SEISMIC ASSESSMENT OF TRANSMISSION TOWERS

by

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ABSTRACT

SEISMIC ASSESSMENT OF TRANSMISSION TOWERS

In the 21^{st} century, necessity for the electricity is growing more and more every day. In order to transfer huge amount of electricity, engineering is finding its way between mountains, rivers and valleys with the help of electricity transmission lines. However, external obstacles are not limited to geographical characteristics of the environment but also natural hazards such as earthquakes as the supply of electricity must be continuous in terms of economic and social outcomes. In order to keep continuous supply, seismic design of electricity transmission lines is proven to be very crucial in the late decades as a lot of catastrophic events were witnessed. In light of this need, an electrical transmission line in Istanbul region is instrumented with accelerometers and a modal identification study is conducted. Natural frequencies of the system are obtained by frequency domain decomposition method. These results are compared with modal values obtained from finite element model (FEM) of the system created according to the technical drawings. Furthermore, as transmission lines covers long spans, spatially varying ground motion excitations are simulated and applied in time history analysis to capture the realistic response of the system. In this study, it is shown that spatially varying ground motions and FEM updating based on modal identification results are significant in the determination of seismic demand on electrical transmission lines.

ÖZET

İLETİM KULELERİNİN SİSMİK DEĞERLENDİRMESİ

21. yüzyılda elektrik kullanımına duyulan talep hiç olmadığı kadar artmıştır. Bu yüksek talebi karşılamak için çok çeşitli mühendislik çözümleri geliştirilmiş, elektrik iletim hatları çok zorlu coğrafi şartlarda çok uzun mesafeleri kat edecek şekilde inşa edilmiştir. Ancak bu uzun mesafeleri kat ederken, depremler gibi doğal afetler de en az zorlu coğrafi koşullar kadar önemli bir engel oluşturmaktadır. Elektrik arzının sağlanamaması durumunda yaşanabilecek sosyal ve ekonomik zararların boyutu ne yazık ki geçtiğimiz on yıllarda gözlemlenmiştir. Bu ihtiyaçlar doğrultusunda, Istanbul ili sınırları içerisinde bulunan bir elektrik iletim hattı, ivmeölçer sensörler yardımı ile mod tanımlama çalışmasına tabi tutulmuştur. Elde edilen doğal salınım frekansı, teknik çizimlere göre hazırlanan sonlu elemanlar modelinden elde edilen sonuçlar ile karşılaştırılmıştır. Bunlara ilave olarak, elektrik iletim hattının kat ettiği uzun mesafelerde goz onunde tutularak, uzaysal olarak değişkenlik gösteren yer hareketleri simüle edilmiş ve zaman tanım analizi olarak sistem üzerinde uygulanmıştır. Bu çalışmada gösterilmiştir ki, mod tanımlama değerlerine göre güncellenen sonlu elemanlar modeli ve uzaysal olarak değişkenlik gösteren yer hareketleri analizleri sistem üzerine gelecek olan deprem yükü talebinin belirlenmesinde belirgin bir rol oynamaktadır.

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LIST OF SYMBOLS

A/V	Peak Ground Acceleration to Peak Ground Velocity Ratio
f	Frequency
g	Gravitational acceleration
HV	High Voltage
Hz	Hertz
kV	Kilovolt
kWh	Kilowatt hour
M	Magnitude
m	Meter
MPa	Megapascal
sec	Second
ζ	Damping ratio
π	Pi
ω	Angular frequency

LIST OF ACRONYMS/ABBREVIATIONS

AFAD	The Disaster and Emergency Management Presidency
FDD	Frequency Domain Decomposition
FEM	Finite Element Model
FEMA	The Federal Emergency Management Agency
FFT	Fast Fourier Transform
GMPE	Ground Motion Prediction Equations
NAFZ	North Anatolian Fault Zone
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Analysis
SVGM	Spatially Varying Ground Motions
TEIAS	Turkish Electricity Transmission Corporation

1. INTRODUCTION

1.1. Overview

In the late 19^{th} century, electricity began to take its role in the fate of humanity. In parallel with the beginning of electricity usage, it was realized that it was essential to find a way to transfer it over very long distances.

As a result of that need in the last century, the transfer of electricity has become a main problem to solve. Humanity created millions of kilometers of electric power transmission lines, transporting energy from where it is produced to where it is used. While it began as a very primitive system in the beginning, today these power transmission lines cover the whole earth like a huge spider web.

However, this was never an easy quest, as electric power transmission lines span continent-wide distances over challenging topographies. Passing rivers, mountains, and valley ranges are formidable obstacles and in addition to that, high winds and heavy snow make it even more difficult.

The factor of earthquakes has been long neglected in the installation and maintenance of electric power transmission lines, as extreme climate events such as hurricanes and blizzards comparingly occur much more frequently. However, in the last decades, this question has become more prominent, especially in earthquake-prone countries.

Turkey can be easily defined as an earthquake-prone region with several active seismic zones. Due to its high population, energy demand is increasing every day. However, intensive energy-usage zones in Turkey are highly concentrated in geographically small but highly populous and industrial urban areas which are usually very far away from energy production zones. Turkey's considerably large total area of electric power transmission lines are very important in its ability to meet the country's energy demand. In a post-earthquake scenario, maintaining electrical power is very crucial in terms of both saving human lives and preventing further economic loss. All rescue and medical services are dependent on electrical power systems, as are nearly all communication, natural gas, and water distribution systems. While electrical power systems are so vital in our modern day and age, these systems can be very old and/or inadequately designed in terms of withstanding earthquake loadings.

In understanding the current condition of an existing electricity power transmission line, there might be many unknowns. This is also true for its earthquake performance, as it will require detailed simulations to be run and analyzed. Spatially varying ground motions, which show the changes in ground motions due to filtering effects as the seismic waves travel in soil medium or coupling effect in the response of tower-cable systems can be an example to those unknows. Unknowns in excitations or structure can affect dynamic responses of the transmission line system and such an effect should not be neglected in seismic analyses and design. At this point, modal identification provides very valuable information for an existing structure to understand both its current condition and its real dynamic characteristics in the case of an earthquake.

In light of this need, a 60m tall tower-conductor electric power transmission line system is studied to understand its existing conditions and its seismic performance. Dynamic characteristics of the system are obtained by employing frequency domain decomposition (FDD) method. A finite element model (FEM) is created according to design drawings and compared with modal identification results. Spatially varying ground motions (SVGM) are simulated with several soil conditions, distances, and models to use in time-history analyses. This work showed that modal identification, adequate modeling of the system, and SVGM simulations are significant in the determination of seismic demands on electrical power transmission lines.

1.2. Literature Review

1.2.1. Historical Catastrophic Events

Historical catastrophic earthquake events show many examples of extensive damage occurred to electric transmission lines. Although the emphasis has been on the production and distribution systems, especially on the mechanical systems/parts of substations, transmission towers have also been shown to be susceptible to earthquake damage. In the literature, there have been only a few events where transmission tower damage was reported before the 90s. Subsequently, following the Loma Prieta and Landers earthquakes, there are many incidents where damaged transmission towers were observed. In particular, consecutive earthquakes in China over the last 20 years have resulted in devastating damage to electric transmission lines.

There have been many earthquakes reported where electric systems were heavily damaged. First, it should be noted that these recordings, and technology in general, were not as advanced in the beginning of the last century as they are today, and there remain many questions regarding post-earthquake damage reports from old events.

Although wind load is primarily considered in the design of transmission towers, earthquakes also can create drastic damage to transmission towers causing widespread failures within the electric power system. Historically, there are several examples of such damaging events.

The 1923 Kanto, Japan and the 1964 Alaska earthquakes are two examples which reported damaged/destroyed transmission towers, even for such a relatively early era (FEMA-202, 1990). As mentioned before, there is a little knowledge about the specific events that caused damage to the transmission towers. The 1976 Tangshan earthquake is also another example where relatively little information is available about the damage to transmission towers, despite a large portion of the power system having been paralyzed (Liu and Tang, 2012).

On October 17, 1989, the Loma Prieta earthquake (M=7.2) caused significant damage to local power systems. Many transmission towers collapsed, and power substation systems of 230 kV and 500 kV were seriously damaged. As a result, a population of 1.4 million people were affected (Liu and Tang, 2012).

Moreover, during the 1992 Landers earthquake, about 100 transmission lines and several transmission towers failed and/or were damaged (Hall *et al.*, 1995).

Two transmission towers collapsed during the 1994 Northridge earthquake (Liang and Hao, 2008), leading to loss of electric power for approximately 2.5 million people. The entire city of Los Angeles experienced a black out for the first time in its history. Power outages also affected many western regions of United States and even Canada (Hall, 1995).

The Kobe earthquake in 1995 (M=7.2) affected 38 transmission lines, 446 distribution lines and damaged many transmission towers, of which some collapsed. The Chi-Chi earthquake in 1999 (M=7.3) caused damage to 345 kV transmission lines. Wire and wireless telephone communication were also interrupted and not restored until 36 hours after the earthquake (Loh and Tsay, 2001).

The cause of failure for these transmission towers are documented in Table 1.1. While the majority failed because of foundation failures and displacements, the number of collapsed and deformed transmission towers is still significant. Furthermore, other types of electric facilities that sustained damage in the Chi-Chi earthquake can be seen Table 1.2 (Loh and Tsay, 2001).

Table 1.1. Failure of transmission towers in the Chi-Chi earthquake.

	Collapsed	Tilted	Deformed	Foundation Failure	Foundation Displacement	Total
345 kV	1	9	55	271	19	355
161 kV	9	4	9	131	4	155
69 kV	3	6	3	64	2	83

Table 1.2. Types of electric facilities damaged in the Chi-Chi earthquake.

Facility	**Number**
Hydro Power Stations	7
Thermal Power Stations	2
Transformer Stations	
1. 345 kV	5
2. 161 kV	6
3. 69 kV	13
Transmission Lines	
1. Major Switchyard	1
2. Circuits	
a) 345 kV	28
b) 161 kV	30
c) 69 kV	21
3. Towers	
a) 345 kV	355
b) 161 kV	155
c) 69 kV	83

Table 1.2. Types of electric facilities damaged in the Chi-Chi earthquake. (cont.)

Facility	**Number**
Distribution Lines	
1. Power Poles	
a) Broken	678
b) Fallen	773
c) Tilted	2.571
2. HV Switches	164
Underground Switches	44
3. Main Line Breakage	4.56
Customer Line Breakage	20.108
HV Cable Breakage	32.957/m
4. Pole-mounted Transformers	1.039
Box Transformers	93
Station Transformers	15
Underground Distribution Room (Flooded)	7
Office Buildings	30
Death Tolls	2
Water Supply	
Checker Dam	1
Purification Plants	30
Service Offices	12
Affected Customers	360.000

The 2007 Kashiwazaki earthquake was reported to cause nine pieces of 154 kV transmission tower to have member deformations. Several other transmission towers were reported to be damaged due to site ground deformation (Tang *et al.*, 2007).

Another devastating example is the 2008 Wenchuan, Sichuan province, China earthquake. More than 20 transmission towers collapsed and a 220 kV transmission line in Mao County was collapsed (Tian et al, 2017). The power grid lost about 40% of its load following the earthquake, even though only a small portion of the service area lied within the zone of severe shaking. This subsequently delayed the response of emergency responders and resulted in business interruptions (Liu, 2012).

The 2013 Lushan earthquake is another example of the catastrophic outcomes a natural disaster can have on electric power systems, with more than 39 transmission lines destroyed (Tian *et al.*, 2017). Moreover, hundreds of transmission towers (110 kV to 230 kV) were located on mountain ridge tops throughout the epicentral area that would have been exposed to PGA from 0.25g to 0.70g or more (Eidinger *et al.*, 2014).

Possible reasons for the failure of transmission lines can be listed as (Liu and Tang, 2012):

- Soil induced problems, such as liquefaction or differential settlement of the ground, which causes transmission towers to tilt, topple, or damage components, etc.
- Instability problems in the whole structure because of failures at vulnerable points.
- Partial fractures, such as insulators, connection hardware, etc.
- Wire breakage or short-circuits as a result of large earthquake stress responses.
- Tensile forces created by the collapse of a neighboring tower.

Therefore, it is clear that transmission towers must be analyzed under seismic actions in order to obtain data of the current condition of the power network. In order to do that, finite element models of the transmission towers would be created and evaluated under select ground motion excitations.

1.2.2. Finite Element Modeling (FEM)

Long (1974) was among the pioneers who analyzed the seismic response of transmission lines; who analyzed the tower portion without the effects of lines and conductors. As a simpler model, the tower was idealized as a uniform cantilever upper part and rigid bottom part in order to calculate absolute displacements. Transverse, longitudinal, and vertical earthquake directions were considered. The forces calculated in all cases were found to be safe. It is notable that the tower used in this study was a relatively rigid one, with the lowest frequency at 5 Hz.

Kotsubo *et al.*, (1985) measured the dynamic properties of the towers before and after the installation of conductors in order to see their effect on the change of dynamic properties. Ambient vibration measurements were taken before cables were installed. Natural frequencies, mode shapes, and the damping ratios of the towers were measured using FFT analysis. Moreover, a forced vibration analysis was implemented after the installation of cables. A significant change in the dynamic properties of the towers was not observed. Following that, earthquake response calculations for the tower were carried out without modelling cables.

Following them, Li *et al.*, (1991) analyzed a long series of transmission towers with and without considering the effect of conductors. In those analyses, three version of the models were chosen: a tower without conductors, a tower with lumped masses of conductors at relevant points, and the coupled tower-cable model. It is shown that for both vertical and longitudinal ground motions, responses of the models were different, showing that the effects of conductors are not negligible and should be considered.

Suzuki *et al.*, (1992) also conducted an analysis that takes the conductors into consideration. In their approach, the effect of overhead wires is taken into account with the use of spring elements. They carried out a coupled response analysis by using frequency response method to show that it is possible to obtain the response value for the definite phase or stiffness condition, which is the case of equiphase, antiphase or fix.

Li *et al.*, (1994) investigated the seismic response of a transmission line. The tower was modelled as a lumped mass and only free to move in the horizontal direction. The towers were assumed to be vibrating in phase. Cable masses were assigned as lumped masses at each 1/5th section of the cables. Ground motions were also assumed to be acting in a longitudinal direction. Three different ground motions were used to represent three different soil types, namely soft, medium, and stiff site. Two models were used with and without conductors in order to investigate the effects of the conductors. It was shown that the tower-cable interaction was significantly affected by the seismic response of the towers.

El Attar *et al.*, (1995) carried out a study in order to investigate the effects of vertical seismic forces. Two different earthquake ground motions were used in order to show the effects of different peak acceleration/velocity (A/V) ratios. It was shown that responses were significantly different for the low and high A/V earthquakes. There was no analysis for a coupled tower conductor system.

Ghobara *et al.*, (1996) investigated the support movement in transmission lines. Three factors were identified as wave travel effect, incoherency effect and site effect. It was shown that the same ground motion does not produce the worst-case scenario for all towers. It was also seen in this research that the contribution of lateral ground motion to the increase in cable tension was small, with the incoherency of seismic waves being more significant than the velocity of wave propagation.

Lei and Chien (2005) investigated the dynamic behavior of a group of transmission towers. The effects on the cables were analyzed considering both geometric and material nonlinearities in the system. Interaction force between towers and wires were modelled. It was shown that ignoring wire action effects on the dynamic behavior of transmission towers may cause significant errors in member forces.

Liang and Hao (2008) investigated the responses of transmission towers under damage-limitation and rare earthquakes. It was shown that although most of the element forces and displacements under the earthquake loadings are less than the design forces, at different types of sites there are seismic loading dominated elements.

Another issue is in the deflection estimations made via calculations. Actual deflection measurements made in tests are higher than those found via calculations. In addition to the bending and buckling of the members, due to joint properties like bolt slip and splice plate, deformations should be considered in order to calculate the actual deflections (Ramalingam and Jayachandran, 2016).

The effect of horizontal support's movement has also been investigated in the literature (Shu *et al.*, 2016). It was shown that half-scale test tower models can reasonably represent the actual behavior of a full-size tower. It was demonstrated that bracing members close to the supports must be designed in order to reduce their slenderness.

It was also shown that the configuration of towers is very important in the analysis, as it can change the failure mode of the tower. Even if the towers are found to be safe under design level earthquakes, a detailed analysis showed that member failures can happen through buckling or axial yielding (Park *et al.*, 2016).

Tian *et al.*, (2016) conducted an experimental study on the effects of spatial variation of ground motions on dynamic responses of electric transmission line systems. An array of three shake tables is used to determine the effects of non-uniform excitations on dynamic response of transmission towers. It was demonstrated that, SVGM can significantly amplify tower responses.

Miguel *et al.*, (2021) showed that modeling approach on transmission towers have a significant effect on the seismic assessments. A stand-alone transmission tower model is compared with a tower-line section, and it is shown that responses are significantly different. Moreover, it is also shown that significant structural damage is observed even for moderate ground motions.

1.2.3. Spatially Varying Ground Motions (SVGM)

Harichandran and Vanmarcke (1986) examined recorded accelerograms to determine the frequency-dependent spatial correlation of earthquake ground motions. A preliminary mathematical model is suggested for the space-time correlations.

Luco and Wong (1986) presented a method to obtain the dynamic response of an extended rigid foundation when subjected to a SVGM. Numerical results for a ground motion characterized by a particular spatial coherence function are described.

Zerva *et al.*, (1988) investigated lifeline response to spatially variable ground motions. As lifeline systems cover long spans, significance of SVGM is examined on pipelines and bridges. It is shown that SVGM can give high differential displacements especially in pipelines.

Hao (1989) investigated the SVGM recorded in Taiwan (SMART-1). A coherency function is suggested as a function of frequency and separation distance. A method is represented to simulate spatially varying ground motions. Numerical methods to represent the structural response to SVGM are also presented. Deodatis (1996), proposed a simulation method to generate functions of a stationary, multivariate stochastic process for a prescribed cross-spectral density matrix. An example work on turbulent wind velocity fluctuations is proposed.

Deodatis (1996), introduced a method for generating seismic ground motions for the application of earthquake ground motion simulation. A scheme is described which is compatible with prescribed response spectra. Moreover, this scheme includes the wave propagation effect and correlated according to a given coherence function.

Zerva and Zervas (2002), reviewed the spatial variation of seismic ground motions. The estimation of coherency from recorded data and its interpretation is presented. Simulation techniques for the generation of SVGM is compared.

Chouw and Hao (2004) investigated the effect of SVGM and soil-structure interaction. The study showed that assumption of uniform ground motion excitation can significantly underestimate the pounding potential, where soil is soft and ground motions have low dominant frequencies.

Bai *et al.*, (2010) investigated the effect of SVGM on a case study of a long-span steel trussed arch bridge which resulted in the amplification of structural response compared to uniform excitations. It is also presented that, on this case study, consideration of both vertical and horizontal excitations simultaneously leads to a more accurate response prediction.

Tian *et al.*, (2017) studied the effects of SVGM in seismic response of the transmission towers. It was found that the SVGM can significantly amplify tower responses.

1.3. Objective

Istanbul is a mega city hosting a population of 20 million, with a concordantly gigantic demand for electric power (approx. $35\text{x}10^9$ kWh/year). Therefore, electric power supply is of grave importance as the city stands at the epicenter of the entire national economy. When earthquake performance is concerned, it is even more important due to the post-earthquake needs of the mega city. However, the Turkish Design Code is very limited in electricity power transmission lines. Consequently, a better insight is required to understand the behavior of the system in order to make more realistic assumptions during the design process. Modal identification techniques are utilized at this stage to get a better insight of this electric power transmission line, which will lead to a better reflection of its behavior.

Modal identification is widely used, with a high level of confidence, to understand the behavior of existing structures. Istanbul, and Turkey in general, have always been acknowledged as an earthquake-prone zone with poorly designed structures. Therefore, modal identification techniques can be very helpful in understanding the performance of the system in a very likely event of an earthquake.

In this study, an ambient vibration test is conducted, first, on the electric power transmission line. Subsequently, modal identification is applied, utilizing the frequency domain decomposition method, in order to determine the dynamic characteristics of the system. Then, FEM of the system is created according to the technical drawings and is compared to the findings from the ambient vibration test. A SVGM simulation code is run to get realistic ground motion inputs to use in the time history analyses.

1.4. Scope of the Study

This study is as follows: In Chapter 1, the motivation of the study, a literature review, the objectives of the study and the scope of the project are presented.

In Chapter 2, the modal identification process is explained. Moreover, in this chapter, the frequency domain decomposition method is presented. The chapter covers the theoretical base of the modal identification process. The transmission line system itself, the location of the system, instrumentation of the system and the instruments are also introduced in this chapter.

In Chapter 3, Spatially varying ground motions are discussed. Different models are investigated to find the most suitable approach to use in the analysis of transmission line at focus.

In Chapter 4, the finite element model is described in detail. Different modeling techniques are discussed, and a comparison of such techniques are provided. The mathematical models and the results obtained from these models are presented. The seismic demand on the system is also calculated and presented in Chapter 4. Brief information about the site and seismology of the area are provided. Finally, Chapter 5 provides conclusion, which includes the findings of this study. The results of the analyses, comments on such results and possible future work are discussed.

2. MODAL IDENTIFICATION

2.1. General

Modal identification techniques can be grouped as frequency or time domain, while another approach may be to check if such techniques involve an input-output analysis or an output-only analysis. The former involves an excitation source, such as a forced vibration generator or an earthquake input. The latter, however, can be exemplified with ambient vibration tests, which use comparingly low amplitude and broad band frequency inputs created by natural environment.

This study utilizes an output-only method in the frequency domain. An ambient vibration test is conducted to get such dynamic characteristics via the Frequency Domain Decomposition (FDD) method.

2.2. Instrumented Electric Power Transmission Line

Experimental work is needed in order to understand the real dynamic behavior of a transmission line system. Finite element models created by using technical information from several stakeholders would not be able to reflect the real-world situation as they involve many assumptions and approximations, such as material strength, connection details, etc.

Following this problem, dynamic identification techniques are very useful solutions for understanding the current situation of existing structures. Using accelerometers placed in several points on the structure, ambient vibration tests can be undertaken to obtain vibration data.

In this specific case, it is hard to conduct an ambient vibration test on a transmission line system. One straightforward reason is the need for special technicians who would climb to sixty meters on the transmission towers and place accelerometers as planned before. Another issue is the nature of the transmission line systems, as it is very hazardous and risky in various ways to conduct such an ambient vibration test while the lines are in operation. Therefore, very short window of time exists, when the entire system is ready to operate but is still offline.

The project is planned to incorporate a total of seven sensors at three different locations along the height of the transmission tower. These locations are chosen to capture the possible mode shapes of the transmission tower. The sensors and the data acquisition system used can be seen in Figure 2.1 and Figure 2.2, respectively.

Figure 2.1. Kinemetrics EpiSensor (Kinemetrics).

Figure 2.2. Kinematics Granite Data Acquisition System (Kinemetrics).

The selected transmission tower is a typical transmission tower which is widely used by the state institution, and it has a height of approximately 60m. Station heights are selected to be 20m, 40m and 60m, respectively, and can be seen in Figure 2.3. A single sensor is placed in 60m height in the opposite side to capture the torsional mode shapes.

Following completion of all the preparation and official permission processes, a field work is conducted with the assistance of the state institution and their technicians. The approximate location of the examined transmission tower can be seen in Figure 2.4. The sensors are placed in the selected locations using specifically modified connection parts. Sensors in their respective places can be seen in Figure 2.5. Data acquisition is initiated once all sensors are in place (Figure 2.6).

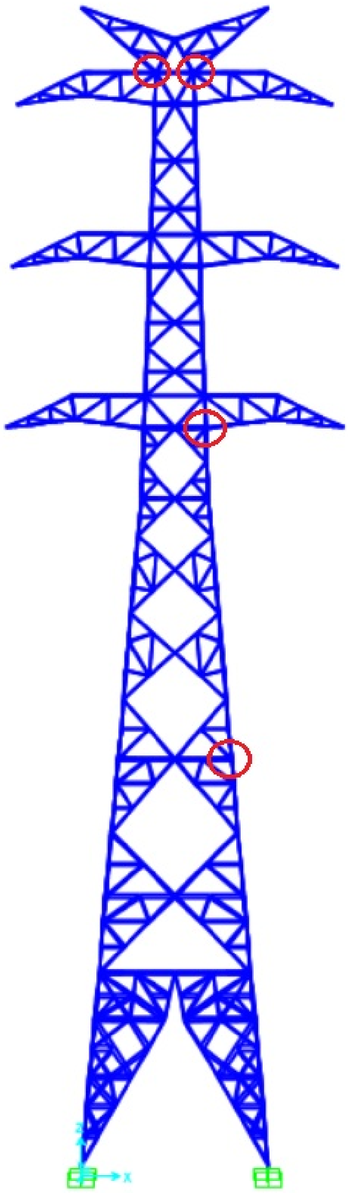

Figure 2.3. Transmission tower and sensor stations.

Figure 2.4. Approximate location of transmission tower examined.

Figure 2.5. Sensors placed.

Figure 2.6. Technicians placing the sensors.

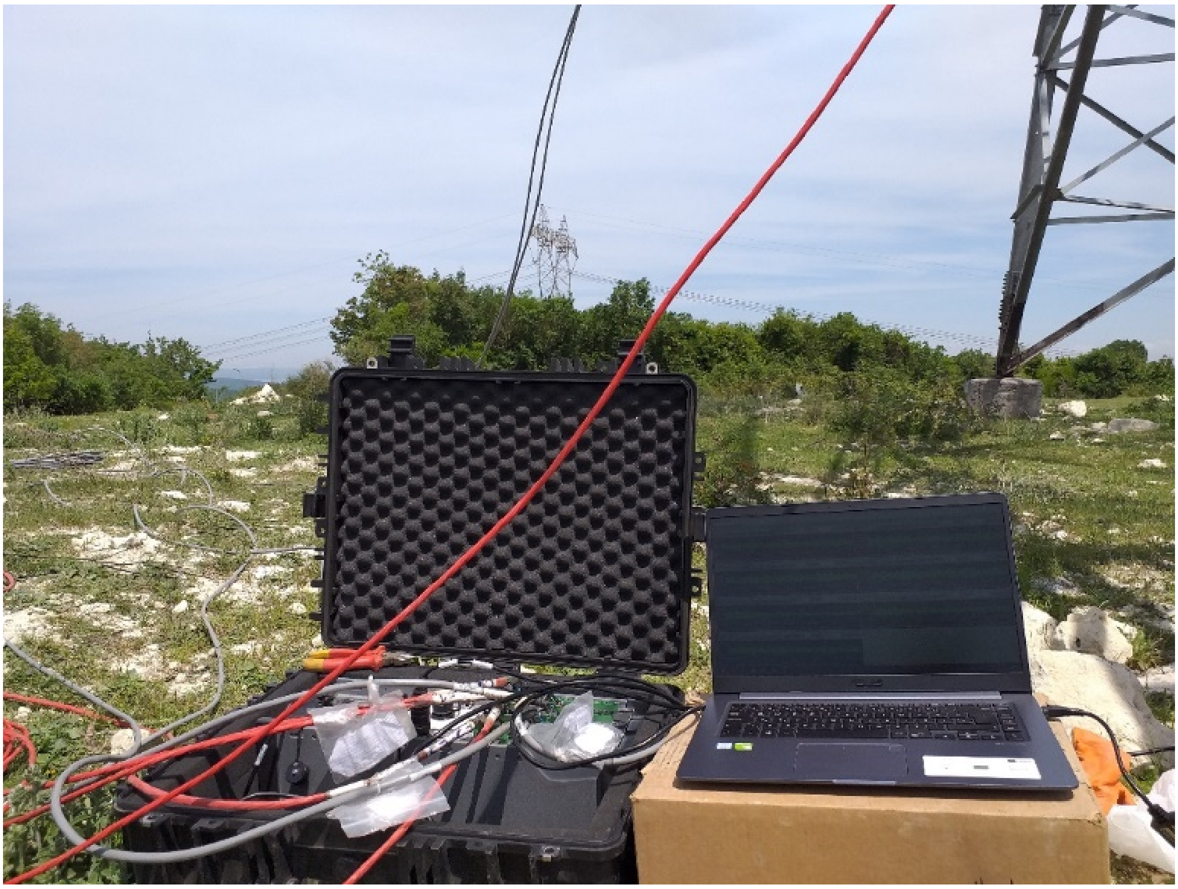

Figure 2.7. Data Acquisition system used.

2.3. Analysis Results

Representative ambient vibration data for the transmission line direction mid-tower sensor and the transverse direction mid-tower sensor can be seen in Figure 2.7 and Figure 2.8, respectively.

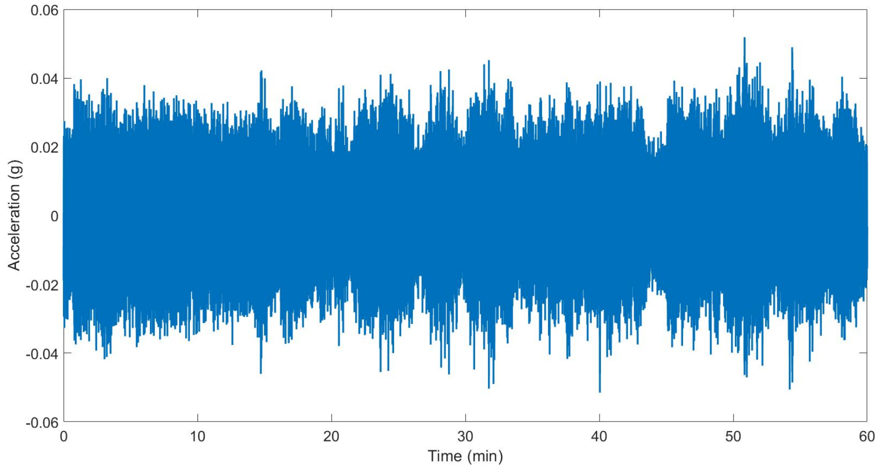

Figure 2.8. Representative ambient vibration data from mid-tower sensor in transmission line direction.

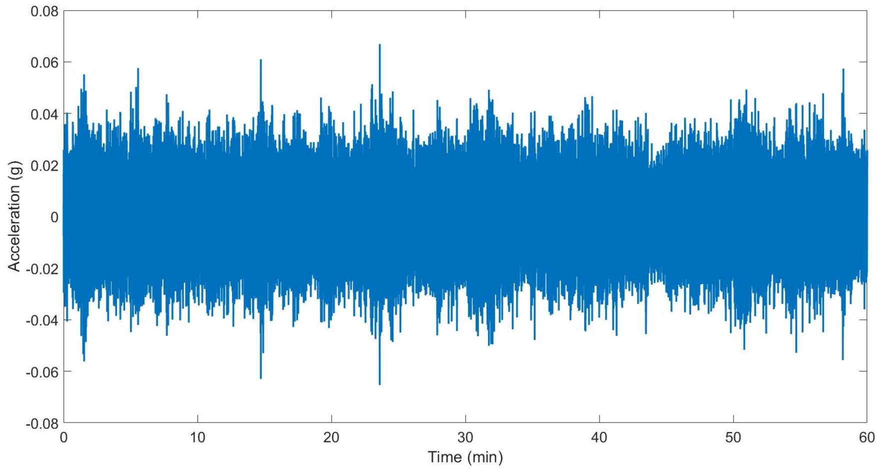

Figure 2.9. Representative ambient vibration data from mid-tower sensor in transverse direction.

Frequency Domain Decomposition (FDD) code is utilized via MATLAB and the data is analyzed to determine the structural dynamic properties of the transmission tower. Mode frequencies in both directions can be seen in the Figure 2.9 and Figure 2.10, respectively. It should be noted that, some twin peaks can be observed in the figures which is caused by the symmetricity of the towers. As a result of the symmetricity of the towers, natural frequencies are very close to each other and this results in twin peaks around natural frequencies.

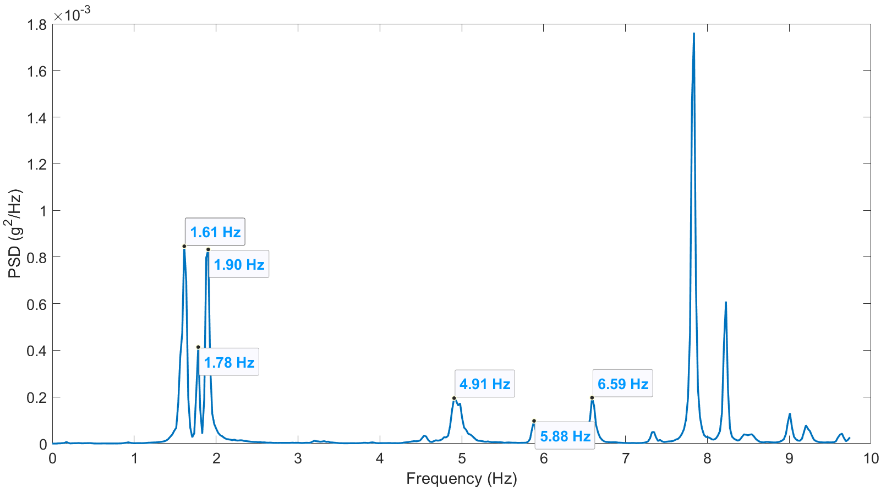

Figure 2.10. Transmission line direction natural frequencies.

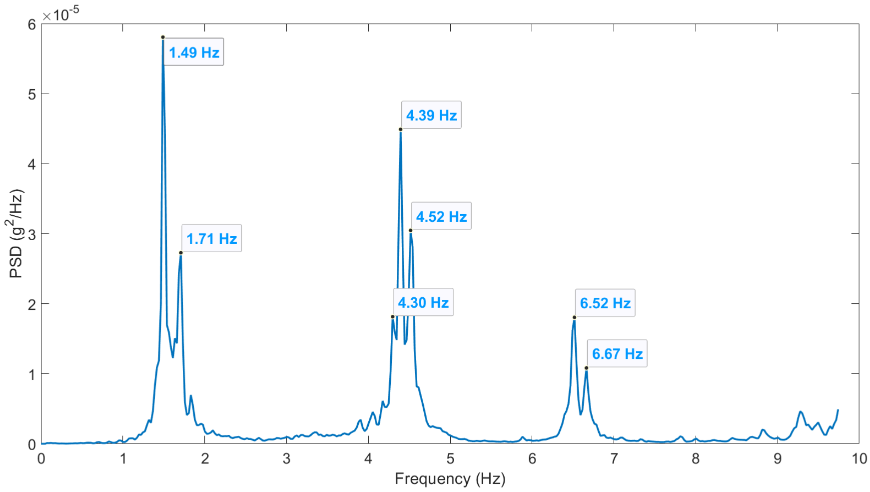

Figure 2.11. Transverse direction natural frequencies.

Following the analysis, first three modal periods are obtained in both transverse and transmission line directions.

Table 2.1. Ambient vibration test results for the first three modes in both directions.

	Transverse direction			Transmission line direction		
	1^{st} mode	2^{nd} mode	3^{rd} mode	1^{st} mode	2^{nd} mode	3^{rd} mode
Ambient Vibration Results (sec.)	0.67	0.23	0.15	0.62	0.20	0.15
Ambient Vibration Results (Hz)	1.49	4.39	6.52	1.61	4.91	6.59

In addition to modal frequencies, an analysis was made to investigate the mode shapes of the tower in both directions. However, significant results could not be obtained due to limited number of sensors in the ambient vibration test. In future works, an ambient vibration test with a dense instrumentation can be more helpful in obtaining the modal shapes. In addition to that, using half power method, damping ratios were investigated however an exact ratio could not be obtained. It should be noted that, damping ratio is obtained as 5% from one data set and 2% from the other data set.

3. SPATIALLY VARYING GROUND MOTIONS

3.1. Simulation of Ground Motions

Ground motions will vary as they travel through a medium, as would any other wave type. As a result, such variation will change the ground motion and the motions will be different at different points along their way. Therefore, such variation along different locations are defined as spatially varying ground motions (SVGM).

This phenomenon is caused by the change of ground motions which is governed by the distance and the medium they travel in. Moreover, ground motions will have different wave passage velocities, as the medium is changed. As a more general description, the same event will be observed differently and will have different effects on structures at different locations.

As distance increases, the similarity between ground motions at different locations will be lower as they will change through the medium they travel in. Such change is described by coherency, in terms of both amplitude and phase. Together with the distance, the velocity of wave passage will be changing and affecting the arrival time of the wave in space. Furthermore, as the arrival time of the ground motions will be different, the response of the structures at such locations will not be synchronized. This unsynchronized response of different parts of the structure will alter the overall behavior as expected.

Another governing parameter is the medium in which the waves travel. If different soil types exist at different locations along the way of the waves, the response of the structures at such locations will again differ.

To summarize, there is a need to describe how these parameters affect the response of the structures, and SVGM are used to address this need. In this study, since there is a very long distance between the examined transmission towers (i.e., 500m), ground motions will not be identical at each tower, and as a result, response of each tower and the overall tower-cable system will be different.

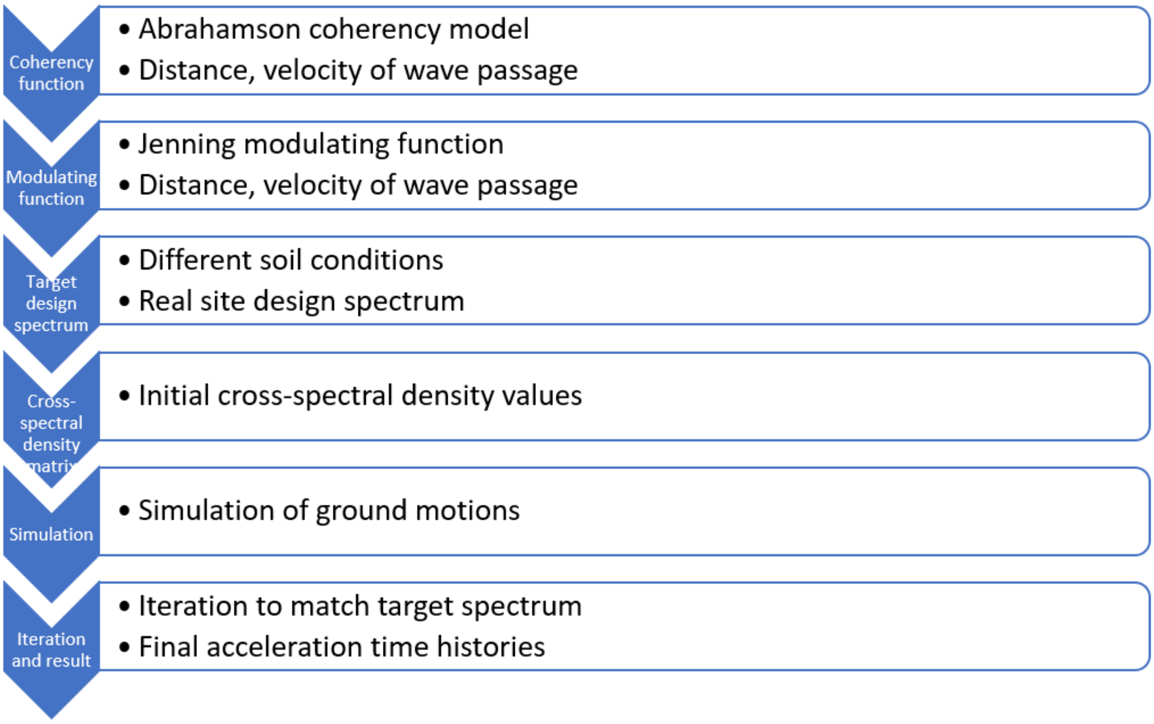

Figure 3.1. Scheme to obtain design spectrum compatible acceleration time histories.

A MATLAB script is written in order to simulate these spatially varying ground motions for three transmission towers.

The script uses given values such as separation distances for three points (50m, 200m and 500m) and velocity of wave propagation (2000m/s, 1000m/s, 500m/s and 250m/s). Three ground motion time histories, which have a duration of 18.85 seconds, are created.

These ground motion time histories are modeled as uniformly modulated non-stationary stochastic vector processes, by using coherency functions to describe the coherency between ground motions, modulating functions to include wave passage effect and the desired target design spectra in order to reflect soil conditions on site.

Three ground motions are modeled in an iterative fashion. Power spectral density functions are set to an initial constant value over the entire frequency range first, then with an iteration of 10, they are matched with the target.

The cross spectral density matrix used is:

$$S^0(\omega,t)\begin{bmatrix} S^0_{11}(\omega,t) & S^0_{12}(\omega,t) & S^0_{13}(\omega,t) \\ S^0_{21}(\omega,t) & S^0_{22}(\omega,t) & S^0_{23}(\omega,t) \\ S^0_{31}(\omega,t) & S^0_{32}(\omega,t) & S^0_{33}(\omega,t) \end{bmatrix} \tag{3.1}$$

where

$$S^0_{jj}(\omega,t) = |A_j(\omega,t)|^2 S_j(\omega), j = 1,2,3 \tag{3.2}$$

$$S^0_{jk}(\omega,t) = \ A_j(\omega,t)A_k(\omega,t)\sqrt{S_j(\omega)S_k(\omega)}\Gamma_{jk}(\omega), j,k = 1,2,3; j \neq k. \tag{3.3}$$

For the special case of a uniformly modulated non-stationary stochastic vector process, the modulating functions $A_j(\omega,t) = j = 1,2,3$ are independent of the frequency ω where

$$A_j(\omega,t) = A_j(t), j = 1,2,3. \tag{3.4}$$

Therefore, cross-spectral density is represented by:

$$S^0(\omega) = \begin{bmatrix} S_1(\omega) & \sqrt{S_1(\omega)S_2(\omega)}\Gamma_{12}(\omega) & \sqrt{S_1(\omega)S_3(\omega)}\Gamma_{13}(\omega) \\ \sqrt{S_2(\omega)S_1(\omega)}\Gamma_{21}(\omega) & \sqrt{S_2(\omega)} & \sqrt{S_2(\omega)S_3(\omega)}\Gamma_{23}(\omega) \\ \sqrt{S_3(\omega)S_1(\omega)}\Gamma_{31}(\omega) & \sqrt{S_3(\omega)S_2(\omega)}\Gamma_{32}(\omega) & \sqrt{S_3(\omega)} \end{bmatrix}. \tag{3.5}$$

Subsequently, the cross-spectral density matrix is decomposed using the Cholesky Method, such as;

$$S^0(\omega, t) = H(\omega, t)H^{T*}(\omega, t) \tag{3.6}$$

$$S(\omega, t) = \begin{bmatrix} H_{11}(\omega, t) & 0 & 0 \\ H_{21}(\omega, t) & H_{22}(\omega, t) & 0 \\ H_{31}(\omega, t) & H_{32}(\omega, t) & H_{33}(\omega, t) \end{bmatrix}. \tag{3.7}$$

If the off-diagonal elements are written in polar form as:

$$H_{jk}(\omega, t) = |H_{jk}(\omega, t)|e^{i\theta jk(\omega,t)} j = 2, 3; k = 1, 2; j > k \tag{3.8}$$

where

$$\theta_{jk}(\omega, t) = tana^{-1}\left(\tfrac{\mathrm{Im}[H_{jk}(\omega,t)]}{\mathrm{Re}[H_{jk}(\omega,t)]} \right). \tag{3.9}$$

Following the above, the non-stationary stochastic vector process can be simulated by the following series:

$$f_j\,(t) = 2\sum_{m=1}^{3}\sum_{l=1}^{N} |H_{jm}\,(\omega_l, t)|\,\sqrt{\Delta\omega} \times cos\,[\omega_l t - \theta_{jm}\,(\omega_l, t) + \Phi_{ml}] \tag{3.10}$$

where

$$\omega_l = l\Delta\omega, l = 1, 2, \ldots, N \tag{3.11}$$

$$\Delta\omega = \tfrac{\omega_u}{N} \tag{3.12}$$

$$\theta_{jm}\,(\omega_l, t) = tan^{-1}\left(\frac{Im\,[H_{jm}\,(\omega_l, t)]}{Re\,[H_{jm}\,(\omega_l, t)]}\right). \tag{3.13}$$

ω_u represents an upper cut-off frequency and $\Phi_{1l}, \Phi_{2l}, \Phi_{3l}, l = 1, 2, \ldots, N$ are the three sequences of independent random phase angles distributed uniformly over the interval $[0,2\pi]$ (Deodatis, 1996). As a result of this randomness, each simulation will create a different set of ground motions. An example this randomness can be seen in Figure 3.2 a) and Figure 3.2 b).

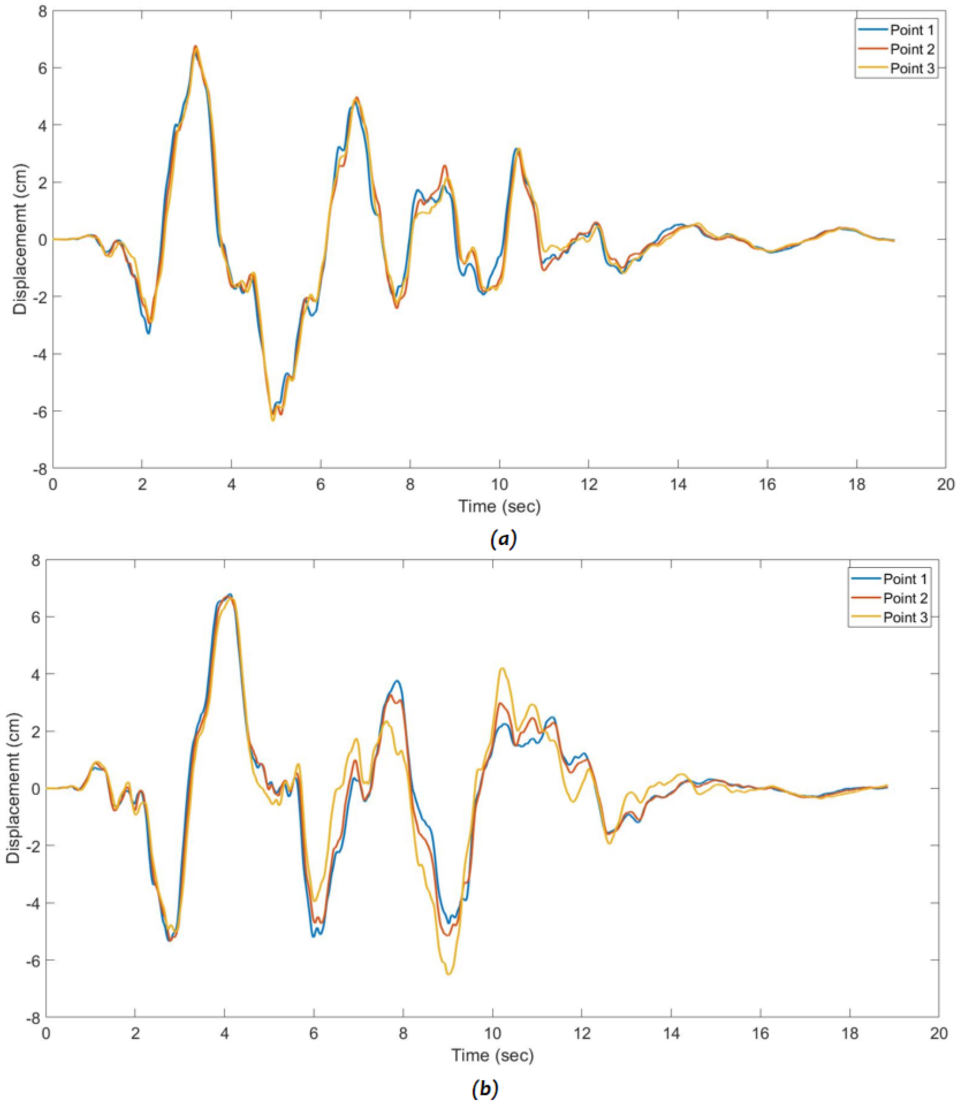

Figure 3.2. Simulated displacement time histories with 50m distance and same soil types. Even though they have exactly same values, due to the random nature of the process, each ground motion simulated is unique ((a) first run of the simulation code, (b) second run of the simulation code).

It should be noted here that another approach in literature is using a pre-determined power spectral density function which also represents the soil conditions for each point, and then comparing such three ground motions by their response spectra. However, in reality, power spectral densities of the expected ground motions cannot be known due to their random nature. Therefore, this study utilizes the former method.

Several different coherency models are compared in order to analyze the effects of different approaches.

3.1.1. Modulating Function

Jennings modulating function is used for all different distances between transmission towers with all velocity of wave passage values. This model includes wave passage effect and amplitude variation as a function of time (Jennings, 1968).

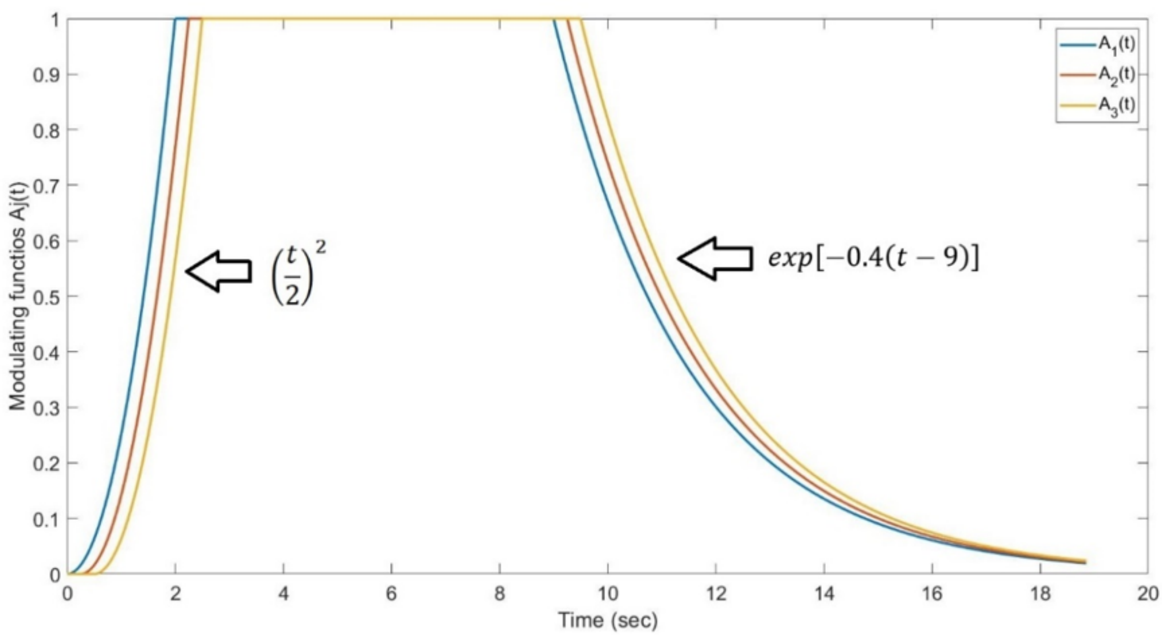

Figure 3.3. Jennings modulating function for 500m distance between each tower with Vs=2000m/s.

3.1.2. Coherency Models

As the distance increases between points that are examined, ground motions will differentiate as a natural outcome of their travel in soil medium (lagged coherency, absolute part of coherency). Such differentiation will be governed by velocity of wave passage as well, since it will change the time passing to reach the next point (complex coherency, phase spectrum).

Coherency is used to describe the similarity of ground motions as it travels in soil medium. As distance increases, coherency will be lower, as expected, i.e. the ground motions will change and will not be identical. Therefore, their effects on structures or parts of structures separated with a certain distance will not be same.

Different coherency models are developed and compared in order to investigate their effects. All models are developed for Vs=2000m/s as a benchmark value, while different distances are compared to see the effects in detail. For each coherency model, a displacement-time history is also created for comparison.

<u>3.1.2.1. Luco-Wong Model.</u> Luco-Wong model (Luco and Wong, 1986) with ad equal to 0.0002 and ξ equal to 50m vs 100m and 500m vs 1000m where

$$|\gamma\left(\xi,\omega\right)| = \exp\left(-a_d^2.\omega^2.\xi^2\right). \tag{3.14}$$

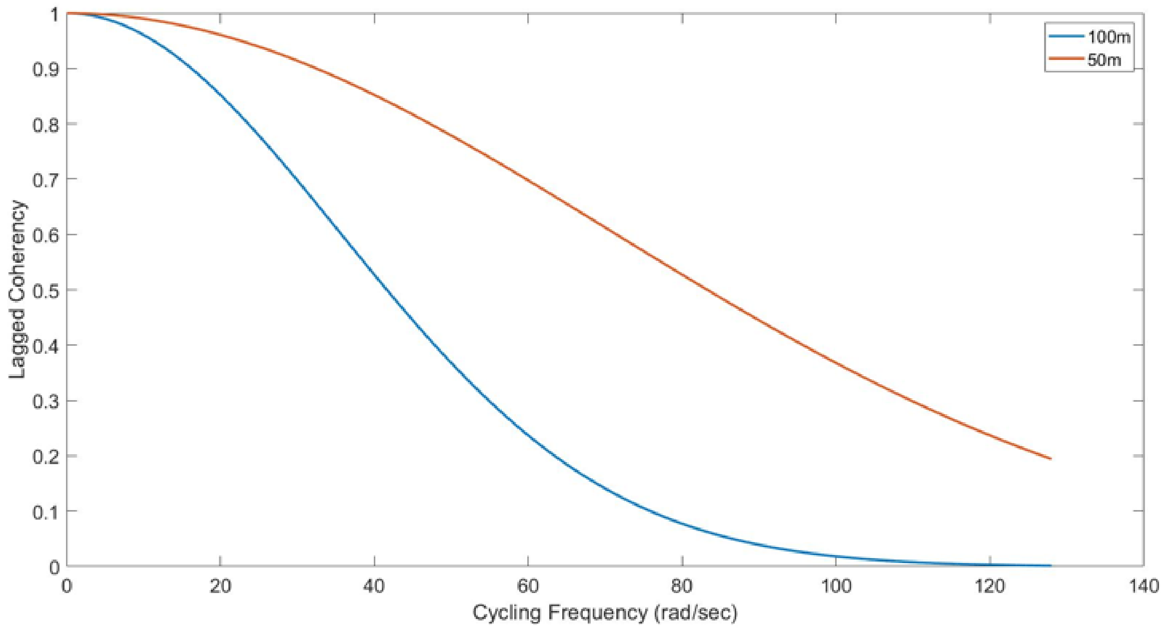

Figure 3.4. Coherency between signals with 50m separation distance for Luco-Wong lagged coherency model.

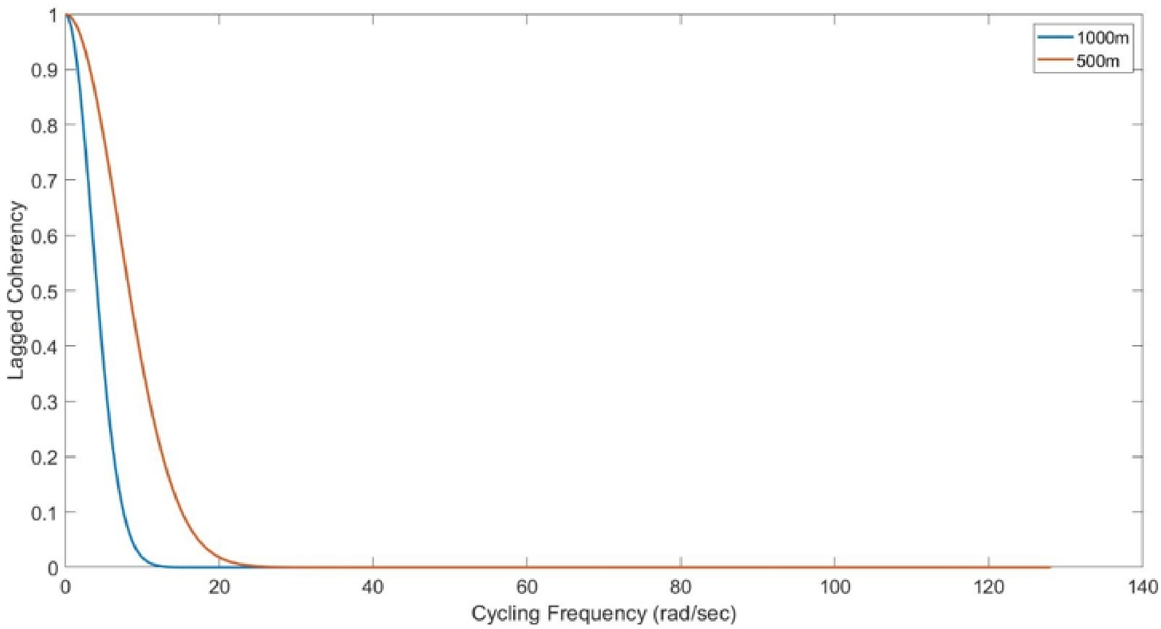

Figure 3.5. Coherency between signals with 500m separation distance for Luco-Wong lagged coherency model.

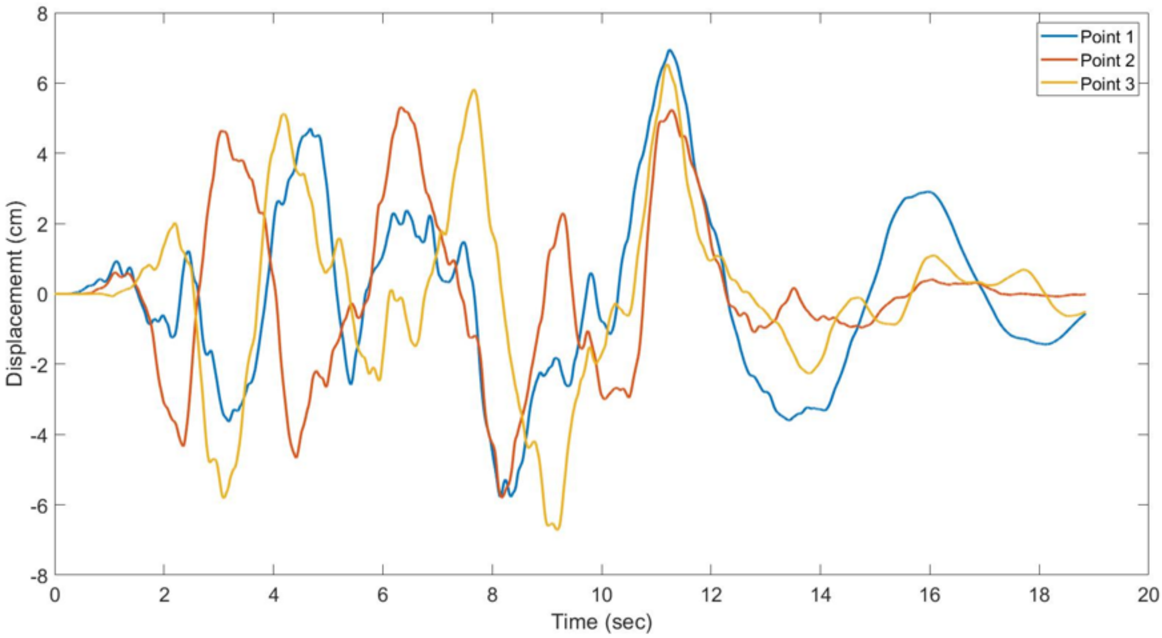

Figure 3.6. Simulated displacement time histories with 500m distance and same soil types with Luco-Wong lagged coherency model.

3.1.2.2. Harichandran-Vanmarcke Model.

$$\begin{aligned}\gamma_{jk}(\omega) = A \exp\left[-\tfrac{2\xi_{jk}}{\alpha\theta(\omega)}(1 - A + \alpha A)\right] \\ + (1 - A)\exp\left[-\tfrac{2\xi_{jk}}{\theta(\omega)}(1 - A + \alpha A)\right] j, k = 1, 2, 3, j \neq \mathrm{k}\end{aligned} \tag{3.15}$$

where $\xi_j k$ is the distance between points j and k, $\theta(\omega)$ is the frequency-dependent correlation distance.

$$\theta(\omega) = k\left[1 + \left(\frac{\omega}{\omega_0}\right)^b\right]^{-1/2} \tag{3.16}$$

and A, α, k, ω_0 and b are the model parameters.

where

A = 0.626, α = 0.022, k = 19700m, ω_0 = 12.692 rad/s, b = 3.47 (Harichandran, 1986).

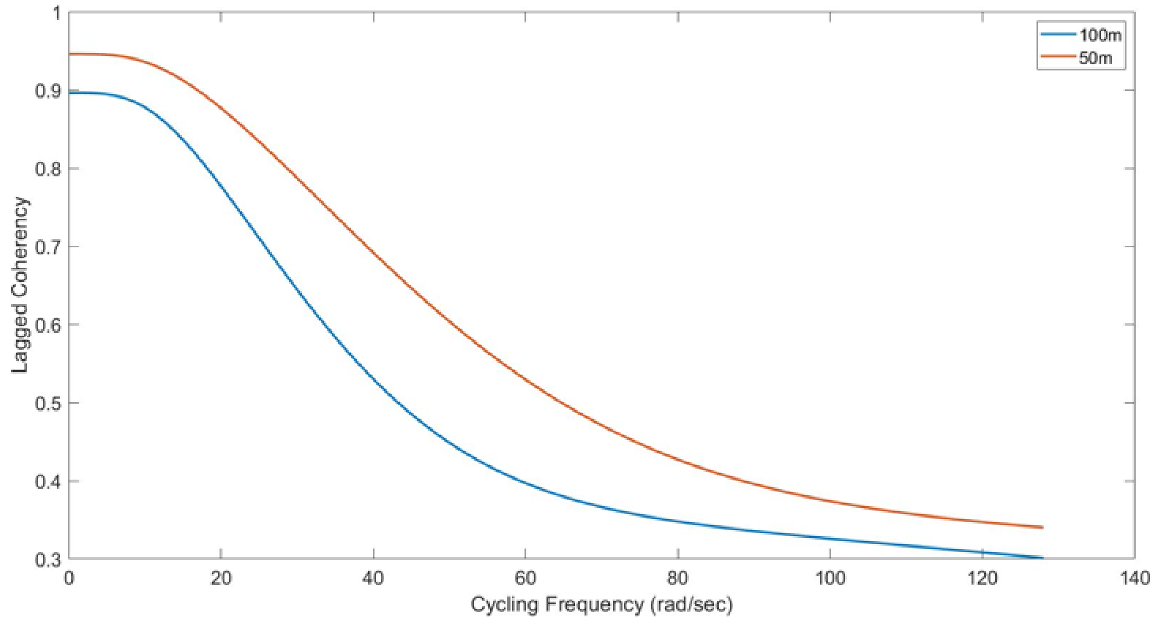

Figure 3.7. Coherency between signals with 50m separation distance for Harichandran-Vanmarcke lagged coherency model.

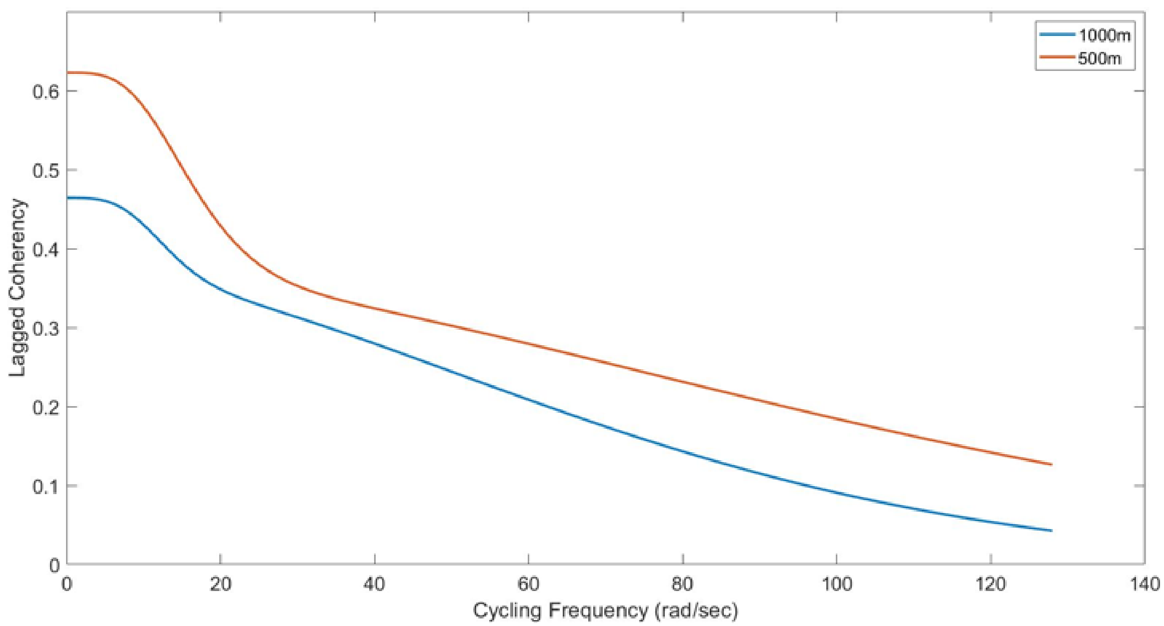

Figure 3.8. Coherency between signals with 500m separation distance for Harichandran-Vanmarcke lagged coherency model.

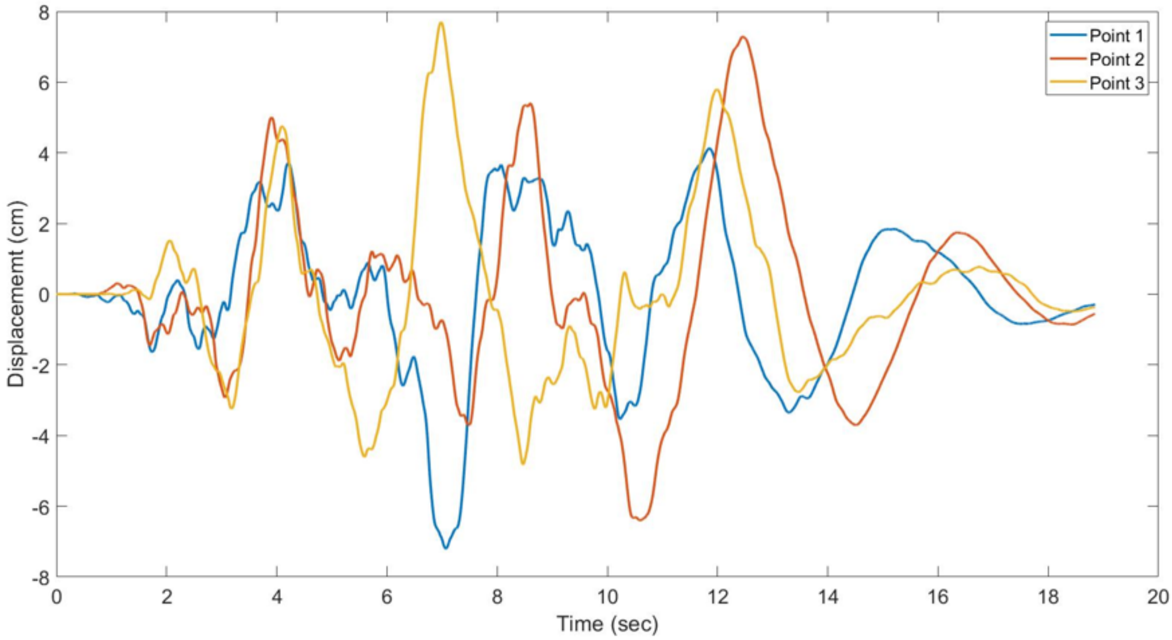

Figure 3.9. Simulated displacement time histories with 500m distance and same soil types with Harichandran-Vanmarcke lagged coherency model.

3.1.2.3. Hao Model.

$$\left|\gamma_{i'j'}\left(i\omega, d_{i'j'}\right)\right| = \exp\left(-\beta d_{i'j'}\right) exp\left[-\alpha\left(\omega\right)\sqrt{d_{i'j'}}\left(\omega/\left(2\pi\right)\right)^2\right] \tag{3.17}$$

where $d_{(i'j')}$ is the projected distance between points i' and j' in the wave propagation direction, β is a constant and $\alpha(\omega)$ is a function with the form

$$a\left(\omega\right) = \left\{ \begin{array}{c} 2\pi a/\omega + b\omega/\left(2\pi\right) + c, \quad 0.314rad/s \leq \quad \omega \leq 62.83rad/s, \\ 0.1a + 10b + c, \omega > 62.83rad/s, \end{array} \right\} \tag{3.18}$$

where a = 0.003853, b = -0.0000181, c = 0.0001177 and β = 0.0001109 (Hao *et al.*, 1989).

Hao lagged coherency model with 50m distance for each tower shows that after a certain frequency (10Hz), coherency values are constant for higher frequency values.

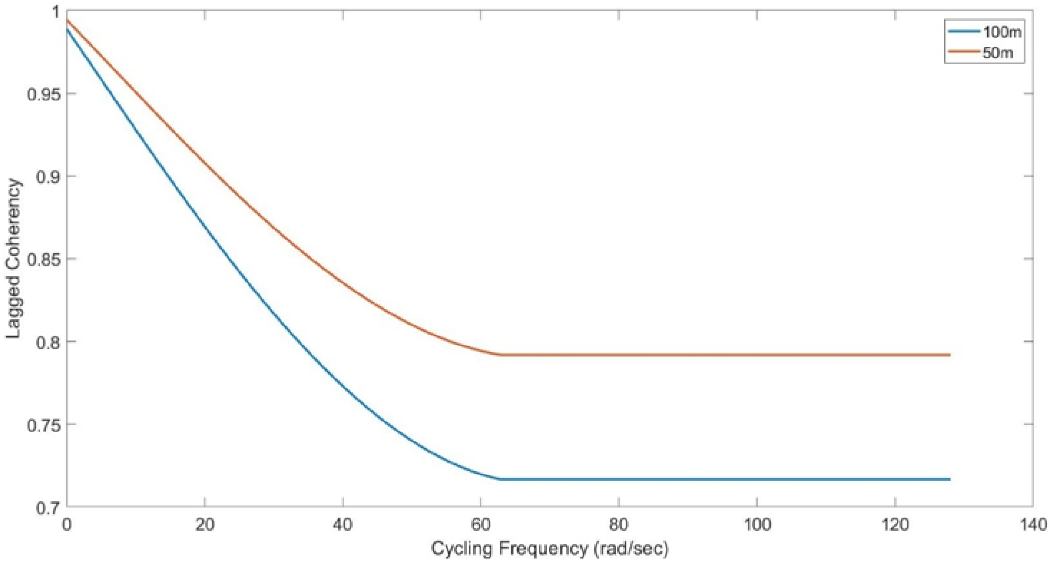

Figure 3.10. Coherency between signals with 50m separation distance for Hao lagged coherency model.

As the distance increases coherency values are decreases as expected

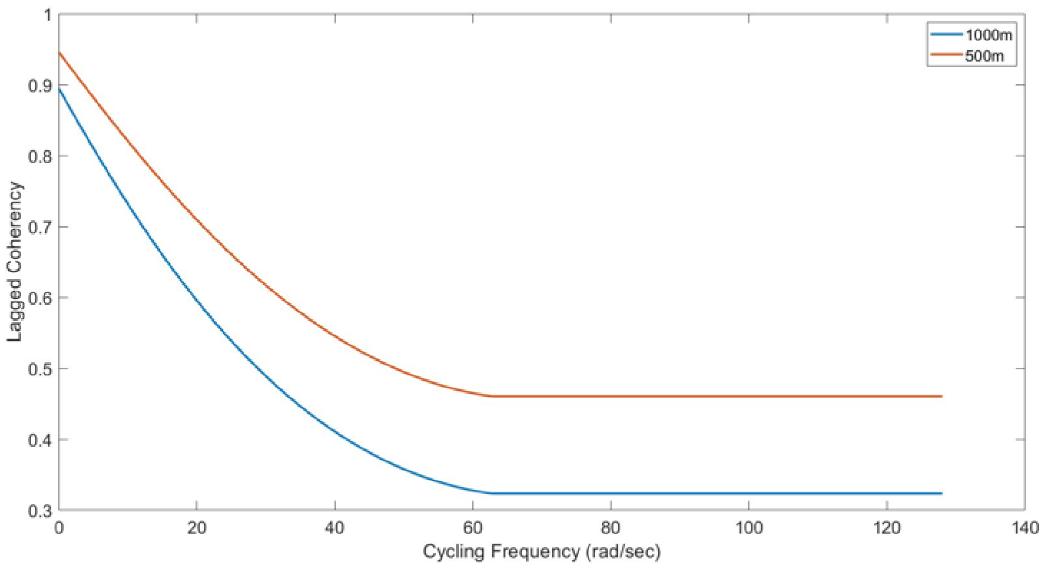

Figure 3.11. Coherency between signals with 500m separation distance for Hao lagged coherency model.

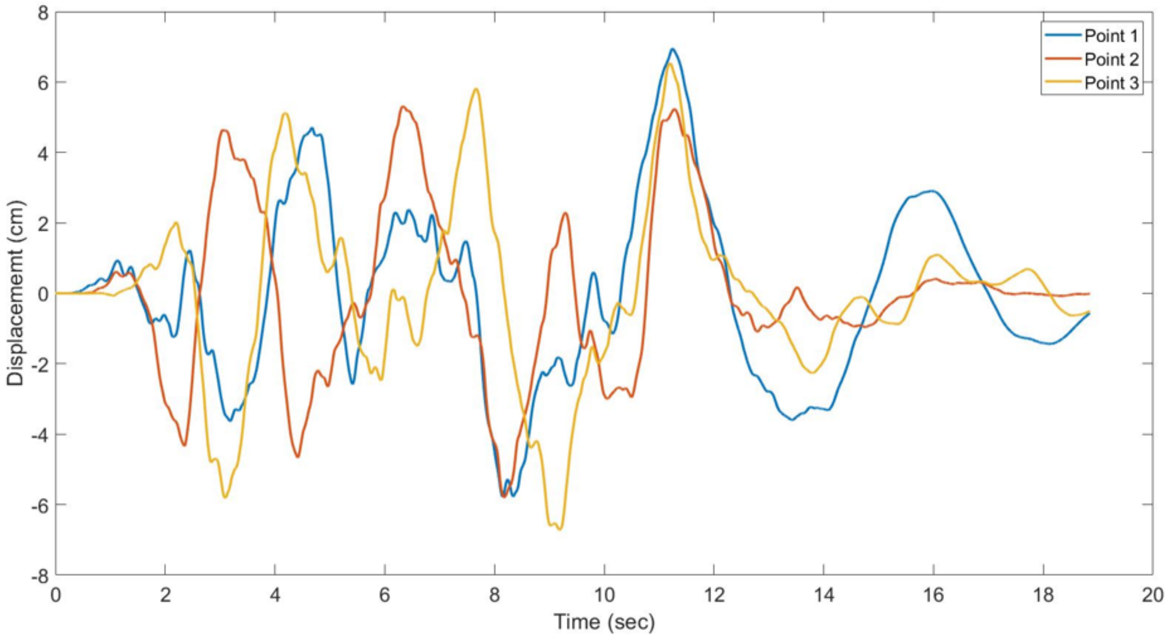

Figure 3.12. Simulated displacement time histories with 500m distance and same soil types with Hao lagged coherency model.

3.1.2.4. Abrahamson Model.

$$\begin{aligned}\gamma_{jk}(\omega) = &\frac{1}{1+\left[\frac{\omega}{2\pi c_8(\xi_{jk})}\right]^6} \\ &\times tanh\left\{\frac{c_3(\xi_{jk})}{1+\frac{\omega}{2\pi}c_4(\xi_{jk})+\frac{\omega^2}{4\pi^2}c_7(\xi_{jk})}\right. \\ &\left. +\left[4.80 - c_3(\xi_{jk})\right] exp\left[c_6(\xi_{jk})\frac{\omega}{2\pi}\right] + 0.35\right\} j,k = 1,2,3, j \neq k\end{aligned} \tag{3.19}$$

where $\xi_j k$ is the distance between points j and k, and

$$c_3(\xi_{jk}) = \frac{3.95}{\left(1+0.0077\xi_{jk}+0.000023{\xi_{jk}}^2\right)} + 0.85\exp\{-0.00013\xi_{jk}\} \tag{3.20}$$

$$c_4(\xi_{jk}) = \frac{0.4\left[1-\frac{1}{1+\left(\frac{\xi_{jk}}{5}\right)^3}\right]}{\left[1+\left(\frac{\xi_{jk}}{190}\right)^8\right]\left[1+\left(\frac{\xi_{jk}}{180}\right)^3\right]} \tag{3.21}$$

$$c_6(\xi_{jk}) = 3\left(\exp\left\{-\frac{\xi_{jk}}{20}\right\}-1\right) - 0.0018\xi_{jk} \tag{3.22}$$

where

$$c_7\left(\xi_{jk}\right) = -0.598 + 0.106\ln\left(\xi_{jk} + 325\right) - 0.0151\exp\left\{-0.6\xi_{jk}\right\} \quad (3.23)$$

$$c_8\left(\xi_{jk}\right) = \exp\left\{8.54 - 1.07\ln\left(\xi_{jk} + 200\right)\right\} + 100\exp\left\{-\xi_{jk}\right\} \quad (3.24)$$

Complex coherence function

$$\Gamma_{jk}\left(\omega\right) = \gamma_{jk}\left(\omega\right)\exp\left[-i\frac{\omega\xi_{jk}}{v}\right] j,k = 1,2,3, j \neq k. \quad (3.25)$$

where the velocity of wave propagation v is set equal to ν=2000m/s (Abrahamson, 1993).

Abrahamson plane-wave coherency model with 50m distance for each tower shows that, when the distance is comparably small, there is a high coherency between signals in low frequencies, while it decreases as frequency increases. It can also be seen that the coherency value decreases with increasing distance.

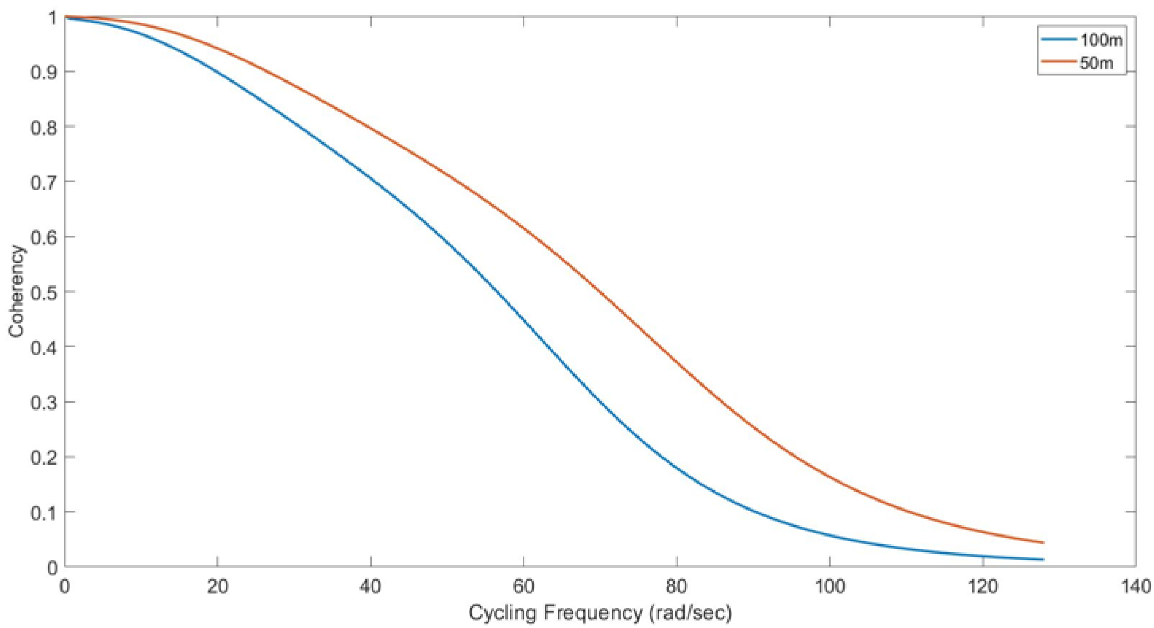

Figure 3.13. Coherency between signals with 50m separation distance for Abrahamson horizontal plane-wave model.

On the other hand, when the distance is increased further, as in the case of this work, coherency values significantly decrease for all frequencies, as mentioned before.

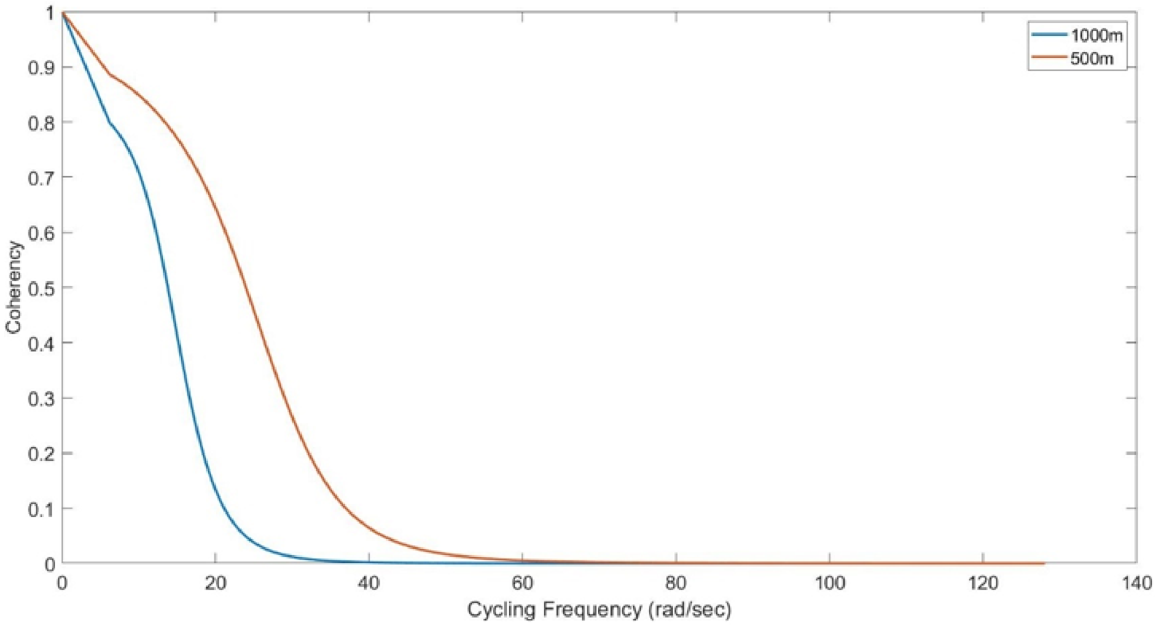

Figure 3.14. Coherency between signals with 500m separation distance for Abrahamson horizontal plane-wave model.

It should be noted that for the lagged coherency model for Abrahamson, the results are in parallel with the other coherency models.

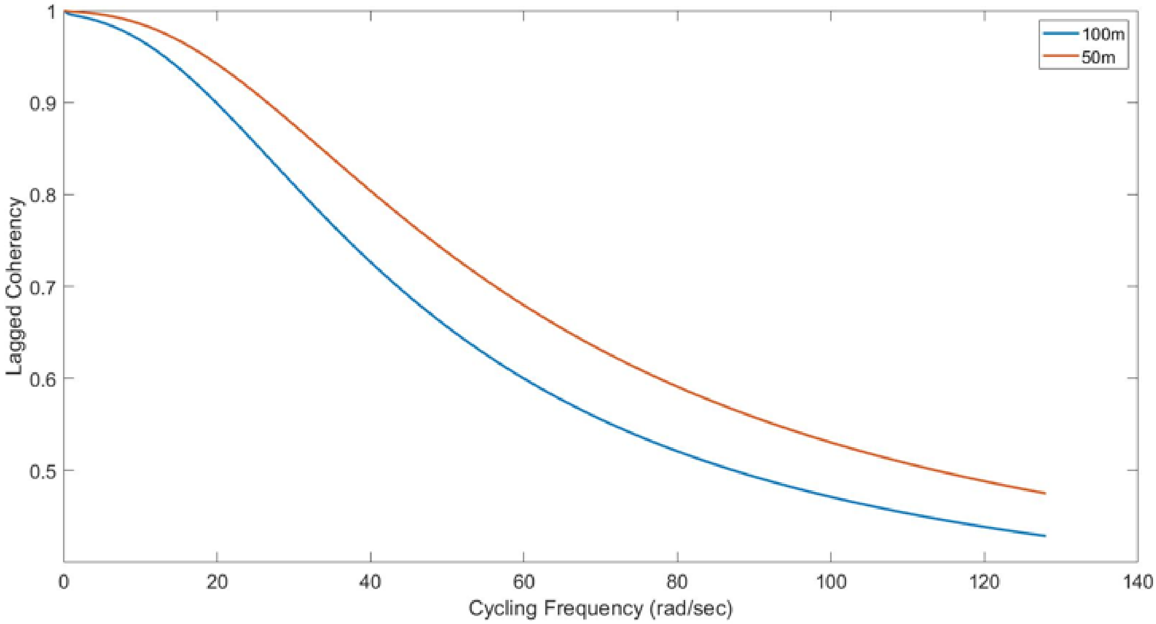

Figure 3.15. Coherency between signals with 50m separation distance for Abrahamson lagged coherency model.

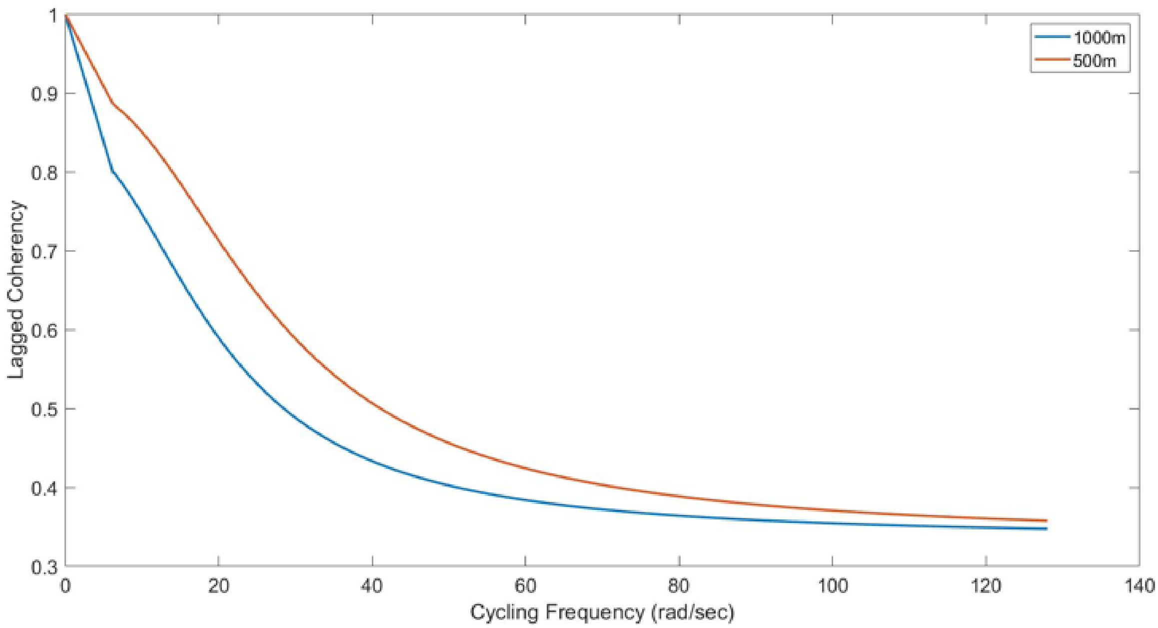

Figure 3.16. Coherency between signals with 500m separation distance for Abrahamson lagged coherency model.

3.1.3. Target Design Spectrum

Target design spectra are obtained from the AFAD website for the actual locations. DD-1 is selected for three tower locations with soil conditions of ZB, ZC and ZD. Target design spectra have a PGA value of 0.462g and a PGV value of 27.455 cm/sec.

3.1.3.1. Rock Soil Condition (ZB). Design spectrum for DD-1 and rock soil condition can be seen in Figure 3.17.

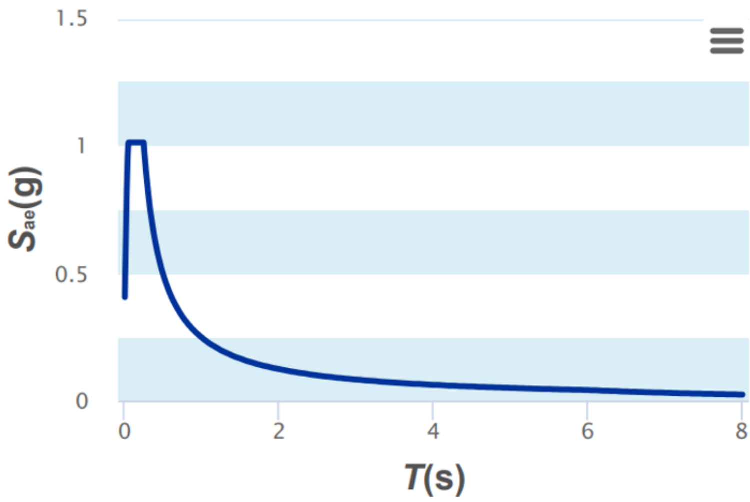

Figure 3.17. Design spectrum for ZB soil condition assigned to transmission tower 1.

3.1.3.2. Medium soil condition (ZC). Design spectrum for DD-1 and medium soil condition can be seen in Figure 3.18.

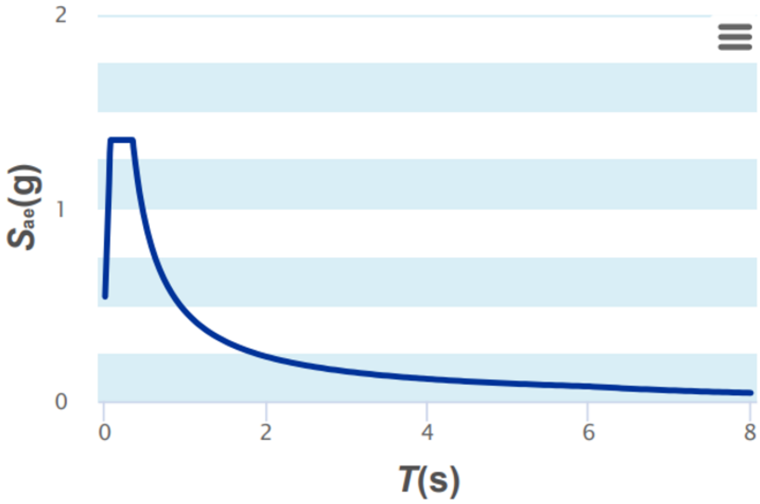

Figure 3.18. Design spectrum for ZC soil condition assigned to transmission tower 2.

3.1.3.3. Soft soil condition (ZD). Design spectrum for DD-1 and soft soil condition can be seen in Figure 3.19.

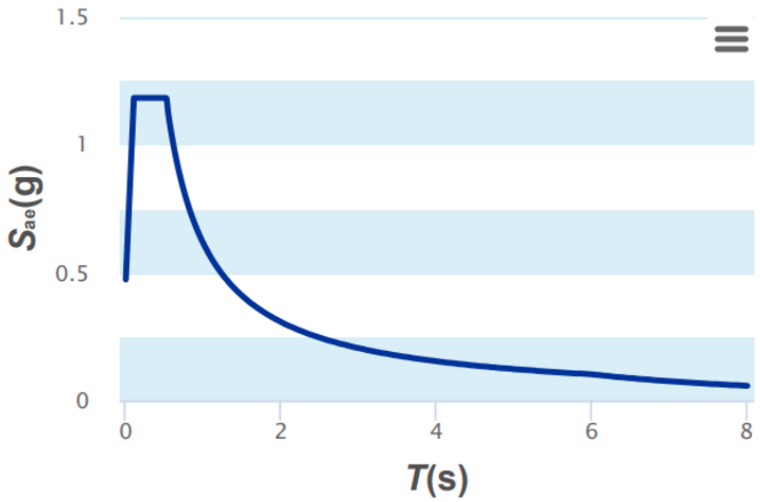

Figure 3.19. Design spectrum for ZC soil condition assigned to transmission tower 3.

3.2. Simulation Results

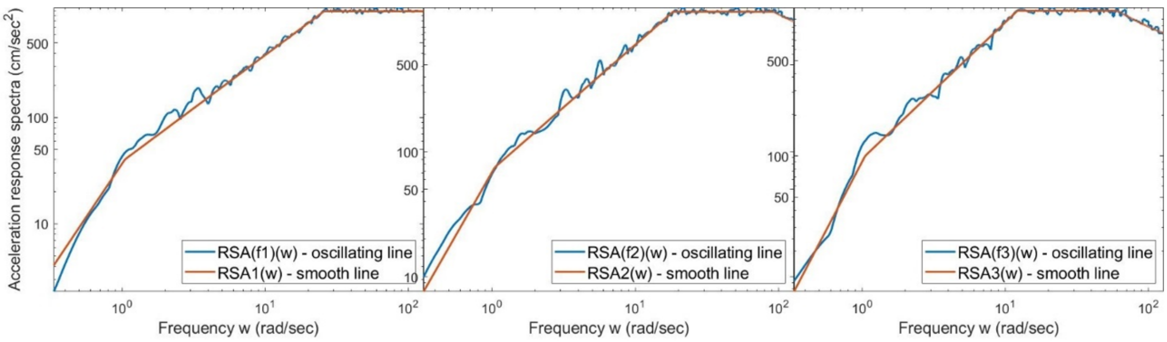

Figure 3.20. Response spectra of simulated ground motions vs target design spectra.

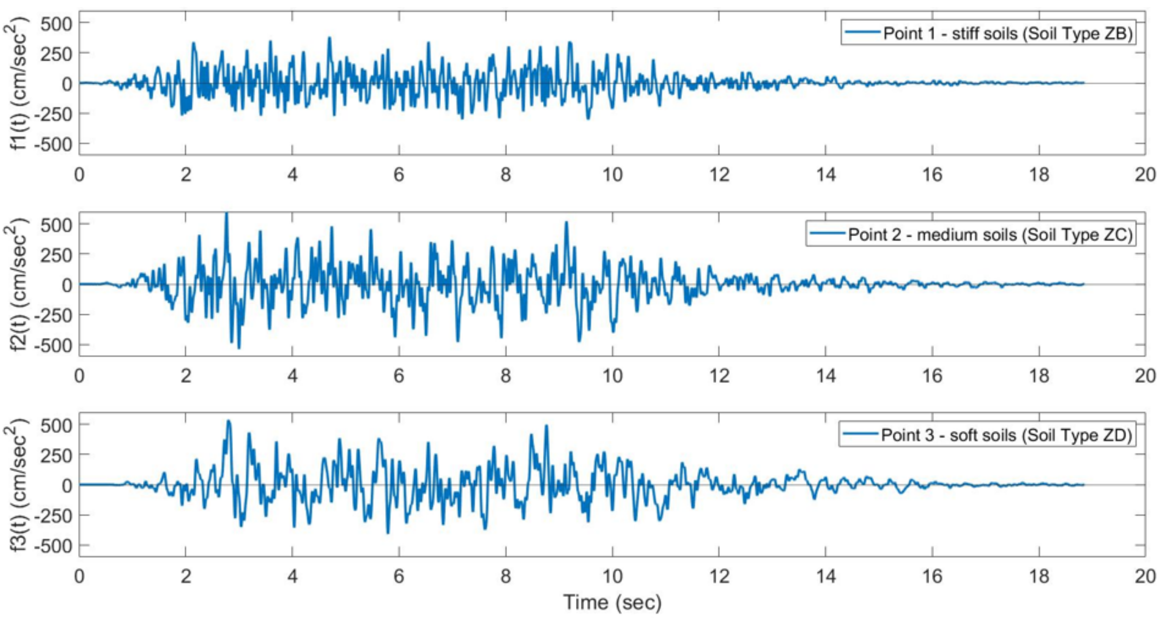

Figure 3.21. Simulated acceleration time histories.

As it can be seen in Figure 3.22, three acceleration time histories are obtained which represent the ground motions at the locations of each tower (f1, f2 and f3). First tower is assumed to be on stiff soil, second tower is assumed to be on medium soil and third tower is assumed to be on soft soil. In order to derive the displacement time histories from acceleration time histories, a baseline correction and Butterworth filter with (fmax=25Hz, fmin=0.15Hz and n=4) is applied. Then, by double integration, the displacement time histories are acquired.

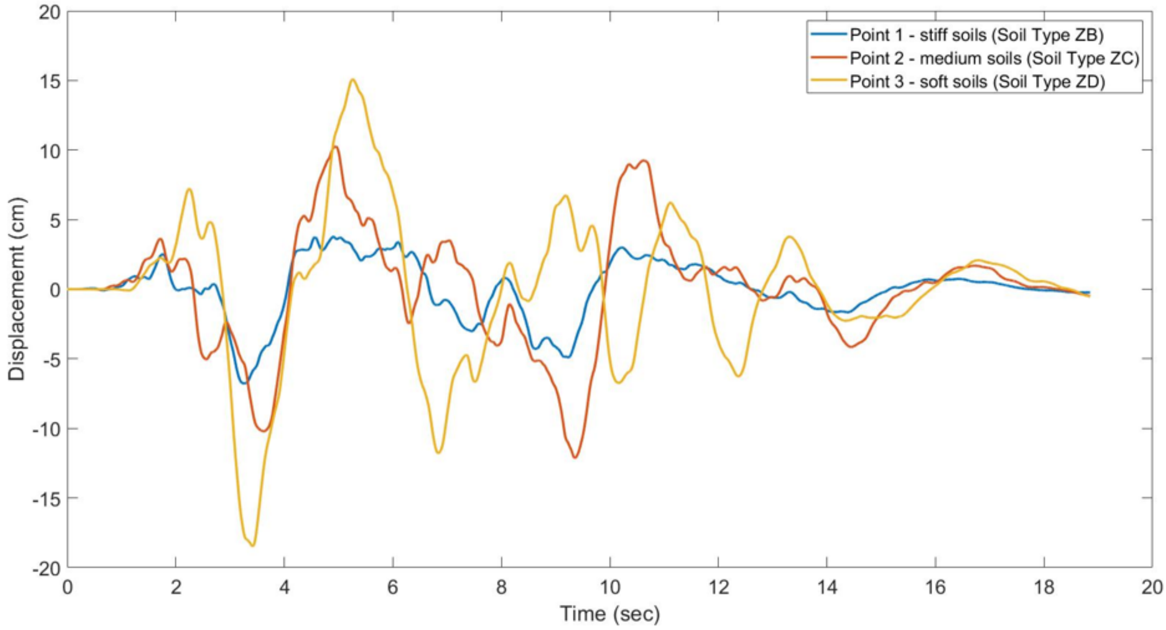

Figure 3.22. Simulated displacement time histories.

3.3. Discussion of Effects of Soil Types, Distance and Velocity of Wave Propagation

As distance increases, coherency decreases, as previously mentioned in the coherency chapter. As a result, with shorter distances, coherency will be higher between ground motions. Furthermore, wave passage effect will be smaller. In Figure 3.23, the distance is set as 50m for the same soil type. As a result time histories at each point are very similar to each other as coherency is high.

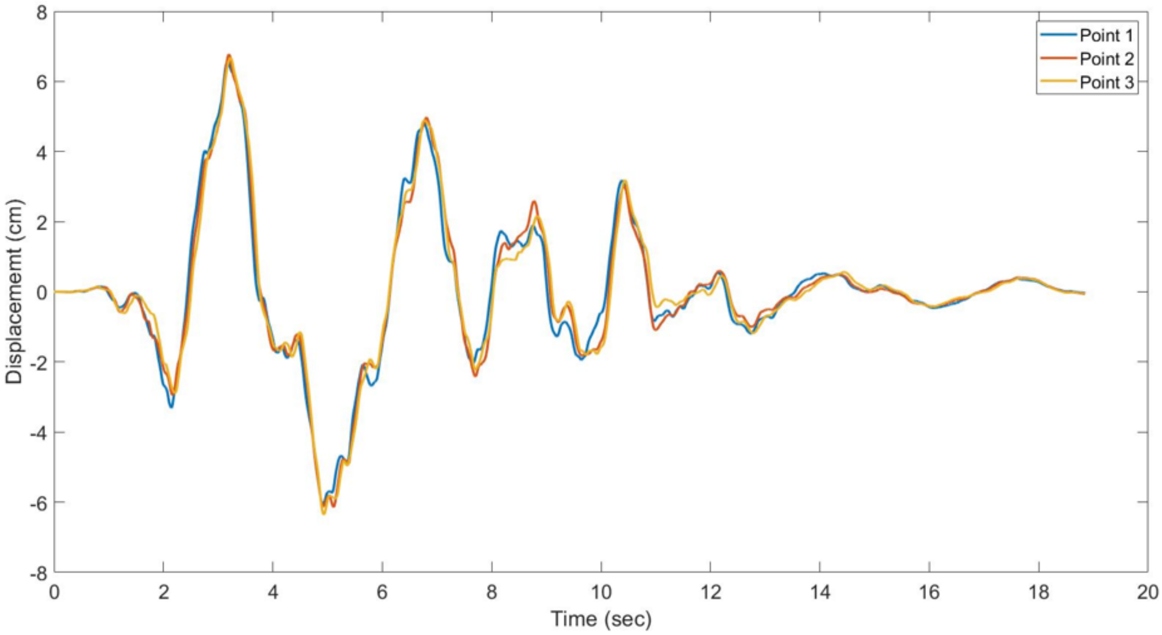

Figure 3.23. Simulated displacement time histories with 50m distance and same soil types.

On the contrary, as distance increases, coherency will be lower between ground motions. Furthermore, the wave passage effect increases. This can be seen in Figure 3.24 and Figure 3.25 as the distances are set to 200m and 500m respectively. As the distance increases, coherency is getting lower. Therefore, similarity between the time histories is getting lower as well.

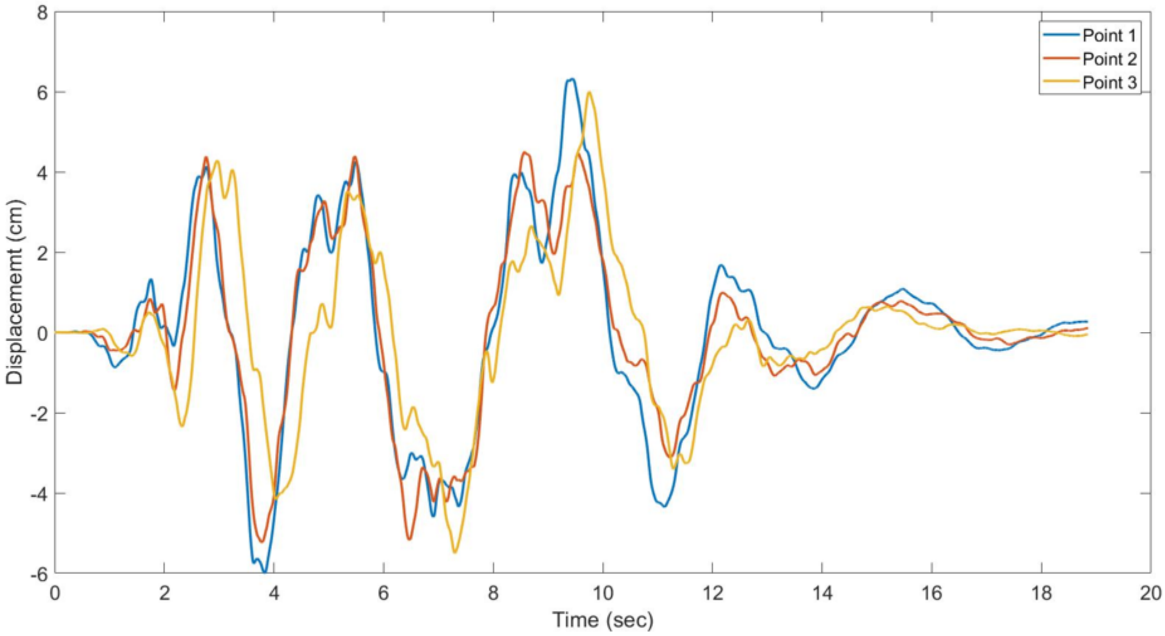

Figure 3.24. Simulated displacement time histories with 200m distance and same soil types.

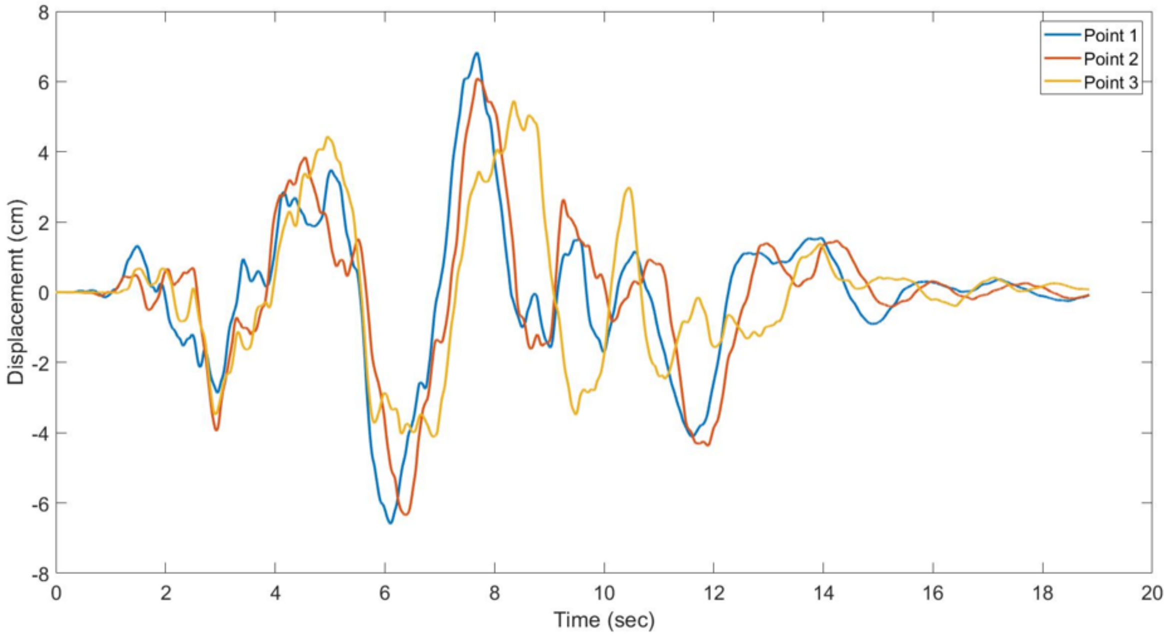

Figure 3.25. Simulated displacement time histories with 500m distance and same soil types.

Moreover, soil types have an impact on ground motions, since softer soil types will have an increasing effect on amplitudes. This can be clearly seen in Figure 3.26, as the soil type getting softer, amplitudes are getting higher. Amplitude change is also significant even for higher distance values as it can be seen in Figure 3.27 and Figure 3.28.

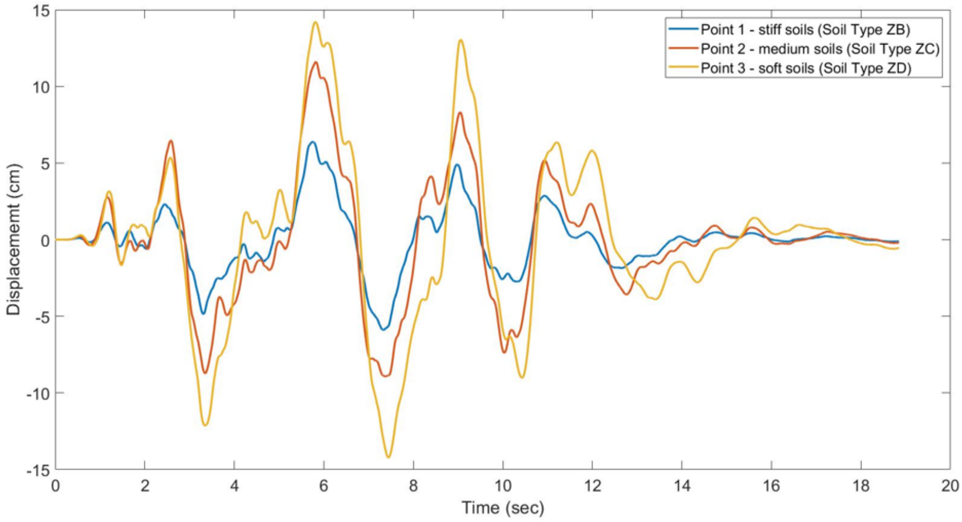

Figure 3.26. Simulated displacement time histories with 50m distance and different soil types.

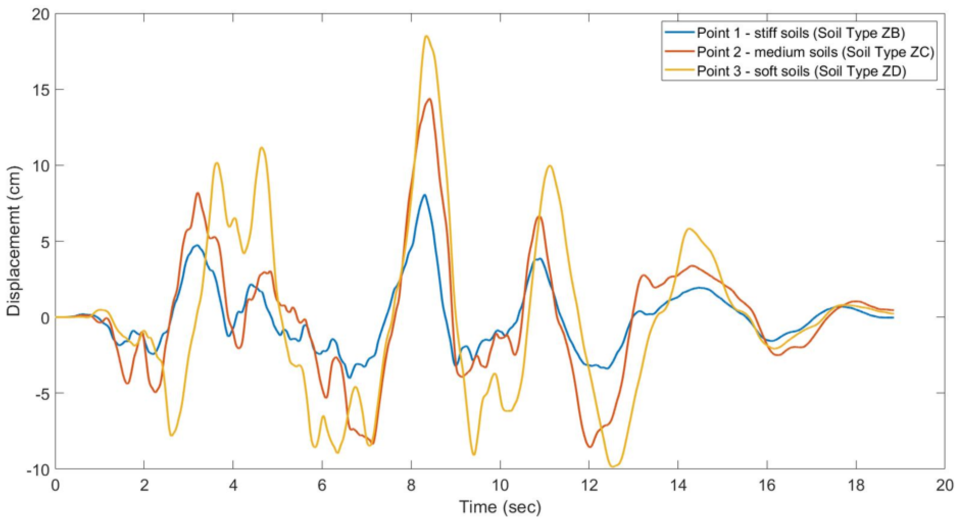

Figure 3.27. Simulated displacement time histories with 200m distance and different soil types.

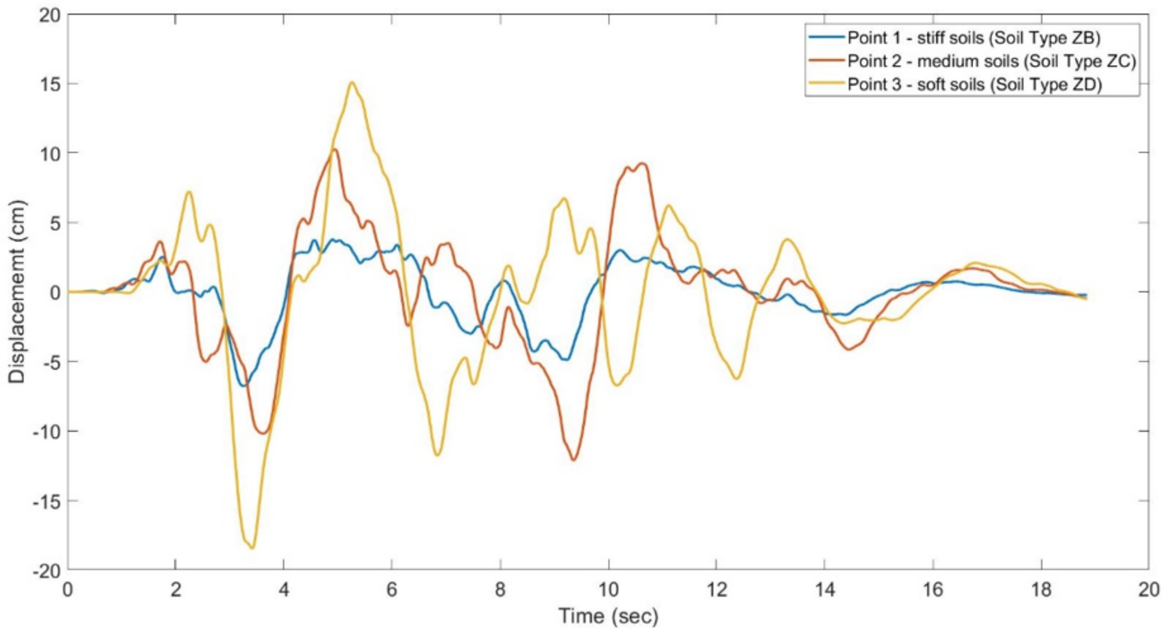

Figure 3.28. Simulated displacement time histories with 500m distance and different soil types.

In addition, velocity of wave passage affects both coherency and the wave passage effect, similar to the effect of distance but in an opposite fashion. Wave passage effect differentiates the ground motion arrival time as a natural outcome. As a result, this will have an effect on separated structures as their response will not be identical at a given point in time. This difference in ground motions can be seen in Figure 3.29 as the ground motions are asynchronous. As the velocity of wave decreases, asynchrony between the ground motions gets more significant as it can be seen in Figure 3.30 and Figure 3.31.

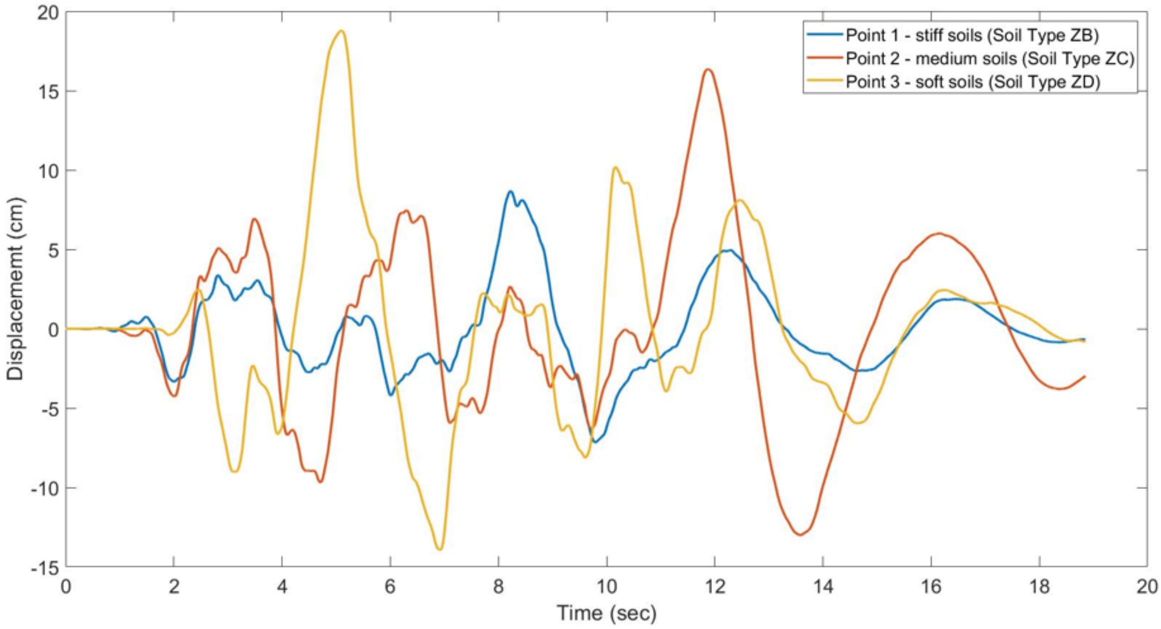

Figure 3.29. Simulated displacement time histories with 500m distance, different soil types and 1000m/sec velocity of wave passage.

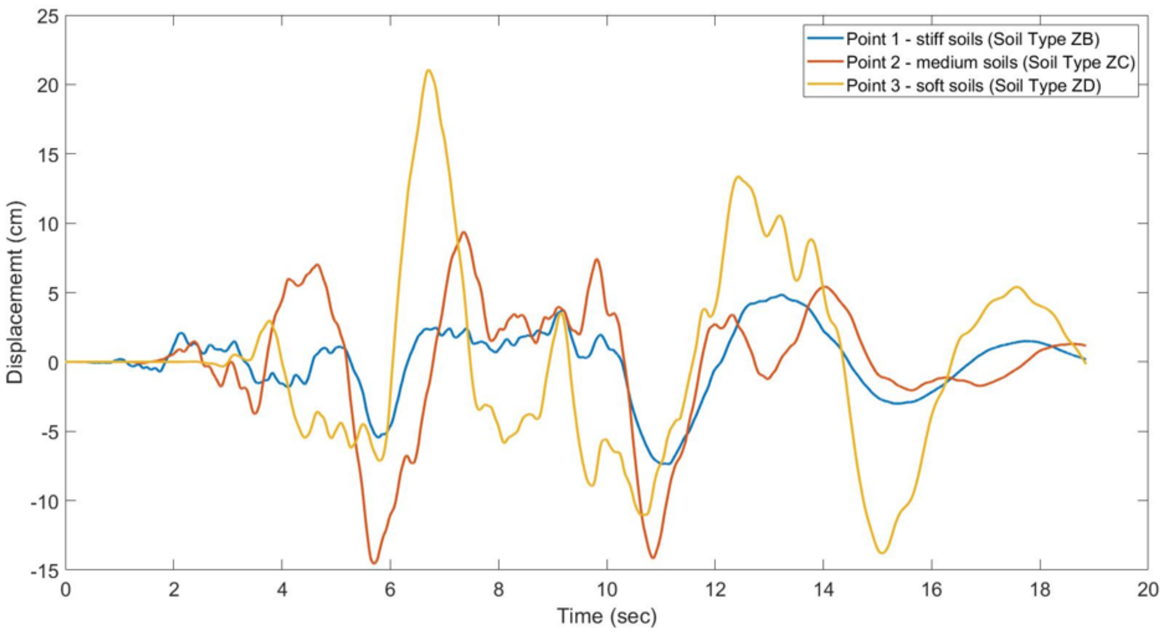

Figure 3.30. Simulated displacement time histories with 500m distance, different soil types and 500m/sec velocity of wave passage.

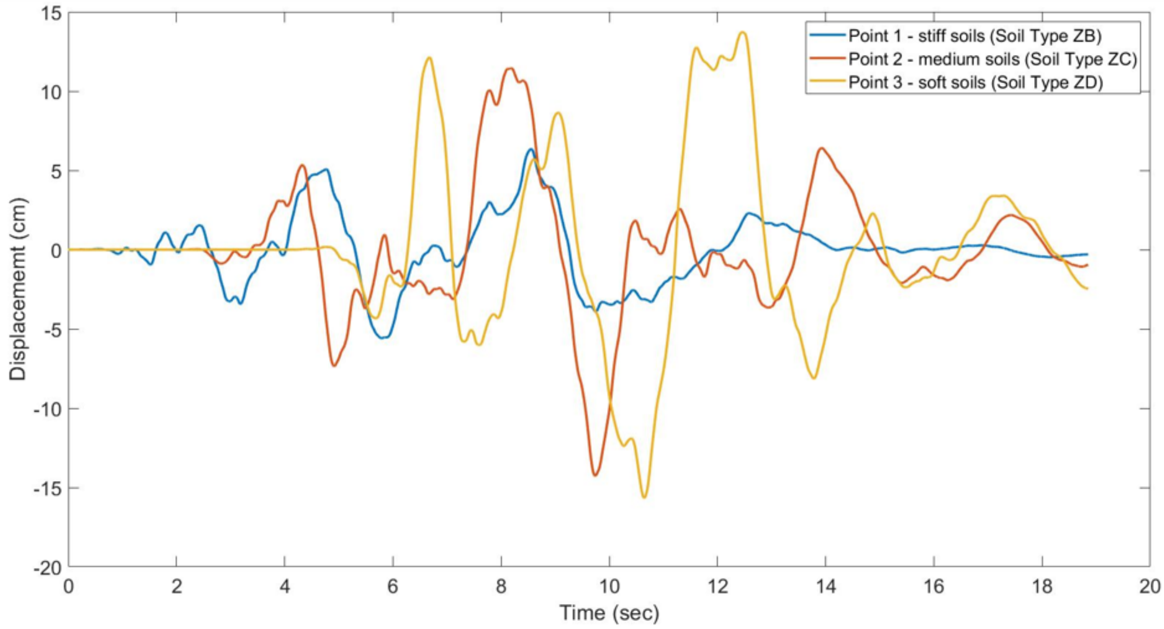

Figure 3.31. Simulated displacement time histories with 500m distance, different soil types and 250m/sec velocity of wave passage.

4. FINITE ELEMENT MODEL

4.1. Creating Models

A transmission system is modelled in SAP2000 in order to represent the system analyzed. Meetings were held with several stakeholders prior to the modeling phase. The actual situation in the field was investigated, technical drawings of the towers were collected, and all technical information was gathered.

It should be noted here that there are only a few private companies working in this niche sector and transmission line systems are operated by a state institution in Turkey, which makes collaboration quite difficult in terms of research in this area. Collecting any kind of information, technical knowledge etc., or communication through bureaucracy to obtain permissions etc. were the first bottlenecks to beat.

The transmission system is modeled as a system of three transmission towers connected by transmission cables. In order to keep model feasible, the $4th$ and $5th$ towers are represented as simple supports and are also connected via transmission cables to the outer towers.

Each tower is separated by a distance of 500m, as observed in the field and the technical project documentation. For the sake of simplicity, the towers are assumed to be in the same elevation level. Cable and tower material properties and sections are modeled according to the technical information collected.

Each tower consists of 1059 members, 455 of which are of S235 and 583 are of S355 grade. All members are L-shape lattice steel with 41 different section properties, while 7 are double-angle sections.

Transmission tower members are modeled as pin connections at the member ends, as they are connected to each other with simple bolt connections. Bolts, plates and cable connection details are not designed, as it is beyond the scope of this study. All towers are modeled as fixed connection at their bases.

Each tower has an approximate weight of 22 tons and height of 62m, while their base dimensions are 10m x 10m.

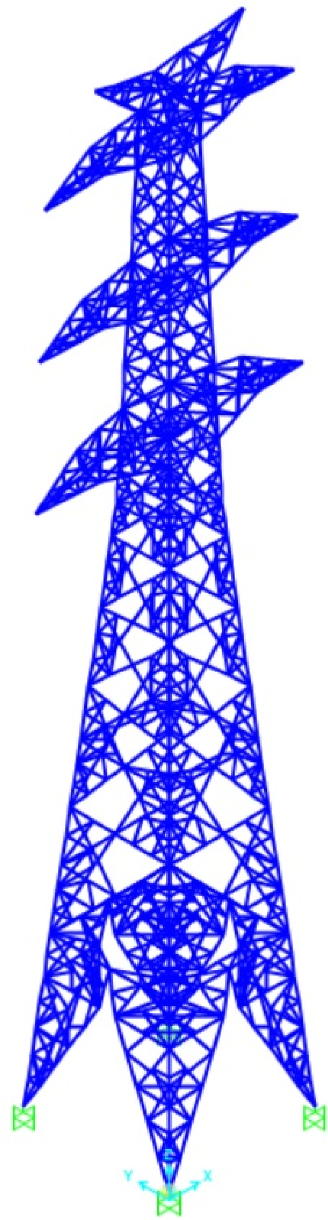

Figure 4.1. Transmission tower finite element model.

Cables in the model are designed using the SAP2000 cable geometry screen. Each cable is assumed to have a sag of 20m. Cables are designed as 10-segment objects. The number of segments used in modeling has a significant effect on their behavior, as will further be discussed in the following chapters.

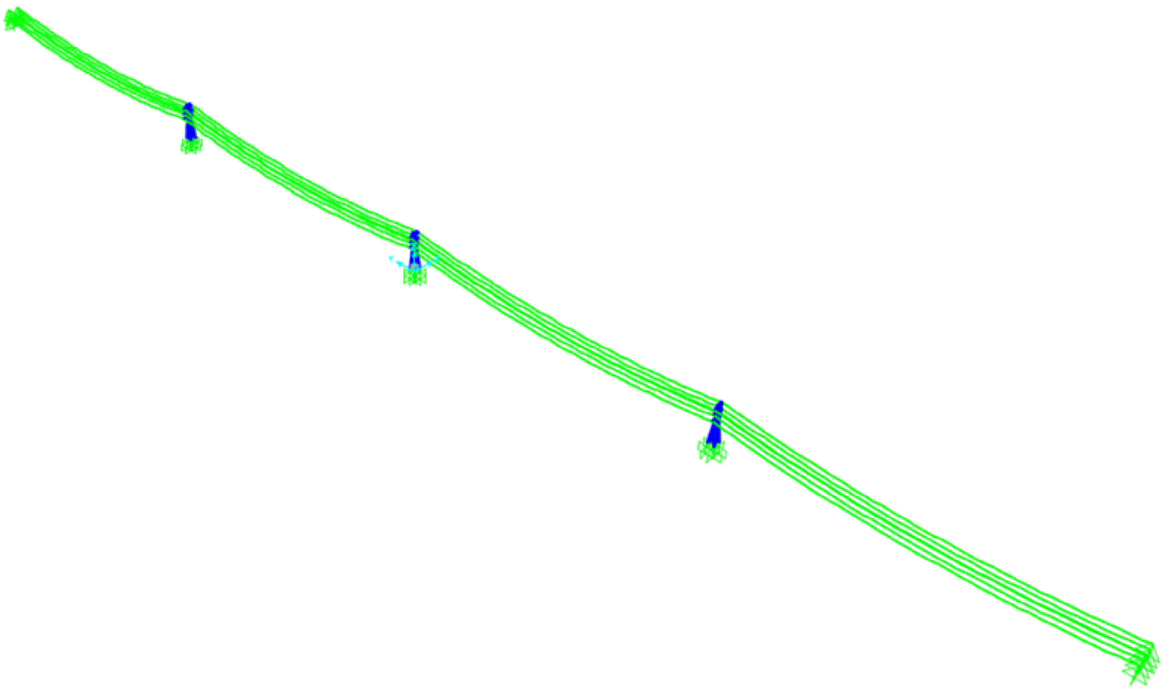

Figure 4.2. Transmission system finite element model.

4.2. Analysis

4.2.1. Analysis Parameters

In order to investigate the effects of spatially varying ground motions (SVGM), excitations are designed as multi-support units and applied as displacement-time histories at the supports of each tower.

The SVGM created in MATLAB simulations are defined as time-history functions. Subsequently, a non-linear direct integration history load case is defined using these functions and applied following a non-linear static dead load case.

As the system includes cables, the modal analysis must also take cable behavior into account. Accordingly, an analysis was conducted to understand the modal participating mass ratios, and over 90% was achieved in both directions (95% in transverse and 92% in the transmission line direction.). The analysis included the first 576 modes, as higher values of modal participating mass ratios can be only achieved by such a high number of modes, due to the dynamic behavior of the cables in the system.

In order to address this issue, an analysis was carried out to optimize the model. It is found out that the number of segments used in cable modeling is the governing parameter. As the number of segments is increased, the modal period and shape of the cables converge to more realistic values. On the other hand, as the number of segments is increased, modal participating mass ratios decrease for a given number of modes analyzed. Continuously increasing the number of modes to fulfill this need would create a very large computational effort, which, in turn, would render the solution infeasible.

As a result, the modes to be analyzed and the number of segments to be used in cable modeling are determined as 576 and 10, respectively.

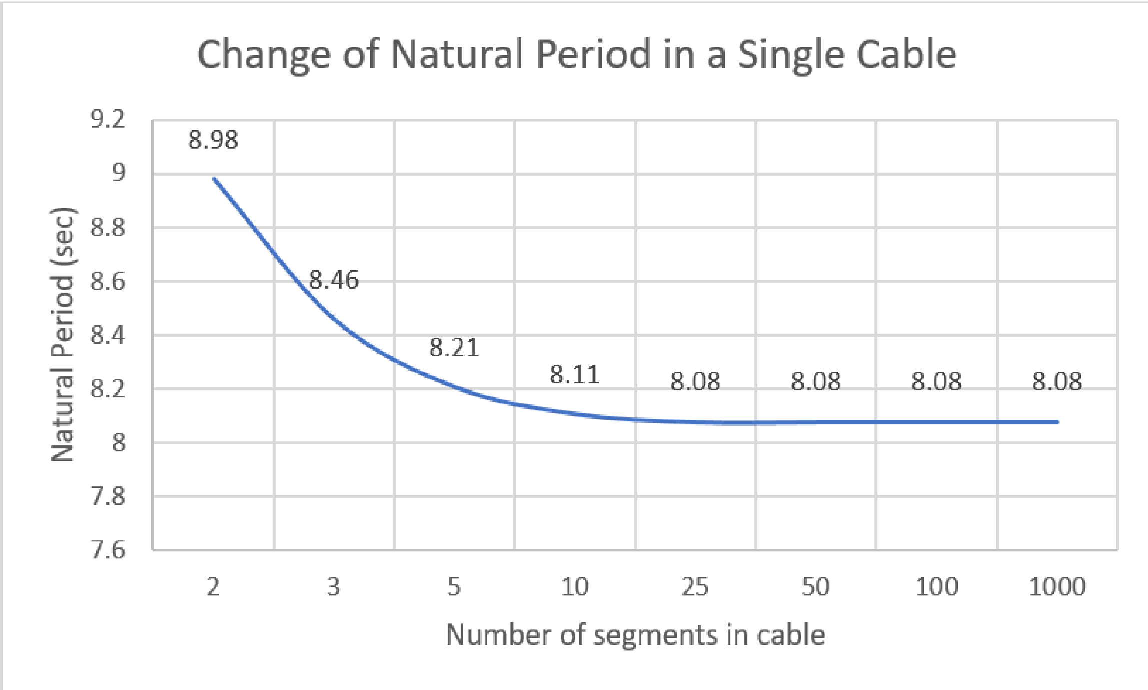

Figure 4.3. Change of natural period in a single cable.

As the system includes cables, SAP2000 is not capable of producing correct results through linear analyses. Therefore, a non-linear static dead load case is followed by the non-linear direct integration history load case, to enable SAP2000 to create a new stiffness matrix for cables with their on dead loads.

The functions for the non-linear direct integration history load case are created with the help of a MATLAB routine, which was explained in the previous chapters. Figure 4.4 represents the SVGM for each tower.

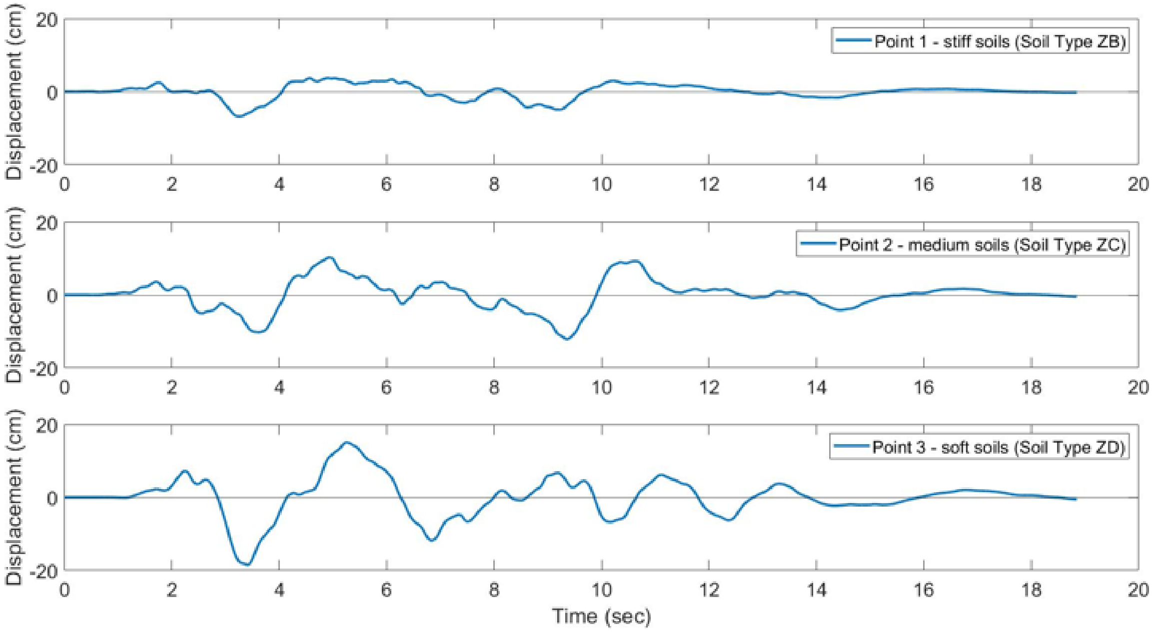

Figure 4.4. Time history functions representing SVGM in SAP2000.

These functions are applied as load patterns to each tower at their bases as displacement-time histories, as SAP2000 does not have the capability to apply different acceleration-time histories in the same system. A constant damping of 5% is used for all modes in the analysis. The default SAP2000 parameters are used for time integration and non-linear parameters. In order to compare the results of the analysis, three more models are analyzed. First, a solo tower model is analyzed under only static loads representing the cable weights to simulate the real-world testing of the cables after production. Second, this solo tower model is analyzed under earthquake loading and finally third case is the analysis is of three towers with cables that are excited with the same and SVGM earthquake loading to compare.

4.2.2. Analysis Results

4.2.2.1. Modal Analysis. Two different cases are analyzed in modal analysis, in order to understand the effect of cables. The first case includes a single transmission tower without cables, while the second case involves the entire system with all three transmission towers and all cables.

The SAP2000 modal analysis of a single transmission tower for the first modes produced 0.58 and 0.57 sec. (Transverse and transmission line direction modal periods, respectively). The results for the second modes are 0.23 and 0.23 sec., and 0.15 and 0.15 sec. are obtained for the third modes (Transverse and transmission line direction modal periods, respectively). Obtaining similar results in both directions was expected since the structure is nearly symmetrical, as previously discussed.

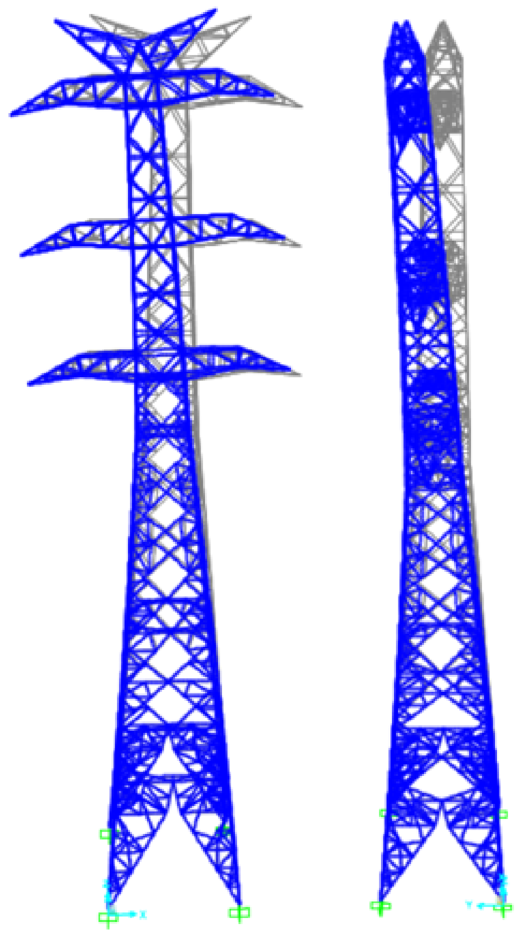

Figure 4.5. First mode shapes of the SAP2000 solo transmission tower model (Transverse and transmission line direction modal periods respectively).

Moreover, a SAP2000 modal analysis for the transmission line system is also utilized. In this case, the effects of the cables are very significant in terms of the first SAP2000 found modes, as the first mode starts from 8.14 sec., which was already expected to be one of the modes of the cables.

However, when the latter modes are analyzed, it can be seen that the modes obtained from the ambient vibration test can be found in the SAP2000 system. The first modes are found to be 0.64 and 0.69 sec. (Transverse and transmission line direction modal periods, respectively), while second modes are found to be 0.24 and 0.19 sec. (Transverse and transmission line direction modal periods, respectively). Finally, the third modes are found to be 0.15 and 0.15 sec. (Transverse and transmission line direction modal periods, respectively).

As previously discussed in the ambient vibration results chapter, the first modes are 0.67 sec and 0.62 sec (Transverse and transmission line direction modal periods, respectively), the second modes are 0.23 and 0.20 sec. (Transverse and transmission line direction modal periods respectively) and finally the third modes are 0.15 and 0.15 sec. (Transverse and transmission line direction modal periods, respectively).

Table 4.1. Comparison of ambient vibration and SAP2000 for first three modes in both directions.

	Transverse direction			Transmission line direction		
	1^{st} mode	2^{nd} mode	3^{rd} mode	1^{st} mode	2^{nd} mode	3^{rd} mode
Ambient Vibration Results (sec.)	0.67	0.23	0.15	0.62	0.2	0.15
SAP2000 results (sec.)	0.64	0.24	0.15	0.69	0.19	0.15

As seen in the comparison, the SAP2000 results are quite close to the values obtained from the ambient vibration test results (90% to 100% match).

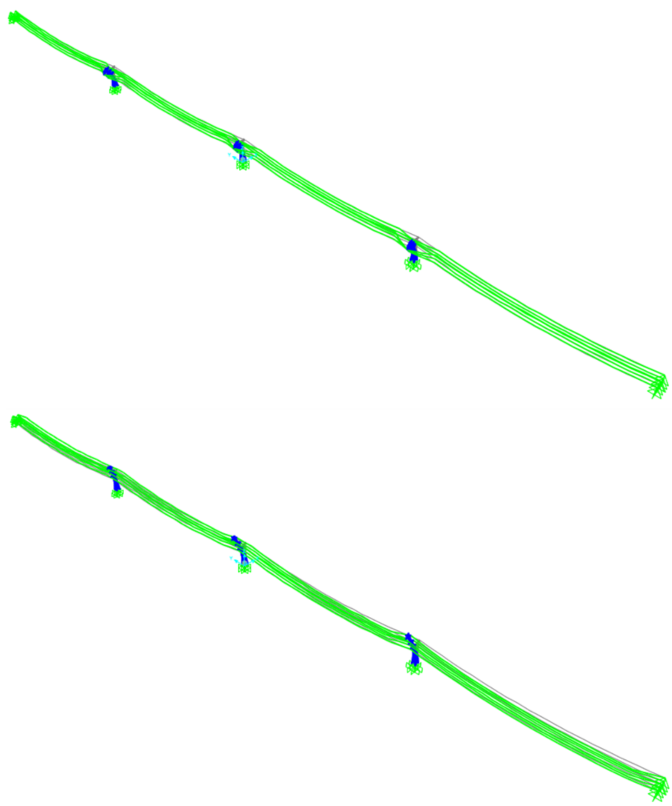

Figure 4.6. First mode shapes of the SAP2000 transmission system model (Transverse and transmission line direction modal periods respectively).

4.2.2.2. Static and Dynamic Analyses. As stated before, in real-world analysis of the towers, only a single tower is modeled, and weight of the cables are applied as static loads on the tower. As expected, stress values are quite low in this case and all the members are performing well.

In the second version of analysis, a solo tower is analyzed under earthquake load that is obtained via SVGM following the static dead loading. There is only one member that fails as all other members are below their capacities (Failing member is a S235 tie member). In the third version of the analysis, three towers with cables are analyzed. In this analysis effects of cables are obvious as it can be seen the previous modal analysis part. Cables changes the dynamic behaviors of the towers drastically, therefore the effects of earthquake loading.

In order to understand the effects of SVGM, two analyses are performed in this version. In the first analysis, all towers are loaded with the same earthquake loading assuming that all towers are on stiff soil and the earthquake excitation is exactly the same. In the second analysis, SVGM records are used which consider different soil conditions (stiff, medium and soft, respectively), coherency effect and wave-passage effect.

In addition to the stress analyses, the top displacement of the transmission towers is examined. It can be seen in Figure 4.8 and Figure 4.9 the effects of SVGM are significant in the top displacements of the transmission towers. This is result a of the characteristics of SVGM as wave-passage effect, soil differences and coherency. As the ground motions are different in arrival time, frequency content and amplitude; an asynchronous response in transmission towers is observed.

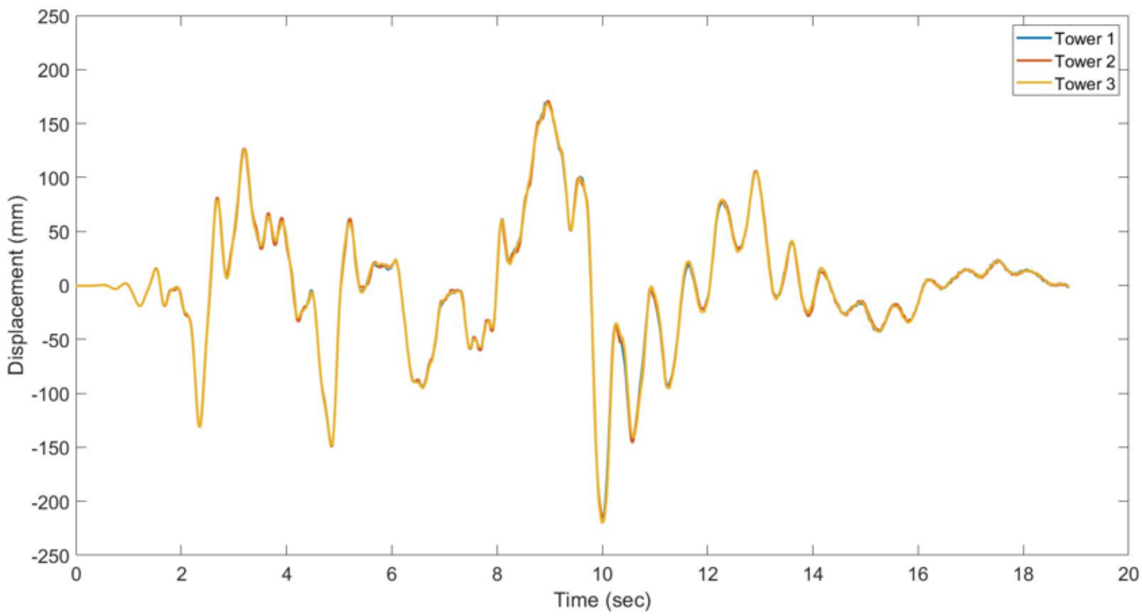

Figure 4.7. Top displacement of the transmission towers under uniform excitation.

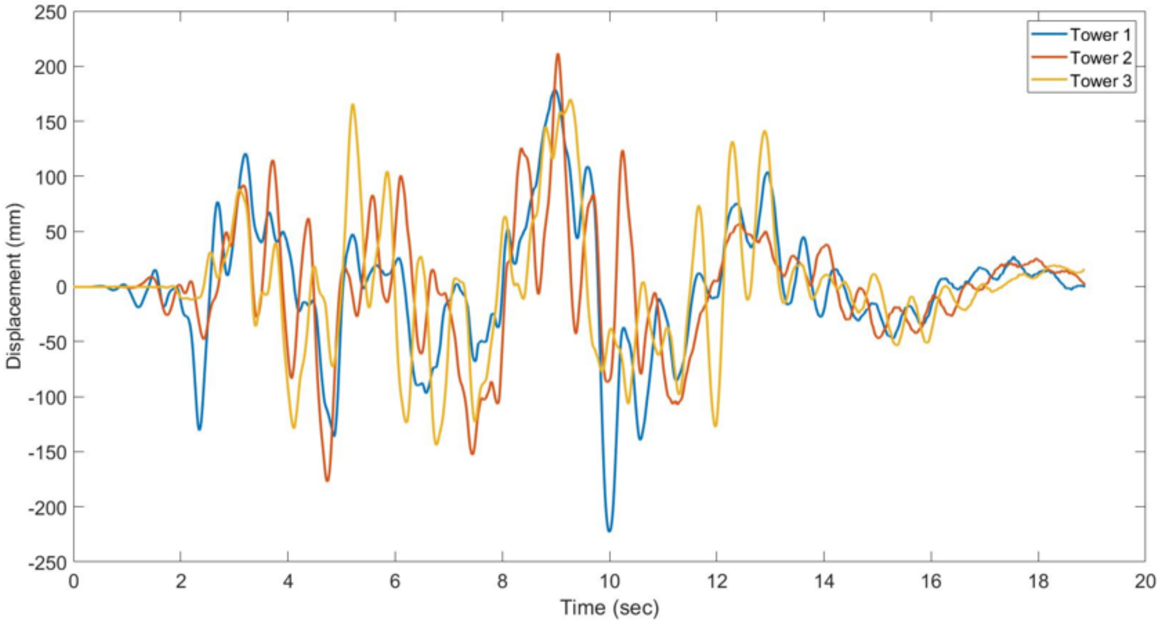

Figure 4.8. Top displacement of the transmission towers under SVGM.

Comparison of the two analysis shows that neglecting SVGM effects can lead to an underestimation of the response of transmission towers. In order to show that, second and third towers are investigated to show the effects of SVGM. In the analysis of with SVGM, the second tower has an average increase in the member stresses approximately by 10%. In the third tower this increase in around 15%. As expected, the effects of SVGM are more obvious in the third tower as all soil, coherency and wave-passage effects are higher compared to the second tower. All towers have an average of 15 members that are overstressed. Especially it must be noted that in the second tower there are 8 more overstressed members comparing to non-SVGM loading. Finally, steel design check of SAP2000 for the middle tower under SVGM loading can be seen in Figure 4.9.

Table 4.2. Comparison of member stresses between uniform ground motion and SVGM.

Member ID	Class	Stress value in uniform ground motion (MPa)	Stress value in SVGM (MPa)	Change
877	S355	289	361	25%
939	S355	292	357	22%
784	S235	201	260	29%
39	S235	212	253	20%

These results can be considered as a design recommendation as it is shown that the response of the towers can be underestimated in traditional analysis methods. As mentioned previously, stress changes can increase by up to 29% for specific members and by 10% to 15% in terms of average stress in the towers. Such significant changes should be taken int consideration in practice as well as in design codes.

Several different simulations were conducted in order to demonstrate the effects of distance, wave passage velocity and soil conditions. In a series of analyses, all soil conditions were set to soft to see the effect of SVGM only. It is shown that, in soft soil conditions, the effect of SVGM could increase the number of overstressed members by 33% to 133%, compared to uniform ground motion (Figure 4.9).

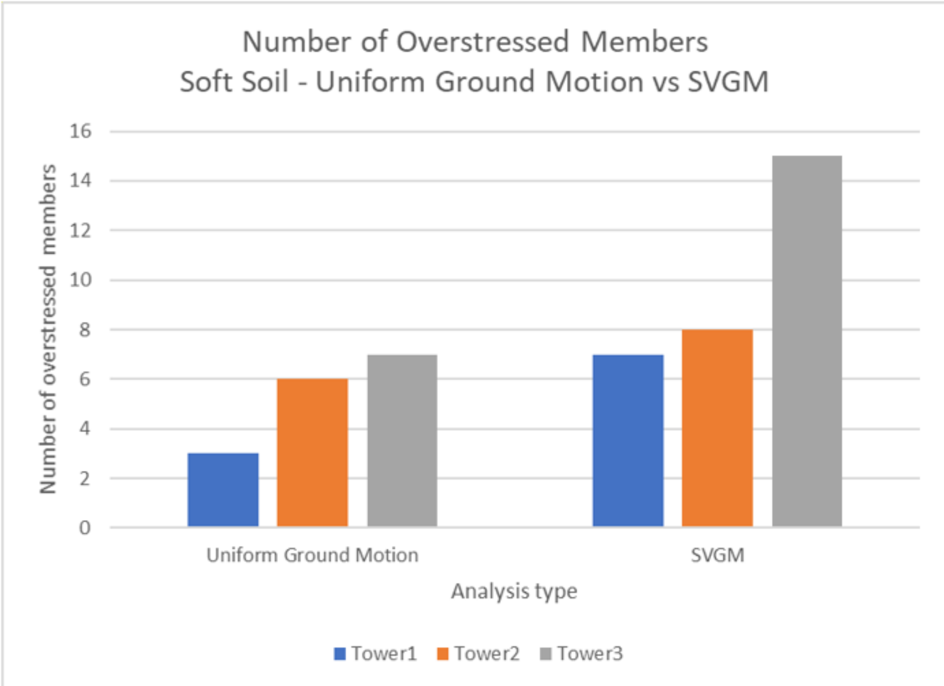

Figure 4.9. Number of overstressed members in soft soil: Uniform ground motion vs SVGM.

The same analysis was also conducted by setting all soil conditions to medium and stiff soil. In the analysis with medium soil conditions, the effect of SVGM can be up to 100% in the number of overstressed members (Figure 4.10).

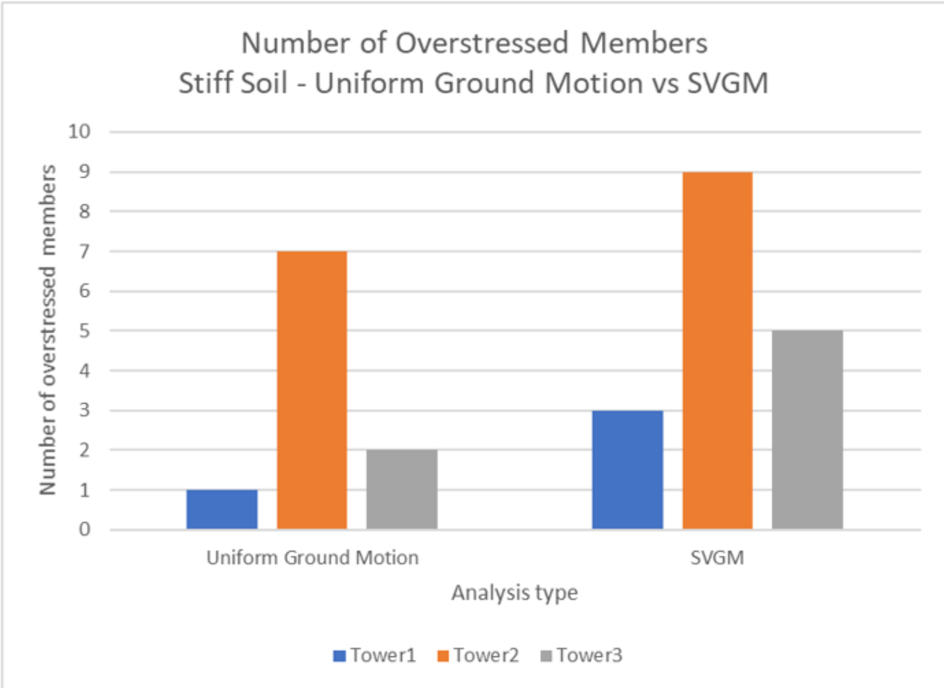

Figure 4.10. Number of overstressed members in medium soil: Uniform ground motion vs SVGM.

Finally, the last set of analyses were conducted by setting all soil conditions to stiff soil. This time, the calculated increase in the number of overstressed members due to SVGM was from 29% to 200%. This series of analyses indicate that SVGM analyses are resulting in more overstressed members in all three soil conditions, compared to those found in uniform ground motion analyses (Figure 4.11).

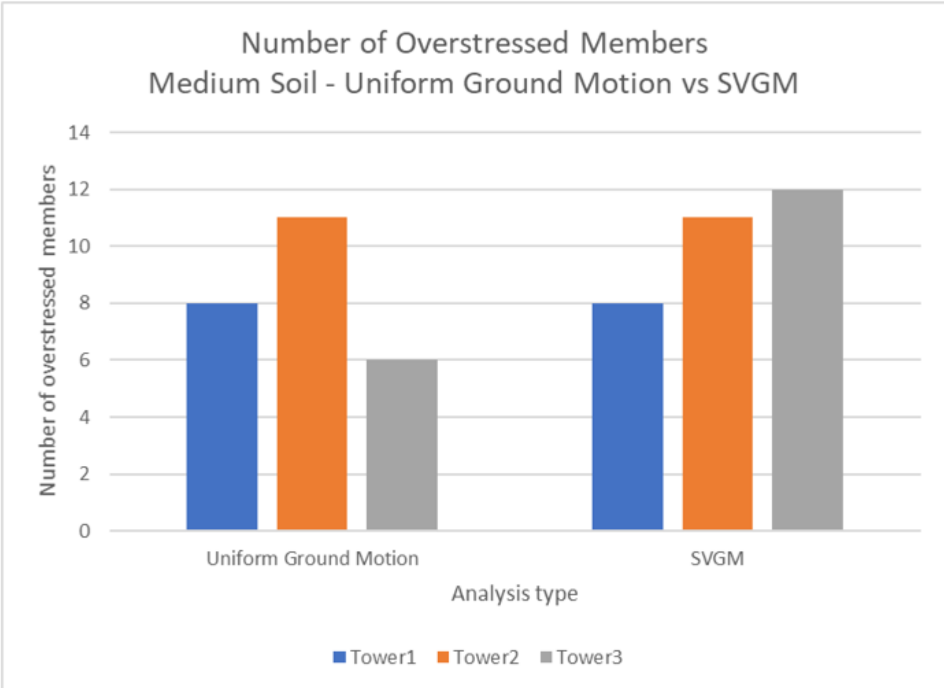

Figure 4.11. Number of overstressed members in stiff soil: Uniform ground motion vs SVGM.

Moreover, when the SVGM analyses were run together with the different soil conditions such that each tower has a different soil condition, the effects of SVGM become much more significant. This is obtained via another series of analyses by applying SVGM with the soil conditions for towers with stiff, medium, and soft soil conditions, respectively. As each tower is subject to different soil conditions in these analyses, it was demonstrated that the assumption of uniform soil conditions for all towers underestimates the number of overstressed members in each tower. The increase in the number of overstressed members was found to be between 100% and 217% when comparing SVGM with different soil conditions (soft, medium, and stiff respectively) with uniform ground motions for soft soil conditions (Figure 4.12). Such increase is between 13% and 133% when comparing SVGM with different soil conditions (soft, medium, and stiff respectively) with uniform ground motions for medium soil conditions (Figure 4.13), and between 171% and 800% when comparing SVGM with different soil conditions (soft, medium, and stiff respectively) with uniform ground motions for stiff soil conditions (Figure 4.14).

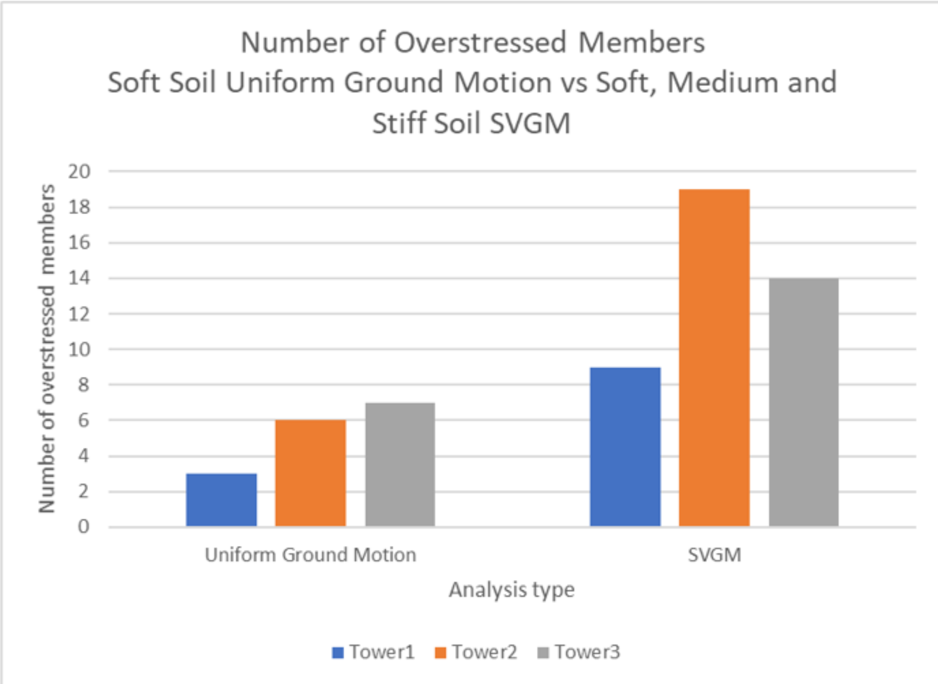

Figure 4.12. Number of overstressed members: Soft soil uniform ground motion vs Soft, medium and stiff soil SVGM.

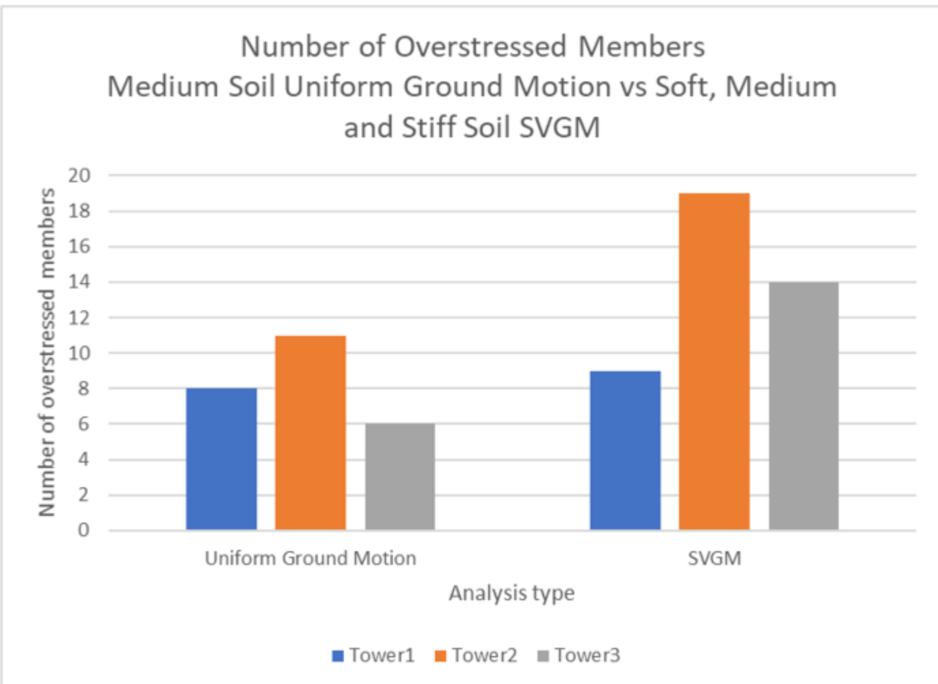

Figure 4.13. Number of overstressed members: Medium soil uniform ground motion vs Soft, medium and stiff soil SVGM.

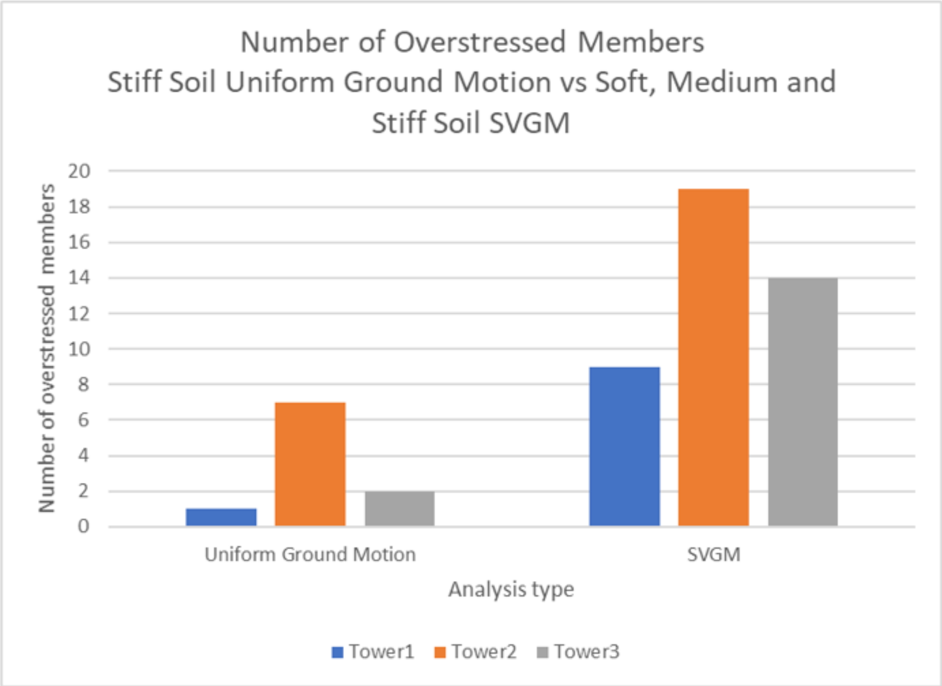

Figure 4.14. Number of overstressed members: Stiff soil uniform ground motion vs Soft, medium and stiff soil SVGM.

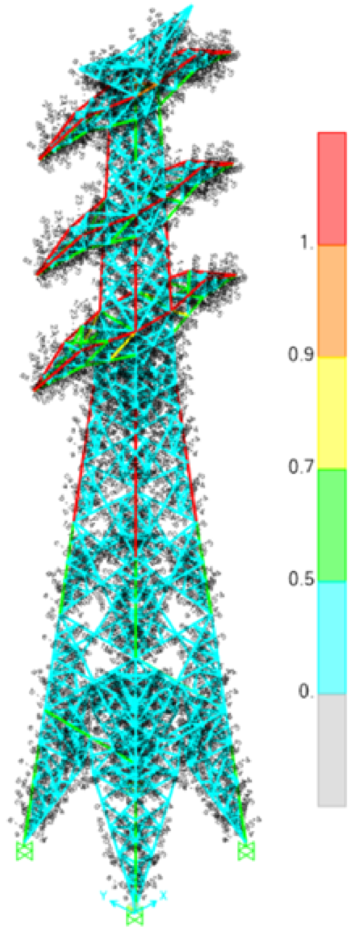

Figure 4.15. Steel Design Sections of the mid-transmission tower (Eurocode 3-2005).

It should be noted that, none of the previously mentioned analyses are currently conducted, by either state institutions or the private sector. In the design phase, a prototype tower is built and loaded with static loads to represent the vertical loads on the tower. Apart from the experimental loading, only static loads are taken into consideration in the general design process, making use of special software packages. Earthquake loads or dynamic conductor effects are completely ignored in the codes currently in effect.

5. CONCLUSION AND RECCOMENDATIONS

In this study, a real transmission line system is analyzed to understand its performance in the expected Istanbul earthquake. It covers ambient vibration test, modal identification, finite element modeling of a transmission line system and its performance analyses under SVGM records.

Ambient vibration test of the transmission line is very important in this study as there are limited research on this topic due to the nature of these kind of structures. As it is nearly impossible to make such a test as transmission line system is operating, findings are very important as they show the real dynamic characteristics of the transmission line system, especially the transmission towers. Without true dynamic behavior obtained from this ambient vibration test, modeling and simulation of the system will not be possible. In this study, it is shown that natural frequencies of the system can be matched up to 90% to 100% in finite element model. This would not be possible without an ambient vibration test, as there would not be any information about the natural characteristics of the transmission line, which would therefore not be reflected in the finite element model. As a result, ambient vibration tests should be used in design processes, as assumptions made in such calculations may not reflect the actual behavior of the transmission line systems. These results can be used particularly in the design codes for typical transmission towers which are currently under use.

In the modal identification process, FDD procedure is applied to obtained modal frequencies of the system. Due to the dangerous environment in the field, the test was carried with some obstacles. A limited number of sensors were placed by TEIAS professionals to the towers as there were a time limitation. In order to improve the sensitivity of mode shape extraction, more sensors could be used. Moreover, due to limitations of the permissions it was not possible to make any kind of dynamic measurement on the conductors. Despite all, modal frequencies are obtained with a high confidence level and presented in the study. It was demonstrated that without a proper modal identification process, ambient vibration data could not be analyzed to obtain the exact natural characteristics of the transmission line system, which, in the finite element model, would lead to an incorrect reflection.

In order to understand the performance of a transmission line system under an earthquake, ground motion selection must be done with care. A transmission line system cannot be analyzed with traditional ways as it is a special structure with three transmission towers connected with conductors to each other. As the towers are far away from each other, strong ground motions that affect them will be different naturally. This difference can be in soil type they stand on, coherency of ground motion and phase different caused by wave-passage effect. Therefore, a SVGM procedure is created via a MATLAB code that governs distance between towers, coherency between ground motions, wave-passage effect and target design spectrum of the transmission line system site with specified soil conditions. In this study, it is shown the effects of SVGM compared to traditional ground motion selection in terms of difference they can have over long distances and soil conditions which is exactly the case in a transmission line system. In FEM analyses, difference of two types of records is compared.

Technical drawings of the transmission line system were obtained and modeled in SAP2000 software. Different analysis versions are created to understand the effect of cables and SVGM excitations. It is shown clearly that cables must be modeled in FEM. Dynamic behavior of the system is drastically changed as cables are added. Following that, earthquake effects on the towers are also drastically changed compared to a single tower model in terms of both member stresses and top displacements. It should be noted that as system includes cable members a non-linear direct integration time history analysis is utilized following a dead load analysis in order to let the software to calculate the stiffness values correctly in each iterative step. Moreover, as the analysis software is not able to use three different excitations for three towers at the same time, a multi-support excitation analysis is utilized to use the SVGM created. In this study, it is shown that modeling cables in FEM improves natural frequency accuracy by up to 11%.

It is shown that SVGM can change the response of transmission line system. Ignoring this effect can lead to incorrect predictions of the structural responses. Wave-passage effect, loss of coherency and local site condition effects must be considered simultaneously in transmission line systems to obtain a realistic earthquake response. In this study it is demonstrated that application of SVGM improved top tower displacements, in comparison to uniform ground motion application. In stress calculations, such improvement can be as high as 29% for individual members. Moreover, member stresses in average improved by 10% to 15%. As transmission line systems cover very long distances, the use of SVGM in dynamic analysis of these systems should be considered in both current engineering practices and design codes.

Furthermore, a more detailed analysis indicated that the effect of SVGM compared to uniform ground motions in the same type of soil for all towers could significantly increase the number of overstressed members. This is observed in all uniform soft, medium and stiff soil cases, but significantly higher in the case of stiff soil assumption for all towers. Moreover, when the effect of different soil conditions for each tower is considered (stiff, medium and stiff soil assumption for towers, respectively) the effect of SVGM in the increase in the number of overstressed members was even higher. Such results prove the significance of SVGM in terms of distance, velocity of wave propagation and soil type assumption, all together.

On the other hand, temperature changes have a significant impact on transmission line conductors, as it can cause high thermal expansion. This would have an effect on the sag, therefore the tension on the cable. This effect should be taken into account for seasonal changes. In order to capture such effect, seasonal temperature changes must be obtained for a long enough time period, in order to get the average changes in years. Subsequently, the effect of temperature changes can be studied to see its outcomes in transmission lines. Unfortunately, it is beyond the scope of this work.

Another topic can be the effect of vertical components of the ground motions on transmission line systems. This has been studied in the literature for uniform excitations, however it has practical application problems in the case of spatially variable ground motions. Therefore, the effect of vertical components of ground motions can be studied on the conductors and towers with the help of uniform excitations.

Furthermore, non-structural parts of the transmission line system can be analyzed to investigate their effects on the response of transmission line system under ground motion excitations. This will require in-detail modeling in FEM as there are various elements in the transmission line towers which were not included in this work as it is beyond the scope of this study.

In conclusion, it is demonstrated that traditional analysis procedures could lead to significant underestimations in transmission tower responses. In case of a seismic event, such analysis flaws may cause catastrophic results. Therefore, this study can be applied as a framework in the analysis of transmission line systems. SVGM application according to the local site characteristics should be followed, as described in this study, in the design procedure for each transmission line, tower and cable modeling.

Further studies may involve more detailed ambient vibration tests with more sensors. In addition to that, extracting the dynamic characteristics of conductors can be investigated. Following that, a more detailed modeling and analysis on conductors can be utilized. Furthermore, in SVGM part, effects of different models can be investigated. Using different SVGM models, a different set of analysis can be made in different type of transmission line systems to investigate the effect of each parameter in detail.

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