

GROUND MOTION SIMULATION IN LARGE BASINS

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ABSTRACT

GROUND MOTION SIMULATION IN LARGE BASINS

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A significant component of seismic risk evaluation estimation is the assessment of potential earthquake ground motion records which are anticipated during future earthquakes. For this purpose and other engineering applications, simulated ground motions are being used increasingly. Simulated full waveforms are useful for realistic nonlinear structural dynamic analyses and performance-based earthquake engineering purposes in general. This is particularly true for the regions where the probability of large earthquakes is high despite the lack of such large events recorded within the instrumental era and the regions with sparse ground motion datasets. In this study, two different study areas are selected: Erzincan basin and İstanbul metropolitan.

In the first part, the March 13, 1992, Erzincan (eastern Türkiye) earthquake ($M_w=6.6$), which was recorded at only three strong ground motion stations, will be simulated using the hybrid ground motion simulation method. The source and regional path parameters for this destructive earthquake will be adopted from previously validated studies whereas the local site parameters are derived herein. The high-frequency attenuation (κ) factors are derived from regional strong

motion data while the local soil models are obtained in the field with one of the most prevalent noninvasive methods: Multi-Mode Spatial Autocorrelation. Consequently, peak ground acceleration distributions and full waveforms are presented.

In the second part, hybrid ground motion simulations of several earthquake scenarios are performed to obtain broadband ground motion time histories for potential events in Istanbul. Next, for validation purposes, the peak ground motion amplitudes are compared against existing empirical ground motion models.

Keywords: Broadband Ground Motion Simulation, Stochastic Finite-Fault Model, Deterministic Simulations, Istanbul, Erzincan.

ÖZ

GENİŞ HAVZALARDA YER HAREKETİ MODELLEMESİ

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Sismik risk tahmininin önemli bir bileşeni, gelecekteki depremlerde öngörülen olası yer hareketi kayıtlarının değerlendirilmesidir. Bu amaçla, simüle edilmiş sismik yer hareketlerinin kullanımı mühendislik uygulamalarında giderek artmaktadır. Genel olarak, simüle edilmiş tam dalga formları gerçekçi doğrusal olmayan yapısal dinamik analiz ve performans bazlı deprem mühendisliği çalışmaları için yararlıdır. Bu, özellikle büyük deprem olma olasılığının yüksek olmasına rağmen benzer büyüklükte bir deprem kaydı verisinin bulunmadığı ve çok kısıtlı olduğu bölgelerde geçerlidir. Bu çalışmada iki farklı çalışma sahası seçilmiştir: Erzincan havzası ve İstanbul metropolü.

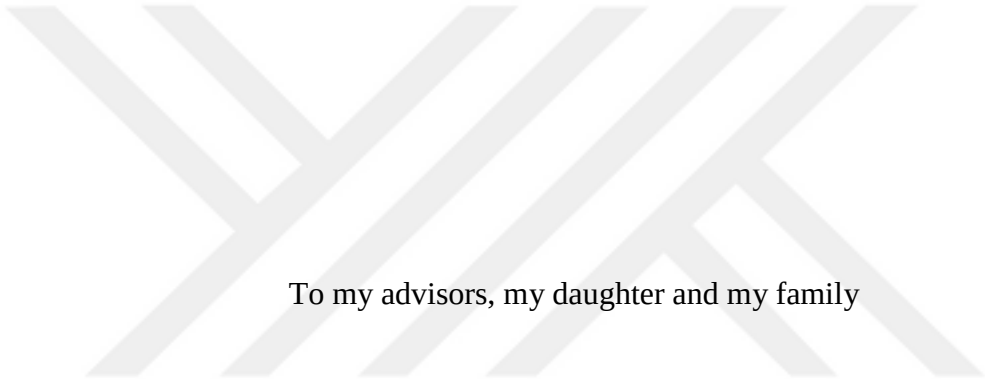
İlk bölümde, sadece üç adet kuvvetli yer hareketi istasyonunca ölçülen 13 Mart 1992 (Türkiye'nin doğusu), Erzincan ($M_w=6.6$) hibrit metot ile simüle edilecektir. Bu yıkıcı deprem için kaynak ve bölgesel yayılım parametreleri daha önceden doğrulanmış çalışmalardan uyarlanacak, yerel zemin parametreleri ise bu çalışmada türetilenlerdir. Yüksek frekanslı sönümleme faktörü (κ), bölgesel kuvvetli yer hareketi verilerinden elde edilirken, yerel zemin modelleri en popüler tahribatsız modellerden biri olan Çoklu-Mod Uzaysal Özilişki modeli ile oluşturulmuştur.

Çalışmanın son kısmında, elde edilen sonuçlar pik yer ivmesi dağılımlarının ve tam dalga formları şeklinde sunulacaktır.

Bu çalışmanın ikinci bölümünde, İstanbul'daki gerçekleşmesi muhtemel depremler için geniş bantlı yer hareketi kayıtlarını elde etmek amacıyla çeşitli deprem senaryolarının hibrit yer hareketi simülasyonları gerçekleştirilmiştir. Daha sonra, doğrulama amacıyla, en yüksek yer hareketi genlikleri, mevcut amprik yer hareketi modelleri ile karşılaştırılır.

Anahtar Kelimeler: Yer Hareketi Simülasyonu, Stokastik Sonlu Fay Modeli, Determistik Simülasyon, İstanbul, Erzincan.





To my advisors, my daughter and my family

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LIST OF ABBREVIATIONS

ABBREVIATIONS

CMF	: Central Marmara Fault
DWFE	: Discrete wavenumber finite element method
ERC	: Strong Ground Motion Station in Erzincan city center
FAS	: Fourier Amplitude Spectra
f-k	: Frequency-Wavenumber
GMM	: Ground Motion Models
H/V	: Horizontal-to-Vertical
HF	: High Frequency
HVSR	: Horizontal-to-Vertical Spectra Ratio
IES	: Integrated Earthquake Simulation
Kappa	: High Frequency Attenuation Factors
LF	: Low Frequency
MCA	: Multi-Channel Array
MMI	: Modified Mercalli Intensity
MMSPAC	: Multi Mode Autocorrelation Method
NAFZ	: North Anatolian Fault Zone
NBF	: North Boundary Fault
NEHRP	: National Earthquake Hazards Reduction Program
PGA	: Peak Ground Acceleration

PGV	: Peak Ground Velocity
PS	: P-wave and S-wave
REF	: Strong Ground Motion Station in Refahiye
ReMi	: Refraction Microtremor
SA	: Spectral Acceleration
SASW	: Spectral Analysis of Surface Waves
SPEED Method	: Spectral Elements in Elastodynamics with Discontinuous Galerkin
TER	: Strong Ground Motion Station in Tercan
TUJJB	: Turkish National Geodesy and Geophysics Union

CHAPTER 1

INTRODUCTION

Earthquakes are among the most impactful natural disasters, still causing major loss of life and property worldwide, with our country being particularly and continuously affected. Despite valuable lessons learned from historical and instrumental earthquakes, fully mitigating the destructive effects of earthquakes remains a challenge in our country. Earthquake ground motion parameters play a crucial role in designing earthquake-resistant structures and retrofitting existing ones in urban areas. However, obtaining these parameters can be challenging in some cases due to the absence of earthquakes of varying magnitudes in a region or an insufficient number of seismic networks to record the earthquakes. Particularly full time series of past events at locations of no recordings and those motions for potential earthquakes is crucial for accurate earthquake engineering applications. At this particular point, ground motion simulations become vital and increasingly practical.

In its most general definition, ground motion simulation is to obtain full ground motion time histories of past earthquakes or potential scenario events using various methods in time or frequency domain. With the recent advances in numerical methods and computational platforms, ground motion simulations have become even more popular and practical within the last decade. Global earthquake databases operated by well-known institutions such as PEER and COSMOS aim to include simulated datasets in the near future for use in engineering practice (e.g.: Askan et al.,2024).

In this thesis, hybrid ground motion simulations within a broadband frequency range are performed for two selected regions in Türkiye: Erzincan and İstanbul.

Mainly two different approaches which exist in literature are combined with site specific parameters to obtain a hybrid simulation approach in this study.

1.1 A General Summary of Ground Motion Simulation Methodologies

A thorough chronological development of the methods used in this thesis will be presented in Chapter 2 while presenting the algorithms. Herein, a general summary of the main simulation approaches and recent studies is presented regarding the scope of this study. The novelty of this thesis is also briefly discussed in this section by stating the main differences of this study from the available literature.

Three primary simulation techniques exist in the literature: deterministic, stochastic, and hybrid simulations. The categorization of simulation procedures is based on the frequency content of the simulated records, modeling assumptions and the solution techniques employed.

Deterministic simulations are utilized to generate the low-frequency portion of the simulated time histories, while stochastic simulations are employed for the high-frequency portion of the time series. In recent years, there has been a growing trend to combine these methodologies, either in the frequency domain or time domain, to implement hybrid simulations capable of generating broadband acceleration time series (e.g.: Pitarka et al., 2000; Erdik et al., 2001; Hisada et al., 2008; Mai et al., 2003, Mena et al., 2010; Mai et al., 2010; Moratto et al., 2015). Deterministic ground motion simulations utilize numerical solutions for the partial differential equations governing wave propagation. These simulations require well-defined seismic sources and accurate spatial variations of the material properties within the ground. Various methods have been employed in the literature to solve the equation of motion that corresponds to seismic wave propagation through a three-dimensional heterogeneous medium. Some notable examples include the works of Bouchon (1981), Frankel (1992), Olsen et al., (1995), Komatitsch et al., (2004), and Aagaard et al. (2010). These methods provide different approaches to

accurately simulate deterministic ground motions and capture the complexities of wave propagation in heterogeneous environments. These methods are the boundary-element method (e.g.: Kawase, 1988; Luco et al., 1990; Pedersen et al., 1994), the finite difference method (e.g.: Frankel and Vidale, 1992; Frankel, 1993; Yomogida and Egten, 1993; Olsen et al., 1995; Olsen and Archuleta, 1996; Moczo et al., 2002), the finite element method (e.g.: Li et al., 1992; Rial et al., 1992; Toshinawa and Ohmachi, 1992; Bao, 1998), the spectral element method (e.g.: Cohen et al., 1993; Priolo et al., 1994; Komatitsch, 1997; Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999; Komatitsch et al., 2004), the theoretical Green's function method (e.g.: Bouchon, 1981; Hisada, 1994; Chen and Zhang, 2001), and the empirical Green's function method (e.g.: Hartzell, 1978; Irikura, 1986; Mai and Beroza, 2003; Mena et al., 2010; Mai et al., 2010; Moratto et al., 2015).

The high-frequency portion of seismic waves exhibits random behavior in nature and lacks phase coherence in their spectra. As a result, deterministic methods are not always suitable for modeling high-frequency ground motions. The pioneering work by Housner (1947), later expanded upon by Housner (1955) was one of the first attempts to model ground motions of stochastic nature. These studies involved superposing random amplitude and duration impulses with random time delays to model the time histories of ground motions. Subsequently, the studies by Haskell (1966) and Aki (1967) provided advancements in this subject, building upon the original model.

Aki (1967) introduced a model where earthquake source dislocation was represented as a ramp function of time. On the other hand, Haskell (1966) used the autocorrelation function of dislocation acceleration and showed that the source spectrum decreases proportionally to the cubic power of frequency (ω^{-3}). Through comparison with seismological observations, several authors concluded that the (ω^{-2}) model more realistically represents the high-frequency behavior of earthquakes (Aki, 1967; Brune, 1970; Hanks, 1979). Aki's innovative observations

inspired numerous studies in the ground motion simulation field, providing valuable insights into modeling the high-frequency behavior of ground motions.

After successfully representing the seismic spectrum in the frequency domain, the source-time function remained challenging to model. Among various models in literature (Haskell, 1964; Aki, 1968), the most common one is the source model proposed by Brune (1970 and 1971). Subsequently, in their early work, Hanks (1979) and McGuire and Hanks (1980) applied Parseval's theorem on the Brune source spectrum to obtain the far-field shear wave root-mean-square acceleration (a_{rms}). They then related this parameter to the peak ground acceleration (a_{rms}) through the application of random-vibration theory (Vanmarcke and Lai, 1980). Additionally, they demonstrated that the randomness in high-frequency ground motions can be effectively represented with white Gaussian noises.

In 1983, Boore combined the source spectra of Aki (1967) and Brune (1971) with the findings of Hanks and McGuire (1981) to propose a methodology for generating time-domain simulations. This approach treated faults as stochastic point-sources. Later, Beresnev and Atkinson (1997) extended this methodology to model finite-faults. The finite-fault model divides a rectangular fault plane into smaller subfaults, each of which is treated as a stochastic point-source. The contribution of each sub fault is then summed up to obtain the ground motion simulation. Motazedian and Atkinson (2005) further developed this stochastic finite-fault methodology, significantly improving the definition of the corner frequency.

Both deterministic and stochastic methods have their own merits and limitations while simulating a wide frequency range of ground motions. Hybrid methods have been developed to overcome these limitations while generating realistic broadband simulations. The hybrid methods combine stochastic and deterministic approaches, using mostly stochastic methods for high-frequency ground motions and deterministic methods for low-frequency ground motions. Several researchers have validated the effectiveness of these hybrid methods (e.g.: Kamae et al., 1998;

Pitarka et al., 2000; Hisada and Bielak, 2003; Graves and Pitarka 2004; Pulido and Kubo 2004; Liu et al. 2006; Wuttke F., 2009; Smerzini et al., 2014; Guidott, et al., 2019).

In this study, a hybrid ground motion simulation method (Mai and Beroza, 2003; Moratto et al., 2015) is utilized to model past and potential earthquakes in the Erzincan and İstanbul regions, respectively. Additional relevant literature will be referenced throughout the text whenever required for further context and validation.

In this thesis, two significant regions in Türkiye with both dense seismic activities are chosen. Extensive fieldwork is conducted to determine site-specific parameters, in addition to validated source and path characteristics, followed by the execution of strong ground motion simulations. As observed during the recent earthquakes in Pazarcık ($M_w=7.7$) and Elbistan ($M_w= 7.6$) occurred on February 6, 2023, which caused numerous casualties and property losses in Türkiye, two buildings with similar dynamic characteristics located on varying local site conditions exhibit different behaviors during the earthquakes due to variations in dynamic soil properties. One of the crucial points here is the necessity of actively incorporating geological, geophysical, and geotechnical information into seismic designs for resilient urban regions. For this purpose, local wave velocity models along with local attenuation properties are aimed in this study. Therefore, different from most other studies in literature, the majority of the input parameters used for broadband ground motion simulations in this thesis are site-specific and more importantly, derived as part of this study. This effort makes this study innovative and original for these seismically active locations.

1.2 Objective and Scope

The main objective of this thesis is to develop a comprehensive platform for generating broadband ground motion simulations, specifically targeting potential events in large basins such as Erzincan and metropolitans such as Istanbul. For this purpose, firstly deterministic and stochastic ground motion simulations are performed for the low and high frequency of the ground motion records, respectively. Secondly, the combination of the low and high frequencies is performed in the frequency domain. The thesis focuses on two specific study areas: the province of Erzincan, situated in a pull-apart basin within a very active seismic zone, and the Zeytinburnu district in Istanbul Metropolitan, known for its industrial, population wise and cultural significance. Zeytinburnu is also located very close to the Marmara Sea segment of the North Anatolian Fault Zone.

In this thesis, the following chapters are discussed in the order presented.

- Chapter 2 provides theoretical information on ground motion simulation methodologies within a chronological development context.
- Chapter 3 presents the first application of the proposed approach for simulating broadband time histories in Erzincan region. It includes detailed information about the site-specific parameters such as regional velocity models, amplification factor, transfer functions and kappa models. The chapter concludes with the 2D velocity model for the basin constituted by Multi Mode autocorrelation method, a presentation of estimated time histories for the 1992 Erzincan earthquake, and a discussion of the results.
- Chapter 4 delves into the second application for simulated broadband time histories focusing on the İstanbul region. It covers the calculation of site-specific parameters and the simulation of ground motion under a potential scenario earthquake in the Marmara Sea. A discussion is also provided on the numerical results obtained in İstanbul and their implications in terms of seismic risk in the region.

- Chapter 5 presents a summary, conclusions, and recommendations for future research in this field.

Briefly, these chapters present a chronological progression of current state of the art, starting with the theoretical foundations, applying ground motion simulations in selected regions with site-specific parameters followed by validations, and finally culminating in conclusions and recommendations for further studies.





CHAPTER 2

METHODOLOGY

In this thesis, broadband ground motion simulations are performed for two seismically active regions in Türkiye. For this purpose, a deterministic ground motion simulation method is used to obtain the low-frequency part of the records and a stochastic ground motion simulation method is used for the high-frequency part of the seismic records. The results are combined to obtain the broadband seismic records. Very recently, machine learning approaches have also been proposed (e.g.: Hu et al., 2023) which are out of scope of this study. This thesis involves the recent numerical and stochastic approaches.

In this chapter, details of the deterministic and stochastic methods are presented with their chronological developments. Figure 2.1 shows a general view of the existing ground motion simulation methods.

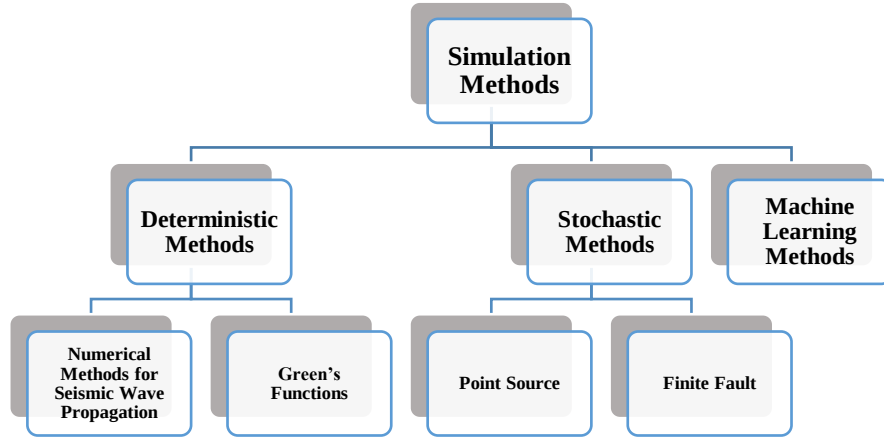


Figure 2.1. General view of existing ground motion simulation methods

2.1 Deterministic Ground Motion Simulation Method

For obtaining the low-frequency part of the synthetic ground motion, a deterministic ground motion simulation method is performed. To model this aforementioned frequency range ($f \leq 1\text{--}3$ Hz) Green's functions are used.

In the literature, deterministic Green's functions-based methods which are developed from the main findings of Hartzell (1978) and advances by Irikura (1986) are used for low-frequency portion of the ground motions. These approaches require detailed soil profiles at the site of interest.

Hartzell's approach utilizes the aftershock records of a large earthquake as Green's functions to simulate the strong ground motion of that particular earthquake. The ground motion of the large earthquake, represented by $U(t)$, is obtained by adding the responses of aftershocks $U_i(t)$, which are all defined as point sources expressed in Equation (2.1) as;

$$U(t) = \sum_{i=1}^n [U_i(t) * Q_i(t)] \cdot H(t - \tau_i) \quad (2.1)$$

$$U_i(t) = S_i(t) * M_i(t) * R_i(t) \quad (2.2)$$

The convolution operation (*) is used to indicate the mathematical process in Hartzell's method. Here, $Q_i(t)$ represents a generalized scaling factor, while n denotes the total number of point-sources on the fault plane. The Heaviside unit step function (H) and τ_i represent the phase delay term, which is influenced by both rupture propagation and the travel time from the source to the receiver. In Equation (2.2), $S_i(t)$ represents the source function, $M_i(t)$ is the earth response, and $R_i(t)$ is the constant receiver function. It is assumed that the focal mechanism of the aftershocks is the same as that of the main event. Moreover, the variation in earth response is accounted for by originating the aftershocks from different points on the fault plane. The phase delay term τ_i depends on the rupture velocity and

direction, and to accurately determine its values, detailed knowledge of the rupture location is necessary.

Irikura (1986) expressed the ground motions of a large event by superposing observed records of a small event, where the equation is related not only to time but also to distance from the large event.

$$U(x, t) = \sum_{i=1}^l \sum_{j=1}^m \sum_{k=1}^n \frac{F_{ij}^s}{F_s} \cdot \frac{r_o}{r_{ij}} \cdot u(x - t - t_\xi - t_d) \quad (2.3)$$

In Equation (2.3), the simulated motion for the large event is represented as $U(x, t)$, while u denotes the observed record for a small event. F_{ij}^s and r_{ij} represent the radiation pattern and focal distance for the (i, j) element, respectively. The parameters l , m and n are determined from scaling relations proposed by Kanamori and Anderson (1975). The phase term, t_ξ , is expressed in Equation (2.4) as:

$$t_\xi = \frac{r}{v_s} + \frac{\xi_{ij}}{v_r} \quad (2.4)$$

where v_r and v_s are the ruptures and S-wave velocities, ξ_{ij} is a distance parameter from the point where rupture starts to (i, j) element and r is the distance between large event to a receiver.

Finally, in Equation (2.3) t_d is the uniform time shift as given in Equation (2.5):

$$t_d = (k - 1) \cdot \frac{\tau}{n} \quad (2.5)$$

where τ is the rise time of the large event.

Irikura (1986) then made some revisions in terms of periodicity, time shifts and assuming the parameters l , m and n are equal to N :

$$U(R, t) = \sum_{n=1}^{N \times N} \left(\frac{R_0}{R_n} \right) \cdot F \left(t - \frac{\xi_n}{v_r} - \frac{R_n}{v_s} \right) \cdot u(R_0, t) \quad (2.6)$$

In Equation (2.6), R , R_0 , and R_n represents the distances from the large event to the receiver, the small event to the receiver, and the distance from the n^{th} sub-fault to the receiver, respectively. The fault plane is divided into sub-faults in a $N \times N$ grid. Here, $F(t)$ is a function used to correct the slip velocity difference between the target large event and the small event. The term ξ_n is another distance parameter that measures the distance from the point where the rupture starts to the n^{th} sub-fault. The variables v_r and v_s represent the rupture and S-wave velocities, respectively.

The function $F(t)$ is expressed by a delta function $\delta(t)$, and a boxcar function $b_T(t)$, with the fault width T and amplitude D as follows:

$$F(t) = \delta(t) + D \cdot b_T(t) \quad (2.7)$$

2.1.1 Discrete Wavenumber Finite Element Method (DWFE)

The discrete wavenumber finite element method (DWFE) is employed to compute Green's function in this study (Olson et al., 1984; Spudich and Archuleta, 1987). The method models the Earth in one dimension. In the DWFE method, the horizontal dependence of the seismic wavefield is represented by separable solutions of elastic equations, while the vertical and time dependence are solved using finite element and finite differences numerical methods, respectively. Olson et al. (1984) determined the Fourier-Bessel series representation of the elastic displacement field caused by point force vectors and point-couple force systems. The expression for the displacement is given as:

$$\begin{aligned} \mathbf{u}(r, \phi, z, t) = \sum_m \int_0^\infty \frac{k}{2\pi} [& U_{zk}^m(z, t) \mathbf{R}_k^m(r, \phi) + U_{rk}^m(z, t) \mathbf{S}_k^m(r, \phi) \\ & + U_{\phi k}^m(z, t) \mathbf{T}_k^m(r, \phi)] dk \end{aligned} \quad (2.8)$$

where the vertical derivative is:

$$\mathbf{u}'(r, \phi, z, t) = \sum_m \int_0^\infty \frac{k}{2\pi} [U'_{zk}(z, t)\mathbf{R}_k^m(r, \phi) + U'_{rk}(z, t)\mathbf{S}_k^m(r, \phi) + U'_{\phi k}(z, t)\mathbf{T}_k^m(r, \phi)] dk \quad (2.9)$$

To validate the (r, ϕ) dependence of the separable solution to the equation of motion using surface vector harmonics, Olson et al. (1984) define a body force density vector $\mathbf{f}$ and a displacement vector $\mathbf{u}$. The same surface harmonics expresses to represent their (r, ϕ) dependence, as given in Equation (2.9).

$$\begin{aligned} \mathbf{f}(r, \phi, z, t) &= F_{zk}^m(z, t)\mathbf{R}_k^m(r, \phi) + F_{rk}^m(z, t)\mathbf{S}_k^m(r, \phi) \\ &\quad + F_{\phi k}^m(z, t)\mathbf{T}_k^m(r, \phi) \\ \mathbf{u}(r, \phi, z, t) &= U_{zk}^m(z, t)\mathbf{R}_k^m(r, \phi) + U_{rk}^m(z, t)\mathbf{S}_k^m(r, \phi) \\ &\quad + U_{\phi k}^m(z, t)\mathbf{T}_k^m(r, \phi) \end{aligned} \quad (2.10)$$

The other dependence (z, ϕ) is described by the complex scalar coefficients which are also given in Equation (2.10): $F_{zk}^m, F_{rk}^m, F_{\phi k}^m, U_{zk}^m, U_{rk}^m$ and $U_{\phi k}^m$.

In addition, Olson et al. (1984) presented a discrete wavenumber expansion for the impulse response of the elastic medium, which is the solution to the equation of motion given in Equation (2.11). The discrete wavenumber expansion is expressed as:

$$(\lambda + \mu)\nabla(\nabla \cdot \mathbf{u}) + \mu\nabla^2\mathbf{u} + \nabla\lambda(\nabla \cdot \mathbf{u}) + 2(\nabla\mu) \cdot \mathbf{E} + \mathbf{f} = \rho\partial_{tt}\mathbf{u} \quad (2.11)$$

In the equation, λ and μ represent the Lamé parameters, $\mathbf{u}$ denotes the displacement field, $\mathbf{E}$ is Cauchy's infinitesimal strain tensor, $\mathbf{f}$ represents the force density vector, and ρ is the material density. The expression for Cauchy's infinitesimal strain tensor $\mathbf{E}$ is given in Equation (2.12) as:

$$\mathbf{E} = \frac{1}{2}[\nabla\mathbf{u} + (\nabla\mathbf{u})^T] \quad (2.12)$$

Furthermore, in a homogeneous medium, the terms $\nabla\mu$ and $\nabla\lambda$ involved in Equation (2.11) become zero, simplifying the equation of motion. The total motion of the half-space due to a horizontal point load at z_0 is then given by Equation (2.13) as:

$$\begin{aligned}
\mathbf{u}_z^1(r, \phi, z, t; z_0) &= \sum_{n=0}^{\infty} W_n^1 U_{zk_n}^1(z, t; z_0) J_1(k_n r) \cos(\phi) \\
\mathbf{u}_r^1(r, \phi, z, t; z_0) &= \sum_{n=0}^{\infty} W_n^1 \left[U_{rk_n}^1(z, t; z_0) \left(\frac{1}{k_n r} J_1(k_n r) - J_2(k_n r) \right) \right. \\
&\quad \left. + U_{\phi k_n}^1(z, t; z_0) \frac{1}{k_n r} J_1(k_n r) \right] \cos(\phi) \\
\mathbf{u}_\phi^1(r, \phi, z, t; z_0) &= - \sum_{n=0}^{\infty} W_n^1 \left[U_{\phi k_n}^1(z, t; z_0) \left(\frac{1}{k_n r} J_1(k_n r) - J_2(k_n r) \right) \right. \\
&\quad \left. + U_{rk_n}^1(z, t; z_0) \frac{1}{k_n r} J_1(k_n r) \right] \cos(\phi) \\
W_n^1 &= \frac{1}{\pi [R J_0(k_n R)]^2}
\end{aligned} \tag{2.13}$$

where $J_0(k_n r)$, $J_1(k_n r)$ and $J_2(k_n r)$ are Bessel functions over the interval $0 \leq r \leq R$.

2.1.2 Deterministic Ground Motion Simulation Parameters

The low-frequency portion of broadband records of the earthquakes modeled in this study is simulated using an open-source code named as COMPSYN implementing the Discrete Wavenumber Finite Element method for calculating 1-D Green's Functions. COMPSYN is a relatively old but well-established code widely used for ground motion simulations. It employs finite element and finite difference methods to solve the elastic equations, allowing for incorporating complex three-dimensional earth structures (Olson, 1984). The aforementioned open-source code follows a process of three main steps for generating velocity, fault, and slip models. These main steps are presented in Figure 2.2.

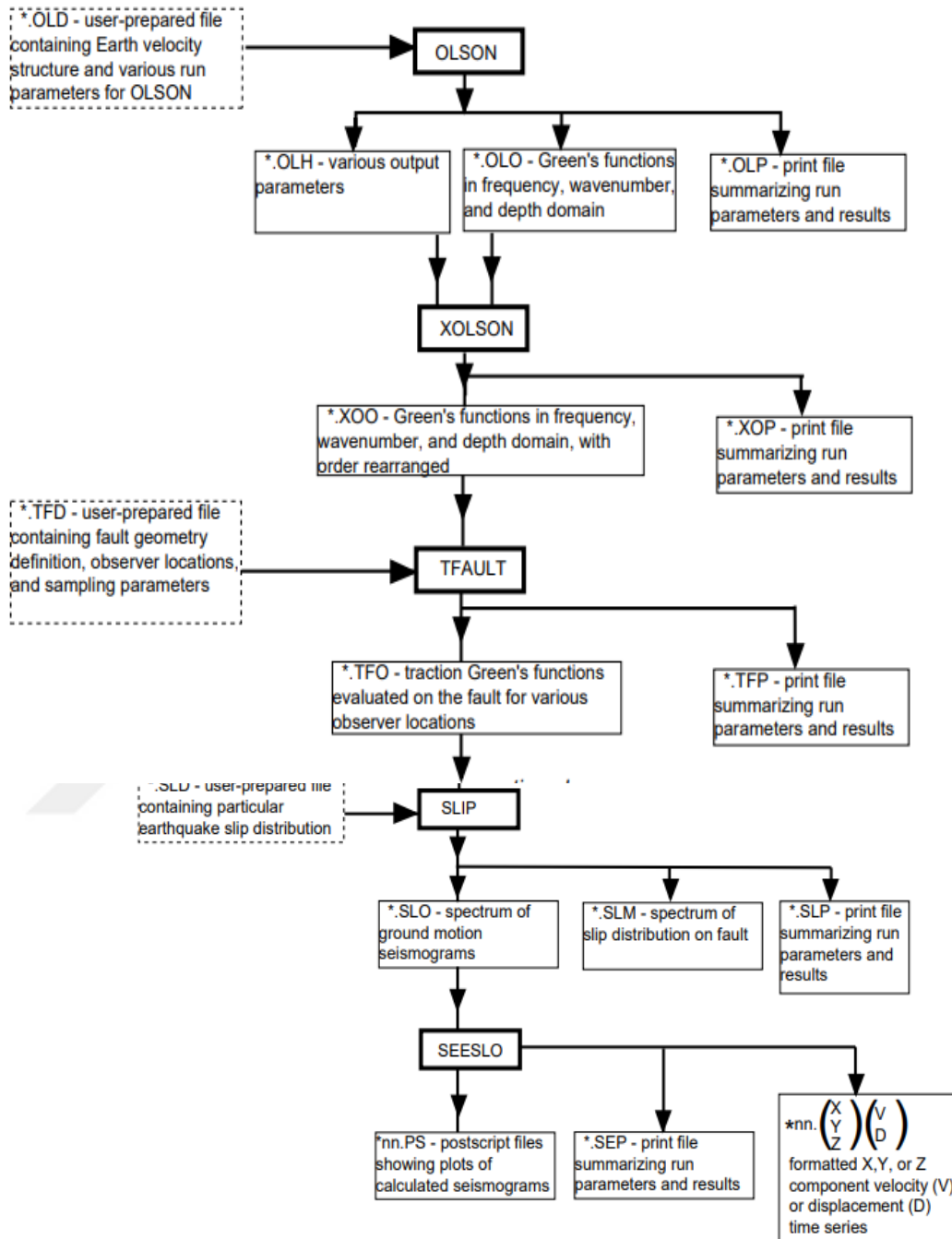


Figure 2.2. Flowchart for the velocity, fault and slip models of the COMPSYN code (Adapted from Spudich and Xu, 2002)

2.1.2.1 Parameters in the OLSON Model

The initial step involves generating a detailed 1D wave velocity (earth) structure. This structure includes values for V_p (compressional wave velocity), V_s (shear wave velocity), corresponding density values, and depth information for each layer. Additionally, several parameters related to the finite element grid and time series calculation are specified. These parameters include the maximum resolving frequency of the finite element grid (f_{max}), the cut-off frequency (f_{cut}), the total length of the calculated time series (t_{max}), and the time step length for the finite element calculation (d_t).

2.1.2.2 Parameters in the TFAULT Model

Within the TFAULT model, specific details regarding the fault geometry are defined. This includes parameters such as the dip of the fault, the strike of the fault, and the boundary conditions associated with the fault, both along the down-dip and strike coordinates. In Figure 2.3, the variables x_1 and x_2 represent the strike coordinates, while z_1 and z_2 correspond to the downdip coordinates of the fault plane.

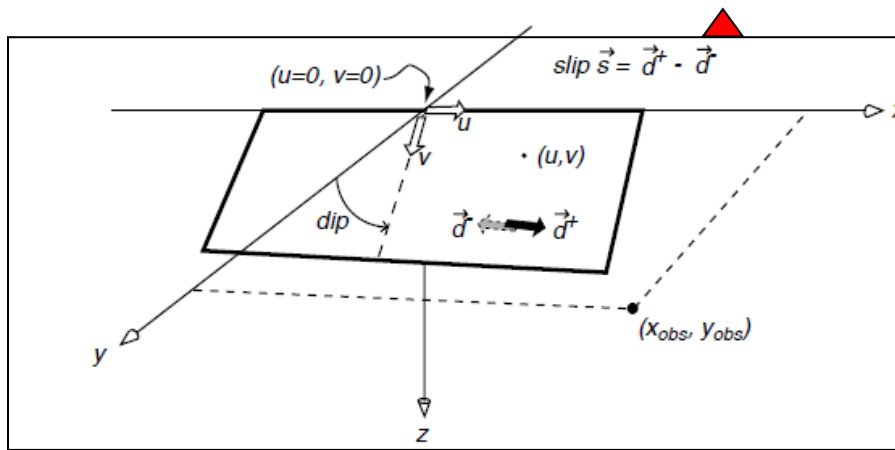


Figure 2.3. Detailed of the fault geometry and red triangle indicates the station (Adapted from Spudich and Xu, 2002)

2.1.2.3 Parameters in the SLIP Model

In this step, the user specifies the horizontal and down-dip limits for integrating the fault plane. Additionally, rupture times are calculated based on the ratio of rupture velocity to shear velocity. Figure 2.4 provides a visual representation of the slip model, where the blue area represents the fault region calculated in the preceding TFAULT section. The green portion indicates the slip model, representing the distribution of slip along the fault. The pink portion represents the calculated surface integral, indicating the contribution of the slip to the ground motion at the surface.

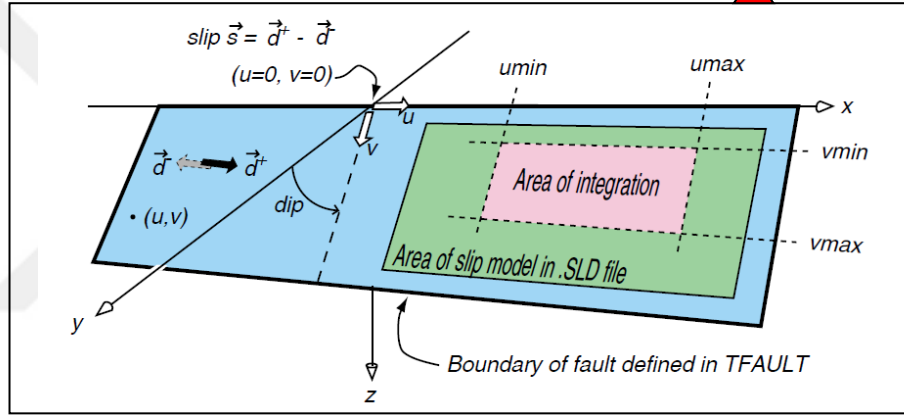


Figure 2.4 Properties of the slip model and red triangle indicates the station
(Adapted from Spudich and Xu, 2002)

2.2 Stochastic Ground Motion Simulation Methods

The stochastic strong ground motion simulation methodology is mainly motivated by the random nature of the high-frequency component of strong ground motion, typically occurring at frequencies above 1 Hz. Deterministic approaches become challenging at higher frequencies due to the requirement of highly detailed soil profiles, which are often not feasible as well as the high computational cost for simulating those higher frequencies. Stochastic strong ground motion simulation

methods can be categorized into two main approaches: stochastic point-source modeling and stochastic finite-fault modeling.

2.2.1 Stochastic Point–Source Modeling

Stochastic ground motion modeling encompasses two primary components: the stochastic time series and the Green's function solution of the elastic wave propagation equation.

The stochastic point-source modeling technique, initially proposed by Hanks and McGuire (1981), combines seismological models of ground motion spectral amplitudes with high-frequency motions. Then, Boore (1983) developed a method to model the S-wave portion of the acceleration-time series, representing the high-frequency component of ground motion. This method represents shear waves as finite-duration, band-limited, white Gaussian noise.

The finite duration is defined within the interval of $0 \leq t - \frac{R}{\beta} \leq T_d$, where R represents the source-to-receiver distance, β is the shear-wave velocity, and T_d is the faulting duration. The band-limited property is determined within the frequency range $f_0 \leq f \leq f_{max}$, where f_0 represents the corner frequency of far-field shear radiation and f_{max} is the highest recorded frequency captured by the seismometer. This methodology aims to generate a transient time series that matches the desired spectrum in terms of amplitude.

In this modeling approach, random band-limited Gaussian white noise with unit variance is initially generated for a specified finite duration of motion. This noise is then windowed using Saragoni-Hart or boxcar windows to achieve a more realistic acceleration-time series. The ground motion simulation results are transformed from the time domain to the frequency domain, and the amplitudes are normalized by cutting off frequencies above the cut-off frequency (Brune, 1970). Subsequently, inverse Fourier transformation converts the modeled and shaped

noise spectrum back to the time domain, resulting in a stochastic acceleration-time series (Boore, 2003).

The filter functions are defined as the product of the source function $E(M_0, \omega)$, the path function $P(R, \omega)$, the site function $G(\omega)$, and the instrument response $I(\omega)$. The results are represented in the Fourier Amplitude Spectrum of a seismic signal, as shown in Equation (2.14):

$$A(M_0, R, \omega) = E(M_0, \omega) \cdot P(R, \omega) \cdot G(\omega) \cdot I(\omega) \quad (2.14)$$

where M_0 is the seismic moment, R is the source-to-receiver distance, and ω is the frequency.

2.2.1.1 The Source Function, $E(M_0, \omega)$

The source function depends on various factors, including earthquake magnitude, frequency, source-time function, and the shear modulus of the earth material at the fault depth. The definition of the source function is given in Equation (2.15), which describes the far-field shear wave displacement in a homogeneous, isotropic, and unbounded medium due to a point shear dislocation.

$$u(x, t) = \frac{\Re^{\theta\gamma}}{4\pi\rho\beta^3 R} \cdot M'(t) \cdot \left(t - \frac{R}{\beta}\right) \quad (2.15)$$

where $u(x, t)$ is the dynamic displacement field at point x and at time t , $\Re^{\theta\gamma}$ is the radiation pattern reflecting the variation of the displacement field for different directions due to a shear dislocation, ρ is density, and lastly β is shear wave velocity, R is the source to receiver distance and $M'(t)$ is the time derivative of the seismic moment $M(t)$ (Aki and Richards, 1980).

2.2.1.2 The Path Function, $P(R, \omega)$

The path function is an essential component in modeling the changes that seismic waves undergo as they propagate through the layers of the Earth. It accounts for variations in characteristics such as amplitude, duration, and frequency content of the waves. The parameters of the path function include geometric spreading, quality factor (anelastic attenuation factor) and duration.

Geometric spreading is a phenomenon that considers the decrease in wave amplitude as seismic waves propagate over a distance. In an ideal scenario where the Earth is considered a homogeneous spherical body, geometric spreading can be described as inversely proportional to the distance, R . However, since the Earth is not homogeneous, the definition of geometric spreading becomes more complex and challenging.

The path function used in stochastic modeling is expressed in Equation (2.16) as:

$$P(R, \omega) = Z(R) \cdot e^{\frac{\pi f R}{Q(f)\beta}} \quad (2.16)$$

where $Z(R)$ is the geometric spreading, $Q(f)$ is the frequency-dependent quality factor. The term $e^{\frac{\pi f R}{Q(f)\beta}}$ represents the effect of anelastic attenuation, which directly influences the shape of the high-frequency spectrum (Motazedian, 2006).

2.2.1.3 The Site Function

In this thesis to show the significance of using site-specific parameters in the simulations, the site functions are explained in detail. The soil profile of a site plays a crucial role in the amplification or attenuation of strong ground motions. The behavior of the site is determined by the processes of reflection and refraction that occur within the complex structure of the Earth beneath the site. Key parameters that influence this behavior include the soil type, layer thickness, and wave

velocity. To create a simplified yet accurate representation of the Earth, one-dimensional soil layers can be utilized.

Site conditions directly impact the frequency content, amplitude, and duration of seismic waves. Typically, soil density and velocity decrease from deeper soil layers to the surface. Consequently, the seismic impedance also decreases. According to Kramer (1996), wave amplitudes must increase to preserve elastic wave energy. However, amplitudes can decrease due to seismic wave damping in softer soils. Therefore, the site function used in stochastic modeling of ground motions incorporates both an amplification function, $A(f)$, and a diminution function, $D(f)$, as expressed in Equation (2.17) as;

$$G(f) = A(f) \cdot D(f) \quad (2.17)$$

i. Amplification Function

The amplification function is a crucial component in simulating ground motions. Various methods are employed to ascertain the factors associated with the amplification function. Among these methods, the theoretical approach stands out as the most commonly utilized and accurate one. It involves utilizing a well-defined velocity profile specific to the site of interest. Velocity profiles can be obtained through two primary means: in-situ techniques and empirical methods. In-situ techniques such as borehole drilling, seismic reflection, and refraction offer precise results but can be challenging and expensive. Consequently, empirical methods are often preferred over in-situ techniques in certain situations.

Once a well-defined velocity profile is available, site amplifications can be estimated using one-dimensional (1-D) methods such as Haskell (1960), Schnabel et al. (1972), and Kennett (1983). In this approach, wave propagation is solved in a one-dimensional manner, considering infinite horizontal soil layers. By employing this method, the theoretical transfer function is derived. Alternatively, the transfer function can also be obtained through two-dimensional (2-D) methods as proposed

by Sánchez-Sesma (1987), or even three-dimensional (3-D) methods as demonstrated by Pitarka et al. (1998). However, it should be noted that 2-D and 3-D approaches are more intricate and challenging to define due to the complexities introduced by soil profiles in multiple dimensions.

In many cases, velocity profiles obtained through in-situ techniques need more detail due to the inherent difficulty of these methods. As an alternative approach, surface waves are measured across a broad frequency range. Various active sources are employed on-site to induce waves into the soil layers, including hammers, electromechanical shakers, weight drops, bulldozers, and seismic vibrators. Among the techniques used for surface wave measurement, two popular methods are the spectral analysis of surface waves (SASW) as defined by Stokoe et al. (1994), and the Multi-Channel Array (MCA) surface wave method with the iterative matching of theoretical and measured dispersion curves proposed by Park et al. (1999). These techniques aim to obtain a velocity profile that accurately matches the measured data. Further work on this topic has been presented by Rosenblad and Li (2009).

Passive seismic methods involve the measurement and analysis of microtremors or ambient noise. These methods include the passive refraction microtremor (ReMi) technique introduced by Louie (2001), the frequency-wavenumber (f-k) method proposed by Schmidt (1986), and the spatially averaged coherency (SPAC) method developed by Asten et al. (2003) based on the findings of Aki (1957). The SPAC method's measured and theoretical coherency curves are iteratively adjusted to achieve a desired velocity profile. This iterative process allows for fitting the measured data to the theoretical model, thereby obtaining the velocity profile of interest.

The amplifications are commonly employed in conjunction with the NEHRP (National Earthquake Hazards Reduction Program) soil classes, as proposed by Boore and Joyner (1997). In cases where specific parameters for site

characterization are lacking, these amplification functions can be combined with the NEHRP soil class to estimate site response characteristics.

An alternative empirical method, known as the Horizontal-to-Vertical ratio (H/V) technique, was introduced by Nakamura (1989) for cases where the velocity profile of the site is unknown. This method estimates site amplifications by assuming that the vertical components of ground motion at the surface and bedrock level are equal. The seismic source and path effects can be eliminated by dividing the horizontal component by the vertical component of ground motions. This allows for the estimation of amplification using weak ground motions or aftershocks. Researchers such as Lermo and Chávez-García (1994), Suzuki et al. (1995), Huang and Teng (1999), and Raghukanth and Somala (2009) have utilized the H/V method to derive velocity profiles for various studies.

ii. Diminution Function

In near-field conditions, there is a rapid decrease in the spectral values of ground motions in the high-frequency range. This decay is not caused by attenuation during wave propagation (Boore et al., 1993). Various studies have been conducted to determine the underlying cause of this decay (Papageorgiou and Aki 1983, Hanks 1982, Atkinson 2004, Askan et al, 2014, Altındal and Askan 2023).

In literature, there are two filter types to model rapid decay: the f_{max} filter (Hanks, 1982) and the kappa operator. The diminution function $D(f)$ is given in Equation 2.18 as:

$$D(f) = \left(1 + \left(\frac{f}{f_{max}}\right)^8\right)^{-0.5} \quad (2.18)$$

where f_{max} is the cut-off frequency.

The kappa operator, introduced by Anderson and Hough (1984), is the second type of filter used in the diminution function. It is applied as an exponential component. A specific procedure is followed to determine the kappa parameter. Firstly, the Fourier Amplitude Spectra (FAS) of the recorded data is plotted on a semi-logarithmic scale. Secondly, a best-fit line is drawn to the decaying portion of the FAS curve. Finally, the kappa parameter is calculated by dividing the slope of the best-fit line by $-\pi$.

When considering the effects of the path from the earthquake hypocenter to the recording station, a zero-distance kappa value (κ_0) is used in site effect calculations. To determine this κ_0 value, the kappa values of the recorded data are plotted against the corresponding epicentral distances. The zero-distance kappa value (κ_0) is obtained by identifying the ordinate of the best fit line on the plot. The filter function with κ_0 used in the stochastic modeling is given as:

$$D(f) = e^{-\pi\kappa_0 f} \quad (2.19)$$

2.2.2 Stochastic Finite Fault Modeling

Stochastic point-source modeling is effective in providing accurate simulations for stations located at distances from the fault that are greater than the dimensions of the fault itself (referred to as far-fault stations). However, when simulating near-fault scenarios, it is necessary to consider the fault dimensions. The stochastic finite-fault simulation method, developed by Beresnev and Atkinson (1997), addresses this requirement.

In the stochastic finite-fault simulation method, the fault is divided into smaller sub-faults, with each sub-fault assumed to behave as a stochastic point source. The time history of the ground motion is obtained by summing up the response of each sub-fault in the time domain. This approach draws inspiration from the concept of large-event discretization and the superimposition of sub-fault contributions in the

discretized space, as proposed by Hartzell (1978). Figure 2.5 illustrates the stochastic finite-fault methodology on the fault plane.

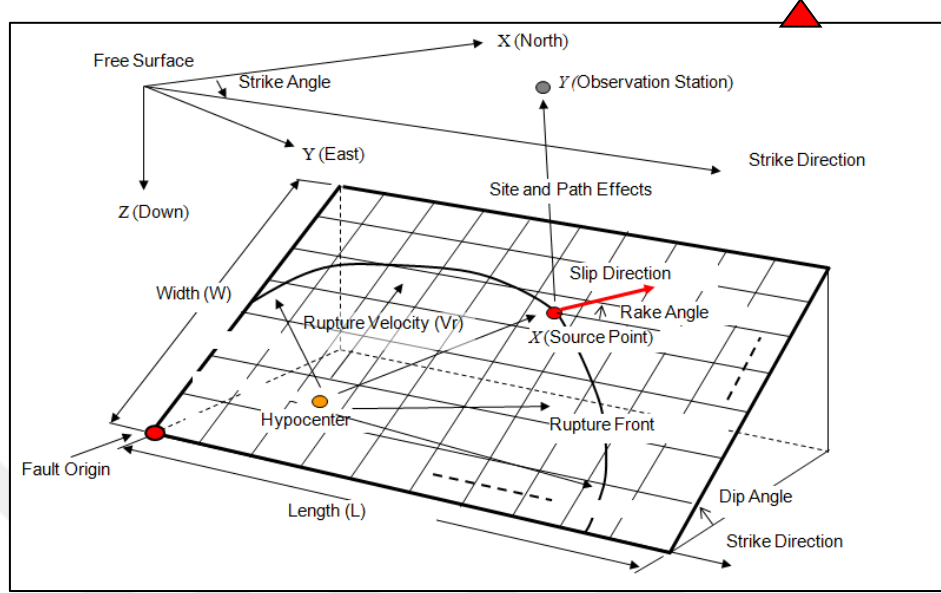


Figure 2.5. Stochastic finite-fault methodology (Adapted from Hisada, 2008)

Motazedian and Atkinson (2005) introduced a frequency-dependent scaling factor, denoted as H_{ij} , to account for this decrease in radiated energy at higher frequencies. This scaling factor is applied to the spectrum, modifying to compensate for the reduction in energy at higher frequencies. By applying this scaling factor, the decrease in radiated energy at higher frequencies is effectively preserved, allowing for a more accurate representation of the seismic wave characteristics in the simulation. The final acceleration spectrum is given as:

$$A_{ij}(f) = C \cdot M_{0ij} \cdot H_{ij} \cdot \frac{(2\pi f)^2}{\left[1 + \left(\frac{f}{f_{c_{ij}}}\right)^2\right]} \cdot e^{-\frac{\pi f R_{ij}}{Q(f)\beta}} \cdot D(f) \cdot e^{-\pi \kappa f} \quad (2.20)$$

In this thesis, the methodology developed by Motazedian and Atkinson (2005) is employed to accurately capture and model the behavior of high-frequency seismic waves during the earthquake event.

2.3 Hybrid Ground Motion Simulation Method

Numerous approaches have been suggested to merge low frequency (LF) and high frequency (HF) seismograms, resulting in hybrid broadband ground motions. These methodologies have been proposed in various studies, such as Irikura and Kamae (1994), Berge et al. (1998), Hartzell et al. (1999), Graves and Pitarka (2004), Pulido and Kubo (2004), and Liu et al. (2006). Each of these studies utilizes different approaches to model the earthquake rupture and generate two sets of seismograms. The combination of these seismograms can be accomplished either in the time domain, where the two-time series are amplitude-scaled (e.g., Berge et al., 1998; Graves and Pitarka, 2004) or in the frequency domain, where a pair of matched filters is applied (e.g., Hartzell et al., 1999; Pulido and Kubo, 2004).

However, in certain instances, response spectra obtained through frequency domain combination may exhibit peculiar behavior at transition frequencies. This is because some frequency-domain matching techniques only take into account the amplitude spectra of the low frequency (LF) and high frequency (HF) time series, disregarding the crucial phase information required to generate accurate broadband synthetics. Consequently, the structural responses based on these broadband synthetics may need to be more realistic and consistent when compared with corresponding observations at the transition frequency (Bazzurro et al., 2004).

Mai et al. (2010) identifies this inconsistency as a result of solely matching the amplitude spectra, which fails to adequately capture the spectral energy levels due to the lack of synchronization between LF and HF phases at the intersection frequency. To address this issue, a solution involves obtaining hybrid ground motion records through a frequency-domain combination that considers matching both amplitude and phase spectra around the target frequency (Mai and Beroza, 2003). This comprehensive approach aims to enhance the fidelity of the resulting hybrid ground motion records and mitigate the anomalies observed in previous methods. In this study, the hybridization method presented by Mai and Beroza

(2003) is utilized. The COMPLEX open-source code is used as implemented by Moratto et al. (2015). The procedure involves merging the Fourier amplitude spectra of velocity seismograms obtained from both deterministic and stochastic implementations. Before merging, an amplitude equalization of the stochastic and deterministic spectra is carried out. The primary objective of this methodology which is proposed and used herein is to acquire broadband seismograms that encompass the entire frequency range relevant to earthquake and civil engineering applications (ranging from 0.1 to 25 Hz) as presented in Figure 2.6.

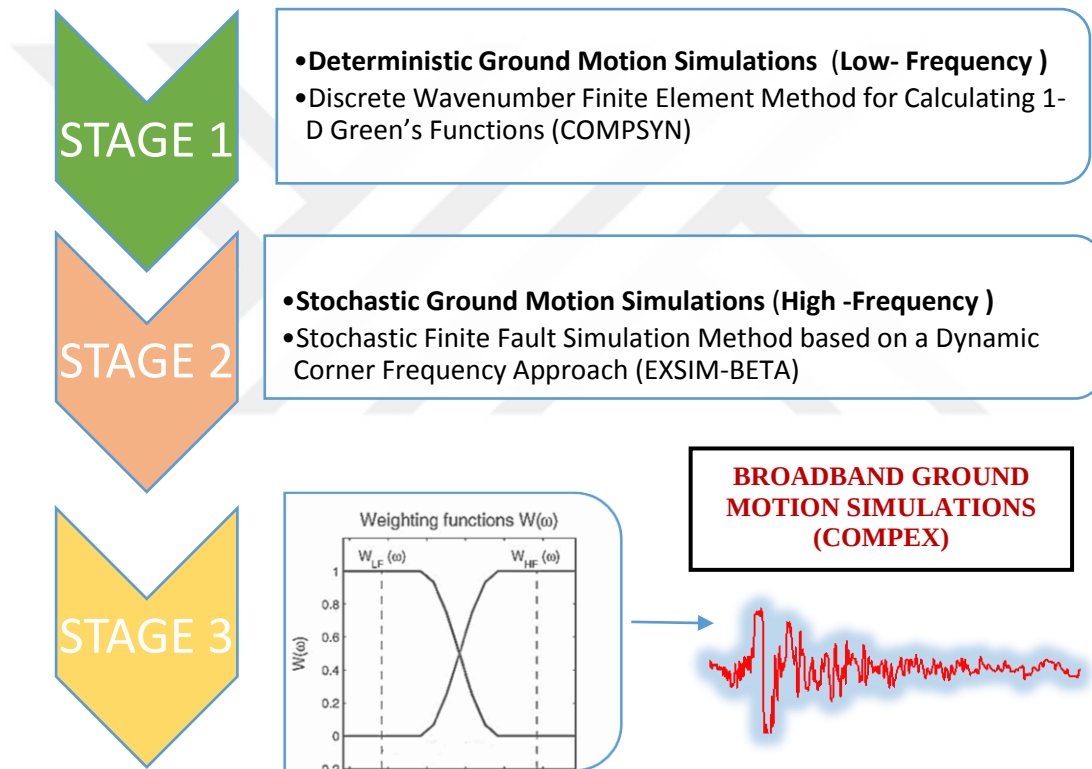


Figure 2.6 Flowchart of the hybrid methodology used in this study

In this approach, the Fourier amplitude spectra of seismograms are combined at intermediate frequencies where their domain of validity overlaps in the frequency domain (Mai and Beroza, 2003) as follows:

$$A(f) = A^{LF}(f) * W^{LF}(f) + A^{HF}(f) * W^{HF}(f) \quad (2.21)$$

where $A(f)$ is the broadband spectrum, $A^{LF}(f)$ and $A^{HF}(f)$ are the low and high frequencies, respectively. $W^{LF}(f)$ and $W^{HF}(f)$ are two smoothed frequency-dependent weighing functions. The summation of the weighing function is set to be equal to one at every frequency. To accommodate potential uncertainties in the EXSIM parameterization, equalizing the high frequency (HF) spectra is necessary before proceeding with the search for frequency matches and signal combinations. This involves computing a scaling ratio, representing the average ratio of HF/LF (high frequency/low frequency) velocity amplitude spectra within a predefined frequency range associated with the transition from deterministic to stochastic behavior.

Once the scaling ratio is determined, it is applied to the stochastic spectra, effectively scaling them to match the deterministic spectra. This process helps to mitigate artificial spectral steps and ensures a smoother and more continuous transition between the deterministic and stochastic components in the resulting hybrid broadband seismograms. By performing this equalization of HF spectra, uncertainties in the EXSIM parameterization are considered, contributing to a more accurate and reliable representation of the seismic signals across the specified frequency range.

2.4 Machine Learning Method

The utilization of machine learning techniques has become increasingly prevalent in numerous scientific disciplines. The machine learning methods for ground motion simulations rely on a comprehensive database of ground motions. Such techniques not only match the target response spectrum but also fulfill constraints on the duration, thereby addressing the substantial variations in the input response caused by the diverse matching results.

In a recent study by Hu et al. (2023), the algorithm commences by extracting the characteristic ground motions from the comprehensive ground-motion database using principal component analysis, and then matches the amplitude, spectrum, and duration. A multi-objective genetic algorithm is employed to combine the extracted characteristic ground motions, which are then used to identify the most reasonable ground motions. This algorithm has been shown to be successful in various cases, and it determines the optimal solution by taking multiple constraints into account. It enables the linear combination of the extracted characteristic ground motions (Hu et al,2023).





CHAPTER 3

GROUND MOTION SIMULATION IN THE ERZINCAN REGION

This chapter of the thesis includes simulations in the city of Erzincan. Despite being located in a very seismically and tectonically active region, it is a relatively less studied and sparsely monitored area of Türkiye.

The March 13, 1992, $M_w=6.6$ Erzincan earthquake is simulated with the hybrid ground motion simulation technique described in the previous chapter. The earthquake was recorded only at three strong ground motion stations located in the Erzincan (ERC), Refahiye (REF) and Tercan (TER) city center (Figure 3.1).

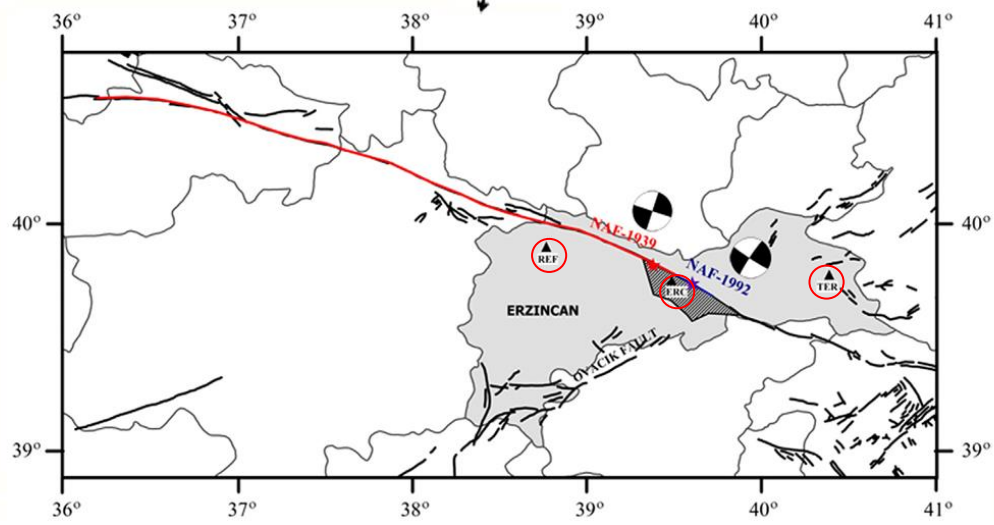


Figure 3.1 Regional map of Erzincan presenting the epicenters and the mechanism of the 1939 and 1992 earthquakes, red circles indicate the ERC, REF and TER strong ground motion stations (Adapted from Askan et al., 2013)

Since the available ground motion records for the area are limited, selecting input parameters for these simulations becomes crucial. For modeling the source and path effects, well-constrained regional models from previous studies in the field of study are used. The source and regional path parameters for this earthquake have already been validated in previous studies (Bernard et al., 1997; Askan et al., 2013), so those parameters were adopted. The important local site parameters for both deterministic and stochastic simulations were derived herein (Askan et al., 2013 and Askan et al., 2015). Combining the information from this regional kappa, amplification factor, transfer function and velocity models, the 1992 Erzincan earthquake with a moment magnitude of 6.6 is simulated to generate reliable and accurate broadband ground motion records for the Erzincan region, where the seismic data is limited. The results in the form of peak ground acceleration, and full waveforms were presented by combining all this information.

Firstly, unlike other simulation studies performed in the Erzincan basin, the 1992 Erzincan earthquake are simulated with the hybrid ground motion technique at the aforementioned ERC, REF and TER stations to validate the input source, path and site parameters. Then, the misfits between observed and simulated data are calculated.

Secondly, the 2D velocity structure is determined using the Multimode Spatial Autocorrelation method (MMSPAC) with selected nine in the Erzincan basin (Askan et al., 2015). Then, the hybrid ground motion simulations are performed at these selected nine sites.

Before presenting the details of the steps taken in this thesis, a short review of the past studies in this region is given.

3.1 Literature Survey in the Erzincan Region

The literature contains studies related to the rupture process, fault location, seismotectonic characteristics and basin structure in the Erzincan region following the earthquakes in 1939 and 1992. A quick summary is provided herein.

In a study by Pınar et al. (1994), teleseismic body waves were inverted using the Kikuchi and Kanamori method to deduce the rupture process of the 1992 earthquake in Erzincan. The study's results were found to be consistent with the regional seismotectonics in eastern Türkiye.

Later, Bernard et al. (1997) focused on investigating the hypocenter location and rupture kinematics of the March 13, 1992, $M=6.9$ Erzincan earthquake. Local and regional seismic records were utilized to comprehend its relationship with the tectonic activity of the Erzincan basin and the North Anatolian Fault. The best-fit fault models were located near the epicenter, within 1 km, with their northwestern ends within 5 km of ERZ. The up-dip limit of the rupture in the vicinity of ERZ ranges from 5 to 2 km in depth, in agreement with the absence of surface breakage. The estimated rupture velocity was 3 km/sec; the rise time was 0.35 sec.

Legrand and Delouis 1999 explored the possibility of determining the actual fault plane of an earthquake by inverting near-source displacement seismograms. They used finite-dimensional source models and considered complete displacement, including near-field waves. The results, based on synthetic seismograms and real data from Erzincan in 1992 were showed compatibility with other seismological findings.

Kaypak (2008), employed local earthquake tomography to model the three-dimensional V_P and V_P/V_S velocity structure of the Erzincan basin and its surroundings using aftershocks of the 1992 Erzincan earthquake. The resulting tomographic images revealed velocity anomalies related to geological and tectonic structures beneath the Erzincan basin.

Concerning the simulation studies in literature, Askan et al. 2013, focused on the March 13, 1992, Erzincan earthquake ($M_w=6.6$), which occurred in eastern Türkiye and was recorded at only three strong ground motion stations, namely Erzincan (ERC), Refahiye (REF) and Tercan (TER). In this paper, only the high-frequency part of the 1992 Erzincan earthquake was simulated using the stochastic finite-fault method. The source and regional path parameters for this event were adopted from previously validated studies, while the local site parameters were derived within this study. Towards the end of the article, despite obtaining satisfactory results in the high-frequency portion, discrepancies were observed at low frequencies, highlighting the need for hybrid ground motion simulation, which is the focus of this thesis.

Then in Karimzadeh and Askan (2018), the 1939 Erzincan earthquake was simulated using regional behavior and geological structure. The results were presented in the form of the anticipated spatial distribution of selected ground motion parameters and felt-intensity maps in the region.

In Karimzadeh et al. (2018), based on the simulated ground motions in Askan et al. (2013), building fragility curves are derived. Computed damage ratios are compared against the observed damage ratios during the 1992 event.

Different from other studies performed in the study region, in this thesis, the hybrid ground motion simulation technique is used to simulate the 1992 earthquake to understand and generate both low-frequency and high-frequency parts of the full waveform. Similarly, this thesis is site-specific as it involves inversions for local velocity models with the MMSPAC method.

3.2 Study Area

Understanding a region's geological structure and tectonic behavior are essential for comprehending its seismic activity and the potential impacts of earthquakes. This information plays a crucial role in earthquake risk assessment and mitigation

strategies. This section focuses on geological information, seismotectonic behavior of the Erzincan and its surroundings as well as detailed velocity structure of the Erzincan basin obtained from the MMSPAC method.

3.2.1 Geology of the Erzincan Region

Studies in the literature reveal that Erzincan Province has a complex geological structure, with the city situated on a 45kmx15km plain surrounded by high mountains in the north and south. The valley under the plain, nourished by the Euphrates River, features a V-shaped profile, and the plain has been filled with alluvium from the river and slope materials from the mountains due to rainfall. The thickness of the alluvium layer is higher in the middle of the basin, reaching hundreds of meters, while it is lower near the mountain slopes (Lav et al., 1993; Hayfavi and Gülkan, 1995).

According to the report prepared by the Erzincan Governorship Provincial Directorate of Environment and Urbanization (2011), the geological composition of the Erzincan plain includes a combination of Paleozoic undifferentiated metamorphic series, Mesozoic limestones, Cretaceous flysch, Eocene flysch, Neogene limestones, Neogene terrestrial, and volcanic rocks. Additionally, the area is characterized by travertine, alluvial, and alluvial cones from the Quaternary period.

Mesozoic limestones are scattered randomly within large areas covered by serpentine diabase masses and some of the limestones have a semi-crystalline texture. These limestones can be seen in the mountains southeast of the city. They have a rigid and non-stratified structure with abundant fractures and cracks. Groundwater flows through them and is discharged by springs. The limestones exhibit light brownish, gray, and locally brown coloration.

Cretaceous flysch is situated in the Erzinçan plain and is primarily composed of sandstone, marl, and conglomerate. Serpentine pebbles within the flysch indicate that this formation was created during the Upper Cretaceous periods. The geological map of Erzinçan and its surrounding area and the basin itself are shown in Figure 3.2. and Figure 3.3, respectively.

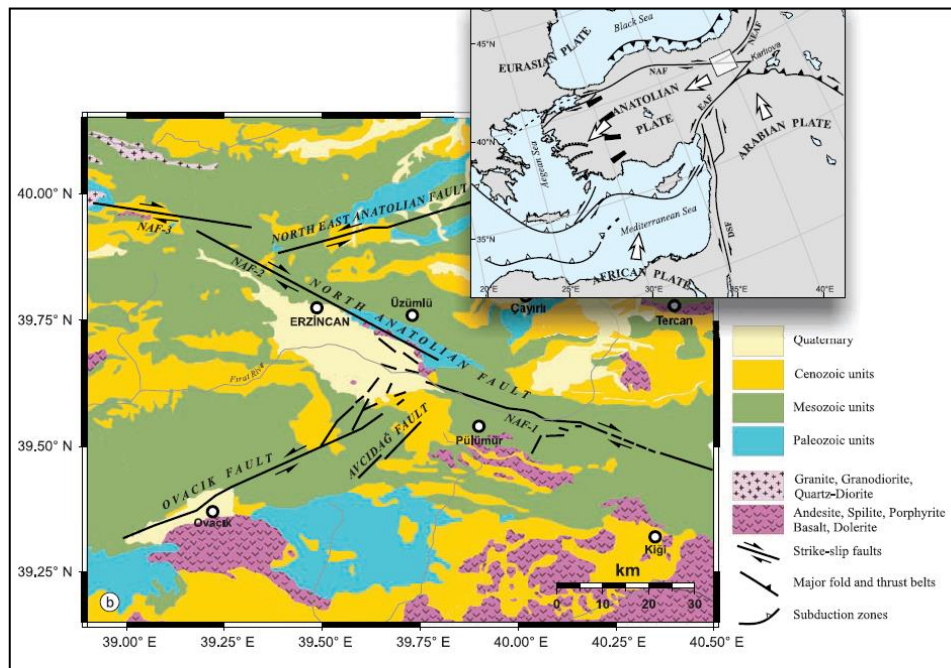


Figure 3.2 Geological and tectonic features of Erzinçan region (Adopted from Kaypak 2008)

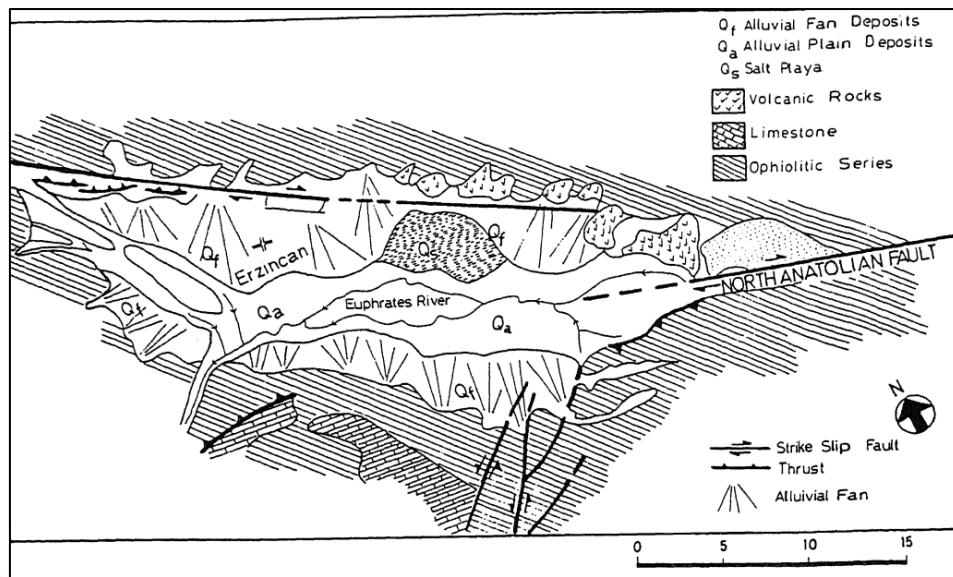


Figure 3.3 : A close view of the geological map of Erzincan basin. (Adopted from Barka and Gülen,1989).

The Eocene formation is part of a flysch facies characterized by gray sandstone and conglomerates. Claystone and limestones can be found in certain areas within this formation. However, the formation is not significant regarding groundwater storage.

The Neogene formation encompasses a wide range of facies. At the lowest level, there are limestones believed to be of Miocene age, while at the top, there is a clayey, marl series in lagoon facies, followed by red-colored conglomerate and sandstones. The limestones at the base of the formation contain abundant fossils. However, the Neogene formation is not highly significant in terms of groundwater storage.

In summary, the geology of Erzincan plain includes travertine, alluvium, and alluvial cones from the Quaternary period. Most of this Quaternary section is covered by alluvial cones, which are quite common in the area, making them significant for geological investigations. Alluvial cones mainly consist of materials such as sand and gravel, serving as the primary aquifer layers carrying

groundwater. Serpentine is commonly found at the base of these alluvial cones, with a thickness ranging from 50 to 150 meters.

These sediments consist of looser material than alluvial fan deposits that are more common around the edges of the basin. (Barka and Gülen,1989).

3.2.2 Seismotectonics of the Erzincan Region

The Erzincan basin and its surroundings are characterized by three major strike-slip fault systems with different orientations. One of these fault groups is the Northeast Anatolian Fault, which is a left-lateral strike-slip fault running along the southern boundary of the Black Sea Mountain range. Another significant fault system observed in a wide zone within the Erzincan basin is the North Anatolian Fault Zone, the most active and extended fault system in Türkiye. It starts from the Biga Peninsula in Western Anatolia, passes through the north of Çanakkale, crosses the Marmara Sea, and reaches Erzincan near the north of the Bursa-Çankırı-Çorum line, extending further through Çorum, Amasya, and Tokat (Çakmak, 2009). From there, one branch turned northwards and continued towards Armenia via Erzurum-Kars, while the other branch extended towards Lake Van (Duman, 2013). The third fault system in the Erzincan basin is a left-sided strike-slip fault (Ovacık Fault) extending from the basin to the Ovacık District. The continuous development of the Erzincan pull-apart basin is influenced greatly by these three fault systems (Barka,1993; Tüysüz, 1993).

When examining the earthquake catalogs to understand historical seismic activity, it was found that in Erzincan, earthquakes with an approximate maximum MMI intensity of 8 and above, which caused significant loss of life and property, occurred in the years 1045, 1166, 1168, 1254, 1268, 1281, 1287, 1290, 1356, 1374, 1458, 1482, 1578, and 1784. The locations of these historical earthquakes indicate a notable activity along the eastern part of the North Anatolian Fault (Şengezer, 1999).

The seismic activity of the Erzincan region is presented in Figure 3.4 and Figure 3.5. During the instrumental period from 1900 to 2024, there were 333 earthquakes that occurred with $4.0 < M_w < 7.9$ and 9 earthquakes occurred with $6.0 < M_w < 7.9$ respectively. The most significant earthquake occurred on December 26, 1939, with an approximated moment magnitude of 7.9. This devastating earthquake resulted in the loss of 30,000 lives where approximately 100,000 people were injured, and around 120,000 buildings were destroyed (Barka, 1996).

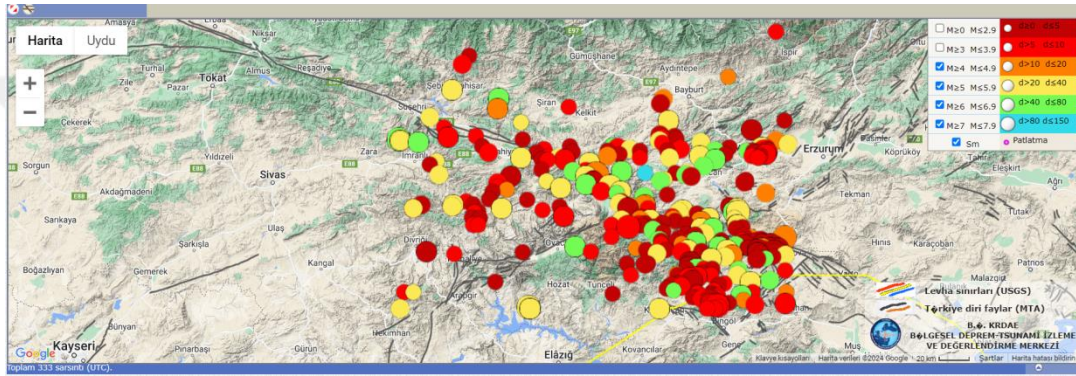


Figure 3.4. Earthquake catalogue which shows the earthquakes during the last 124 years with $M_w=4-7.9$. (<http://www.koeri.boun.edu.tr/sismo/zeqdb/default.asp>)

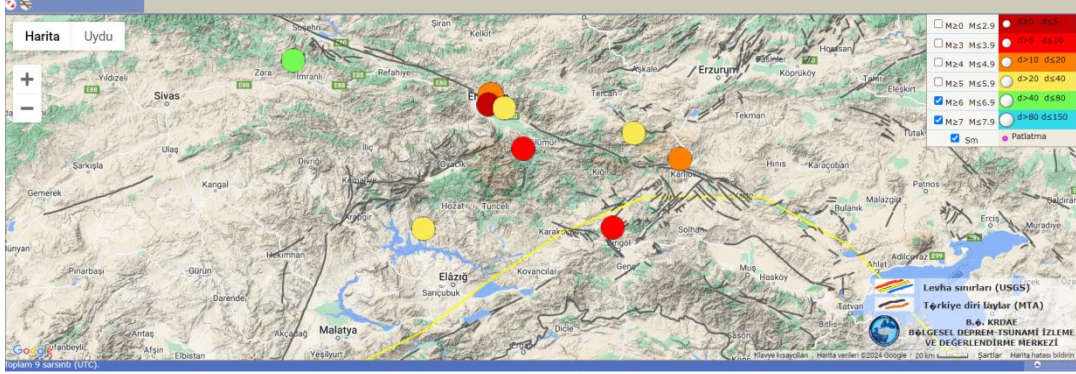


Figure 3.5. Earthquake catalogue which shows the earthquakes during the last 124 years with $M_w=6-7.9$. (<http://www.koeri.boun.edu.tr/sismo/zeqdb/default.asp>)

After the 1939 earthquake, the city was relocated to the north. However, the new city center, situated on alluvium and being closer to the fault, experienced another earthquake with a magnitude of $M_w:6.6$ on March 13, 1992. During this Erzincan earthquake, a maximum horizontal acceleration of $0.49g$ was recorded in the East-West component (Lav, 1994). Following the main earthquake, four significant aftershocks with surface wave magnitudes of 5.8, 4.9, 4.5, and 4.7 occurred within two days, causing further damage to already be weakened buildings. In the subsequent week, four additional monitoring stations were set up around the Erzincan basin and approximately 3,900 earthquakes were recorded during this period (Gürbüz et al., 1993).

The earthquake in Erzincan on March 13, 1992, showed some differences compared to previous earthquakes of similar magnitudes. Although it was deeper and had aftershocks with magnitudes of 5 and more, no continuous surface rupture was observed. The earthquake's relatively deeper location and the presence of a thick sediment layer over the epicentral region prevented the rupture from fully reaching the surface. It occurred in an area where the North Anatolian Fault zone and the Ovacık fault intersect, forming a tension-opening geometry. As a result of this location, the released energy was mostly absorbed at depth (Gürbüz et al., 1993).

3.2.3 Estimation of the Wave Velocity Structure in the Region

Different from the simulation studies performed in the Erzincan area before, in this part of the study, the velocity structure is determined locally using the MMSPAC method.

In brief, The MMSPAC is one of the most popular passive seismic methods used to obtain the one-dimensional velocity profile of the sediments. This method involves array-based field measurements of seismic noise with a frequency above 1 Hz, measuring Rayleigh-wave velocity dispersion. The MMSPAC method described

here is based on the original work of Asten et al. (2004), which is an advancement of the original SPAC method introduced by Aki (1957). In traditional SPAC studies, such as those performed by Aki (1957), Okada (2003), and others, the coherency spectrum is calculated first. Then the phase velocity dispersion curve is inverted to obtain the model fits.

Various alternative approaches to the SPAC method have been introduced in several studies, including those by Asten et al. (2004), Roberts and Asten (2004), Wathelet et al. (2005), Asten (2006), and Kocaoğlu and Firtana (2011). These alternative approaches offer different perspectives and improvements to the original SPAC method.

The main objective of the MMSPAC method used herein is to fit the observed SPAC spectra directly to the modeled SPAC spectra. In other words, instead of directly inverting the dispersion curve, the method focuses on obtaining the dispersion curve as a by-product of fitting the observed and modeled SPAC curves. The MMSPAC method offers several advantages, including facilitating the identification of higher mode surface wave energy if present (Asten et al., 2004), reducing the Vs bias by avoiding the intermediate and highly nonlinear process of calculating Rayleigh-wave phase velocities from observed data and enabling the use of SPAC curves on secondary peaks and troughs of the Bessel function (Equation 3.1). The MMSPAC method is carried out by fitting the observed and modeled SPAC data through a specific relation, which allows for a more direct and efficient determination of the dispersion curve.

$$C_m(f) = J_0[2\pi fr/C_p(f)] \quad (3.1)$$

where $C_m(f)$ is the modeled spatially averaged coherency, f is frequency, r is the station separation and $C_p(f)$ is the modeled phase velocity for a layered earth.

A centered equilateral triangular array of four stations allows measurement of SPAC at two station separations, being the radius r_1 and the side length r_2 , and from geometry:

$$r_2 = r_1 \times \sqrt{3} \quad (3.2)$$

During the field measurements of this thesis which have been supported by a TUJJB project with code TUJJB-UDP-01-12, Guralp CMG-6TD seismometers are used to record the microtremor data. These seismometers are ultralight-weight digital three-axis instruments equipped with three sensors that can record the north-south, east-west, and vertical components of ground motion.

For data processing, segments of typical length (approximately 20 minutes) are selected from the total recording time of around 60 minutes. Only the vertical-component data from the center station G and stations A, B, and C of a triangular array are used in the analysis. Each data segment is first weighted with a Hann window function. Then, a discrete Fourier transform is applied to the data segment, which consists of n points sampled at a spacing of $\Delta t = 0.001$ seconds. This process transforms the data into a complex spectrum. The complex coherency spectrum is computed for every possible pair of stations using frequency averaging in windows of width Δf , where $\Delta f = 1 / (n \times \Delta t)$ is the sample interval of the digital spectrum. The length of the selected time series determines this interval. A triangular array with a side length L allows for spatial averaging of coherencies (SPAC) using station pairs GA, GB, and GC (interstation spacing $L / \sqrt{3}$), as well as station pairs AB, BC, and CA (interstation spacing L).

The two observed SPAC spectra are fitted simultaneously with model SPAC spectra during the interpretation. The fitting process involves iterative forward modeling, where a least-squares criterion is used to find the best fit of a 1D layered earth model over a chosen range of frequencies. This process helps in determining the subsurface structure and properties.

3.2.3.1 Velocity Models obtained from the MMSPAC Method in the Region

The MMSPAC method is employed to collect microtremor data at nine sites in the Erzincan basin. The locations of these selected sites are shown in Figure 3.6.

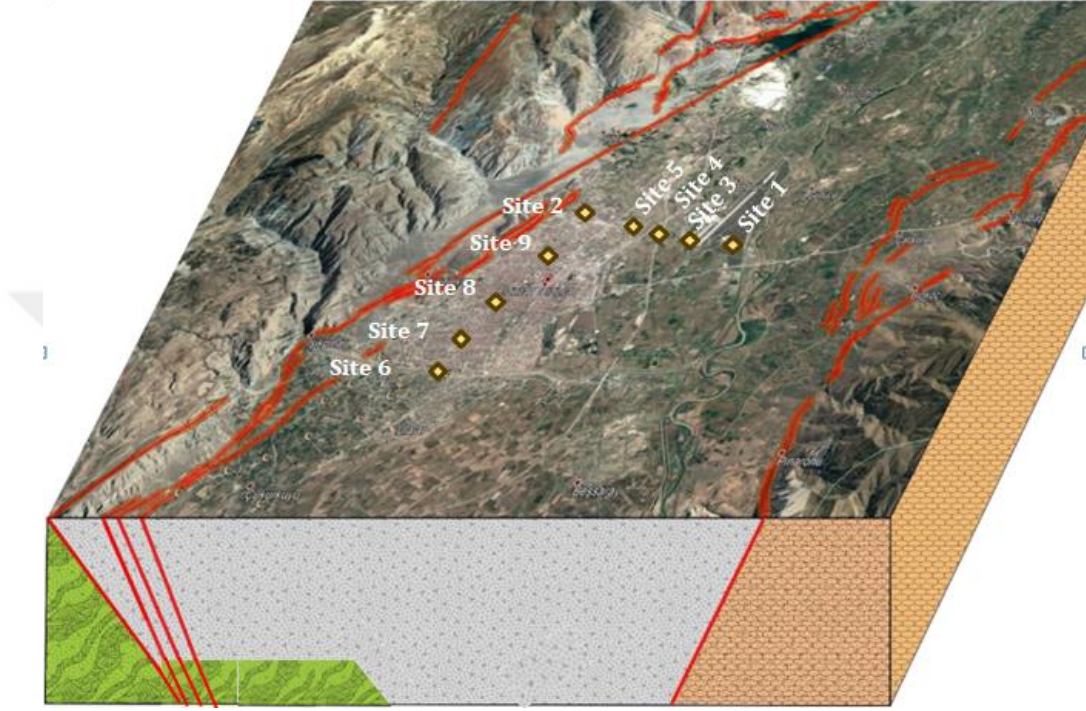


Figure 3.6 Location of the selected nine sites in Erzincan basin (Adapted from https://www.jmo.org.tr/resimler/ekler/22772b05c44cd6f_ek.pdf?dergi=JEODERG%DD)

In the North-South (N-S) direction, Site 2 is in the northern part of the Erzincan basin, near Esentepe. Two nested triangular arrays with side-lengths of 30 m and 100 m are used around this hill. Site 5 is situated on an asphalt-surfaced playground and is equipped with two single triangle arrays of side-lengths 30 m and 100 m. Site 4 and Site 3 are positioned in the middle of the basin along the N-S direction and employed arrays of side-lengths 30 m and 100 m. Site 1 is in the southern part of the basin, near the Erzincan airport area. Three nested four-station triangle arrays with side-lengths of 30 m, 100 m, and 300 m are utilized at Site 1 to minimize noise interference.

In the East-West (E-W) direction, array measurements are conducted with side-lengths of 30 m and 100 m at Site 6, Site 7, and Site 8. However, due to the geometry of the study area, Site 9 is subjected to T-array measurements. A best-fit horizontally layered velocity model is obtained through several iterations by adjusting the S-wave velocity and thickness parameters.

In Figures 3.7 to 3.15, the left columns show the coherency curves at the sites for different station separations (r_1 , r_2) and the Horizontal to Vertical Spectral Ratio (HVSr) curve. The black curve represents the observed MMSPAC spectra, while the thick red curve corresponds to the fitted model SPAC for the Rayleigh fundamental mode. Additionally, the yellow and green curves represent the model SPAC for the first and second higher modes, respectively, included for reference purposes. The thin red curve represents the imaginary part of the SPAC spectra, which is used for quality control. In the right column, 1D shear wave velocity profiles are displayed for depths of up to 30 m (top panel) and 400 m (bottom panel). These velocity profiles provide valuable information about the subsurface structure and properties at different depths within the study area.

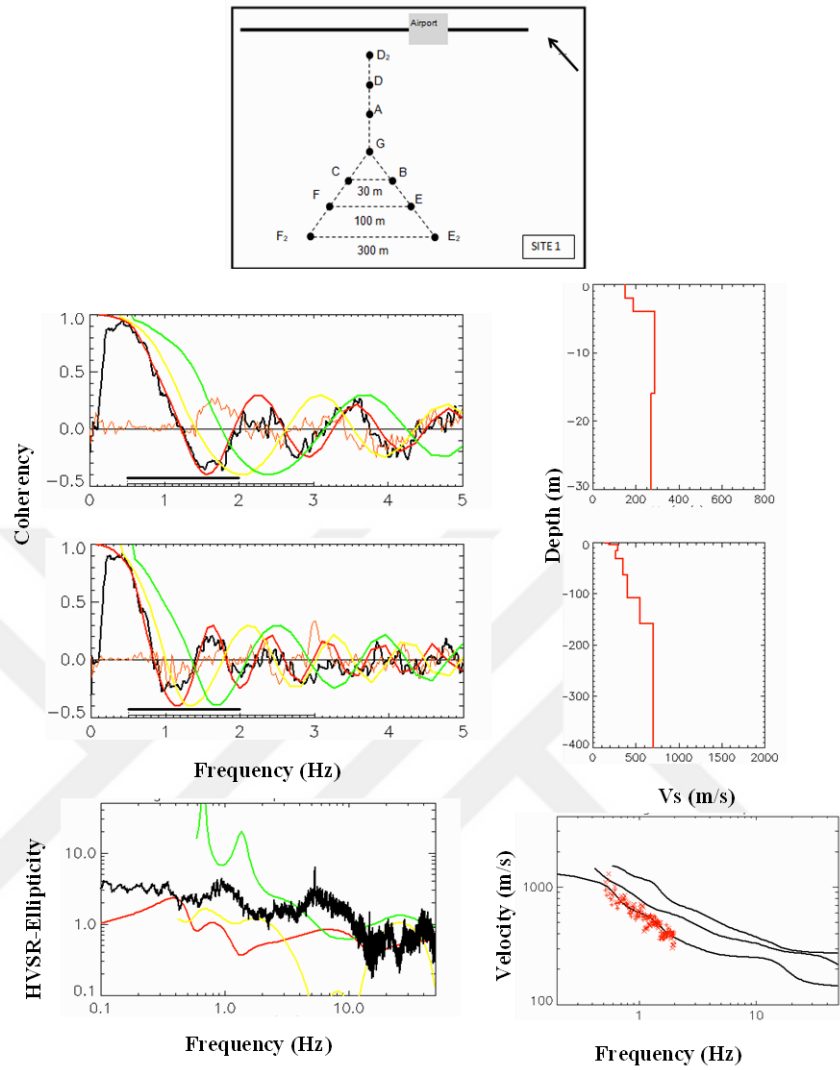


Figure 3.7. MMSPAC results for Site 1 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 1 is 0.5 Hz and the high frequency limit is ~2 Hz. The HVSR curve shows peaks at approximately 0.1 Hz, 1 Hz, and 6 Hz.

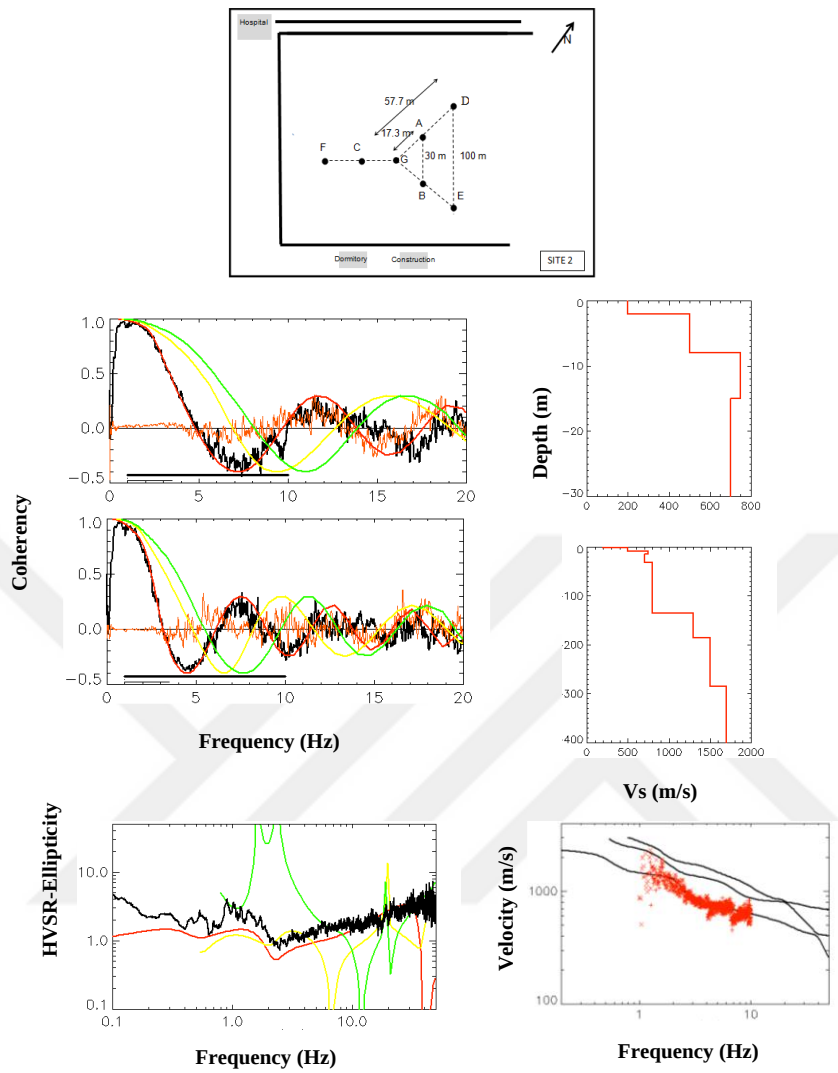


Figure 3.8. MMSPAC results for Site 2 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 2 is 1 Hz and the high frequency limit is ~10 Hz. The HVSR curve shows peaks at approximately 0.3 Hz, 0.5 Hz, and 1 Hz.

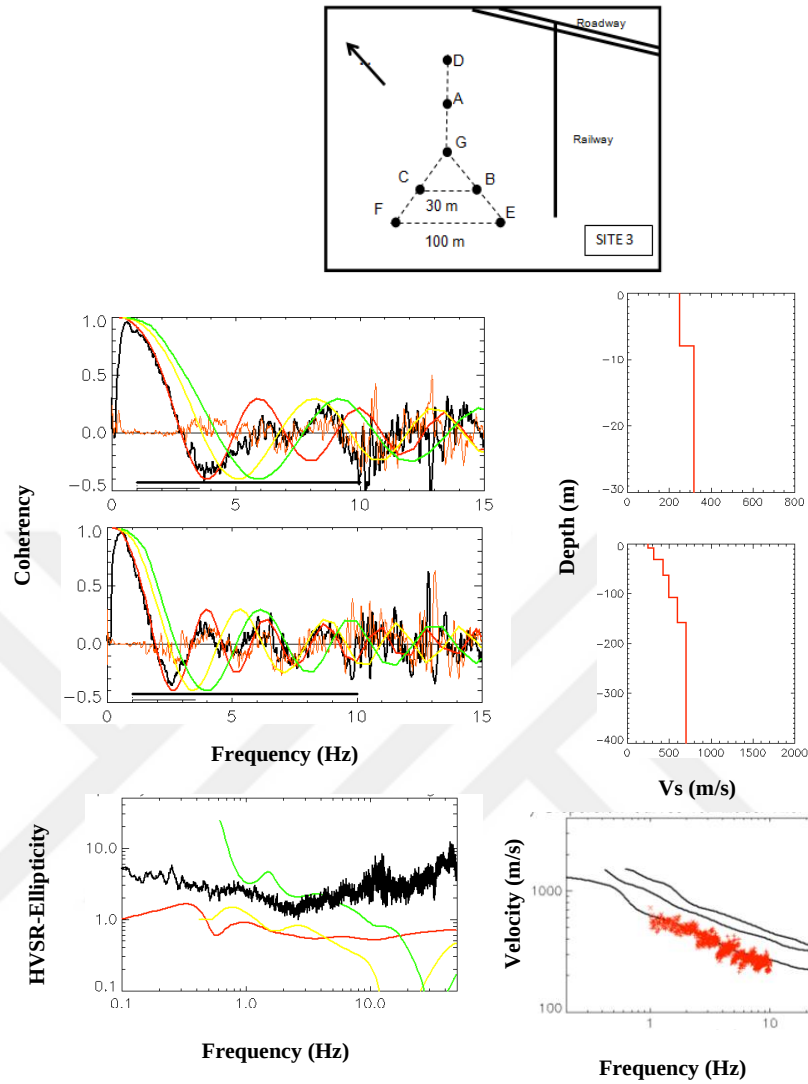


Figure 3.9. MMSPAC results for Site 3 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 3 is 1 Hz and high frequency limit is ~10 Hz.

The HVSR curve shows peaks at approximately 0.4 Hz and 1 Hz.

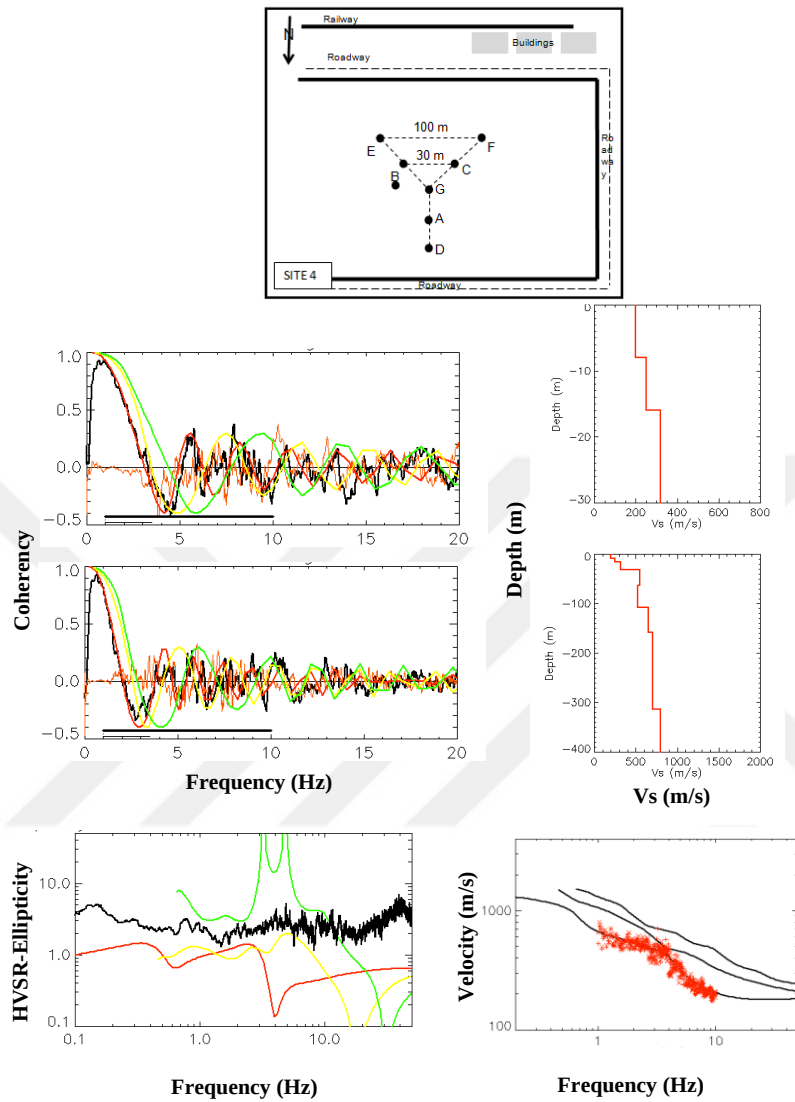


Figure 3.10 MMSPAC results for Site 4 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 4 is 1 Hz and high frequency limit is ~10 Hz. The HVSR curve shows peaks at approximately 0.15 Hz, 0.3 Hz, 1 Hz and 4 Hz.

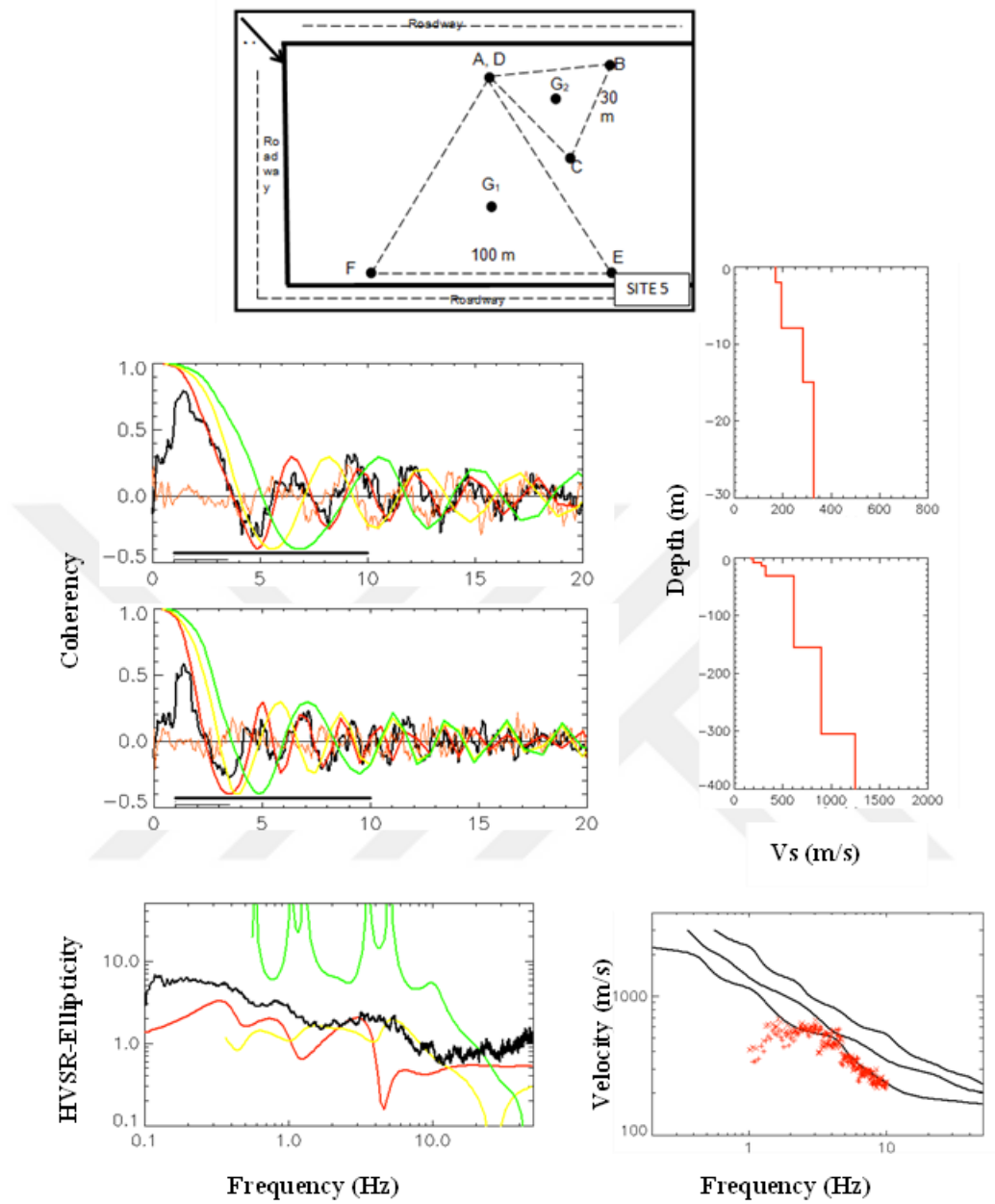


Figure 3.11 MMSPAC results for Site 5 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 5 is 1 Hz and high frequency limit is ~10 Hz.

The HVSR curve shows peaks at approximately 0.3 Hz, 1 Hz, 4 Hz and 10 Hz.

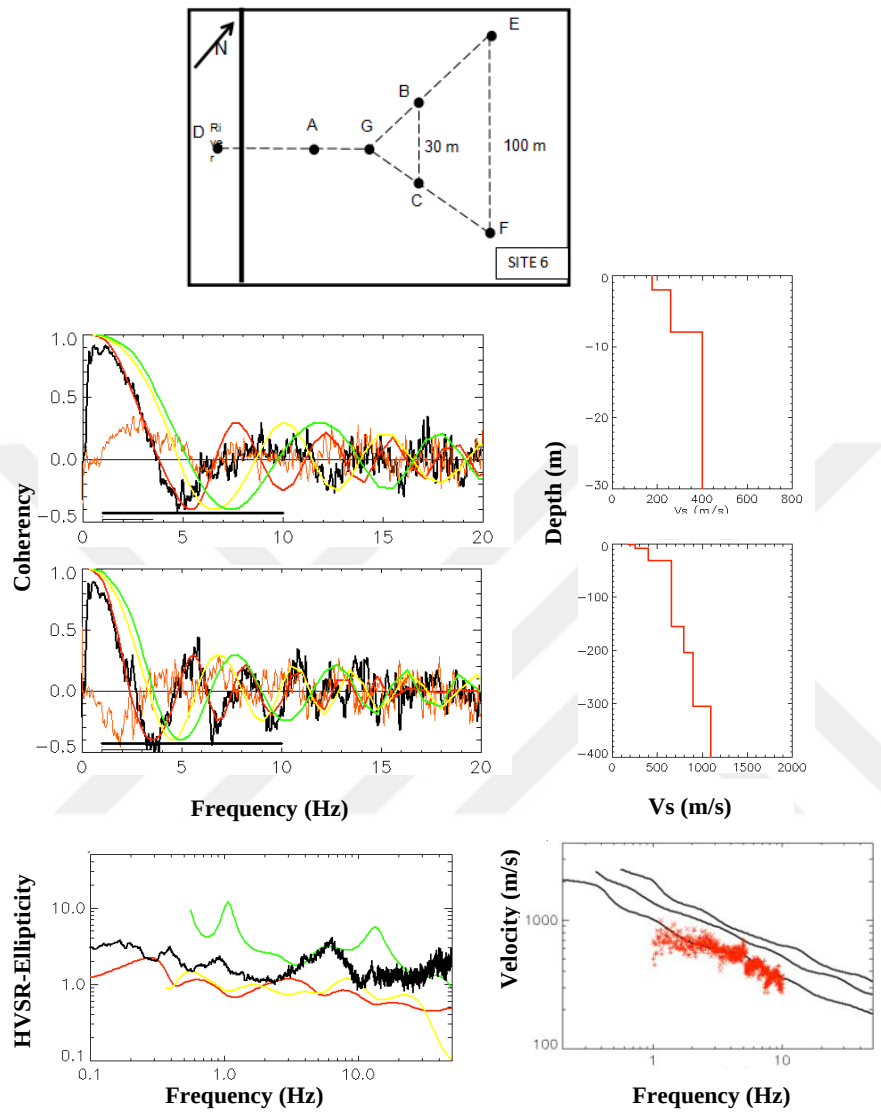


Figure 3.12 MMSPAC results for Site 6 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 6 is 1 Hz and the high frequency limit is ~10 Hz. The HVSR curve shows peaks at approximately 0.15 Hz, 0.4 Hz, 1 Hz, 6 Hz and 11 Hz.

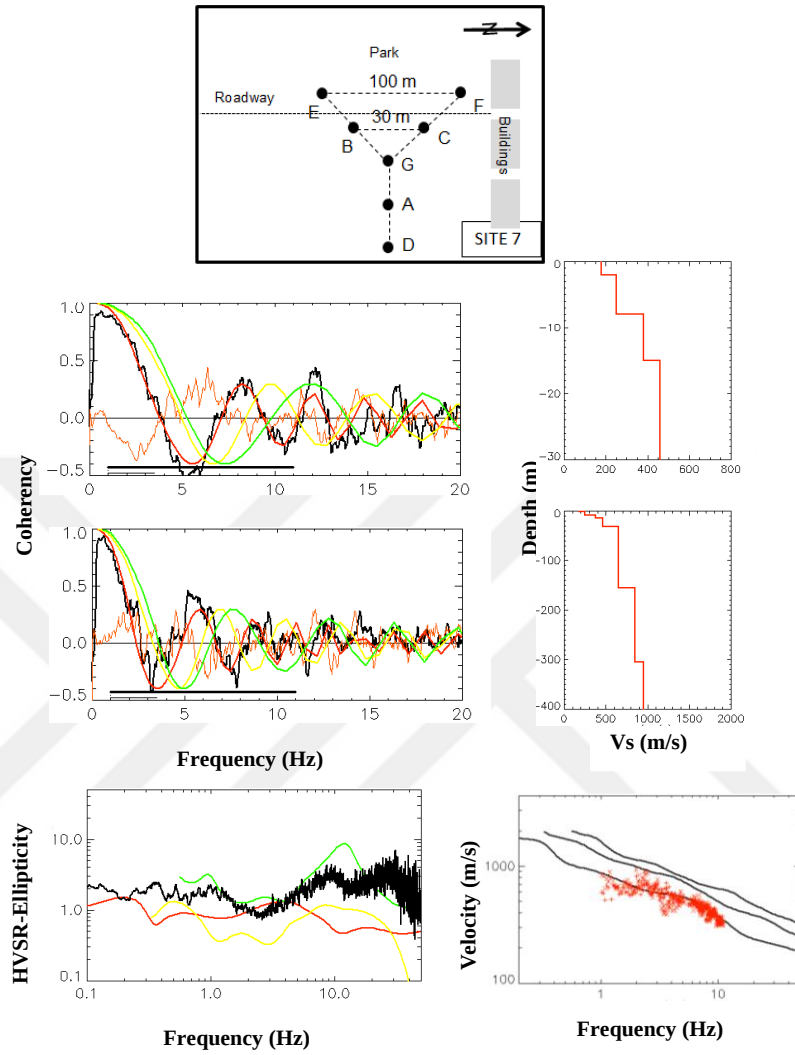


Figure 3.13 MMSPAC results for Site 7 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 7 is 1 Hz and high frequency limit is ~11 Hz. The HVSR curve shows peaks at approximately 0.15 Hz, 0.3 Hz, 1 Hz, 8 Hz and 11 Hz.

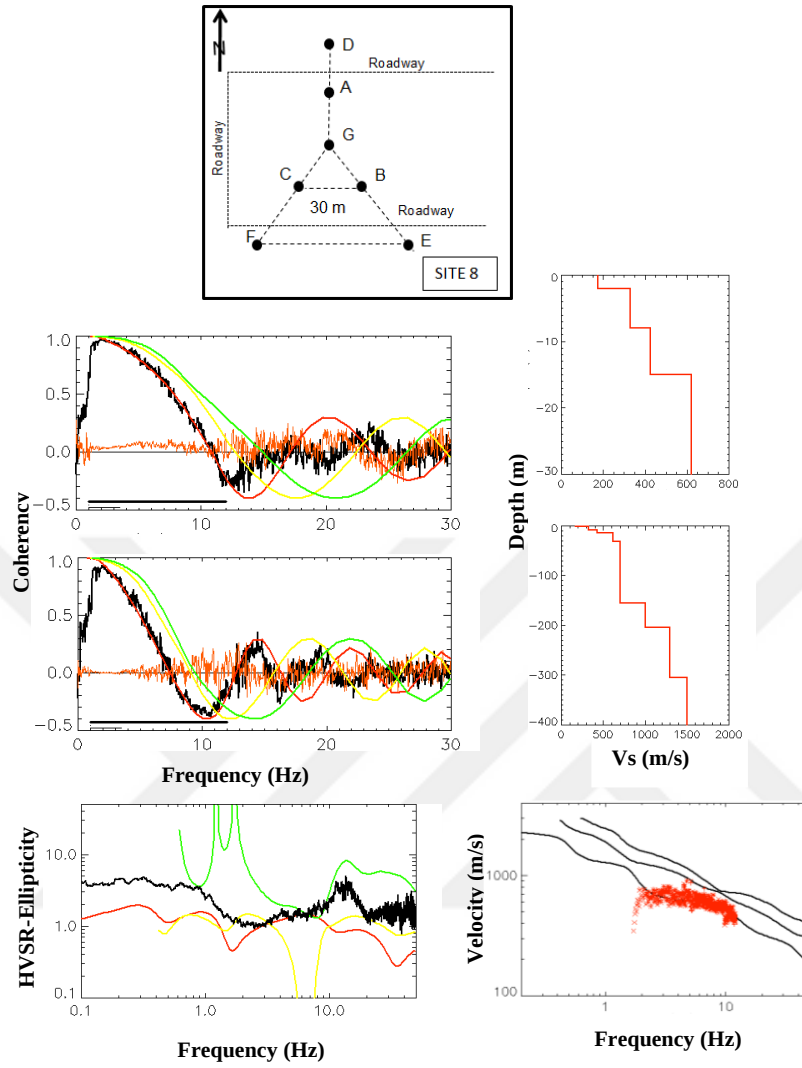


Figure 3.14 MMSPAC results for Site 8 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 8 is 1 Hz and high frequency limit is ~12 Hz. The HVSR curve shows peaks at approximately 0.2 Hz, 0.7 Hz, 4 Hz and 10.5 Hz.

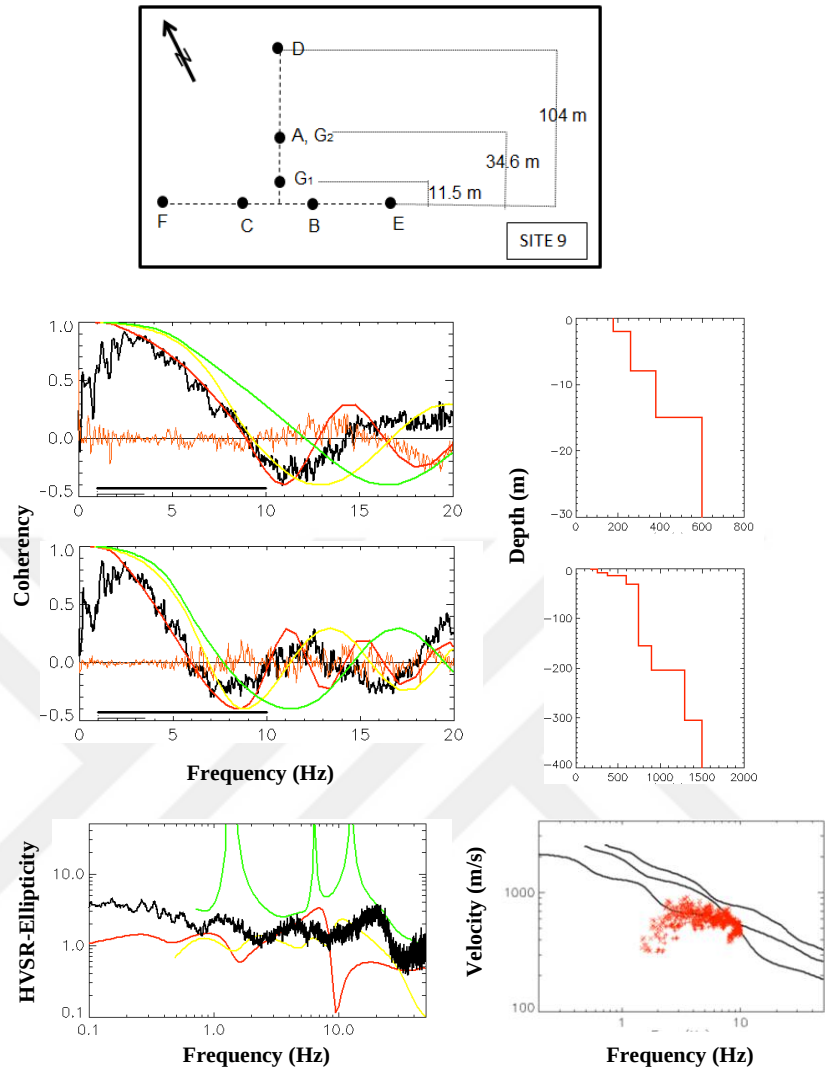


Figure 3.15 MMSPAC results for Site 9 (Adapted from Askan et al.2015)

The useful low frequency limit at Site 9 is 1 Hz and high frequency limit is ~10 Hz.

The HVSR curve shows peaks at approximately 0.5 Hz, 1.5 Hz, 4.5 Hz and 11 Hz.

In engineering applications, it is common to focus on velocity profiles from both shallow and deeper parts of the soil to understand the subsurface conditions. In this thesis, velocity profiles are observed not only for shallow parts of the soil but also for deeper layers. Two important parameters used to identify local soil conditions at any site are $V_s 10$, $V_s 30$, $V_s 100$ and $V_s 300$ representing the 10-meter, 30-meter, 100-meter and 300 meter average shear wave velocity, respectively, in units of m/s. Table 3.1 and 3.2 display the V_s values for the North-South (N-S) and East-West (E-W) directions at nine sites of interest. The selection of these sites is based on their positions in the East-West and North-South directions to investigate the geometry of the basin. In the North-South direction, the selected sites are Site 2, Site 5, Site 4, Site 3, and Site 1. For the East-West direction, the selected sites are Site 6, Site 7, Site 8, Site 9, and Site 2.

The results show that the northern part of the basin, specifically Site 2 and 8, have relatively high stiffness, indicating the presence of stiffer soil materials. This observation is consistent with the topography of the region. On the other hand, the southern areas near the Erzincan airport (Site 1) are located on softer soil materials with lower V_s values. In the E-W direction, especially at Site 6 and Site 7, lower V_s values are obtained.

Table 3.1 Time-averaged shear wave velocities down to depths of 10m, 30m, 100m and 300m along the N-S array

Site	2	5	4	3	1
$V_s 10$ (m/s)	400	200	208	261	224
$V_s 30$ (m/s)	569	267	287	304	256
$V_s 100$ (m/s)	712	439	442	502	327
$V_s 300$ (m/s)	1000	627	551	540	484

Table 3.2 Time-averaged shear wave velocities down to depths of 10m, 30m, 100m and 300m along the E-W array

Site	6	7	8	9	2
Vs10 (m/s)	255	248	291	253	400
Vs30 (m/s)	336	348	427	387	569
Vs100 (m/s)	510	514	587	582	712
Vs300 (m/s)	670	667	806	801	1006

In Figures 3.16-3.17, initial 2D velocity models obtained from the MMSPAC method are demonstrated. This information is crucial for several purposes to understand the seismic behavior of the region and the basin effects.

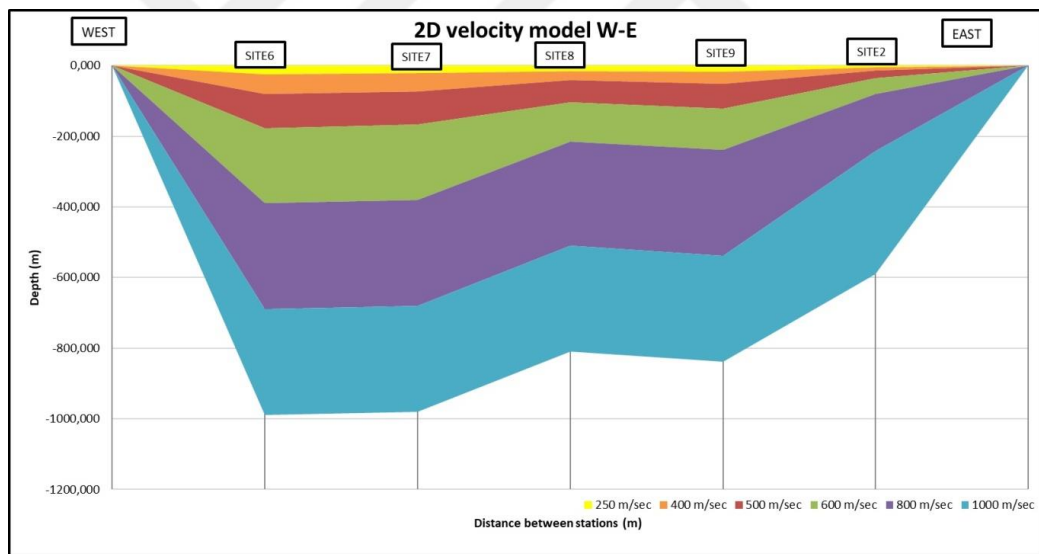


Figure 3.16. 2D velocity model along the E-W array.

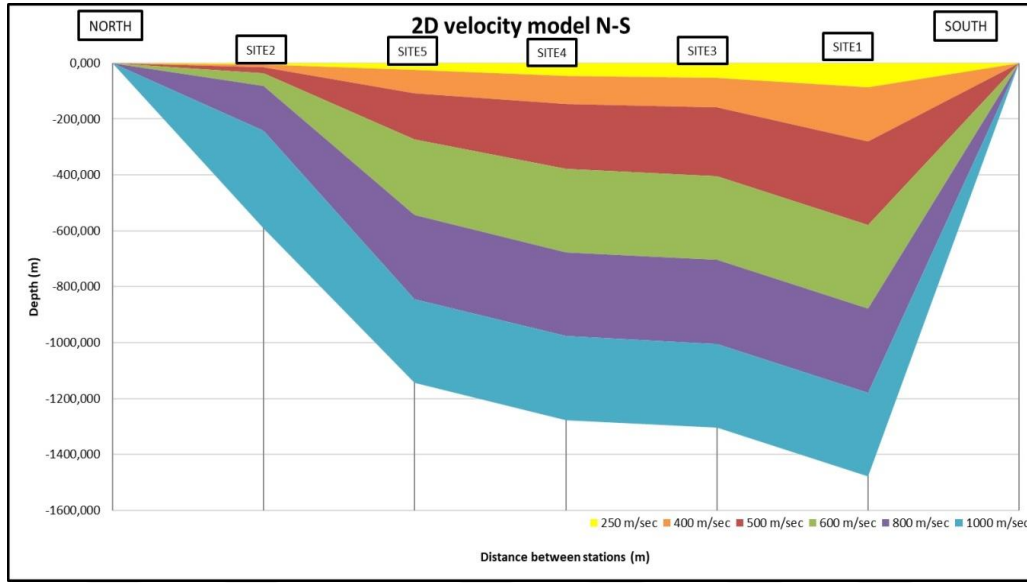


Figure 3.17. 2D velocity model along the N-S array

3.3 Input Parameters for Broadband Ground Motion Simulations in Erzincan Region

Accurate hybrid ground motion simulations require detailed knowledge of source, path, and site parameters. The source and regional path parameters for this earthquake have already been validated in previous studies (e.g.: Bernard et al., 1997; Askan et al., 2013), so those parameters are adopted while the most important local site parameters are derived herein. The main site parameters including the kappa, site amplification factors, transfer function are computed from the local geology and the regional strong motion data (Askan et al., 2013). With regional input model parameters, the 1992 Erzincan earthquake is simulated to generate reliable and accurate broadband ground motion records of the event.

First, to validate the input parameters, the 1992 Erzincan earthquake is simulated at the ERC, REF, and TER strong ground motion stations. The misfits between the simulated and the observed records are calculated to evaluate the goodness of the fit for the results. It is noted that for the shallow part of the soil, the ERC, REF and TER stations, the geotechnical parameters defined in the AFAD database are used

to perform the hybrid simulations. Next, the validated source and path parameters are used along with the detailed velocity models from the MMSPAC to investigate the variations in ground motions at different locations within the basin.

3.3.1 Parameters of Deterministic Ground Motion Simulation of the 1992 Erzincan Earthquake

The low-frequency portion of the broadband record is simulated using the open-source COMPSYN code. In the program, mainly the OLSON, TFAULT and SLIP scripts are used respectively, to model the velocity structure, fault model and slip distributions of this earthquake.

3.3.1.1 Parameters of the OLSON Model

The earth velocity structure is the main parameter in the OLSON model. Both the shallow and deeper parts of the soil structure must be modeled carefully. This structure includes values for V_p (compressional wave velocity), V_s (shear wave velocity), corresponding density values and depth information. For the hybrid simulations in Erzincan, the velocity model for ERC, REF, and TER stations (Figure 3.18) and the nine sites where velocity models obtained from the MMSPAC method (Askan et al. 2015) are used.

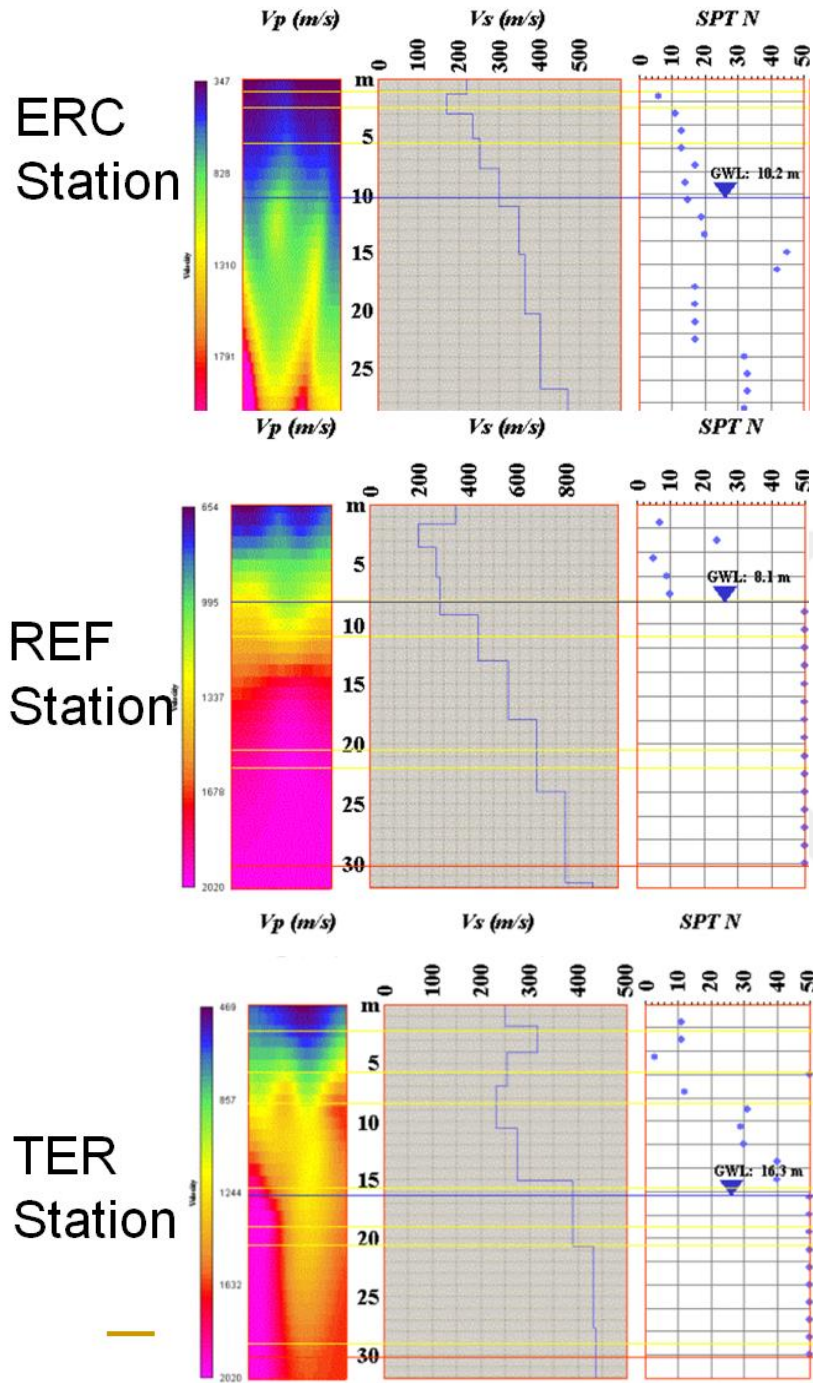


Figure 3.18. From left to right: P wave and S wave velocity models, uncorrected SPT N values at ERC, REF, and TER stations (Adapted from AFAD database)

The deeper part of the earth model is adapted from previous studies of Kaypak and Eyidoğan (2005) and Kaypak (2008).

The Table 3.3 presents the P-wave velocity (V_p), S-wave velocity (V_s), and densities (ρ) at various depths. This velocity structure has been implemented into the OLSON script for the current application.

Table 3.3 The crustal earth model used for the simulations in Erzincan region
(Adapted from Kaypak and Eyidoğan, 2005 and Kaypak, 2008)

Depth (km)	V_p (km/s)	V_s (km/s)	Q (g/cm ³)
0-20	6	3.2	2.7
20-35	6.7	3.7	2.8
>35	8.1	4.7	3.3

3.3.1.2 Parameters of the TFAULT model

In the TFAULT model, the geometry of the fault including the strike, dip and the boundary conditions are selected from Askan et al. (2013) and Askan et al. (2015). The entire geometry is defined in the TFAULT model. The coordinates of each selected site are also calculated. The input files are prepared manually at this stage.

3.3.1.3 Parameters of the SLIP Model

In the SLIP scripts, horizontal limits of integration on fault plane, down-dip limits of integration on fault plane parameters are required. In literature, slip distribution studies applied in the Erzincan region are very limited. The slip model is adapted from Askan et al. (2013) and Şanlı et al. (2017) (Figure 3.19).

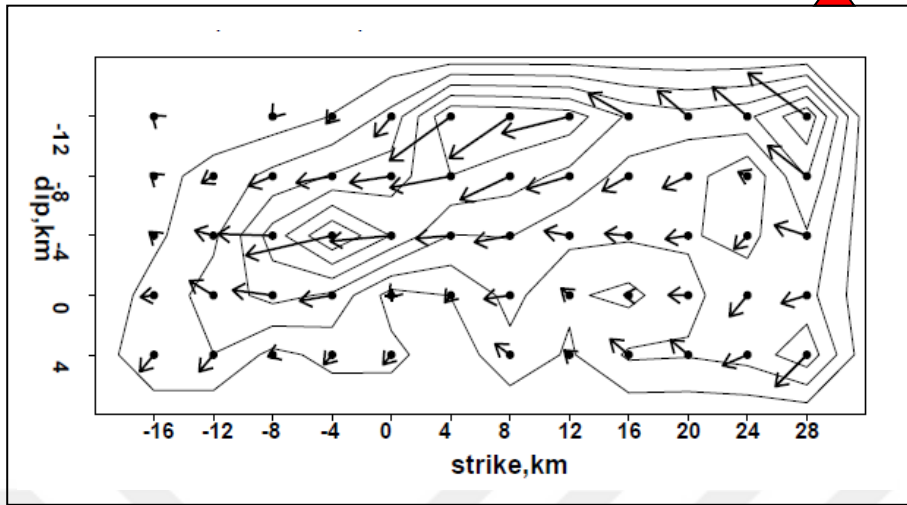


Figure 3.19. Distribution of slips for the 1992 Erzincan Earthquake and red triangle indicates a station. (Adapted from Şanlı et al. 2017)

3.3.2 Parameters of Stochastic Ground Motion Simulation of the 1992 Erzincan Earthquake

Stochastic finite-fault modeling for the 1992 Erzincan earthquake ($M_w=6.6$) source, path, and local site parameters are carefully selected from Askan et al. (2013) and Askan et al. (2015). The local site parameters approach ensures a realistic simulation of the earthquake's ground motion characteristics and helps assess the local seismic hazard.

3.3.2.1 Source Parameters

In stochastic finite-fault modeling, various source parameters are essential, including the orientations of the fault (dip and strike angles), the fault dimensions, depth, and coordinates of the hypocenter, slip distribution along the fault plane, stress drop, and pulsing area percentage. These parameters are crucial for accurately simulating the earthquake's source and ground motion characteristics, enabling a comprehensive analysis of the seismic event.

As mentioned, the orientations of the fault (dip and strike angles), the fault dimensions, depth, and coordinates of the hypocenter are provided. The stress drop and pulsing area percentage are selected from the parameters listed in Bernard et al. (1997). The sub-fault dimensions are set as 5×3 km along the strike and dip directions.

3.3.2.2 Path Parameters

To define the path model for the stochastic finite-fault modeling, several parameters are required, including geometric spreading, anelastic attenuation (quality factor), and a distance-dependent duration model. For the Erzincan region, the geometric spreading model is adapted from Akinci et al. (2009) and is given as follows:

$$\begin{aligned} R^{-1} & \quad R \leq 25 \text{ km} \\ R^{-0.5} & \quad R > 100 \text{ km} \end{aligned} \quad (3.3)$$

In the strong ground motion simulation part, the crustal shear-wave quality factor is modeled using the equation $122f^{0.68}$ proposed by Grosser et al. (1998). For the distance-dependent duration model, it is adapted from Hermann (1985) and is given as follows:

$$T = T_0 + 0.05 \quad (3.4)$$

where T_0 is the source duration.

3.3.2.3 Site Parameters

In strong ground motion simulations, site effects are taken into account by considering local soil amplification and kappa (high-frequency decay) parameters.

To ensure accurate simulated records, these site-specific parameters are calculated from past events recorded at ERC, REF, and TER strong ground motion stations.

In this section of the thesis, records with good quality from ERC stations are utilized to evaluate empirical site amplification. In the HVSR analyses, the S-wave portion of the records is first manually selected. Next, the computed Fourier amplitude spectra are smoothed between 0.25 and 25 Hz using a Hann filter with a bandwidth of 0.4 Hz. The resulting mean HVSR spectrum is presented in Figure 3.20.

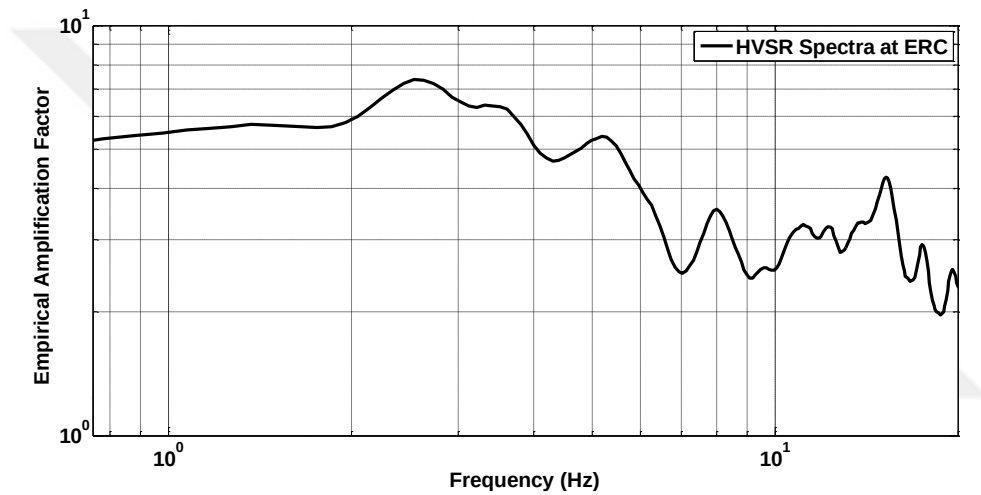


Figure 3.20. Amplification spectra at station ERC based on HVSR analyses (Adopted from Askan et al. 2013)

Furthermore, one-dimensional (1-D) site response analyses are conducted at each station using available geophysical and geotechnical information (Table 3.4, 3.5 and 3.6). The soil profiles at the three stations are modeled as a series of infinite horizontal layers atop a uniform half-space, and the theoretical transfer function in the frequency domain is computed (Figure 3.21). To perform these analyses, input parameters such as the thickness, density, wave velocity, shear modulus reduction, and damping curves of each layer are used. Detailed of these input parameters for the theoretical transfer functions are presented in Askan et al., (2013).

Table 3.4 Geophysical and geotechnical information at ERC station for site response analyses (Adapted from Askan et al. 2013)

Layer	Material Name	Depth(m)	Vs (m/s)	Damping curve	Modulus curve
1	Filling	1.4	219	Linear	Linear
2	Clay (Cl)	3	170	Clay (Average-Sun et al.)	Clay –PI=10-20 (Sun et al.)
3	Sand (Sa)	5.1	234	Sand (Seed and Idriss)	Clay –PI=10-20 (Sun et al.)
4	Sand (Sa)	7.8	251	Sand (Seed and Idriss)	Clay –PI=10-20 (Sun et al.)
5	Clay (Cl)	11.1	300	Clay (Sun et al.)	Clay –PI=10-20 (Sun et al.)
6	Clay (Cl)	15.5	349	Clay (Sun et al.)	Clay –PI=10-20 (Sun et al.)
7	Clay (Cl)	20.6	362	Clay (Sun et al.)	Clay –PI=10-20 (Sun et al.)
8	Clay (Cl)	27.1	402	Clay (Sun et al.)	Clay –PI=10-20 (Sun et al.)
9	Clay (Cl)	32.3	469	Clay (Sun et al.)	Clay –PI=10-20 (Sun et al.)
10	Rock	42.3	800	Rock	Rock (Idriss)
11	Rock	52.3	1000	Rock	Rock (Idriss)
12	Rock	Infinite	2000	Rock	Rock (Idriss)

Table 3.5 Geophysical and geotechnical information at REF station for site response analyses (Adapted from Askan et al. 2013)

Layer	Material Name	Depth(m)	Vs (m/s)	Damping curve	Modulus curve
1	Filling	0.40	305	Linear	Linear
2	Clay (Cl)	1.3	305	Clay –PI=40-80 (Sun et al.)	Clay (Sun et al.)
3	Gravel	4.1	155	Gravel (Seed et al.)	Gravel (Seed et al.)
4	Sand (Sa)	7.1	339	Sand (Seed and Idriss)	Sand (Seed and Idriss)
5	Clay (Cl)	31	319	Clay P1=40-80 (Sun et al.)	Clay (Sun et al.)
6	Sand (Sa)	18.6	507	Sand (Seed and Idriss)	Sand (Seed and Idriss)
7	Sand (Sa)	24.4	619	Sand (Seed and Idriss)	Sand (Seed and Idriss)
8	Sand (Sa)	31.8	717	Sand (Seed and Idriss)	Sand (Seed and Idriss)
9	Sand (Sa)	34.8	786	Sand (Seed and Idriss)	Sand (Seed and Idriss)
10	Rock	44.8	1000	Rock	Rock (Idriss)
11	Rock	Infinite	2000	Rock	Rock (Idriss)

Table 3.6 Geophysical and geotechnical information at TER station for site response analyses (Adapted from Askan et al. 2013)

Layer	Material Name	Depth(m)	Vs (m/s)	Damping curve	Modulus curve
1	Filling	0.8	250	Linear	Linear
2	Clay (Cl)	1.8	250	Clay (Sun et al.)	Clay –PI=20-40 (Sun et al.)
3	Clay (Cl)	4.1	316	Clay (Sun et al.)	Clay –PI=10-20 (Sun et al.)
4	Gravel	7.2	253	Gravel (Seed et al.)	Gravel (Seed et al.)
5	Clay (Cl)	10.8	230	Clay (Sun et al.)	Clay –PI=20-40 (Sun et al.)
6	Clay (Cl)	15.3	274	Clay (Sun et al.)	Clay –PI=40-80 (Sun et al.)
7	Sand (Sa)	20.9	389	Sand (Seed and Idriss)	Sand (Seed and Idriss)
8	Clay (Cl)	27.9	431	Clay (Sun et al.)	Clay –PI=20-40 (Sun et al.)
9	Sand (Sa)	32.2	436	Sand (Seed and Idriss)	Sand (Seed and Idriss)
10	Rock	42.2	800	Rock	Rock (Idriss)
11	Rock	Infinite	2000	Rock	Rock (Idriss)

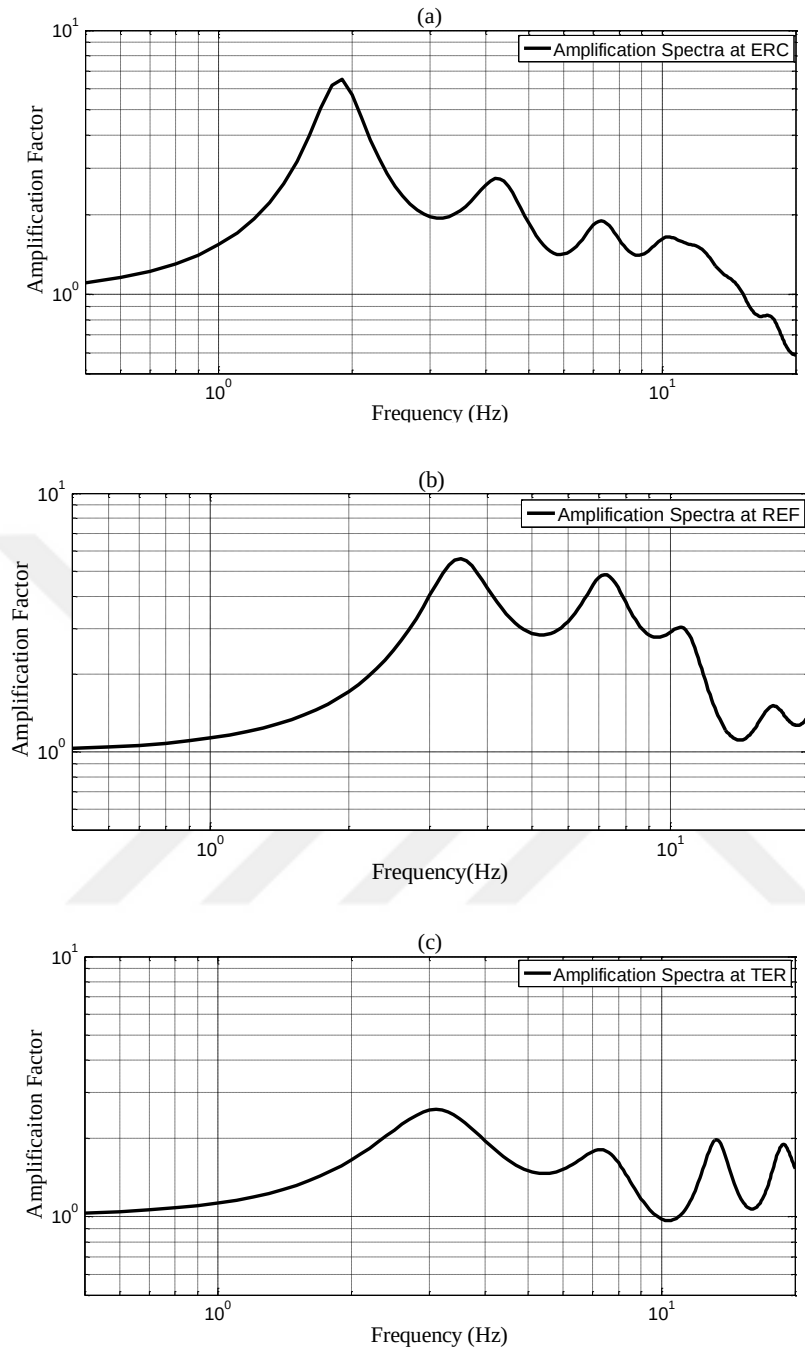


Figure 3.21. Amplification spectra computed from the theoretical transfer functions at the stations (a) ERC, (b) REF, and (c) TER (Adopted from Askan et al 2013)

Another crucial site parameter is the kappa factor. To determine the regional kappa factor in the Erzincan region, the linear model for regional distance-dependency of kappa is calculated based on the original study by Anderson and Hough (1984).

The availability of high-quality ground motion records in the region is limited, particularly at REF and TER stations. As a result, the majority of the records used in kappa analyses come from measurements at the ERC station. Since the high-frequency decay of the records obtained from these stations appears to be similar, a regional kappa model is created by combining records from all stations.

In summary, a total of 40 ground motion records measured at the three stations are used for the regional kappa model. Only records with clear S-wave arrivals and no signal-to-noise issues are selected to ensure reliable kappa computations. For the simulations, the corresponding zero-distance kappa value ($\kappa_0=0.066$) is employed to consider the near-surface high frequency attenuation effects. It is noted that this value is also consistent with the results of a very recent study by Altindal and Askan (2023) regarding regional kappa values in Türkiye.

The input parameters used in the deterministic and stochastic simulations for the 1992 Erzincan earthquake are presented in Table 3.7.

Table 3.7: Input parameters used in the hybrid simulation of the 1992 Erzincan Earthquake

Moment Magnitude		6.6	
Fault Orientation		Strike: 125° Dip: 90°	
Fault Dimensions		25 x 9 km	
Hypocenter location		39°42.3 N, 39°35.2 E	
Specific Parameters of Deterministic Ground Motion Simulations		Specific Parameters of Stochastic Ground Motion Simulations	
Velocity Structure	ERC-REF and TER station velocity profiles /Askan et al. (2015)	Stress Drop Mohammadioun and Serva (2001)	80 bars
		Pulsing Area Percentage Bernard et al. (1997)	50%
Crustal Velocity Model	Kaypak and Eyidoğan (2005) Kaypak (2008)	Duration Model Hermann, (1985)	$T_0+0.05R$
Subfault Dimensions	5 x 3 km	Attenuation Model, Q(f) Grosser et al. (1998)	$122f^{0.68}$
Crustal Density	2800 kg/m ³ Bernard et al. (1997)	Geometric Spreading Akinci et al. (2009)	$R^{-1.1}$ $R \leq 25\text{km}$ $R^{-0.5}$ $R > 25\text{km}$
Slip Distribution	Şanlı et al. (2017)	Kappa (κ_0) Askan et al. (2013)	Regional kappa model: 0.066
		Site amplification factors	Amplifications based on local soil models Askan et al. (2015)

3.4 Simulation of the 1992 Erzincan Earthquake with Hybrid Method

The 1992 Erzincan earthquake is simulated with hybrid ground motion method at ERC, REF, TER strong ground motion stations. As the first comparison, the observed and simulated PGA values are also compared in Table 3.8. Simulated values at all stations are close to the recorded PGAs. Next, for a detailed visual assessment, the simulated accelerations at the ERC, REF and TER stations in time and frequency domain are shown in Figures 3.20, 3.21 and 3.22, respectively.

Table 3.8: PGA values (in cm/s^2) of the 1992 Erzincan earthquake for Station ERC, Station REF, and Station TER

	REAL ERC	SIMULATE D ERC	REAL REF	SIMULATED REF	REAL TER	SIMULATED TER
N-S	404.9	435.53	67.2	78	39.38	41.67
E-W	470.9	486.1	85.93	97	29.97	28.16
U-S	238.5	208	31.57	37.05	22.66	22.37

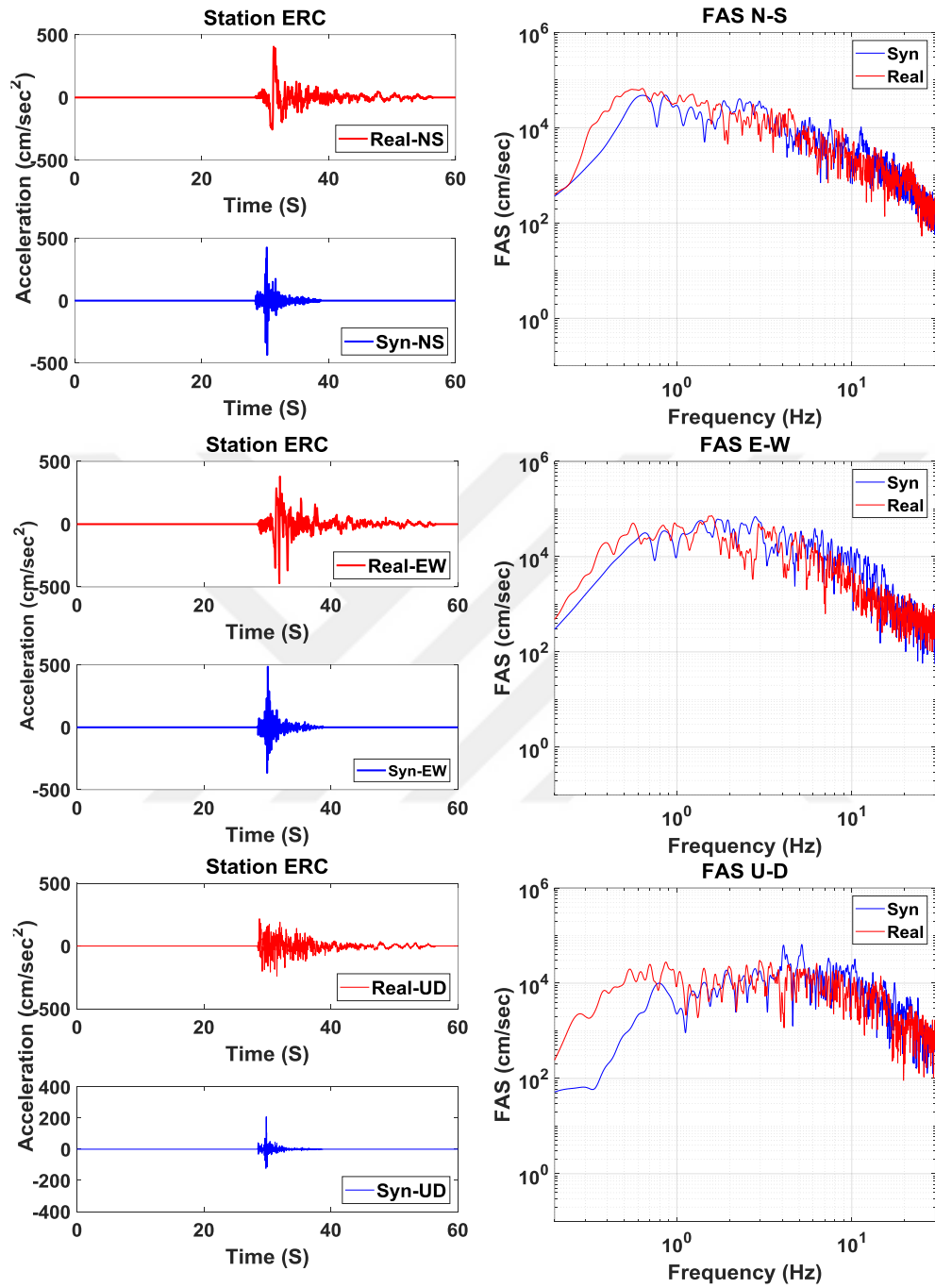


Figure 3.22. Comparison of broadband acceleration-time series (Left panel) and the FAS (Right panel) of the observed and synthetic ground motions of the 1992 Erzincan earthquake at ERC station.

From Figure 3.22, it is observed that at ERC there is a very close match between the simulated and real records for both N-S and E-W components. However, the low frequency portion of the U-D component clearly underestimates the real one. This discrepancy can be attributed to the uncertainties in the Vp model. It is worth to note that this station is located right in the middle of the basin. The simulated low frequencies slightly underestimate the recorded ones for even the horizontal components: This could potentially be the long-period enhancement of the amplitudes due to the basin effects which cannot be fully simulated with the wave propagation approach based on 1D velocity model here.



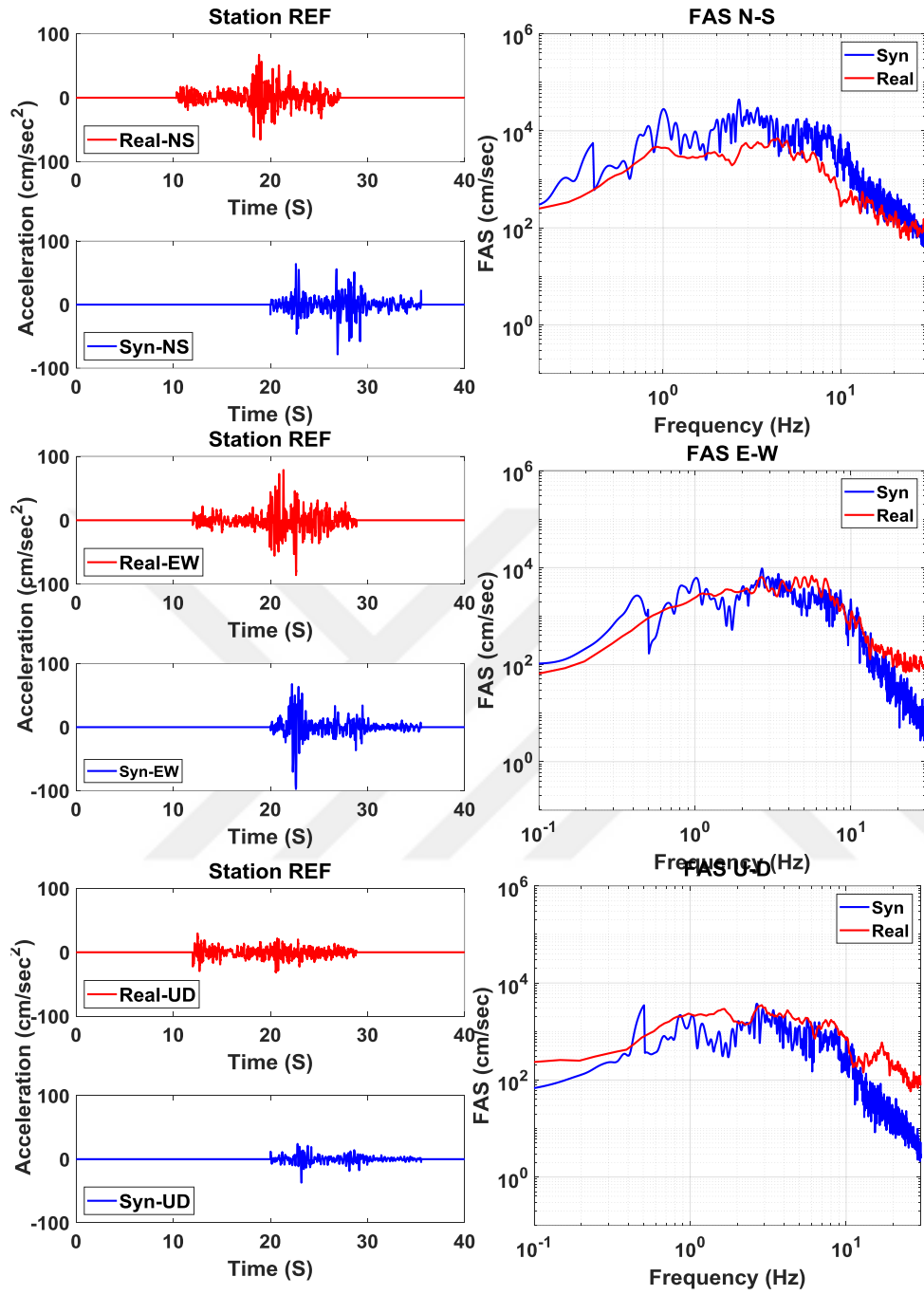


Figure 3.23. Comparison of broadband acceleration-time series (Left panel) and the FAS (Right panel) of the observed and synthetic ground motions of the 1992 Erzincan earthquake at REF station.

In Figure 3.23 concerning the data at the REF station, both low and intermediate frequency bands of the observed records are closed matched by the simulated spectra for the EW and UD components. However, there is some discrepancy for the higher frequencies which seem to arise from the kappa model at this station. On the other hand, the NS component of the observed ground motion yields smaller amplitudes than the synthetic record in the frequency domain despite the close match in time domain.



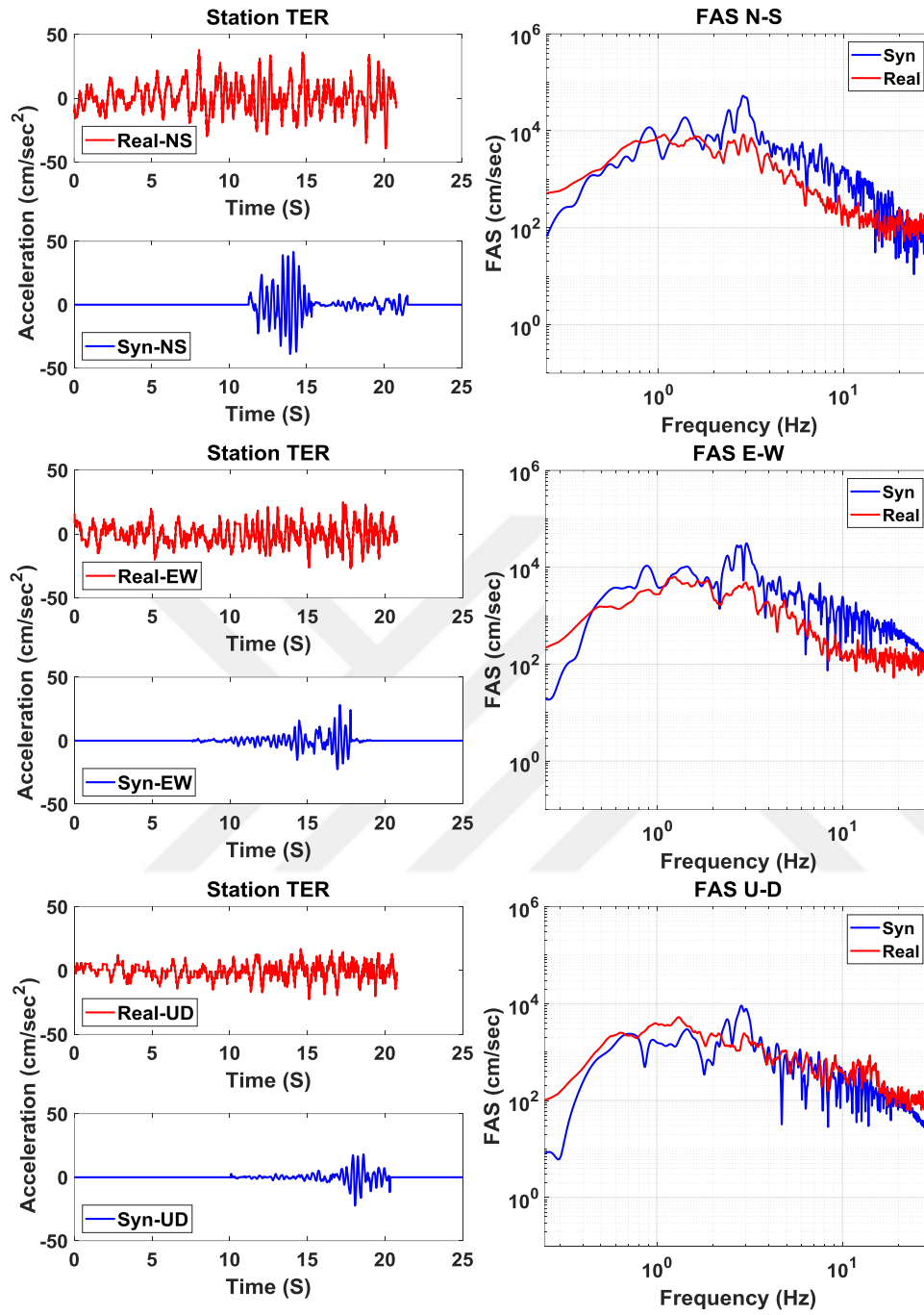


Figure 3.24. Comparison of broadband acceleration-time series (Left panel) and the FAS (Right panel) of the observed and synthetic ground motions of the 1992 Erzincan earthquake at TER station.

In Figure 3.24, at TER station, a close match between the real and the simulated spectra for the UD component is obtained while the horizontal simulations

overestimate the recorded high frequency amplitudes. This can be attributed to the kappa factor. In time domain, the simulations are close to records amplitude wise but not in terms of durations.

Next, quantitative comparisons are made between the observed and simulated data at the ERC, REF and TER stations. A misfit function is used in the frequency domain (Karimzadeh *et al.*, 2017) as follows:

$$Misfit_{FAS} = \frac{1}{n_f} \cdot \sum_f \left| \log \left(\frac{FAS_{syn}(f)}{FAS_{obs}(f)} \right) \right| \quad (3.5)$$

where n_f is the number of discrete frequencies, $FAS_{syn}(f)$ and $FAS_{obs}(f)$ are the synthetic and observed Fourier amplitudes at frequency f , respectively.

Misfits for the PGA values are defined as follows (Karimzadeh *et al.*, 2017):

$$Misfit_{PGA} = \left| \frac{PGA_{syn}}{PGA_{REAL}} \right| - 1 \quad (3.6)$$

A perfect match would give both FAS and PGA misfit values of 0.

The misfits in terms of PGA and FAS are presented in Table 3.9 to 3.14 for Station ERC, Station REF and Station TER, respectively. The hybrid simulation misfits are shown with respect to only stochastic approach misfits in order to highlight the advantages of the hybrid approach.

Table 3.9: Results of the Misfit FAS for Station ERC

MISFITS - STATION ERC				
	f INTERVAL	MISFIT-FAS (E-W)	MISFIT-FAS (N-S)	MISFIT- FAS (U-D)
Stochastic Simulation Misfit	LF Part	0.87	0.95	0.66
	HF Part	0.39	0.44	0.39
Hybrid Simulation Misfit	LF Part	1.49	0.98	0.9
	HF Part	0.52	0.54	0.62

Table 3.10: Results of the Misfit FAS for Station REF

MISFITS - STATION REF				
	f INTERVAL	MISFIT-FAS (E-W)	MISFIT-FAS (N-S)	MISFIT-FAS (U-D)
Stochastic Simulation Misfit	LF Part	0.52	0.48	0.68
	HF Part	0.65	0.69	0.86
Hybrid Simulation Misfit	LF Part	0.236	0.21	0.27
	HF Part	0.346	0.36	0.38

Table 3.11: Results of the Misfit FAS for Station TER

MISFITS - STATION TER				
	f INTERVAL	MISFIT-FAS (E-W)	MISFIT-FAS (N-S)	MISFIT-FAS (U-D)
Stochastic Simulation Misfit	LF Part	0.41	0.43	0.38
	HF Part	0.47	0.46	0.37
Hybrid Simulation Misfit	LF Part	0.23	0.19	0.25
	HF Part	0.35	0.36	0.37

The broadband simulations in all E-W, N-S and U-D directions in general give more accurate results when compared to stochastic simulations. The only discrepancy is the ERC station which is located at 3.32 km Rjb distance from the 1992 earthquake source. The COMPSYN code has a limitation in calculating static displacements very close to a fault that ruptures the surface of the Earth (Spudich and Xu, 2003). This is the reason for the high misfit values for the broadband simulations at the ERC station. At the REF and TER stations, hybrid simulations perform better than stochastic-only method as anticipated.

Table 3.12: Results of the Misfit PGA for Station ERC

Station ERC			
	E-W	N-S	U-D
Misfit PGA	0.03227	0.0756	-0.12788

Table 3.13: Results of the Misfit PGA for Station REF

Station REF			
	E-W	N-S	U-D
Misfit PGA	0.13	0.16	0.173583

Table 3.14: Results of the Misfit PGA for Station TER

Station TER			
	E-W	N-S	U-D
Misfit PGA	-0.06039	0.058151	-0.0128

When the PGA misfits are studied, it is observed that the misfits are smaller mostly due to the fact that the time domain characteristics at all stations are simulated efficiently.

3.5 Simulation of 1992 Erzincan Earthquake with Hybrid Method at the Selected Nodes in Erzincan Region

After the input parameters validated from the 1992 Erzincan earthquake presented in the previous section, a hybrid simulation with velocity structure obtained from the MMSPAC application in the Erzincan basin is performed to evaluate the potential source-to-site and local soil effects variable within the basin. The hybrid

ground motion simulation results performed at the selected nine sites are presented in Figures 3.25-3.33.

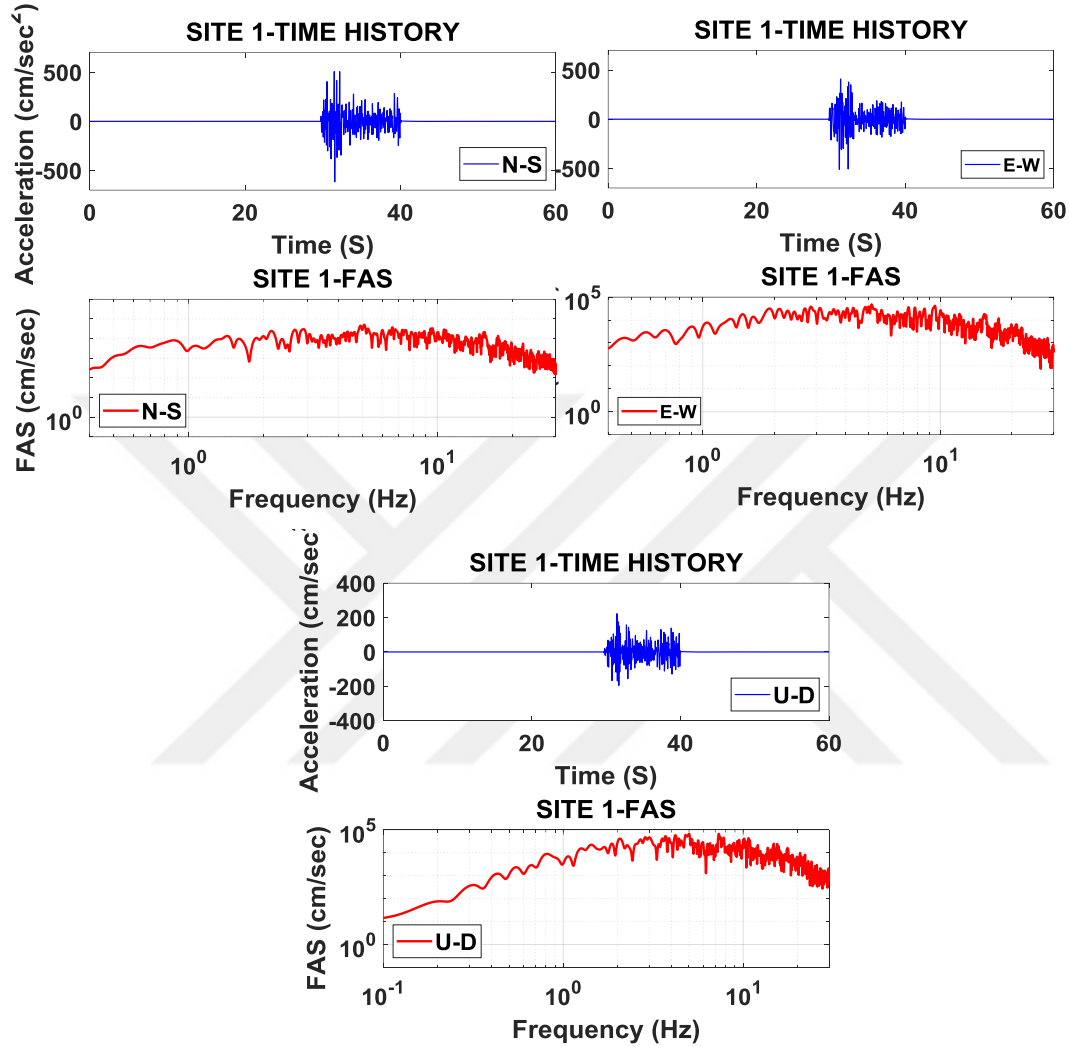


Figure 3.25. Broadband time history and FAS observed at Site 1

The PGA values for N-S, E-W and U-D components are 615 cm/s^2 , 509 m/s^2 and 222 m/s^2 in Site 1, respectively. Site 1 is located on the alluvial part of the Erzincan basin, so the PGA values are higher at this site.

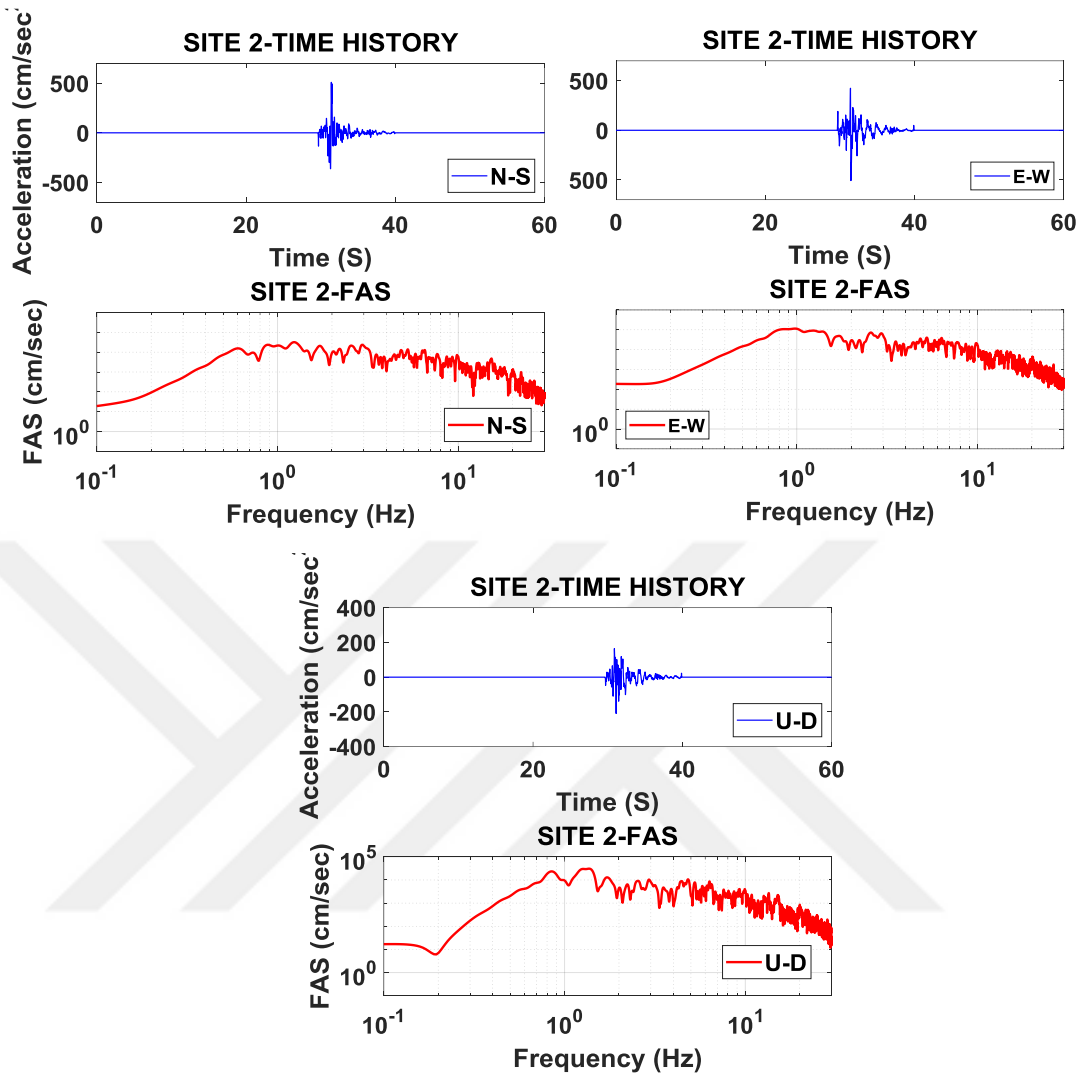


Figure 3.26. Broadband time history and FAS observed at Site 2

The PGA values for N-S, E-W and U-D components are 509 cm/s², 546 m/s² and 200 m/s² in Site 2, respectively.

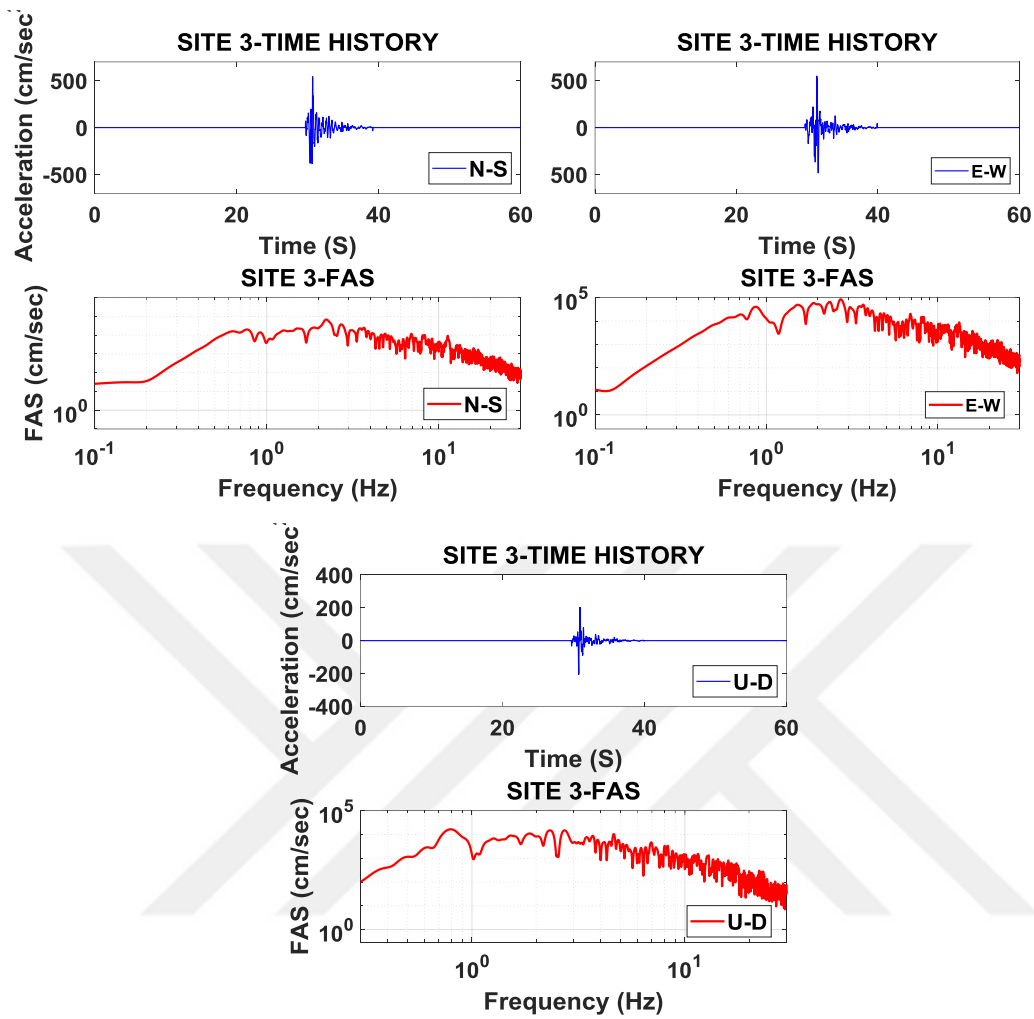


Figure 3.27. Broadband time history and FAS observed at Site 3

The PGA values for N-S, E-W and U-D components are 542 cm/s^2 , 549 m/s^2 and 205 m/s^2 in Site 3, respectively.

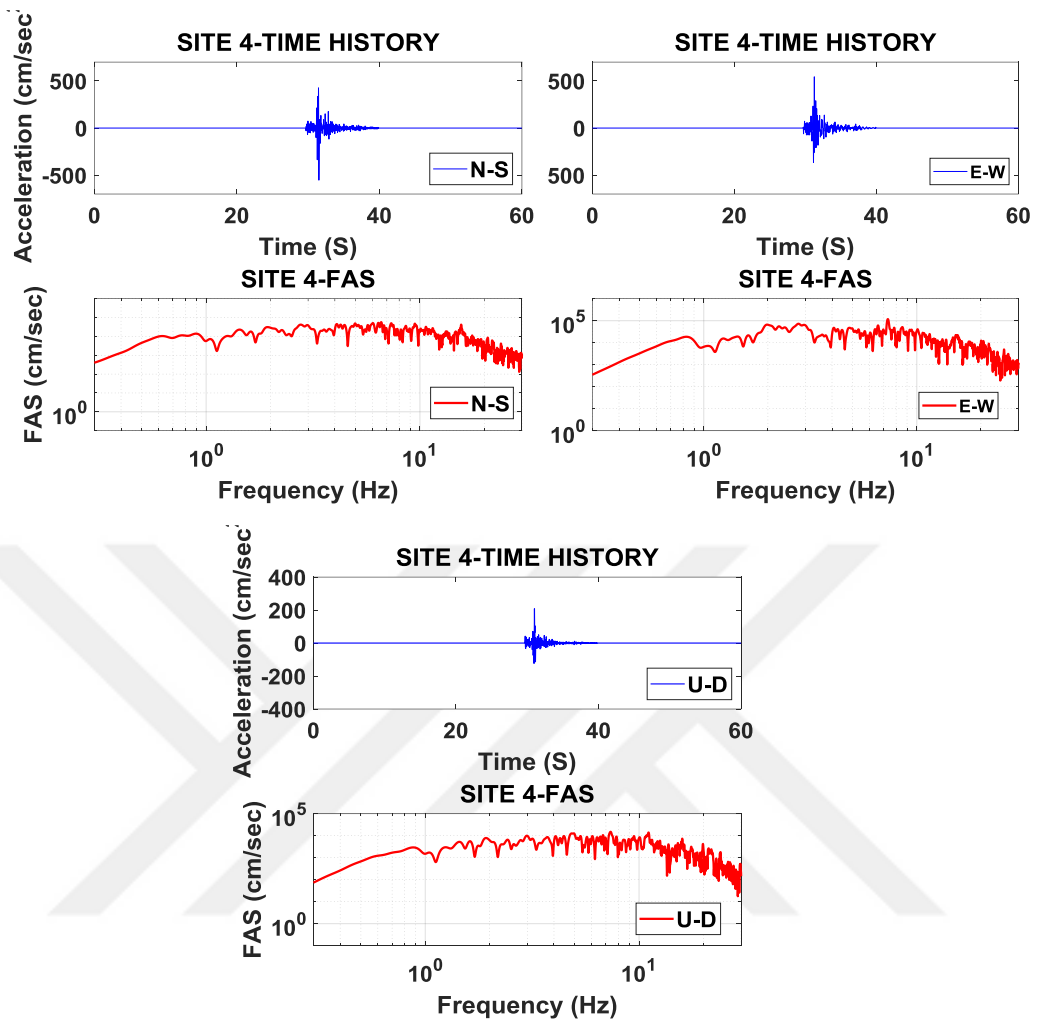


Figure 3.28. Broadband time history and FAS observed at Site 4

The PGA values for N-S, E-W and U-D components are 552 cm/s^2 , 543 m/s^2 and 208 m/s^2 in Site 4, respectively.

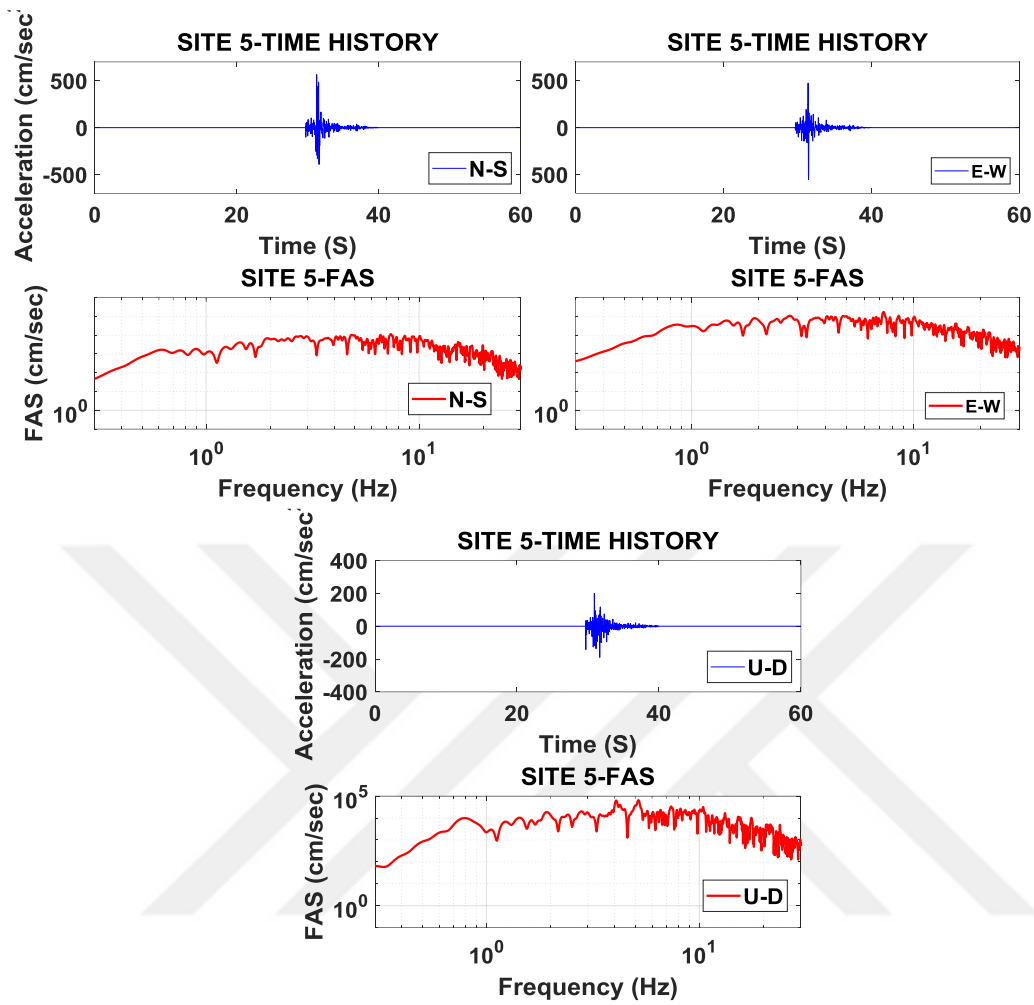


Figure 3.29. Broadband time history and FAS observed at Site 5

The PGA values for N-S, E-W and U-D components are 564 cm/s², 569 m/s² and 202 m/s² in Site 5, respectively.

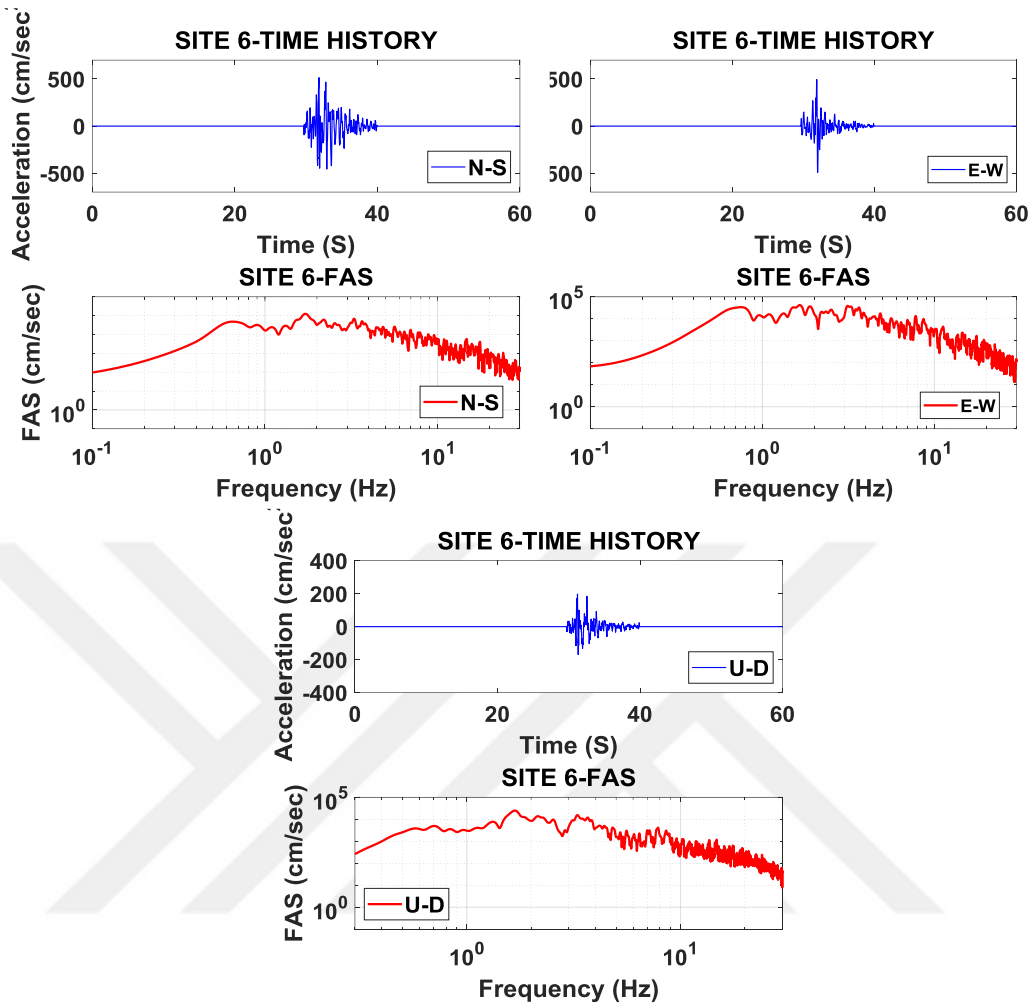


Figure 3.30. Broadband time history and FAS observed at Site 6

The PGA values for N-S, E-W and U-D components are 452 cm/s², 488 m/s² and 195 m/s² in Site 6, respectively.

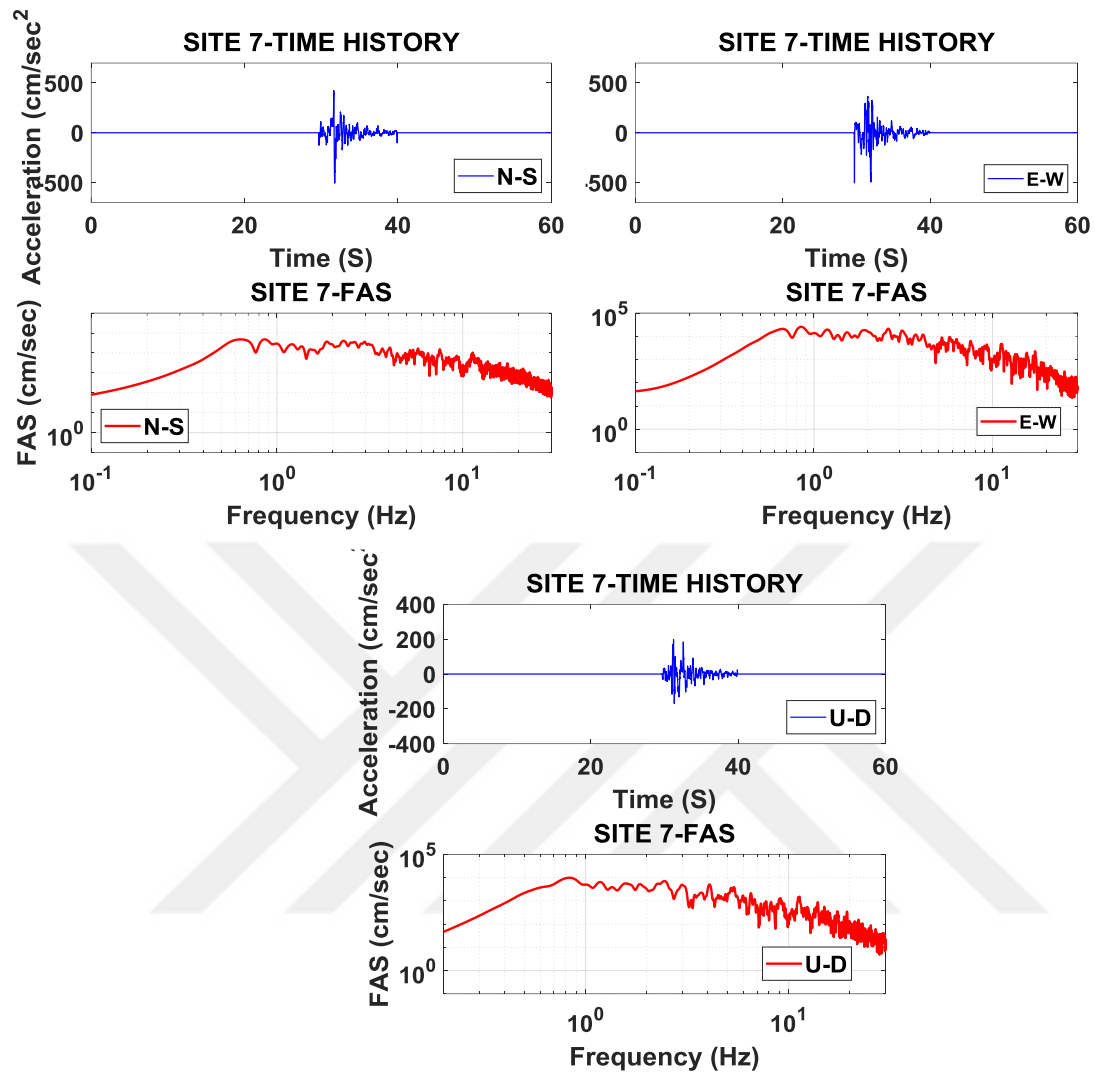


Figure 3.31. Broadband time history and FAS observed at Site 7

The PGA values for N-S, E-W and U-D components are 506 cm/s², 495 m/s² and 197 m/s² in Site 7, respectively.

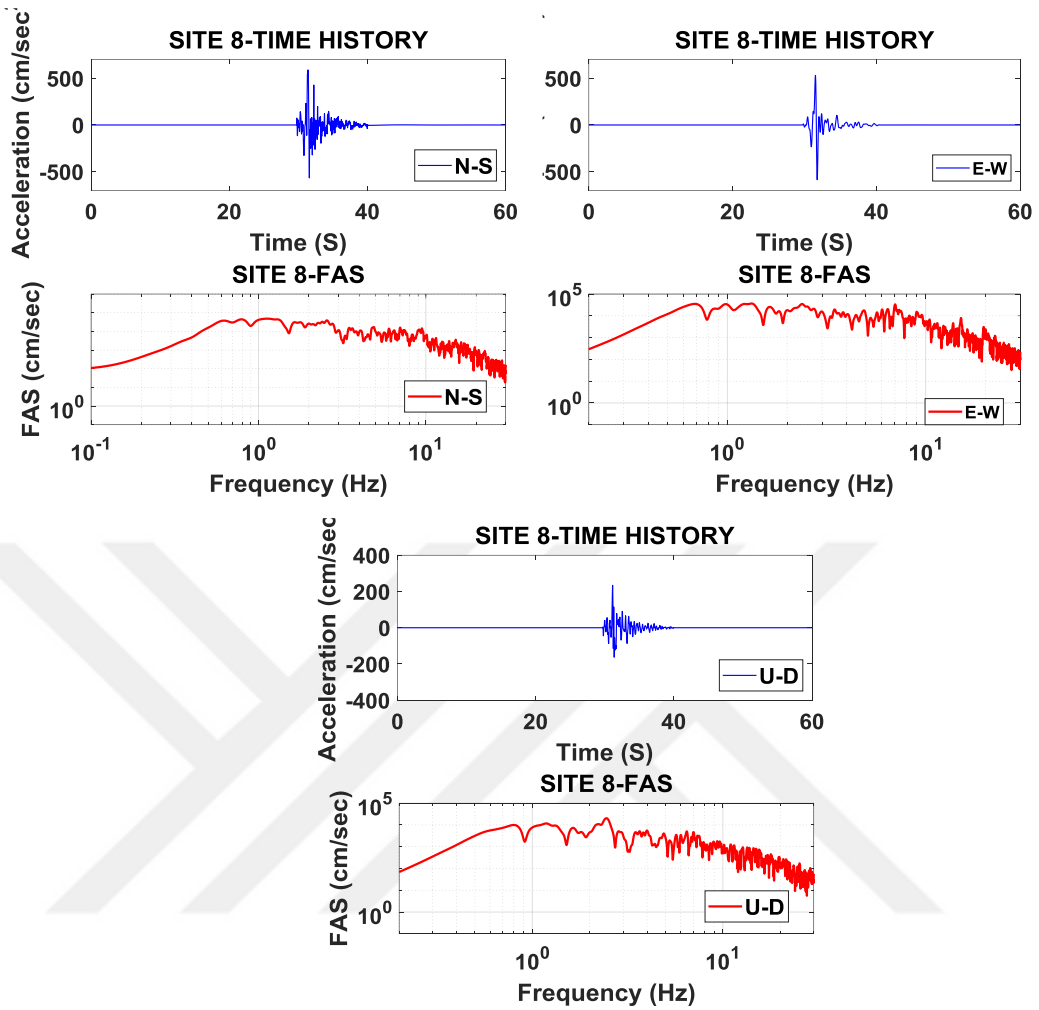


Figure 3.32. Broadband time history and FAS observed at Site 8

The PGA values for N-S, E-W and U-D components are 560 cm/s², 552 m/s² and 234 m/s² in Site 8, respectively.

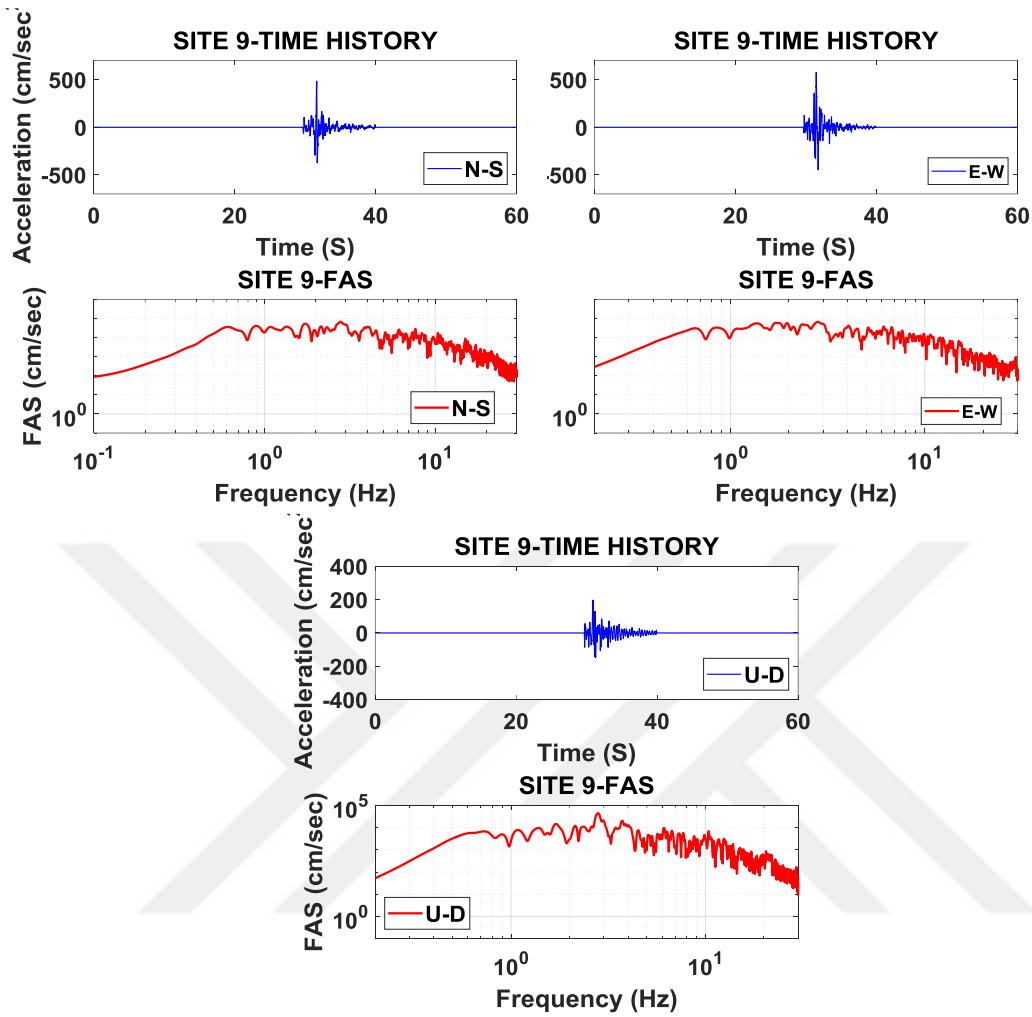


Figure 3.33. Broadband time history and FAS observed at Site 9

The PGA values for N-S, E-W and U-D components are 483 cm/s^2 , 575 m/s^2 and 196 m/s^2 in Site 9, respectively.

Tables 3.15 and 3.16 are prepared to evaluate the results geographically. The distance between the hypocenter of the 1992 Erzincan Earthquake and the location of the selected sites are increased in the following order: Site 2, Site 8, Site 9, Site 5, Site 7, Site 6, Site 4, Site 3 and Site 1.

Table 3.15: PGA values at selected sites along the N-S array

cm/sec ²	Site 2	Site 5	Site 4	Site 3	Site 1
N-S	509	564	552	542	615
E-W	549	569	543	549	509
U-D	205	200	208	205	222

Table 3.16: PGA values at selected sites along the E-W array

cm/sec ²	Site 6	Site 7	Site 8	Site 9	Site 2
N-S	514	506	590	483	509
E-W	493	495	586	575	549
U-D	195	197	234	196	205

The main purpose of this part of the study was to investigate the effect of a possible basin effect on the PGA values obtained as a result of the hybrid simulation. As a result, if the simulations made in all sites are evaluated considering the S wave velocity, the highest PGA values were calculated in Site 1, which has the lowest S wave velocity values. On the other hand, while a low PGA value was expected in Site 2, where a high Vs30 was obtained due to its proximity to Esentepe Mountain, a relatively high PGA value was obtained due to its location very close to the epicenter of the earthquake. Site 6 and the ERC station are very close to each other in terms of both distance and velocity structure. Due to this closeness, PGA values were calculated to be compatible with each other. Although the velocity profiles of Site 6 and Site 7 are very close to each other, PGA values were obtained higher in Site 7 due to its close distance from the epicenter of the earthquake. Site 1, Site 2, Site 3 and Site 5 are the fields where the local site effects become noticeable.

Finally, Figure 3.34 shows the comparisons of the simulated motions at the stations and selected nodes against ground motion models.

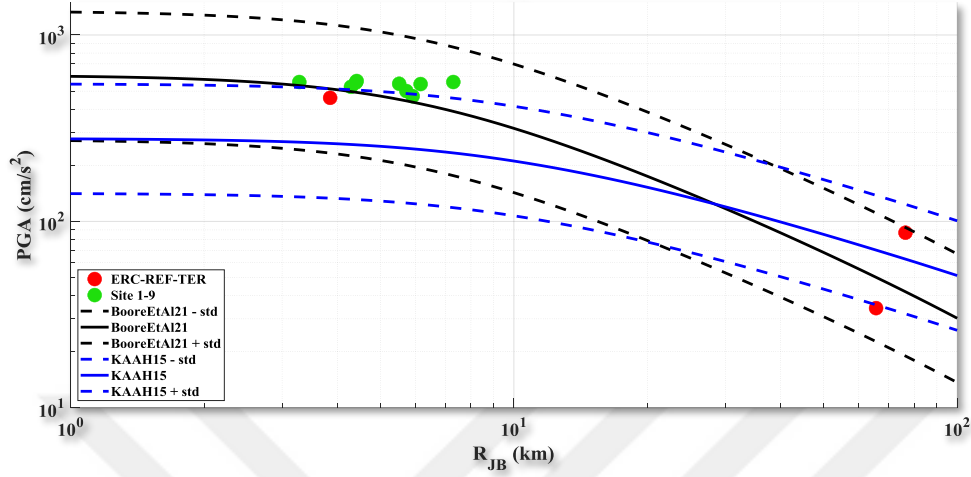


Figure 3.34. Comparison of the attenuation of synthetics with a global (BooreEtAl21) and a local (KAAH15) GMM in terms of PGA

It is observed that the simulations remain within $\pm 1\sigma$ of the GMMs. In this figure to plot the GMMs, a generic soil of $V_{s30}=310$ m/s is used. The red dots are the observed PGA at ERC, REF and TER stations where green dots are the PGA values at Site 1 to Site 9. The distance attenuation of the simulated peaks matches more closely with Boore et al. 2021.

CHAPTER 4

GROUND MOTION SIMULATIONS IN ISTANBUL METROPOLITAN

In this chapter, a potential scenario earthquake with $M_w=7.4$ in the Marmara Sea is simulated using a hybrid method to obtain full waveform time histories in southern İstanbul. The hybrid method involves both deterministic and stochastic ground motion simulations to capture both low and high-frequency components of the full waveforms, respectively. What sets this study apart from others is the utilization of site-specific input parameters for the hybrid simulations, enhancing the accuracy of the results.

In this section, the Central Marmara Fault (CMF) is chosen for simulation. This region is a seismic gap that did not produce large earthquakes in the instrumental period, although it experienced devastating earthquakes in the historical period. Different from other simulation studies carried out in İstanbul, local input parameters are chosen herein rather than a global approach, and hybrid analyses are carried out in two stages: first for rock conditions and second for local soil conditions. The aim here is to examine the possible impact of site-specific parameters. For this reason, at 88 selected points in the Zeytinburnu pilot region, rock conditions are assumed along with all source and path parameters with which the hybrid analysis is carried out. Secondly, hybrid analysis is performed at the same 88 nodes using local ground velocity models.

Since there are no large events for validation of simulated motions, GMM's are used to compare and validate the simulated ground motion peaks. Following this, the seismic intensity maps are generated based on local relationships between Modified Mercalli Intensity (MMI) and critical ground motion parameters such as PGA, PGV and SA. This approach, as put forth by Bilal and Askan (2014), is tailored to İstanbul herein. These intensity maps offer valuable perspectives on the

potential repercussions throughout the area under consideration in the event of hypothetical earthquake scenarios.

4.1 Past Studies in the İstanbul Region

Studying earthquake scenarios holds great significance, particularly in seismically active regions such as İstanbul situated along the Marmara Sea Segment of the NAFZ. More recently, stress change generated by the 2019 İstanbul-Silivri earthquakes along the complex structure of NAF in the Marmara Sea. The earthquake causing a non-negligible structural damage at several locations in İstanbul pointed out to the need for scenario earthquake simulations in the area presented in the Figure 4.1 (Şahin et al., 2022).

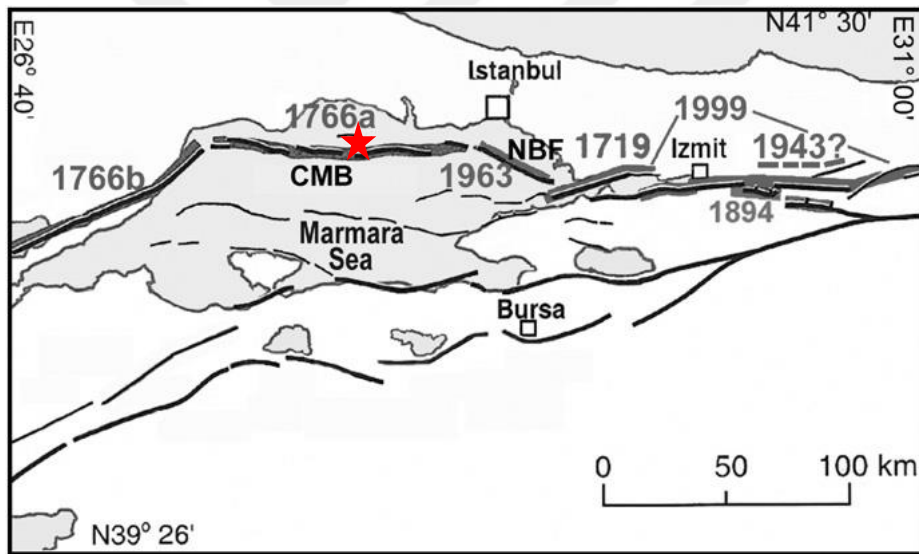


Figure 4.1. Major faults around İstanbul region, and historical earthquakes. Red star shows the epicenter of the 2019 Silivri earthquake (Adapted from Ansal et al., 2009).

In addition, the presence of significant microseismic activity in the Marmara Sea, as observed through recent seismic studies with ocean bottom seismographs, further underscores the importance of studying various earthquake scenarios in this densely industrial area (Sato et al., 2004). Therefore, understanding and assessing

different earthquake scenarios are essential steps toward mitigating and managing seismic risks in the future (Parsons et al., 2000). By conducting comprehensive studies on potential large earthquakes in Istanbul, researchers and authorities can develop effective strategies for earthquake preparedness, response, and recovery, which are critical in ensuring the safety and resilience of the region against seismic activities.

In the existing literature, various ground motion simulations have been conducted near the study region area using deterministic, stochastic, or hybrid approaches. Pulido et al. (2004) employed deterministic (Bouchon, 1981) and semi-stochastic methods (Pulido and Kubo, 2004) to model bedrock ground motions. They explored three distinct rupture scenarios and fault configurations, merging the low and high-frequency constituents of the waveforms within the time domain through the empirical Green's function approach introduced by Irikura (1986). The primary emphasis of this work was centered on the CMF and the NBF.

In Sorensen et al. (2007), a scenario earthquake with $M_w=7.5$ was employed within the Marmara Sea. The objective was to particularly examine the impact of source parameter variations on broadband ground motion recordings. The simulations are carried out at the bedrock level at six selected stations in Istanbul. The researchers employed a hybrid approach that combined the methodologies of Pulido and Kubo (2004), and Pulido et al. (2004) to model the ground motions. One of the selected stations, ATA, is situated close to the study area in the Zeytinburnu district. This thorough investigation seeks to provide insights into how different seismic parameters affect the characteristics of ground motion observed within the Marmara Sea area, specifically focusing on locations close to Istanbul. That research provides valuable insights into seismic hazard assessment and the potential impacts of significant events in the region, contributing to the understanding and managing seismic risks.

In another study by Ansal et al. (2009), the earthquake loss scenarios were studied in terms of buildings damage and casualties in the Marmara Region. For this

purpose, they employed a deterministic-stochastic method (DSM) for their simulations of the CMF with a magnitude of $M=7.4$ with different scenarios on a grid of 180 receivers distributed throughout Istanbul region (both Asian and European sides). They obtained PGA distributions in Istanbul contributing to a general understanding of the seismic behavior and hazard in the region.

In a more recent study by Infantino et al. (2020), simulations were conducted for different earthquakes within an M_w range of 7.0-7.4 in the Marmara region with the Spectral Elements in Elastodynamics with Discontinuous Galerkin (SPEED) open-source code by Mazzieri et al. (2013). A numerical model was created with a 3D velocity model for increased numerical usability, where V_{s30} was set to 400 m/s, and the lowest layer had an S-wave velocity of 250 m/s. Due to the limitations of the selected velocity model, the simulations were performed up to 1 Hz.

Different from the other studies, the input parameters in this thesis for broadband ground motion simulation are site-specific and the method is hybrid to take into account the accuracy of alternative methods in the frequency bands that they are reliable. This study is also not globally oriented but instead focuses on a more specific scale, providing a foundation for site-specific assessment of all buildings of interest and potential urban transformation projects in the pilot region.

Such studies, whether in İstanbul or different cities, will offer accurate alternatives to the commonly used input motions during the design process.

4.2 Study Area

The chosen study area is Zeytinburnu, an industrial, cultural, and residential district located close to the CMF in the southwest of Istanbul as shown in Figure 4.2. Zeytinburnu represents a relatively soft-soil structure, particularly at some locations close to the shoreline. The district's unique geotechnical characteristics make it an essential focus for earthquake research and seismic hazard assessment, as the soil conditions can significantly influence ground shaking and amplification

effects during seismic events. Understanding the seismic behavior of Zeytinburnu is crucial for developing appropriate seismic risk mitigation strategies and ensuring the seismic safety and resilience of the area.

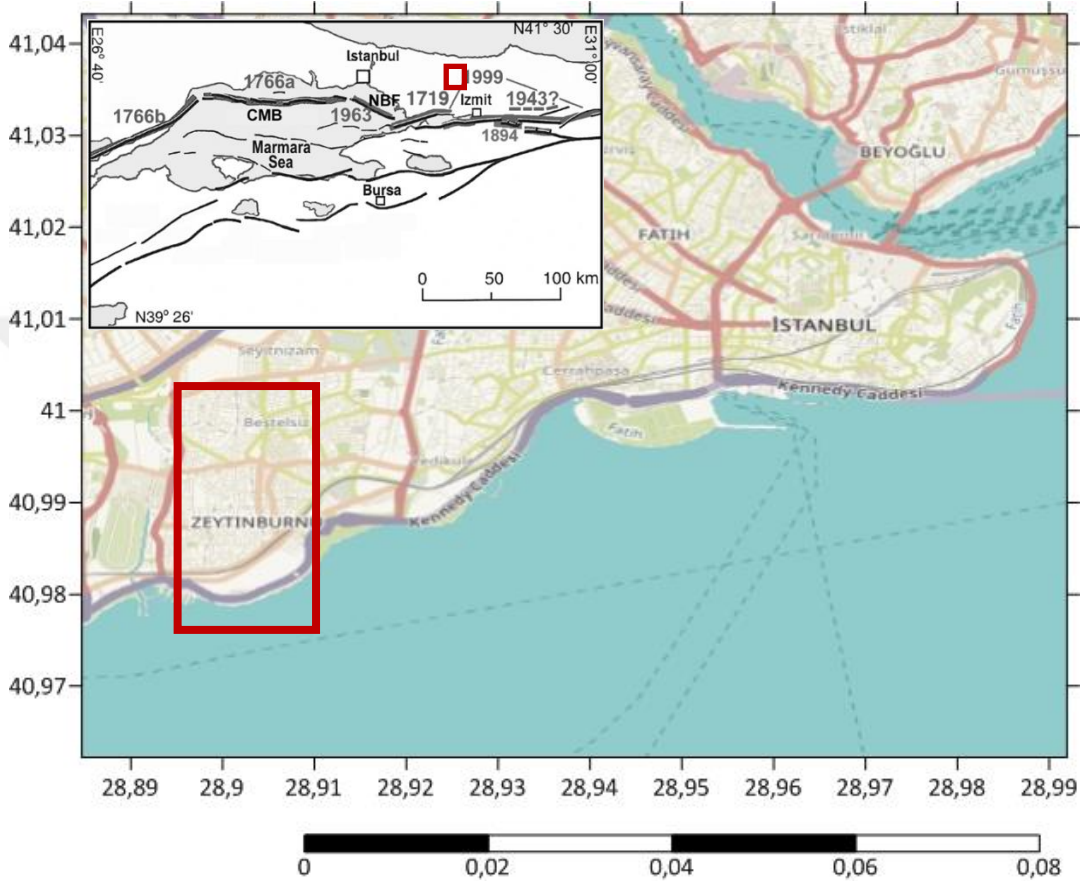


Figure 4.2 : Main panel: The Zeytinburnu area as highlighted by the red box ,upper left panel: Major faults around Istanbul region and historical earthquakes. (Adapted from Ansal et al., 2009).

4.2.1 Geology of the İstanbul Region

Understanding the geological structure of Zeytinburnu is crucial for interpreting the results of hybrid ground motion simulations. The district is distinguished by the presence of Miocene-age geological formations referred to as the Bakırköy and

Gürpınar Formations. The Bakırköy Formation is situated above the Gürpınar Formation, with a thickness ranging from 20-30 m consisting of sequence of interbedded sand, clay, marl, and low-strength limestone. The thickness of the Gürpınar Formation is 40-60 m towards the north parts of the Zeytinburnu. The SPT-N values is presented to understand the structure of the soil in Table 4.1. (Kurtuluş et al., 2011).

Table 4.1. SPT- N values for the formations in Zeytinburnu (Adapted from Kurtuluş et al., 2011)

Soil Properites	SPT-N values
Fill	5-10 s
Alluvial materials	5-25 s
Bakırköy Formation	Up to 7m depth 10-30s , below > 30
Gürpınar Formation	at 4-20 m depth 12-30 s, at 20-40m depth 30 s, below 40 m depth refusal

This complex soil structure significantly influences ground motion and site amplification effects during seismic events. The general geological structure of the Zeytinburnu district is presented in Figure 4.3.

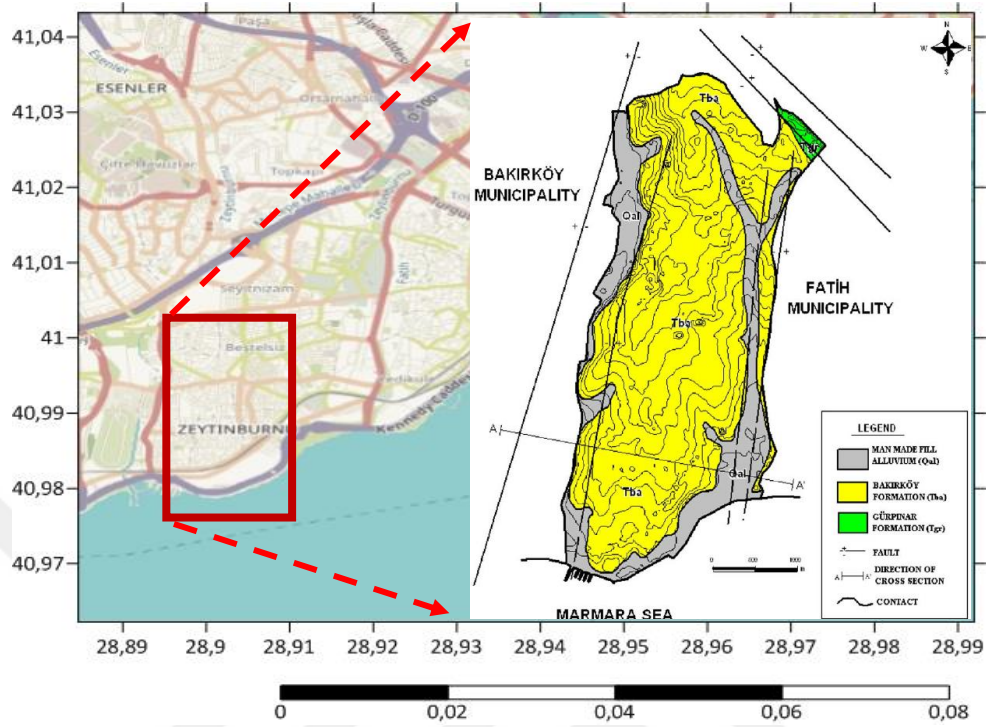


Figure 4.3. Detailed geological map of the Zeytinburnu region. (Adapted from Kılıç et al., 2006).

4.2.2 Seismotectonics of the İstanbul Region

Istanbul is located particularly in seismically active regions situated along the NAFZ. This fault zone extends for about 1500 km and is a significant right lateral strike-slip fault running between the Eurasian plate and the Aegean-Anatolian plate (Ketin, 1966). Throughout history, the town has experienced four devastating earthquakes with intensities ranging from X to XI (1509, 1719, 1766, and 1894) (Ambraseys and Finkel, 1991, Ambraseys and Jackson, 2000, Ambraseys 2000, Pondard et al., 2007, Ansal et al., 2009). Moreover, the NAFZ has been responsible for large events in the last century, including the 1912 Ganos ($M_w=7.4$), the 1999 Düzce ($M_w=7.1$), and the 1999 Kocaeli ($M_w=7.4$) earthquakes (Toksöz et al. 1979; Barka 1996; Stein et al. 1997; Nalbant et al., 1998; Pondard et al., 2007).

The Marmara Sea Segment consists of the following active faults: The CMF and the NBF. These fault lines are situated roughly 20-30 km to the south of the Istanbul city center, as documented by Okay et al. (2000), Le Pichon et al. (2001), and Ansal et al. (2009).

Due to these historical seismic events and recent observations of increasing Coulomb stress in the NAFZ of the Marmara Sea Segment, it is evident that the region is prone to seismic activity (Hubert- Ferrari et al., 2000).

The seismic activity of the Marmara region is presented in Figure 4.4 and the Figure 4.5. During the last 124 years, there were 253 earthquakes occurred with $4.0 < M_w < 7.9$ and 7 earthquakes occurred with $6.0 < M_w < 7.9$ respectively. These figures indicate that on the CMF, there is no earthquake with $M_w \geq 6$ or during the instrumental period.

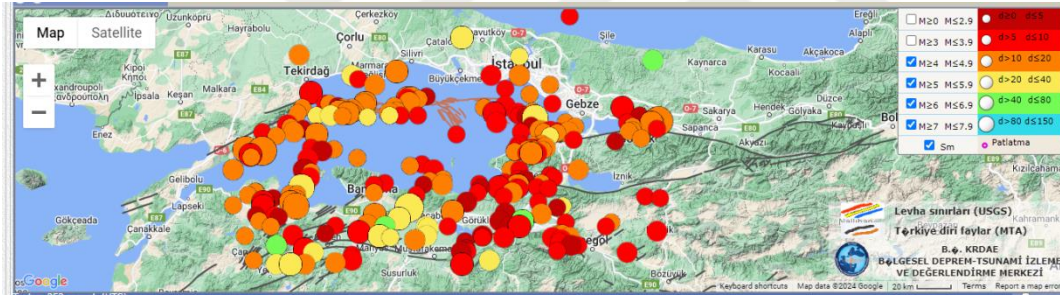


Figure 4.4. Earthquake catalogue which shows the earthquakes during the last 124 years with $M_w=4-7.9$. (<http://www.koeri.boun.edu.tr/sismo/zeqdb/default.asp>)

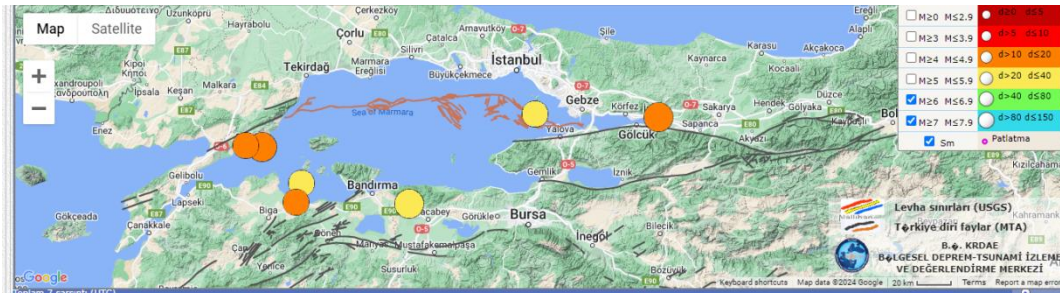


Figure 4.5. Earthquake catalogue which shows the earthquakes during the last 124 years with $M_w=6-7.9$. (<http://www.koeri.boun.edu.tr/sismo/zeqdb/default.asp>)

Therefore, it is crucial to study potential earthquake scenarios in order to manage and mitigate the potential vulnerability due to earthquake hazards in the study area effectively. Understanding the potential impact of large earthquakes in this seismic gap is essential for implementing appropriate measures to enhance the safety and resilience of Istanbul and its surrounding regions.

4.3 Input Parameters for Broadband Ground Motion Simulation in the İstanbul Region

The densely populated metropolis of Istanbul is situated near the CMF segments of the NAFZ. Attention is directed toward broadband ground motion simulations on this fault segment within this thesis due to its close proximity and significant seismic hazard.

In the literature, there are several ground motion simulations focused on the Marmara region. Most of these studies efforts have employed generic soil parameters or solely taken into account the V_{s30} values of the pertinent stations (Pulido et al., 2004; Sorensen et al., 2007; Ansal et al., 2009, Infantino et al. 2020). However, it is crucial to incorporate more detailed and site-specific soil parameters in the simulations.

In this part of the study, the simulations are conducted in two stages for a scenario event of magnitude $M_w=7.4$ on CMF. Firstly, at the selected nodes, rock site conditions are assumed (those results are presented in Appendix A). Secondly, the actual wave velocity profiles are used in selected nodes to understand the effects of the soil properties on PGA and PGV values.

Specifically, we concentrate on 88 nodes in the Zeytinburnu district where an enhanced wave velocity model is accessible (Şahin et al., 2016). Figure 4.6 presents the locations of the selected 88 nodes.

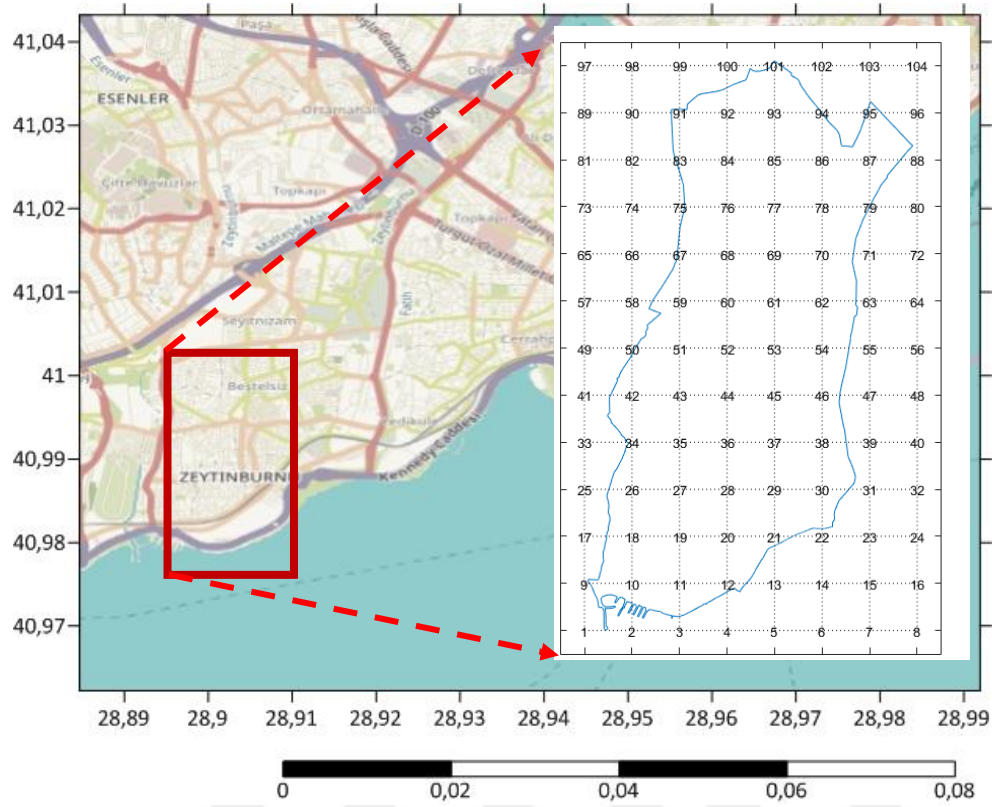


Figure 4.6. Spatial distribution of the selected nodes in the study area (Adapted from Sahin et al., 2016)

It should be noted that out of all these nodes, 16 of them with IDs 1, 2, 3, 4, 5, 6, 7, 8, 13, 14, 15, 16, 22, 23, 24, and 32 are situated in the Sea of Marmara. Consequently, broadband simulations are not performed at these aforementioned nodes.

In this part of the study, a comprehensive soil structure is incorporated, encompassing layer thicknesses alongside their corresponding S-wave velocities and densities. The data concerning the uppermost soil layers is generated following the methodology outlined in Sahin et al. (2016). In Sahin et al. (2016), the construction of a three-dimensional velocity model is based on geotechnical information gathered from diverse sources, including borings, P-wave and S-wave) loggings, as well as passive seismic techniques such as microtremor and refraction

microtremor (ReMi). Figure 4.7 displays the arrangement of nodes, the bedrock level, and geological formations.

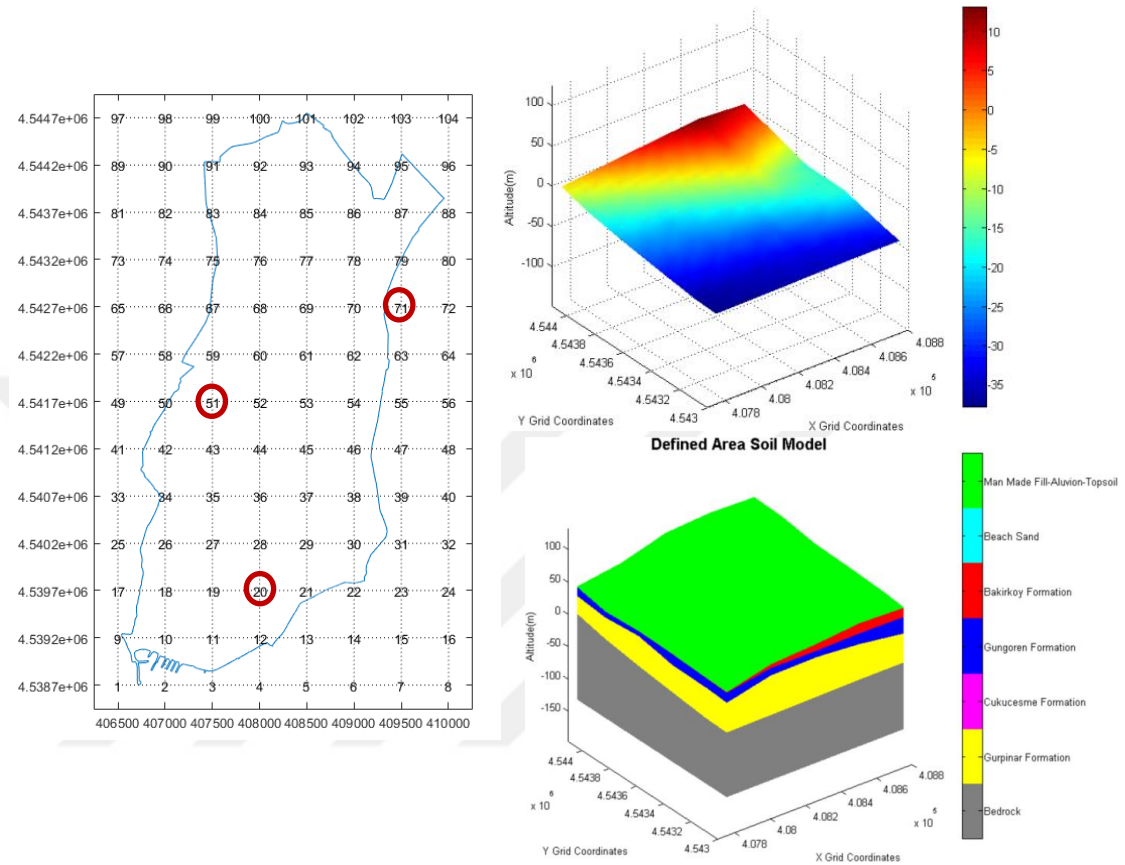


Figure 4.7. Left Side: Spatial arrangement of the selected nodes involved in the simulations. Right Upper Side: Bedrock level of the selected nodes. Right Lower Side: Final 3D soil model. Red circles indicate the selected nodes where simulated motions will be presented. (Adapted from Sahin et al., 2016).

For the deeper soil layers, the model introduced by Pulido et al. (2004) is adapted in this thesis (Figure 4.8).

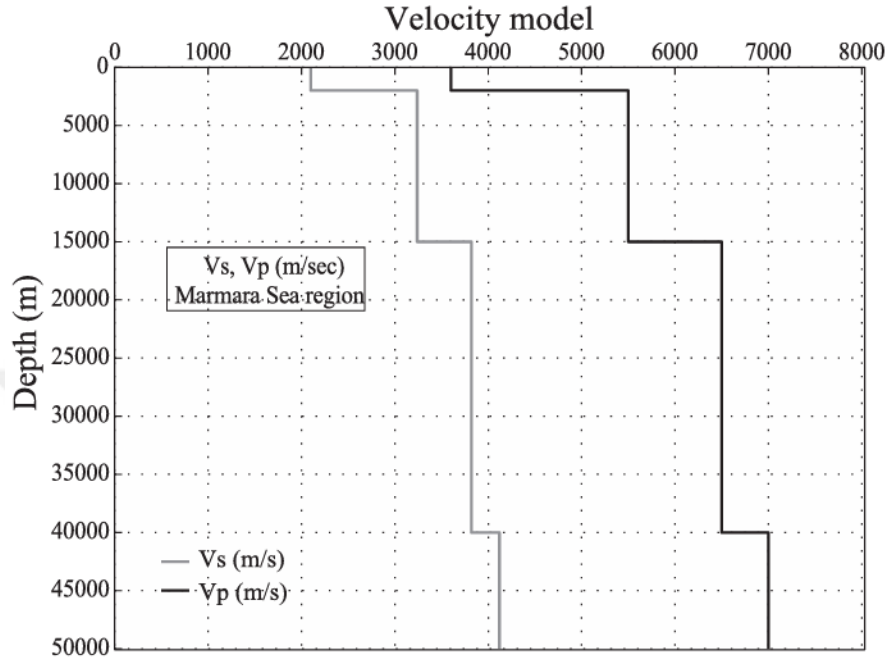


Figure 4.8. The crustal earth model used for the simulations in İstanbul region (Adopted from Pulido et al. (2004))

The source and path input parameters which are validated from previous studies for deterministic and stochastic simulations are presented in Table 4.2.

Table 4.2. Input parameters for the Mw=7.4 earthquake scenario on CMF.

Moment Magnitude		7.4	
Fault Orientation		Strike: 81.5° Dip: 90°	
Fault Dimensions		Central Marmara Fault (CMF)-108 x 16 km	
East end coordinate of the fault		40.89° N-28.87° E	
West end coordinate of the fault		40.80° N-27.59° E	
Epicenter		Located in the center of the fault	
Specific Parameters of Deterministic Ground Motion Simulations		Specific Parameters of Stochastic Ground Motion Simulations	
Velocity profiles at 88 Nodes	Rock condition/ Sahin et al. (2016) for soil condition	Stress Drop Ansal et al. (2009)	100 bars
		Pulsing Area Percentage	50%
Crustal Velocity Model	Pulido et al. (2004)	Duration Model (Hermann, 1985)	$T_0 + 0.05R$
Subfault Dimensions	4.15x 2.67 km	Attenuation Model, Q(f) (Boore, 1983)	$88f^{0.9}$
Crustal Density	2800 kg/m ³	Geometric Spreading Ansal et al. (2009)	$R^{-1} \quad R \leq 30\text{km}$ $R^{-0.4} \quad 30 < R \leq 60\text{km}$ $R^{-0.6} \quad 60 < R \leq 90\text{km}$ $R^{-0.8} \quad 90 < R \leq 100\text{km}$ $R^{-0.5} \quad R > 100\text{km}$
Slip Distribution	Yagi and Kikuchi (2000)	Kappa (κ_0)	Askan et al. (2014)
		Generic Rock Amplifications	Boore and Joyner (1997)

In comprehending the outcomes of ground motion simulations, it is vital to account for the distance between the source and the site in addition to local soil characteristics. Figure 4.9 visually represents the distances from the epicenter to the location of the nodes.

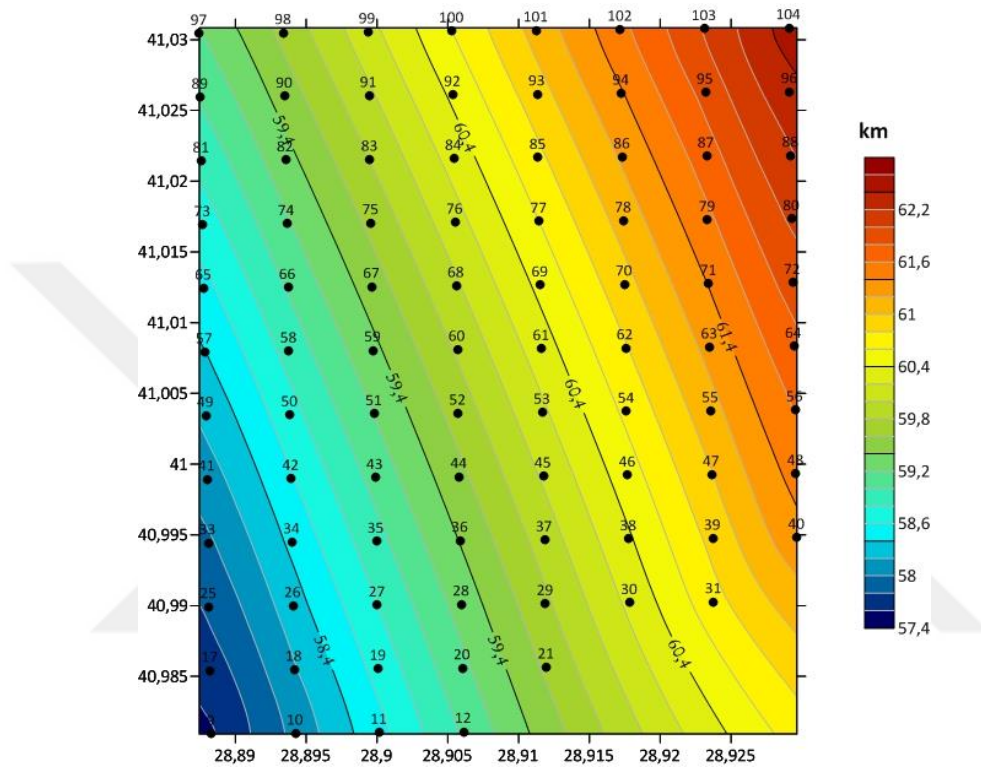


Figure 4.9. The epicentral distances of the nodes.

4.4 Simulation of Scenario Earthquake on Central Marmara Fault with Hybrid Method at the Selected Nodes in the İstanbul Region

The hybrid ground motion simulation results performed at the selected 88 nodes are presented in Figures 4.10-4.12.

Due to space constraints, it is not feasible to incorporate the ground motion time histories for all nodes in this section. Instead, the acceleration time series and FAS are presented for three selected sites, namely Node 20, Node 51 and Node 71.

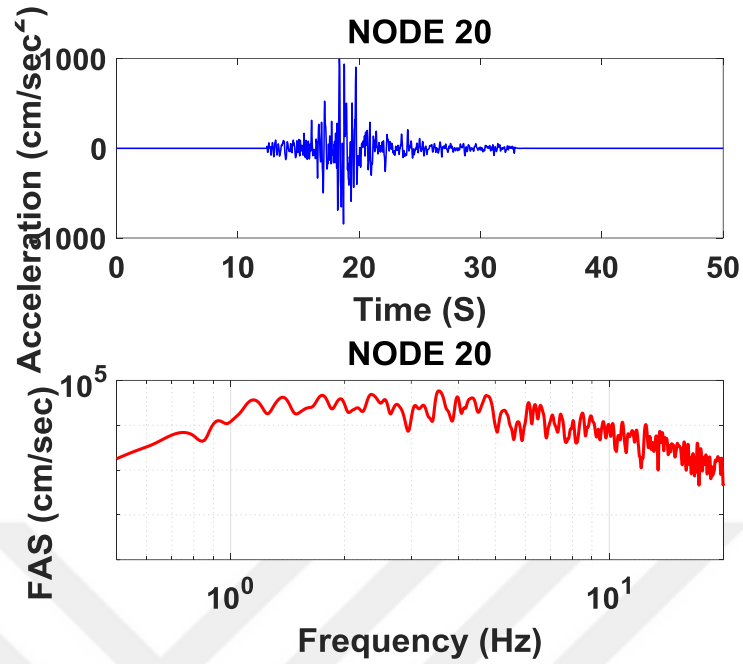


Figure 4.10. Simulation results at Node 20 in the form of corresponding time histories (top panel) and FAS (bottom panel)

A PGA value of 960 cm/s^2 is obtained at Node 20 from the hybrid simulation with the local soil profile at the node (Figure 4.10). On the other hand, a PGA value of 550 cm/s^2 is obtained at Node 20 from the hybrid simulation performed with the rock condition presented in Appendix A.

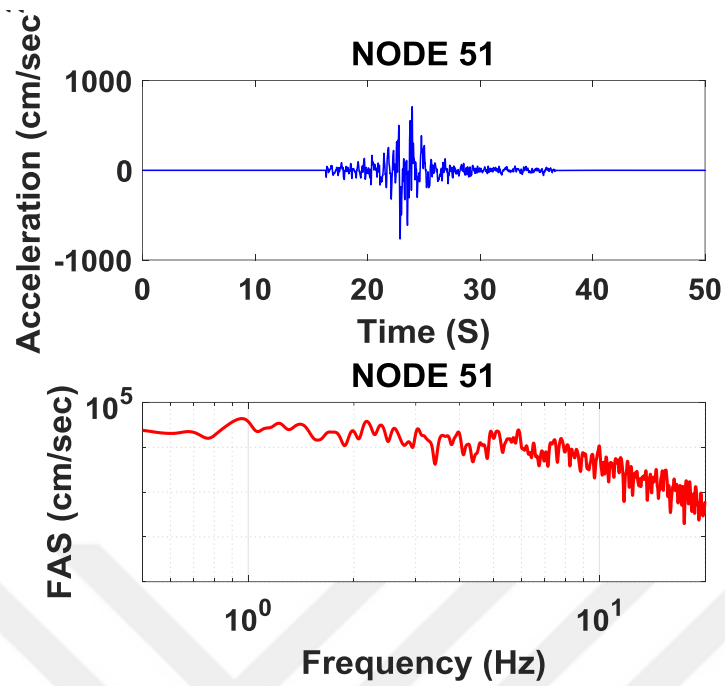


Figure 4.11. Simulation results at Node 51 in the form of corresponding time histories (top panel) and FAS (bottom panel)

A PGA value of 840 cm/s^2 is obtained at Node 51 from the hybrid simulation with the local soil profile at the node (Figure 4.11). On the other hand, a PGA value of 428 cm/s^2 is obtained at Node 51 from the hybrid simulation performed with the rock condition presented in Appendix A.

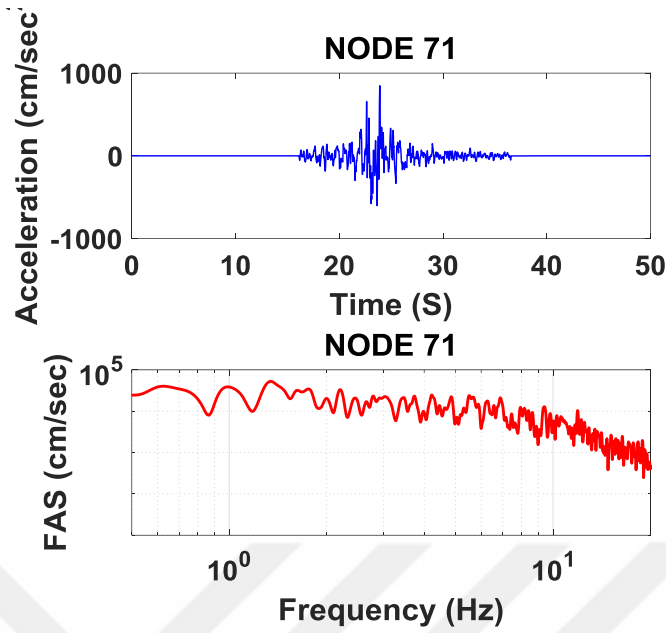


Figure 4.12. Simulation results at Node 71 in the form of corresponding time histories (top panel) and FAS (bottom panel)

A PGA value of 750 cm/s^2 is obtained at the Node 71 from the hybrid simulation with the local soil profile at the node (Figure 4.12). On the other hand, a PGA value of 309 cm/s^2 is obtained at the Node 71 from the hybrid simulation performed with the rock condition presented in Appendix A.

Finally, the ground motion amplitudes at Station 20 surpass those at the other sites, primarily attributed to a low-velocity layer within the soil profile at that location.

Next, Figures 4.13 and 4.14 display the spatial distributions of the PGA and PGV values within the study area for the scenario event ($M_w=7.4$), respectively. The maximum PGA values in the region are estimated to be approximately 1085 cm/s^2 , and the maximum PGV values are around 120 cm/s .

On the other hand, for the simulations performed for rock conditions presented in Appendix A, the PGA values vary between 200 cm/s^2 and 600 cm/s^2 and the PGV value varies between 32 cm/s to 65 cm/s . However, the maximum PGA and maximum PGV values obtained from the site-specific hybrid analyses are 1085 cm/s^2 , and 120 cm/s respectively.

The spatial distributions demonstrate that nodes situated closer to the fault plane and those featuring low-velocity profiles display markedly greater ground motion amplitudes than other nodes within the study area. In particular, the southern segment of the study region encounters high ground motion amplitudes mostly due to the presence of low-velocity profiles. The eastern region also experiences high values due to the close proximity to the earthquake source.

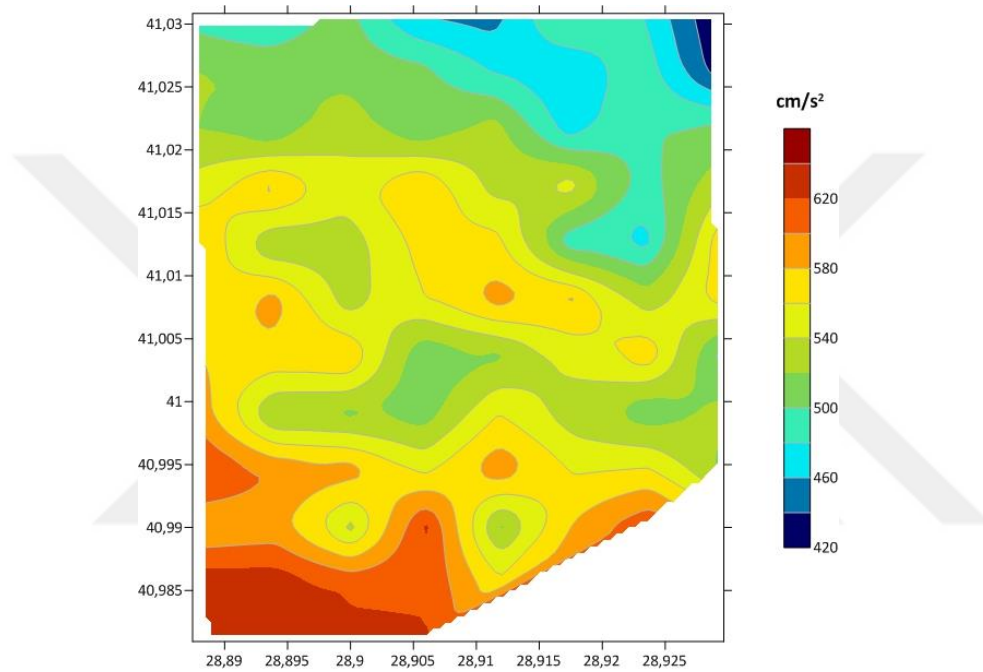


Figure 4.13. Spatial distribution of the simulated PGA values with $M_w=7.4$ in the Istanbul region

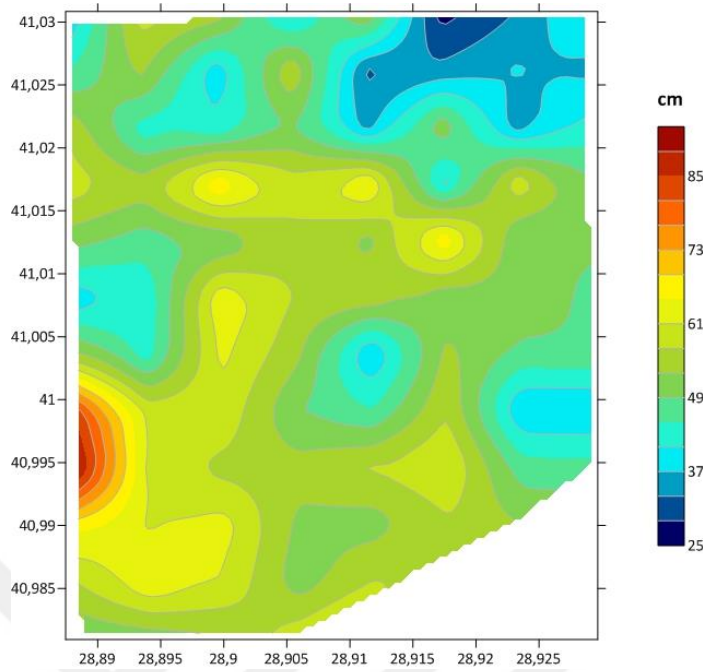


Figure 4.14. Spatial distribution of the simulated PGV values with $M_w=7.4$ in the Istanbul region

4.5 Comparison of Simulated Peak Ground Motion Parameters against Empirical Ground Motion Models

Since there has not been a significant earthquake in the region with a magnitude of 7.4 during the instrumental era, direct validation of the simulation model is not possible. The previously mentioned 2019 Silivri event which occurred on the Kumburgaz segment of NAFZ is neither very close to the area of interest nor a large event to model with the finite-fault assumptions used in this thesis.

However, empirical ground motion models derived with data from other earthquakes can be employed to validate the hybrid ground motion simulations conducted in this study. To achieve this, the attenuation characteristics of 88 simulated records with distance is compared against two selected ground motion models (GMMs). For the comparison, two GMMs are chosen: one global model by Boore et al. (2021) (BooreEtAl21) and one local model by Kale et al. (2015)

(KAAH15). Figure 4.15 and Figure 4.16 present a comparison of the attenuation of simulated ground motions with aforementioned global and local models, in terms of PGA and PGV as well as SA with 5% damping at selected periods, respectively. In this part of the study, to plot the GMMs, a generic soil of $V_{s30}=310$ m/s is used.

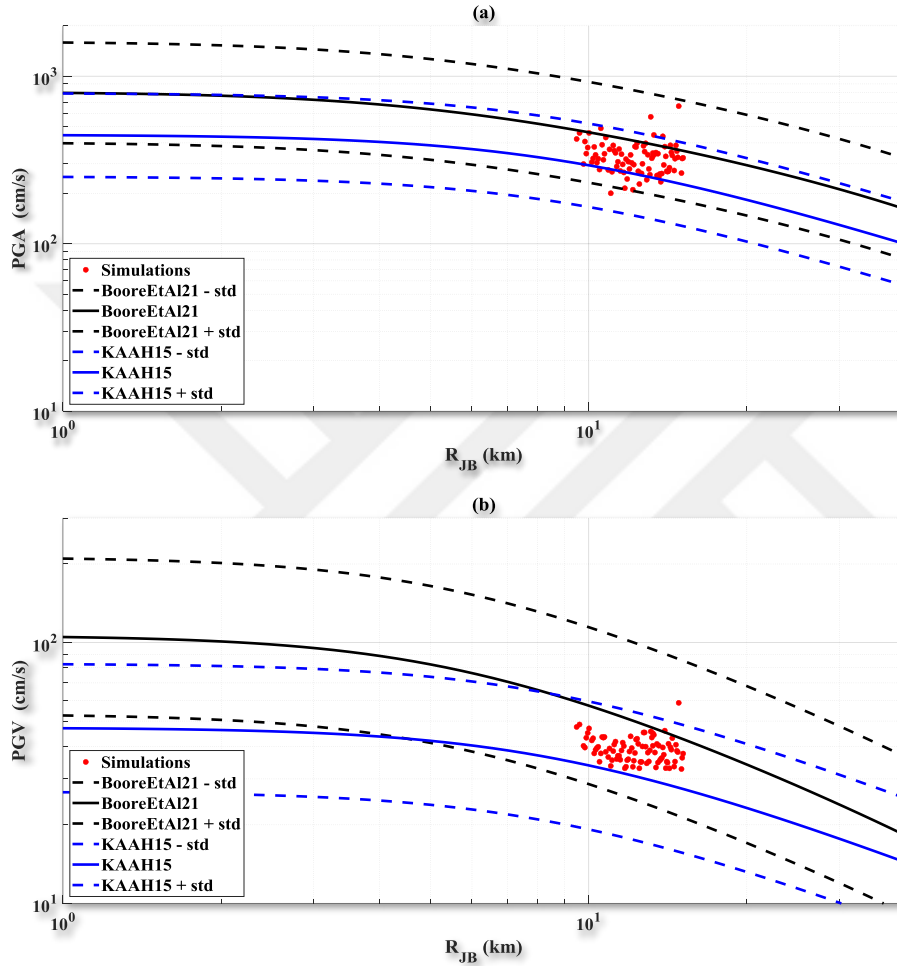


Figure 4.15. Comparison of the attenuation of synthetics with a global (BooreEtAl21) and a local (KAAH15) GMM in terms of (a) PGA, (b) PGV

The distance attenuation of ground motion synthetics matches more closely with Boore et al. (2021) model for PGA and PGV, while it does so with the Kale et al. (2015) model for short and intermediate period-SA values. For long period- SA values, both models are similar and the simulations overestimate medians of both models but still within +1 standard deviation.

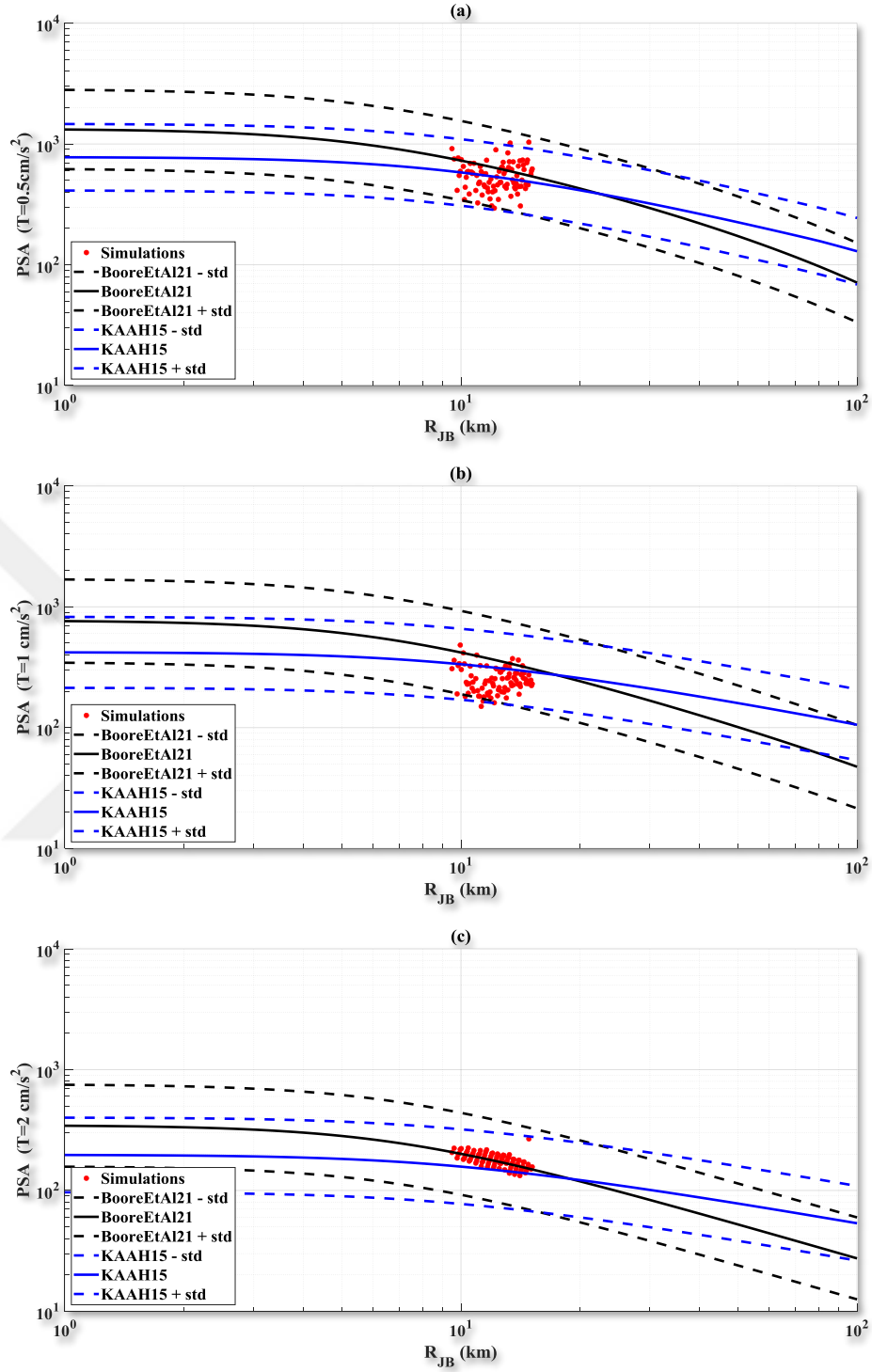


Figure 4.16. Comparison of the attenuation of synthetics with a global (BooreEtAl21) and a local (KAAH15) GMM in terms of (a) SA- $T=0.5 \text{ cm/s}^2$ (b) SA- $T=1 \text{ cm/s}^2$ (c) SA- $T=2 \text{ cm/s}^2$

Overall, the simulated PGA, PGV, and SA with 5% damping at selected periods fall within ± 1 standard deviation of the BooreEtAl21 and KAAH15 models. Although there are some discrepancies between the simulated ground motions and the empirical models, the simulated ground motions generally agree with the predictions of the BooreEtAl21 and KAAH15 models.

4.6 Spatial Distribution of Felt Intensity Values in the İstanbul Region

In the final section, the effects of the scenario earthquake in İstanbul are also assessed in terms of felt intensity, which is evaluated herein using the MMI scale. Seismic intensity maps are prepared with the local correlations between MMI and PGA as well as PGV proposed by Bilal and Askan (2014) for Türkiye.

The following conversion equations from PGA and PGV to MMI, as provided by Bilal and Askan (2014) are used to estimate the intensity levels experienced at different locations in the study area:

$$\text{MMI}=0.132+3.884*\log (\text{PGA}) \quad (4.1)$$

$$\text{MMI}=2.673+4.340*\log (\text{PGV}) \quad (4.2)$$

In Türkiye, where flexible reinforced concrete buildings and rigid masonry structures are prevalent, both PGV and PGV play vital roles in evaluating the felt intensities during earthquakes.

Figure 4.17 illustrates the intensity maps obtained from simulated PGA and PGV values for the region of interest, respectively. The results show that the studied scenario earthquake leads to extreme shaking intensities (IX and above) in the region. Specifically, the Southern part of Zeytinburnu experiences higher MMI values than the Northern part. This observation can be attributed to the fault's location in the South, and softer sites in the southern regions close to the Marmara Sea.

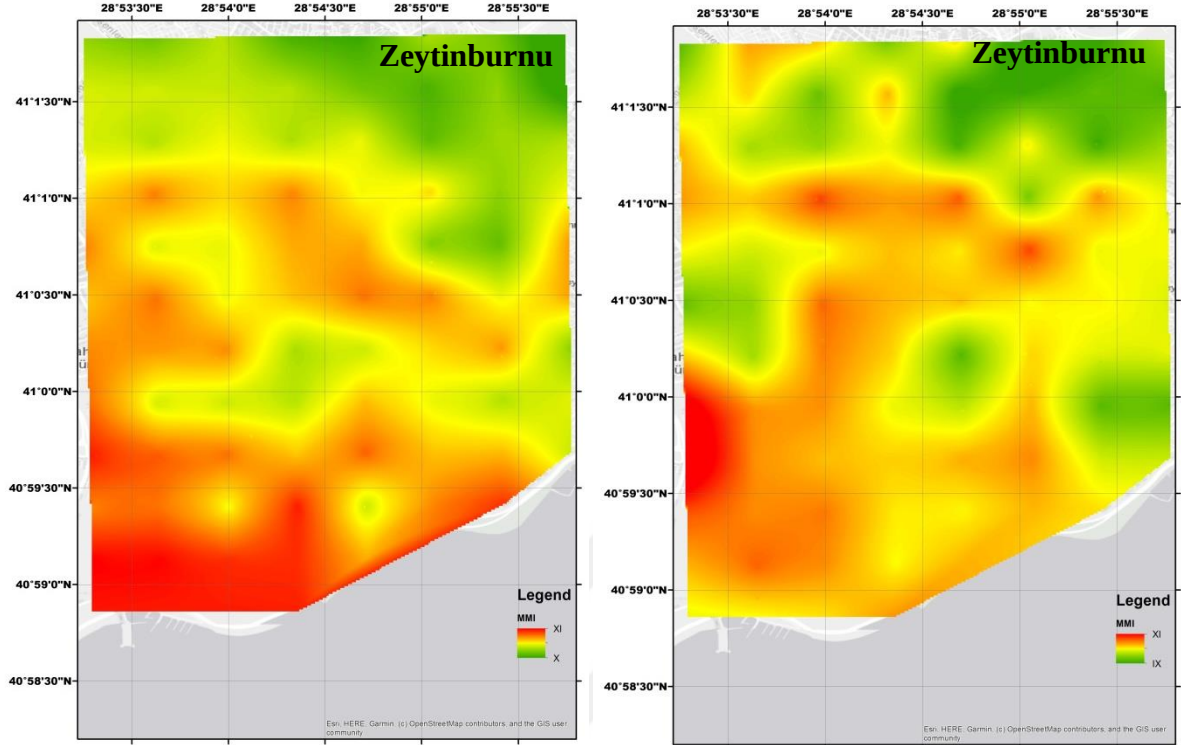


Figure 4.17. Spatial distribution of the simulated MMI values in the Istanbul region using MMI-PGA (left panel) and MMI-PGV (right panel) correlations

It is noted that in some areas, the MMI values obtained from the MMI-PGV correlation are one unit less than those derived from the MMI-PGA correlation. These discrepancies can be attributed to the larger standard deviation of the MMI-PGV relationship compared to the MMI-PGA relationship, as reported in the work of Bilal and Askan (2014). Overall, the anticipated MMI values provide valuable insights into the seismic risk in the region, highlighting the importance of conducting rapid risk evaluation of existing structures.

The spatial distribution of PGAs and felt intensities around the city center clearly indicates the high seismic threat faced by Istanbul. The city's close proximity to the central Marmara fault in the South, and the presence of softer soil conditions both contribute to the increased seismic risk in the region. Considering the potential

poor construction quality at some locations in the area and the anticipated high ground motions, there is an urgent need for structural safety evaluations throughout the region. Extensive validation of the results obtained from this study, as well as similar studies, is crucial. Once thoroughly validated, these findings can be utilized for effective risk mitigation and disaster management strategies. By understanding the seismic hazards and vulnerabilities highlighted in these studies, appropriate measures can be taken to enhance the safety and resilience of the city's infrastructure and communities against potential seismic events. These efforts are essential to safeguarding lives and minimizing damage in the face of earthquakes, ultimately contributing to a safer İstanbul.

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 Summary

In this thesis, strong ground motion simulations are performed in two different areas prone to earthquake hazard in Türkiye. The pilot areas İstanbul and Erzincan are both critical due to historical seismic activity while the former is the industrial and cultural center along with dense population and the latter is a tectonically very hazardous zone with potential basin effects. The goal of this thesis is to determine the influence of local parameters on strong ground motion simulations with hybrid methods, rather than utilizing global input parameters. Along with many others, one of the most important lessons to be drawn after the Pazarcık (Mw:7.7) and Elbistan (Mw:7.6) earthquakes is to consider soil properties not globally but locally. Another lesson is to study potential events in seismic gaps in advance to understand the potential impacts of large earthquakes before they occur. Ground motion simulations with locally derived input parameters help understand past earthquakes as well as future ones in terms of scenarios.

In the first part of this study, different from the previous simulation studies performed in the Erzincan basin, the 1992 Erzincan earthquake is simulated with the hybrid ground motion technique at the recording stations in order to validate the input source, path and site parameters. The comparisons are made both visually and quantitatively through misfit functions computing the differences between recorded and simulated ground motions. Consistent with the objectives, local soil profiles are established within Erzincan basin at nine locations. The inversions are performed with the MMSPAC method based on microtremor measurements. The results are presented

in terms of 2.D soil velocity profiles as well as Vs10, Vs30, Vs100 and Vs300 values. The wave velocity models in the North-South and East-West directions confirm the basin structure of the Erzincan city center. The nine locations are then used as nodes for blind simulations of the 1992 Erzincan event. The simulations results are compared against ground motion models.

After the validation of the simulation method in Erzincan, a second application of the method is performed in this thesis. A simulation was conducted for a seismic event of magnitude Mw: 7.4 on the Central Marmara Fault, which could affect the Istanbul metropolitan area, located on a seismic gap. Zeytinburnu district in Istanbul was selected to conduct hybrid simulations. The hybrid simulation carried out in Zeytinburnu was designed in two stages: In the first stage, all sites are assumed as rock and hybrid analysis were performed (presented in Appendix A). In the second stage, using the same source and path input parameters are used, the analysis is made using detailed velocity structure of 90 different points. The main purpose here is to observe the changes in the ground motion fields with varying velocity structure.

Finally, the simulated ground motion records for selected sites in İstanbul are presented in terms of FAS and time histories. Since there has not been a seismic event of a magnitude close to the simulated earthquake during the instrumental period, validations are conducted here in terms of comparisons of simulated data with both local and global ground motion models. Intensity and ground motion distribution maps of the scenario event are also presented.

5.2 Conclusion

The main findings and conclusions derived in this thesis are given next. From the simulations in Erzincan Basin, following conclusions are derived:

- It is crucial to meticulously choose local site parameters, including kappa and velocity structures in both the shallow and deeper layers of the soil in order to ensure ground motion simulations. This is because when both shallow and deeper parts of the soil are more intricately defined, simulations can achieve a more successful representation of both low and high-frequency contents.
- The significance of hybrid ground motion simulations lies in the combination of low and high frequencies, allowing the broadband frequency range to encompass the essential structural frequency range. Thus, the hybrid results perform better than only stochastic results in this thesis.
- The southern parts of Erzincan are found to be located on much softer soils while the northern sites involve relatively stiffer soil layers. This finding is also consistent with the local topography indicating hills and mountains in the North of the city center.
- The misfit values are calculated for quantitative comparisons at the ERC, REF and TER stations. The broadband simulations in all E-W, N-S and U-D directions give more accurate results when compared to only stochastic simulations in terms FAS with a maximum reduction in the error term by 60%.
- Examining the results of the hybrid ground motion simulations conducted at 9 points where velocity profiles are derived, higher ground motion amplitudes were obtained at Site 1 and Site 3, which exhibit softer soil properties. On the other hand, despite a higher V_{S30} value at Site 2, slightly elevated PGA values were obtained due to its close proximity to the epicenter of the 1992 earthquake.

Based on the simulations in İstanbul region, following conclusions are derived:

- The distribution of simulated peak ground motion amplitudes for the scenario event and the corresponding felt intensities around the city center

demonstrated the significant seismic hazard in Istanbul due to its proximity to the Central Marmara Fault and the presence of softer soil conditions. Particularly the southern coast of the city is anticipated to experience higher ground motions due to the source-to-site distances and local site effects.

- Considering the poor construction quality at some locations in the city and the anticipated ground motions, thorough structural safety evaluations must be urgently performed in the area.
- Once extensively validated at other sites in the city, the outcomes of this study, along with similar research involving different scenarios, can be utilized for risk mitigation strategies and disaster management planning in Istanbul.

5.3 Future Recommendations

Several modeling assumptions are made in this study in addition to inherent limitations of the approaches which require further exploration in future investigations. The associated recommendations are as follows:

- Studying broadband ground motion simulations in other regions with various seismotectonic characteristics is of utmost importance. Such a study would enhance and further validate the findings presented in this thesis.
- Exploring different scenarios for both the Erzincan and Istanbul regions due to their seismic hazard levels is recommended. Ground motion simulations for Istanbul being located on a seismic gap are vital in assessment of potential future earthquakes.
- Improving the accuracy of simulations, such as transitioning from hybrid simulations with 1D earth models to full 3D simulations holds the potential to yield more accurate results. This is particularly true for Erzincan region located on a basin. Full basin effects can only be studied with 3D wave propagation approaches in the future.

- Conducting detailed extensive fieldwork and models based on the field data can help to obtain more realistic regional parameters, including kappa, quality factors, and site amplifications. Incorporating such regional models directly enhances the accuracy of ground motion simulations.





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APPENDICES

A. Application of the Simulations for Rock Conditions

In this section, the potential M.7.4 Istanbul earthquake at the same 88 points is performed for rock condition, which was simulated using the detailed site-specific soil properties in Chapter 4. The main purpose here is to prove the effects of the site-specific parameters. When the results are examined, PGA and PGV values are low in hybrid analyses performed by ignoring the soil velocity structure. This situation may increase damage and loss during the potential Istanbul earthquake. For this reason, all analyses are always carried out using site-specific soil parameters.

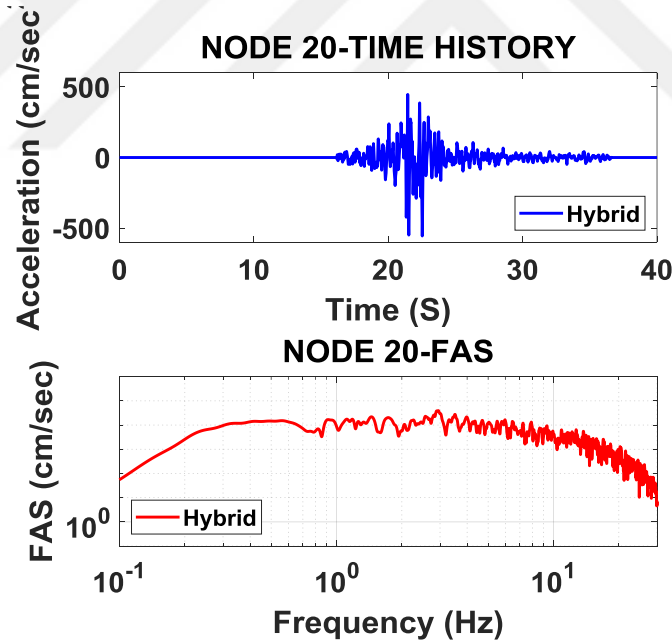


Figure A.1. Simulation results at Node 20 in the form of corresponding time histories (top panel) and FAS (bottom panel)

The PGA value at the selected Node 20 is 550 cm/s². In Chapter 4, the PGA value obtained from the site-specific analysis is 960 cm/s².

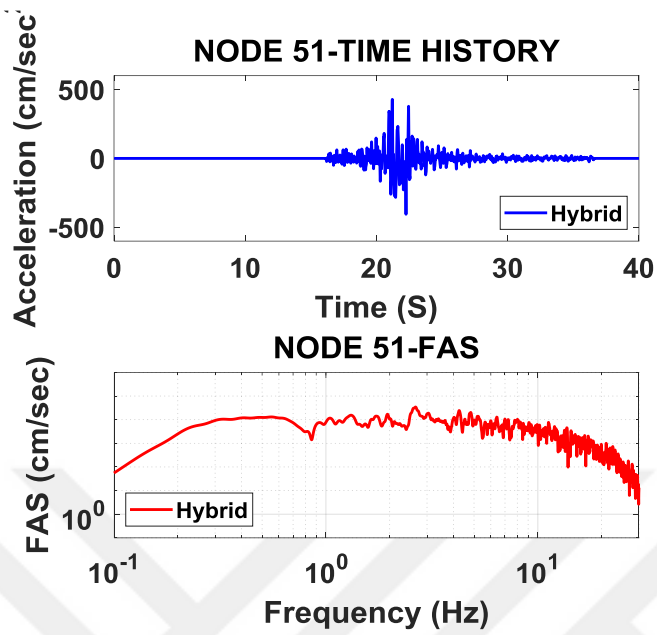


Figure A.2. Simulation results at Node 51 in the form of corresponding time histories (top panel) and FAS (bottom panel)

The PGA value at the selected Node 51 is 428 cm/s². In Chapter 4, the PGA value obtained from the site-specific analysis is 840 cm/s².

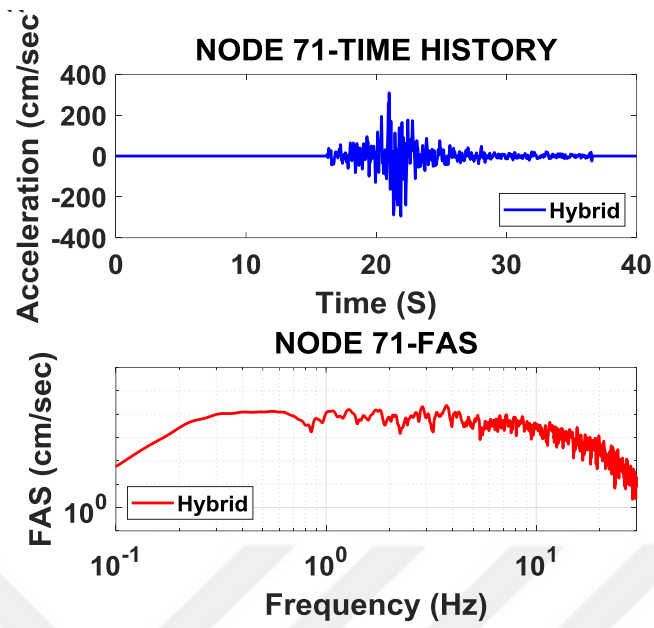


Figure A.3. Simulation results at Node 71 in the form of corresponding time histories (top panel) and FAS (bottom panel)

The PGA value at the selected Node 71 is 309cm/s². In Chapter 4, the PGA value obtained from the site-specific analysis is 750 cm/s².

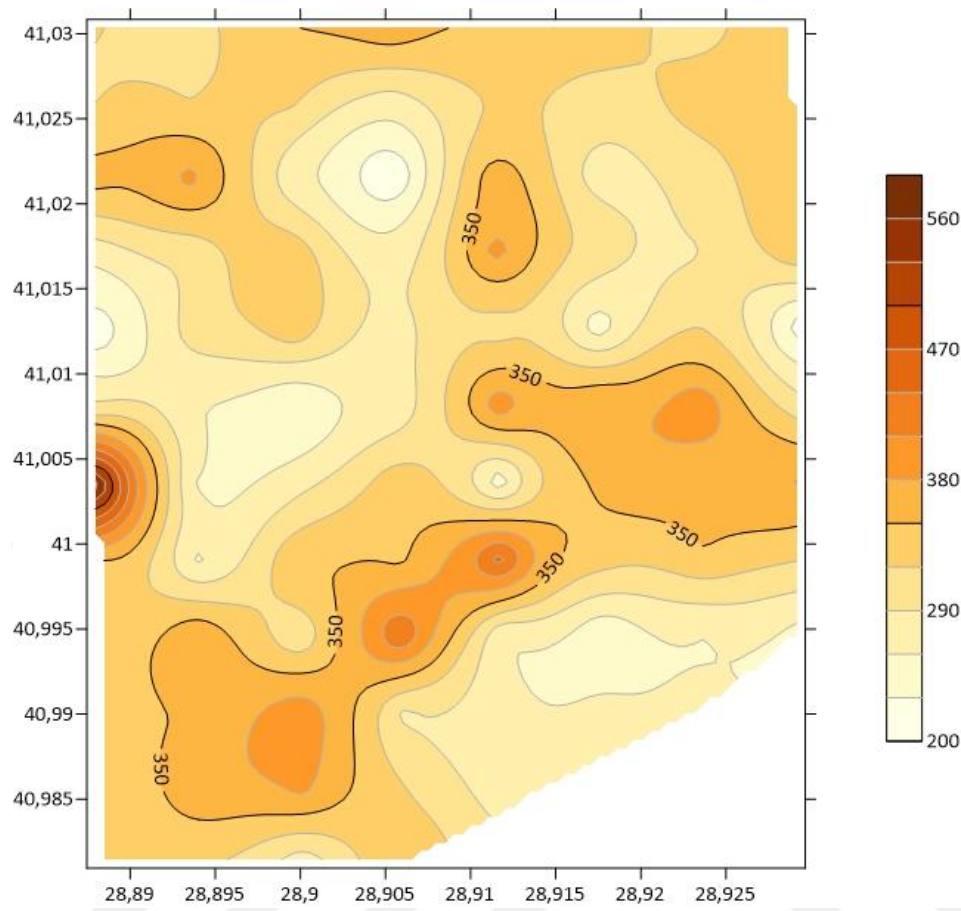


Figure A.4. Spatial distribution of the simulated PGA values with $M_w=7.4$ in the Istanbul region

Figure A.4 displays the PGA values within the study area for a scenario event with magnitude $M_w=7.4$ for rock conditions. The PGA value varies between 200 cm/s^2 to 600 cm/s^2 . However, the maximum PGA values obtained from the site-specific hybrid analyses is 1085 cm/s^2 .

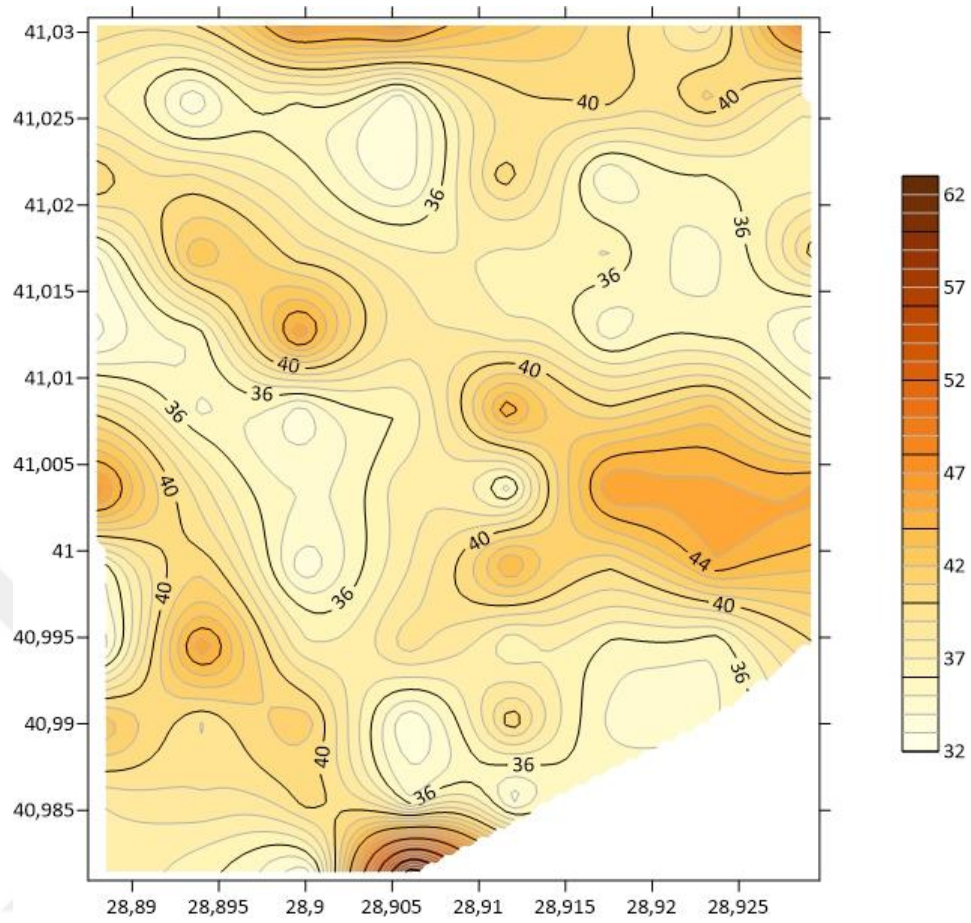


Figure A.5. Spatial distribution of the simulated PGV values with $M_w=7.4$ in the Istanbul region

Figure A.5 displays the PGV values within the study area for a scenario event with magnitude $M_w=7.4$ for rock conditions. The PGV value varies between 32 cm/s to 65 cm/s. However, the maximum PGV values obtained from the site-specific hybrid analyses is and 120 cm/s.



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