

SEISMIC RESPONSE ANALYSIS OF DIFFERENT SOIL TYPES WITH EQUIVALENT LINEAR ANALYSIS METHOD

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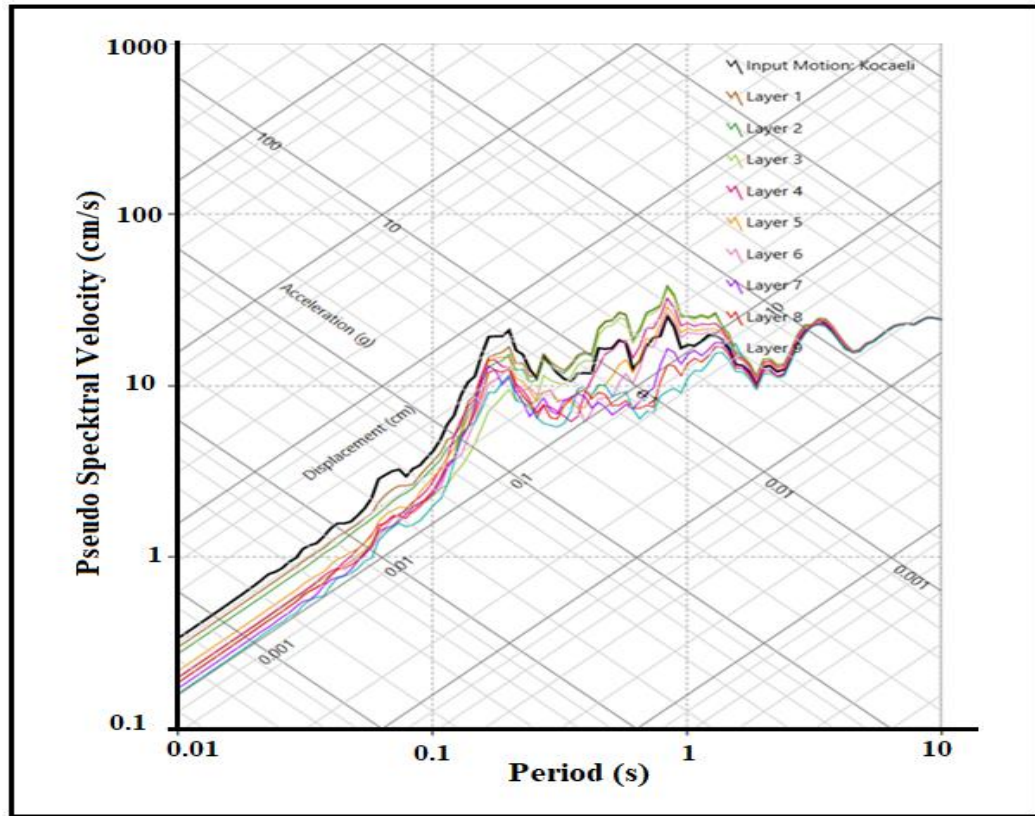
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Highlights

- Seismicity of the Kocaeli earthquake record in a region soil profile.
- The “Acceleration Velocity-Displacement-Time” graphs were defined.
- The seismicity of the region was investigated.

Graphical Abstract



Pseudo Spectral Velocity-Period Graph



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ABSTRACT: In this study; With DEEPSOIL v7 software, seismic behavior analyzes of a region were made with 1D, “Equivalent Linear Analysis Method”. The method that offers the closest solution to the reality in the solution of engineering problems is the nonlinear solution method. However, it is very difficult to obtain and analyze the necessary parameters. For this reason, this method was chosen, which is not difficult to solve and gives the closest results to the nonlinear solution. Analyzes were made in the direction of whether the soil profile will absorb the earthquake in the event of a possible earthquake or, on the contrary, will increase the earthquake effect and transmit it to the building foundation. As a result of the analysis, the peak acceleration values were calculated and defined with acceleration-time-depth graphs. In this study, in which the seismic responses of different types of soil structures were investigated, it was observed that the soil structure was non-linear, the shear wave velocity value was an important parameter in determining the dynamic behavior of the soil, and the damping ratio of the soil increased with the increase in the shear wave velocity value.

Keywords: Earthquake, Equivalent Linear Analysis Method, Shear Wave Velocity

1. INTRODUCTION

Earthquake is a natural event that needs to be investigated and involves uncertainties. For this reason, it is extremely important to carry out soil studies in the areas where buildings are planned to be built accurately and in detail. In addition, the obtained soil parameters and the general structure of the soil need to be examined in terms of seismicity. In this study, DEEPSOIL software was used to investigate seismicity [1]. In this direction, many researchers have seismologically evaluated different regions and soil structures using numerical and experimental methods. To give examples of these studies:

Researchers conducted seismic analyses for the Fatih and Eminönü districts of İstanbul and evaluated the region through mapping operations [2]. One- and two-dimensional dynamic response analyses were performed by examining the seismicity of a region in Zeytinburnu district with different software. As a result of the analyses, surface accelerations and spectral acceleration values were compared by taking into account the surface topography [3]. Some researchers have conducted microzonation studies in Bakırköy district of İstanbul province. Using the data obtained from drilling and seismic studies carried out in the region, spectral acceleration distribution was defined with graphics and microzonation maps were prepared against earthquake hazard with different correlations [4].

In a study prepared the change of maximum soil acceleration value (PGA) depending on shear wave velocity was investigated. The effect of the change of shear wave velocity (V_s) on the maximum soil acceleration value (PGA) at varying depths was interpreted with graphics. As a result of the analysis, it was observed that as the shear wave velocity V_s increased, the damping effect against the earthquake also increased. In addition, it was determined that the equivalent linear analysis method gave faster results compared to the nonlinear analysis method [5].

Researchers have performed dynamic response analyses using the equivalent linear analysis method and investigated the seismicity of the regional soil using the soil parameters of a part of Eskişehir province

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and the Kocaeli earthquake records [6]. Some researchers have also performed one-dimensional dynamic analyses of an engineering fill compacted with high energy using drilling data and eleven different earthquake records. As a result of the analyses, surface response spectra were plotted graphically [7]. A researcher examined the effect of topographic features on the dynamic behavior of the soil using one-dimensional and two-dimensional analyses [8]. In addition, researchers examined the seismicity of the Hamidiye region in Aksaray province. According to the analysis results, the soil amplification ratios were found to be between 0.6-0.8. In line with this information, it was concluded that the soil of the region was in the "B medium hazard level" class [9].

The seismicity of a region with a homogeneous sandy soil structure was also investigated and the soil amplification rates were determined. The shear wave velocity values of the regional soil varied between 587 m/sec and 622 m/sec. As a result of the analysis: the peak acceleration value, which is an important parameter in structural design, varied between 0.3g and 1g. It was also observed that the maximum peak acceleration value occurred in 0.2 seconds. It was concluded that the soil layers would not amplify the earthquake during an earthquake and would create a damping effect [10], [11], [12] [13].

1.1. Definition of Seismic Parameters

Earthquake is an important natural event whose time and intensity are unknown. It is the reflection of the energy that occurs as a result of the movement of the plates on the earth. Earthquake is a result of dynamic forces. There are some characteristic earthquake parameters used to determine the effect of dynamic forces on the soil and structure. These seismic parameters are: earthquake amplitude, earthquake frequency and earthquake duration (period).

1.2. Earthquake Amplitude

The records of earthquake motion in the time domain are defined by the amplitude parameters: acceleration, velocity and displacement. The intensity of the earthquake is expressed by drawing graphs of the amplitude parameters depending on time (period). One of the most decisive parameters used in determining the earthquake amplitude is PGA. PGA is the maximum horizontal soil acceleration value. To summarize briefly, PGA is the ground acceleration value. At the same time, PGA provides information about the destructiveness of the earthquake occurring.

1.3. Earthquake Frequency

In order to determine the earthquake frequency, the general properties of dynamic forces must be known. Therefore, Fourier spectra and Response spectra must be defined. Response spectra express the effect of the earthquake on the surface at varying frequencies, while the Fourier spectrum expresses the frequency content of the earthquake [14]. Response spectrum has an important effect in structural design.

1.4. Earthquake Duration

As the duration of the earthquake increases, the destructive effect of the dynamic forces that occur at the time of the earthquake increases. Therefore, the duration of the earthquake is one of the most important factors affecting the intensity of the earthquake. Because the increase in earthquake acceleration also increases the damage caused by earthquake.

2. SOIL RESPONSE ANALYSIS TO SEISMIC FORCES

Earthquake acceleration progresses between the soil layers from the main rock to the surface and reaches the foundation of the structure. Dynamic forces can have different effects on the surface and the main rock. The reason for this is that the earthquake effect can be reduced between the soil layers and can

be damped until it reaches the surface, or it can reach the surface and increase the magnitude of the earthquake by increasing its effect with logarithmic loading. Therefore, determining how the soil will behave is possible with soil behavior analysis.

As shown in Figure 1, earthquake acceleration continues from the bedrock to the foundation of the structure along the soil layers. It is seen in Figure 1 (a): the soil profile consists of A, B and C. The earthquake coming from bedrock (2) increased the earthquake effect logarithmically until it reached the surface of (1) and therefore the possible earthquake, intensity increased. In Figure 1 (b), the opposite effect occurred and the earthquake acceleration coming from the bedrock was damped while passing between the soil layers X, Y and Z and the destructiveness of the earthquake was reduced. In Figure 1, the acceleration-period graphs are defined for points (1) and (2). This situation shows that the earthquake effect may differ depending on the soil structure.

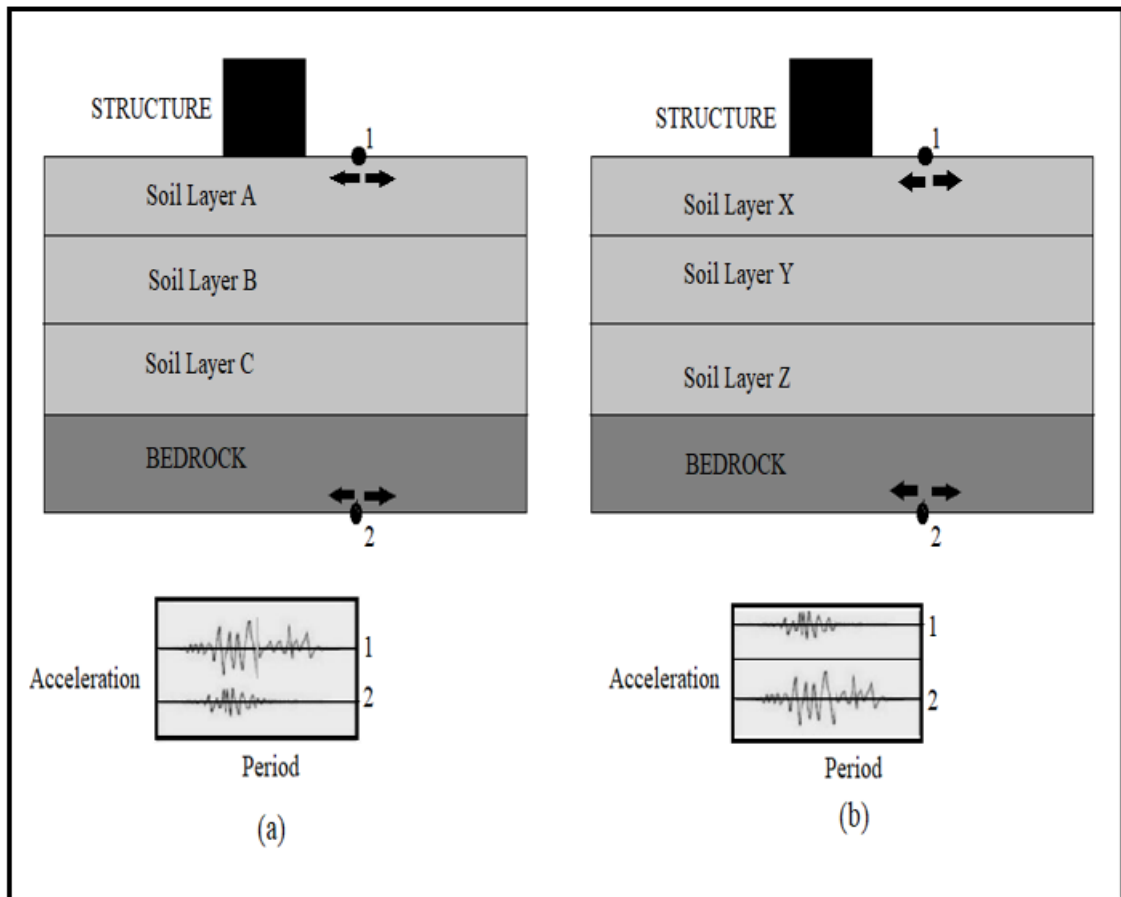


Figure 1. The types of behavior that the soil profile shows in response to the earthquake acceleration are (a) The earthquake acceleration coming from the main rock (2) cannot be damped and its effect increases and reaches the soil surface numbered (1), (b) The earthquake acceleration coming from the main rock (2) damps through the soil layers and reaches the soil surface numbered (1)

To summarize: as shown in Figure 1, the earthquake acceleration coming from the main rock progresses through the soil layers and reaches the foundation of the structure and from there to the structure. The acceleration value can be damped between the layers, or its effect can continue to increase. For this reason, it is necessary to determine in advance how the soil will behave against dynamic effects during an earthquake. Soil behavior analyses can be performed in one-dimensional, two-dimensional and three-dimensional. Two dimensional and three-dimensional analyses are preferred especially when the importance of the structure is high and the surface geography is different. As a method: Equivalent Linear analysis and Nonlinear analysis methods are used.

2.1. One-Dimensional (1D) Analyses

During the movement of the earth's layers, the waves emitted from the fault fractures that occur are distributed in all directions. They are reflected and refracted in the geological surface units they advance. One-dimensional soil response analyses are based on the assumption that the soil profile boundaries are horizontal, and that this situation is caused by earthquake waves coming vertically from the main rock. In one-dimensional analyses, the Theory that the soil and main rock surfaces continue horizontally infinitely is adopted [3]. The formulations developed in one-dimensional soil response analyses can be explained as follows:

$$\rho \cdot \frac{\partial^2 u}{\partial z^2} = \frac{\partial \tau}{\partial z} \quad (1)$$

The equation parameters defined in equation (1) are, ρ : Density, τ : Shear stress, z : Soil length, u : Displacement amount. The relationship between shear stress and shear strain can be defined as follows.

$$\tau = G\gamma + \eta \frac{\partial \gamma}{\partial t} \quad (2)$$

In equation (2), G : shear modulus, η : Viscosity, γ : Shear strain. According to equation (2), equation (1) can be rearranged as follows to obtain equation (3).

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial z^2} + \eta \frac{\partial^3 u}{\partial z^2 \partial t} \quad (3)$$

Against dynamic effects, soil response analyses are performed to investigate the effects of earthquake waves propagation through the soil surface. Analyses are based on two main principles. Soil response is examined with "Equivalent Linear Soil Response Analyses" in the frequency domain and "Nonlinear Soil Response Analyses" in the time domain.

Many researchers have shown that analyses performed in the frequency domain provide practical and easy solutions [15], [16], [17]. However, in some cases, the structure of the earth does not allow the "Equivalent Linear Analysis Method". For this reason, the "Nonlinear Analysis Method" is preferred [18].

2.1.1 One-dimensional equivalent linear analysis method:

It creates the transfer capacities of the analyses stored in the frequency definition area. With the transfer force, shear regression, shear deformations, acceleration and velocity values are determined. With the transfer calendar, it is possible to determine the rate at which the dynamic acceleration from the bedrock is magnified and at which rate it is damped between the soil layers [14].

2.1.2 One-dimensional nonlinear analysis method:

Engineering problems are generally nonlinear in structure. Therefore, the most accurate solutions close to reality can be obtained with nonlinear analysis methods. A nonlinear behavior structure occurs between soil layers under cyclic loads. In addition, the soil stress-dependent deformation behavior is not linear. Therefore, nonlinear solutions offer more realistic solutions in determining the behavior of the soil against dynamic effects. However, the parameter values that enable this solution method cannot be reached in every case [18], [19]. The equivalent linear analysis method adopts the principle that soil layers have an equal and constant shear modulus and damping ratio in the horizontal and infinite directions. In the nonlinear analysis method, the shear modulus and damping ratio of each layer in the soil profile are calculated differently.

It has been shown by many studies that it is correct to decide according to the soil structure in the selection of “Equivalent Linear Analysis Method” and “Nonlinear Analysis Method” [16], [20]. In cases where parameter selection and analysis are not easy, “Equivalent Linear Analysis Method” should be preferred. However, in cases where repetitive loads are very large, “Nonlinear Analysis Method” should be adopted because it gives more realistic results.

2.2. Two-Dimensional (2D) Soil Response Analyses

One-dimensional analyses are a suitable analysis method for many problems encountered in geotechnical engineering. Because in many cases, the soil material properties are horizontal, parallel or have a very slightly inclined structure. This situation allows one-dimensional (1D) analyses. However, in many problems encountered in practice, the one-dimensional wave propagation assumption does not reflect a result close to reality. For this reason, two-dimensional analyses should be preferred in cases where inclined, irregular surfaces and rigid, network structures or walls and tunnels are considered important [3].

In addition, in general engineering problems, two-dimensional analysis solutions are selected when one dimension is considerably larger than the other.

2.3. Three-Dimensional (3D) Soil Response Analyses

Three-dimensional analyses are used when one-dimensional and two-dimensional soil response analyses are not possible. It is generally preferred in cases where changes in soil conditions are observed in three dimensions. Three-dimensional analyses can be performed with both Equivalent Linear and Nonlinear analyses using the dynamic finite element method.

3. MATERIAL AND METHODS

In this study, the shear wave velocity unit volume weight values and layer thicknesses were taken into account and the behavior of the Kocaeli earthquake records in 1999 was analyzed and examined in the event of a possible earthquake. The layer properties of the soil in which the deformation of the soil against the earthquake acceleration was investigated are presented in Table 1. The properties of the bedrock are given in Table 2.

Table 1. Soil layer properties defined in the analysis system

Soil Layer Number	Layer Name	Layer Thickness (m)	Unit Weight (kN/m ³)	Shear Wave Velocity (m/s)
1	Layer 1	5	18.5	350
2	Layer 2	5	18.5	345
3	Layer 3	8	19.0	304
4	Layer 4	7	19.0	357
5	Layer 5	6	19.0	410
6	Layer 6	20	19.5	450
7	Layer 7	7	19.5	470
8	Layer 8	12	20.0	515
9	Layer 9	38	20.0	585

Table 2. Bedrock fetures of the area

Soil Layer Number	Forward Analysis	Unit Weight (kN/m ³)	Shear Wave Velocity (m/s)	Damping Ratio %
Bedrock	Elastic Halfspace	19.00	398	5

The general structure of the soil has a solid clay soil structure. The soil parameters presented in Table 1 were defined in the analysis software and the soil profile and interlayer shear wave velocity profile presented in Figure 2 were drawn. The reference curves to be used in the analyses were determined through the formulations defined in the software according to the general structure of the soil type. The damping ratio was determined as 5%. After the selection of the earthquake records, dynamic response analyses were performed. In this study, the Kocaeli earthquake record was selected and the dynamic behavior of the soil at the time of possible earthquake was interpreted.

The Kocaeli earthquake that occurred in 1999 occurred in Turkey with a magnitude of $M_w=7.5$ and depth of 16.3 km. Analyses were performed with the “Equivalent Linear Analysis Method” in the DEEPSOIL software using the defined and selected analysis data.

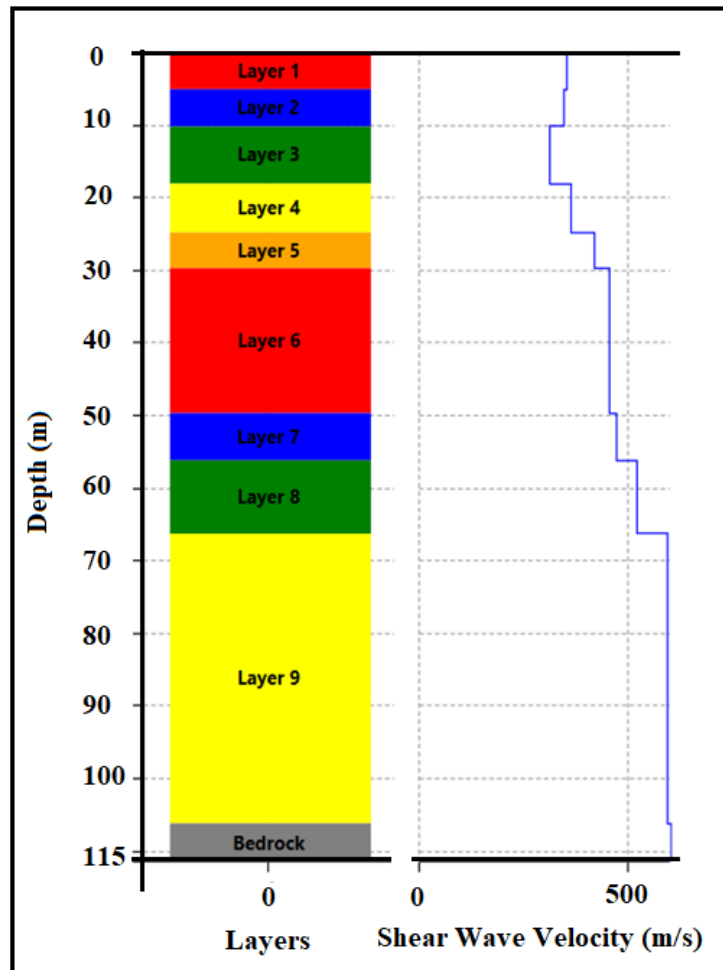


Figure 2. Soil Profile and Interlayer Shear Wave Velocity Profile

In the analyses performed using the “Equivalent Linear Analysis Method”, the soil exhibited a damping behavior against the earthquake acceleration due to the fact that the soil movements were relatively small and the general structure of the soil consisted of solid clay layers. The results obtained are presented graphically in Figure 3 and Figure 4. In Figure 3, the response spectrum-acceleration-time graph formed between the soil layers is defined and Figure 4, the triple acceleration-time graphs is defined.

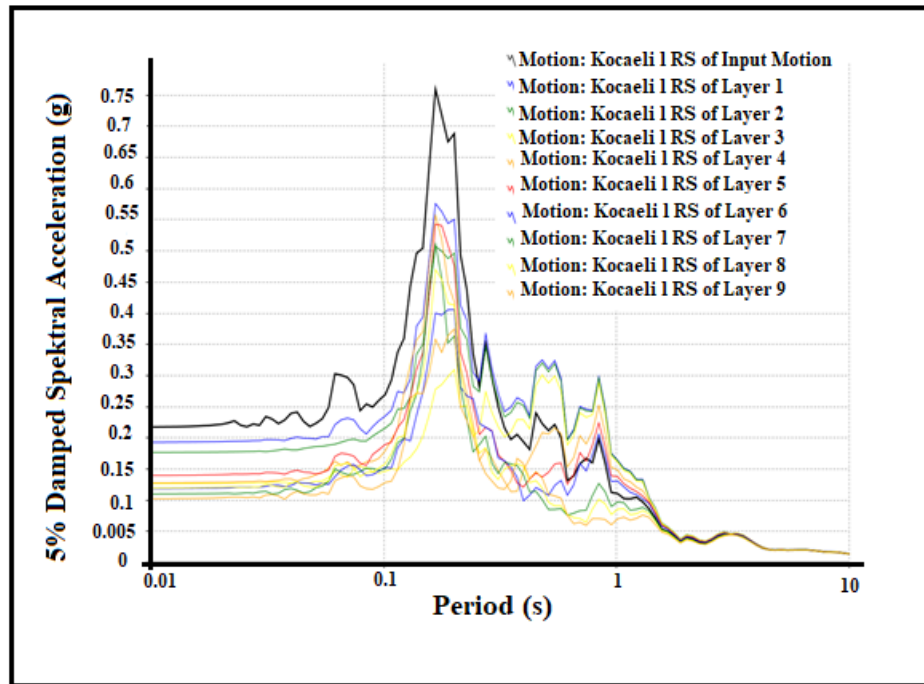


Figure 3. 5% Damped Spectral Acceleration-Period Graph (For PGA and Spectral Acceleration Amplification)

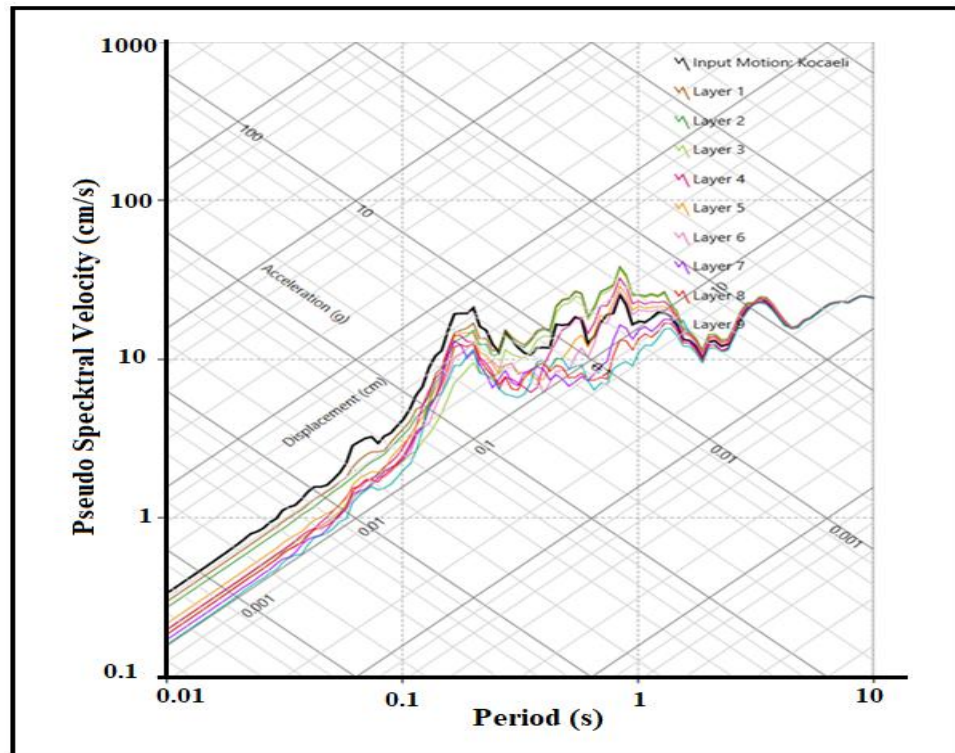


Figure 4. Pseudo Spectral Velocity-Period Graph

According to the "Spectral Acceleration-Time" graph presented in Figure 3, the difference ratio of the PSA (Maximum Spectral Acceleration) value is 0.5g. This value shows that the soil exhibits a damping behavior against dynamic effects. The triple acceleration-time graph is presented in Figure 4. The triple acceleration-time graph is the joint definition of the acceleration-displacement-velocity-time graph.

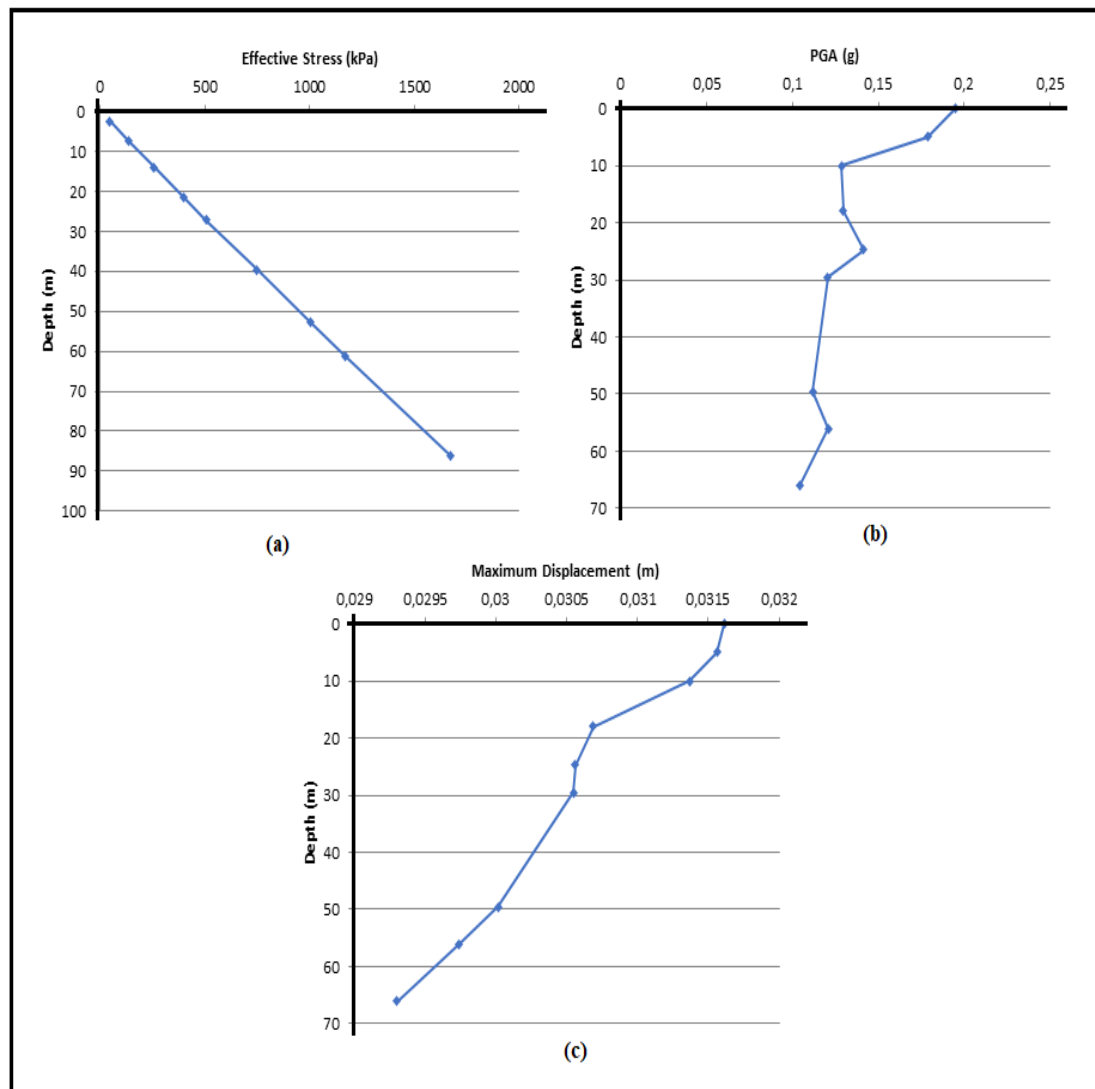


Figure 5. Analysis Results (a) Depth-Effective Stress Graph, (b) Depth-Peak Soil Acceleration (PGA) Graph, (c) Depth-Maximum Displacement Graph

Figure 5 (a) shows the “Depth-Effective Stress Graph”, (b) shows the “Depth-Peak Soil Acceleration Graph” and (c) shows the “Depth-Maximum Displacement Graph”. According to Figure 5 (a), it is seen that the effective stress increases linearly along the depth, up to 1500 kPa-2000 kPa.

4. RESULTS AND DISCUSSION

Within the scope of this study: the study area was seismically investigated with the records of the Kocaeli earthquake that occurred in 1999. It was investigated how the soil of the region would behave against an earthquake in a possible case. The “Acceleration-Velocity-Displacement-Time” graphs obtained as a result of the analyses were defined with DEEPSOIL software [1]. The “Equivalent Linear Analysis Method” was chosen as the analysis method, which has the advantages of being fast and giving results using less data.

In the analyses, 9 layers of the soil profile were defined and analyzed in the system by considering the shear wave velocity, unit volume weight values and layer thicknesses. In the analyses, the earthquake damping ratio was determined as 5%. According to the analysis results: Spectral Acceleration-Time graph was drawn and it was observed that the maximum peak spectral acceleration value difference was around 0.5g. This value indicates that the earthquake could result in a damping effect without increasing its

intensity between layers. This result is for PGA and spectral acceleration amplification.

In addition, it was understood that in the event of a similar earthquake in the regional soil, the effective stress would increase linearly with depth. At the same time, it was determined that the soil parameters obtained through geotechnical studies (unit volume weight, layer thicknesses, general soil class, shear wave velocity etc.) were important in determining the dynamic behavior.

Declaration of Ethical Standards

The authors declare that study complies with all applicable laws and regulations and meets ethical standards.

Credit Authorship Contribution Statement

Raziye BOZKURT: Formal analysis, Investigation, Software, Methodology, Resources, Writing-original draft, Writing- review and editing, **Atila DEMİRÖZ:** Methodology, Supervision, Validation, Writing-review and editing

Declaration of Competing Interest

The authors declare that have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data available on request from the authors.

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