Dynamic Response Analysis of Trapezoidal Basins on Numerical Models

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Abstract. The severity and spatial distribution of ground motion are affected by geological and geotechnical conditions as well as earthquake source properties. The characteristics of ground motion at a particular site depend on many factors such as tectonics of the region, rupture mechanism, source distance, geological formations and local soil conditions and subsurface topography. Thus, the estimation of surface ground motion during earthquakes is a challenging issue in civil engineering. Consequently, the research investigates an answer to the question of how the surface movement would change as a result of combinations of basic wave phenomena in alluvial basins with soil nonlinearity where basin width is comparable to depth. In this study, one and two-dimensional dynamic analyses were performed under different levels of bedrock motion excitation by using idealized symmetrical basin models to research the effects of geotechnical site conditions and bedrock inclination of basin edge for soft site class defined by seismc codes. Geotechnical properties of the soft soil layers in the models were defined as site class E that mostly needed site specific dynamic analysis by classification of NEHRP 2015 provisions. The top layers of basin models are soft cohesive alluvium underlain by stiffer material. In the basin models, the soil layers were assumed to extend horizontally and limited with basin edges having a constant slope. The acceleration time histories and response spectrums were calculated at surface points with equal interval on the top of the basin performing one and two-dimensional dynamic analyses by excitation of 22 strong ground motions. The response spectrum values and amplifications calculated for different sections of the basin from the two and one dimensional (2D and 1D) dynamic analyses. Consequently, the impact factors of the basin effect could be derived depending on location and periods as $S_{a}e(T)_{2D}/S_{a}e(T)_{1D}$.

1. Introduction
The reliable prediction of resultant ground motions of an earthquake is a crucial issue for design of earthquake resistant buildings. In the studies in progress, the interaction of the earthquake movement with the local site condition has been comprehensively investigated by one-dimensional (1D) site response analysis using free field models created by the idealization of the semi-infinite soil space, and the change of the motion amplitude from the source to the surface is defined as soil amplification. The determinative parameters of the earthquake-induced surface movement are regarded as earthquake magnitude, depth of the resulting fracture, source type and distance from the structure site and local soil condition. However, contrary to the simple assumption of the semi-infinite 1D soil model, the soil
media has both horizontal and vertical discontinuities and changes topographically and stratigraphically. The discontinuity of soil media is typically formed by fault ruptures or topographic depressions filled with sediments and this highly present geological formation is identified as a basin. The sedimentary basins generally appear as surrounded by roughly circular or elliptical harder layers or the bedrock outcrops.

The effects of discontinuities in the alluvial basin section on the surface motion firstly explained by the interaction of waves as a result of reflection and refraction in elastic media by Aki and Larner (1970) and expanded by King and Tucker (1884), Bard and Bouchon (1985), Trifunac (1990), Zhang and Papageorgiou (1996) and Kawase (1996) argued the hypothesis that changes in surface motion intensity in the 1995 Kobe Earthquake occurred as a result of Rayleigh surface waves moving horizontally towards the middle of the basin and reflected and refracted SH and SV shear waves at the basin edge [1-6]. In later studies, the aggravation factor relations are proposed for the basin effects by performing analysis with stratigraphically detailed 2D and 3D models. Pitilakis et al. (2001), within the scope of Euroseistest, Raptakis et al. (2004), Iyisan and Hasal (2011), Khanbabazadeh and Iyisan (2014), Abraham et al. (2016), Zhu et al. (2018) focused on different aspects of basin effects and proved its significance on site response analysis. As a result, studies on the numerical determination of the changing soil amplification used to calculate earthquake forces affecting buildings, depending on the features of the basin, and the definition of the regions where the edge effects occur due to geometric properties will contribute to the elimination of the uncertainties related to the structural damages [6-12].

In this study, one and two-dimensional dynamic analyses were performed under different levels of bedrock motion excitation by using idealized symmetrical basin models to investigate the effects of geotechnical site excitations and bedrock inclination of basin edge for different site class defined by seismic codes. Geotechnical properties of the soil layers in the models were defined as site class E that mostly needed site specific dynamic analysis by classification of NEHRP provisions. The top soil layers supporting building foundations are soft-to-firm cohesive soil or alluvium underlain by stiffer material. In the basin models, the soil layers were assumed to extend horizontally and limited with basin edges having a constant slope. The acceleration time histories and acceleration spectrums were calculated at different points on the ground surface using fully nonlinear one and two-dimensional dynamic analyses for 22 strong ground motions by finite difference approach. The absolute acceleration spectrum values and amplifications calculated for different sections of the basin from the two and one dimensional (2D and 1D) dynamic analyses. Thus, the impact factors of the basin effect could be derived depending on periods and location as $S_{ae}(T)_{2D}/S_{ae}(T)_{1D}$. The results of the 2D and 1D dimensional dynamic analyses were compared, and the variations of the amplifications were calculated depending on the distance from the basin center [13].

2. The Analysis method
A numerical analysis of the geotechnical dynamic problem in civil engineering can be summarized by discrimination of semi-infinite soil media, selection of constitutive laws of materials to be defined for the elements on the created finite model, determination of initial and boundary conditions in accordance with the problem examined, calculation of the current initial equilibrium state and changes of the initial state and consequently examination of stress-strain values in the elements and force-displacement at the model boundaries. Currently, there are several numerical methods but finite element and finite difference methods, boundary element method and hybrid methods are the most used numerical analysis methods. The preferred numeric analysis method needs to satisfy investigation of the responses depending on the strain level at each point in time and space by using hysteretic type constitutive models for soils and running fully nonlinear dynamic analysis with geometrical differences by using advanced dynamic boundary conditions. For this purpose, Fast Lagrangian Analysis of Continua 3D (FLAC3D) software which gives results in a shorter time by calculating with the explicit finite difference method, has been used for performed 2D and 1D analysis [14]. In this type of analysis, the minimum size of the
elements in the discriminated volume, named as the zone in this program, and the smallest time steps for each calculation need to ensure propagation of the highest frequency wave transmitted in the model. Thus, the motion started from the base of finite zones can be transferred to the surface accurately throughout the defined soil model. Therefore, this type of analysis requires a comprehensive knowledge of numerical methods and the stress-strain relationship of soil material under dynamic loadings.

2.1. Material properties and model geometry

In models established to investigate the site response on basins, soil class have been defined very soft to very loose as ZE according to NEHRP 2015. The properties of the soil media have been given by the Table 1 and the shear wave velocity ($V_s$), dynamic shear modules ($G$), volumetric bulk modules ($K$), mean shear wave velocities of layers from surface to 30 m depth ($V_{s30}$), poisson ratios ($\nu$), unit weights ($\gamma$) and shear strength parameters of soil ($c$, $\phi$) have been presented. During dynamic loading standard models, such as the Mohr-Coulomb model present the derived plastic deformations at high strain levels, while the hysteretic model generates the cyclic damping in the loads at small strain levels, thus using this type of combined constitutive models, dynamic analysis can be performed without the need for additional damping.

**Table 1.** The material properties of soils and bedrock.

| #  | $\tan\alpha$ | $V_s$ (m/s) | $G$ (MPa) | $K$ (MPa) | $V_{s30}$ (m/s) | $\nu$ | $\gamma$ (kN/m$^3$) | $c$ (kPa) | $\phi$ (°) |
|----|-------------|-------------|-----------|-----------|----------------|-----|-----------------|---------|---------|
| ZE | 1/2         | 150-550     | 35-550    | 130-1180  | 170            | 0.32-0.38 | 16-18            | 60-80   | 5       |
| ZB | -           | 750-1200    | 1200-3000 | 2000-4800 | >760-         | 0.25 | 22              | -       | -       |

In the following Figure 1, defined shear modulus for each sublayers changing by depth considering the increase in effective stresses in 2D (a) and 1D (b) model and parameters of geometrical properties (c) were given respectively. The artificial seismographs (S1-S21) on the surface which provide resultant time histories have been located as 25 m equal interval between each other. The hypothetical models were defined with bedrock inclination $\tan\alpha$, the slope of the interface between the bedrock and the soft soil layers, as 1/2 with site class E which has $V_{s30}$ values under 180 m/s$^2$. The basin half width is defined by L and basin depth is H. The width of the studied symmetric basins is 1000 m and the depth is 100 m.

**Figure 1.** Shear modulus of sublayers and geometric properties of the trapezoid basin models.

2.2. Boundary condition and damping

While civil engineering problems occur in semi-infinite space, engineering solutions are made by discretizing a finite region in numerical analysis. Thus, the boundary conditions on the solution of the
problem are crucial and need to be provided suitable with the surveyed wave propagation on infinite site conditions. In dynamic analysis, advanced boundary conditions have been developed to prevent the waves from being trapped inside the model without reflections that occur at the finite model borders. The viscous boundaries developed by Lysmer & Kuhlemeyer (1969) are defined as “Quiet Boundary” at the bottom and “Free Field Boundary” at both sides given in Figure 2 (a) and assigned dashpots to produce normal and shear stresses traction along the model boundaries that match the properties of the existing material given by Equation 1, 2 [15].

The hysteretic curves, defined by Ishibashi and Zhang (1993), used in the analysis is given in Figure 2 (b). The presented degradation method allows to take into account the plasticity index of the soils and to consider the increase in effective stresses changing by depth [16]. The hysteretic model provides wide spacing data only in table forms with discontinuity but in numerical solutions, the modulus-reduction curve must be fitted with a continuous function to avoid intolerable errors. Therefore, data of the preferred modulus-reduction model has been fitted with appropriate asymptotic function by using the special codes in the FLAC3D software.

![Figure 2. Quiet and free field boundary conditions (a) and material damping (b).](image)

\begin{align}
    t_n &= -\rho \ C_p \ v_n \\
    t_s &= -\rho \ C_s \ v_s
\end{align}

Where, \( C_p \) and \( C_s \) are the pressure (P) and shear (S) wave velocities, \( \rho \) is the mass density, \( v_n \) and \( v_s \) are the normal and shear components of velocity at the quiet boundary.

2.3. Properties of strong ground motions

Estimating an earthquake that will arise at an interesting construction site is a difficult process, therefore seismic provisions prescribe directive approaches that can be used in the selection but not obligatory. Assertedly in the seismic codes by using the spectral matching method, 22 strong ground motions recorded on outcrop have been selected by 0.2 g and 0.4 g. Thus, it is aimed to see how the basin effect is changed by different earthquakes levels on the 2D model. The selected sets of two different levels of strong ground motions were given by the following Figure 3. In Figure 3. (a) spectral accelerations for the level of 0.2 g and in Figure 3. (b) for the level of 0.4 g have been illustrated with their matched target spectrums of site class B.
3. Results and discussions

In the performed dynamic analysis, propagation of SH waves in one-dimensional soil columns defined for each artificial seismographs point, selected with certain distances throughout the basin surface, was investigated by 1D analysis. Moreover, in established 2D models, the effects of two or three dimensional discontinuity of the stratigraphy, formed by refraction and reflection of SV waves, were examined in the basins. It is also aimed to identify the spectral aggravation factor $S_{ae}(T)^{2D}/S_{ae}(T)^{1D}$ which is defined as the ratio between the 2D and 1D acceleration response spectra throughout the basin surface.

The underlying method of the study is computing 1D and 2D response spectra for several different ground motions on the defined basin model and investigate the effects of lateral discontinuities with compared smoothed spectra. Figure 4-7 illustrates the result for one ground motion from each level of earthquake set as E1 and E12. In Figure 4, considering the positions of the artificial seismographs on the surface which provide resultant time histories, the response spectrums of E1 input motion given for S1, S4, S8, S12, S17 and S21 respectively.

![Figure 3](image1.png)

**Figure 3.** Strong ground motions selected by spectral matching to 0.2 g (a) and 0.4 g (b).

![Figure 4](image2.png)

**Figure 4.** Spectral acceleration at different points of basin surface for 0.2 g earthquake E1 in 2D.
The response of the 2D analysis calculated with highest values reaching 3.5 for excitation level of 0.2 g. On the other hand, in 1D analysis Sae(T) values has been obtained maximum as 2 in Figure 5. In Figure 4 and 5, the results clearly note that the peak values of dynamic amplifications in 2D models are spreading and totally differs from 1D responses.

![Figure 5](image.png)

**Figure 5.** Spectral acceleration at different points of basin surface for 0.2 g earthquake E1 in 1D.

The response fractionation depends mostly on the vibrational characteristics of wave propagation, changing natural frequencies of the basin soil media and the characteristic frequencies of the excited ground shaking. In the 2D analysis of the basin recorded surface motions seem to have a more complex behavior due to reflection, focusing and superposition of shifting seismic waves.

Moreover, in given Figure 6 and 7, similar results obtained as almost reaching 2 times higher spectral accelerations under the level of 0.4 g. The highest Sae(T) values have observed on the position of S21 artificial recorder which is located on center on the symmetric basin model in Figure 4. As a result of the resonance of the motion period and natural period of the soil media the position of the maximum value has moved from center to position S12 in Figure 6.

![Figure 6](image.png)

**Figure 6.** Spectral acceleration at different points of basin surface for 0.4 g earthquake E12 in 2D.
Figure 7 Spectral acceleration at different points of basin surface for 0.4 g earthquake E12 in 1D.

In the result, time histories of the surface motions were recorded at top of throughout the basin by synthetic recorders which had been placed equally across the surface. The effect of stratigraphy which is derived from discontinuities of the layers on the basin edges was investigated by calculating spectral acceleration ratios for each period. Mostly used spectral periods given as 0.2 s and 1 s were presented with graphs for investigated models. In the Figure 8 (a) the increase in response accelerations of 2D analysis has reached 5.5 g at 0.2 second period on location x/L=-0.45 for E1. Due to the increase in the intensity of strong ground motion and changed motion periods, the position of the largest value in Figure 9 (a) has been found as 5.0 g on location x/L=-0.75 for E12.

Figure 8 Spectral amplifications at T=0.2 s (a) and T=1.0 s (b) for 2D and 1D analysis depending on location as x/L under 0.2 g earthquake level.
Figure 9. Spectral amplifications at T=0.2 s (a) and T=1.0 s (b) for 2D and 1D analysis depending on location as x/L under 0.4 g earthquake level.

On the contrary to short periods, the response acceleration of 2D analysis has reached 4.5 g at 1 second period on location x/L= -0.60 for E1 in Figure 8 (b) and 5.5 g at 1 second period on location x/L= -0.60 for E12 in Figure 9 (b). In 2D models especially at 1 s period amplifications increase dramatically and higher aggravations are collected in a region towards the basin edges.

As a result of the analyses, when the response spectra are compared during the period of 0.2 second, it is observed that local peaks were formed in the basins with relatively high edge slope, by the reverberation of ground motion at high frequencies, and resultant \( \text{Sae}(T)_{2D}/\text{Sae}(T)_{1D} \) span in a band between 1.6 - 1.8 throughout the basin in Figure 10.

Figure 10. \( \text{Sae}(T)_{2D}/\text{Sae}(T)_{1D} \) (T=0.2 s), site class ZE, \( \tan \alpha =1/2 \), level of excitation 0.2 g and 0.4 g.
Additionally, Sae(T)_{2D}/Sae(T)_{1D} ratios increase dramatically to 1.4 and collected in a region beyond the inclined zone of tanα=1/2, between values of x/L are -0.5 to -0.7, as given by Figure 11. Appropriately to the edge effect phenomena, this localization slightly shifts to the edge under a higher level of excitation as a result of higher frequencies of the second ground motion set, in Figure 11.

![Figure 11](image_url)

**Figure 11.** Sae(T)_{2D}/Sae(T)_{1D} (T=1 s), site class ZE, tanα=1/2, level of excitation 0.2 g and 0.4 g.

4. Conclusions

Consequently, the symmetrical basin models consisting of site classes E were examined, and the results of time domain analysis were presented by comparing. In the models, time histories of the surface motions were recorded at top of throughout the basin by synthetic recorders which had been placed with equal interval across the surface. In order to investigate the sensitivity of the alluvial basins to the parameters related to the dynamic properties of the soil deposits, the response of the basins was investigated with nonlinear soil behavior. The effect of stratigraphy which is derived from discontinuities of the layers was investigated by calculating Sae(T)_{2D}/Sae(T)_{1D} response of a given structure to a specific ground motion, given as 0.2 s and 1 s by presenting with graphs for investigated models.

As a result, the reciprocation of the surface waves which are derived from both edges of the basin and superposition of the motions, progressive into the center of the basin, cause larger amplification particularly at lower frequencies in 2D analysis with respect to results of the 1D soil column approach. Thus, this kind of analysis is crucial to reliable prediction of resultant earthquake for design of earthquake resistant buildings in basin type residential area. The results of this investigation present that, with higher earthquake levels the maximum response of basin becomes higher but Sae(T)_{2D}/Sae(T)_{1D} ratios take place around similar values. Furthermore, while the level of strong motion slightly gives similar spectral ratios but changes the frequency of the peak response. The inclination of the rigid edge of the basin has dominancy on the localization of the maximum Sae(T)_{2D}/Sae(T)_{1D} values.

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