Importance of confining pressure on nonlinear soil behavior and its impact on earthquake response predictions of deep sites

L'importance de la pression de confinement sur le comportement non linéaire du sol et l'impact dans les predicitions de la réponse sismique de deposits profonds

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ABSTRACT: As part of the ROSRINE (Resolution of Site Response Issues from the Northridge Earthquake) project, numerous strong motion stations that were subjected to the 1994 Northridge earthquake (M_w=6.7) were drilled and sampled. Intact samples recovered from these sites over a depth range of several hundred meters were tested in the laboratory to characterize the linear and nonlinear dynamic properties of the soils. Test results clearly show that isotropic confining pressure, which is directly related to sample depth, has an important effect on these properties. One-dimensional site response analyses were performed to evaluate the effect of including confining-pressure dependency in the nonlinear soil model. Inclusion of this dependency results in higher intensity ground motions calculated at the ground surface.

RESUME: Comment part du ROSRINE (Resolution of Site Response Issues from Northridge Earthquake) project, un grand nombre de stations de forage et échantillonnage du soil ont monté sur les lieus qui ont exposé en le tremblement de Northridge en 1994 (M_w=6.7). Échantillons du soil ont obtenú en cetes lieus jusqu'à deux cents metrés de profondeur. Les échantillons ont essayé en laboratoire par connaître ses proprietes dynamiques linéaire et non linéaire. Les résultats de l'essais fait preuue de que la pression de confinement est très importante sur les propriétes dynamiques du soil. Aussi, analyses sismiques ont executé par évaluer l'effet de la pression du confinement dans un non linéaire model. L'addition de cet effet a exposé plus grandes mouvenents en la surface de terre.

1 INTRODUCTION

In geotechnical earthquake engineering, dynamic soil properties are typically expressed as shear modulus, G, and material damping ratio in shear, D. Over the past three decades, numerous studies of these properties and the parameters affecting them have been conducted. Various investigators have synthesized this work and proposed nonlinear generic curves for use in earthquake analyses (e.g., Seed et al.,1986 for sands and Vucetic and Dobry, 1991 for soils with plasticity). In these curves, the relationship between shear modulus, G, and shearing strain, γ, is typically presented as a normalized modulus reduction curve, G/G_{max} - log γ, where G_{max} is the small-strain shear modulus. One such curve is shown by the solid line in Figure 1a. Nonlinear material damping ratio is always presented in the form of D - log γ as shown by the solid line in Figure1b.

One important point regarding the previous studies is that most soils were tested at effective confining pressures less than about four atmospheres. Furthermore, most of the generic curves were derived from dynamic measurements at effective confining pressures around one atmosphere (e.g., Seed et al., 1986 and Vucetic and Dobry, 1991). Only a few investigations have considered the effect of confining pressure on dynamic soil properties (e.g., Kokusho, 1980, and Ishibashi and Zhang, 1993). The general trends from these studies show that the G/G_{max} - log γ and D - log γ relationships become increasingly linear as confining pressure increases. However, most studies were restricted to pressures less than 10 atmospheres.

In the 1990's, several studies were undertaken to evaluate the effect of confining pressure on nonlinear soil properties (e.g., EPRI, 1993). The most recent study, called the ROSRINE (Resolution of Site Response Issues from the Northridge Earthquake) project, involved investigating deep soil sites shaken by the 1994 Northridge earthquake (M_w=6.7). This work necessitated modeling soil behavior at high confining pressures representing significant depths (100 to 300 m). The results from a portion of the laboratory work involving intact silty sands and confining pressures up to 30 atmospheres are presented below. The impact on predicted ground response of including pressure-dependent nonlinear soil properties is then illustrated.

2 EFFECT OF CONFINING PRESSURE ON NONLINEAR SOIL BEHAVIOR

In the ROSRINE project, numerous intact soil samples were recovered over a depth range of 3 to 300 m. Some of these samples were tested in the laboratory at the University of Texas at Austin using combined resonant column and torsional shear (RCTS) equipment. Linear and nonlinear dynamic properties were evaluated at isotropic confining pressures ranging from 0.25 to 30 atmospheres. The results of these tests were analyzed in an effort to characterize the impact of soil type, confining pressure, number of loading cycles and loading frequency on dynamic soil behavior.

A total of 13, nonplastic silty sand specimens was tested. The linear and nonlinear dynamic properties were analyzed, and families of G/G_{max} - log γ and D - log γ relationships were developed which reflected the effect of isotropic confining pressure, σ_o', on these relationships. The G/G_{max} – log γ relationship for the silty sand is illustrated by the family of dashed lines in Figure 1a. Similarly, the effect of σ_o' on the D – log γ relationships is illustrated by the family of dashed lines in Figure 1b. Clearly, the normalized modulus reduction and material damping curves of nonplastic silty sands are affected by confining pressure. Both relationships shift to higher strain levels with increasing confining pressure (Stokoe et al., 1999, and Darendeli, 2001). The shift in the relationships results in increasingly linear soil response as confining pressure increases; hence, soil linearity increases as depth increases.

It is interesting to see that the confining-pressure-dependent G/G_{max} - log γ and D - log γ curves for silty sands at one atmosphere agree quite well with the average generic curves for sands proposed by Seed et al. (1986). This observation supports the point stated earlier that most generic curves were derived from dynamic measurements at an effective confining pressure around one atmosphere.

It is important to realize that the confining-pressure effect also impacts the G - log γ relationships. This impact occurs from the fact that both the average generic sand curve and the family of pressure-dependent normalized curves presented in Figure 1a would be scaled to field conditions using in-situ shear wave velocities; hence,

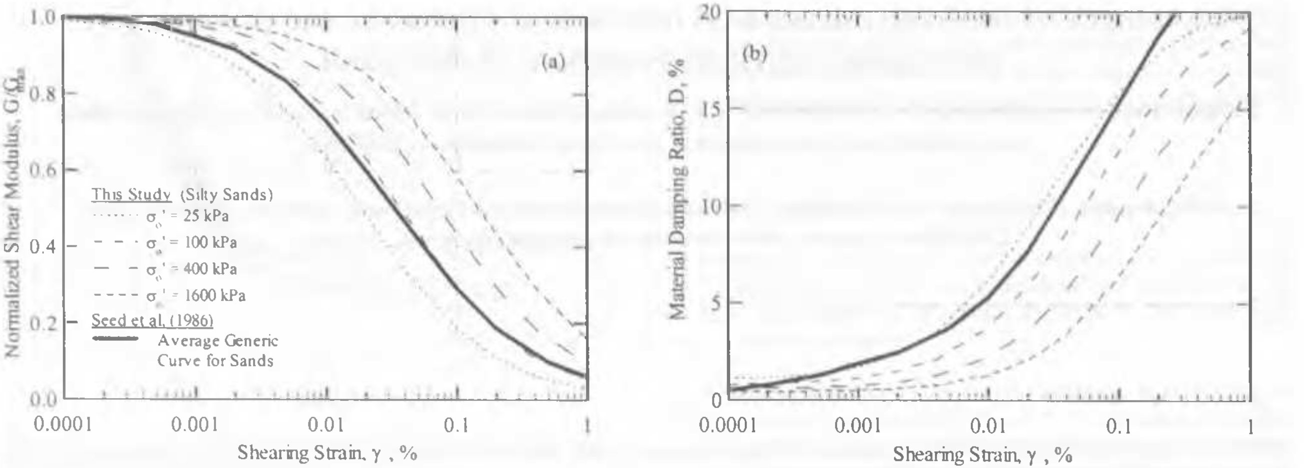

Figure 1. Effect of confining pressure on dynamic soil properties and its comparison with an average generic curve: (a) nonlinear normalized modulus reduction curve, and (b) nonlinear material damping curve.

using field G_{max} values. As a result, the pressure-dependent G - log γ curves tend to deviate from the pressure-independent generic curves at higher strain amplitudes at a given confining pressure. The exception occurs at a confining pressure of approximately one atmosphere when both sets of curves are nearly the same. Therefore, the stiffness of deep soil layers at larger strains will be underestimated with average generic curves. Because the damping curves presented in Figure 1b are directly used in site response analysis without any scaling, damping characteristics of the same soil layer will be overestimated with average generic curves. Depending on the characteristics of the problem at hand, this will likely lead to deep soil profiles as discussed below.

3 IMPACT ON SITE RESPONSE ANALYSES

The impact of accounting for confining pressure when assigning nonlinear soil properties in site response analyses of deep (>50 m) soil sites is discussed below. This point is addressed because site response analyses are often performed using average, pressure-independent generic curves. To illustrate the impact, a 120-m thick silty sand (SM) deposit was analyzed using the shareware version of ProShake (EduPro, 1998). A confining-pressure-dependent shear wave velocity, V_s, profile was modeled after the in situ seismic measurements at the silty sand sites. The Topanga motion (Maximum Horizontal Acceleration, MHA, = 0.33 g) recorded during the 1994 Northridge earthquake was used as the input "rock" motion.

In Figure 2, the acceleration response spectra from the two analyses are presented; 1) the analysis using average generic curves to model all layers, and 2) the analysis using the family of nonlinear curves that account for the effect of confining pressure on dynamic behavior. The response spectra indicate that the confining-pressure-dependent curves produce an MHA almost twice as large as that predicted by the generic curves (0.53 g vs. 0.29 g). Additionally, larger spectral accelerations (typically 50% - 90% higher) are calculated at all periods less than 1 sec for the analysis utilizing confining-pressure-dependent curves.

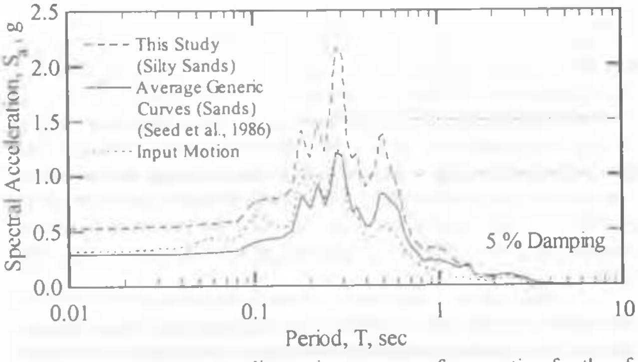

Figure 2. Impact on nonlinear site response of accounting for the effect of confining pressure on dynamic soil properties.

The change in response characteristics can be explained by the nonlinear soil properties incorporated in the analyses. The shift of the modulus reduction curve to higher strain levels in deep layers (Figure 1a) results in less modulus reduction (Figure 3a). The shift of the pressure-dependent damping curves to higher strains (Figure 1b) cause a significant reduction in damping at depth. These two phenomena have a counteracting effect on shearing strain (Figure 3b). However, the reduction of damping at depth (Figure 3c) has a major impact on peak acceleration at the surface as presented in Figure 3d. Because damping significantly affects only the motion at frequencies greater than the natural frequency of the site, the MHA and spectral accelerations at smaller periods are affected the most.

4 PARAMETRIC STUDY

Silty sand (SM) deposits were analyzed to investigate further how modeling confining-pressure-dependent nonlinear soil properties affects seismic response. The depth of these sites ranged between 15 to 240 m and the sites were subjected to the Topanga ground motion. To investigate the effect of input motion intensity, the Topanga motion was scaled to 0.1 g, 0.33 g and 0.6 g. The results of this parametric study are summarized below.

For larger intensity motions and deeper soil deposits, the more linear response modeled by confining-pressure-dependent curves results in slightly shorter (about 10%) fundamental periods. However, for most of the cases studied, the fundamental periods calculated using the different nonlinear curves are within 5%.

Table 1 presents the ratio of the average equivalent linear damping ratio for the confining-pressure-dependent and average curves. Average equivalent linear damping ratio was calculated by averaging the damping ratio in each layer weighted by the layer thickness. The difference in average equivalent linear damping ratio is significant, particularly for sites deeper than 30 m. Utilizing confining-pressure-dependent curves reduces the average equivalent linear damping ratio as much as 60% relative to values estimated using average generic curves. Consequently, larger ground motions are sustained in analyses utilizing confining-pressure-dependent nonlinear soil properties.

The ratio of predicted MHA values are presented in Table 2. MHA values predicted using confining-pressure-dependent curves are higher, with the largest difference occurring at higher intensity input motions and deeper sites (>30m). At a period of

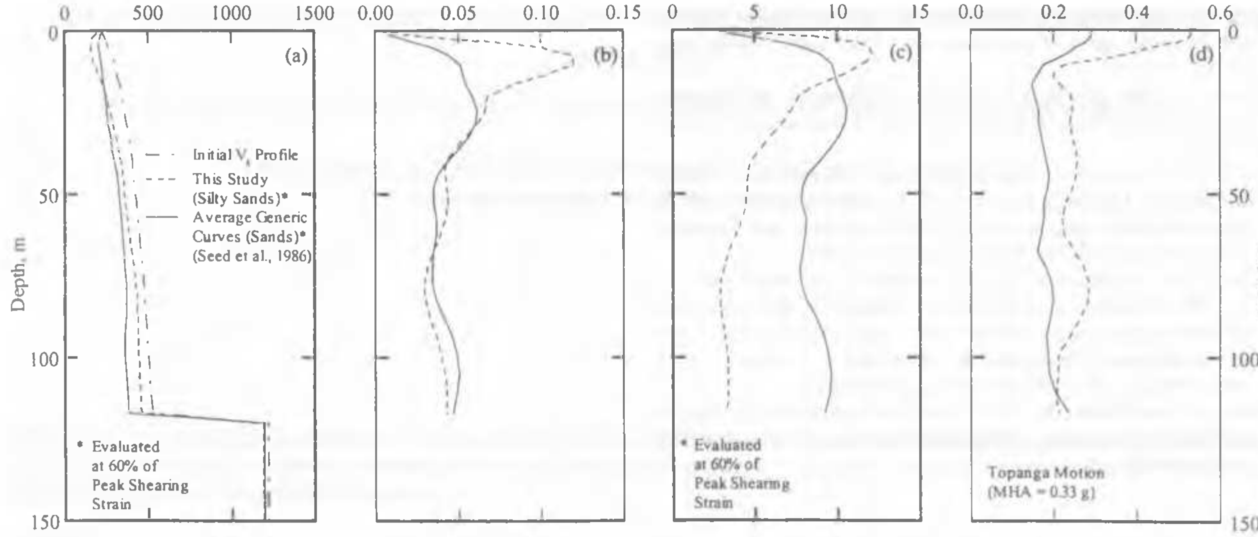

Figure 3. Comparison of (a) peak shearing strain, (b) equivalent linear damping ratio, and (c) peak acceleration profiles predicted by using confining-pressure-dependent and generic modulus reduction and material damping curves.

0.3 sec, the confining-pressure-dependent curves also predict larger spectral accelerations than the average curves (Table 2). However, at a period of 1.0 sec, the spectral accelerations are similar (Table 2). These motions are similar because at periods greater than the natural period of the site, the response of the site is dominated by the overall stiffness (site period). Also, material damping has only minimal impact on site response in this period range. Consequently, confining-pressure-dependent analyses tend to predict a smaller response at longer periods due to more linear behavior (less modulus reduction) in deep layers. The trends at these longer periods will also be affected by the frequency content of the input ground motion. The results from this parametric study indicate that the intensity of ground motions at spectral periods less than about 1 sec can be substantially underestimated when generic normalized modulus reduction and material damping curves are used at deep soil sites.

5 CONCLUSIONS

The laboratory results presented in this study show that confining pressure, and therefore depth, has a significant impact on both the normalized modulus reduction and material damping curves for silty sands. As confining pressure increases, both curves shift to higher strain levels resulting in more linear soil behavior.

Site response analyses were carried out to evaluate the impact of modeling confining-pressure-dependent nonlinear soil properties on predicted ground motions. The analyses indicate that utilizing a family of confining-pressure-dependent curves results in larger intensity ground motions than those predicted with average generic curves, particularly at periods less than about 1.0 sec. This result is more pronounced for deeper sites subjected to higher intensity input motions due to lower damping introduced by the confining-pressure-dependent curves. At longer spectral periods, the response is dominated by the overall stiffness of the site. As a result, the confining-pressure-dependent analyses will tend to predict a smaller response at longer periods due to the more linear response modeled by these curves.

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Table 1 Comparison of average equivalent linear damping ratio, (%), predicted using confining-pressure-dependent and generic modulus reduction and material damping curves.

	Input MHA=0.1g	Input MHA=0.3g	Input MHA=0.6g
Depth	CPD/Average	CPD/Average	CPD/Average
15 m	0.82	0.93	0.93
30 m	0.71	0.84	0.87
60 m	0.60	0.70	0.74
120 m	0.47	0.58	0.61
240 m	0.40	0.45	0.52

Table 2 Comparison of spectral accelerations, (g), predicted using confining-pressure-dependent and generic modulus reduction and material damping curves.

	Input MHA=0.1g			Input MHA=0.3g			Input MHA 0.6g		
	CPD/Average			CPD/Average			CPD/Average		
Depth	MHA	0.3s	1.0s	MHA	0.3s	1.0s	MHA	0.3s	1.0s
15 m	1.00	1.01	1.00	1.10	1.07	1.02	1.14	1.05	1.06
30 m	1.08	1.13	0.98	1.35	1.34	1.01	1.25	1.37	1.01
60 m	1.00	1.01	0.94	1.41	1.46	1.00	1.47	1.47	1.10
120 m	1.19	1.06	1.16	1.83	1.81	1.50	1.92	1.80	1.69
240 m	1.45	1.62	1.11	2.53	2.15	1.07	2.50	2.60	1.25

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