Effect of Edge Slope on Soil Amplification at a Two Dimensional Basin Model

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SUMMARY:
Basin edge effect phenomena can be defined as the change in frequency content and intensity of ground motion near basin edges. In this study, the effect of the edge slope and bedrock earthquake motion frequency content on surface ground motion was investigated. For this purpose, one (1D) and two dimensional (2D) dynamic analyses were performed by using a basin model with surface layers which were mainly composed of stiff sandy medium plasticity clay. The acceleration time histories and absolute acceleration spectra were calculated for different points of the basin surface and the results were compared. The variation of soil amplifications, intensity parameter values and 2D/1D aggravation factors were evaluated. The variation of normalized acceleration response spectra with distance from the basin edge were compared with the design spectra given in Turkish Earthquake Code for Buildings and Eurocode 8.

Keywords: Basin Edge Effect, 2D Analysis, Soil Amplification, Aggravation Factor

1. INTRODUCTION

At a specific site, the earthquake characteristics are mainly dependent on tectonical structure, rupture mechanism, hypocentral distance as well as site geology and local soil conditions. The change in the characteristics of the ground motion such as amplitude, frequency content and duration due to the geotechnical and geological properties at a specific site can be defined as local site effects. The changes in amplitude, frequency content and duration of earthquake waves that occur while passing through near surface soil layers is defined as soil amplification. Local site conditions such as seismic bedrock depth, slope of edge bedrock, geometry and characteristics of soil layers and topographical irregularities are the most important factors affecting soil amplification (Safak, 2001). Thus, local site conditions affect the damage variation occurred during the earthquakes and play an important role in the design of earthquake resistant structures. The purpose of the studies for estimating local site effects is to determine the characteristics of earthquake design motion used for calculating the dynamic forces acting on structures during earthquakes. The variation of ground motion is denoted as an amplification or de-amplification of amplitudes at all frequencies and it is dependent on many parameters. Some of them are related to the dynamic behavior of soil and the characteristics of the incoming wave field, others are dependent on geometrical features such as surface/bedrock topography, lateral geological discontinuities, bedrock depth or the slope of the edge bedrock etc. In fact, two and even three dimensional effects may occur at sites with topographical irregularities such as narrow valleys, basin edges, steep ridges and crests (Pitilakis, 2004). These effects which become dominant with the existence of surface waves in addition to body waves can be studied with two and three dimensional numerical methods (Iyisan and Hasal, 2007). Although 1D, 2D and 3D approaches have been developed for the dynamic analyses of soil layers, 1D analysis method is still the most preferred one among them because of its limited data requirement compared with others. It is based on the principle of vertically propagating body waves in the horizontally layered soil medium without any lateral boundaries. The assumptions and boundary conditions of 1D approach become valid especially for the sites far from edges when the half-width of soil layers is much greater than its depth in shallow and wide basin models. However in nature, the soil deposits form mediums which can be defined only with two or three dimensional models. This kind of deposits with lateral geological discontinuities show trap behavior. This trap affects the surface waves and generally provides them to reach their peak amplitude values. As a result of the two and three dimensional effects, the frequency content and amplitude of strong ground motion may vary with the distance from edge to center. For the conditions where 2D effects have to be considered on soil amplification, the amplitude and frequency content of surface ground motion will differ from the results of 1D dynamic analyses executed for the same sites.

The change in frequency content and intensity of ground motion near basin edges can be defined as basin edge effect. Strong lateral discontinuities in soil layers cause wave transformations and surface waves at basin edges. Consequently, soil amplification values at basins mainly depend on the types and dynamic properties of soil layers, also frequency content of bedrock motion and the location of the site where the dynamic behavior is being evaluated (Rassem and oth., 1997; Iyisan and Hasal, 2007). Therefore, the amplitude of the ground motion will show variation with distance from basin edges and its frequency content and amplitude may differ from the results obtained by one dimensional dynamic analysis. Basin edge effect can not be estimated by one dimensional dynamic approach and only two or three dimensional numerical models can be used to study on these effects that become more dominant with the existence of surface waves in addition to body waves (Hasal, 2008).

In this study, in order to investigate the effects of the basin edge slope and frequency content of bedrock motion on dynamic response of soil layers, 1D and 2D dynamic analyses were performed by using a real basin edge model under different earthquake excitations and the results were compared. Shear wave velocity profile and seismic bedrock depth of the basin model was selected by using the results of microtremor array measurements that had been performed at a basin in Turkey. The acceleration time histories and absolute acceleration spectra were calculated for different regions of the basin surface and the variations of soil amplification and acceleration spectrum intensity (ASI) values with the distance from edge bedrock outcrop were obtained. The 2D/1D spectral acceleration ratios-aggravation factors were calculated and the change in aggravation factor values with distance from basin edge was investigated for different period values. Also the effective spectrum coefficients were obtained for different period values (T=0.3 s, 0.4s and 0.6 s), afterwards the variation of these spectrum coefficient values with distance from the basin edge were compared with the design spectra defined in Eurocode 8 and Turkish Earthquake Code for Buildings (2007). So that, the appropriateness of the selected design spectra for reflecting the dynamic behavior at basin edges was tried to be investigated. 1D and 2D dynamic analyses were performed by using Dyne-q and Quake/W softwares that are based on equivalent linear soil model, respectively. Dyne-q software operates in frequency domain and Quake/W software works in time domain.

2. CHARACTERISTICS OF STRONG GROUND MOTION USED IN THE STUDY

With the aim of reflecting the effects of change in the earthquake bedrock motion frequency content and intensity level to the dynamic behavior of soil layers, four different strong ground motion accelerograms were used for the dynamic analyses of the two dimensional basin models. Two of them belonged to Turkey earthquakes which had been recorded at 1999 Kocaeli and 1995 Dinar Earthquakes. The other strong ground motions belonged to 1992 Mendocino and 1986 Palm Spring Earthquakes that took place at San Andreas Fault system which has similar characteristics with North Anatolian Fault Zone located in Turkey. Although seismic bedrock has a great depth from the surface, the recorded surface ground motion of 1995 Dinar Earthquake was deconvoluted to bedrock with 1D dynamic analysis by using the soil profile obtained from the extensive field and laboratory studies carried out in the region, including microtremor array measurements (Ansal and oth., 2001). The obtained accelerogram was used as a bedrock motion in the dynamic analyses. The accelerograms used in the dynamic analyses were band-pass filtered between 0.10 Hz and 25 Hz, and their baseline corrections were made. Then, their peak accelerations were scaled to the nearest values among 0.1g, 0.2g, 0.3g and 0.4g. The properties and absolute acceleration spectra of the strong ground motions used in this study were given in Table 2.1 and Figure 2.1, respectively.

Table 2.1. General characteristics of strong ground motion accelerograms used in the study (Hasal, 2008)

Earthquakes	Palm Springs, 1986	Dinar, 1995	Mendocino, 1992	Kocaeli, 1999
Station	Silent Valley	Dinar Station	Cape Petrolia	Sakarya Station
Formation	Weathered Granite	Deconvolution	Rock	Sandstone
Magnitude	M_L=5.9	M_L=5.9	M_L=6.5	M_d=7.4
Depth (km)	11.1	12.0	14.6	18.0
Distance (km)	19.5	2.0	15.0	35.0
a_{max} (g)	0.10	0.20	0.30	0.40

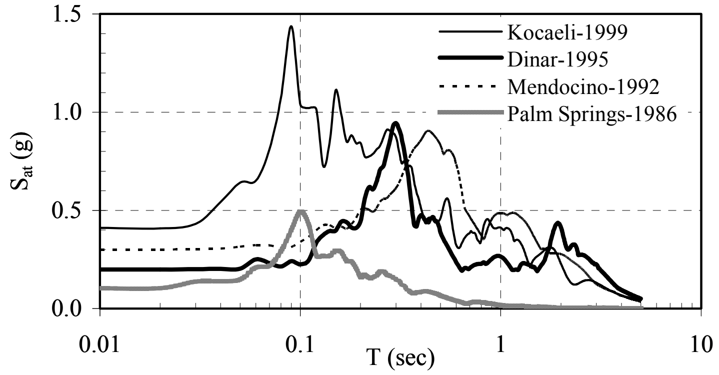

Figure 2.1. Absolute acceleration spectra of the accelerograms used in dynamic analyses

3. BASIN EDGE MODEL AND SOIL PROFILE

The bedrock slope at basin edge is one of the most important factors affecting the dynamic behavior of soil layers during earthquakes and in 2D dynamic analyses the depth and slope of bedrock are required. The microtremor array measurements become very useful for estimating the seismic bedrock depth in case the boreholes are not deep enough to reach bedrock. In order to investigate the effect of basin edge slope on surface motion, a basin model was set up initially by using the results of microtremor array measurements and extensive field studies carried out in a basin (Dinar) located at mid-western part of Turkey before. 1D and 2D dynamic analyses were performed on this model by using acceleration time histories with different frequency content. Seismic bedrock depth was determined by three microtremor array measurements carried out in the region (Hasal, 2008). In order to consider the edge effect, the changes in the dynamic behavior of the basin model were evaluated by using four different edge slope values (α) which were selected as 6°, 11°, 27° and 45° respectively and the obtained results were compared. While the bedrock depth (D) of the models was kept constant as 180 m, basin edge width (H) took values between 180 m and 1800 m. So that, basin edge models with H/D values of 1, 2, 5 and 10 were used in the 2D dynamic analyses. In the basin model, the soil profile over bedrock was divided into 18 different layers with 10 m thickness for each and shear wave velocity values of 200 m/sec and 1000 m/sec were assigned to uppermost layers and seismic bedrock respectively. The soil layers above weathered bedrock were assumed to be composed of intermediate plasticity clay (CI, I_p=%20~25). The geometry, soil and shear wave velocity profile of basin model and its boundary conditions were shown in Figure 3.1. In the figure, D shows bedrock depth, H is basin edge width and X can be defined as the distance from edge bedrock outcrop to basin center.

The variation of damping ratio with cyclic shear strain and stiffness degradation was obtained by using Ishibashi-Zhang (1993) relation. Also it was assumed that the transition zone between rigid bedrock and soil layers was composed of weathered and soft rocks, so the change in damping ratio values with cyclic shear strain and stiffness degradation for this zone was modeled with the relation proposed by Schnabel and others (1972). The stiffness degradation curve of the soil layers and the change in damping ratio with cyclic shear strain is depicted in Figure 3.2.

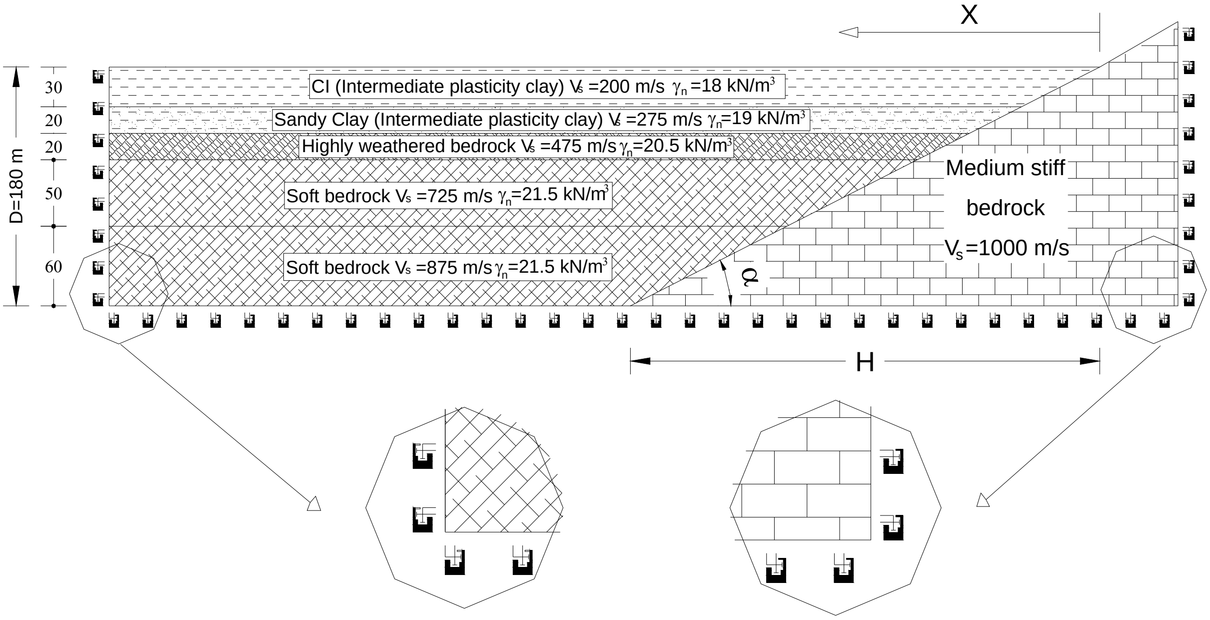

Figure 3.1. Idealized basin edge model and soil profile used in the dynamic analyses

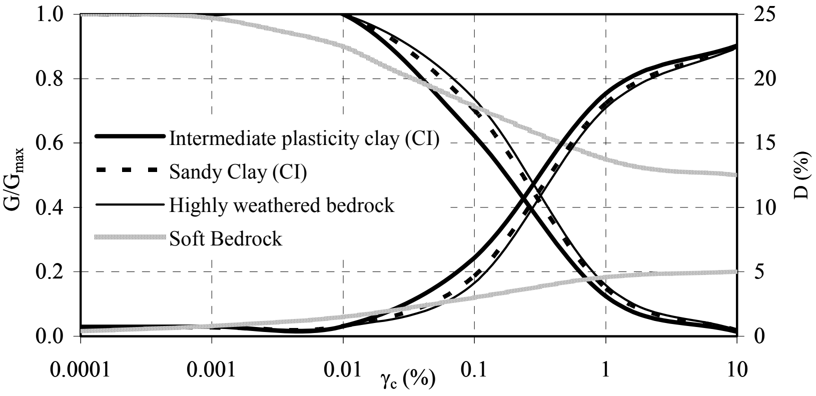

Figure 3.2. Variation of normalized shear modulus and damping ratio of soil layers with cyclic shear strain

4. TWO DIMENSIONAL DYNAMIC ANALYSES

Boundary conditions are very important for 2D dynamic analyses. It is appropriate to put viscous dashpots at the vertical boundaries in order to emit the energy of pressure and shear waves and to prevent reflection of them at the boundaries. The restraint conditions of horizontal boundaries also become important in addition to vertical boundary conditions. In case the base of the model is fixed with restraints in both directions and especially when studied with strong ground motion accelerograms which cause nonlinear behavior of the soil layers, the soil amplifications at the surface layers may reach to unrealistic high values during the numerical analyses. For this reason, viscous dashpots which have coefficients proportional to pressure and shear wave velocity values of soil layers were put at the base of the model. In addition to the dashpots, the effect of 1D free field motion was added to the model by applying time dependent stress functions at both of the vertical boundaries. These boundary forces were calculated by multiplying the 1D particle velocity values of the soil layers with the relevant horizontal dashpot coefficients, then they were applied to the model at the boundaries as stress functions changing throughout the earthquake ground motion. After 2D analyses, the peak horizontal surface acceleration values (a_{max_s}) were normalized by the peak horizontal acceleration at rock outcrop (a_{max_r}) and the normalized values were defined as soil amplification (a_{max_s}/a_{max_r}). The variations of the soil amplifications with bedrock slope and X/D are illustrated in Figure 4.1.

Acceleration spectrum intensity, ASI, which had been proposed to define the behavior of rigid structures with predominant periods lower than 0.5 sec under strong ground motion, is given as below (Von Thun and oth., 1988). In the equation S_a and ξ show acceleration spectrum and damping ratio respectively and T is period value.

$$ASI = \int_{0.1}^{0.5} S_a(\xi = 0.05, T)dT \tag{4.1}$$

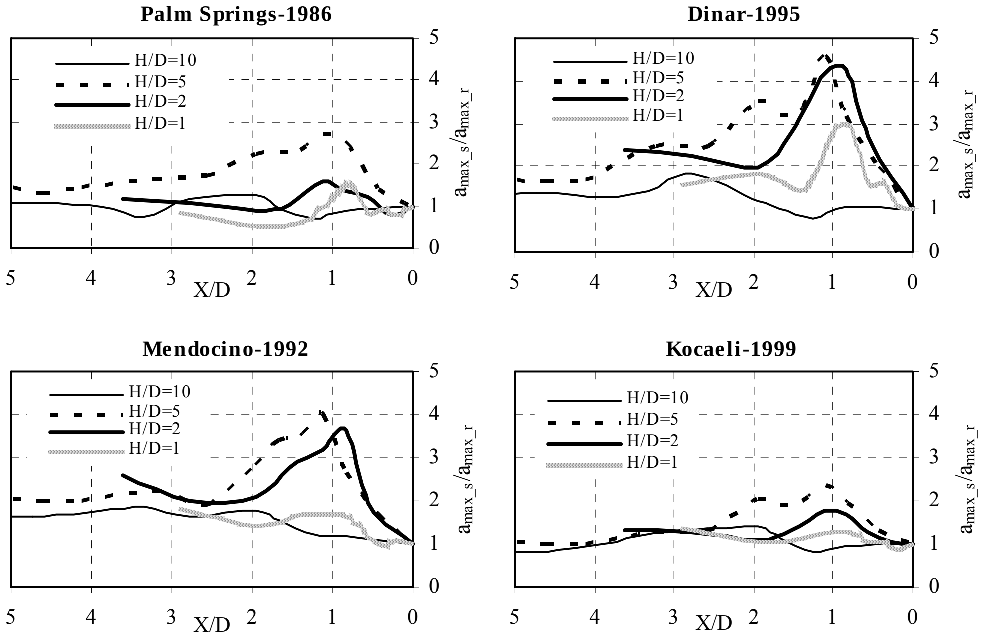

Figure 4.1. Variation of soil amplifications with bedrock slope and X/D for different accelerograms

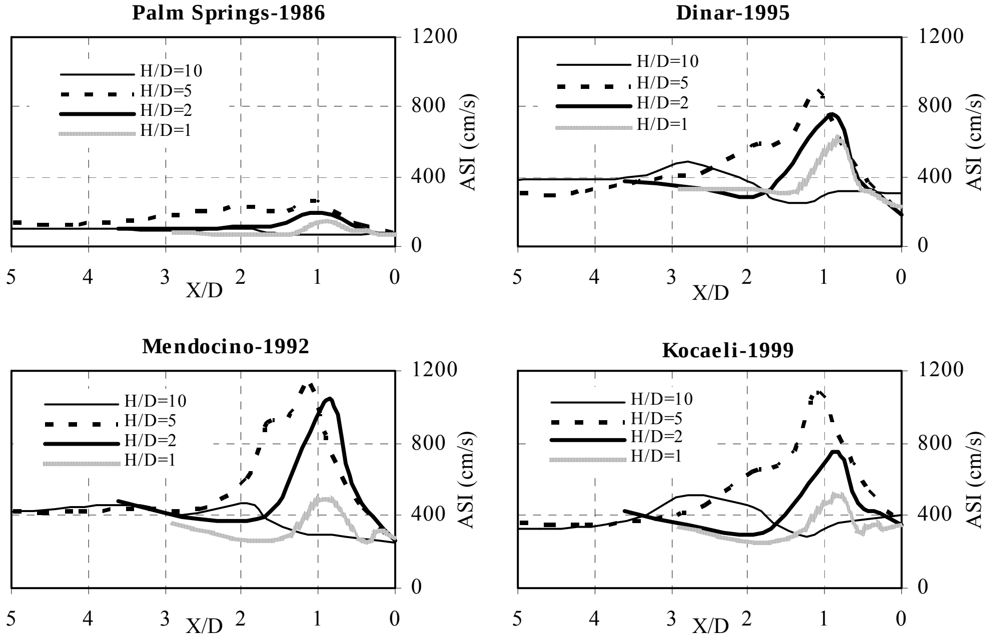

Figure 4.2. Variation of ASI values with bedrock slope and X/D for different accelerograms

The variations of calculated ASI values with distance from edge outcrop to middle sections of basin are illustrated in Figure 4.2 for models with different edge bedrock slope values. As it can be seen from Figure 4.1 and 4.2, soil amplification and ASI values reach to their peak values at a definite edge section while moving away from rock outcrop to basin center and afterwards, with the increase in X/D value they converge for every earthquake excitation without depending on the bedrock slope value.

Also, effective spectrum coefficients (S(T)) were obtained by using the absolute acceleration spectra that were calculated with 2D dynamic analyses and the variation of them were compared with the design spectra given in Turkish Earthquake Code (2007) and Eurocode 8 for related local soil classes. Both of the design spectra types proposed in Eurocode 8 for the earthquakes with high ($M_s>5.5$) and medium magnitudes, were selected to be used in this comparison. The variations of the calculated effective spectrum coefficients and also design spectrum coefficients with the distance from edge rock outcrop to basin center at models having H/D=10, 5, 2 and 1, are depicted respectively in Figure 4.3 for T=0.4 sec. During the calculation process of spectrum coefficients, the absolute acceleration values which were obtained for different sections of basin were normalized by dividing into to the peak acceleration value of rock outcropping motion and after this, effective spectrum coefficients were evaluated by taking the 65 % of normalized elastic absolute acceleration spectra (Pitilakis, 2004).

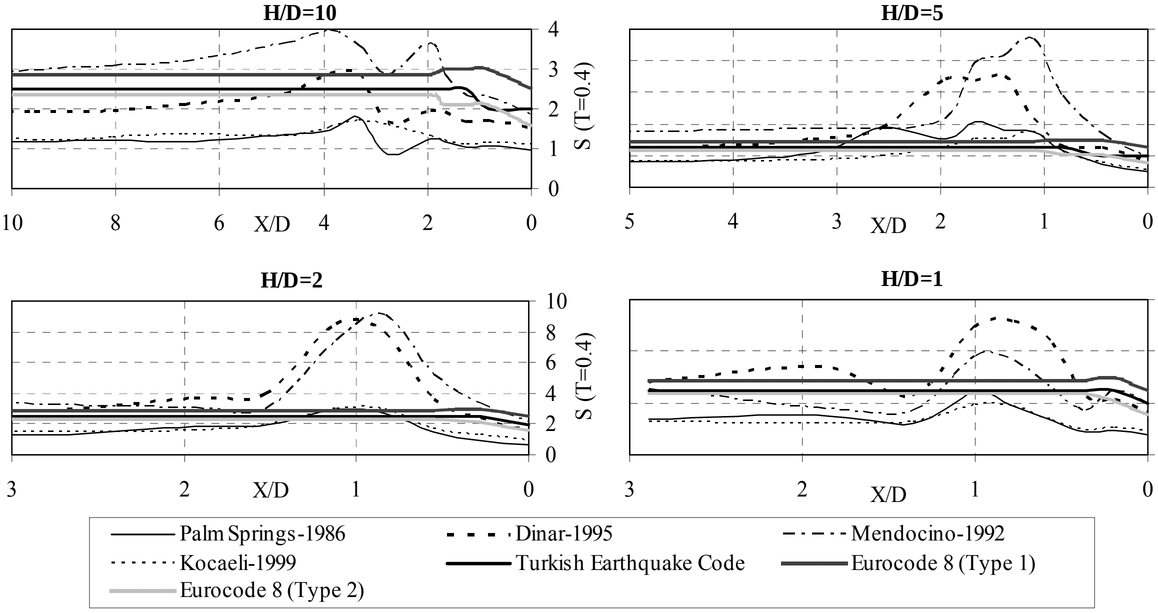

Figure 4.3. The comparison of calculated spectrum coefficients from 2D dynamic analyses with the design spectrum coefficients given in Turkish Earthquake Code and Eurocode 8

5. COMPARISON OF ONE AND TWO DIMENSIONAL DYNAMIC ANALYSES

In order to estimate the surface ground motion at basin edges with different bedrock slope values, two dimensional finite element method which is based on equivalent linear method was used in the dynamic analyses for different earthquake excitations and the findings were compared with the results of one dimensional dynamic analyses. With this purpose, absolute acceleration spectra were obtained for the different sections of all models by using the acceleration time histories calculated by one and two dimensional dynamic analyses. Dyne-q (2003) software that had been developed basing on modified equivalent linear method was used to execute one dimensional dynamic analysis.

The difference between 2D and 1D dynamic behavior was evaluated by proportioning the acceleration spectra that were calculated by 2D and 1D analyses respectively. The ratio of the acceleration spectra which are obtained as a result of 2D and 1D dynamic analyses is defined as “aggravation factor” (Makra, 2001). In order to investigate the effects of surface ground motion on structures with different rigidity, 2D/1D aggravation factors were calculated for 5 different periods (T=0, 0.3, 0.4, 0.6, 0.9 s) by using different basin edge geometry and earthquake excitations. The relevant 2D/1D aggravation factor curves are shown in Figure 5.1 for the case of T=0.4 s.

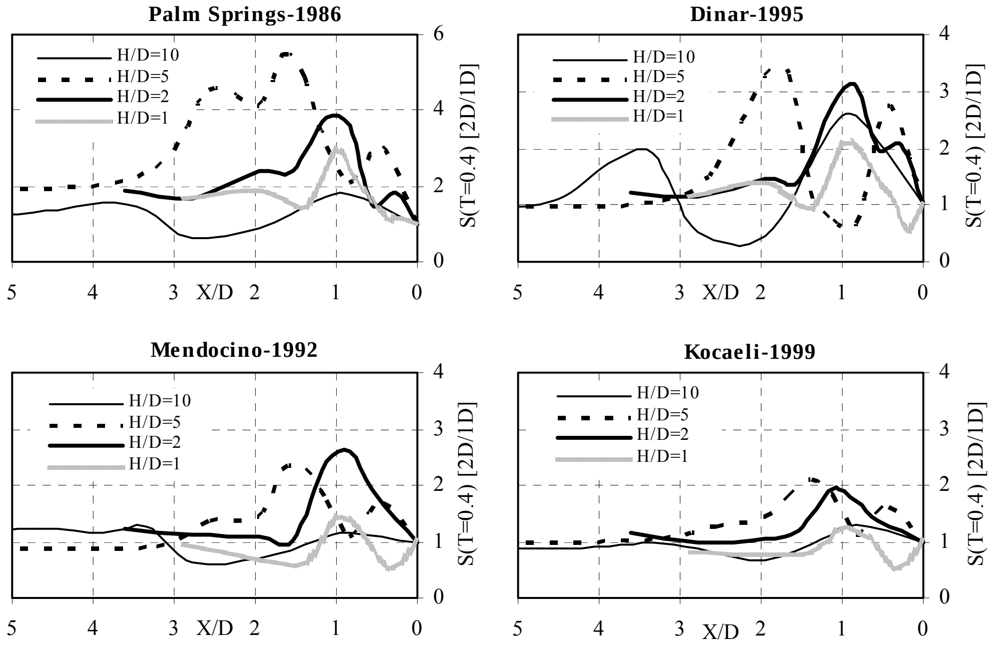

Figure 5.1. Variation of aggravation factors with bedrock slope and X/D for different accelerograms

Aggravation factor values reached to their peak values at a definite edge section and afterwards, while moving away from rock outcrop to basin center, they approximately approached to 1 for every period value. Also it can be realized that 2D/1D aggravation factor values converged after a definite value of X/D (X/D=3) regardless of the edge bedrock slope values. Aggravation factors took values between 2~4 depending on the edge bedrock slope and they reached to their peak values when H/D is equal to 5 (α=11°) especially. The 2D/1D aggravation factors especially decreased for the models with lower edge bedrock slope values. The highest aggravation factor values were calculated at the period interval of 0.2~0.5 s for all basin models. As the edge bedrock slope value decreased, the difference between spectral acceleration values decreased too. Without depending on the period values, average 2D/1D aggravation factor values approached to 1 after the point of X/D=5, 4, 2 and 1.5 when the edge bedrock slope values were α=6°, 11°, 27° and 45° respectively. After these points, two-dimensional effects were much reduced. By benefiting from these results, the validity limits of 2D dynamic effects at basin edges can be obtained.

6. RESULTS

In this study, the effect of basin edge slope on surface ground motion was estimated by performing 1D and 2D dynamic analyses on a basin model for 4 different edge slope values. Acceleration time histories, acceleration spectra and intensity parameters were obtained for different bedrock accelerograms at 17 points of basin surface. Also, the variation of effective spectrum coefficients (S(T)) were compared with both of the elastic design spectra given in Turkish Earthquake Code (2007) and in Eurocode 8. In order to determine the difference between the results of 1D and 2D dynamic analyses, the acceleration spectra calculated by using 2D dynamic analyses were divided by the ones calculated with 1D dynamic analyses, and 2D/1D aggravation factors were obtained.

The maximum increments in horizontal acceleration and acceleration spectrum intensity (ASI) values, appeared between the beginning of edge bedrock outcrop and X/D=3 point, especially for the edge bedrock slope angle values of 11° and 27° (H/D=5 and 2) in comparison with other models. The effective spectrum coefficients that were calculated for basin edge surface took higher values for lower periods (T<0.6 s) in comparison with the spectrum coefficient values proposed in "Turkish Earthquake Code" (2007) and "Eurocode 8". Especially for the basins with H/D=5 and 2, the effective spectrum coefficient values obtained from 2D dynamic analyses for basin edge surface exceeded the given values in both of the earthquake codes for related local soil classes. The calculated 2D/1D spectral acceleration ratios reached their maximum values at a certain zone (X/D<3) near basin edge for every interested period value. At this zone, average aggravation factors took values between 0.5 and 4.0 for different strong ground motions. While moving to the center of basin models, especially at the zones after X/D=3 point, it can be noticed that aggravation factor values generally approached to 1 regardless of the edge bedrock slope values. At these sections, 1D and 2D dynamic analyses gave similar results. For all the basin models with different edge bedrock slope values, the maximum average aggravation factors were obtained for the edge bedrock slope angle value of 11° (H/D=5). With the decrease in edge bedrock slope value (H/D=10, α=6°), the difference between 1D and 2D spectral acceleration values became negligible relatively. For all the models, the highest average aggravation factor values were calculated when the relevant periods were between T=0.2~0.5 s. The average aggravation factor values vary between 2 and 3 for this period interval.

One dimensional dynamic analysis is still the most preferred method which is being used in the estimation of site response under earthquake excitations and the current design spectra are mainly based on the results of one dimensional dynamic analysis. However during strong ground motion unusual effects can occur near edges of formations with limited width such as basin/valley. In order to clarify the edge effect during earthquake excitations, more 2D and 3D numerical studies should be performed on realistic models. The results and findings obtained from numerical studies have to be verified by using ground motion data recorded at sites with resembling geotechnical, geological and topographical conditions. Also 2D/1D aggravation factor relations can be developed in order to reflect the second dimension effect to the spectral acceleration values calculated from 1D dynamic analyses depending on edge bedrock slope value and X/D term.

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