One-Dimensional Seismic Response Study Using Different Soil Models

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Abstract

Using the equivalent linear method and the nonlinear method, the dynamic response of a layered system resting on rigid base is investigated. The nonlinear soil models considered are the Iwan model and the failure seeking model using the hyperbolic stress-strain relationship for backbone curve. The equivalent material properties computed from the corresponding nonlinear hysteresis loops are used for the equivalent linear analysis. Harmonic and transient (Taft Record) base motions are considered to study the response differences between the equivalent linear and the nonlinear method. Some clear response differences are observed when the system is excited with high amplitude of maximum acceleration.

1. Introduction

Solution to the problem of free field systems subjected to earthquake loading is an important step for environmental safety evaluation of many critical structures such as nuclear power plants and offshore structures. A realistic solution to the problem may be obtained by considering the appropriate wave field and the true behavior of soil materials. At present, most of the analyses are based on the assumption of vertically propagating shear waves from the underlying medium. While this assumption has been widely accepted and is valid for many practical cases, the effect of modeling the soil behavior remains to be the subject of the study mainly due to continuous development in formulating the stress-strain behavior of the soil. It is the purpose of this study to compare the results of free field analysis using the equivalent linear method (SHAKE[1]) with those obtained by the nonlinear method (NANSSI[2]) using two different soil models and to investigate the response differences due to soil modeling techniques.

The soil profile considered for this study is a 100 ft deposit resting on rigid bed rock. The shear moduli and shear strength of the materials are increased with depth. Different input waves are considered in two phases. In the first phase, the soil profile is subjected to series of harmonic base accelerations. The maximum accelerations examined are 0.05 g, 0.1 g, 0.2 g and 0.5 g. The frequencies of excitation considered are 0.5 Hz, 1.0 Hz, 2.0 Hz, 5.0 Hz and 10 Hz. In the second phase, an actual recorded earthquake motion (the N21E component of 1952 Kern County) scaled to maximum accelerations of 0.05 g, 0.25 g and 0.50 g, are used to examine the responses of different soil model. The results are presented in terms of the maximum acceleration and maximum shear stress distributions along the soil depth. The response spectra are also computed to investigate the frequency contents of the motions. A discussion is presented which compares the results of the different soil models and specifies the response differences that may encounter if the equivalent linear method is used.

2. Method of Analysis

The equivalent linear analyses are preformed using the computer program SHAKE. Since the code and the equivalent linear method of analysis are well known, they are not discussed herein.

The nonlinear analyses are performed using the newly developed computer program NANSSI. NANSSI is a finite element code which solves the incremental equation of motion in time domain using the tangent stiffness method. The integration technique employed is the implicit-explicit method developed by Hughes et. al. [3]. With this integration technique one has the option to use a mixed explicit and implicit method to solve the equation of motion efficiently by utilizing the advantages of each method simulataneously. The nonlinear soil models considered are the Iwan model [4] and the failure seeking model [5,6]. In both models the backbone curve is defined by the hyperbolic stress-strain relation of the form

$$\frac{\tau}{\tau_y} = \frac{\gamma/\gamma_y}{1 + \gamma/\gamma_y} \qquad (1)$$

where τ and γ are the shear stress and shear strain; τ_y and γ_y are the reference shear stress and shear strain, respectively. In this study τ_y is assumed to be the shear strength of the material and γ_y is obtained from

$$\gamma_y = \tau_y / G_{max} \qquad (2)$$

where G_{max} is the shear moduli at low strain level.

The Iwan model is a mechanical model which consists of series of elasto-plastic elements assembled in parallel form. The properties of these elements will be determined from the backbone curve in eq. (1). The model satisfies the original and extended Masing rules, which are widely used in formulating the stress-strain behavior of soils. The failure seeking model is formulated based on the modified Masing rules in which the stress point seeks for the maximum shear stress starting from the reversal point. In this model the scaling of unloading and reloading branches of the hysteresis loops is not constant and depends on the magnitude of stress at reversal points. The detailed descriptions of the models are beyond the scope of present work. Rather it has been attempt to compare the equivalent linear method and the nonlinear method using above soil model collectively.

3. Soil Profile and Material Properties

The properties in terms of shear moduli and yield stress of the soil profile used for the analyses are shown in Fig. 1. The profile is divided into 20 layers with equal thickness of 5 ft in both SHAKE and NANSSI analyses. The equivalent soil properties in terms of equivalent secant moduli and equivalent damping ratio are obtained from the properties of the hysteresis loops using the hyperbolic stress-strain relationship. The equivalent soil properties depend on the reference strain in eq. (2) which in turn is a function of depth for the profile shown in Fig. 1. In order to obtain the equivalent soil properties for the profile, 5 representative reference strains are selected to compute the corresponding 5 sets of moduli and damping curves for SHAKE analysis. One set of these curves are compared with the most commonly used equivalent property curves provided by Seed and Idriss [7] in Fig. 2. It should be noted that the computed equivalent properties may not represent the real property of soil materials and they are only used to properly compare the different methods of analysis.

4. Parametric Study

Two sets of base motion are considered in this study. In the first set, the system is subjected to harmonic base excitation. The amplitude and the frequency of excitation studied are 0.05 g, 0.1 g, 0.2 g, 0.5 g, and 0.5 Hz, 1.0 Hz, 2.0 Hz, 5.0 Hz, 10.0 Hz, respectively,resulting in total of 20 cases for each soil model. In nonlinear analysis several cycles of motion are used to reach to steady state response, and only explicit method of integration is used for computation.

Due to the limitation of space, only selected cases are shown in this paper. The soil profile subjected to harmonic base acceleration with amplitude of 0.05 g and 0.50 g and frequencies of 0.5 Hz and 5.0 Hz are selected as representative cases. The results in terms of variation of maximum acceleration are shown in Fig. 3 for frequency of 0.5 Hz and Fig. 4 for 5.0 Hz. The variations of maximum shear stress with depth are also shown in Fig. 5 for frequency of 0.5 Hz and Fig. 6 for 5.0 Hz. The figures indicate that for low level of excitation, the equivalent linear method and the nonlinear method produce results in excellent agreement. The agreement continues to hold even as the frequency of vibration increases. For higher levels of base excitation, however, the soil profile will experience larger strains and the nonlinear effects due to the difference of soil models are more pronounced in the results. Figs. 3 and 4 show that the equivalent linear method tends to produce lower values of maximum acceleration in the deep layers of the profile when compared to the results obtained by the nonlinear methods. Similar discrepancies shown in maximum acceleration distribution can be observed in the variations of maximum strain, which are not presented here. The results of maximum stress distribution in Figs. 5 and 6 indicate that the maximum stresses in the profile can be computed accurately with either of the equivalent linear or nonlinear method. In all the harmonic base excitation cases considered, the failure seeking model and the Iwan model with hyperbolic stress-strain relationship produce compatible responses.

In the second set of analyses, the soil profile is subjected to the first 20 seconds of the N21E Component of 1952 Kern County earthquake motion. In order to cover the linear to nonlinear range, the motion is scaled to three levels of maximum acceleration of the orders 0.05 g, 0.25 g, and 0.50 g. The response spectra of the surface motion are shown in Figs. 7 to 9. The variation of maximum acceleration and maximum shear stress for two levels of excitation, 0.05 g and 0.50 g, are shown in Figs. 10 and 11, respectively. For low intensity of motion (a_{max} = 0.05 g at base), the results of both methods of analyses are in very good agreement as expected from harmonic excitation study. The response spectrum computed from the use of failure seeking model, shown in Fig. 7, has somewhat lower response when compared to the other two responses. This may be due to the different mechanism of the model. The response spectrum for moderate base excitation level (a_{max} = 0.25 g at the base), plotted in Fig. 8, shows that the equivalent linear method has overestimated the response between the periods of 0.5 to 1.0 second. The fundamental period computed from SHAKE is 0.63 second which corresponds to the overestimated peak response of the response spectrum. The equivalent linear method tends to create sharp peak at the fundamental period of the system due to the fact that only one representative material property value is used for each layer based on the effective strain level. However nonlinear method will evaluate new material property in each time step which results in creating less distinct peaks. For high intensity of motion (a_{max} = 0.5 g at the base in Fig. 9), the equivalent linear method tends to underestimate the response at low periods. This phenomenon is reported by many other researchers and it is due to the fact that the equivalent linear method tends to overestimate the damping in lower periods. A similar trend in the maximum acceleration distribution observed in the harmonic excitation study is shown in Fig. 10. The variations of maximum stresses with depth, shown in Fig. 11 are, however, less sensitive to the method of analysis when compared to the variation of maximum accelerations.

5. Summary and Conclusion

A parametric study has been performed using the equivalent and the nonlinear methods to compare the responses of 100 ft soil deposit system resting on rigid base subjected to base excitation. The shear moduli and the shear strength of the soil profile are assumed to increase with depth. The equivalent soil properties are obtained from the properties of the hysteresis loops used in nonlinear analysis. The soil models considered are the Iwan model and the failure seeking model using the hyperbolic stress-strain relationship. The effects of harmonic and transient (Taft record) base excitation with different levels of excitation are studied. The results of the analyses show that for low level of excitation, either of the equivalent linear method or nonlinear method may be used to compute the responses. As the intensity of the base motion increases, the equivalent linear method tends to produce different responses compared to the true nonlinear results. The study indicates that for maximum acceleration level of less than 0.20 g, which corresponds to overall strain level of approximately less than 0.2 %, the equivalent linear and the nonlinear method produce compatible results. It is, however, found that maximum stresses are less sensitive to the method of analyses and for some cases either of the two methods may be used to compute maximum stress response.

More study is required to clarify the range of the excitation level and frequency of analysis applicable to the equivalent linear method and nonlinear method. The applicability of nonlinear soil models is also an important subject to be studied in future. However it is believed that the results and the discussion will help the engineer to understand the nonlinear soil behavior compared to the equivalent linear method and help to make proper engineering judgement in solving the seismic response problems.

Acknowledgements

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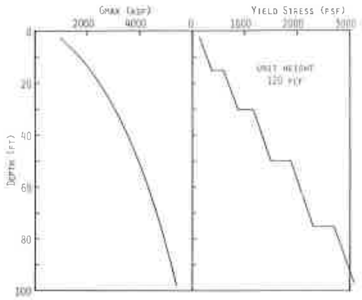

Figure 1 Variation of Soil Properties with Depth

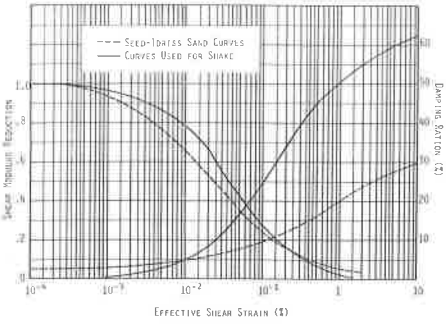

Figure 2 Comparison of One Set of Equivalent Properties with the Curves Given by Seed & Idriss

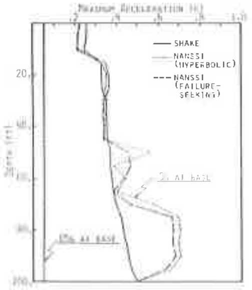

Figure 3 Variation of Maximum Acceleration with Depth, Harmonic Case, f = 0.5 Hz

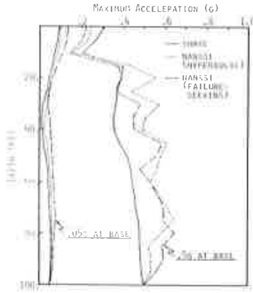

Figure 4 Variation of Maximum Acceleration with Depth, Harmonic Case, f = 5.0 Hz

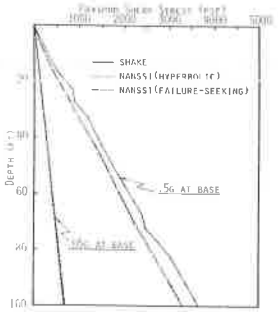

Figure 5 Variation of Maximum Shear Stress with Depth, Harmonic Case, f = 0.5 Hz

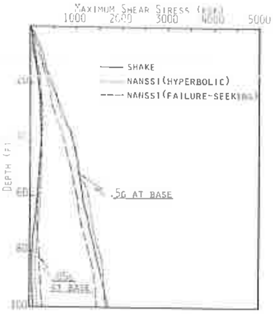

Figure 6 Variation of Maximum Shear Stress with Depth, Harmonic Case, f = 5.0 Hz

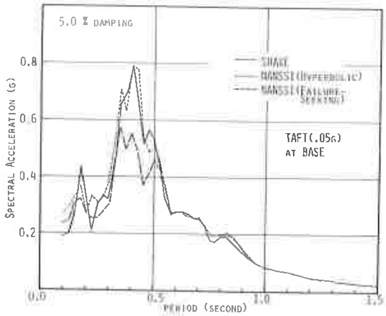

Figure 7 Computed Response Spectrum at the Surface, a_{max} (base) = 0.05 g

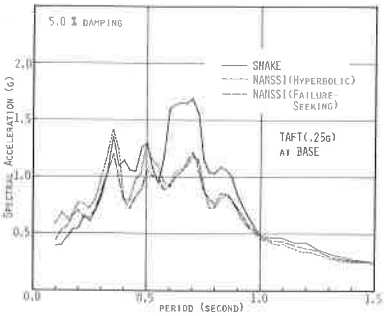

Figure 8 Computed Response Spectrum at the Surface, a_{max} (base) = 0.25 g

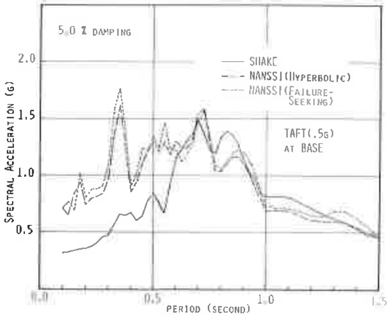

Figure 9 Computed Response Spectrum at the Surface, a_{max} (base) = 0.50 g

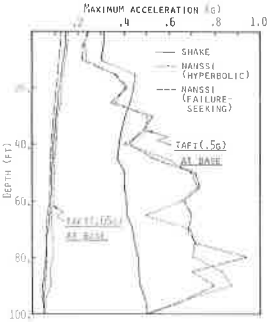

Figure 10 Variation of Maximum Acceleration with Depth, Transient Case

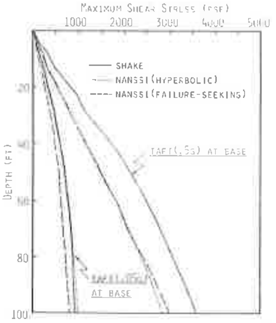

Figure 11 Variation of Maximum Shear Stress with Depth, Transient Case