Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-925

Linear and nonlinear seismic analysis of layered soil stratum

Analyse séismique linéaire et non-linéaire de strate posée de sol

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ABSTRACT
In this paper the material nonlinearity of soil has been taken into account for finding the seismic response of a soil stratum. A finite element model is used to properly account inhomogeneous nature of soil. Analyses are performed in the time domain. Comparisons of linear and nonlinear free field responses have been made. To consider the material nonlinearity of soil, two advanced plasticity based models are considered. Responses obtained with both models are compared with that obtained using elastic soil model. Thus effects of material nonlinearity considering both models are investigated. It was found that material nonlinearity of soil significantly effects free field response and the effect is much dependent on the frequency of excitation.

RÉSUMÉ
En cet article, la non-linéarité matérielle du sol a été prise en considération pour trouver la réponse séismique d'une strate de sol. Un modèle finite d'élément est employé pour rendre compte correctement la nature inhomogène de sol. Des analyses sont exécutées dans le domaine de temps. Des comparaisons des réponses linéaires et non-linéaires de libre champ ont été faites. Pour considérer la non-linéarité matérielle du sol, deux ont avancé les modèles basés par plasticité sont considérés. Des réponses obtenues avec les deux modèles sont comparées à cela obtenue en utilisant le modèle élastique de sol. Ainsi des effets de la non-linéarité matérielle considérant les deux modèles sont étudiés. On l'a constaté que la non-linéarité matérielle du sol affecte de manière significative la réponse de libre champ et l'effet dépend beaucoup de la fréquence de l'excitation.

1 INTRODUCTION

Significant research had been reported in literature for seismic response of soil stratum (e.g. Idriss & Seed, 1968; Lysmer & Kuhlemer, 1969; SHAKE: Schnabel et al., 1972; Prevost, 1981). In most cases, the behavior of soil is assumed linear or at the most equivalent linear. This assumption is not valid during strong excitations as shear strains induced in the soil is large and its behavior becomes nonlinear.

In this paper the effect of material nonlinearity of soil on the seismic response of free field is investigated. When the properties of soil are homogeneous in lateral direction, a layered soil stratum can be used. However to properly account inhomogeneous nature of soil a finite element model is required. The model can be used for layered soil stratum as well as for a soil stratum in which material properties are varying in all the three directions. To introduce plasticity of soil, two advanced plasticity based models namely Drucker-Prager and HiSS (Hierarchical Single Surface) are used. Analyses are performed in the time domain. Verification of the model is performed and then linear and nonlinear free field responses are compared. Analyses are performed for both harmonic and transient excitations.

2 MODELLING

A soil block is selected to represent the free field or a soil stratum (Fig. 1). To analyze this soil block a full three-dimensional geometric model may be considered. However, when seismic loading and configuration of imposed foundation (e.g. piles) and superstructure are symmetric, then advantage of symmetry and anti-symmetry is exploited. Thus, in that case only one fourth of the actual model is required to be considered.

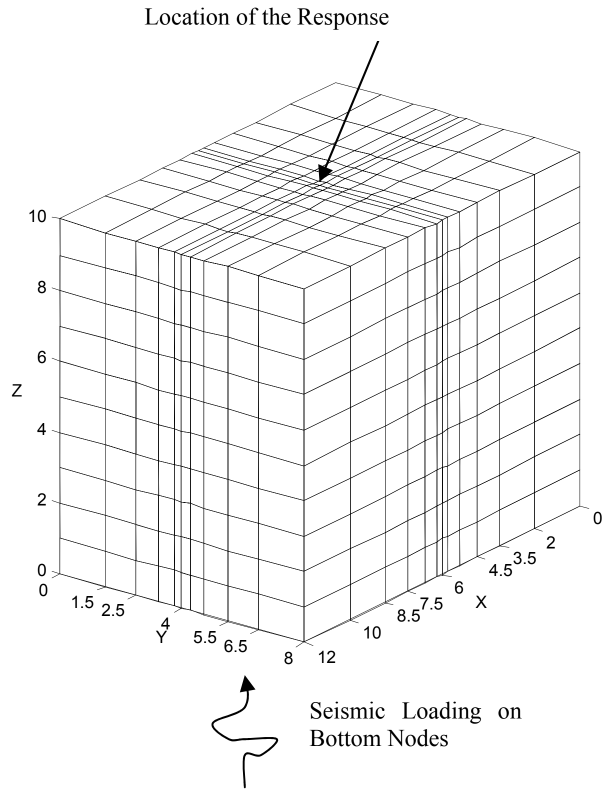

Figure 1. Three-dimensional finite element model for a soil stratum

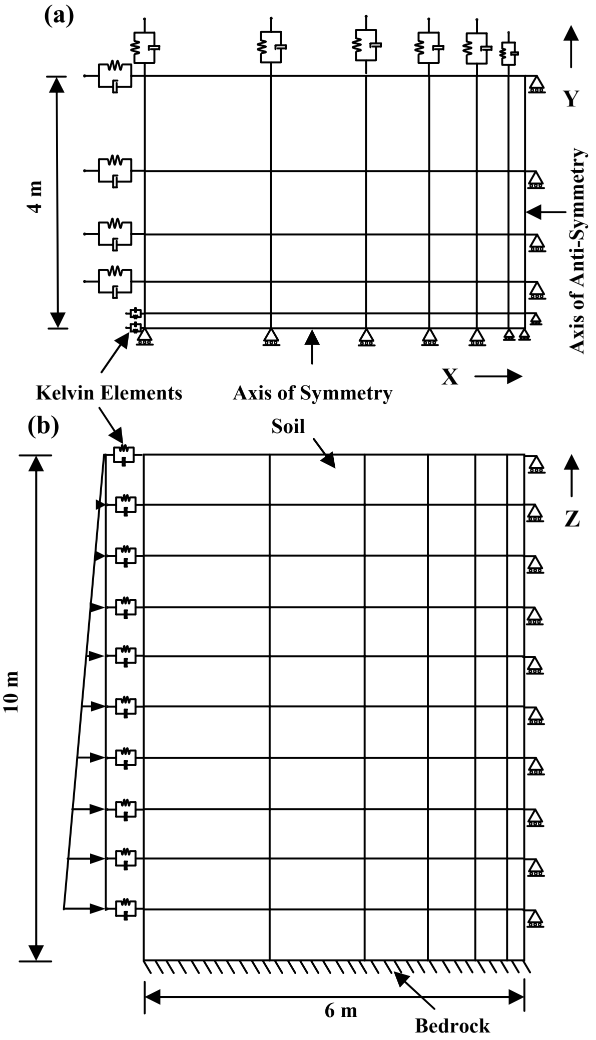

Figure 2. . Finite element mesh for quarter model showing boundary conditions: (a) Top plan (b) Front elevation with initial pressure distribution.

Figure 2, shows the plan and elevation of the three-dimensional quarter model used for the soil block. Consideration of quarter model reduces degrees of freedom significantly and in–turn dramatically decreases computation time.

Model is idealized as an assemblage of eight-node hexahedral solid element. Each node of the element has three translational degrees of freedom. All the nodes on the bottom are fixed as it was assumed that layered soil stratum is resting on the bedrock. To simulate radiation conditions for infinite soil media, side boundaries of the block are simulated using Kelvin elements (spring and dashpot), Fig. 2a. The Kelvin elements are used in all three directions along the boundary. The coefficients of springs and dashpots are derived separately for the horizontal (Novak & Mitwally, 1988) and vertical (Novak et al., 1978) directions. Sizes of finite elements are fairly small near the center and gradually increase as moving away. Seismic excitation is assumed to act on the fixed base nodes and consist of vertically propagating shear waves. The initial stress condition in the soil is governed by the confining pressure of the soil and is proportional to the depth (Fig. 2b).

3 FORMULATION

3.1 *Governing equation*

The governing equation of motion at time $t+\Delta t$ is:

$$M\,{}^{t+\Delta t}\ddot{U} + C\,{}^{t+\Delta t}\dot{U} + K\,{}^{t+\Delta t}U = {}^{t+\Delta t}R = -MR_F\,{}^{t+\Delta t}\ddot{V}_b \tag{1}$$

where ${}^{t+\Delta t}R$ is the external load at this time step due to vertically propagating shear waves at the base. M, C and K are mass, damping and stiffness matrices respectively and found using routine finite element technique. Above equation is solved for displacement ${}^{t+\Delta t}U$ using constant average acceleration method.

3.2 *Nonlinear soil models*

To introduce material nonlinearity of soil in the analysis, two nonlinear models were considered. Both models assume associative plasticity and based on incremental stress-strain relationship. Brief description follows:

3.2.1 *Drucker-Prager soil model*

This model assumes that soil behave like a perfectly plastic material. Yield surface for this model is given by:

$$F = \sqrt{J_{2D}} - \alpha J_1 - k = 0 \tag{2}$$

where J_1 is the first invariant of the stress tensor σ_{ij}; J_{2D} is the second invariant of the deviatoric stress tensor; α and k are material parameters. For further details reader is referred to (Chen & Baladi, 1985).

3.2.2 *HiSS soil model*

In this model, both plasticity and work hardening of the soil are considered. Dimensionless yield surface for this model is given by (Watugala & Desai 1993):

$$F = \left(\frac{J_{2D}}{p_a^2}\right) + \alpha_{ps}\left(\frac{J_1}{p_a}\right)^{\eta} - \gamma\left(\frac{J_1}{p_a}\right)^2 = 0 \tag{3a}$$

where γ and η are material parameters; α_{ps} is the hardening function defined in terms of plastic strain trajectory ξ_v, as:

$$\alpha_{ps} = h_1 / \xi_v^{h_2} \tag{3b}$$

where h_1 and h_2 are material parameters. ξ_v denotes trajectory of the volumetric plastic strain.

4 DATA USED AND VERIFICATION OF THE MODEL

It was assumed that soil is clay at Sabine Pass, Texas. Material properties of this is listed as:

$$E_s = 11777\,kPa;\quad \rho_s = 1610\,Kg/m^3;\quad \nu_s = 0.42;\quad \alpha = 0.0346$$

$$\gamma = 0.047;\quad \eta = 2.4;\quad h_1 = 0.0034;\quad h_2 = 0.78;\quad k = 35.54\,kPa$$

Both harmonic and transient excitation is considered for dynamic loading. Harmonic excitation consists of a sinusoidal wave of given amplitude and frequency. El Centro Earthquake 1940 (N-S component) is used for transient excitation.

Since a rigorous approach is used, its verification is imperative, this is performed by comparing the results obtained from present three dimensional finite element analysis with those obtained using simplified approaches for elastic and elasto-plastic soil. These are found in good agreement (Maheshwari, 2003; Maheshwari et al., 2005).

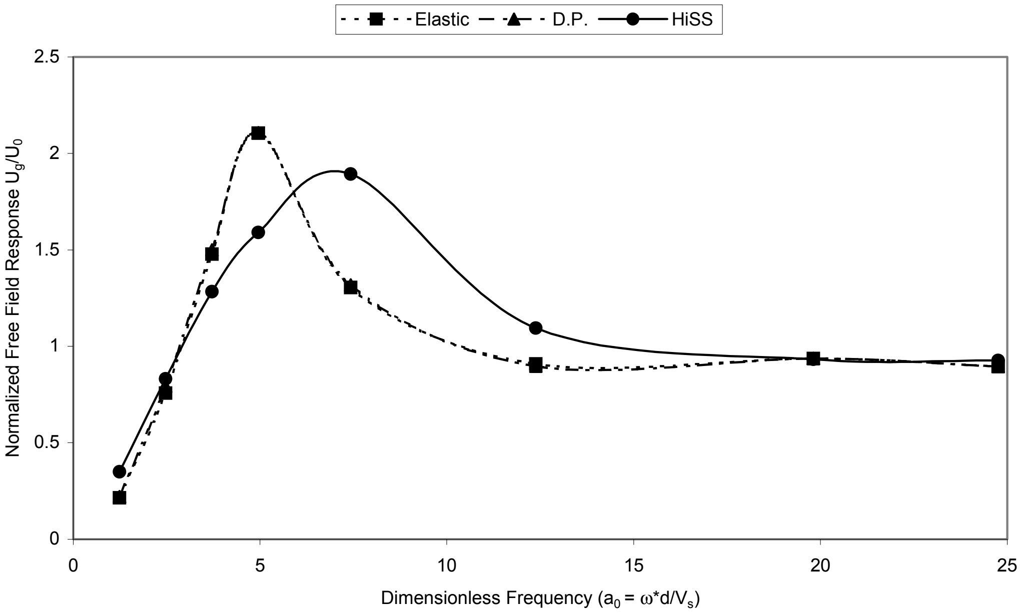

Figure 3. Effect of nonlinearity on free field response at different frequencies of excitation

5 EFFECTS OF NONLINEARITY ON THE SEISMIC RESPONSE

The effect of material nonlinearity of soil on the seismic response of a soil stratum is investigated. Analyses are performed separately for both harmonic and transient excitations.

5.1 *Harmonic excitations*

Harmonic excitation of amplitude (= 50 m/s^2 i.e. about 5 g) with varying frequency is applied at the base of the soil block and resulting response at the ground surface (free field response) is computed at the center of the block (Fig. 1). Such a high value of amplitude for input motion is selected as at lower values of amplitude the Drucker-Prager soil model show little yielding and soil behavior is like an elastic material.

Resulting acceleration-time history of the response is plotted and amplitude of steady-sate response is noted. Results are represented in dimensionless form as shown in Fig. 3. Where amplitude of response is normalized with respect to amplitude of-input bedrock motion and frequency (ω) is represented using dimensionless parameter $a_0 = \omega^*d/V_s$ where d is the depth of the soil block and V_s is shear wave velocity of soil, (Wolf, 1985).

It can be observed from Fig. 3 that when Drucker-Prager (D.P.) model is considered the effect of plasticity on the response is insignificant. In fact in this case, the difference between linear and nonlinear response is very small (not visible in the figure). Contrary to this, when HiSS soil model is considered, it shows large gap between linear and nonlinear response especially at low and moderate frequencies. Response due to HiSS soil model is significantly increased at moderate frequencies.

The difference in nonlinear behavior of soil considering these two models may be attributed to the fact that only plasticity of soil is considered in the D.P. model while both plasticity and strain hardening are considered in the HiSS soil model. It appears that strain hardening effect is dominating for the considered data for material properties and dynamic loading.

Further the HiSS model shows that effect of nonlinearity is quite dependent on frequency. In this case, significant increase (or decrease) in response is attributed to the change in natural frequency of soil layers (due to softening) and consequently shifting it near (or away from) the frequency of excitation.

5.2 *Transient excitation*

Linear (elastic) and nonlinear responses (considering both D.P. and HiSS models) are obtained due to El Centro earthquake loading and shown in Figs. (4a, 4b, 4c). For clarity, only first 10 seconds of time history is shown. As D.P. model show little yielding at original amplitude (PGA = 0.32g), transient motion was amplified 10 times for deriving these results. It can be observed that the effect of material nonlinearity is only at few times (Figs. 4b and 4c) and pattern is similar as for the elastic case (Fig. 4a). Peak values of responses for elastic, D.P. and HiSS cases are 6.42g, 6.94g and 5.88g respectively. Thus, considering D.P. model peak response is increased while considering HiSS model it is decreased. However, a comparison of Figs. 4a and 4c reveals that though for HiSS soil model peak response is less (than elastic case) but responses at other times are higher.

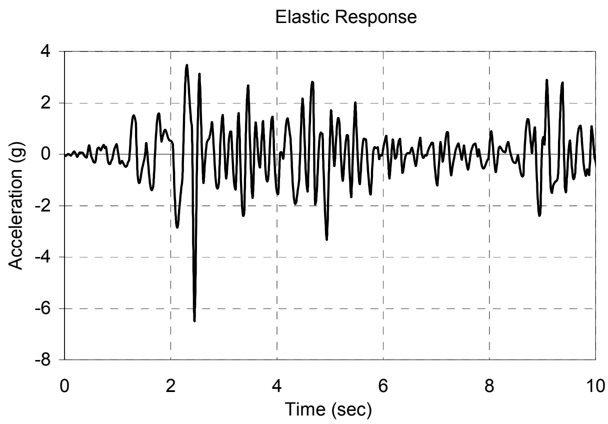

Figure 4a. Linear (Elastic) response (acceleration) time history due to El Centro earthquake loading

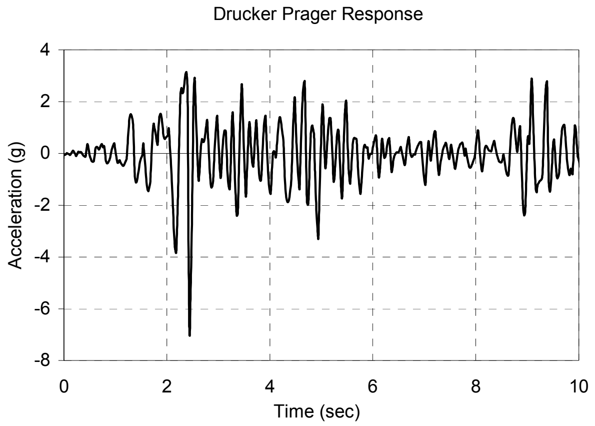

Figure 4b. Nonlinear (Drucker-Prager) response (acceleration) time history due to El Centro earthquake

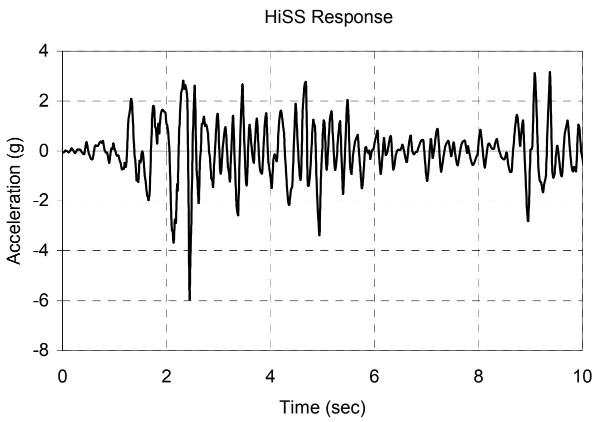

Figure 4c. Nonlinear (HiSS) response (acceleration) time history due to El Centro earthquake

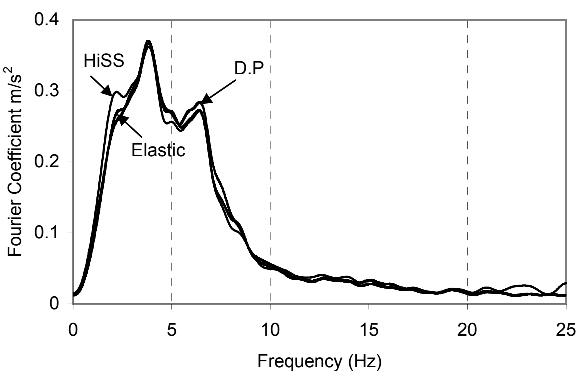

Figure 5. Comparison of Linear (Elastic) and Nonlinear (D.P. & HiSS) Fourier Spectra

To further investigate the effect of material nonlinearity, Smoothed Fourier spectra for the responses shown in Figs. 4 are derived and shown in Fig. 5. From this figure it can be observed that effect of material nonlinearity is similar to that observe for harmonic excitations. The D.P. models shows that effect of nonlinearity is insignificant and response obtained in this case is similar to that for elastic case except at relatively high frequencies. The HiSS soil model reveals that effect of nonlinearity is significant at low and moderate frequencies only and at higher frequencies it is insignificant. Maheshwari et al. (2004) also observed similar trend while analyzing the behavior of pile groups with the HiSS soil model.

6 SUMMARY AND CONCLUSIONS

Using a three-dimensional finite element approach the effect of material nonlinearity on a soil stratum is investigated. It was found that this effect of plasticity is quite sensitive to the frequency of excitation. For the data considered effect was significant at low and moderate frequencies and not sensitive at higher frequencies. Also it was observed that HiSS soil model indicates higher effect of nonlinearity than Drucker-Soil model. It appeared that effect of strain hardening is dominated. However, author would like to acknowledge that more systematic study is required before these conclusions can be generalized.

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