29 May 2010, 8:00 am - 9:30 am

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Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
*and Symposium in Honor of Professor I.M. Idriss*
May 24-29, 2010 • San Diego, California

# THE LIMITATIONS OF EQUIVALENT LINEAR SITE RESPONSE ANALYSIS CONSIDERING SOIL NONLINEARITY PROPERTIES

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ABSTRACT

Seismic site effect has been a major issue in the field of earthquake engineering due to the large local amplification of the seismic motion. This paper presents the importance of an appropriate soil behavior model to simulate earthquake site response and gives a critical overview of the field of site response analysis.

Some of the well known site response analysis methods are summarized and discussed. The objective of this paper is to investigate the influences of nonlinearity on the site response analysis by means of a more precise numerical model. In this respect, site responses of four different types of one layered soil deposit, based on various shear wave velocities, with the assumption of linear and rigid base bedrock, were analyzed by using the equivalent linear and fully nonlinear approaches. Nonlinear analyses' results were compared with those of the linear method and the similarities and differences are discussed. As a result, it is concluded that, in the case of nonlinearity of soil under strong ground motions, 1-D equivalent linear modeling overestimates the amplification patterns in terms of absolute amplification level, and cannot correctly account for resonant frequencies and hysteric soil behavior. Hence more practical and appropriate numerical techniques for ground response analysis should be surveyed.

## INTRODUCTION

It has been known that it is substantial to understand the local site effects on earthquake ground motions, due to the devastating damages to structures, frequently caused in soft-soil regions during strong ground shaking, as seen during the Michoachan earthquake of 1985 (e.g., Sanchez- Sesma *et al.,* 1988; Kawase and Aki, 1989) and the Loma Prieta earthquake of 1989 (e.g., Jarpe *et al.,* 1989; Shakal *et al.,* 1990; Darragh and Shakal, 1991). In theory, the term of site amplification refers to the increase in the amplitudes of seismic waves passing through the soft soil layers near the earth's surface. The increase is because of the low impedance of soil layers near the surface, (impedance is defined as the product of the mass density of soil and the wave propagation velocity). In practice, the term of site amplification is used to represent any differences in ground motions between two nearby sites, irrespective of whether or not these differences are due to impedance contrasts. Other factors that can also create differences in ground motions of two nearby sites include wave focusing, rupture directivity, basin geometry, and topography.

One of the fundamental problems to be solved by geotechnical engineers in regions, where sever earthquake hazards exist, is to estimate the site-specific dynamic response of the soil deposit under a level ground motion. This problem is commonly referred to as a site-specific response analysis or soil amplification study (although motions may be deamplified). The solution of this problem allows the geotechnical engineers to evaluate the potential for liquefaction, to conduct the first analytical phase of seismic stability evaluations for slopes and embankments, to calculate site natural periods, to assess ground motion amplification, and to provide structural engineers with various parameters, primarily response spectra, for design and safety evaluations of structures which are considered as significant issues in civil engineering fields.

For dynamic analysis of ground response, different theories as linear, equivalent linear and nonlinear have been put forward, which have their own especial advantages and surely limitations. The importance of site specific design spectra in engineering of structure and earthquake, clarifies the necessity of more precise study of these theories. Among the various aspects of the local site effects, nonlinear soil response in sedimentary layers during strong ground shaking has been a controversial issue for a long time. First nonlinear soil behavior under cyclic loading was studied by Seed and Idriss (1969). A number of experimental works have been done to establish the stress-strain behavior of various types of soil (e.g., Seed and Idriss, 1970; Hardin and Drnevich, 1972a, 1972b).

Owing to the complexity of the nonlinearity mechanism, dynamic behavior of soil during strong ground shaking has not been evaluated quantitatively based on the observed ground-motion records. The 1D Equivalent linear modeling is the most used approach in earthquake engineering; it supposes that the layers extend horizontally and the incident signal at the base of the deposits is a vertical shear.

In an equivalent linear approach proposed by Schnabel et al. (1972) the effects of nonlinearity are approximated by performing a series of linear analyses in which the average, or secant shear modulus and the damping ratio are varied until their values are consistent with the level of the strain induced in the soil. As will be discussed in the following, Yoshida (1994), Huang et al. (2001) and Yoshida and Iai (1998) showed that equivalent linear analysis exhibits larger peak acceleration.

The nonlinearity of soil behavior is known very well thus most reasonable approaches to provide reasonable estimates of site response is a very challenging area in geotechnical earthquake engineering. In this paper, we will consider a numerical analysis based on the Finite Difference Method. The main advantage of this method is that it allows a description of the infinite extension of the medium. The main objective of this paper is to compare the linear and nonlinear site response analysis techniques as an overview and numerically and to show their similarities and differences.

## PREVIOUS STUDIES ON EQUVALENT LINEAR AND NONLINEAR APPROACHES OF SITE RESPONSE ANAYSIS

The potentially strong influence of site conditions has been known for almost 200 years. Site effects were also recognized in Japan earthquake of 1891 (Milne, 1898), the 1906 San Francisco earthquake (e.g., Wood, 1908), and the Long Beach earthquake of 1933 (Wood, 1933). The first quantitative study of sediment amplification in southern California was by Gutenberg (1957). Since then, many studies have been conducted. Linear and nonlinear site effects have been examined in several studies (e.g., JOYNER and CHEN, 1975; YU et al., 1993; AGUIRRE and IRIKURA, 1995, 1997; NI et al., 1997).

To evaluate the amplification of seismic waves, the dynamic response of the soil is treated as a linear behavior under low levels of strain. For larger stress-strain levels, however, the results of laboratory testing of soil samples show a nonlinear relation that represents the nonlinear character of the soil response.
Many authors have been trying to determine observational evidence of nonlinearity from seismological data and to estimate to what degree it influences strong ground motions (CHIN and AKI, 1991; BERESNEV et al., 1995a; BERESNEV et al., 1998a, b; SU et al., 1998; CULTRERA et al., 1999). In those studies, the nonlinear effect causes a reduction in waveform amplitude in the time domain and the shifting of predominant frequencies and peak reduction in the frequency domain. This is on the nonlinear response of the material which causes a great change in the elastic properties of the medium dependent on waveform amplitudes. AGUIRRE and IRIKURA (1997) studied nonlinearity, liquefaction and velocity variation of soft soil layers in Port Island, Kobe, during the 1995 Hyogo-ken Nanbu earthquake. The S-wave velocity structure before and after the main shock was found to be different.

Several techniques have been used to detect the nonlinear effect. One is spectral ratio evaluation of observed data between surface and bedrock during strong and weak ground motions (ORDAZ and FACCIOLI, 1994; BERESNEV et al., 1995a; HARTZELL, 1998; SU et al., 1998). Another way of estimating the soil layer effect is to use recordings from a vertical array of seismometers (WEN et al., 1994, 1995; AGUIRRE and IRIKURA, 1995; BERESNEV et al., 1995b; SATOH et al., 1995; ELGAMAL et al., 1996; BORJA et al., 1999, 2000). The reduction and/or shift in the peaks during strong motion are indications of nonlinearity. The other used to evaluate nonlinearity is based on the comparison of observed ground motions during strong motion with those simulated by a linear method. The difference from the observed data can be interpreted as nonlinearity. Two commonly used linear methods are the 1-D Haskell method and the empirical Green's function method (e.g., AKI and IRIKURA, 1991; AGUIRRE et al., 1994). Generally, all strong motion studies have shown the presence of nonlinear site amplification at soft soil sites when subjected to large amplitude motions.

Numerical approaches to predict the nonlinear response of soil can be classified as either an equivalent secant approach (e.g., the SHAKE program by SCHNABEL et al., 1972) or a direct nonlinear approach (e.g., the DESRA2 program by LEE and FINN 1982; the CHARSOIL program by STREETER et al., 1974).

Numerical wave propagation in horizontally stratified media (1-D modeling) has been long developed (HASKELL, 1960; KENNETT, 1983; MU¨ LLER, 1985), and became classical with the known SHAKE-code. Subsequently, various 2-D modeling techniques were developed and exhaustive information regarding existing methods was provided in SA´ NCHEZ-SESMA (1987), AKI (1988), BIELAK et al. (1997) or TAKENAKA et al. (1998). 2-D modeling was often used for parametric studies. As mentioned by AKI (1988), direct comparisons with experimental records of local small-scale amplification effects occurring over short distances remain rare (BARD, 1983; OHTSUKI et al., 1984; PEDERSEN et al., 1994), mainly due to limited experimental observations. With the advances of computer memory, three- dimensional modeling became possible (PITARKA et al., 1998; RIEPL and BARD, 1998; BAO et al., 1997; OLSEN et al., 1995; OLSEN and ARCHULETA, 1996; OHORI et al., 1992; HORIKE et al., 1990; SA´ NCHEZ-SESMA, 1983), but remains limited to exemplary case studies and are not yet suitable for general applications.

On the other hand analytical methods for site response analysis include many parameters that could affect earthquake ground motions and corresponding response spectra. So it is important to investigate the effect of these parameters on site response analysis in order to make confident evaluations of earthquake ground motions at site. Seed and Idriss (1970), Joyner and Chen (1975) and Hwang and Lee (1991) investigated the effects of site parameters such as secant shear modulus, low-strain damping ratio, types of sand and clay, location of water table, and depth of bedrock. The parametric studies have shown that the secant shear modulus, depth of bedrock, and types of sand and clay have a significant effect on the results of site response analysis. However, the low-strain damping ratio and variations of water tables have only a minor influence on site response analysis.

The main shortcoming of the linear method is referred to its inability to take account of the strong strain dependence which is observed experimentally in regard to shear modulus and damping ratio. The best can be done is to apply the method of iterations, and to set values of shear.

The variation of shear modulus and material damping ratio with shear strain, known as G–γ and D–γ curves, is known as a significant feature of the soil behavior submitted to cyclic loading (Seed and Idriss ,1970). These observations resulted in the equivalent-linear approach, extensively used though of its shortcomings since then due to its simplicity.

Besides, the development of cyclic elastoplastic constitutive models for soils in the late 1970s and early 1980s has opened a new horizon for soil dynamics studies, (e.g. Prévost and Hoeg 1975; Ghaboussi and Dikmen 1978; Aubry et al. 1982 among others). The information concerning the capability of these models in representing the variation of the shear modulus and the damping ratio in a wide range of shear strain, namely from $10^{-6}$ to $10^{-2}$ is scarce.

In the present study, we compare results obtained from equivalent linear estimates of local site amplification effects with those from numerical modeling using four different types of soil deposits, considering a wide range of cohesive and non cohesive materials.

## EQUIVALENT LINEAR AND FULLY NONLINEAR SITE RESPONSE ANALYSIS

To simulate numerically seismic soil response, two approaches can be considered: the equivalent-linear approach and a truly non-linear elastoplastic modeling. In the following, firstly the theory and background of these two methods are reviewed.

### The Equivalent Linear Site Response Analysis

The theory of approximation of real nonlinear dynamic soil behavior by equivalent linear approach first was proposed by Schnabel et al. (1972), Idriss and Sun (1992) and Kramer (1996). Equivalent-linear modeling uses relationships describing the variation of material shear modulus (*G*) and hysteretic damping ratio (ζ) with shear strain. These relationships are referred to as modulus reduction and damping curves. One of the first computer programs developed for this purpose was SHAKE (Schnabel et al., 1972). SHAKE computes the response in a horizontally layered soil-rock system subjected to transient and vertical travelling shear waves. SHAKE is based on the wave propagation solutions of Kanai (1951), Roesset and Whitman (1969), and Tsai and Housner (1970). This code based on the multiple reflection theory, and nonlinearity of soil is considered by the equivalent linear method. The basic assumptions used are: **a)** The soil layers are horizontal and extend to infinity, **b)** The ground surface is level, **c)** Each soil layer is completely defined by the shear modulus and damping as a function of strain, the thickness, and unit weight, **d)** The non-linear cyclic material behavior is adequately represented by the linear visco-elastic (Voigt) constitutive model and implemented with the equivalent-linear method, and **e)** The incident earthquake motions are spatially-uniform, horizontally-polarized shear waves, and propagate vertically.

In 1998, the computer program EERA was developed in FORTRAN 90 starting from the same basic concepts as SHAKE. EERA stands for Equivalent-linear Earthquake Response Analysis. EERA is a modern implementation of the well-known concepts of equivalent linear earthquake site response analysis.

To illustrate the basic approach used in EERA, consider uniform soil layers lying on an elastic layer of rock that extends to infinite depth, as illustrated in Fig. (1).

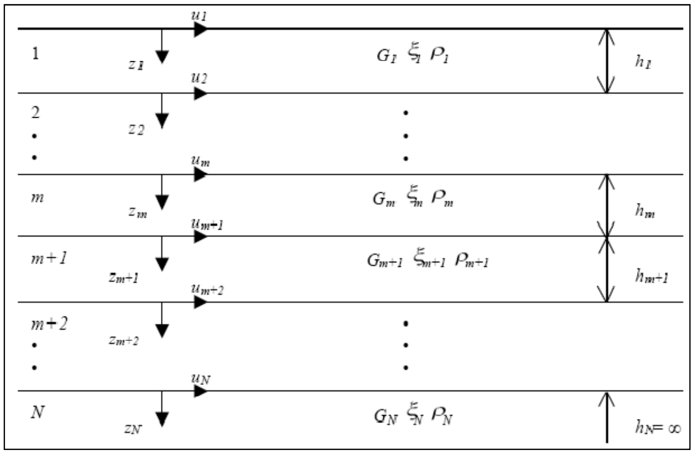


*Fig. 1. One-dimensional layered soil deposit system (after Schnabel et al., 1972).*

For harmonic waves, by solving one-dimensional equation of motion for vertically propagating shear waves the displacements and the corresponding stresses can be obtained as:

$$u(z,t) = Ee^{i(\omega t + K^* z)} + Fe^{i(\omega t - K^* z)} \qquad (1)$$

$$\tau(z,t) = G^* \frac{\partial u}{\partial z} = (G + i\omega\eta)\frac{\partial u}{\partial z} = G(1+2i\xi)\frac{\partial u}{\partial z} \qquad (2)$$

$\omega$ is the circular frequency of the harmonic wave and k* is the complex wave number.

$$K^* = \omega / v_s^* \qquad (3)$$

Where $v_s^*$, complex shear wave velocity equals to:

$$v_s^* = \sqrt{\frac{G^*}{\rho}} = \sqrt{\frac{G(1+i2\xi)}{\rho}} \approx \sqrt{\frac{G}{\rho}}(1+i\xi) = v_s(1+i\xi) \qquad (4)$$

Compatibility of displacements at the interface between layers m and m+1, and Continuity of shear stresses imply that:

$$E_{m+1} = \frac{1}{2}E_m(1+\alpha_m^*)e^{iK_m^* h_m} + \frac{1}{2}F_m(1-\alpha_m^*)e^{-iK_m^* h_m} \qquad (5)$$

$$F_{m+1} = \frac{1}{2}E_m(1-\alpha_m^*)e^{iK_m^* h_m} + \frac{1}{2}F_m(1+\alpha_m^*)e^{-iK_m^* h_m} \qquad (6)$$

Where $\alpha_m^*$ is the complex impedance ratio at the interface between layers m and m+1:

$$\alpha_m^* = \frac{K_m^* G_m^*}{K_{m+1}^* G_{m+1}^*} = \frac{\rho_m (v_s^*)_m}{\rho_{m+1}(v_s^*)_{m+1}} \qquad (7)$$

Finally the transfer function $A_{mn}$ relating the displacements at the top of layers m and n is defined by:

$$A_{mn}(\omega) = \frac{u_m}{u_n} = \frac{\dot{u}_m}{\dot{u}_n} = \frac{\ddot{u}_m}{\ddot{u}_n} = \frac{E_m + F_m}{E_n + F_n} \qquad (8)$$

The equivalent linear approach consists of modifying the Kelvin-Voigt model to account for some types of soil nonlinearities. Eq. (9) and Fig. (2) illustrate this model. Where G is shear modulus and $\eta$ is the viscosity.

$$\tau = G\gamma + \eta\frac{\partial \gamma}{\partial t} \qquad (9)$$

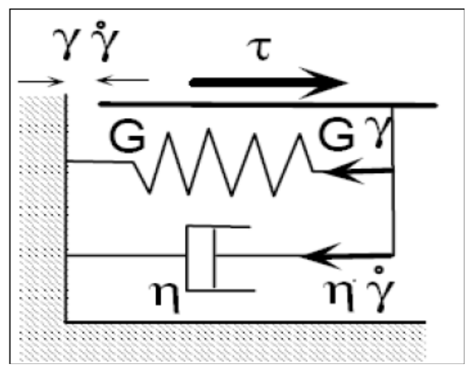


*Fig. 2. Schematic representation of stress-strain model used in equivalent-linear model*

The nonlinear and hysteretic stress-strain behavior of soils is approximated during cyclic loadings as shown in Fig. (3).

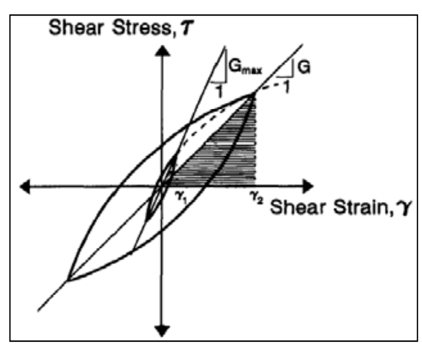


*Fig. 3. Equivalent-linear model, hysteresis stress-strain curve*

The equivalent linear shear modulus $G_s$ is taken as the secant shear modulus $G_{sec}$, which depends on the shear strain amplitude g. As shown in Fig. (3), $G_{sec}$ at the ends of symmetric strain-controlled cycles is:

$$G_{sec} = \frac{\tau_c}{\gamma_c} \quad (9)$$

Where $\tau_c$ and $\gamma_c$ are the shear stress and strain amplitudes, respectively. The equivalent linear damping ratio $\xi$ is the damping ratio that produces the same energy loss in a single cycle as the hysteresis stress-strain loop of the irreversible soil behavior. The critical damping ratio ξ can be expressed in terms of $W_D$ and $W_s$ as follows:

$$\xi = \frac{W_D}{4\pi W_s} = \frac{1}{2\pi} \frac{A_{loop}}{G_{sec}\ \gamma_c^2} \quad (10)$$

$W_D$ and $W_s$ are the energy dissipated during a complete loading cycle and the maximum strain energy stored in the system respectively.

In the equivalent linear approach, as previously described in Fig.(3), the shear modulus and damping ratio are taken as functions of shear strain amplitude by iterations so that they become consistent with the level of the strain induced in each layer. The effective shear strain of the equivalent linear analysis is calculated as:

$$\gamma_{eff} = R_y \gamma_{max} \quad (11)$$

Where $\gamma_{max}$ is the maximum shear strain in the layer and $R_y$ is a strain reduction factor often taken as:

$$R_\gamma = \frac{M-1}{10} \quad (12)$$

In which M is the magnitude of earthquake. The Equivalent linear method uses linear properties for each element that remain constant throughout the history of shaking and are estimated from the mean level of dynamic motion. The method does not directly provide information on irreversible displacements and the permanent changes that accompany liquefaction, since oscillatory motion only is modeled. The interference and mixing phenomena that occur between different frequency components in a nonlinear material are missing from an equivalent linear analysis. On the other hand this theory relates strain tensor with stress tensor by means of elasticity theory. In contrast in real plastic flow, tensor of growth of strain is related with stress tensor by functions which conduct flow rule in plasticity theory.

## The Fully Nonlinear Site Response Analysis

An important consequence of nonlinear and hysteretic nature of cyclic behavior of soils is that the amplification function for a particular site is dependent on the strain amplitude level reached during a seismic event. This phenomenon, while being well qualitatively understood, still requires a comprehensive quantitative analysis. A constitutive relationship utilized in this kind of analysis will determine to a large extent its results; therefore the reliability of the constitutive relationship is a central problem to be solved.
Nonlinear site response analyses follow the evolution of nonlinear, inelastic soil behavior in a step-by step fashion in the time domain and therefore require characterization of the stress–strain behavior of the soil. The nonlinearity of soil stress–strain behavior implies that the shear modulus of the soil is constantly decreasing and the inelasticity implies that the soil unloads along a different path than its loading path, thereby dissipating energy at the points of contact between particles. Nonlinear analyses have been shown to have better agreement with the earthquake observation than the equivalent linear analysis.

Today numerical methods are the most pervasive calculating methods for different engineering problems. Numerical modeling can determine details of stress and strain in various points of structure and soil. The major trait of numerical methods is that they divide a large medium to quite small elements and establish specific equations up to getting complete balance. FLAC (**F**ast **L**agrangian **A**nalysis of **C**ontinua) is one of the powerful numerical softwares in geotechnical engineering. The performance of this program is based on method of finite difference which can be used for simulation of behavior of soil and rock or other materials with potential of plasticity. The finite difference method is the oldest numerical technique used for the solution of sets of differential equations, given initial values and/or boundary values (Desai and Christian 1977).

The common issue regarding the preference of FLAC than other finite element programs is its ability of plastic analysis and modeling the real behavior of materials.

In contrast to irritations involved in equivalent linear methods, only one run is done with a fully nonlinear method, since nonlinearity in the stress-strain law is followed directly by each element as the solution marches on in time. Provided that an appropriate nonlinear law is used, the dependence of damping and apparent modulus on strain level is automatically modeled. An elastoplastic model taking into account the elementary necessary plastic mechanisms such as progressive friction mobilization, Coulomb type failure, critical state and dilatancy/contractance flow rule, is used. Consider an elastic/plastic model with a constant shear modulus, (G∘), and a constant yield stress, ( $\tau_m$ ), subjected to a cyclic shear strain of amplitude (γ). Below yield, the secant shear modulus G is simply equal to (G∘). For cyclic excitation that involves yield, the secant modulus is derived by Eq. (13):

$$G = \frac{\tau_m}{\gamma} \qquad (13)$$

The maximum stored energy, W, during the cycle and the dissipated energy (corresponding to the area of the loop) are obtained by Eq. (14) and (15):

$$W = \frac{\tau_m \gamma}{2} \qquad (14)$$

$$\Delta W = 4\tau_m(\gamma - \gamma_m) \qquad (13)$$

Where:

$$\gamma_m = \frac{\tau_m}{G_0} \qquad (14)$$

Hence:

$$\frac{\Delta W}{W} = 8(\gamma - \gamma_m)/\gamma \qquad (15)$$

Denoting the damping ratio by D and noting that 4πD ≈ W/W (Kolsky 1963), for small D, Eq. (19) can be inferred:

$$D = 2(\gamma - \gamma_m)/\pi\gamma \qquad (18)$$

Normalized modulus (G/G∘) from Eq. (13), and damping D from Eq. (18) against normalized cyclic strain $\gamma / \gamma_m$ , are plotted in Fig. (4).

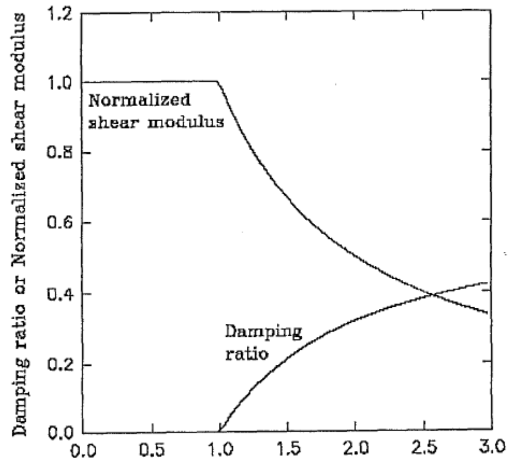


*Fig. 4. Modulus and damping ratio versus cyclic strain for the elastoplastic model FLAC*

Numerical methods relying on the discretization of a finite region of space require that appropriate conditions be enforced at the artificial numerical boundaries. In dynamic problems, boundary conditions should not cause the reflection of outward propagating waves back into the model. The seismic input is normally represented by plane waves propagating upward through the underlying material and the boundary conditions must account for the free-field.

Both the frequency content of the input wave and the wave-speed characteristics of the system will affect the numerical accuracy of wave transmission. Kuhlemeyer and Lysmer (1973) show that for accurate representation of wave transmission through a model, the spatial element size, ( $\Delta L$ ), must be smaller than approximately one-tenth to one-eighth of the wavelength associated with the highest frequency component of the input wave. Hence the minimum dimension of elements can be determined from Eq. (19).

$$\Delta L \leq \frac{\lambda}{10} \qquad (19)$$

Where λ is the wavelength associated with the highest frequency component that contains appreciable energy. In this paper, since input earthquake records have been filtered by the technique of Fast Fourier Transform up to 10 Hz and the minimum shear wave velocity equals to 150 m/s, according to Eq. (19), the dimensions of elements in modeling are derived:

$$\lambda = \frac{c}{f} \qquad (21)$$

$$\Delta L = \frac{c}{10 \times f} = \frac{150}{10 \times 10} = 1.5m \qquad (22)$$

NUMERICAL MODELS

In this study nonlinear and linear approaches have been used to estimate the dynamic site responses and to compare the results in 4 different sites. The sites are selected in a wide range of cohesive and non cohesive materials to cover the most common types of deposits in natural alluvial fields or engineering practices. They also meet the basis of soil classifications recommended in the Iranian Earthquake Code (2800) having different shear wave velocities. Dynamic nonlinear analyses have been done on models by FLAC using an elastoplastic Mohr-Coulomb model. Properties of soil materials for these sites are given in table (1). For investigating the influence of frequency content of seismic excitations on response spectra, three types of ground motion are used including far, medium and near field records with PGA 0.1g. Table (2) shows the features of the selected records.

Table 1. Geotechnical properties of the materials used in the models

| site | Vs(m/s) | D(kg/m$^3$) | Gs(Mpa) | Coh.(kpa) | Fric.(deg) |
|---|---|---|---|---|---|
| 1 | 800 | 2300 | 1500 | 5 | 45 |
| 2 | 500 | 2000 | 510 | 5 | 45 |
| 3 | 250 | 1800 | 115 | 50 | 25 |
| 4 | 125 | 1700 | 27 | 50 | 25 |

Table 2. Properties of the ground motions

In all models one uniform soil layer of 30 m thickness lying over bedrock is assumed. The shear wave velocity of the half-space interface is 800 m/s.

| ID-Eq. | Magnitude | Type | PGA (g) | Depth (Km) | Distance (Km) | Period (sec) |
|---|---|---|---|---|---|---|
| Chichi-Taiwan | 6.2 | Far-field | 0.03 | 10 | 116 | 0.3 |
| Northridge | 6.6 | Medium-field | 0.1 | 17 | 56 | 0.41 |
| Sanfernando | 6.6 | Near-field | 0.08 | 13 | 21 | 0.53 |

Linear analyses of the models have been carried out with EERA. Seed and Idriss (1970) curves, presented in Fig. (5), are used as the modulus and damping curves for soil type 1 and 2 which can be considered as dense sand or silty soil deposits. Similarly, for soil type 3 and 4 with clay properties Sun and et al curves are used.

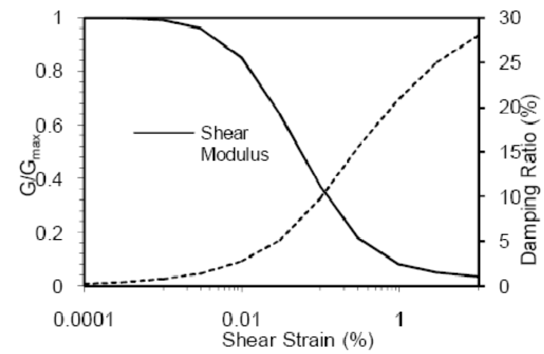


*Fig. 5. The Modulus ratio and damping curves used in the equivalent-linear model*

The results of site response analyses were presented in terms of acceleration time history and response spectra. As explained in previous sections, EERA uses linear equivalent approaches with an iterative procedure to obtain soil properties compatible with the deformations developed in each stratum. The method of analysis used in EERA cannot allow for nonlinear stress–strain behavior because its representation of the input motion by a Fourier series and use of transfer functions for solution of the wave equation rely on the principle of superposition-which is only valid for linear systems.

THE RESULTS

<u>The Response Spectra and the Ground Acceleration</u>

The comparison of linear elastic analysis by using EERA and fully nonlinear analysis by using FLAC are given in Fig. (6), Fig. (7). A popular method to characterize site amplification has been the use of spectral ratios, introduced by Borcherdt. The spectral ratio is calculated by taking the ratio of the Fourier amplitude spectrum (FAS) of a soil-site record to that of a reference-site (i.e. a rock-site) record. Five percent damping ratio is used in this study.

As shown in all figures, there are some differences between obtained spectra from two approaches: equivalent linear and fully nonlinear analyses. The main reason for these discrepancies is that the formulation and background theories in dynamic analysis of these methods differ from each other. Equivalent-linear method depends on Thin-Layered Theory whereas the fully nonlinear approach is based on Spring-Concentrated Mass method and it considers soil dynamic behavior in a more realistic way than the other method. However, in all cases there is a similarity in shape of spectra.

As shown in figures amplitude of acceleration response spectra obtained in nonlinear method is smaller than linear ones implying nonlinearity of site.

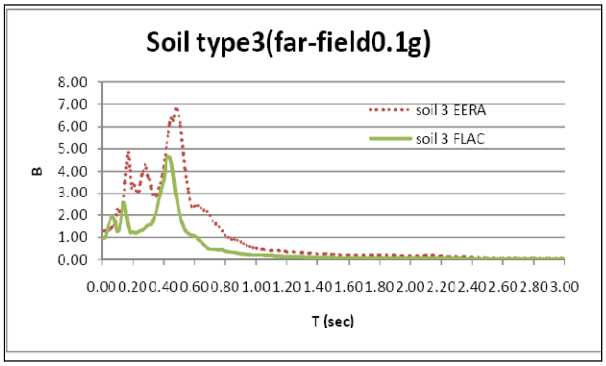


*Fig. 6. Acc. Response spectra through the linear and nonlinear approaches (under Eq. Chichi-Taiwan).*

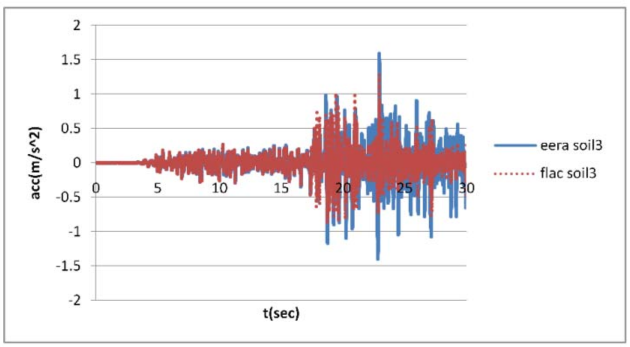


*Fig. 7. Top acceleration records by the linear and nonlinear approaches (under Eq. Chichi-Taiwan).*

Fig. (7) illustrates the nonlinearity of the soft soil apparently while the main duration of the earthquake. As shown, at the beginning of the excitation the top accelerations are computed with similar amounts, but by passing time and entering of soil strain to the nonlinear area (after 20 seconds) FALC, presenting fully nonlinear approach, results in lower acceleration.

By comparing spectra of far, medium and near field analysis presented in Fig. (8), (9) and (10), it can be seen that the similarity of response spectra becomes more distinctive. That may be due to the convergence of 1D and 2D wave propagation in near field cases with high frequency content of ground motion.

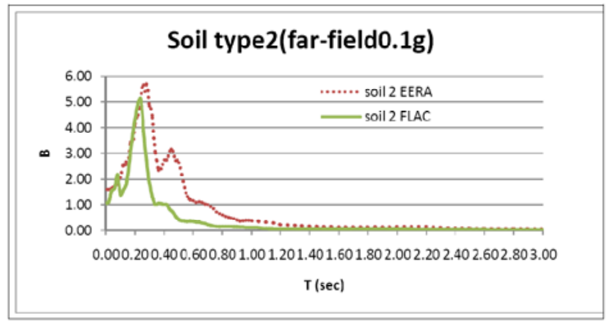


*Fig. 8. Acc. Response Spectra through linear and nonlinear approaches in soil type 2 (far field)*

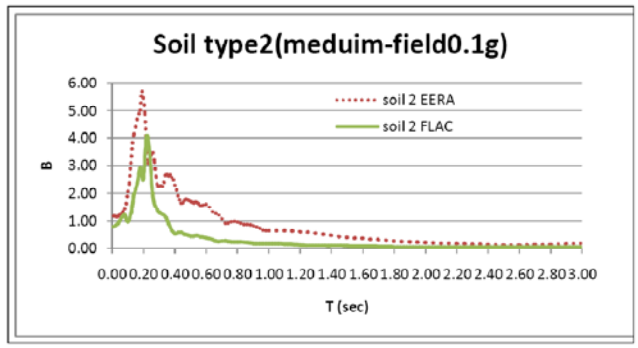


*Fig. 9. Acc. Response Spectra through linear and nonlinear approaches in soil type 2 (medium field)*

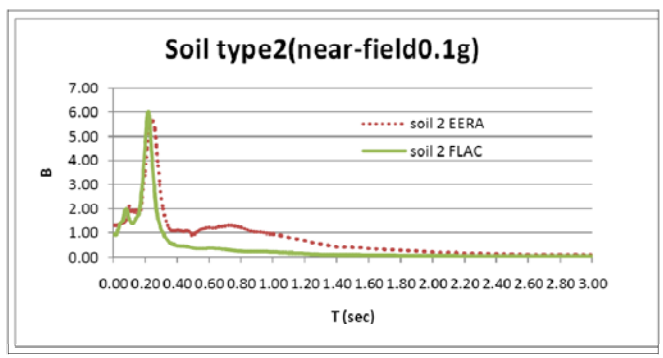


*Fig. 10. Acc. Response Spectra through linear and nonlinear approaches in soil type 2 (near field)*

As shown in these figures two approaches have more similarity in near field case due to similarity of the wave propagation in 1D and 2D media.

In this section, natural period of the site which is one of the important features in site response analysis is calculated and compared with each other. For this purpose natural period of different types of soil deposits gained through linear and fully nonlinear approaches in far, medium and near field cases is presented in Fig. (11), through (14).

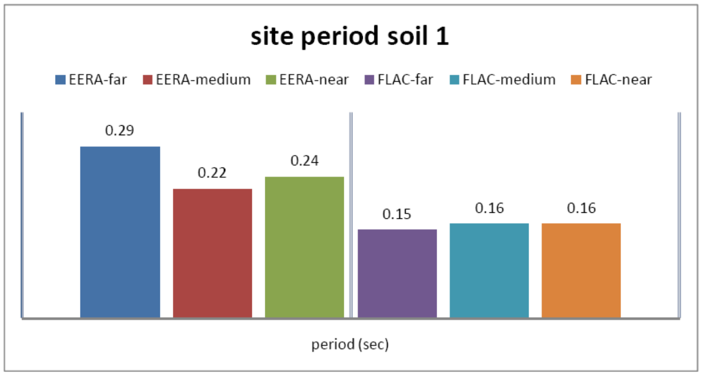


*Fig. 11. Comparison of natural site period by linear and nonlinear approaches in soil type 1*

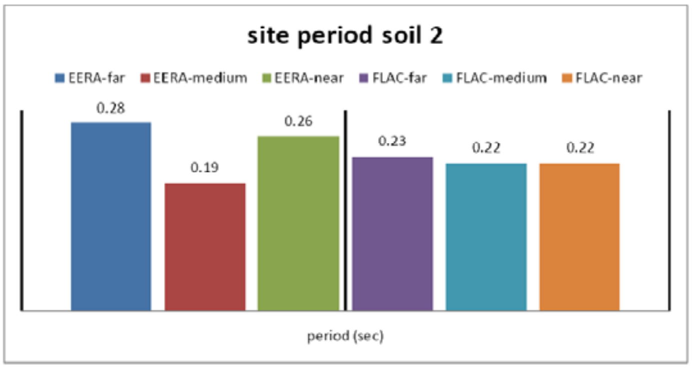


*Fig. 12. Comparison of natural site period by linear and nonlinear approaches in soil type 2*

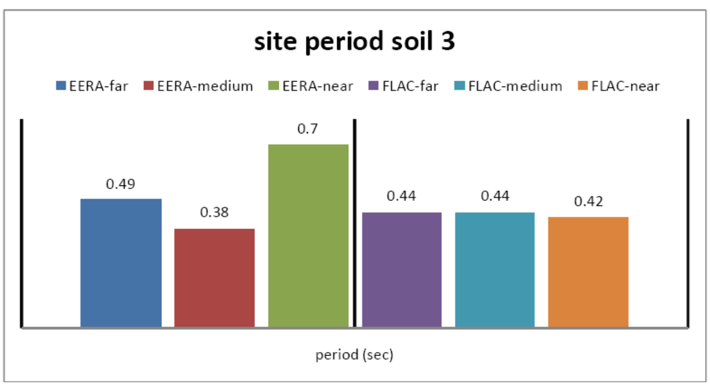


*Fig. 13. Comparison of natural site period by linear and nonlinear approaches in soil type 3*

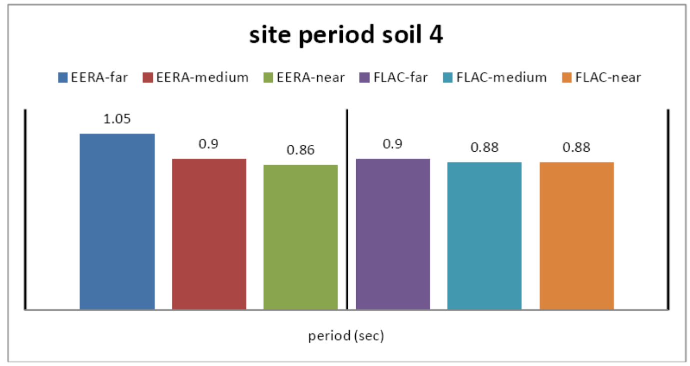


*Fig. 14. Comparison of natural site period by linear and nonlinear approaches in soil type 4*

The fundamental period T of the soil profile is calculated as $T = 4\ H/V$ , where H is the total thickness of the soil profile and V is the average shear wave velocity of the soil profile .

Thus natural site period is determined independently of the input motion and it just depends on soil properties and site conditions. This issue can be seen easily in results of FLAC natural period, since there is no significant difference in T of the soil profiles of all different frequency content cases.

In contrast to FLAC, the equivalent linear method cannot give the true fundamental period of the sites and its results depends on the motion used.

Stress-Strain Loops

In all results of site response analysis, stress-strain in loops are the best feature to identify soil behavior especially nonlinearity. Therefore, the hysteresis curves from both approaches regarding to model soil type 2 and 3 under far-field motion, which is expected to show nonlinearity, are presented in Figs. (15) and (16).

According to these figures, it is apparently seen that equivalent method (Fig. 17) cannot evaluate nonlinear soil behavior properly. Figures suggest that used nonlinear method calculate irreversible plastic strains which exist in nonlinear inelastic materials.

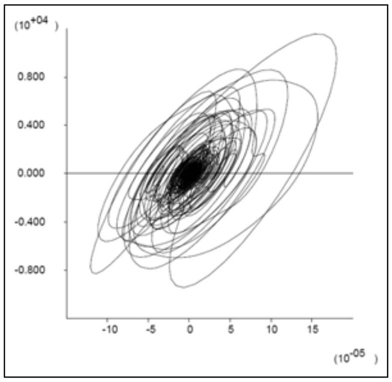

*Fig. 15. The hysteresis stress-strain loops of soil 2 obtained in FLAC*

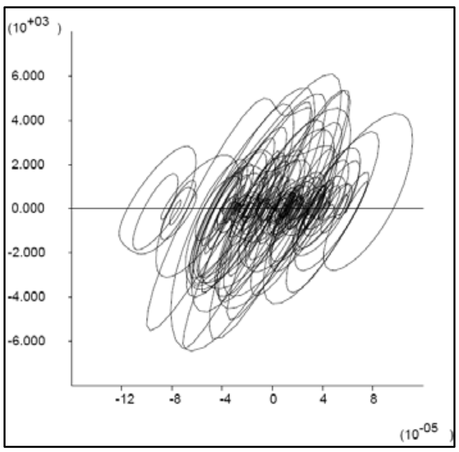

*Fig. 16. The hysteresis stress-strain loops of soil 3 obtained in FLAC*

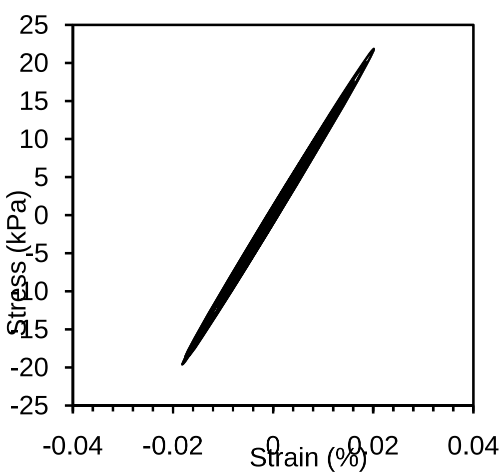


*Fig. 17. The hysteresis stress-strain loops of soil type 3 obtained in EERA*

As shown, permanent strains cannot be computed. However, the equivalent linear approach has been shown to provide reasonable estimates of the soil response under many conditions.

## SUMMARY AND CONCLUSIONS

This paper is presenting the results of a comparative study of linear and nonlinear site response analyses. It summarized some of the well-known site response analysis methods and compared similarities and differences between linear and nonlinear methods by implementation of a nonlinear method of site response analysis. After an overview on the site response analyses, the methods of site response analyses using linear and nonlinear approaches have been expressed and discussed. Then, the site response analyses of four different sites, considering a wide range of cohesive and non cohesive materials, are carried out using linear and nonlinear approaches and numerical simulation.

Site response analysis results of computer program EERA, widely used in engineering practice, and a nonlinear method of solution using computer software FLAC, one of the most powerful finite difference programs are compared numerically. The present study as the past one has shown that equivalent linear analysis estimates maximum acceleration and spectrum ratios larger than observed records.

Since linear site response analysis calculates acceleration in high frequency range, the method gives higher acceleration.

The use of models based on the elastoplasticity theory is more suitable than equivalent-linear approach as they represent a rational mechanical process. In this kind of model, parameters should be chosen so that they are closely related to the rheology that describes the material properties at various strain levels.

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