The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

A study on nonlinear dynamic properties of soils

* Chih-Hao Hsu[1)], Shuh-Gi Chern [2)] and Howard Hwang[3)]

[1), 2)] *Department of Harbor and River Engineering, NTOU, Taiwan*
[1)] *willie2567@hotmail.com*
[3)] *Graduate Institute of Architecture and Sustainable Planning, NIU, Taiwan*

ABSTRACT

This paper presents a study on dynamic characteristics of soils, particularly, the shear modulus reduction curves and damping curves for cohesionless and cohesive soils. In this study, available research documents including reports and papers are collected and reviewed to find the factors that affect dynamic characteristics of soils. It is found that the confining pressure and plastic index are the influential factors for cohesioneless and the cohesive soils, respectively. On the basis of these factors, the dynamic characteristics for cohesionless and cohesive soils are discussed, and the shear modulus reduction curves and damping curves for cohesioneless and cohesive soils are determined. The results of this study can be utilized in the field of disaster reduction, such as the calculation of ground response subject to earthquakes using the SHAKE computer program and then the evaluation of safety of buildings in a seismic event.

1. INTRODUCTION

In the development of analytical procedures for evaluating the response of soil deposits under seismic ground motion, adequate information on non-linear dynamic soil properties, especially dynamic shear modulus and damping ratio, is essencial for accurate computations of ground response. Shear modulus and damping ratio are generally expressed in the forms of relationships as a function of shear strain. In this study, available data on dynamic shear moduli and damping ratio for cohesive and cohesionless soils under cyclic loading conditions are summarized. The results of this study can be utilized in the field of disaster reduction, such as the calculation of ground response subject to earthquakes using the SHAKE computer program and then the evaluation of safety of buildings in a seismic event.

[1)] Ph.D. Candidate
[2)] Professor
[3)] Professor

2. SOIL DYNAMIC CHARACTERISTICS

Laboratory triaxial compression tests conducted under cyclic loading conditions are usually used to determine soil dynamic characteristics. Because most soils have curvilinear stress-strain relationships as shown in Fig. 1, the shear modulus is generally expressed as the secant modulus determined by the extreme points on the hysteresis loop, while the damping factor is proportional to the area inside the hysteresis loop.

The shear modulus G, at a strain level γ, is then evaluated from the relationship:

$$G = \frac{\tau}{\gamma} \quad (1)$$

Where τ and γ are the shear stress and shear strain amplitudes, respectively. Secant modulus has greater value when strain is smaller. Under elastic condition scant shear modulus of soil reaches a maximum value G_{max} when γ is zero. G_{max} can also be computed from shear wave velocity by the following equation:

$$G_{max} = \rho v_s^2 \quad (2)$$

Where ρ is soil density, V_s is shear wave velocity in the soil layer. In the study of soil dynamic characteristics, shear modulus G is generally normalized by G_{max} to obtain shear modulus ratio G/G_{max}. Fig. 2 illustrates the shear modulus reduction curves. As shown in Fig. 2, shear modulus ratio is greater if strain level is smaller. Value of shear modulus ratio decreases as strain level increases.

Similar relationships may also be derived for the damping ratio ξ at a strain level γ and presented by the following equation:

$$\xi = \frac{W_D}{4\pi W_s} \quad (3)$$

Where W_D is the dissipated energy; W_S is maximum strain energy. The damping curve is also presented in Fig. 2. The curve shows that damping ratio increases as shear strain level increases.

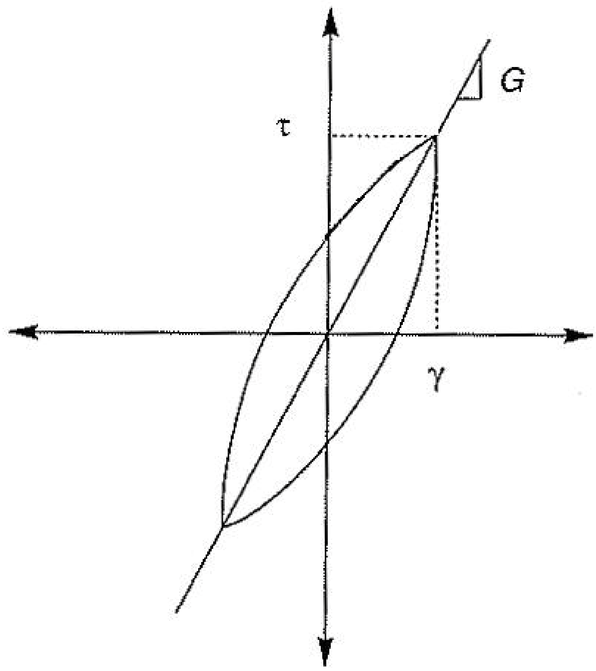


Fig. 1. Hyperbolic loop, non-linear soil model with extended Masing rule to define loading and unloading behavior.

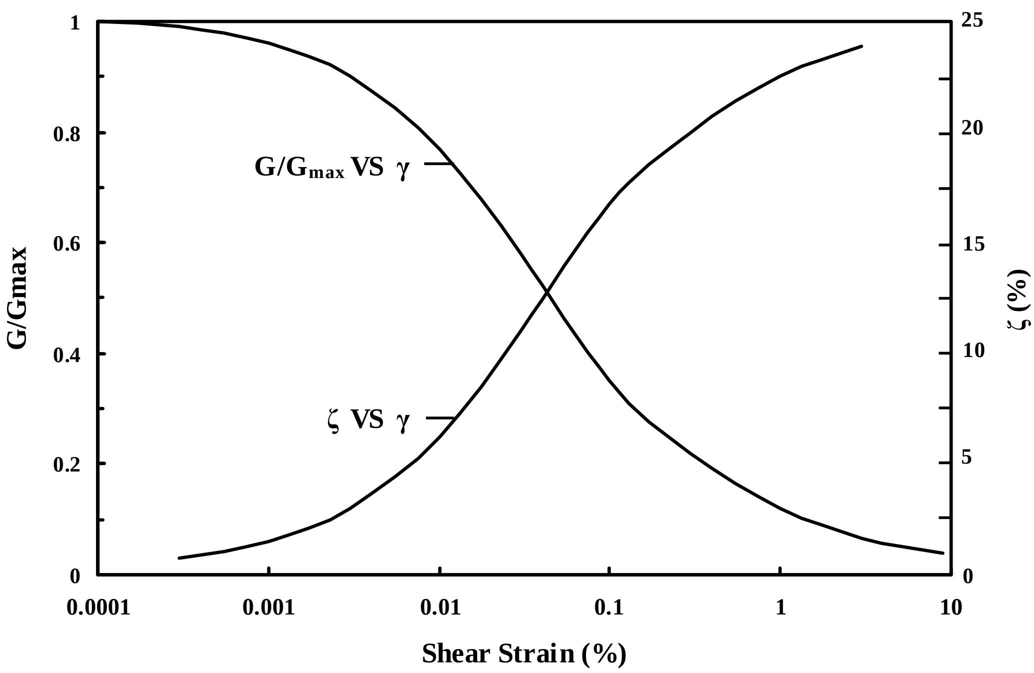


Fig. 2. Shear modulus reduction and damping curves of soils.

3. FACTORS AFFECT SOIL NON-LINEAR CHARACTERISTICS

3.1 Cohesionless Soil

A comprehensive survey of the factors affecting the shear modulus and damping ratio of cohesionless soils have been presented by many researchers, such as Seed and Idriss (1970), Hardin and Drnevich (1972), Iwasaki et al.(1978), Dobry and Vucetic (1987), Ishibashi and Zhang (1993), Hashash and Park (2001), and Stokoe et al.(2004). In their studies, it was suggested that the primary factors effecting shear modulus and damping ratio are: effective confining pressure σ'_m; void ratio e; and shear strain γ; and that less important factors include: number of loading cycles N; and overconsolidation ratio OCR.

In recent years, many investigators had also studied factors influencing shear modulus reduction curves and damping curves of cohesionless soil by effective confining pressure σ'_m, such as Hardin and Drnevich (1972) and Seed and Idriss (1970) had shown clearly that modulus values for sands are strongly influenced by effective confining pressure. In addition, Iwasaki et al. (1978) showed that influence of shear strain on shear modulus reduction decreases as effective confining pressure increases. On the other hand, Ishibashi and Zhang (1993), Hashash and Park (2001), and Stokoe et al. (2004) pointed out that influence of shear strain on shear modulus reduction, decreases as effective confining pressure increases. In the damping curves, Dobry and Vucetic (1987) showed that damping ratio increases as effective confining pressure increases.

3.2 Cohesive Soil

Many investigators (Iwasaki et al. (1978); Ishibashi and Zhang (1993); Hashash and Park (2001); Stokoe et al. (2004); and Vucetic and Dobry (1991)) had also studied factors influencing shear modulus and damping ratio of cohesive soil. Most of these studies have shown that the primary factors affecting shear modulus and damping ratio factors are: plasticity index (PI), void ratio e and frequency of cyclic loading.

In recent years, many investigators had also studied factors influencing shear modulus reduction curves and damping curves of cohesive soil by plastic index, such as Kokushu et al. (1982) had suggested that damping ratio values may be related to the plasticity index of a soil. Stokoe et al.(2004) and Vucetic and Dobry (1991) found that damping ratio decreases as PI increases, however, under higher shear strain level, damping ratio may decrease as PI increases.

3. DYNAMIC CHARACTERISTICS OF COHESIONLESS SOILS

As noted previously, for the study of factors affecting shear modulus and damping ratio of cohesionless soil, many investigators had also studied factors influencing shear modulus reduction curves and damping curves of cohesionless soil by confining pressure σ'_m, he consider that the effective confining pressure σ'_m is the primary factor affecting dynamic characteristics of cohesiveness soil. Thus for practical purposes, available information (Ishibashi and Zhang (1993); Hashash and Park (2001); and

Stokoe et al. (2004)) on the dynamic characteristics for sands under different effective confining pressures is reviewed.

This study considering influence of effective confining pressure, Ishibashi and Zhang (1993) presented shear modulus reduction curves and damping curves under different effective confining pressures of 27.6kPa, 55.2kPa, 110kPa, 221kPa, and 442kPa. Hashash and Park (2001) also presented shear modulus reduction curves and damping curves under different effective confining pressures of 27.6kPa, 55.2kPa, 110kPa, 221kPa, 442kPa, 833kPa, 1776kPa and 10MPa. From study results, they showed that under higher effective confining pressure, effect of confining pressure on shear modulus reduction and increase of damping ratio may be more significantly. In the studies of shear modulus reduction curves, and damping curves under effective confining pressure of 25kPa, 250kPa and 2500kPa, Stokoe et al. (2004) found that effective confining pressure did affect shear modulus reduction curves.

In general, effective confining pressure increases as soil layer depth increases. Performing laboratory dynamic tests to determine both modulus and damping characteristics, samples are taken from different depths with different effective confining pressures. To investigate the effect of effective confining pressure variations on dynamic characteristics, effective confining pressures are separated into four categories in this study, i.e., σ'_m=25~27.6kPa, 55.2kPa, 110kPa, and 221~252kPa.

(1) Effective confining pressure σ'_m = 25~27.6 kPa

Fig. 3(a) shows the shear modulus reduction curves under effective confining pressure σ'_m = 25~27.6 kPa. It may be seen that variation in these three curves is very closed each other at shear stain lower than 3×10^{-3}%, shear modulus presented by Hashash and Park (2001) has higher values than that of Ishibashi and Zhang (1993) and Stokoe et al. (2004) when shear stain values are higher than 3×10^{-3}%. The damping curves under effective confining pressure σ'_m=25~27.6kPa are shown in Fig. 3(b). As shown in Fig. 3(b), the damping ratio presented by Hashash and Park (2001) has lower values than that of Ishibashi and Zhang (1993) and Stokoe et al. (2004). The differences become bigger as shear strain increases.

(2) Effective confining pressure σ'_m = 55.2 kPa

Fig. 4(a) shows the shear modulus reduction curves. It is shown that two curves are very close each other at strain values of 1×10^{-4} % to 1×10^{-1} %. The damping curves are shows in Fig. 4(b) under effective confining pressure σ'_m=55.2kPa. It is shown that difference between these two curves is very small at shear strain value of 1×10^{-4} % to 3×10^{-3} %; however, damping ratio presented by Hashash and Park (2001) has smaller values than that of Ishibashi and Zhang (1993) when shear strain value is higher than 3×10^{-3} %. The difference becomes bigger as shear strain value increases. However, the shear modulus curves and damping curves of cohesioneless soils under effective confining pressure σ'_m=55.2kPa were not reported by Stokoe et al. (2004).

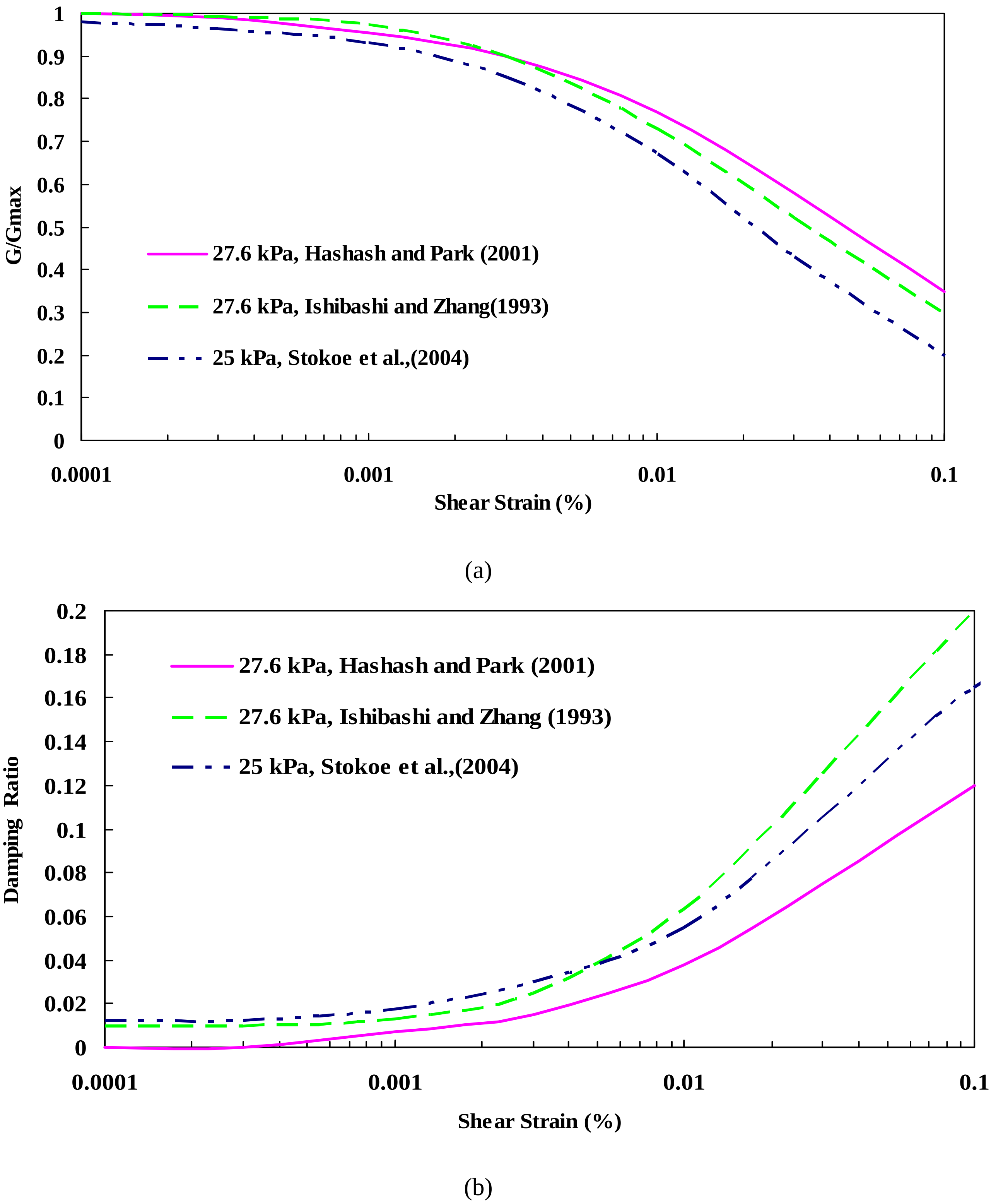
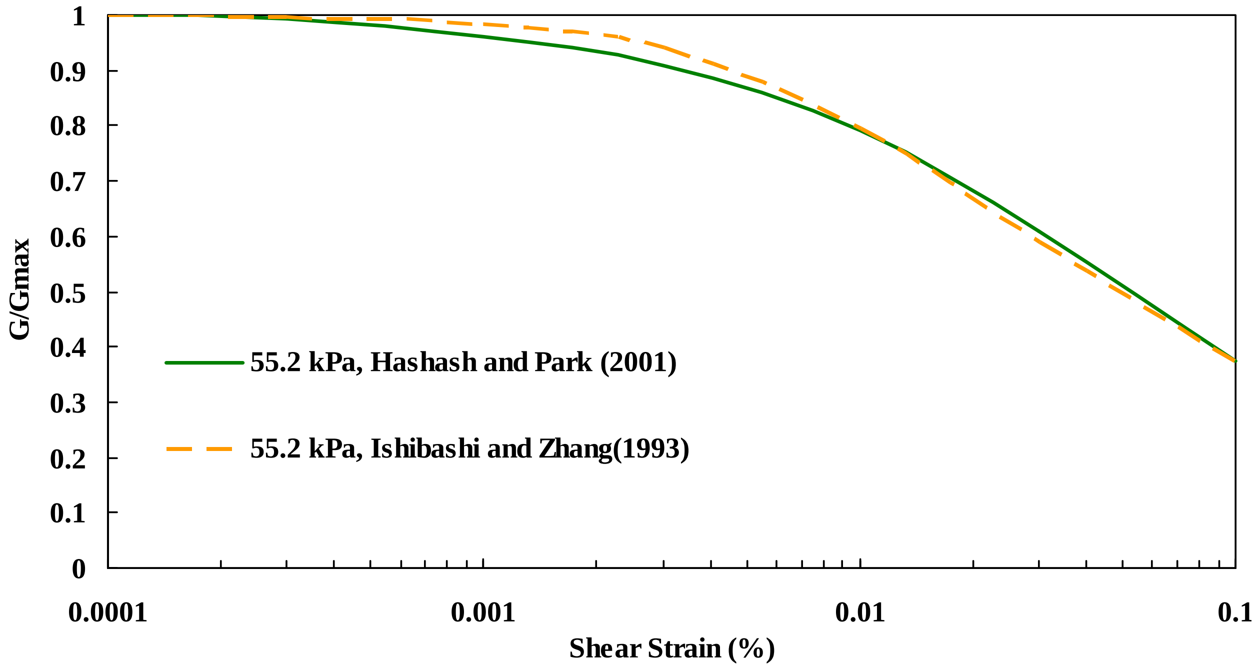
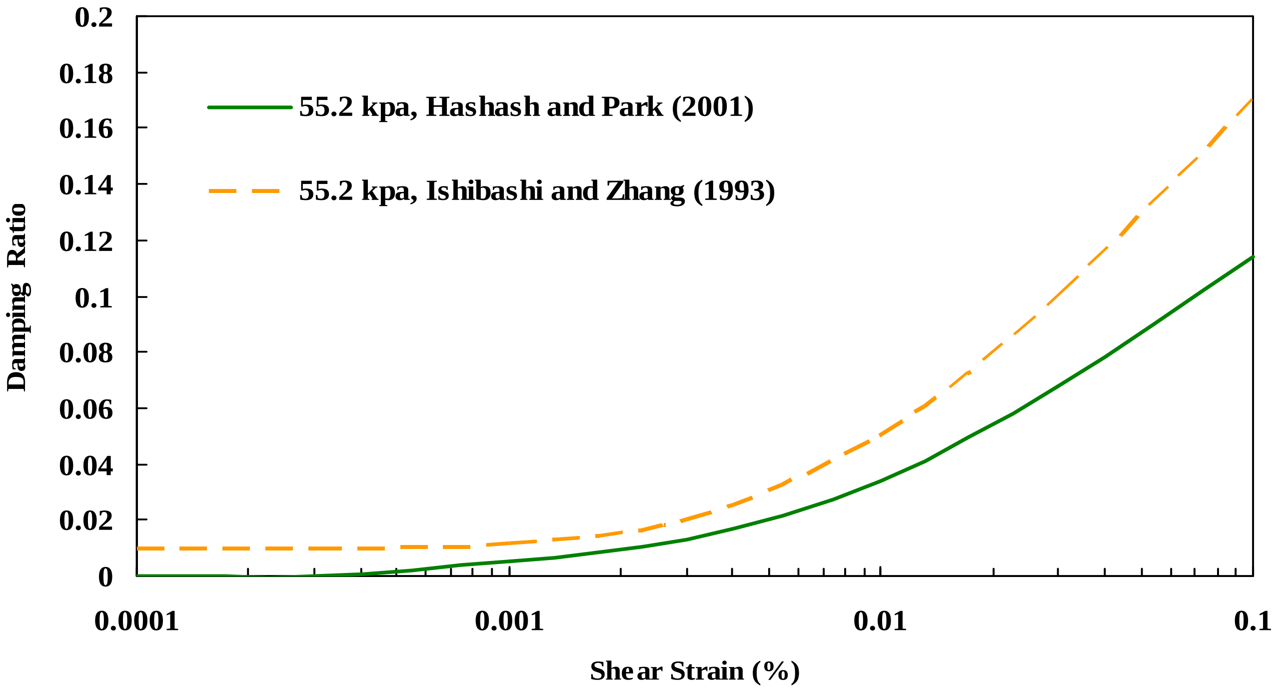


Fig.3. Influence of confining pressure for cohesionless soils with σ'_m = 25~27.6 kPa, (a) shear modulus reduction curves, (b) damping curves.



(a)



(b)

Fig.4. Influence of confining pressure for cohesionless soils with σ'_m = 55.2kPa, (a) shear modulus reduction curves, (b) damping curves.

(3) Effective confining pressure σ'_m = 110 kPa

Fig. 5(a) shows the shear modulus reduction curves under σ'_m=110kPa. It is seen that curves are close each other at shear strain of 1×10^{-4} % to 1×10^{-1} %. The damping curves are shown in Fig. 5(b). No significant difference can be seen between these two curves at shear strain of 1×10^{-4} % to 1×10^{-2} %, however, Hashash and Park (2001) result has lower values than that of Ishibashi and Zhang (1993). The difference becomes bigger as shear strain increases. However, the shear modulus reduction curves and damping curves for cohesioneless soils under effective confining pressure σ'_m=110kPa were not reported by Stokoe et al. (2004).

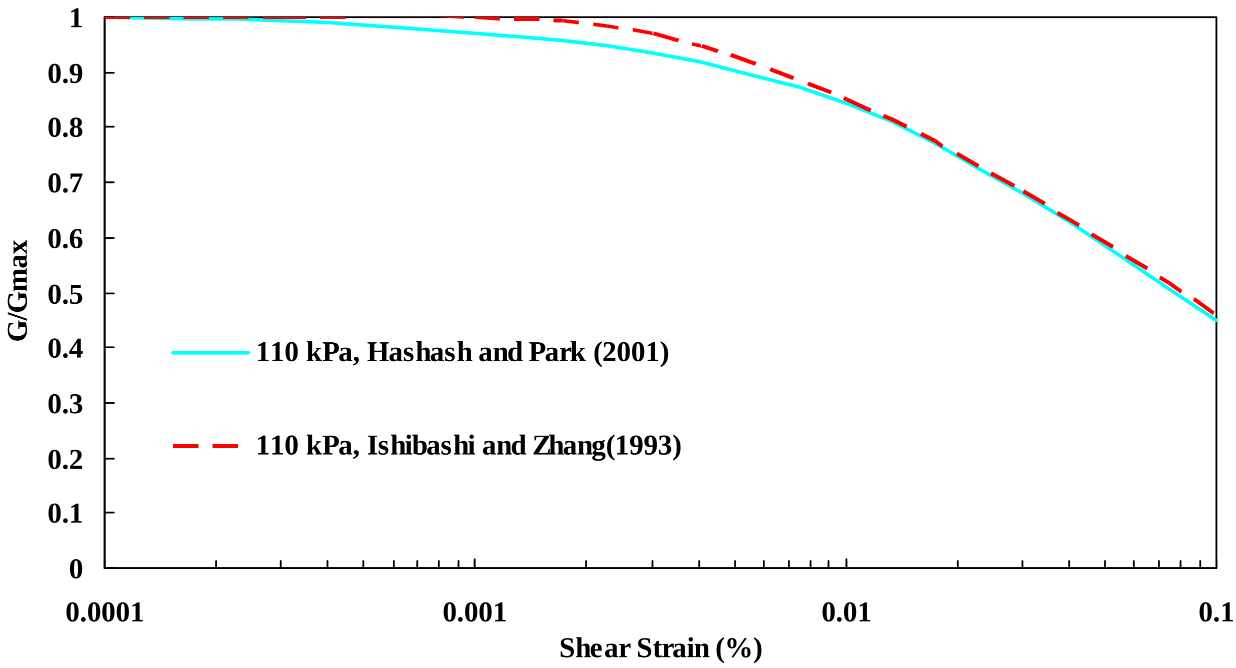
(4) Effective confining pressure σ'_m = 221~250 kPa

Fig. 6(a) shows the shear modulus reduction curves under σ'_m=221~250kPa. Curves are very close together at shear strain smaller than 1×10^{-3}%, however, Ishibashi and Zhang (1993) result has higher values than that of Hashash and Park (2001) and Stokoe et al. (2004). The curves obtained by Stokoe et al. (2004) reduces significantly as shear strain increases. The damping curves are shown in Fig. 6(b). Both Ishibashi and Zhang (1993) and Stokoe et al.(2004) have the same damping ratio as shear strain is smaller than 1×10^{-3}%, however, Ishibashi and Zhang (1993) result has less values than Stokoe et al.(2004) result as shear stain is greater than 1×10^{-3}%. Hashash and Park (2001) result is always less than both of them.

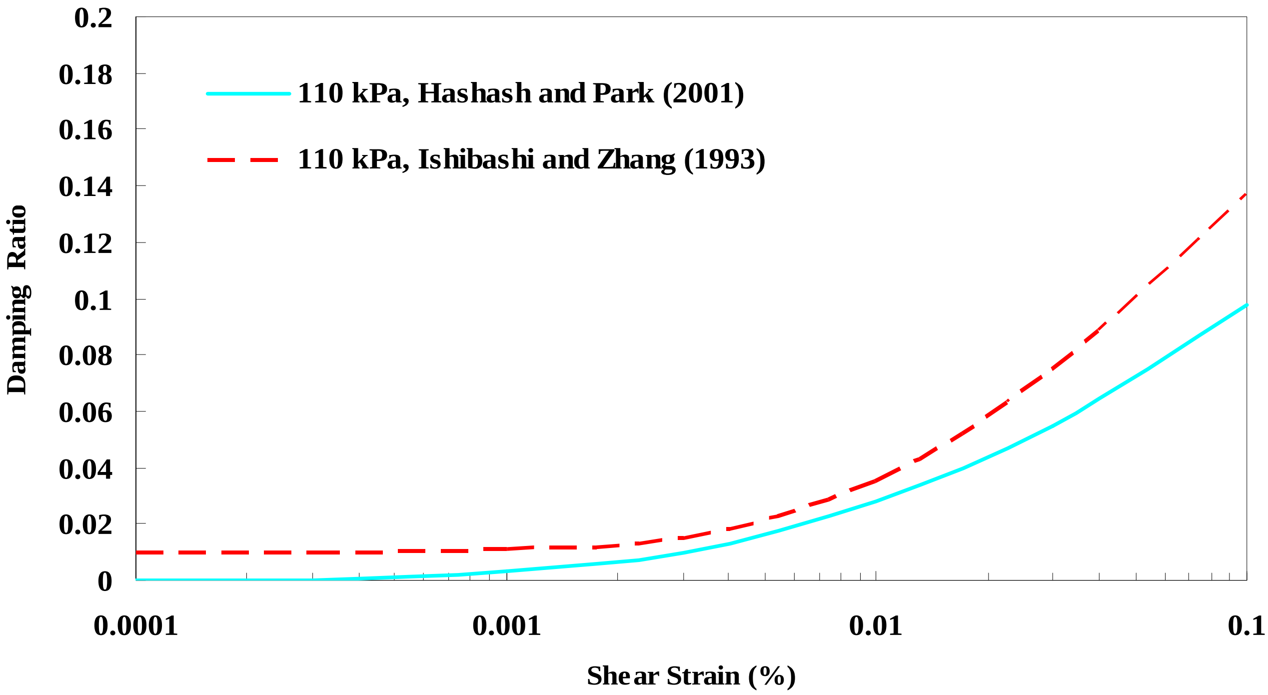
In summary, differences among shear modulus reduction curves are limited as strain is less than 1×10^{-4} %. Results obtained by Stokoe et al. (2004) have less values than the others. The difference between them increases as shear strain value increases. In contrast, difference among curves relating damping ratio with shear strain are more significant. Damping ratios presented by Hashash and Park (2001) are all less than that of Ishibashi and Zhang (1993), with Stokoe et al. (2004) results in between. From the comparison of these results, it appears that Hashash and Park (2001) dynamic characteristics result may better reflect depth effects. In view of confining pressure effect, Hashash and Park (2001) results can better express subsurface structure.

For practical purposes, the dynamic shear modulus reduction curves and damping curves obtained by Hashash and Park (2001) for σ'_m=27.6kPa and 55.2kPa are compared with Seed and Idriss (1970) and Seed et al.(1986) results, as shown in Fig. 7. Vucetic and Dobry (1991) results for soils with PI=0 are also presented in Fig. 7.

From Fig. 7(a), it is clear that shear modulus values obtained by Hashash and Park (2001) are close to Seed and Idriss (1970) and Vucetic and Dobry (1991) results. Damping ratio presented by Hashash and Park (2001) has less values than both of Seed and Idriss (1970) and Vucetic and Dobray (1991). Since effective confining pressure, except for shear strain level, has strong influence on evaluating the shear modulus and damping ratio, in dynamic analyses, it is suggested to use shear modulus reduction curves and damping curves considering different σ'_m presented by Hashash and Park (2001).

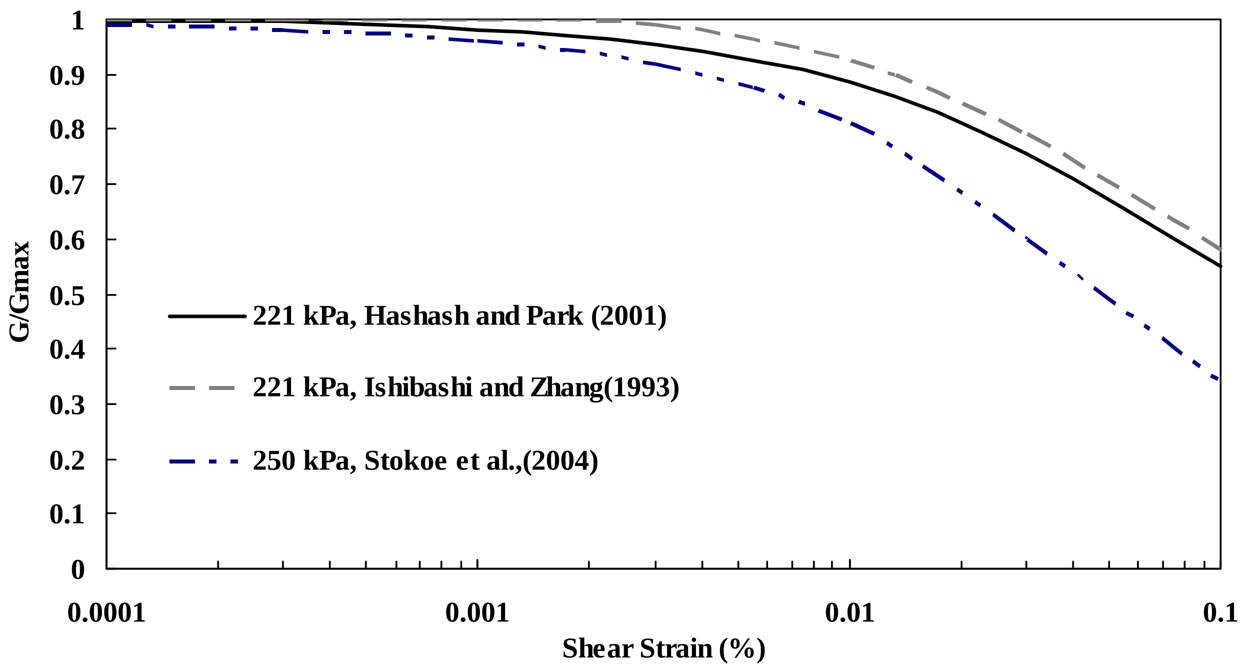


(a)

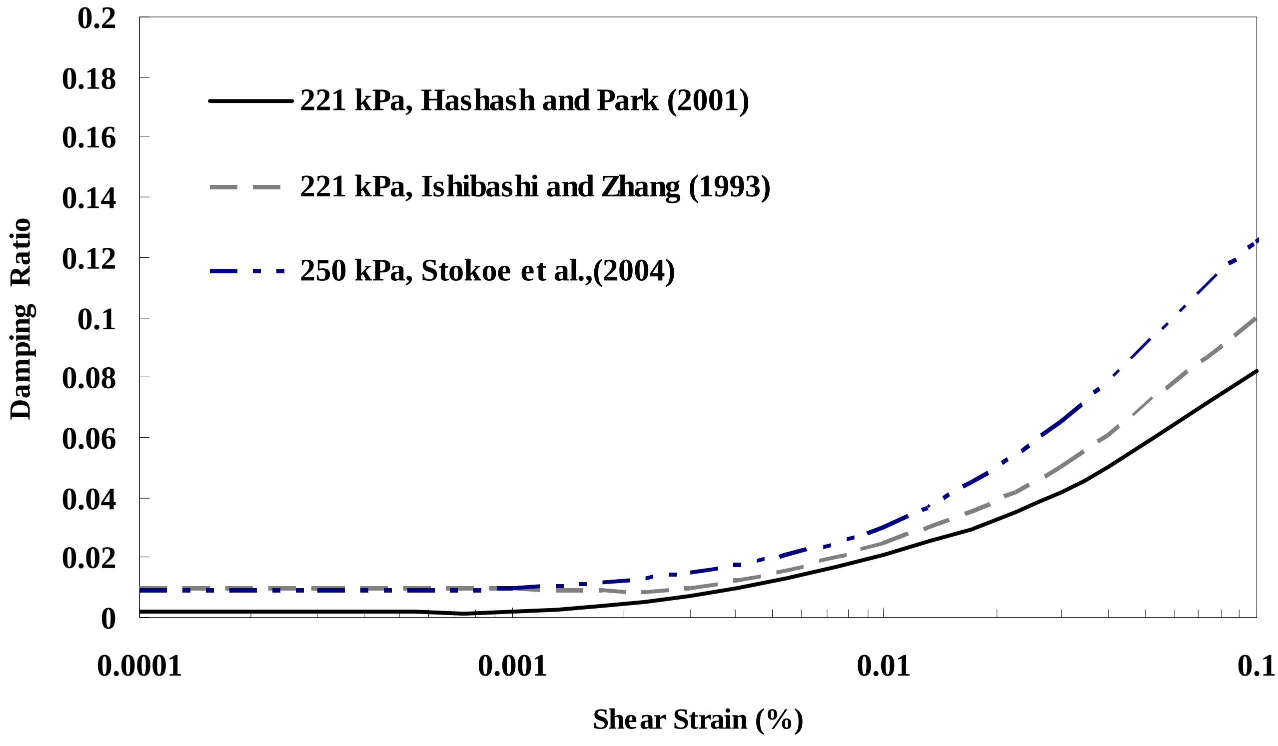


(b)

Fig.5. Influence of confining pressure for cohesionless soils with σ'_m = 110kPa, (a) shear modulus reduction curves, (b) damping curves.

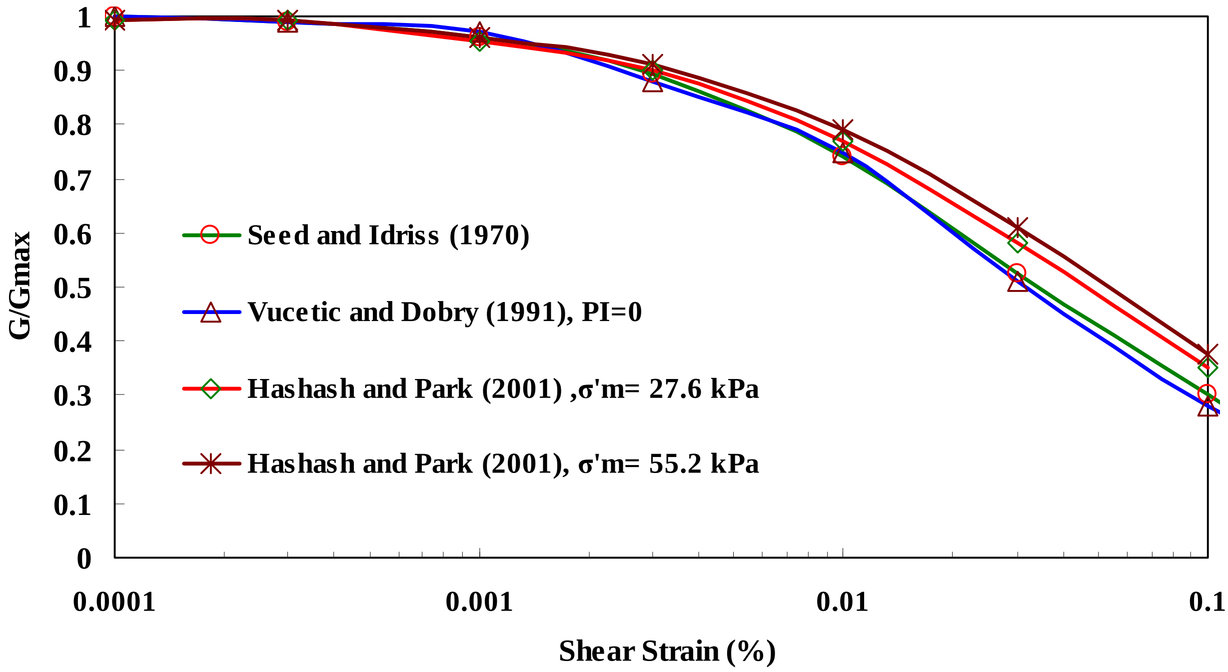


(a)

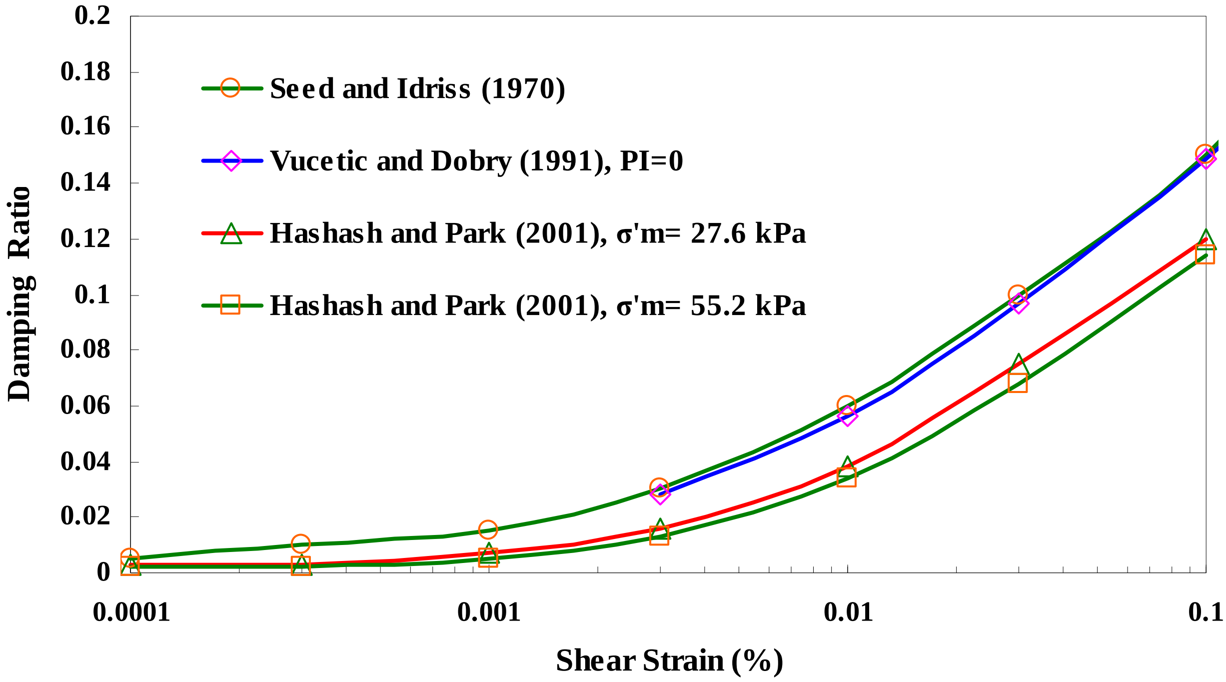


(b)

Fig.6. Influence of confining pressure for cohesionless soils with σ'_m= 221~250kPa, (a) shear modulus reduction curves, (b) damping curves.



(a)



(b)

Fig.7. Comparison of results for cohesionless soils, (a) shear modulus reduction curves, (b) damping curves.

4. DYNAMIC CHARACTERISTICS OF COHESIVE SOILS

Based on examination of the effects of factors which many influence the form of the normalized modulus reduction relationship for cohesive soils, Sun et al. (1988) showed that plasticity index (PI) seems to be the most dominant and consistent factor. Fig 8 shows the shear modulus reduction curves for cohesive soils of different plasticity. However, damping characteristics of cohesive soils related to PI of a soil were not reported by Sun et al. (1988). In their studies concerning dynamic characteristics of cohesive soils, effect of PI was not considered as an major factor by Seed and Idriss (1970). After extensive laboratory testing on saturated cohesive soils with different PI, Vucetic and Dobry (1991) reported the importance of PI on the forms of shear modulus reduction curves and damping curves. In the study of dynamic characteristics of cohesive soils, shear modulus and damping ratio should be included. Therefore, Vucetic and Dobry (1991) results are used in this study. Fig. 9 shows the results of their studies. PI values are separated into six categories, i.e., PI =0, 15, 30, 50, 100 and 200. It is clear that normalized modulus decreases as PI increases. In contrast, damping ratio increases as PI increases. For small shear strain, differences among damping ratios are small, however, differences become larger as shear strain increases.

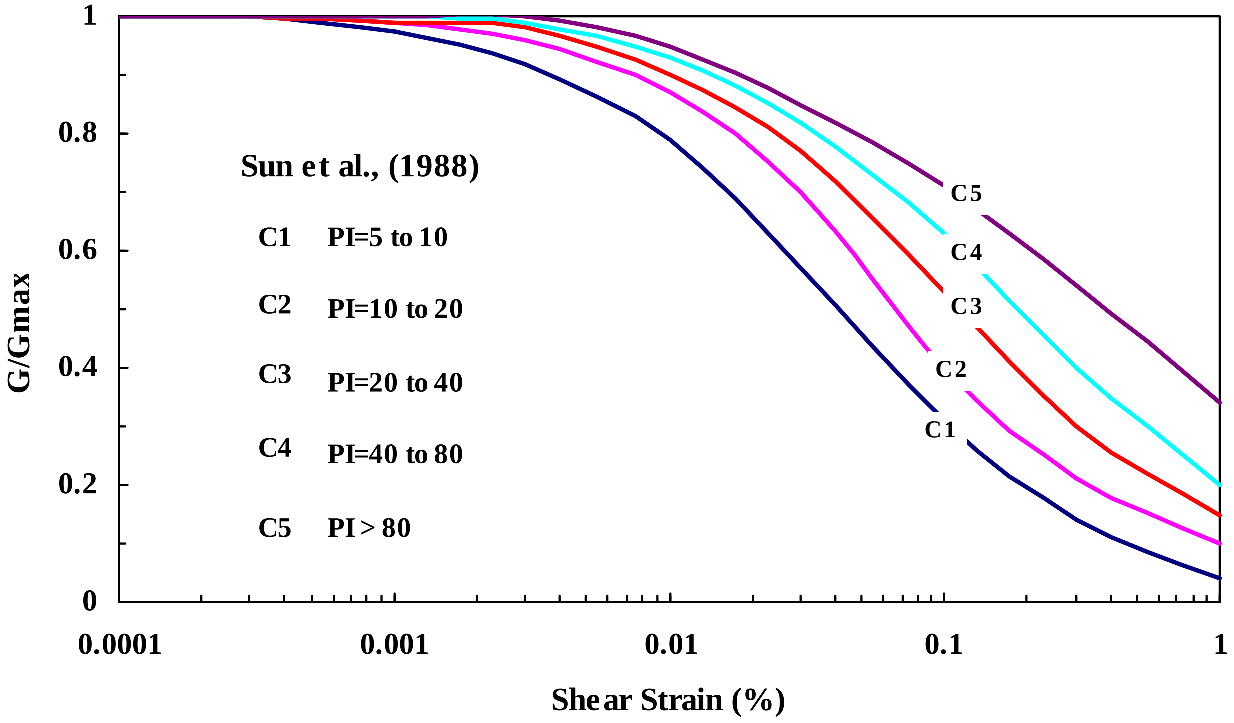
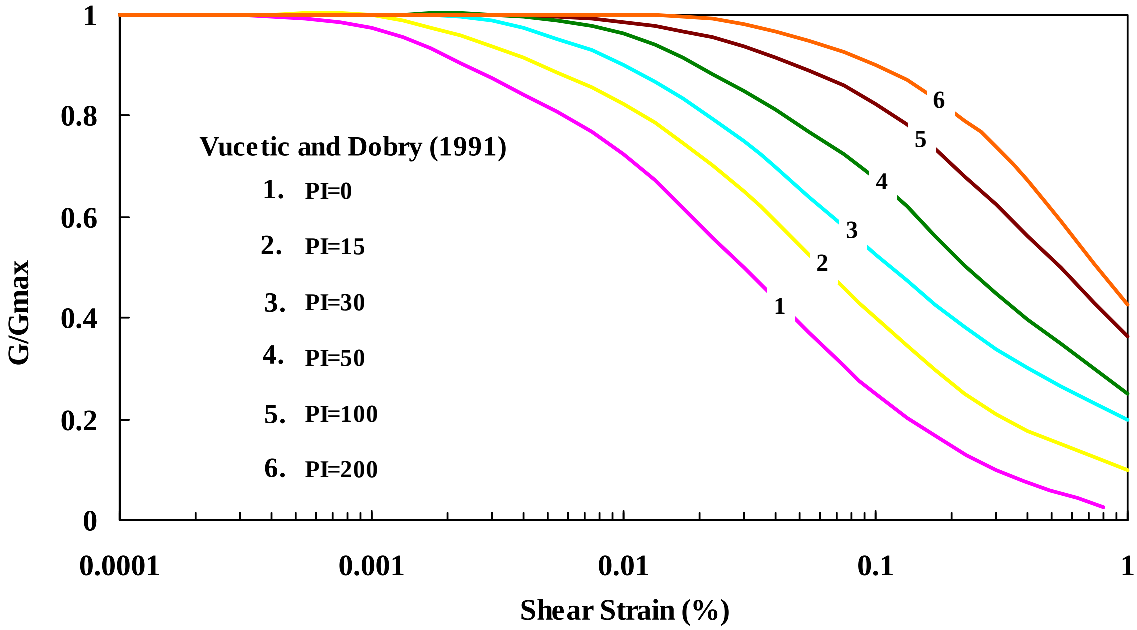
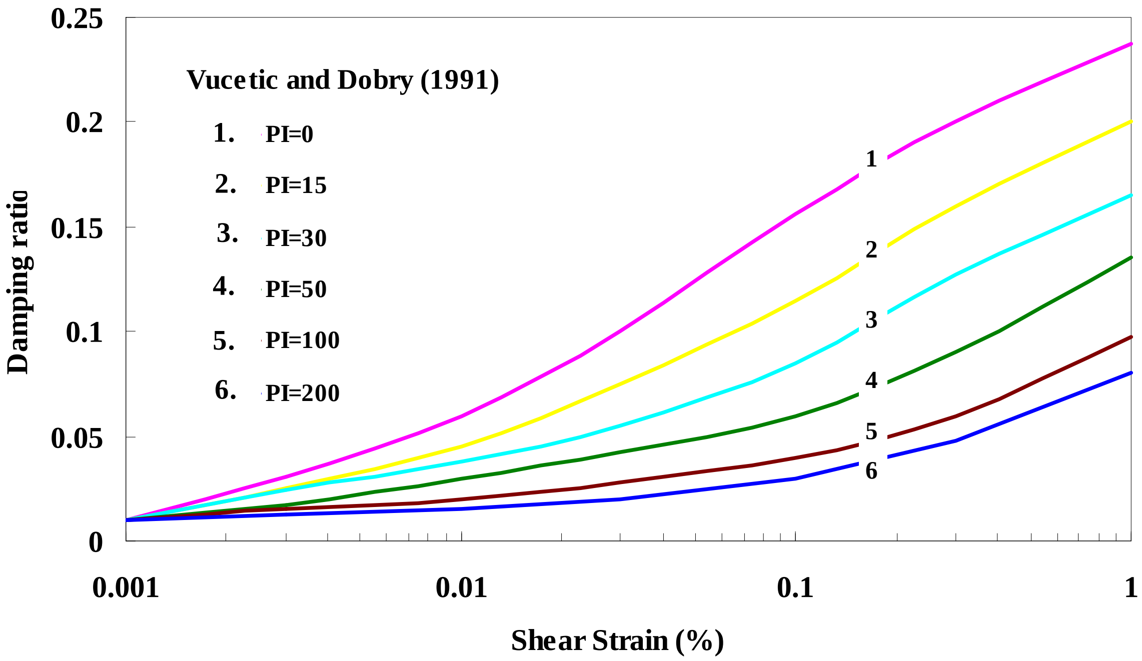


Fig.8. Shear modulus reduction curves for cohesive soils of different plasticity.



(a)



(b)

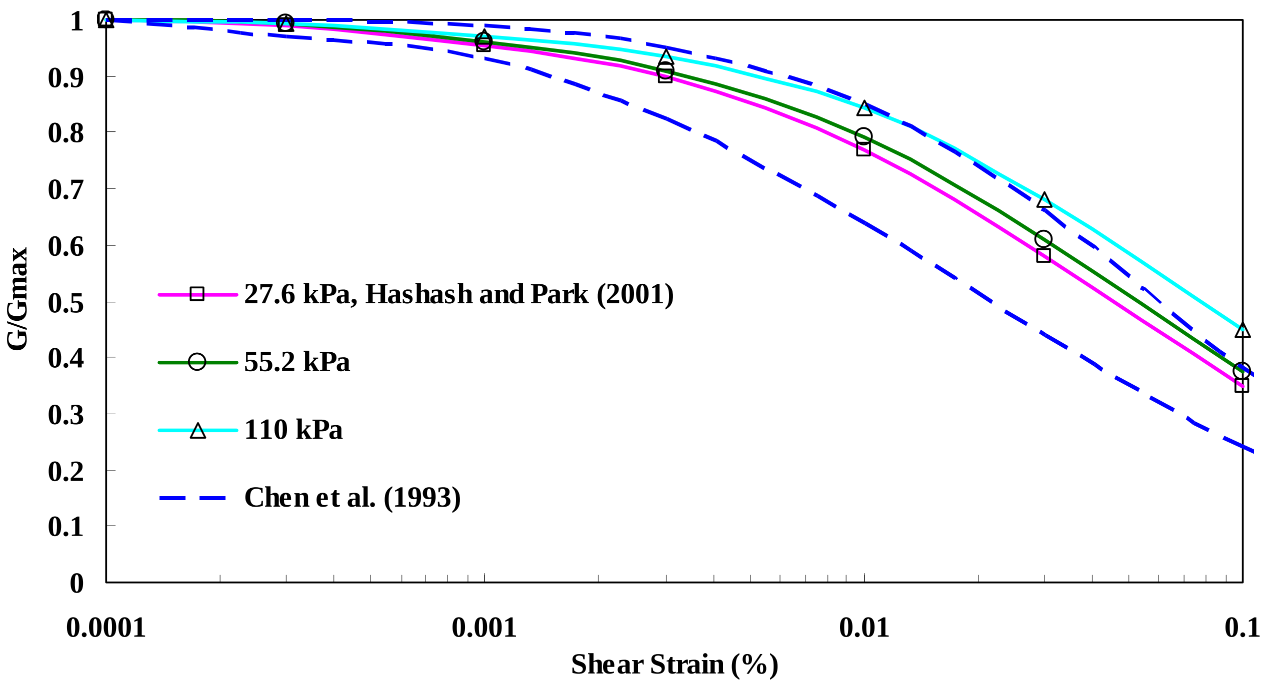
Fig.9. Influence of soil plasticity index (PI) for cohesive soils, (a) shear modulus reduction curves, (b) damping curves.

5. SHEAR MODULUS AND DAMPING RATIOS OF SANDY SOILS IN LANYANG PLAIN

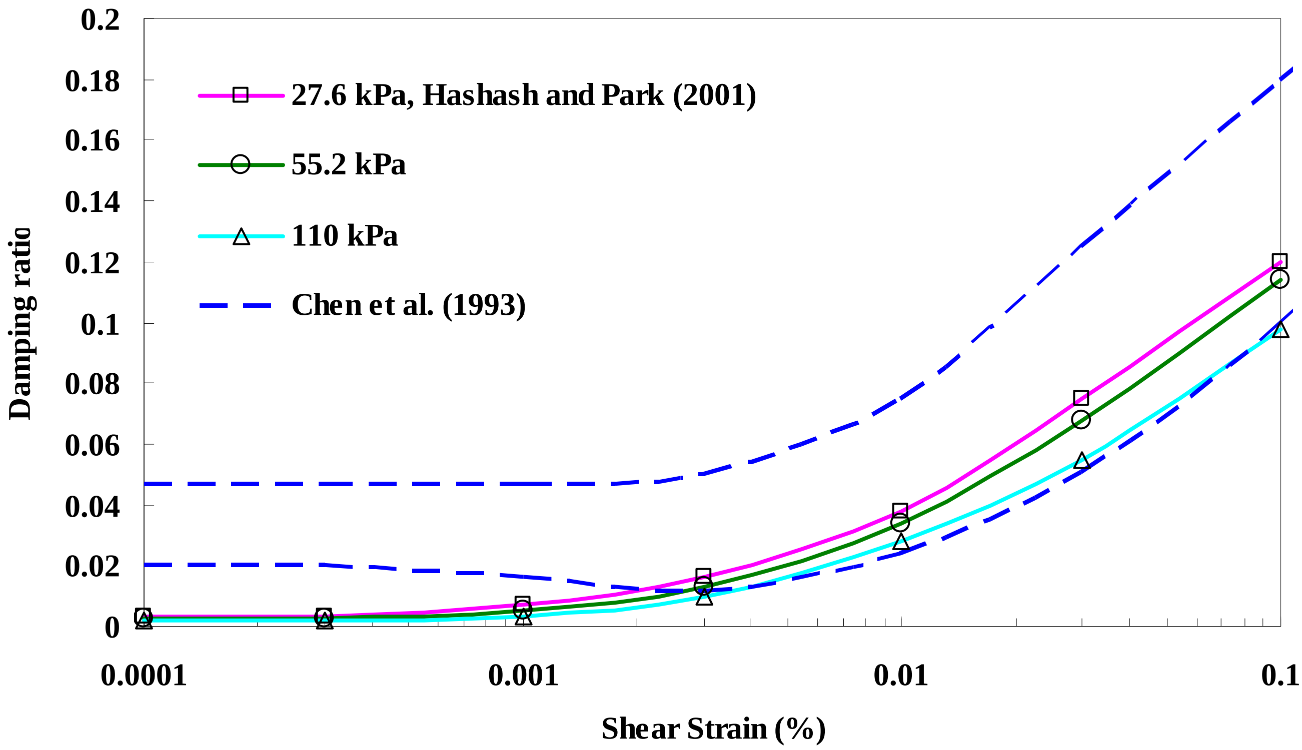
Resonant column tests and cyclic torsional shear tests were performed by Chen et al. (1993) on tube samples and remolded samples to investigate the maximum shear modulus and the minimum damping ratio of Lanyang plain sandy soils. The shear modulus reduction curves and damping curves were also studied by Chen et al. (1993). Fig. 10 shows the results of their studies where two dash lines are the upper and lower bounds of their results. For comparison, Hashash and Park (2001) results under σ'_m=27.6kPa, σ'_m=55.2kPa and σ'_m=110kPa are also presented in Fig. 10. As shown in Fig. 10(a), it shows that for shear stain amplitude smaller than 3×10^{-2}%, Hashash and park (2001) modulus results all fall within the range of Chen et al. (1993). For shear strain amplitude greater than 3×10^{-2}%, only one curve with σ'_m=110kPa has normalized modulus little higher than upper bound of Chen et al. (1993).

Fig. 10(b) shows the comparisons of damping curves obtained by Hashash and Park (2001) with that of Chen et al. (1993). For shear stain amplitude greater than 3×10^{-3} %, Hashash and Park (2001) results all fall within the range presented by Chen et al. (1993), however, for shear strain amplitude smaller than 3×10^{-2} %, Hashash and Park (2001) results all fall below lower bound of Chen et al. (1993).

From above comparisons, it is clear that Hashash and Park (2001) results of dynamic characteristics agree well with that of sandy soils in Lanyang plain. Therefore, they are chosen in this study for the analysis of ground response in Lanyang plain. Since dynamic characteristics of cohesive soils in Lanyang plain were not studied by Chen et al. (1993), Vucetic and Dobry (1991) results are used in this study.



(a)



(b)

Fig. 10. Comparison results of Hashash and Park (2001) and Chen et al. (1993), (a) shear modulus reduction curves, (b) damping curves.

6. GROUND RESPONSE ANALYSIS IN LANYANG PLAIN

The local soil conditions at a site have significant effects on the characteristics of earthquake ground motion. Earthquake motions at the base of a soil profile can be drastically modified in frequency content and amplitude as seismic waves transmit through the soil deposits. Furthermore, soils exhibit significantly nonlinear behavior under strong ground shaking. In this study, the nonlinear site response analysis is performed using SHAKE91 (Idriss and Sun (1992)). In the SHAKE91 program, the soil profile consists of horizontal soil layers. For each soil layer, the required soil parameters include the thickness, unit weigh, and shear wave velocity or low-strain shear modulus. In addition, a shear modulus reduction curve and damping ratio curve also need to be specified.

The National Center for Earthquake Engineering Research (NCREE) has initiated a project to explore the characteristics of the sites in Lanyang plain where the strong motion instruments have been installed. The boring log data of 33 sites in Lanyang County are collected by Hsu et al. (2012). Boring log IanB030 is taken as an illustration for site response analysis. Complete profile of subsurface structure established by combining geophysical method and boring log data is shown in Fig. 11(Hsu et al. (2012)). In this study, nonlinear site response analysis is performed using SHAKE91. For cohesionless soils layers, the shear modulus reduction curves and damping curves used in this study are those suggested by Hashash and Park (2001). For cohesive soils, the shear modulus reduction curves and damping curves used in this study are those suggested by Vucetic and Dobry (1991).

The response spectra at the rock outcrop and at the ground surface are shown in Fig 12. As shown in the figure, the frequency content of the ground motions at the rock outcrop and at the ground surface have significant difference.

CONCLUSIONS

Based on the studies described in the preceding pages, it may be concluded that the plasticity index (PI) and effective confining pressure are the main factors controlling the shear modulus reduction curves and damping curves for cohesive soils and cohesionless soils, respectively. Comparing a number of available cyclic loading results, it is suggested that the use of shear modulus reduction curves, and the damping curves presented by Vucetic and Dobry (1991), and those presented by Hashash and Park (2001) can provide a convenient basis for determining dynamic proporties for cohesive soils and cohesionless soils, respectively. The relationships between the shear modulus and the damping ratio with the shear strain amplitude suggested by this study agree well with that results for soils in site of plain. The results of this study can be utilized in the field of disaster reduction, such as the calculation of ground response subject to earthquakes using the SHAKE computer program and then the evaluation of safety of buildings in a seismic event.

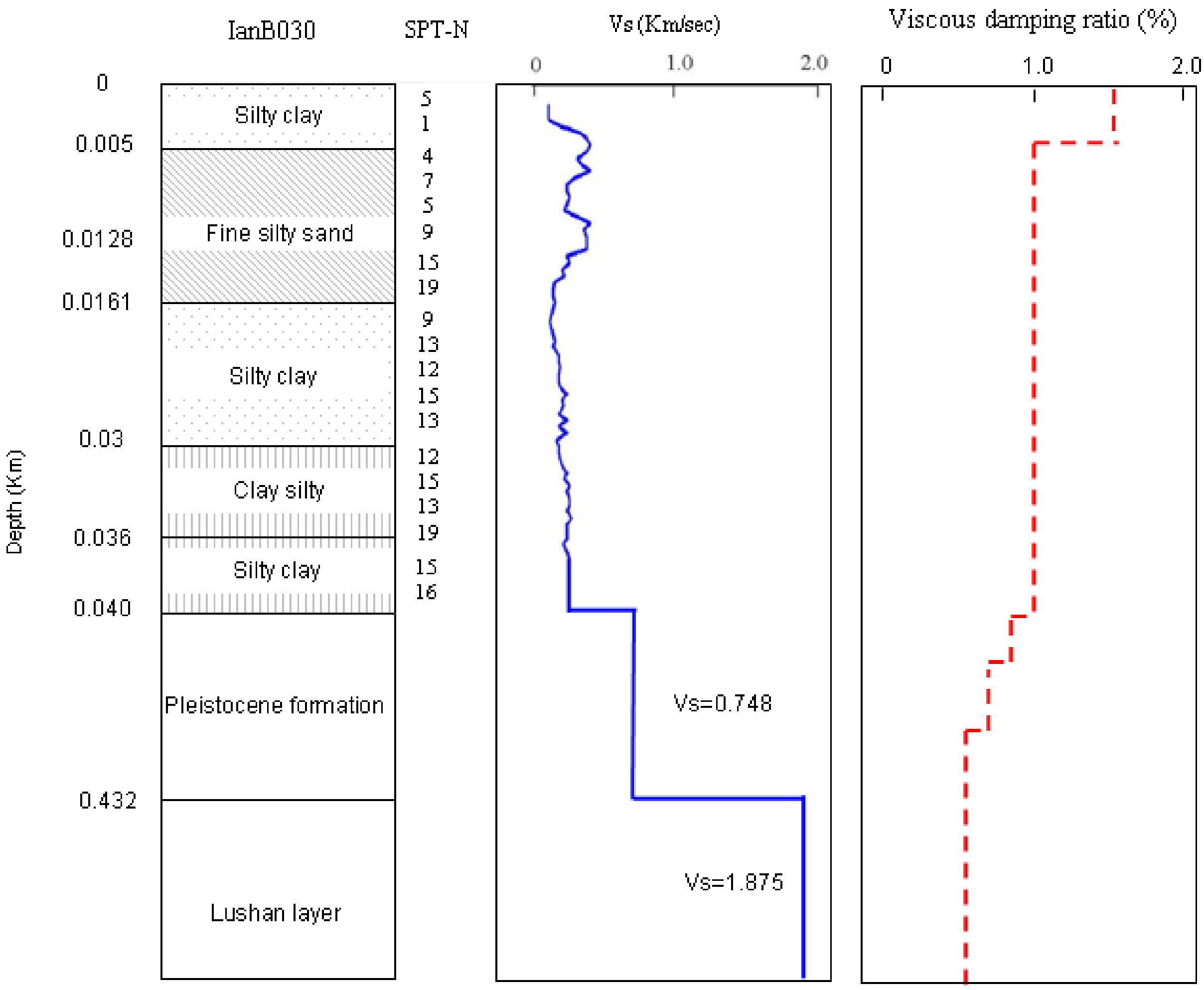


Fig. 11.　Comprehensive subsurface structure at IanB030 site in Ilan County.

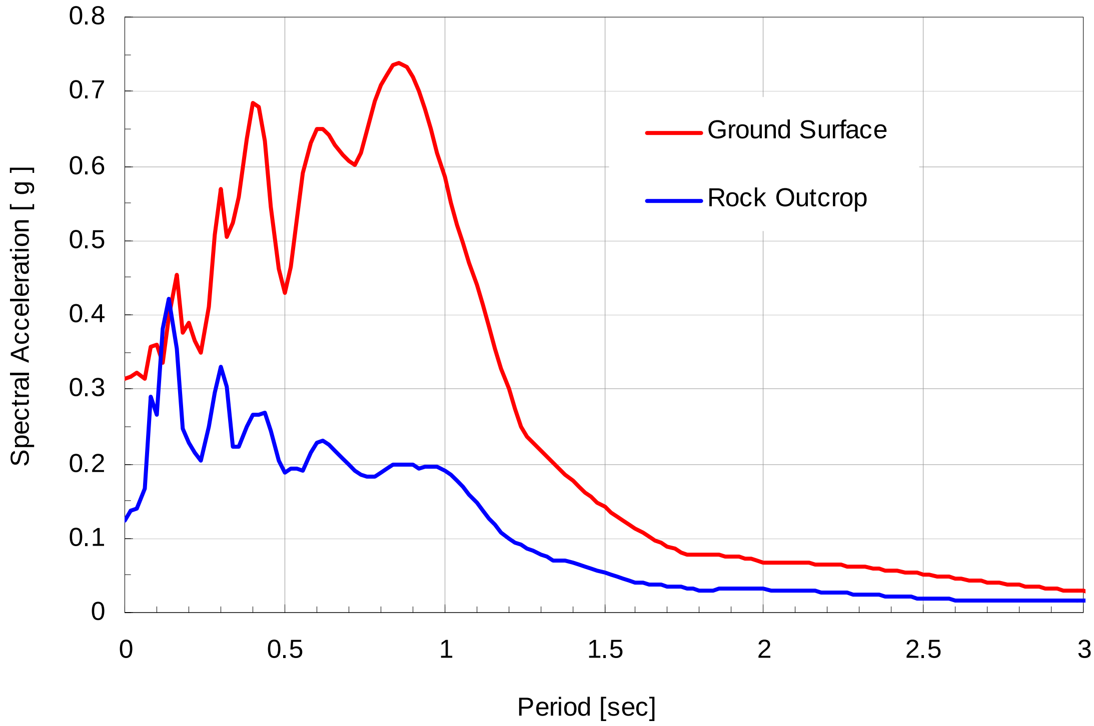


Fig. 12. Acceleration response spectrums at the ground surface and rock outcrop.

REFERENCE

Chen, Y. C., Li, Lee, C. G., and W. K. (1993). "Shear moduli and damping ratios of sandy soils in the Lanyang plane," *Journal of Chinese Institute of Civil and Hydraulic Engineering*, Vol. **5(**1), 55-66.

Dobry, R., and Vucetic, M. (1987). "Dynamic properties and seismic response of soft clay deposits," *Proceedings, International Symposium on Geotechnical Engineering of Soft Soils*, Mexico City, Vol. **2**, 49-85.

EPRI. (1993), Guidelines for determining design basis ground motions, Report EPRITr-102293, *Electric Power Research Institute (EPRI)*, Palo Alto, California.

Hardin, B. O., and Drnevich. V. P. (1972), "Shear modulus and damping in soils: design equations and curves," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. **98**, 667-692.

Hashash, Y., and Park, D. (2001). "Nonlinear one-dimensional seismic ground motion propagation in the mississippi embayment," *Engineering Geology*, ASCE, Vol. **62**, 185-206.

Hsu, C. H., Chao, S. J., Chern, S. G., and Hwang, H. (2012). “Constructing the comprehensive subsurface structure of Lanyang plain,” *Journal of Marine Science and Technology*, Vol. **20**(2), 195-200.

Iwasaki, T., Tatsuoka, F., and Taakagi, Y. (1978). “Shear moduli of sands under cyclic torsional shear loading,” *Soils Found*, JSSMFE, Vol. **18**(1), 39-56.

Idriss, I. M., and Sun, J. I. (1992). “SHAKE91 – A computer program for conducting equivalent linear seismic response analyses of the horizontally layered soil deposit,” *Department of Civil and Environmental Engineering*, University of California, Berkeley, California.

Ishibashi, I., and Zhang, X. j. (1993). “Unified dynamic shear moduli and damping ratios of sand and clay,” *Soils Found*, JSSMFE, Vol. **33**(1), 182-191.

Kokushu, T., Yoshida, Y., and Esashi, Y. (1982). “Dynamic properties of soft clay for wide strain range,” *Soils and Foundations*, Vol. **20**(4), 1-18.

Kramer, S.L. (1996). Geotechnical Earthquake Engineering, *Prentice-Hall International Series in Civil Engineering Mechanics*, Upper Saddle River, New Jersey.

Seed, H. B., and Idriss, I. M. (1970). “Soil moduli and damping factors for dynamic response analysis,” Report EERC 70-10, *Earthquake Engineering Research Center*, University of California, Berkeley, California.

Seed, H. B., Wong, R. T., Idriss, I, M., and Tokimatsu, K. (1986). “Moduli and damping factors for dynamic analysis of cohesionless soils,” *Journal of Geotechnical Engineering*, ASCE, Vol. **112**(11), 1016-1032.

Sun, J. I., Golesorkhi, R. and Seed, H. B. (1988). “Dynamic moduli and damping ratios for cohesive soils,” Report EERC 88-15, *Earthquake Engineering Research Center*, University of California, Berkeley, California, 42.

Stokoe, K. H., H., Darendeli, M. B., Gilbert, R. B., Menq, F. Y., and Choi, W. K. (2004). “Development of a new family of normalized modulus reduction and material damping curves,” Proceedings, *NSF/PEER Int. Work-shop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response*, University of California, Berkeley, California.

Vucetic, M., and Dobry, R. (1991). “Effect of soil plasticity on cyclic response,” *Journal of Geotechnical Engineering*, ASCE, Vol. **117**(1), 89-107.