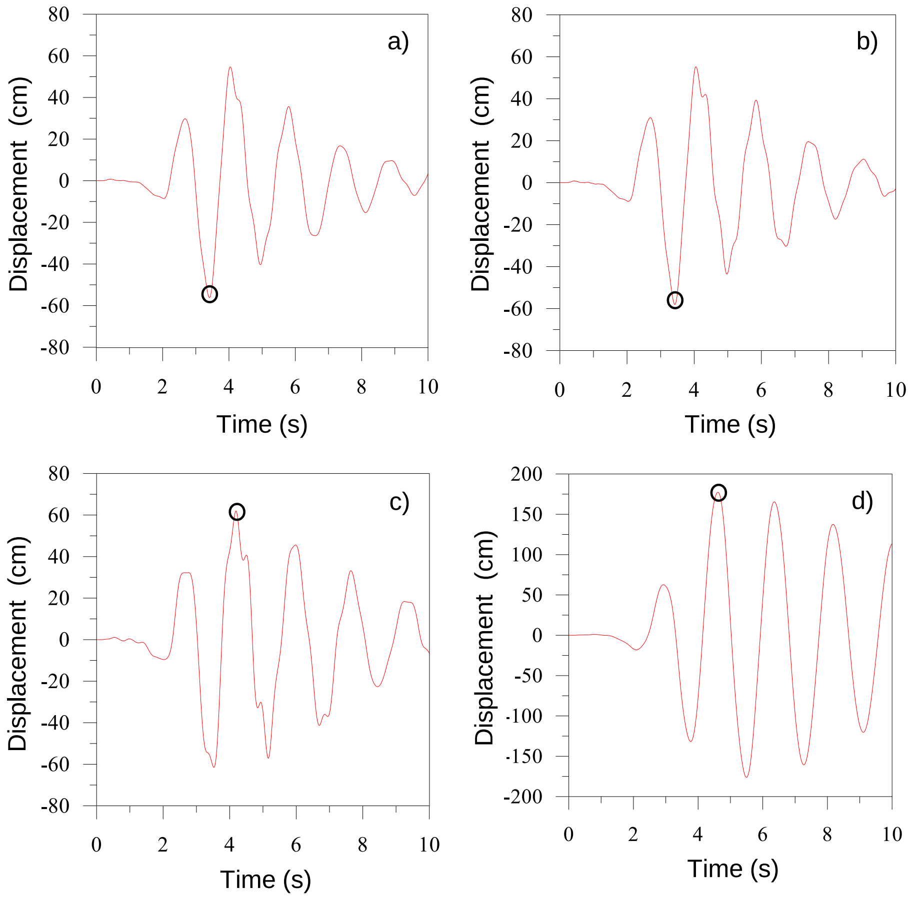


Figure 6. Time-dependent variation of maximum displacements for a) fixed, b) hard, c) medium and d) soft soil

Maximum and minimum principal stress contour diagrams obtained from the dynamic analysis of the fixed-support industrial chimney FE model are given in Figure 7 and Figure 8, respectively. These contour diagrams show the stress distributions in the structure when the maximum and minimum principal stresses are occurred. As seen in Figure 7, the maximum stress value is 46.10 MPa and occurred on the local point of window in the chimney body. Except for these parts, maximum stresses are generally concentrated on the facade where the window is located and decrease along the height as they move away from the window. While the tensile stress did not occur partially in the door areas at the entrance of the chimney, it was observed that the maximum stress obtained exceeded the tensile strength of the concrete on the window sides. As seen in Figure 8, the minimum stress value is 44.90 MPa and occurred on the local point of window in the body of chimney. Except for these parts, minimum stresses are generally concentrated on the facade where the window is located and increase along the height as they move away from window. While compressive stress nearly did not occur in the door areas at the entrance of the chimney, it was observed that the minimum stress obtained exceeded the compressive strength of the concrete on the window sides. The variation of the maximum and minimum principal stresses obtained from the fixed-support industrial chimney finite element model with time is given in Figure 9.

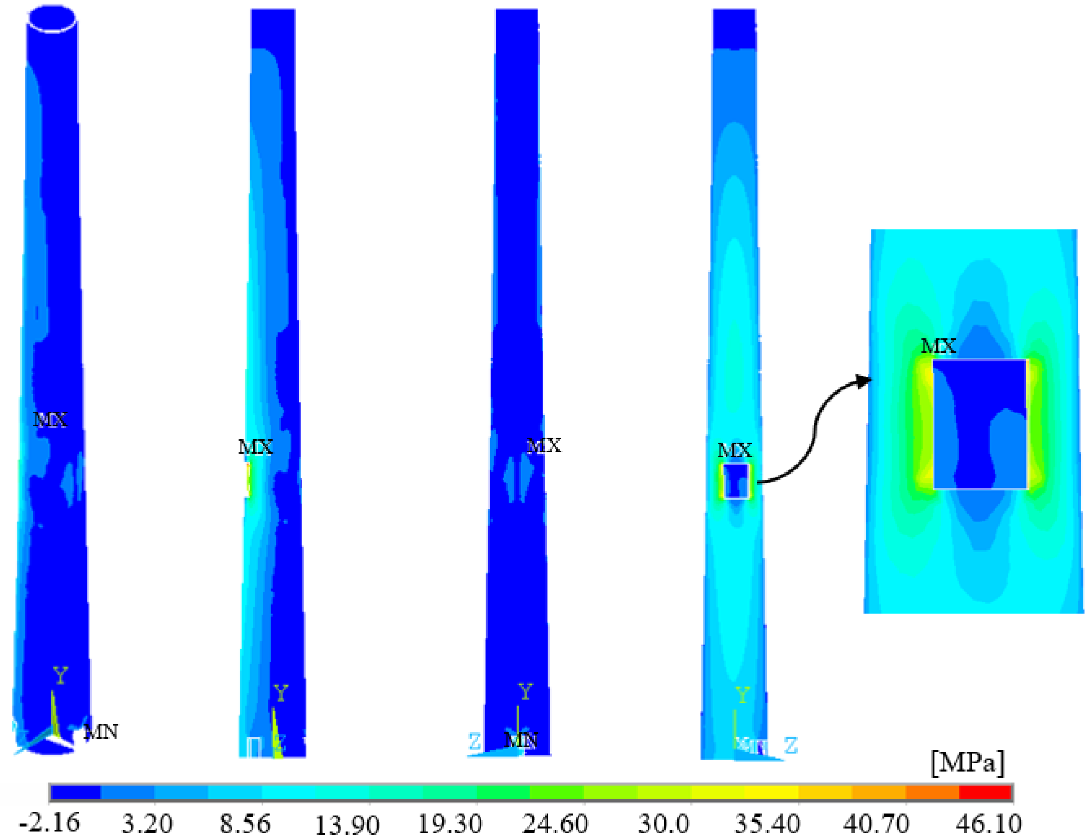


Figure 7. Maximum principal stress contour diagrams for FEM with fixed support

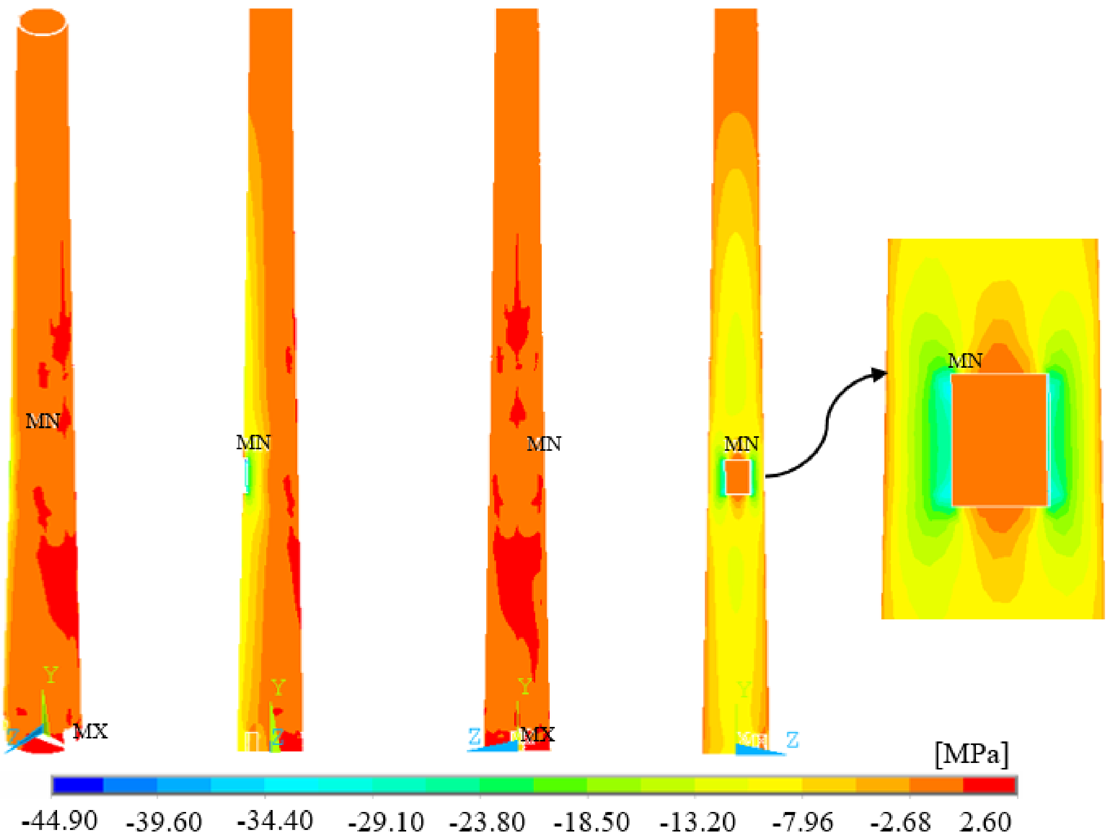


Figure 8. Minimum principal stress contour diagrams for FEM with fixed support

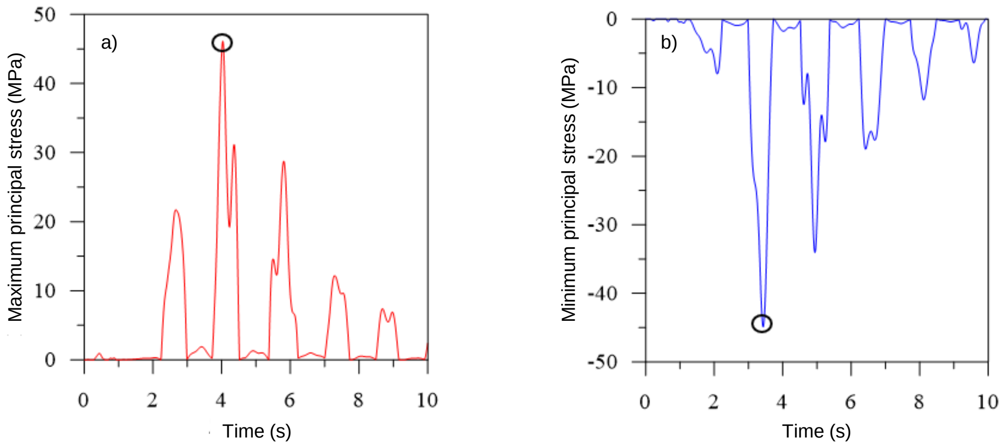


Figure 9. Variation of a) maximum and b) minimum principal stresses with time for fixed support

Maximum and minimum principal strain contour diagrams obtained from the dynamic analysis of the fixed-support industrial chimney FE model are given in Figure 10 and Figure 11, respectively. These contour diagrams show the strain distributions in the structure when the maximum and minimum principal strains are occurred. As can be seen in Figure 10, the maximum strain value is 1.503×10^{-3} and occurred on the local point of window in the chimney body. Except for these parts, maximum strains are generally concentrated on the facade where the window is located and decrease along the height as it moves away from the window and take its minimum value at the top of the chimney. As seen in Figure 11, the minimum strain value is 1.465×10^{-3} and occurred on the local point of window in the body of chimney. Except for these parts, minimum strains are generally concentrated on the facade where the window is located and increase along the height as you move away from the window and take its greatest value at the top of the chimney. The variation of the maximum and minimum principal strains obtained from the fixed-support industrial chimney finite element model with time is given in Figure 12.

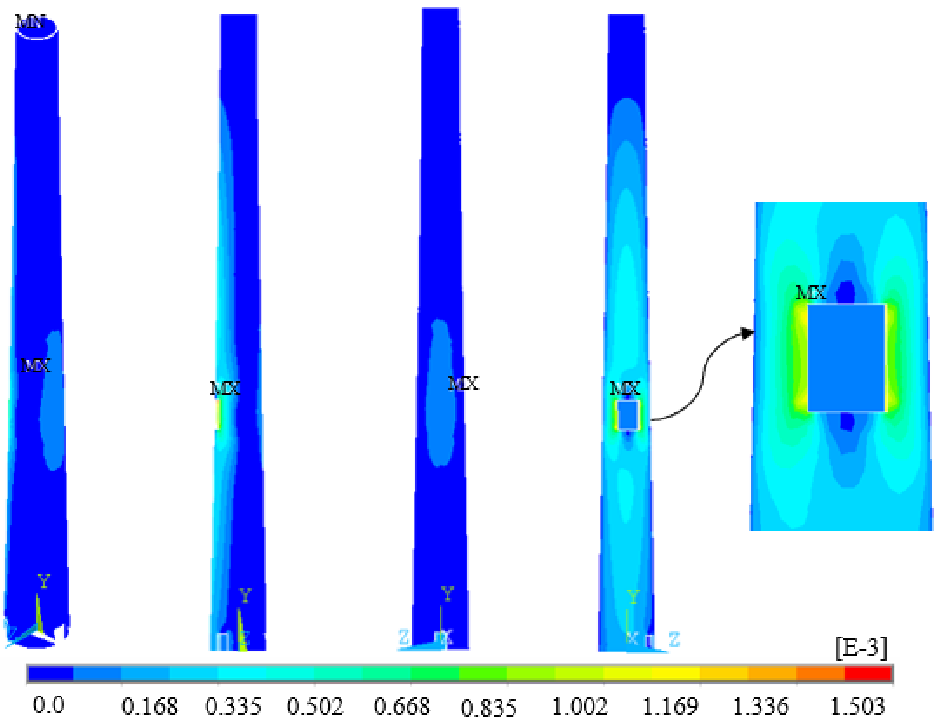


Figure 10. Maximum principal strain contour diagrams for FEM with fixed support

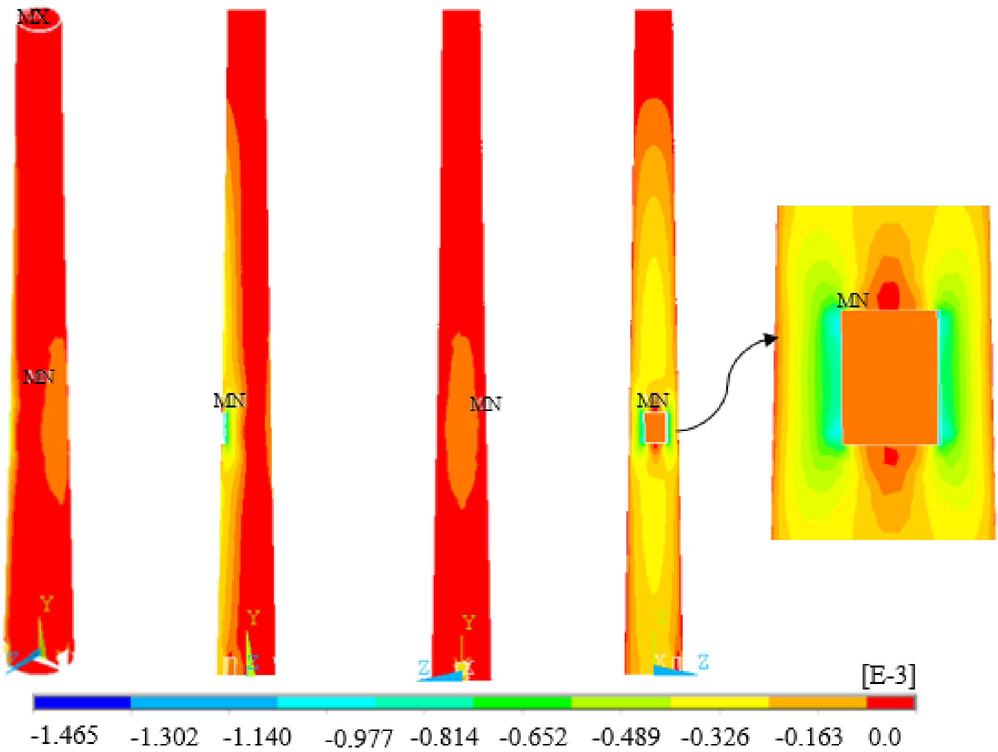


Figure 11. Minimum principal strain contour diagrams for FEM with fixed support

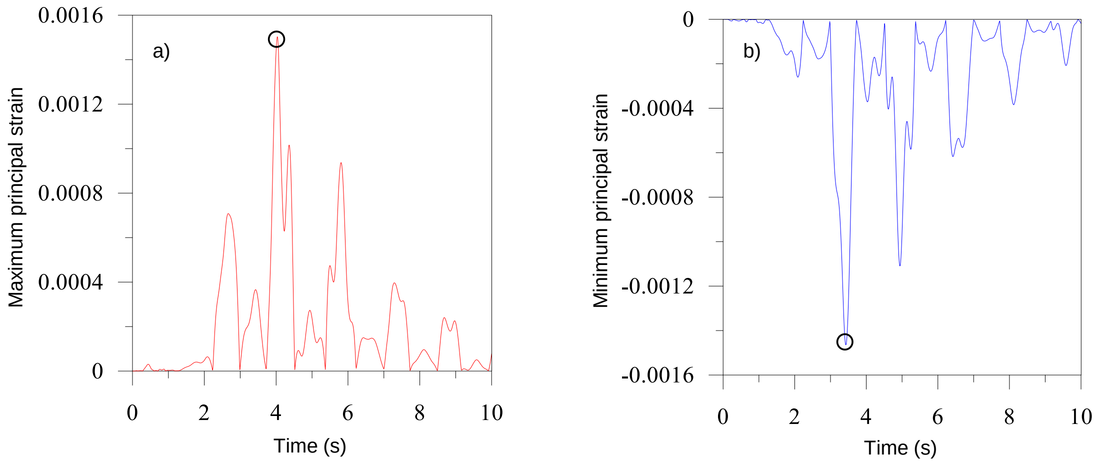


Figure 12. Variation of a) maximum and b) minimum principal strains with time for fixed support

Maximum and minimum principal stress contour diagrams obtained from the dynamic analysis of industrial chimney FE model with soil-structure interaction are given in Figure 13 and Figure 14, respectively. As can be seen from the figures, the results vary depending on the type of soil used in the soil structure interaction. Maximum principal stresses were found to be 47.20 MPa, 50.90 MPa and 102 MPa, respectively, from hard to soft soil type. In addition, the minimum principal stress values reach 46 MPa, 54.50 MPa and 101 MPa for the selected soil types. Maximum and minimum principal strain contour diagrams obtained from the dynamic analysis of industrial chimney FE model with soil-structure interaction are given in Figure 15 and Figure 16, respectively. It was concluded that maximum and minimum strain values increase from hard soil to soft soil. While hard soil structure interaction model has 1.538E-3 maximum strain value, soft soil structure interaction model has 3.340E-3.

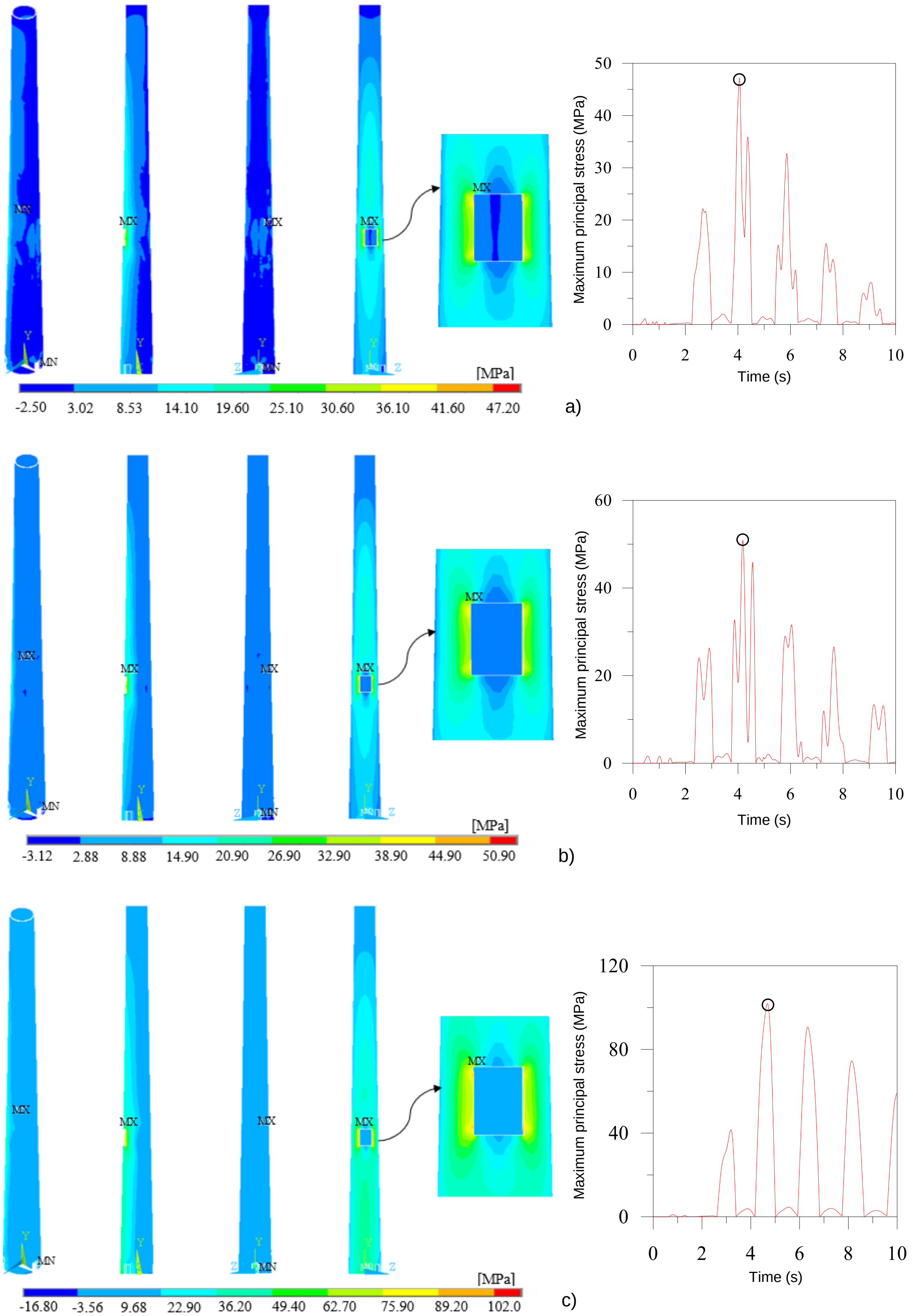


Figure 13. Maximum principal stress contour diagrams for FEMs containing a) hard, b) medium and c) soft soil structure interaction

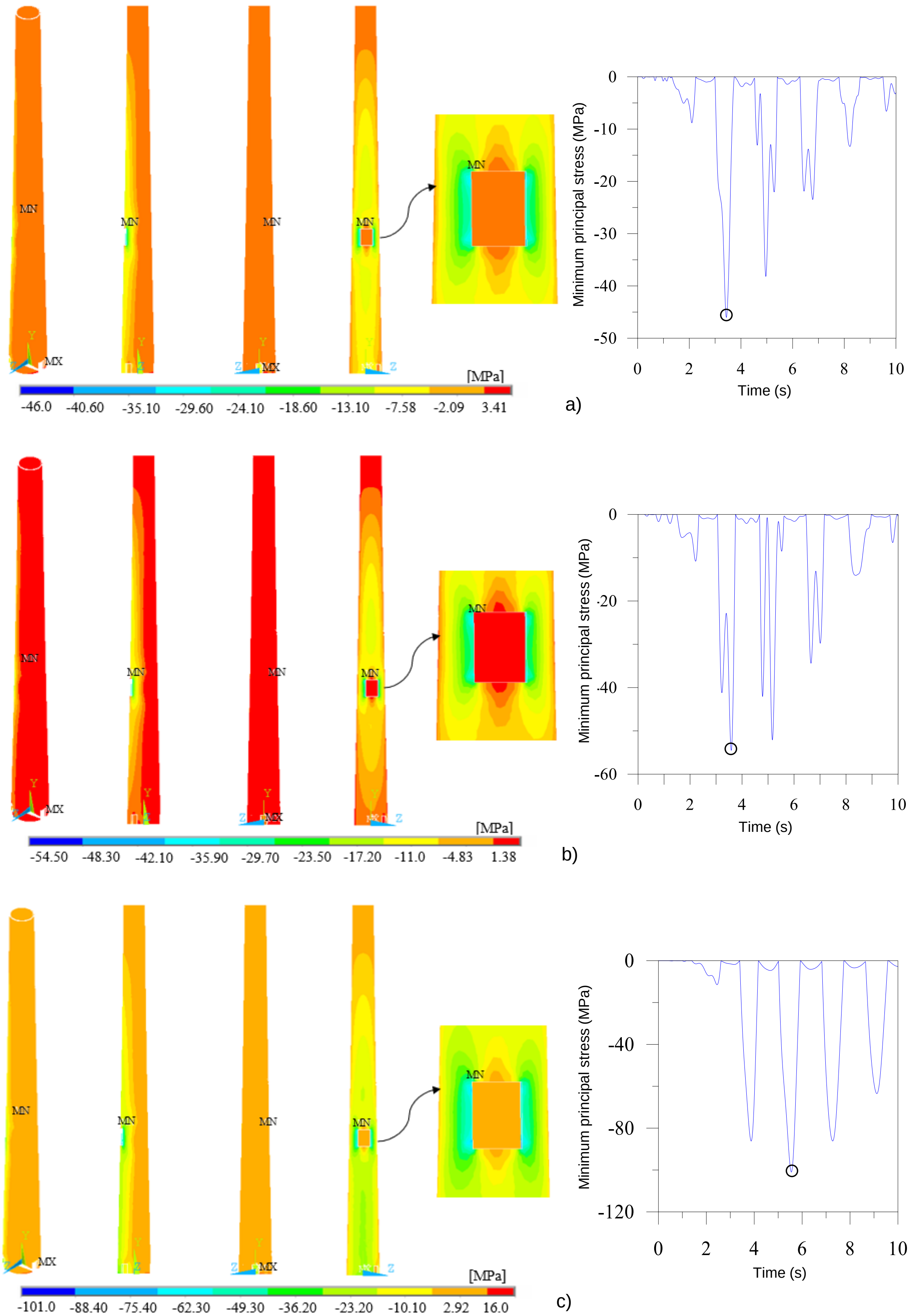


Figure 14. Minimum principal stress contour diagrams for FEMs containing a) hard, b) medium and c) soft soil structure interaction

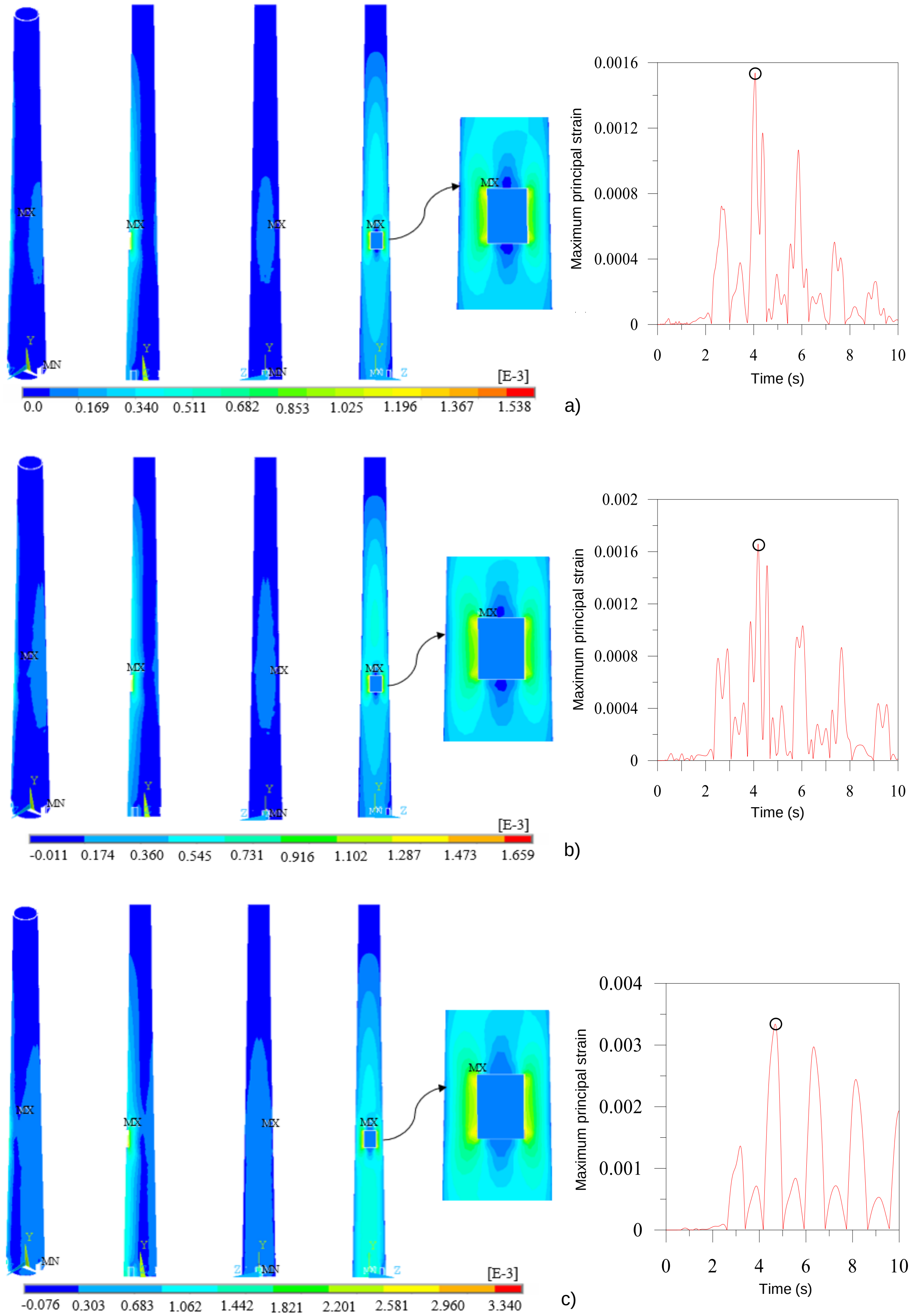


Figure 15. Maximum principal strain contour diagrams for FEMs containing a) hard, b) medium and c) soft soil structure interaction

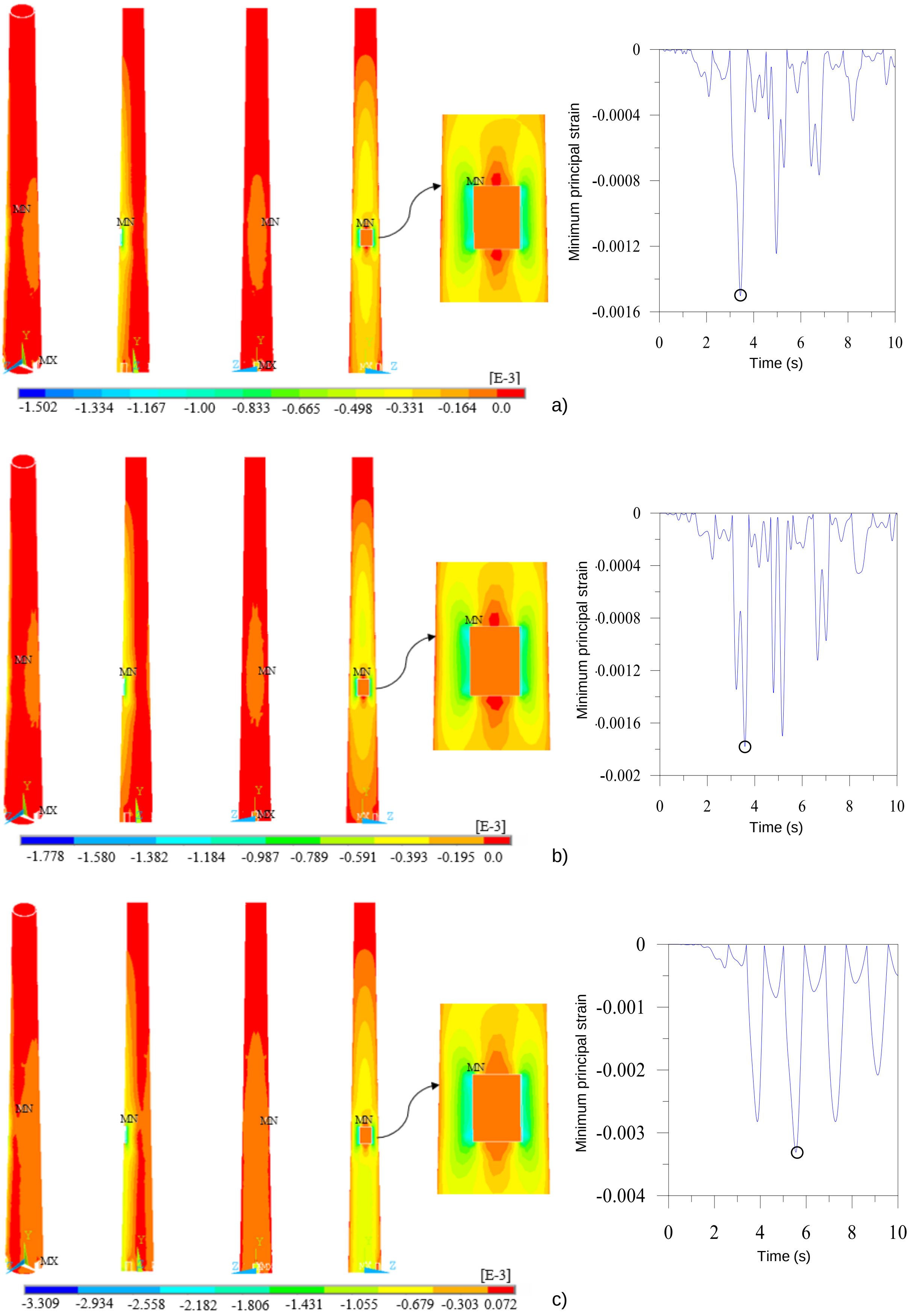


Figure 16. Minimum principal strain contour diagrams for FEMs containing a) hard, b) medium and c) soft soil structure interaction

When Table 5 is examined, it is seen that the smallest displacement (56.10 cm) of the chimney apex is obtained from the fixed-support case analysis, and the largest displacement (177.30 cm) is obtained from the soft soil-structure interaction case analysis. Also, in numerical models with soil-structure interaction, it is seen that the displacement of the chimney apex increases as the soil type changes from hard to soft.

As a result of the analysis, it is concluded that the principal stresses and strains have smaller values in the case of the fixed support. In the analysis involving the soil-structure interaction, it is seen that the principal stress and strain values which obtained in the transition of the soil type from hard soil to soft soil increase and have the greatest values in the case of soft soil-structure interaction.

Table 5. Finite element analysis results of the reinforced concrete chimney

Analysis results	Fixed support	Difference (%)	Hard soil case	Difference (%)	Medium soil	Difference (%)	Soft soil
Displacement (cm)	56.10	3.39	58.00	6.90	62.00	185.97	177.30
Maximum principal stress (MPa)	46.10	2.39	47.20	7.84	50.90	100.39	102.00
Minimum principal stress (MPa)	44.90	2.45	46.00	18.48	54.50	85.32	101.00
Maximum principal strain	1.50E-3	2.33	1.54E-3	7.87	1.66E-3	101.33	3.34E-3
Minimum principal strain	1.47E-3	2.53	1.52E-3	18.38	1.78E-3	86.11	3.31E-3

5. Conclusion

In this study, the effect of fixed support and soil structure conditions on the dynamic behavior of reinforced concrete industrial chimney was investigated by numerical methods. Within the scope of the study, the finite element models of the chimney were created in ANSYS program and dynamic characteristics (mode shapes and frequencies) were obtained. Linear dynamic analysis was carried out on different numerical models in which the chimney was created with fixed support or soil structure interaction by using viscous boundary condition. The results obtained from the studies carried out are presented as follows.

- As a result of the modal analyzes carried out to determine dynamic characteristics of structure, the frequency and mode shapes of the chimney were obtained as translation and torsion modes. The frequency values of reinforced concrete chimney obtained from the analysis take values between 0.551 Hz and 15.999 Hz.
- It was concluded that the frequency values obtained from the numerical model created with the assumption of rigid fixed support are larger than the numerical models with soil-structure interaction. In addition, it was observed that the frequency values decreased from the hard soil to the soft soil, thus the period increased.
- As a result of the analysis, it was observed that the displacements obtained in all models increased along the height of the sample chimney and reached the maximum value at the top of the chimney.
- The principal stresses obtained from the analyzes were observed to vary between 44.90 MPa and 102 MPa values, and the

principal strains ranged between 1.47E-3 and 3.34E-3 values.

- It has been observed that the maximum-minimum principal stress and principal strains obtained as a result of the linear dynamic analysis made occur on the local point of the window edges of the chimney body in all numerical models.

Consequently, soil-structure interaction and boundary condition are important parameters for assessment of seismic response of structure such as reinforced concrete chimneys which are weak to external effect especially earthquake because of its slender. So, necessary boundary assumptions and calculations should be made before constructing such structures.

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