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*Research Article*

# Effect of soil-structure interaction on the seismic behavior of RC chimneys

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## ABSTRACT

RC chimneys are occupying the most important part of industrial factories that they are utilized for removing the waste and hot gases to the atmosphere. Nowadays, in order to meet the requirements of the codes related with the environment needs, the height of these slender structures increase that makes them more vulnerable to seismic loads. Therefore, the overall dynamic behavior of these tall and slender structures should be understood by also considering the effect of underlying soil. In this study, the dynamic seismic response of a model chimney was determined by considering openings, foundation and underlying soil separately. Findings of this study revealed that soil-structure interaction (SSI) is an important phenomenon that effects the dynamic response of reinforced concrete (RC) chimneys.

**Keywords:** *Soil, structure, interaction, earthquake, chimney, opening, seismic*

# Zemin-yapı etkileşiminin betonarme bacaların dinamik davranışına etkisi

## ÖZET

Betonarme bacalar, atık ve sıcak gazları atmosfere çekmek için kullanılmakta olup endüstriyel fabrikaların en önemli kısmını oluşturmaktadır. Günümüzde, çevre ihtiyaçları ile ilgili kodların gereksinimlerini karşılamak için, bu narin yapıların yüksekliği artmakta, bu da onları sismik yüklere karşı daha savunmasız hale getirmektedir. Bu sebepten dolayı, bu uzun ve narin yapıların genel dinamik davranışı, zemin etkisi de dikkate alınarak anlaşılmalıdır. Bu çalışmada, bir model bacanın dinamik sismik davranışı, açıklıklar, baca temeli ve zemin etkisiyle ayrı ayrı ele alınarak belirlenmiştir. Bu çalışmanın bulguları, zemin-yapı etkileşiminin (ZYE), betonarme bacaların dinamik davranışını etkileyen önemli bir olay olduğunu ortaya çıkarmıştır.

**Anahtar Kelimeler:** *Zemin, yapı, etkileşim, deprem, baca, açıklık, sismik*

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# I. INTRODUCTION

Reinforced concrete (RC) chimneys are occupying an important part of most industrial factories that they have the responsibility of removal of waste and hot gases to the atmosphere away from the factory. As the development in technology, materials and other related factors, factories need higher RC chimneys with huge openings on the main body for flue ducts. From the preceding studies published in the technical literature that these openings on the main body of the RC chimneys make these tall and slender structures susceptible to wind and earthquake forces [1, 2, 3]. Also, it is known that soil-structure interaction (SSI) plays an important role on the dynamic response of RC chimneys. Some of the studies published in the technical literature about the effect of SSI and the effect of openings on the structural response of RC chimneys and also other engineering structures are given as follows.

Wilson [4] used the results of an experimental program to develop a non-linear dynamic analysis procedure for evaluating the inelastic response of tall RC chimneys. Huang *et.* al [5] presented the results of a response spectrum analysis of the 115 m. high Tüpras stack and a generic U.S. stack. Chmielewski *et.* al [6] studied about the theoretical and experimental free vibrations of tall industrial chimney considering SSI effect. Jaya *et.* al [7] studied about the seismic SSI analysis carried out for a deeply embedded ventilation stack proposed at a nuclear power plant building site, Kalpakkam in the state of Tamil Nadu. Du and Zhao [8] proposed a novel local time-domain transmitting boundary for simulating the cylindrical elastic wave radiation problem. Bagheripour *et.* al [9] dealt with SSI effect by using a new and integrated approach. Lavan and Levy [10] dealt with the optimal seismic design of added viscous dampers in yielding plane frames. Lou *et.* al [11] introduced the concept of structure–soil–structure dynamic interaction and discussed the research methods. Karaca and Türkeli [12] dealt with the determination and comparison of wind loads by using 10 RC chimneys with five different wind loading standards. Jayalekshmi *et.* al [13] carried out a three-dimensional (3-D) SSI analysis of 300 m high RC chimneys having piled annular raft and annular raft foundations subjected to along-wind load. Livaoğlu [14] investigated the effect of SSI on the sloshing response of the elevated tanks. Liu *et.* al [15] studied the responses of tall flexible structures such as TV towers when the vertical eccentricities between the discrete nodes and the corresponding centroids of investigated lumps are considered. Çakır [16] simulated a 3-D backfill–structure–soil/foundation interaction phenomenon using the finite element method in order to analyze the dynamic behavior of cantilever retaining wall subjected to different ground motions. Agelaridou-Twohig *et.* al [17] presented a simple method to calculate fire duration and flue gas temperatures for RC chimneys with fiberglass reinforced plastic liners based on experimentally determined burning characteristics of the liner material. Jisha *et.* al [18] dealt with the 3-D SSI analyses of tall RC chimneys with annular raft foundation subjected to wind loads. Karabork *et.* al [19] investigated the effect of SSI on the response of base-isolated buildings which indicate that SSI is an important factor to consider in the selection of an appropriate isolator for base-isolated structures on soft soils. Torabi and Rayhani [20] described a new 3-D finite element model (FEM) utilizing linear elastic single degree of freedom structure and a nonlinear elasto-plastic constitutive model for soil behavior in order to capture the nonlinear foundation–soil coupled response under seismic loadings. Belver *et.* al [21] studied about the dynamic behaviour of two chimneys in close proximity by using numerical analysis. Jayalekshmi *et.* al [22] presented numerical analysis of SSI of tall RC chimneys with piled raft foundation subjected to El Centro ground motion (1940) using FEM. Karaca and Türkeli [23] studied about the effect of slenderness on the wind response of industrial RC chimneys. Muvafık [24] dealt the field investigations and seismic analyses of a historical masonry brick minaret damaged during October 23 (Erciş) and November 9 (Edremit), 2011 Van earthquakes in Turkey. Jayalekshmi *et.* al [25] dealt with the numerical analysis of tall RC chimneys with piled raft foundation subjected to along-wind loads considering the flexibility of soil. Zhou *et.* al [26] studied about the seismic fragility assessment of a 240 m. tall RC chimney without considering SSI. Karaca *et.* al [27] dealt with the effect of fiber reinforced polymers (FRP) on the dynamic response of RC chimneys. Yön *et.* al [28] studied about the characteristics of ground motions of Van Earthquake and, deficiencies in structural elements and engineering faults such as poor workmanship and quality of construction, soft and weak stories, strong beam-weak column, short column, large overhang, hammering and unconfined gable wall are also investigated. Jayalekshmi *et.* al [29] carried out a parametric study about the SSI analysis for tall RC chimneys with piled raft foundation subjected to wind loads. Liang *et.* al [30] studied linear in-planesoil–structure interaction in 2-D in fluid-saturated, por-oelastic, layered half-space using the Indirect Boundary Element Method. Başaran *et.* al [31] investigated the earthquake behavior of historical masonry minaret of Haci Mahmut Mosque by using destructive and non-destructive tests to determine earthquake safety of this structure. Zhang *et.* al [32] formulated a new model by introducing the effect of soil structure and loading history into the cam clay model. Chen and Dai [33] presented the dynamic fracture analysis of the SSI system by using the scaled boundary FEM. Maedeh *et.* al [34] dealt with the development of the new coefficients for consideration of SSI effects to find the elevated tank natural period. Sharmin *et.* al [35] studied about the SSI effect on the dynamic response of offshore wind turbine by taking earthquake incident angle into account. Khazaei *et.* al [36] dealt with the soil-foundation-structure interaction by investigating the direct and the cone model.

It is clear from the literature survey that there is a need for the determination of the dynamic seismic response of industrial RC chimneys by considering the flexibility of the soil. In this study, direct method (using FEM) was selected for modelling the soil, the main body and foundation of the chimney. Moreover, the foundation and underlying soil of the chimney was developed by using solid finite elements. The main body of the chimney was constructed from shell elements. Also, at the boundaries of the modelled soil, transmitting boundaries (representing the effect of the truncated soil by using viscous dampers) were applied. These boundaries were proposed by Lysmer and Kuhlemeyer [37]. In order to investigate the effect of SSI on the dynamic seismic response RC chimneys, five different models were developed in SAP2000 structural analysis program. The detailed information about the models were given in the following sections of the study. Also, one type of soil under the chimney, i.e. soft soil, was selected from the technical literature and modelled by using direct method.

## II. RESEARCH SIGNIFICANCE

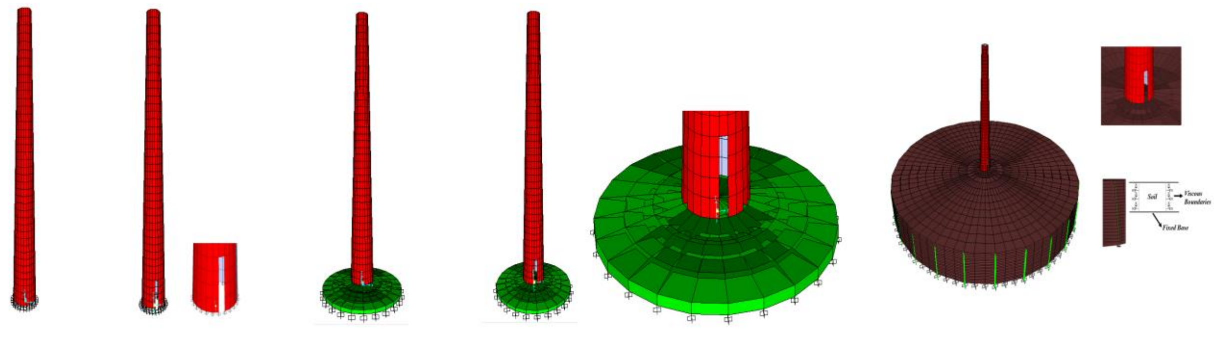
Today, industrial facilities need higher chimneys in order to meet environmental requirements specified in the codes. However, these taller and slender (decreasing shell thickness) structures become irremediable against winds, earthquakes or any other destructive actions of nature. From literature survey, it becomes clear that there are a few studies dealing with the 3-D structural analysis of these structures considering SSI effect. Also, some catastrophic incidents experienced in recent earthquakes compel us to revise our knowledge about the structural analysis of industrial RC chimneys with SSI effect. Therefore, it is inevitable to make such a research study on the effect of SSI on the dynamic seismic response of these tall and slender RC chimneys. This study is believed to form a combining bridge between the current and future studies. Also, in the future studies, the wind response with the other types of soils with different types of viscous boundaries will be studied by utilizing the findings of this study.

## III. Modelling Of Soil-Foundation-Chimney, Viscous Boundaries And Seismic Loading

In this study, the FEM of the underlying soil, the foundation and the main body of the chimney were developed in SAP2000 structural analysis program [38] which has the capability of making linear and non-linear structural analysis of the engineering structures in 2-D or 3-D (Fig.1-a-b-c-d-e). The main body of the chimneys were modelled by using shell elements. Also, the foundation and the underlying soil of the chimneys were developed by using solid finite elements that is called as “Direct Method” for SSI in the technical literature [39].

From Fig.1, it can be clearly seen that Model 1 has no opening and no foundation. Different from Model 1, Model 2 has an opening with no foundation. The Model 1 and Model 2 were modelled as directly fixed to the base without foundation. Model 3 has no opening with a foundation that is 26 m. in diameter. The only difference of Model 4 from Model 3 is the opening that is circumscribing an angle of 15 degrees with 7.50 m. in height. The opening starts from the base as shown in Fig.1. In Model 5, the underlying soil of the chimney was modelled by using solid finite elements (direct method). The diameter of the underlying soil is 2.50 times the diameter of the foundation diameter of Model 5. Moreover, as shown in Fig.1, viscous boundaries were adjusted to the boundaries of the underlying soil of Model 5 in order to investigate the effect of SSI on the dynamic response of RC chimneys. Also, the modelled soil layer has a thickness of 20 m or in other words, the bedrock under the chimney was assumed at 20 m. depth. After 20 m., the soil is assumed as fixed. In this study, one type of soil was taken into account namely S6 and the important characteristics of this soil was obtained from the technical literature and given in Table 1 [40].

Because of the memory limitation of the computer and after the approximation studies, appropriate number of finite elements were utilized in the modelling of soil, foundation and chimney. All of the finite element distribution of the models are given in Fig.1.



(a) (b) (c) (d) (e)

***Figure 1. (a)** No opening, no foundation and **(b)** With opening, no foundation and **(c)** No opening, with foundation and **(d)** With opening, with foundation and **(e)** With opening, with foundation and with soil*

***Table 1.*** *Characteristics of the soil used in the analyses [40]*

| Soil Type | Type | Elasticity Module *(kN/m²)* | Poisson's Ratio *(ν)* | Density (kg/m³) *(γ)* |
|---|---|---|---|---|
| S6 | Soft | 35000 | 0.4 | 1800 |

The chimney given in Fig.1 was selected from the technical literature [41] and there is an annular raft foundation under the chimney. Also, the effect of wind loading is not in the scope of this study. The chimney is constructed from RC whose unit weight, module of elasticity and Poisson's ratio are 23.5 kN/m$^3$, 30.000.000 kN/m$^2$ and 0.2, respectively. Moreover, the important structural characteristics of the chimney were given in Table 2.

The difficulty in simulating the infinite underlying soil under the RC chimneys can be overcome by modelling the near field soil with solid finite elements and considering the rest of the infinite soil by adding artificial boundaries to the end of near field (Fig.2). By using these types of boundaries, the reflecting and radiation effects of the propagating waves from the structure foundation layer may be avoided [40]. In Fig.2, the soil-chimney interaction taken into consideration in this study is given schematically. Moreover, the modelled system was analyzed based on direct method of SSI by considering the linear elastic material behavior of chimney structure, foundation and the underlying soil.

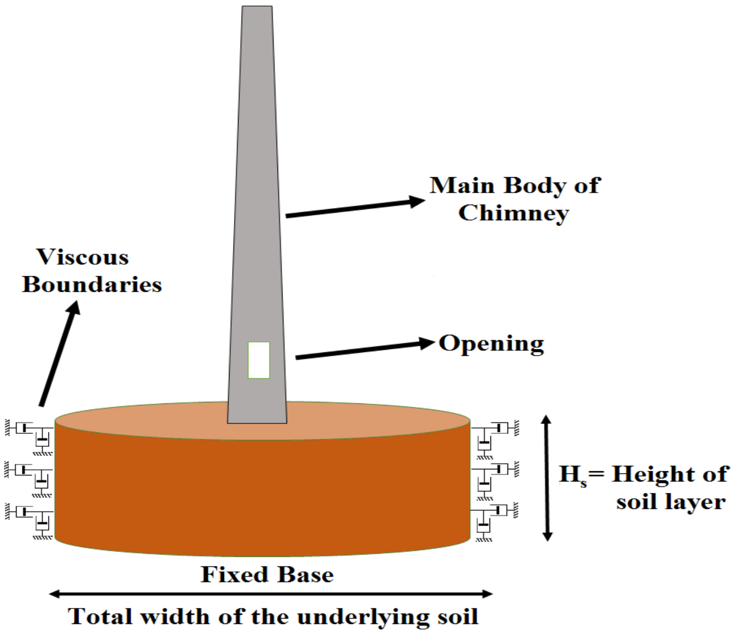



***Figure 2.*** *Schematical figure of soil-chimney-viscous boundaries*

*Table 2. Structural characteristics of the modeled chimney*

| Height from ground (m) | Outer Diameter at Base (m) | Inner Diameter at Base (m) | Outer Diameter at Top (m) | Inner Diameter at Top (m) | Foundation Diameter (m) | Foundation Height (m) |
|---|---|---|---|---|---|---|
| 75 | 7.5 | 6.5 | 4.0 | 3.6 | 26 | 2.5 |

In this study, the boundaries were modelled according to the method proposed by Lysmer and Kuhlemeyer [37]. According to this method, the boundary condition is a pair of stresses expressed as follows [42]:

$$\sigma = a\rho V_p \nu_n \tag{1}$$

$$\tau = b\rho V_s \nu_t \tag{2}$$

In Eq.(1) and (2), σ and τ are denoting the normal and shear stresses on the boundary, respectively. Also, $v_n$ and $v_t$ are the normal and tangential particle velocities of the boundary. The other parameters in Eq.(1) and (2), ρ, $V_p$, $V_s$, a and b are denoting the unit mass, velocities of P and S waves in the boundary material, dimensionless parameters, respectively. According to Lysmer and Kuhlemeyer [37], the standard viscous boundary corresponding to the choice of a = b = 1 provides maximum wave absorption. However, the absorption cannot be perfect over the whole range of incident angles by any choices of a and b. The viscous boundary condition corresponds to a situation in which the boundary is supported by infinitesimal dashpots oriented normal and tangential to the boundary. Also, the damping coefficients of the dashpots are for normal and shear directions [42]:

$$c_n = a\rho l_0 V_p \tag{3}$$

$$c_t = b\rho l_0 V_s \tag{4}$$

where, $l_0$, is the length of the boundary to which the dashpots are attached. Also, in the seismic analysis, it is assumed that the chimney is subjected to East-West component of the strong and severe ground motion (Fig.3) recorded at the Van Muradiye Meteorology Directorate station during the October 23, 2011 $M_w$ 7.2 Van Earthquake in Turkey [43].

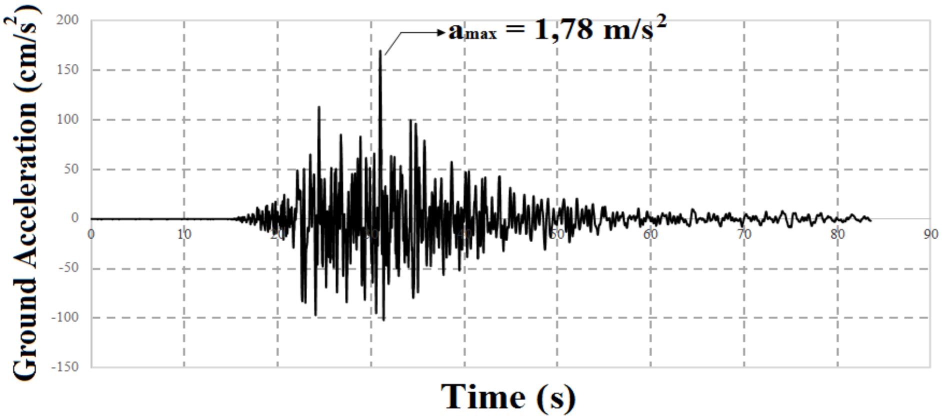



*Figure 3. E-W component of 2011 $M_w$ 7.2 Van Earthquake in Turkey*

## IV. RESULTS OF THE DYNAMIC ANALYSES

### *A. FIRST MODE PERIODS*

The first mode periods of the models are given in Table 3. In Table 3, the first four models are representing the ones without considering SSI effect. However, the last one, fifth model, is the one that considers and includes SSI effect in the dynamic seismic analysis.

***Table 3.*** *First mode periods of the models*

| Boundary Model | Soil Type | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|---|---|---|---|---|---|---|
| Lysmer and Kuhlemeyer [37] | S6 | 0.79366 | 0.80325 | 0.79617 | 0.80599 | 1.19641 |

Also, in order to visualize the difference better, these cited first mode periods are presented on a graph given in Fig.4.

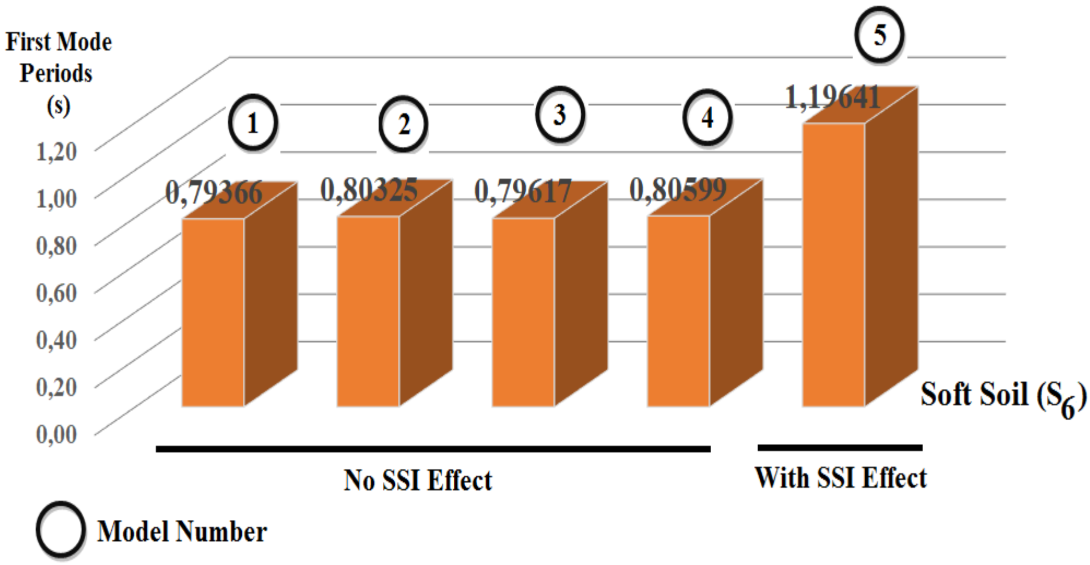



***Figure 4.*** *Graphical representation of the first mode periods of the models*

From the interpretation of Table 3 and Fig.4, some of the following results can be obtained. The only difference of Model 2 from Model 1, the opening on the body of the chimney, increased the first mode period from 0.79366 to 0.80325. Therefore, the effect of opening on the dynamic seismic response of RC chimneys should be taken into account in the dynamic analyses. Also, Model 3 that has no opening and includes foundation has larger first mode period when compared with Model 1. However, Model 3 has a smaller first mode period value when compared with Model 2 which shows that opening has more effect on the increase of first mode period when compared with adding foundation. It is an expected result that opening on the body of the chimney weakens the overall response of the structure. Moreover, Model 4 that has an opening and includes foundation has the largest first mode period among the first four chimney models. This shows that in the dynamic analyses of RC chimneys, both the effect of openings and the foundation should be considered. From Model 4 to Model 5, it is clearly seen that the first mode period increases rapidly and abnormally by considering SSI effect in the dynamic analyses. The first mode periods of the first four models are different but close to each other. However, the first mode period of the fifth chimney is far from the ones of the first four models. From the period point of view, this indicates the importance of considering SSI effect in the dynamic analyses.

## *B. TOP DISPLACEMENTS*

The top displacements of the models are given in Table 4 which are obtained at the time of maximum response.

***Table 4.*** *Top displacements obtained at the time of maximum response*

| Model No | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|---|---|---|---|---|---|
| Displacement (cm) | 36.41 | 37.82 | 36.61 | 38.59 | 105.3 |

It is clearly seen from Table 4 that the model that is constructed with the SSI effect has more top displacement than the others. Moreover, from Model 1 to Model 2, the top displacement increased from 36.41 cm to 37.82 cm which shows the effect of opening on the dynamic response of RC chimneys. Therefore, it can be said that openings adversely affect the dynamic behavior. Also, from Model 1 to Model 3, the top displacement increased from 36.41 cm to 36.61 which shows the effect of adding extra mass to the whole system. This extra mass is the foundation of the chimney. Both opening and the foundation increased the top displacement of the chimney. However, on the displacement point of view, the effect of opening is more dominant on the dynamic response of RC chimneys compared to adding extra mass (foundation). In fact, the effect of SSI is the most dominant when compared to openings and adding foundation to the system. For more clarity, the time history of the top displacements of the two models namely Model 4 and 5 is given in Fig. 5. The reason for selecting the time histories of the top displacements of these two models (Model 4 and 5) is to identify the effect of SSI clearly on the dynamic response of RC chimneys.

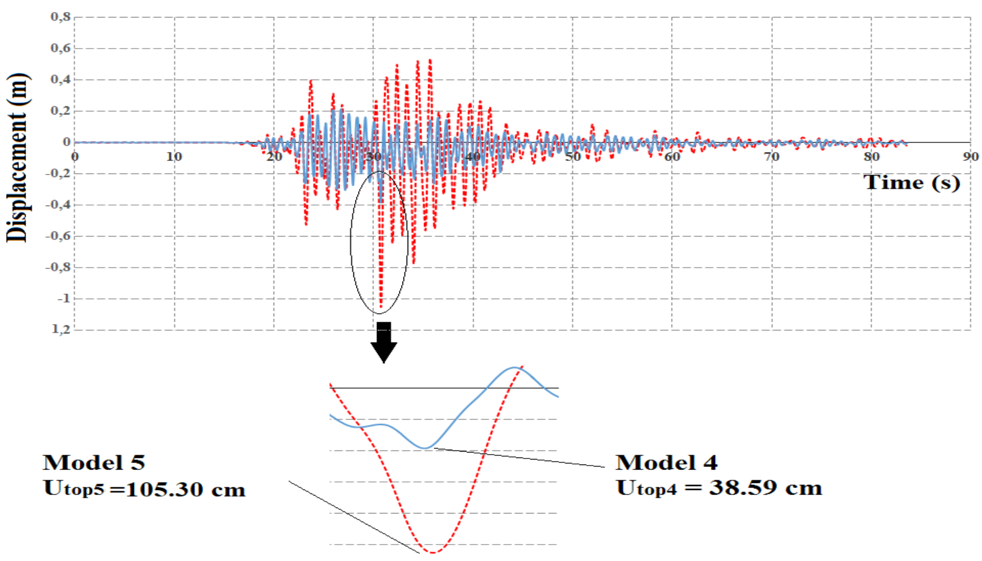



***Figure 5.*** *Time history of the top displacements of Model 4 and 5*

It is clear from Fig. 5 that at the time of maximum response, Model 5 showed approximately 3 times larger displacement compared to Model 4 on soft soil.

## *C. MAXIMUM TENSILE STRESS*

The maximum tensile ($S_{max}$) distribution (*in MPa*) obtained at the time of maximum response over the chimneys are given in Figs.6 and 7.

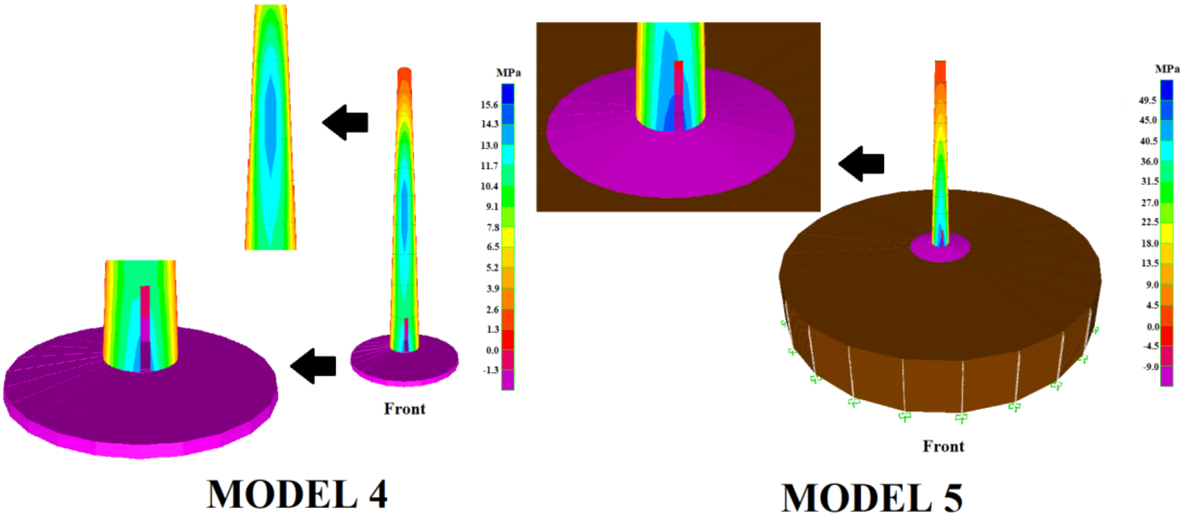



***Figure 6.*** *Maximum tensile stress ($S_{max}$) distribution over Model 4 and 5 (in MPa)*

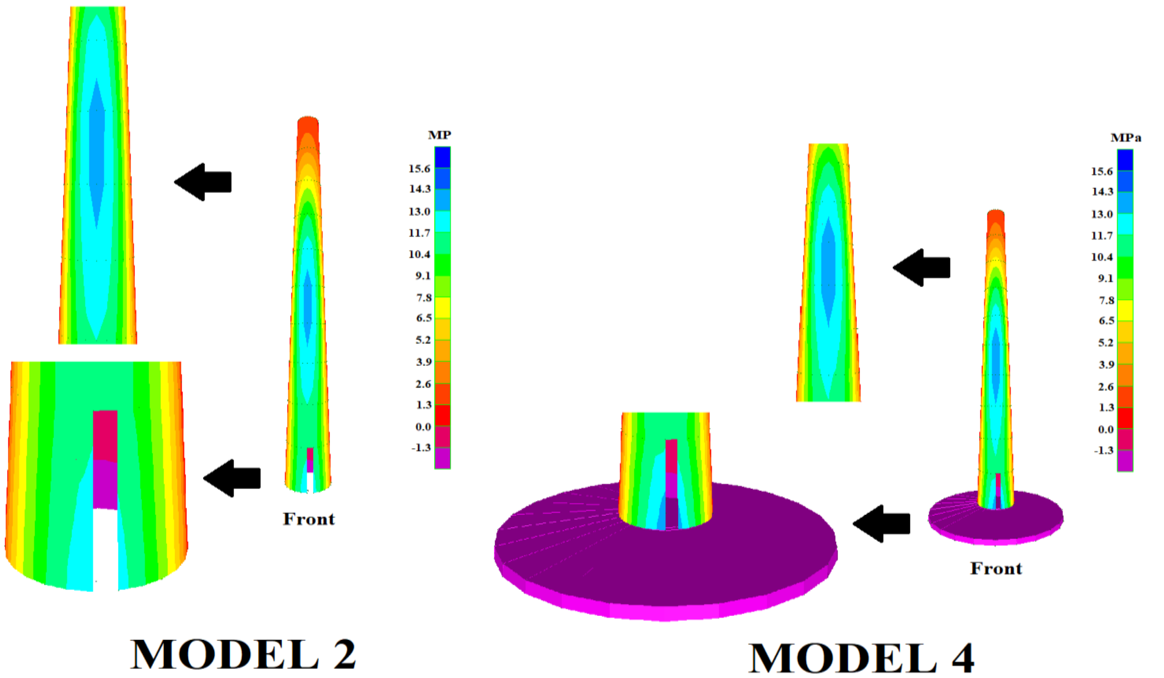



***Figure 7.*** *Maximum tensile stress ($S_{max}$) distribution over Model 2 and 4 (in MPa)*

From the interpretation of Figure 6, it is clearly seen that maximum tensile stress occurred on or over the region of openings for both Model 4 and 5. However, in Model 5, the maximum tensile stress accumulation is approximately 3 times larger than the one obtained from Model 4. It is due to the reason of the property of the soft underlying soil of Model 5 and due to the reason of the tensile stress caused by larger displacement. Morever, by adding extra mass to the structure (adding foundation to Model 2) (Fig.7), it can be clearly identified that the maximum tensile stress increased on the region of openings. These stress results obtained are consistent with the results obtained (Figs.6 and 7) under top displacement section of this study.

## V. DISCUSSION OF THE ANALYSES RESULTS

In this section, the results of the analyses are discussed under three categories namely first mode periods, top displacements and maximum tensile stress comparison. As expected the results of top displacements and maximum tensile stress distribution is closely related with the mode period of the RC chimneys especially with the first mode period [44]. Therefore, in the dynamic seismic analyses of the RC chimney, only the first mode is considered for comparison. From the first mode comparison, Model 5, that includes both opening, foundation and underlying soil (with SSI effect) has the largest first mode period. There is a sudden jump in the first mode period from Model 4 to Model 5. Therefore, especially for the chimneys that are constructed on soft soils, the SSI effect should be considered in the dynamic analyses. Also, for the chimneys that are constructed on soft soils, some extra precautions should be taken in order to enhance the overall behavior of the structure. For example, piled foundation can be preferred in order to limit the first period of the structure. Additionally, the soil can be reinforced by considering the suggestions of the geologists by using special techniques. By this way, the elasticity module of the soil can be enhanced. Other than these, the flexural behavior of the RC chimney is adversely affected from the openings that are on the body of the structure. From technical literature, it is clear that the zone of openings are the most vital regions for RC chimneys (Fig.6). There is maximum tensile stress accumulation at these vital opening regions. One of the collapsed (from opening region) RC chimney in 1999 $M_w$ 7.4 Kocaeli, Turkey Earthquake, 115 meters high Tüpras Refinery RC stack is given in Fig.8 verifying the results of the dynamic analyses obtained in this study [45,46].

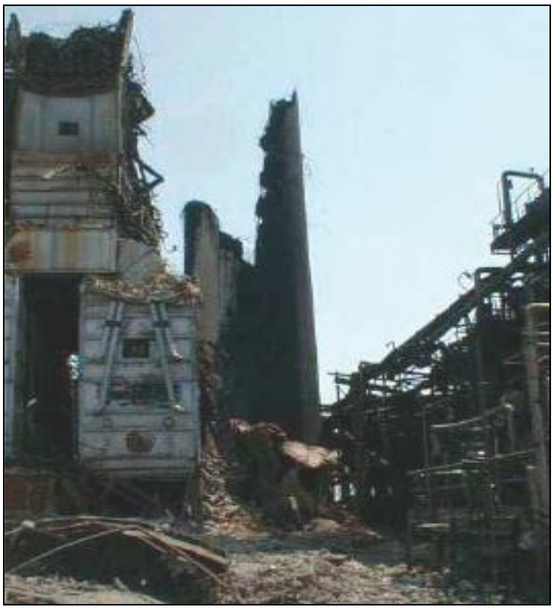


***Figure 8.*** *115 meters high collapsed Tüpras Refinery RC Chimney*

## VI. CONCLUSIONS

In this study, the effect of SSI on the dynamic seismic response of an industrial RC chimney is performed by using the ground motion recorded at the Van Muradiye Meteorology Directorate station during the October 23, 2011 $M_w$ 7.2 Van Earthquake in Turkey. In the dynamic analyses, the type of soil was selected as soft in order to better visualize the effect of SSI on the dynamic behavior of RC chimneys. Also, wind loading is not in the scope of this study. The overall results derived from the findings of this study and the resultant suggestions are summarized below.

The openings on the body of RC chimney and the foundation added to the structure adversely changed the overall dynamic response of the chimney. By adding openings to the shell of the RC chimneys and adding foundation to the structure increased the first mode periods, top displacements and maximum tensile stress accumulated around the region of openings. Therefore, some extra precautions should be taken to decrease these cited subjects. Also, for the region of openings, extra tensile and shear steel should be occupied in order to maintain the ductility and prevent brittle failure and lap splicing of longitudinal steel bars should be avoided.

By considering SSI effect with soft soil, the first mode periods, top displacements and maximum tensile stress accumulated around the region of openings increased approximately and abnormally three times compared to the ones that have no SSI effect. This showed the reason of sudden and brittle failure of RC chimneys around the region of openings. In order to maintain ductile behavior of RC chimneys, piled foundation can be preferred by considering the suggestions of the geologists. Additionally, the soil under RC chimneys can be reinforced by using jet grouting columns. By this way, the mechanical properties of the soft soil can be enhanced.

In summary, this study showed the importance of considering SSI effect on the dynamic response of RC chimneys. Although the results obtained in this study belong to one specific RC chimney with different structural characteristics, the findings, observations and suggestions can be generally used or applied to many situations. In order to generalize the results obtained from this study, it is considered as beneficial to use different boundary conditions with different types of chimneys, to consider different types of soils (medium or stiff), to change the diameter of the underlying soil gradually or to consider the depth of soil in the dynamic analyses.

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