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Examination of Earthquake Intensity Increments on Side-Zones of Valleys within Alluvial Basins by an Analytical Approach

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ABSTRACT

The effect of topography on the seismic wave-motion has been of interest to many studies. In this study, the earthquake-intensity increments (amplification) on side-zones of valleys within alluvial basins, were investigated using finite element method. A set of finite element models for valleys, one with a triangular cross-section, and the rest with trapezoidal cross-sections, taking into account five different side slopes (17º, 22º, 27º, 37º, 45º), were adapted. The acceleration time-histories obtained through the use of the commercial finite element code (QUAD4M) at valley-sides, valley-edges, and at the intermediate points were transformed to Fourier Amplitude Spectra. The amplitude-frequency variations obtained at the three selected reference points of the valley as well as at the bedrock, were investigated in each of the four selected phases of the earthquake duration. As a result of the performed dynamic analysis, the effect of the valley-slope variation at the three reference points on the valley was examined at four distinct phases of the earthquake duration.

1. INTRODUCTION

The fact that the local ground conditions significantly affect the strong earthquake ground- motion is clearly demonstrated by the structural damage and the instrumental measurements observed in devastating earthquakes [1]. Therefore, it can be stated that local ground conditions should be considered in the design of earthquake-resistant structures. The increase in the amplitude of the earthquake-waves, passing through the surface layers, is known as soil amplification. Ground conditions, such as bedrock depth, thickness of the soil layers on the bedrock, their types and dynamic characteristics, changes with depth and deformation, lateral discontinuity of the soil layers, and topographic characteristics, are all important factors affecting the soil amplification. The topographic features include the geometry of the bedrock, which is bounded by the two- or three- dimensional geometry of the ground layers on and under the surface [2].

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Stemming from the cyclic character of the earthquake-waves, formed on the surface of the sloping bedrock, surface-waves running towards the valley-center are generated [3]. These waves produce strong and long-lasting ground motions which cannot be predicted by one-dimensional analysis, based on the dynamic behavior of the ground layers under vertically ascending shear-waves. The ordinates of the long-period side of the spectrum increases, from the edge to the center of the valley, while in critical localities, maximal effects of two-dimensional magnification show up [4].

The surface-waves formed on the edges of the plain, as a result of lateral confinement of loose soil layers, dominate after a certain distance, as they advance through the plain. Surface-waves have lower velocities than the waves formed in three-dimensional environments and have periods greater than 0.5 seconds. If the plain is very wide, it is observed that these waves disappear due to damping effect of the ground. In the case of a narrow valley within an alluvial environment, such surface-waves have been clearly observed in a number of earthquakes, during which the ground-motion has undergone significant changes at the surface, due to multiple reflection of the waves, to-and-fro the rock surface, bounding the valley [5]. Surface topography too, has always been considered as a major factor, affecting the ground-motion. Chaljub et al. concludes that, this is significant in elevated areas; however, they found it less important in the valleys [6]. Lovati et al. evaluated the seismic site response of Narni ridge (central Italy), by comparing experimental results with those from numerical simulations [7]. Barani et al. examine the role of topographic effects on the earthquake ground-motion. However, they attribute little importance to the effects of topography, which, as known, may play a significant role on the level, duration and frequency content of ground-motion [8].

Alielahi et al. make an attempt to study the effect of U-shaped canyon-cavity geometry on strong ground-motion. They performed response analysis for different sizes of a U-shaped canyon, in the presence of differently positioned underground cavities. The results showed that the response is strongly influenced by the size of U-shaped canyon [9]. The earth's surface-irregularities can substantially affect seismic-waves and induce amplifications of ground motions. Ning et al. investigated whether and how the source characteristics affect the site-amplification effects. They proposed an analytical model of a line source of cylindrical waves impinging on an alluvial valley, to link the source and the site. The analytical solution to this problem proves one aspect of the strong effect of source on site amplification, i.e., the wave-curvature effect. They found that the site amplification depends on the source location, especially under conditions of a small source-to-site distance [10].

Khan et al. investigated the influence of ground-surface topography on the spatial distribution of earthquake-induced ground shaking. This study shows the influence of topography on seismic amplification during the 2005 Kashmir earthquake. Earth-surface topography scatters and reflects seismic-waves, causing spatial variation in seismic response. A 3D simulation has been performed for the 2005 Kashmir earthquake in Muzaffarabad, with spectral finite- element method. The moment-tensor solution of the 2005 Kashmir earthquake is used as the seismic source. The results point to amplification of seismic response on ridges and de-amplification on valleys. It is found that slopes facing away from the source receive an amplified seismic response, and that 98% of the highly damaged areas are located in the topographically amplified seismic response zone [11].

Iyisan et al. pointed to the fact that earthquake ground-motion is affected by the local soil conditions, geological structures, as well as earthquake source properties. The amplitude and frequency content of the strong ground-motion can be substantially modified by local site effects. They investigated the effects of basin-edge on the variation of surface-motion using different strong ground-acceleration record, performed one and two dimensional dynamic analyses, employing the Dinar basin-edge model, and compared the results [12].

The aim of this study is to evaluate the ground-motion changes numerically, at a set of three reference points chosen along the axis of the valley, for different valley-slopes, by applying the finite-element method. The starting point of this study stems from the engineering interest in view of determining the causes of the heavy damage in the Çay Small Industrial Area (Çay Küçük Sanayi Sitesi), due to the earthquakes in Afyon, on 03.02.2002, and determining whether the topographical structure of the region showed similar aspects to the topographic conditions observed in the studies, mentioned above. As a result of the examination, the geotechnical and geological reasons of the damage, that played an important role in Çay Small Industrial Area, during 2002 Çay Earthquake, were revealed and the issue of seismic refraction and reflection was clearly addressed [13].

2. MATERIALS AND METHODS

On 03.02.2002, an earthquake occurred near Afyon at 09:11 AM. The location and the magnitude of this earthquake were determined differently by various recording stations. It is thought that the earthquake that occurred later, was not an aftershock but a second independent earthquake, related to a different fault. It is stated that the epicenter of the second earthquake is between Çay and Maltepe. The second earthquake occurred at 11:55 AM local time and the magnitudes were determined as M = 6,5 and M = 6,0 respectively. In this study, 03.02.2002 Eber (Sultandagi) - Çay Earthquake data were used and a set of finite element models were adopted, taking into account five different valley-slopes (17º, 22º, 27º, 37º, 45º), one of them with triangular, and the others with trapezoidal sections. The acceleration time-histories obtained at a point on valley-edge, at a point on the valley-axis and at a point between them, were all transformed into Fourier Amplitude Spectra with the computer program (QUAD4M). The amplitude-frequency variations on the selected three points and on the bedrock are divided into four phases and examined independently. For the four different phases of the earthquake duration, the effect of valley slope-changes in these three different points on the valley has been studied by dynamic analysis.

3. RESULTS

QUAD4M is a program, developed on the basis of plane-strain and used for two-dimensional dynamic analysis in x and y directions. In the program, which is not in the upright direction (z) to the plane, the angle of the valley edge was selected as a variable and dynamic analyses were made for five different angles (17º, 22º, 27º, 37º, 45º). As a result, the horizontal accelerations at points A, B and C in Figure 3.1 were obtained, as a function of time. In all the models, the valley is divided into two by taking the advantage of symmetry principle, between the valley-edge and the valley-axis of 2000 m (2 km), and the depth of the alluvium section being 600 m.
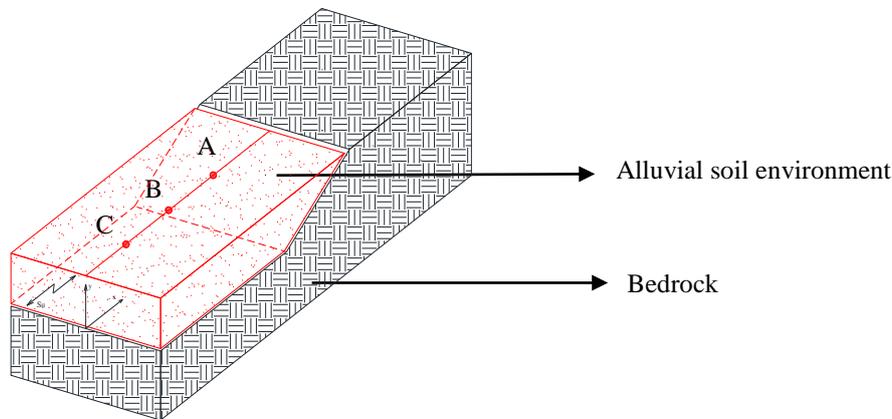

Figure 3.1. Cross-section view of three-dimensional valley

For the QUAD4M program used in the dynamic analysis, the alluvial soil environment of the three-dimensional valley shown in Figure 3.1 is divided into finite-elements (Figure 3.2), a horizontal (x direction) time-varying earthquake force was applied at the interface. Thus, it was thought that the earthquake-waves, emerged from the earthquake-source, as occurred in the nature, climb upwards in the bedrock, can be represented with a more accurate approach.

After the earthquakes on 03.02.2002, the ground data obtained from the studies in the field of application, which can be used in dynamic analysis, are given below:

Unit weight (γ) = 19,4 kN/m³, Shear Modulus (G) = 5.550 kN/m², Shear Modulus Ratio = 0,6 G_{max}, Poisson Ratio (ν) = 0,35 and Elasticity Modulus (E_s) = 25.000 kN/m²
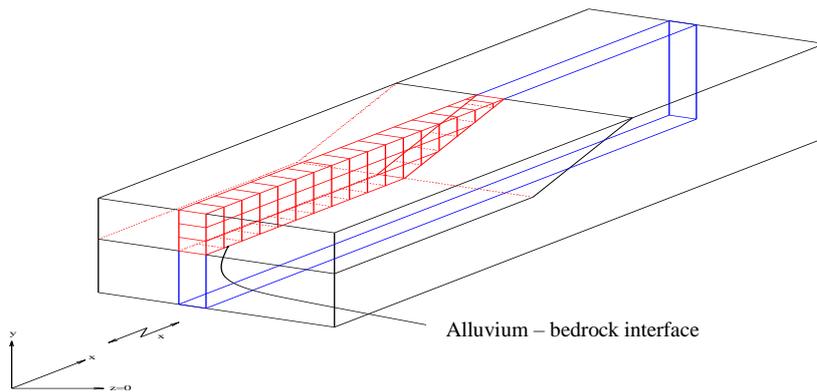

Figure 3.2. Representation of finite-element model, applied to alluvial-basin valley.

The acceleration record of the earthquake, occurred on 03.02.2002, are divided into four phases as shown in Figure 3.3. Since no change could be observed in the first 20 seconds, the stages are listed from the 20th second on.
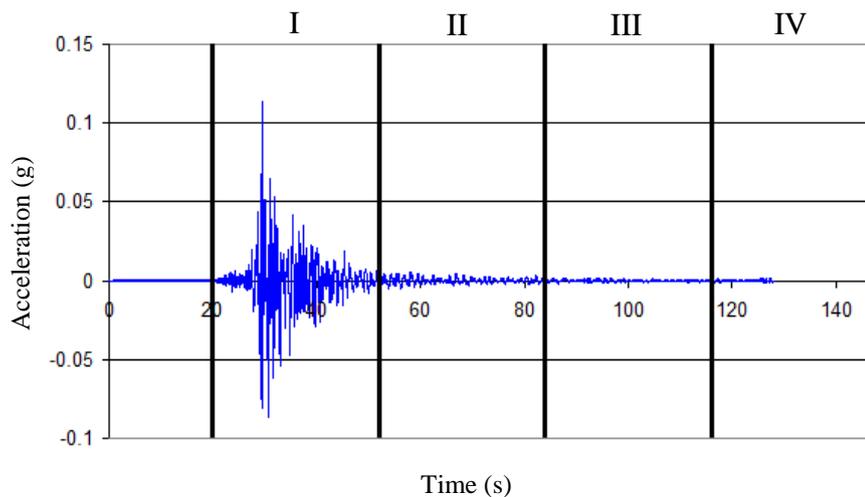

Figure 3.3. Afyon - Sultandağı earthquake acceleration record.

Fast Fourier Transformation (FFT) was performed for each stage of the acceleration record, examined in four stages and shown in Figure 3.4 (a, b, c, d).
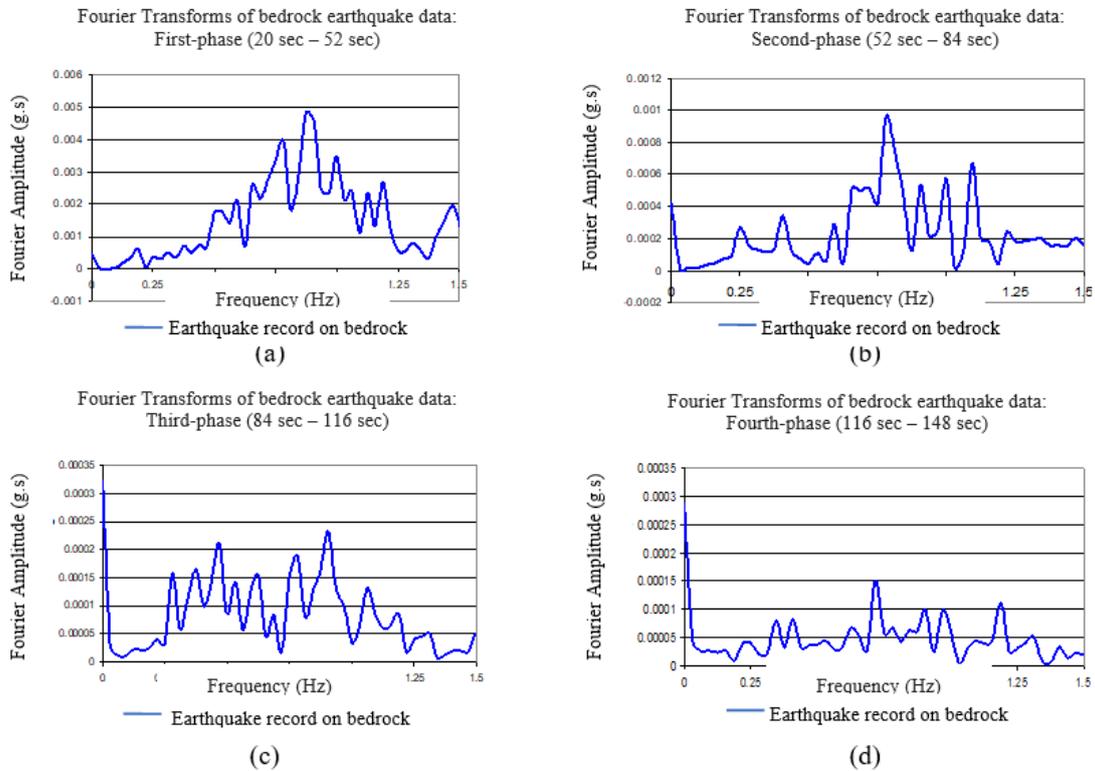

Figure 3.4. Fourier Transforms of four different phases of bedrock earthquake data;
(a) First-Phase, (b) Second-Phase (c) Third-Phase, (d) Fourth-Phase.

Considering the explanations above, it is possible to divide the time during which the data takes place, including the acceleration time-histories in the bedrock, as well as the points A, B and C, in four stages of 4096 points (32 seconds), since the number of points $4096 = 2^{12}$ is in accordance with the approach in Fourier Analysis. For this reason, the acceleration time- histories on both the bedrock and at points A, B and C were divided into four time periods, each consisting of 4096 points (32 seconds), with minor modifications, required to start from zero for each phase, and end in zero. Thus, FFT processing conditions were also met.

In this way, it is possible to assume the earthquake-duration as comprised of four stages and to make the interpretations in a more comprehensive way. The amplitude-frequency composition of the earthquake is thus assumed to change by time. In addition, it was observed that the re-expression of data in four time-periods of 4096 points led to meaningful and consistent results [14].

3.2. First Model

The above-mentioned program is implemented on a 17° inclined model. In this model, a semi-equilateral triangular alluvium layer is divided into finite elements. This model can also be considered to represent the low-slope canyon.

From the valley axis to 1800th m (A), 900th m (B) and 100th m (B) (respectively 167th, 67th and 9th nodes) as a result of the dynamic analysis of the FFT applications are given below with the bedrock earthquake-data.
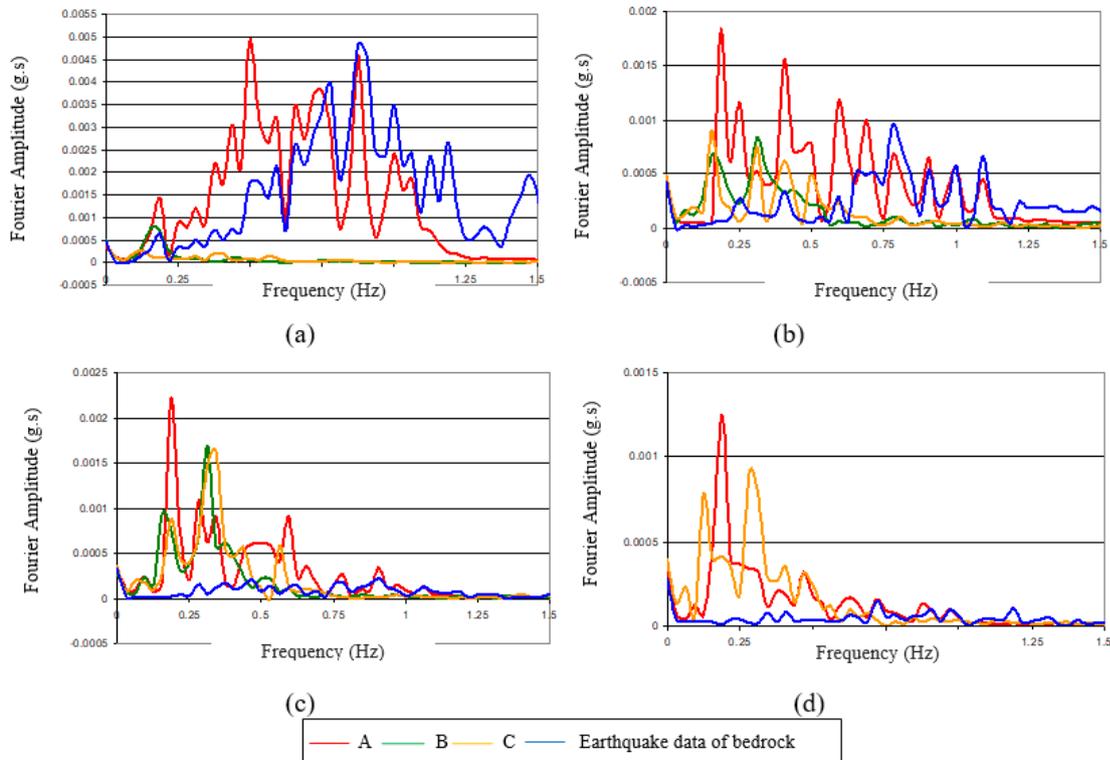

Figure 3.5. (a) Valley slope: 17º; First-Phase; between 20th second and 52th second.
(b) Valley slope: 17º; Second-Phase; between 52th second and 84th second.
(c) Valley slope: 17º; Third-Phase; between 84th second and 116th second.
(d) Valley slope: 17º; Fourth-Phase; between 116th second and 148th second.

It has been determined that point A reached the highest values, especially at low frequencies in all stages and that the amplitudes diminished quantitatively over time. It was observed that points B and C generally exhibit the same behavior and that they coincide with that of the second phase, for the bedrock amplitudes, but never reached the amplitude of point A.

3.3. Second Model

In this case, the finite element network was drawn by taking the slope of the valley at 22º and the dynamic parameters adopted in the first model were repeated.

From the valley axis to 1800th m (A), 900th m (B) and 100th m (B) (respectively 172nd, 82th and 10th nodes) as a result of the dynamic analysis of the FFT applications are given below with the bedrock earthquake-data.
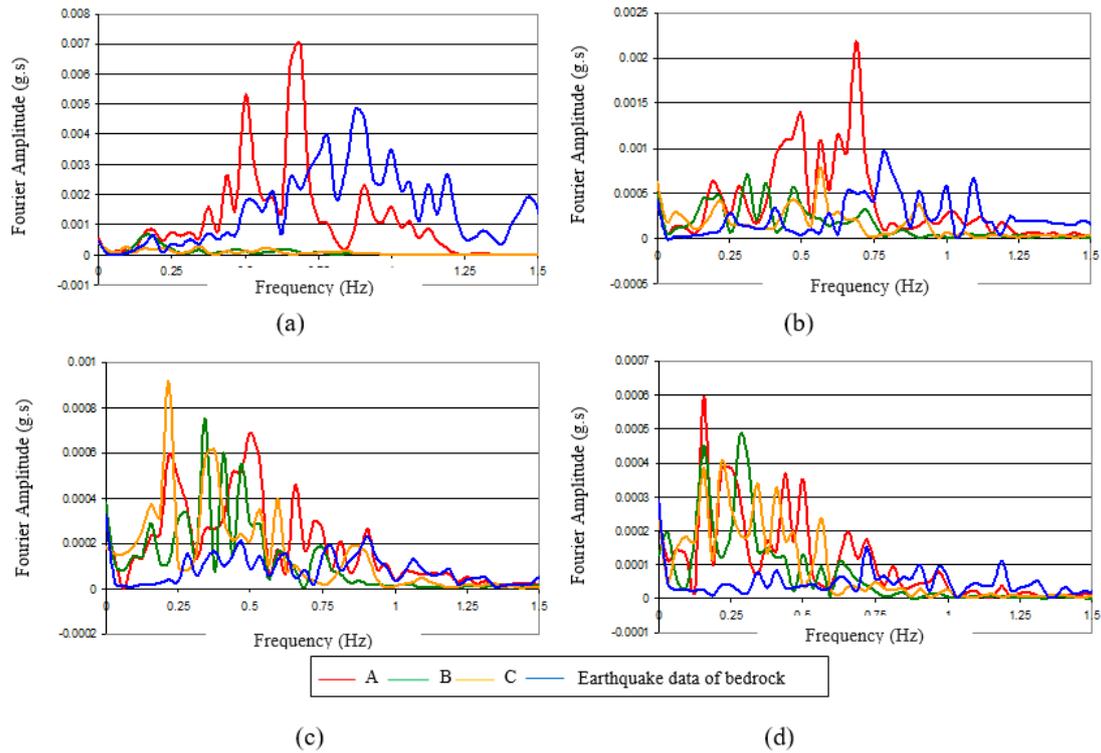
Figure 3.6. (a) Valley slope: 22º; First-Phase; between 20th second and 52th second.
            (b) Valley slope: 22º; Second-Phase; between 52th second and 84th second.
            (c) Valley slope: 22º; Third-Phase; between 84th second and 116th second.
            (d) Valley slope: 22º; Fourth-Phase; between 116th second and 148th second.

In the Second Model, it was determined that point A reached the highest values especially at low frequencies, in almost all stages, and that the amplitudes diminished quantitatively. It was observed that the points B and C generally exhibit a similar behavior and were above the bedrock amplitudes in the second phase. However, unlike the first model, the points B and C were found to pass the amplitude of point A, quantitatively, in the third stage.

3.3. Third Model

In this model, the slope of the valley is 27º, so it is steeper than those of the first two models.

From the valley axis to 1800th m (A), 900th m (B) and 100th m (B) (respectively 181th, 55th and 10th nodes) as a result of the dynamic analysis of the FFT applications are given below with the bedrock earthquake-data.
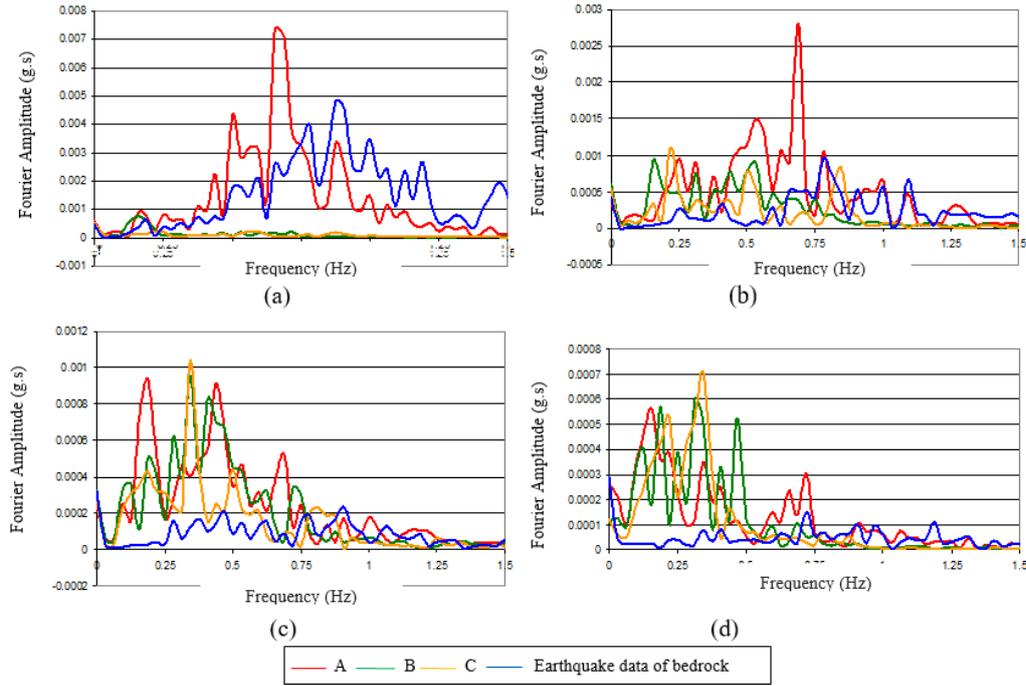
Figure 3.7.　(a) Valley slope: 27°; First-Phase; between 20th second and 52th second.
　　　　　　(b) Valley slope: 27°; Second-Phase; between 52th second and 84th second.
　　　　　　(c) Valley slope: 27°; Third-Phase; between 84th second and 116th second.
　　　　　　(d) Valley slope: 27°; Fourth-Phase; between 116th second and 148th second.

In the third model, similar results were obtained as in the second model. It was observed that point A amplitudes reached the highest values, except the third stage at low frequencies.

3.4. Fourth Model

In this model, the slope of the valley was 37° and results were obtained accordingly. From the valley-axis to 1800th m (A), 900th m (B) and 100th m (B) (respectively 159th, 65th and 9th nodes) as a result of the dynamic analysis of the FFT applications are given below with the bedrock earthquake-data. In this model, it has been determined that, with the increase of the angle of the valley slope, there have been decreases in the amplitudes of point A which reached very high amplitudes at low frequencies than those of the other three models. On the contrary, there were increases in the amplitudes at the points B and C, between the valley-axis and the valley-edge.

3.5. Fifth Model

Finally, the valley-slope was selected as 45°, and the results were compared with those from other models. From the valley axis to 1800th m (A), 900th m (B) and 100th m (B) (respectively 700th, 172nd and 20eth nodes) as a result of the dynamic analysis of the FFT applications are given below with the bedrock earthquake-data. Fifth model was shown to be similar in frequency-fourier amplitude of the fourth model, it has been determined that there was a decrease in the amplitudes of point A, and increase in the amplitude of points B and C. As a result, the critical region shifts from the valley corner to the middle of the valley, as the valley angle of inclination increases. This situation is in accordance with the study by Cılız, 2007.
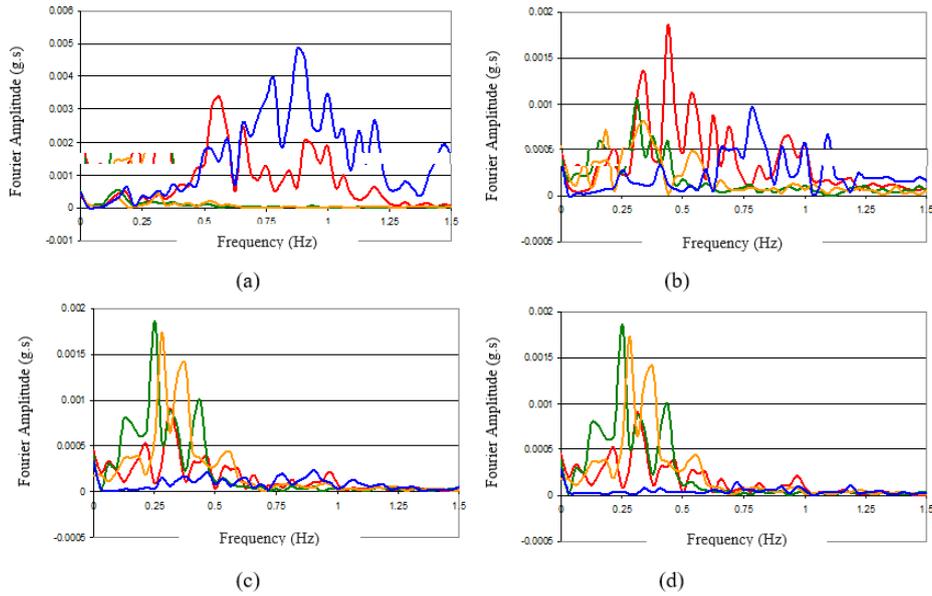
Figure 3.8. (a) Valley slope: 37º; First-Phase; between 20th second and 52th second.
             (b) Valley slope: 37º; Second-Phase; between 52th second and 84th second.
             (c) Valley slope: 37º; Third-Phase; between 84th second and 116th second.
             (d) Valley slope: 37º; Fourth-Phase; between 116th second and 148th second.

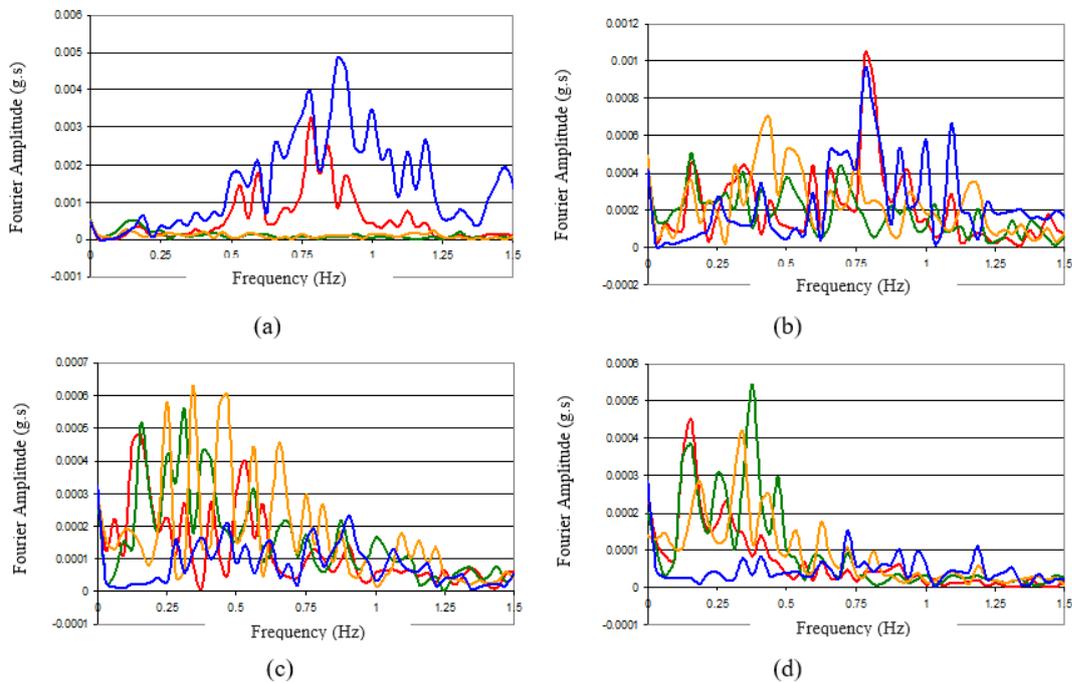
Figure 3.9. (a) Valley slope: 45º; First-Phase; between 20th second and 52th second.
             (b) Valley slope: 45º; Second-Phase; between 52th second and 84th second.
             (c) Valley slope: 45º; Third-Phase; between 84th second and 116th second.
             (d) Valley slope: 45º; Fourth-Phase; between 116th second and 148th second.

4. CONCLUSION

When the acceleration time-histories at the points A, B and C are examined visually, it can be seen that the region at point A near the valley is the most unfavorable locality. The Fourier Amplitude Spectra of the acceleration time-histories obtained at the bedrock and at the three points on the valley-surface ensured a quantitative evaluation of this interpretation.

For Finite Element Analysis, valleys were modeled for five different slopes (17º, 22º, 27º, 37º and 45º), Fourier Amplitude Spectra were obtained from a dynamic analysis with QUAD4M program for three points at side of the valley (A), valley-axis (C) and the intermediate zone (B). Taking three different points for five different angles of inclination, as well as considering the earthquake effect, not as a result of its total duration, but in terms of distinct phases, can be regarded as innovations, brought by this study.

Although the representative earthquake, taken in the study, exhibits a total duration of 128 seconds, its effects vary within certain divisions. These differences can be linked to a phase-specific frequency-amplitude combination.

Since point C corresponds to the deepest part of the valley, this is the place where the effect of frequency (or period, vice-versa) is most likely to be expected. Here, it is expected that the magnified effect of the earthquake-wave components at the ground, the prevailing frequency will be observed and the components at lower and higher frequencies will be weakened, as seen as a result of the analyses. The simple waves in the sine form were able to preserve their visible and recognizable forms, around this point.

An intuitive mind could expect the occurrence of a multitude of reflections and overlaps (superposition) at point A, beforehand. Although there is no physical clue for the presence of such a mechanism, the digital results, especially in low-slope conditions, point to the inappropriateness more than the other two points (B and C), in terms of amplitude increments at lower frequencies, and conforming to actual damage distributions encountered in real earthquakes in nature. In summary, the existence of the aforementioned mechanism is not obtained by an intervention that imposes on the lines of calculation, but as an indirect interpretation.

At point B, for the points between the A and C, it is seen that it conforms to the phenomena observed in nature and that it can be assumed as a control point to check the consistency of the results.

Another result, achieved by the finite element analysis with QUAD4M program, is: It is determined that the amplitude increases in the valley-side regions as the valley slope angle increases. This situation coincides with the conclusions of [15], as mentioned above.

5. REFERENCES

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