Investigation of parameters affecting the soil amplification by means of 1-D analysis

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Abstract The increase in the amplitude of earthquake waves as they pass through layers of soft soil close to the surface can have significant effects on ground amplification and structural damage. The aim of this study is to perform ground response analysis using 1D (One Dimensional) Equivalent Linear Analysis method with DeepSoil software for specific soil profiles. The analyses were carried out with 3 different strong ground motions selected in accordance with the response spectrum. Strong ground motion records selected according to the regulation were scaled in accordance with the spectrum in the frequency domain. Analysis results were compared with the Turkish Earthquake Response Regulations 2018 (TEBR 2018). It is explained how the soil transfer functions, namely how the amplification functions vary depending on the parameters of the soil layer thickness and shear wave velocity. Depending on the characteristics of the soil profile, it has been observed that the incoming earthquake waves only amplify those in a certain frequency range. By performing ground response analysis, it should be known which frequency content of the ground amplification and therefore which types of structures will affect and the design should be made by considering these criteria.

1. Introduction

It is important to determine the characteristics of the layers that make up the foundation soil in the ground studies carried out before the project design and construction, but it is also necessary to determine how the soil layers will behave in a possible earthquake. Many different methods have been used in studies to determine the effects of local soil conditions on strong ground motion, the factors affecting this and the values of these effects. These methods are in the form of one, two- and three-dimensional ground response analysis, microtremor measurements, classical spectral ratio and horizontal to vertical spectral ratio. Among these, one-dimensional site response analysis provides the advantage of easily creating a mathematical model of the soil to be analysed, with the assumption that each layer of the soil environment can be defined precisely with shear modulus, critical damping ratio, density and thickness values.

The significant changes in the degree of damage in settlements based on different soil conditions in the same region prompted researchers to investigate the effect of local soil conditions on earthquake waves. As a result of the observation and analysis of the shear wave velocity during the ground motion, they stated that the average value of the velocity has a significant effect on the amplification of the soil layers that waves travelling from the bedrock through to the soil layers up to the ground surface [1]. In studies on the subject, the amplification factors depending on the period for the analysis made in certain regions and soils have been revealed [2]. Erdal Şafak worked on seismic field amplification types and generation mechanisms and the models and methods used to characterize them [3]. Yalçınkaya investigated the effect of local ground conditions on earthquake waves by using 5 different earthquake
records at 6 stations established within the scope of the BYTNET project. Classical spectral ratio and horizontal vertical spectral ratio methods are used in the calculation of local ground effects. It is observed that stations located on soft soil layers show significant amplification in periods close to the dominant vibration periods that engineering structures can have [4].

2. The Effect of Local Soil Conditions on Soil Amplification

Soil amplification effect is the change in the amplitude, frequency content and duration of earthquake motions depending on the physical and dynamic properties of the soil layers through which the waves pass. The most important factors that cause soil amplification are the density and stiffness of the soil layers through which the earthquake waves pass. As an earthquake wave travelling from the bedrock to a less rigid soil layer, the earthquake wave amplitude increases, changing the frequency content and duration. Another factor due to the conservation of energy principle is the impedance ratio. The ratio of the product of the shear wave velocity and density of the bedrock to the product of the shear wave velocity and density of the soil layer on the surface is called the impedance ratio. The fact that the impedance ratio is greater than one indicates that the bedrock is passed to softer ground and the wave amplitudes will increase. The main reason for the increase in the amplitude of earthquake motion in soft soils is the seismic impedance difference between the ground and the bedrock beneath it. Seismic impedance can be considered as a measure of the resistance of the environment to particle motion [5].

For a vertical S wave propagating in a soil layer, the seismic impedance (z) is the product of the density (ρ) and the S wave velocity (Vs),

\[ Z = \rho V_s \]  

Generally, seismic wave velocities and intensities are smaller in regions close to the surface of the earth. If the losses due to scattering and damping are neglected, the elastic wave energy must remain constant until the earth surface, according to the energy conservation principle. Seismic energy, E(t),

\[ E(t) = \frac{1}{2}(\rho V_s)v(t)^2 \]  

the particle velocity (v(t)) must increase in order to conserve energy because the density (ρ) and S-wave velocity (VS) decrease as the waves approach the earth surface, that is, the seismic impedance decreases [6].

For a one-dimensional single layer model, the fundamental resonance frequency is given by the following relation, respectively [7].

\[ f_0 = \frac{V_s}{4H} \]  

In equation (3) \( V_s \) is the S-wave velocity of the layer and H is the thickness of the layer on the bedrock. Soil pre-dominant period \( T_0 \) is defined as \( \frac{1}{f_0} \). The earthquake characteristics that will affect the responses in earthquakes are significantly affected by the ground conditions in the regions where the responses are located. For this reason, determining the effect of soil layers is an important step in the studies conducted to predict the damages that may occur in the responses. The response of layers differs depending on their thickness, soil type and properties. Likewise, soil layers of different thicknesses and properties may be different from one point to another. For this reason, it should be determined how the dynamic behaviour characteristics such as soil fundamental periods and soil amplification change from one point to another in earthquake resistant response design.

The structure of the soil layers has a great influence on the earthquake behaviour of structures. During an earthquake, seismic waves are transmitted from the bedrock to the foundation by the amplifying effect of the ground through the soils between them. This may cause an amplification or deamplification effect. This shows the soil amplification that can be effective with the presence of the structure due to the soil-structure interaction, which is the result of the difference between the free field motions that will occur at the point where there is no construction and the motion that will occur on the basis of the response [8]. The changes that seismic waves undergo in the soil layers are called "local ground effect".
Since this change is generally observed as increasing amplitudes, the term local ground effect; It is also called soil amplification, transfer function or ground response.

3. 1-D Equivalent Linear Analysis
The aim of this study is to obtain the parameters of the motion on the surface by performing ground response analysis under the effect of 3 different real earthquake records will be analysed using one-dimensional equivalent linear analysis. 1-D analysis can be done with different software that include different material behaviour models. Deepsoil program was used in this study. Parametric values have been chosen for the equivalent linear analysis selected soil profiles.

3.1. Obtaining Data to be Used in Ground Response Analysis
This study is based on Turkish Earthquake Response Regulations 2018 (TEBR 2018) [9]. Response spectrum will be construction by taking site specific spectrum coefficient according the seismic hazard studies from Turkey Earthquake Hazard Maps Interactive Web Applications design by AFAD (Disaster Emergency Management Presidency) [10]. The earthquake records to be used in the analysis were obtained from the PEER (Pacific Earthquake Engineering Research) [11]. The simple scaling of the strong ground motions was done in accordance with the TEBR 2018, and 1-D Equivalent Linear analyses were performed by Deepsoil Program.

3.1.1. Selection and Scaling of Earthquake Records
Web-based Pacific Earthquake Engineering Research (PEER) strong ground motion database; Provides tools to search, select, and download ground motion data. Different spectrum models are available in PEER (ASCE Code, PEER NGA-West2, User Defined). Filtering can be made by entering the desired earthquake parameters. In this study, filtering has been done by selecting the parameters:

User Defined Spectrum was chosen as the spectrum model, and the response spectrum obtained from AFAD was uploaded. Strike Slip, active fault type of lateral faulting is observed in Turkey. 360-760 m / s has been chosen as the shear wave velocity range. The reason for this is that the modelled soil is considered as ZC ground class. The time interval in which the earthquake energy is absorbed by 5-95% (significant duration) has been selected for a minimum of 15 seconds and a maximum of 60 seconds. In order to make the response spectrum on the motion and earthquake code spectrum similar, $T_A$, $T_B$, $T_L$ values were entered by selecting (Minimized MSE) as the scale method. 0.01-2.2 was chosen as the scaling range.

Earthquake acceleration data obtained from PEER has been uploaded to the SeismoSignal program [12]. With the SeismoSignal program, the appropriateness of the maximum acceleration, duration (significant duration and bracked duration) and spectral acceleration values were checked. Scaling was done according to the acceleration responses Scaling of the Earthquake Records in accordance with the Design Spectrum of TEBR 2018[13].

Table 1. Features of Scaled Earthquake Records

| Earthquakes       | Station  | PGA (g) | Significant Duration | Bracked Duration | Magnitude | Scale Factor |
|-------------------|----------|---------|----------------------|------------------|-----------|--------------|
| 28.06.1992-Landers| Amboy    | 0.146   | 25.22                | 45.00            | 7.28      | 3.80         |
| 20.06.1990-Iran   | Abbar    | 0.515   | 28.66                | 45.72            | 7.37      | 1.90         |
| 21.07.1986-Chanfalt Valley02 | Benton | 0.209   | 10.02                | 16.65            | 6.19      | 3.35         |

$^a$Peak Ground Acceleration.
3.2. Ground Response Analysis for Single Layer Soil Profiles

In this section, G / Gmax and damping ratio relationships proposed by Vucetic and Dobry (1991) are used for soil profiles and 0 is chosen as the plasticity index (PI). As the bedrock properties, \( V_S = 760 \text{ m} / \text{s} \), \( \gamma = 23 \text{ kN} / \text{m}^3 \), D (%) = 1 and an elastic solution has been made.

3.2.1 Effect of Soil Layer Thickness

To identify effect of soil layer thickness parametric analysis were performed by keeping the shear wave velocity (Vs) and density (ρ) of the soil layer constant. Analyses were made for 3 different layer thicknesses (Table 2).

| Soil Profiles | \( \gamma_n \) (kN/m\(^3\)) | \( V_s \) (m/s) | H (m) |
|---------------|----------------|--------------|------|
| A             | 20             | 360          | 5    |
| B             | 20             | 360          | 15   |
| C             | 20             | 360          | 30   |

The soil layer thickness is variable 5-15-30 meters, and other parameters are analysed by taking \( V_S = 360 \text{ m} / \text{s} \) and \( \gamma_n = 20 \text{ kN} / \text{m}^3 \) constant. As the thickness of the soil layer increases, the soil predominant frequency shifts towards smaller frequencies. When this is considered in terms of period, it means that as the thickness of the soil layer on the bedrock increases, the value of the period in which the maximum acceleration is observed increases. When the variation of the peak ground acceleration is examined by looking at the average values, it is seen that the PGA values measured on the surface decrease as the thickness of the soil layer increases. Since the soil predominant frequency is \( V_s / 4H \), as the thickness of the soil layer increases, the frequency value at which the highest soil amplification decreases. The period value in which the maximum spectral acceleration observed is the lowest value on the soil profile A, while it reaches the highest value on the soil profile C. Since there is no change in the impedance ratio between the two layers, it is seen that the maximum amplification values from the Fourier Amplitude Spectrum ratio are around 2.3, and the frequency values at which these values are seen progress towards low frequencies as the layer thickness increases. (Figure 1, Figure 2, Figure 3).

**Figure 1.** Analysis Results of Soil Layer A
3.2.2. Effect of Soil Layer Shear Wave Velocities
The shear wave velocity (Vs) has been changed by keeping the soil layer density (ρ) and thickness (H) constant. In this section, the variation of different shear wave velocities with layer thickness is also included (Table 3).

| Soil Profiles | γn (kN/m³) | Vs (m/s) | H (m) |
|---------------|------------|----------|-------|
| D             | 20         | 180      | 5     |
| E             | 20         | 360      | 5     |
| F             | 20         | 760      | 5     |
Figure 4. Analysis Results of Soil Layer D

Figure 5. Analysis Results of Soil Layer E

Figure 6. Analysis Results of Soil Layer F
Table 4. Soil Profile Properties for Different Shear Wave Velocities H=15 m

| Soil Profiles | $\gamma_n$ (kN/m$^3$) | $V_s$ (m/s) | $H$ (m) |
|---------------|------------------------|-------------|---------|
| G             | 20                     | 180         | 15      |
| H             | 20                     | 360         | 15      |
| I             | 20                     | 760         | 15      |

Figure 7. Analysis Results of Soil Layer G

Figure 8. Analysis Results of Soil Layer H
Figure 9. Analysis Results of Soil Layer I

Table 5. Soil Profile Properties for Different Shear Wave Velocities H=30 m

| Soil Profiles | $\gamma_n$ (kN/m$^3$) | $V_s$ (m/s) | H (m) |
|---------------|-----------------|------------|------|
| J             | 20              | 180        | 30   |
| K             | 20              | 360        | 30   |
| L             | 20              | 760        | 30   |

Figure 10. Analysis Results of Soil Layer J
Considering the average values as a result of the analysis made by taking the thickness of the soil layer as 5 meters and the shear wave velocity as 180-360-760 m / s. When the shear wave velocity profile is 760, it is seen that the impedance ratio $\rho V_s^2$ will be very low, so the value measured in the bedrock and the PGA value measured on the surface are very close. When the Fourier Amplitude Ratio graphs are examined, it is seen that as the shear wave velocity increases, the frequency with the highest amplification from Frequency = $V_s / 4H$ increases (Figure 6).

In addition, as a result of the analysis made for the soil layer thickness of 5 meters shear wave velocity 180 m / s, the frequency at which the greatest acceleration will occur is different in Iran earthquake compared to other earthquakes, so the maximum acceleration range has extended (Figure 4).

Analyses for 15 meters and 30 meters of soil layer thickness showed that PGA values decreased, spectral acceleration graphs made smaller peaks, but caused peaks in wider periods, and the frequency at which maximum amplification would be observed was at lower frequency values(Figure 7- Figure 12). As a result, as the shear wave velocity decreases from the shear wave velocity in the bedrock, enlargements or attenuations are observed due to the change in impedance ratio. These amplifications are seen at higher frequencies. As the thickness of the soil layer increases, it is seen that the maximum spectral accelerations decrease and occur in wide periods (Figure 5- Figure 12).
4. Conclusions
In this study, properties of the soil transfer function have been investigated for the different parameters, for example depths and S-wave velocities of soil layers, by using 1-D equivalent linear site response analysis. In conclusion, it has been emphasized that depth of bedrock and S-wave velocity are very important for the fundamental soil period and maximum soil amplification. Physical properties of soil layers determine the frequency interval of earthquake motion that will be amplified by soil layers. If the amplification is at high frequencies, this may not be important for most of the engineering structures. However, the amplification is very important for the cases in which the fundamental frequency of soil is very close to that of the engineering structures.

5. References
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