

# Applied 2D equivalent linear program to analyze seismic ground motion: Real case study and parametric investigations

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(Received June 17, 2021, Revised April 28, 2022, Accepted May 18, 2022)

**Abstract.** Seismic ground response evaluation is one of the main issues in geotechnical earthquake engineering. These analyses are subsequently divided into one-, two- and three-dimensional methods, and each of which can perform in time or frequency domain. In this study, a novel approach is proposed to assess the seismic site response using two-dimensional transfer functions in frequency domain analysis. Using the proposed formulation, a program is written in MATLAB environment and then promoted utilizing the equivalent linear approach. The accuracy of the written program is evaluated by comparing the obtained results with those of actual recorded data in the Gilroy region during Loma Prieta (1989) and Coyote Lake (1979) earthquakes. In order to precise comparison, acceleration time histories, Fourier amplitude spectra and acceleration response spectra diagrams of calculated and recorded data are presented. The proposed 2D transfer function diagrams are also obtained using mentioned earthquakes which show the amount of amplification or attenuation of the input motion at different frequencies while passing through the soil layer. The results of the proposed method confirm its accuracy and efficiency to evaluate ground motion during earthquakes using two-dimensional model. Then, studies on irregular topographies are carried out, and diagrams of amplification factors are shown.

**Keywords:** 2D transfer function; irregular topographies; seismic site response

## 1. Introduction

Long ago, researchers have realized that the severity of damage during earthquakes is affected by geological and topographic conditions. Contrary to studies on the effects of subsurface layers, which in most cases are carefully evaluated by one-dimensional (1D) analyses, topographic effects inherently need two-dimensional (2D) and in some instances, three-dimensional (3D) analyses.

Many researchers have widely used the 1D ground response analysis (e.g., Roy and Sahu 2012, Bazrafshan Moghaddam and Bagheripour 2014, Kaklamanos *et al.* 2015, Phillips and Hashash 2009, Jakka *et al.* 2015, Sonmezer and Celiker 2020). It is worth noting, these analyses often characterize the basic concepts of the response, but may not be able to describe complex and multiple wave reflections in the domain. Gradually, the use of 2D methods has found its special status in geotechnical science because today, it is necessary to construct and analyze structures that inevitably have to use 2D methods (Kramer 1996). Finite Element Method (FEM) is one of the most efficient and flexible approaches used by some researchers to simulate multi-dimensional seismic ground response analyses (e.g., Di Fiore 2010, Soltani and Bagheripour 2018, Nasiri *et al.* 2020, Ravichandran *et al.*

2016, De la Torre *et al.* 2020, Soltani *et al.* 2021). Other methods, such as Finite Difference Method (FDM) (e.g., Bouckovalas and Papadimitriou 2005), Discrete Element Method (DEM) (e.g., Hassan and El Shamy 2019), and Boundary Element Method (BEM) (e.g., Kham *et al.* 2013) are also used to analyze the seismic ground response. Most of the multi-dimensional analyses currently involve 2D methods, and 3D approaches are only used for specific cases and are not general (Mir Mohammad Hosseini and Pajouh 2012, Lu *et al.* 2018, Kramer 1996). Further details on different types of multi-dimensional methods are discussed in some investigations (e.g., Yoshida 2015, Liu *et al.* 2017). Various studies have also been conducted on the application of 1D and 2D methods in different regions, and discussed the conditions that each method could be used considering acceptable accuracy (e.g., Madiari *et al.* 2016, Volpini and Douglas 2019, Jiang *et al.* 2007, Soltani and Bagheripour 2020, Hasal and Iyisan 2014, Volpini *et al.* 2019). In general, in cases where the assumptions of the 1D methods are met, these methods can be used. Otherwise, the results assessed by 1D methods are not precise enough and therefore, multi-dimensional approaches are given priority.

On the other hand, the methods used to evaluate ground response analyses could be divided into linear and non-linear groups in terms of the considered behavior of materials. In linear methods, the shear modulus parameter and the damping ratio of the soil layer are constant relative to the shear strain (Schnabel *et al.* 1972). The non-linear seismic response of the ground could be estimated in both equivalent linear and non-linear approaches. The equivalent linear methods are one of the most important and widely

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used methods in the field of non-linear modeling of soil behavior under seismic load proposed by Schnabel *et al.* (1972). In equivalent linear methods, linear analysis is done using soil parameters that are intermittently corrected with the effective strain value established on the soil. These analyses are performed in the frequency domain. Soltani and Bagheripour (2020), Huang *et al.* 2020, Phanikanth *et al.* (2011), and Di Fiore (2010) conducted the ground response analysis using the equivalent linear method. In non-linear methods using a time-domain approach, any linear or non-linear stress-strain model or complex behavioral model can be solved by integrating the equation of motion in short time steps. Soltani (2021), Nasiri *et al.* (2020), and Borja *et al.* (1999, 2000) performed non-linear ground response analysis in time domain using FEM and Lo Presti *et al.* (2006) conducted a non-linear analysis of ground response using Wilson- $\theta$  method (Wilson 1968).

In this study, the 2D transfer function is proposed in the frequency domain using FEM and then, a program is written in the MATLAB environment, called 2DTF, to apply the proposed method. Two earthquakes are used as input motions with different frequency content and peak ground acceleration. In order to evaluate the performance of the program, the results of the current method are compared with those of recorded data in the Gilroy region. Then different slopes are considered, and 2D seismic response is evaluated. The proposed method is accurate and practical, and it can be used to simulate and analyze a wide range of 2D ground response problems.

## 2. Calculation of 2DTF

### 2.1 The linear 2DTF

To analyze a system under dynamic load, the equation of motion in FEM is written as follows (Kramer 1996)

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f\} \quad (1)$$

In Eq. (1), mass, damping, and stiffness matrices are introduced using  $[M]$ ,  $[C]$ , and  $[K]$ , respectively. Also  $\{\ddot{u}\}$ ,  $\{\dot{u}\}$ ,  $\{u\}$  and  $\{f\}$  are acceleration, velocity, displacement, and force vectors, respectively. The finite element method formulas are removed from this study due to the wide range of sources (e.g., Desai and Kundu 2017).

To evaluate the seismic ground response, displacement is considered as follows (Yoshida 2015)

$$\{u\} = \{u_r\} + \{Iu_b\} \quad (2)$$

In Eq. (2),  $\{u\}$  is the absolute displacement. The subscript  $r$  and  $b$  used to show the relative displacement to the bedrock and the displacement vector of the bedrock, respectively. It should be noted that,  $\{I\}$  is defined as its components are unity if the directions of the degree of freedom and loading are the same. In contrast, these components convert to zero if these directions are different.

Using Eqs. (1) and (2), one may conclude

$$[M]\{\ddot{u}_r + I\ddot{u}_b\} + [C]\{\dot{u}_r + I\dot{u}_b\} + [K]\{u_r + Iu_b\} = 0 \quad (3)$$

Damping can be divided into internal and external terms. During the rigid body motion, the internal damping could be eliminated from the equation. On the other hand, external damping will not be removed if the domain vibrates inside the viscous liquid (e.g., water). However, in the case of vibration of the domain in the air, this term is negligible and can be logically ignored. Therefore, assuming the movement of the simulated model in the air, one can infer

$$[K]\{u_b\} = 0 \quad (4)$$

$$[C]\{\dot{u}_b\} = 0 \quad (5)$$

Then, using Eqs. (3) to (5), the following equation can be obtained

$$[M]\{\ddot{u}_r\} + [C]\{\dot{u}_r\} + [K]\{u_r\} = -\{MI\ddot{u}_b\} \quad (6)$$

The subscript  $r$  is eliminated in the following to simplify the equations. Therefore,  $u$  is then considered as a relative displacement.

Eq. (6) can be rewritten as

$$[M]\{\ddot{u}\} + [K^*]\{u\} = -\{MI\ddot{u}_b\} \quad (7)$$

In Eq. (7),  $[K^*]$  is the complex stiffness matrix and can be formulated based on Eq. (8)

$$[K^*] = [K] + i\omega[C] \quad (8)$$

where  $\omega$  is the circular frequency obtained from the incident seismic wave. Using the complex shear modulus, damping is introduced to the model through the complex element stiffness matrices.

Considering the harmonic displacement of the base, Eq. (9) can be defined as

$$\{TF_{2D}(\omega)\} = \frac{\{u(\omega)\}}{\{\ddot{u}_b(\omega)\}e^{i\omega t}} \quad (9)$$

In the above equation,  $\{TF_{2D}(\omega)\}$  is 2D transfer function and  $\{\ddot{u}_b(\omega)\}$  shows the Fourier transform of  $\{\ddot{u}_b(t)\}$ .

Substituting Eq. (9) into the equation of motion, Eq. (10) can be inferred as follows

$$-\omega^2 [M]\{TF_{2D}(\omega)\}\{\ddot{u}_b(\omega)\}e^{i\omega t} + [K^*]\{TF_{2D}(\omega)\}\{\ddot{u}_b(\omega)\}e^{i\omega t} = -\{MI\ddot{u}_b(\omega)\}e^{i\omega t} \quad (10)$$

Then, utilizing Eq. (10), linear 2D transfer function simplified as follows

$$\{TF_{2D}(\omega)\} = \{MI(\omega^2 M - K^*)^{-1}\} \quad (11)$$

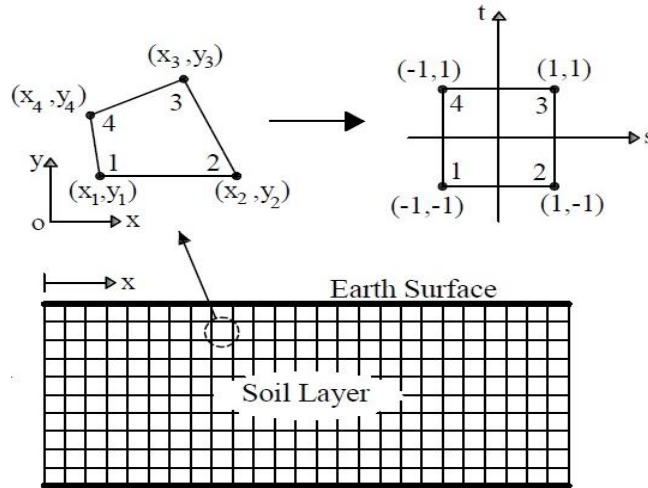


Fig. 1 A schematic model with the bilinear quadrilateral elements

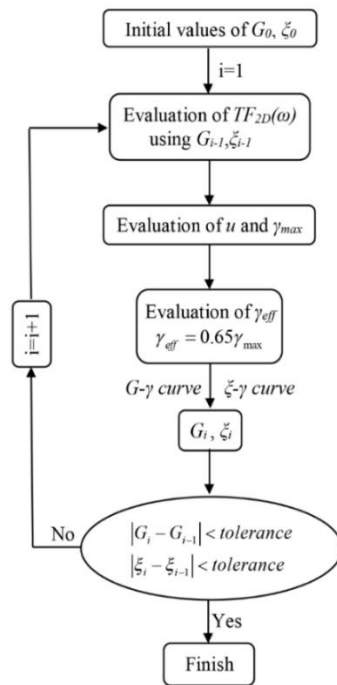


Fig. 2 Summarized flowchart to promote the linear program to equivalent linear

Through the use of Eq. (11), 2DTF program is written. In this approach, the considered domain is simulated based on the bilinear quadrilateral elements in 2D finite element model. Fig. 1 shows a schematic model of the considered domain with elements and local coordinates system, (s,t).

Considering the behavior of seismic waves in the finite element domain, it results that the size of the elements should be less than 1/5th to 1/6th of the wavelength related to the highest frequency content of the input wave (Yoshida 2015). The model boundaries are fixed vertically on both sides and kept free in the horizontal direction to assess the semi-infinite condition in seismic site response analysis. The bottom boundary of the model is constrained in both horizontal and vertical directions to simulate the rigid boundary.

### 2.2 The equivalent linear 2DTF

To estimate the logical and accurate behavior of the soil, the program should be promoted non-linearly. When the soil mass is subjected to cyclic loading, the hysteretic non-linear real stress-strain behavior could be assessed using soil equivalent linear properties (Kramer 1996). In this method, the non-linear behavior of the soil layer is estimated based on the parameters of soil shear modulus and the damping ratio in frequency domain analysis.

Therefore, to accurately estimate the seismic response of the site, the 2D domain of interest is firstly divided into a number of elements using FE approach. Using proposed 2D transfer function and for each of the harmonic waves with a given frequency content of the input seismic wave ( $\omega_i$ ), a

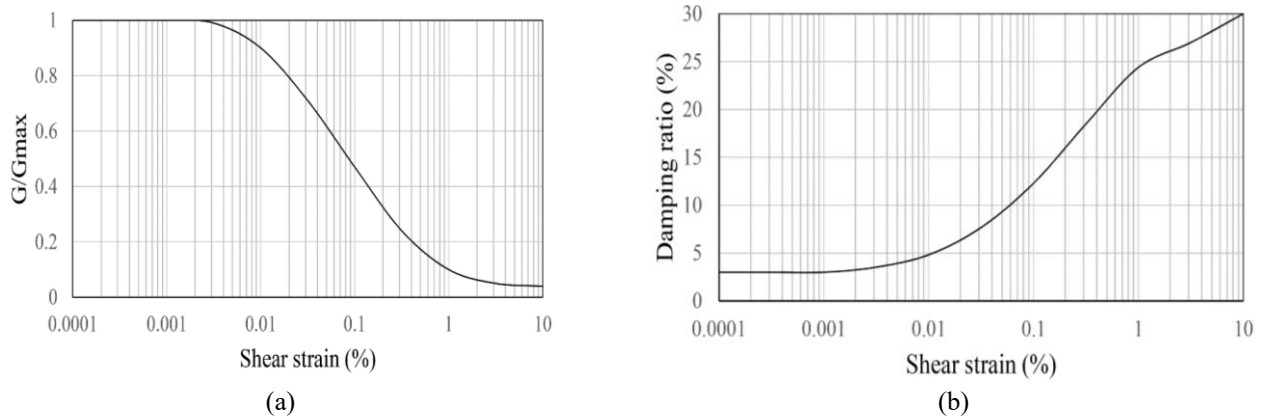


Fig. 3. (a) Shear modulus degradation; and (b) damping ratio curves reported for Gilroy region (Kramer 1996)

transfer function is obtained, which evaluates the amplification and attenuation effect for the corresponding frequency and for the different locations of the domain of interest. The frequency content of the earthquake incident wave, itself, is obtained by the common Fast Fourier Transform (FFT) procedure. The described process is repeated for all frequencies and the final and overall response of each point of interest is calculated by summing up the frequency-dependent responses. Therefore, using the frequency-dependent transfer functions and the characteristics of the nodes (displacements or acceleration) which are selected to use as input nodes (say along the base), one can reach the response characteristics of the desired location (say surface displacements or accelerations). The acceleration time history of the surface motion can also be reached by applying the Inverse Fast Fourier Transform (IFFT) to the response obtained in the preceding stage. Because the calculated strain level depends on the equivalent linear properties of the soil, to ensure the compatibility of soil properties with the level of strain, an iterative procedure should be considered to modify the linear 2DTF and convert it to equivalent linear program (Fig. 2).

Using the procedure shown in Fig. 2, the values of shear modulus and the soil damping in each step are modified based on the described iterative process, and then used for the subsequent step. At this stage, the 2DTF program calculates the transfer functions for all frequencies with the linear approach. Hence, there is no need to choose a certain number of frequencies, and the results obtained with higher precision.

### 3. Evaluation of 2DTF program: The case of Gilroy region

To validate the written program, the soil profile of the Gilroy region is considered. In this region, Gilroy#1 and Gilroy#2 are the stations of earthquake recording data. Gilroy#1 is located on a rocky outcrop, while Gilroy#2 is located on a soil mass. At these two stations, significant earthquakes such as Loma Prieta (1989), Coyote Lake (1979), and Morgan Hill (1984) have been recorded.

Table 1 The average characteristics of soil profile reported for the Gilroy region (Kramer 1996)

Shear wave velocity (m/sec)	Soil unit weight (kN/m <sup>3</sup> )	Poisson's ratio	Bedrock depth (m)
457	19.64	0.3	164

Table 2 Earthquakes used to validate the proposed program

Earthquake	Year	PGA (g)	Magnitude	Station
Loma Prieta	1989	0.484	6.9	Gilroy#1
Coyote Lake	1979	0.116	5.7	Gilroy#1

The relevant information is chosen based on the Electric Power Research Institute (EPRI) reports (EPRI 1993). According to the EPRI reports, Gilroy#1 and Gilroy#2 stations are used as reference sites to control the results.

Gilroy#1 is located 2 km west of Gilroy#2. In Gilroy#2 station, the level of groundwater is deep, and thus the issues of pore water pressure and liquefaction under the earthquake load do not develop into problems. Accordingly, it is suitable for analyzing and confirming the proposed method. By performing a series of extensive experimental studies, ERPI obtained comprehensive information about the modulus of reduction and damping properties of the soil beneath the Gilroy#2 station. Although the soil properties altered with the depth, an initial estimation has been done about the damping properties and reduction of modulus as well as mechanical properties of soil layers as mean values. These values are presented in Fig. 3 and Table 1 (Kramer 1996).

In this research, Loma Prieta and Coyote Lake earthquakes are used as incident waves, whose characteristics are presented in Table 2. Fig. 4 shows the time histories of mentioned earthquakes at Gilroy#1 station. At this stage, by simulating the soil profile of the Gilroy region and with the help of equivalent linear 2DTF program, the mentioned earthquakes are applied to the horizontal boundary of the model, and their results are obtained at the ground level and then compared with the recorded data at Gilroy #2.

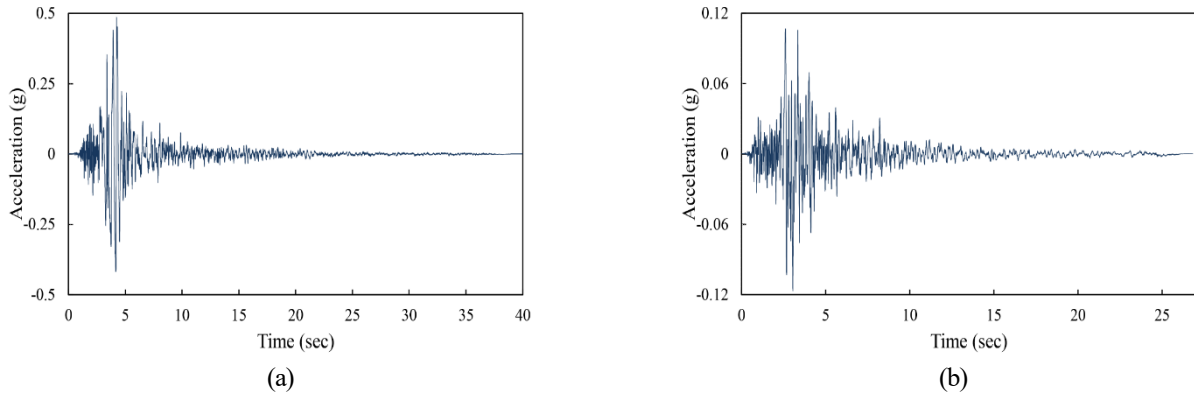


Fig. 4 Acceleration time-histories of (a) Loma Prieta; and (b) Coyote Lake earthquakes in Gilroy#1

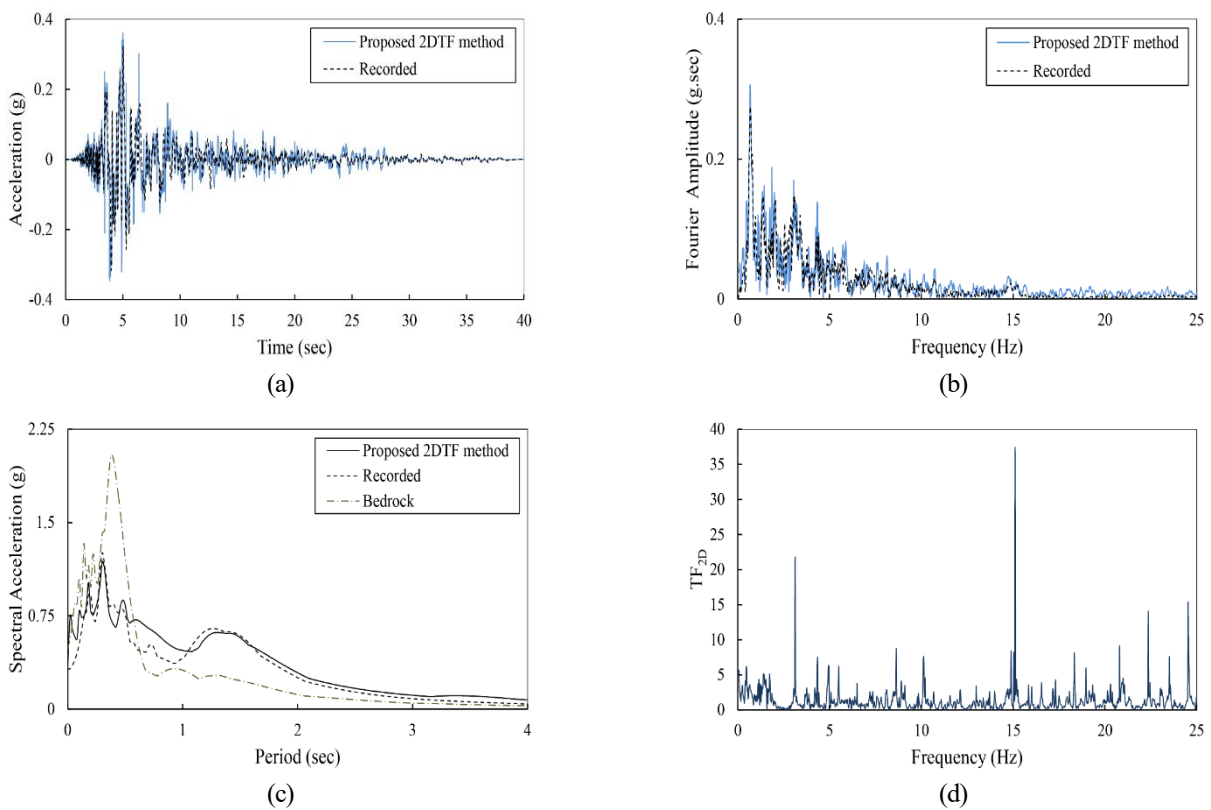


Fig. 5 Comparison of the (a) acceleration time histories, (b) Fourier amplitude spectra, (c) acceleration response spectra (for 5% damping) and (d) proposed 2D transfer function at Loma Prieta earthquake in Gilroy#2

### 3.1 Discussion of the results: Loma Prieta earthquake

In this section, the Loma Prieta earthquake is applied to the model as a seismic incident wave using the 2DTF program. Figs. 5(a) and 5(b) represent calculated and recorded acceleration time histories and Fourier amplitude spectra at the ground level, respectively.

As can be observed, the results of the proposed method are acceptable when compared with the real recorded data. To further evaluate the equivalent linear 2DTF program, the acceleration response spectra are presented for calculated and real acceleration recorded at the ground level in Fig. 5(c). This figure also shows the spectrum of the acceleration response for the incident earthquake (bedrock) for

comparison. Using the equivalent linear 2DTF program, the 2D transfer function can be obtained in different frequency contents as shown in Fig. 5(d). As can be observed, there is a good congruence between the calculated values and those recorded at the ground level, which suggests the proper functioning of the equivalent linear program.

Comparison of the results presented that the Loma Prieta earthquake is attenuated at the ground level in relation to the bedrock. As can be seen in Fig. 5(b), the maximum values of the amplitude are concentrated within a low-frequency range (less than 5 Hz). Note that due to the dependence of shear modulus and damping ratio to frequency content (Kausel and Assimaki 2002), the initial part of the acceleration time history (the first 10 seconds)

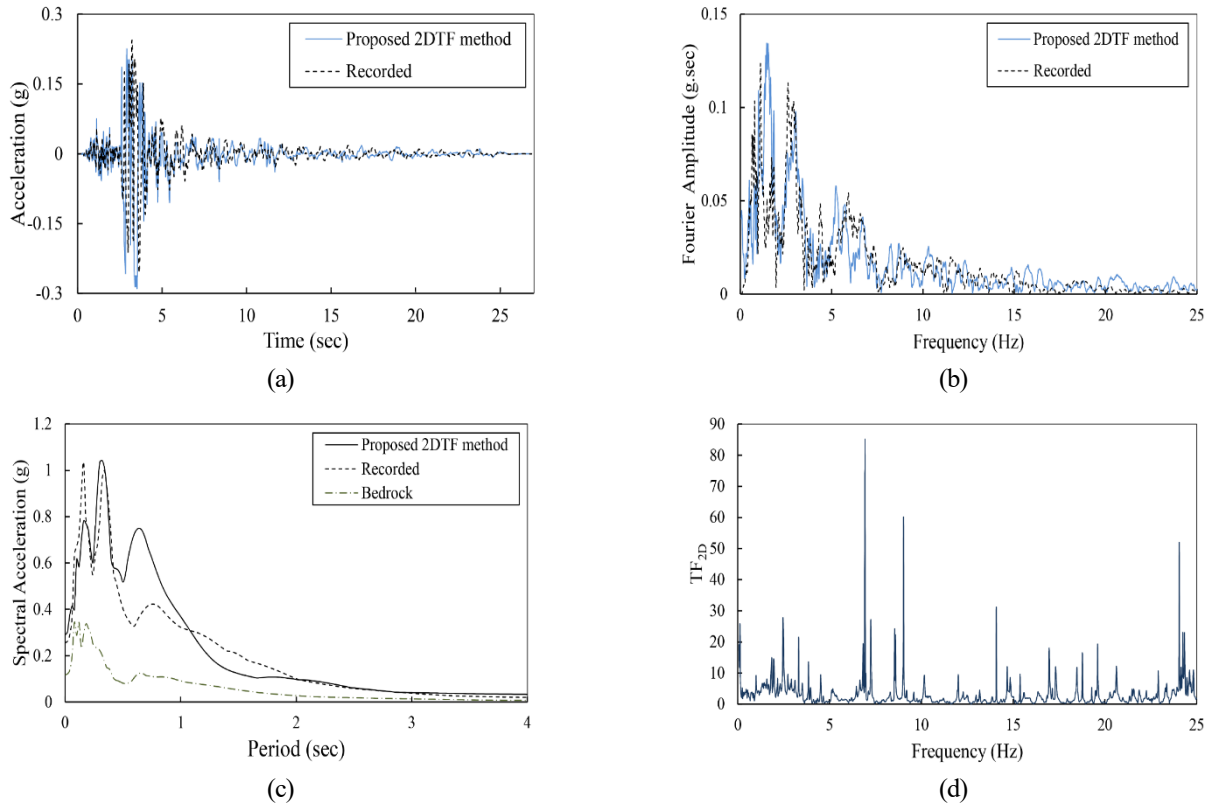


Fig. 6 Comparison of the (a) acceleration time histories, (b) Fourier amplitude spectra, (c) acceleration response spectra (for 5% damping) and (d) proposed 2D transfer function at Coyote Lake earthquake in Gilroy#2

Table 3 Comparison of the PGA and its corresponding time for Loma Prieta earthquake in Gilroy#2

Parameter	2DTF method	Recorded
PGA (g)	0.359	0.323
Time (sec)	5.01	5.035

Table 4 Comparison of the PGA and its corresponding time for Coyote Lake earthquake in Gilroy#2

Parameter	2DTF method	Recorded
PGA (g)	0.290	0.256
Time (sec)	3.52	3.645

has a lower real shear modulus compared with the corrected value based on the shear strain level. Furthermore, this range has a maximum effect on the ground response. Kausel and Assimaki (2002) research has shown that the shear modulus decreases with the reduction of frequency. This extra reduction of shear modulus leads to diminished acceleration recorded at the ground level, which can be observed by the acceleration time history recorded at Gilroy#2. Further, due to the frequency independence of shear modulus and the damping ratio in this research, the calculated acceleration value is a little overestimated compared with recorded data. According to Fig. 5(a), the maximum acceleration and time of its incidence obtained from the proposed method as well as its real recorded values at the ground level are presented in Table 3.

### 3.2 Discussion of the results: Coyote Lake earthquake

To assess the performance of the program within different ranges of loading, in this section, the Coyote Lake earthquake is considered as an input wave. The acceleration time history and Fourier amplitude spectrum are calculated at the ground level and then compared with the real recorded values in Figs. 6(a)-(b), respectively. As can be observed, the values calculated by equivalent linear 2DTF program have good congruence with the real recorded values. Further, Fig. 6(c) demonstrates the calculated acceleration response spectra using the 2DTF method, recorded data at the ground level as well as acceleration response spectrum of an input wave. The satisfactory correspondence of the calculated values confirms the proper performance of the program. According to Fig. 6(a), the maximum acceleration and time of its incidence obtained from the proposed method as well as its real recorded values at the ground level are shown in Table 4.

Comparing the results, it is found that in this earthquake and unlike the Loma Prieta earthquake, the influential region of the earthquake time history has a higher frequency content. In other words, in this earthquake, the effective range of the time history is located within a moderate-to-high frequency content. Based on Kausel and Assimaki (2002) research, it has been observed that reduction of shear modulus and increase of damping ratio with the decrease of

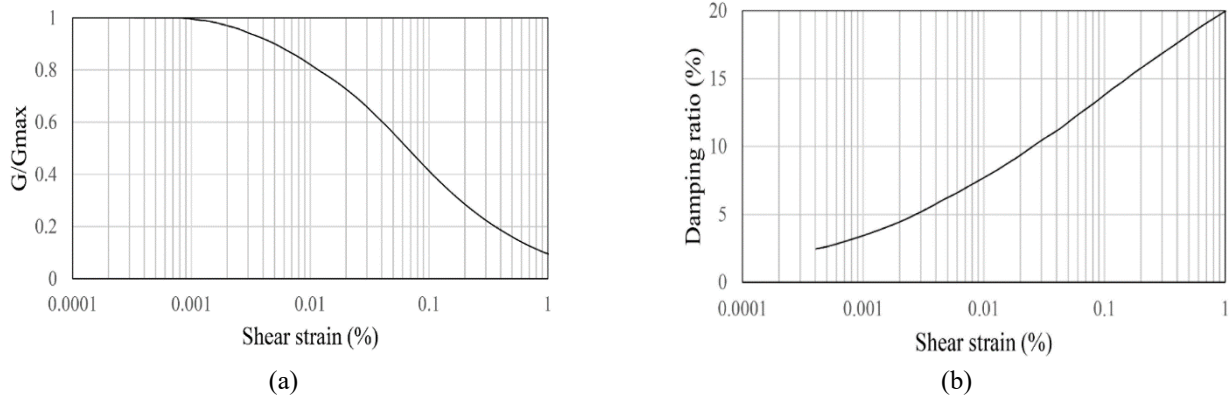


Fig. 7 (a) Shear modulus degradation; and (b) damping ratio curves used in parametric investigations (Vucetic and Dobry 1991)

Table 5 The characteristics of the soil profile used in parametric investigations

Shear wave velocity (m/sec)	Soil unit weight (kN/m <sup>3</sup> )	Poisson's ratio	Friction angle (deg)	Cohesion (kN/m <sup>2</sup> )
300	17	0.3	30	5

frequency only hold for low frequencies. Thus, the frequency dependence of shear modulus and damping ratio does not have any effect on the reduction of the shear modulus of the soil layer. It is caused amplification of seismic waves when passing through the soil layer, as clearly observed in Fig. 6(c).

The transfer function obtained in this section using equivalent linear 2DTF program is presented in Fig. 6(d). The pattern of this figure shows the variation of amplification factor in different frequency contents.

Based on the results obtained using Loma Prieta and Coyote Lake earthquakes, it is observed that for a specific site, both amplification and attenuation of seismic waves have occurred when passing through the soil layers. As previously shown, this depends on the frequency content of the input acceleration, and thus the importance of frequency domain analyses is highlighted.

#### 4. Parametric investigations

In this part, slopes with different angles are considered. Dimensionless parameters are defined to provide better categorization. The Amplification Factor (AF) is determined based on Eqs. (12) and (13) as follows

$$AF_{PHA} = \frac{PHA_{surface}}{PHA_{bedrock}} \quad (12)$$

$$AF_{PVA} = \frac{PVA_{surface}}{PVA_{bedrock}} \quad (13)$$

In Eqs. (12) and (13),  $PHA_{surface}$  and  $PHA_{bedrock}$  show the Peak Horizontal Acceleration at the soil surface and

bedrock, respectively. Also,  $PVA_{surface}$  is used to represent the Peak Vertical Acceleration at the soil surface.

$$AF_{PHV} = \frac{PHV_{surface}}{PHV_{bedrock}} \quad (14)$$

In Eq. (14),  $PHV_{surface}$  and  $PHV_{bedrock}$  are the Peak Horizontal Velocity at the soil surface and bedrock, respectively. Using dimensionless amplification factors, the effect of slopes to amplify or attenuate the incident seismic waves, is assessed.

In this section, to promote the linear 2DTF program to equivalent linear, the curves of shear modulus reduction and damping of material related to the amplitude of shear strain discussed in Vucetic and Dobry (1991) are adopted (Fig. 7). The characteristics of the soil profile used in this example are presented in Table 5.

##### 4.1 Seismic slope response analysis

In this example, the topography of the slope is modeled with different angles. Fig. 8 shows the general properties of the considered model. The slope angle is presented with  $\alpha$ , which varies between 0° to 40°. It should be noted that, slope 0° is considered to evaluate seismic response of a free field condition. L indicates the length of the image of the slope on the x-axis, whose value is considered constant and equal to 100 m for all cases. In this example, a minimum of the bedrock depth is 30 m, and the Kobe earthquake (1995) is applied to the model as a seismic input wave. The properties of this earthquake are presented in Table 6 in detail.

As can be seen in Fig. 9(a), topography has a considerable effect on the seismic response of the site. It can be concluded that, generally, in the presence of slope, the upper points are amplified. This amplification increases significantly with the increase in the angle of slope, where the maximum value of  $AF_{PHA}$  is observed at the angle of 40° and on upper points of the topography. Note that with the increase in the angle of the slope, amplification of seismic waves by topography continues further up to longer distances. On the other hand, the initial points of the

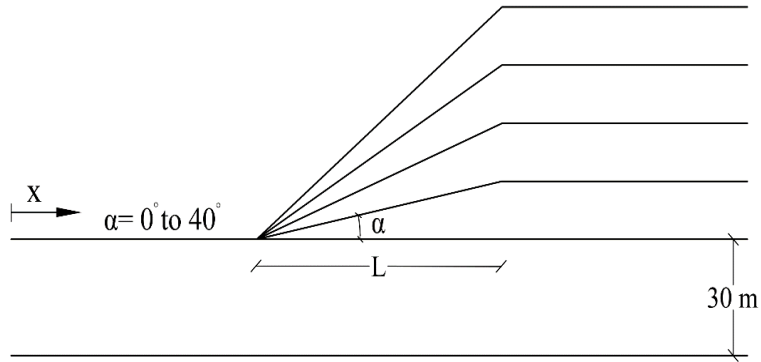
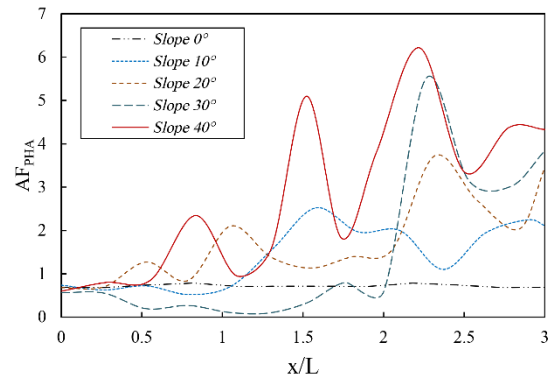
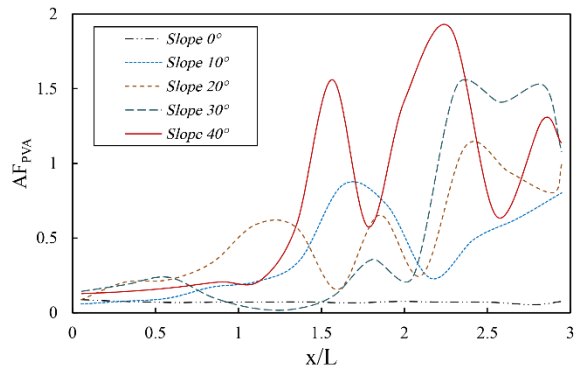


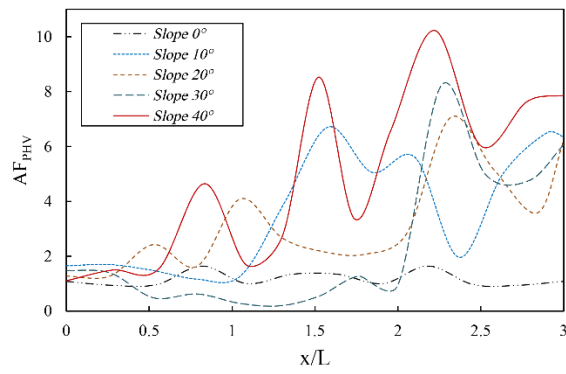
Fig. 8 Slope with different angles used in parametric investigations



(a)



(b)



(c)

Fig. 9 Variation of (a) PHA, (b) PVA; and (c) PHV amplifications in different points of slopes

Table 6 Characteristics of the Kobe earthquake used in parametric investigations

Earthquake	Year	PGA (g)	Magnitude	Station
Kobe	1995	0.599	6.9	KJMA

diagrams are corresponded to the free field diagram, suggesting decay of the effect of topography at these points and achieving free field conditions. These conditions proved a suitable dimension and proper functioning of the model to prevent box effect.

Fig. 9(b) shows the  $AF_{PVA}$  for different slope angles. As mentioned previously, in 1D method, the effect of this component is not considered. On the other hand, this component has considerable value, especially at the points on top of the slope. This phenomenon is due to the interface of surface waves with reflected and refracted waves.

According to Fig. 9(c), the PHV component is also affected by the slope angle. In this regard, with the increase in the slope angle, the extent of amplification of this component is generally increased, where its peak values occur on top of the slope.

Comparison the results of irregular topography and those of free field condition, reveals the significant effect of 2D irregularities on amplification or attenuation of incident waves. Characteristics variation of the waves passing through soil layers in the regions with irregular topographies can lead to asymmetric loading, and ultimately severe damage to structures constructed in these areas, especially those with linear behavior (such as bridges and pipelines).

## 5. Conclusions

In this research, a new method was proposed for linear and equivalent linear evaluation of the seismic response of a site. In this method, the equation of motion was used, and 2D transfer functions were obtained. Based on the proposed formulation, a program was written using the MATLAB environment. To evaluate the performance of the written program, the Gilroy region was considered as a real site, and two recorded earthquakes at the Gilroy station were applied as input loads. The precision and accuracy of the proposed method were evaluated through comparing the results obtained using the 2DTF program (which discussed in this study) with those of recorded data. The satisfactory compliance between the results proved the acceptable performance of the program to assess the 2D site response. It should be noted that, the seismic response calculated on the soil surface in the Gilroy region is attenuated and amplified in the cases of the Loma Prieta and Coyote Lake earthquakes, respectively, which is related to the frequency content of the incident wave. The results of the present study show the importance of developing the frequency domain approaches and the need to increase the accuracy and speed of such analyses.

In order to assess the topographic effect on the seismic ground response, slope with different angles was

considered, and the seismic analysis using the equivalent linear 2DTF program was performed. The amplification factors of PHA, PVA, and PHV were discussed to assess the topographic effects on seismic site response. Based on the results, these topographies have a considerable effect on changing the seismic waves obtained on the soil surface. The differences could have a significant effect on the seismic response of structures constructed in and around the slopes.

Generally, in 2D models, the incident waves are refracted and have multiple reflections in the domain. They can also be in the form of surface waves that are damped at a slower speed than body waves. These waves can cause stronger seismic vibrations, especially at longer distances. The interaction of the waves can create different conditions of amplification or attenuation on the site based on the geometry and type of the irregularity, as well as the different frequency content of the incident wave. It should be noted that, 1D analyses of ground response often elucidate the basic concepts of response, but they may not be able to describe complex wavelengths and long periods of multiple reflections in areas with irregular topographies. The proposed 2D method has practical specifications to simulate different conditions such as topography, inclined soil surface or bedrock and eliminates the limitations of the 1D method.

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