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Evaluation of Seismic Response of a Site Class F Site Using Equivalent Linear and Nonlinear Computer Codes

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EVALUATION OF SEISMIC RESPONSE OF A SITE CLASS F SITE USING EQUIVALENT LINEAR AND NONLINEAR COMPUTER CODES

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ABSTRACT

Evaluation of seismic site response and development of site-specific surface response spectra has evolved in recent years through the use of both equivalent linear (EQL) and nonlinear (NL) computer codes. Before the nonlinear computer codes become popular among practitioners, equivalent linear site response analysis programs were used to develop site-specific design spectra for both soft and stiff sites. Nonlinear site response analysis is now used more routinely for projects planned on Site Class F sites.

This paper presents the results of seismic response analyses completed for a Site Class F site at Grays Harbor, Washington. Both the equivalent linear (SHAKE2000) and nonlinear (D-MOD2000) computer codes were used to evaluate the site response under the maximum considered earthquake (MCE) using the guidelines set forth in 2006 International Building Code (IBC) and American Society of Civil Engineers (ASCE) 7-05 code. Comparison of surface response spectra, soil shear stress and strain at various soil layers computed using both the equivalent linear and nonlinear computer program. Conclusions regarding the limitations of the equivalent linear code and presents recommendations on the use of the nonlinear computer code in site response analysis for practitioners.

INTRODUCTION

The Westway site is located at Port of Grays Harbor in Aberdeen, Washington, as shown in Figure 1. The project is composed of new 120-foot-diameter, 40-foot-high storage tanks with the associated containment structures.

Fig. 1. Vicinity Map

SITE CONDITIONS

Site History

The Westway site was previously developed as two slips with a median finger pier. Dikes were constructed across the slip entrances to form enclosed areas and the slips were filled with materials including hydraulically placed dredge spoils and wood waste. The result is that the site has very soft soil conditions.

The dredge spoils and wood waste were capped with a variable thickness of granular fill consisting of sand and gravel placed during paving activities completed in the late 1980s. Since the slip area was filled and capped, it has been used as a log yard. Settlement has been observed in areas where logs were stacked and in areas of heavy truck traffic.

Subsurface Soil Conditions

Subsurface conditions at the site were explored with three borings and 10 cone penetrometer test (CPT) soundings. Based on our interpretation of the subsurface explorations, the soil profiles generally consisted of fill over native alluvium and gravel units. Fill materials encountered in the explorations include sand and gravel fill, and dredged spoils consisting of silt and wood waste. Alluvium encountered in the explorations generally consists of silt interbedded with silty sand. Organic material was observed in the alluvium. The gravel unit encountered in the explorations consists of fine to coarse sand with varying silt and gravel content, and fine gravel with sand.

SEISMIC HAZARD AND DESIGN PARAMETERS

Regional Seismicity and Earthquake Source Zones

The Westway site is located near the convergent continental boundary known as the Cascadia Subduction Zone (CSZ). The CSZ is the zone where the westward advancing North American Plate is overriding the subducting Juan de Fuca Plate. The interaction of these two plates results in two potential seismic source zones: (1) the Benioff source zone, and (2) the CSZ interplate source zone.

Target Rock Outcrop Uniform Hazard Spectrum

The United States Geological Survey (USGS) 2002 probabilistic seismic hazard model was reviewed and used to evaluate the seismic hazard at the project site (123.855 W, 46.967 N). Using the spectral acceleration values estimated by the USGS, a rock outcrop uniform hazard spectrum (UHS) was constructed for the MCE event per ASCE 7-05 and 2006 IBC (that is, an earthquake event that has a 2 percent probability of exceedance [PE] in 50 years). This rock outcrop UHS was used as the target spectrum in scaling the selected input motions used in our site response analysis, as described in the next section. The spectral acceleration values of the target rock outcrop UHS for periods between 0 and 1 second are presented in Table 1 below.

Table 1. Target Rock Outcrop UHS

Spectral Acceleration	Recommended values
Peak Ground Acceleration (PGA)	0.6g
Sa (T = 0.2s)	1.5g
Sa (T = 1.0s)	0.7g

Selection of Input Ground Motions

In order to provide representative earthquake acceleration time histories for the site response analysis, we reviewed the percent contribution of the regional earthquake source zones to the seismic hazard at the project site using the USGS 2002 probabilistic seismic hazard deaggregation results. From the USGS deaggregation, we observed that the earthquakes associated with the interface between the subducting plate and overriding plate off the coast of Washington contributed approximately 80 percent of the seismic hazard at the project area. Deep gridded Pacific Northwest earthquakes (Benioff source zone) contributed about 20 percent of the seismic hazard at the project area. Based on this evaluation, one intraplate and six interplate subduction zone events were selected and used as input ground motions for the site response analysis. The orthogonal pair of each selected ground motion was used, resulting in 14 input time histories. The ground motions selected are presented in Table 2.

Table 2. Selected Input Earthquake Time Histories

Earthquake	Recording Station	Magnitude
2001 El Salvador	Santiago de Maria	7.6
1985 Michoacan	La Villita	8.1
1985 Michoacan	La Union	8.1
1968 Tokachi-Oki	S252	8.0
2003 Tokachi-Oki	HKD094	8.0
2003 Tokachi-Oki	HKD122	8.2
CSZ Synthetic	n/a	9.2

Prior to completing the site response analysis, the orthogonal pair of each input ground motion was scaled using a constant scaling factor so that the average response spectrum was approximately at the level of the target rock outcrop UHS. The scaled PGA value of each earthquake is presented in Table 3. Table 4 presents the arias intensity and significant duration of the scaled input time histories used.

Table 3. Scaled PGA of Selected Input Time Histories

Earthquake	Time History	Scaled PGA (g)
2001 El Salvador	SSDM 090	0.65
	SSDM 360	0.79
1985 Michoacan	MLV 090	0.60
	MLV 180	0.66
1985 Michoacan	MLU 090	0.68
	MLU 180	0.60
1968 Tokachi-Oki	TO252 EW	0.44
	TO252 NS	0.57
2003 Tokachi-Oki	TO094 EW	0.44
	TO094 NS	0.32
2003 Tokachi-Oki	TO122 EW	0.36
	TO122 NS	0.45
CSZ Synthetic	SC FN	0.92
	SC FP	0.19

Table 4. Arias Intensity and Significant Duration of Selected Input Time Histories

Time History	Arias Int. (m/s)	Sig. Duration (s)
SSDM 090	9.52	15.45
SSDM 360	7.80	15.11
MLV 090	9.96	41.97
MLV 180	14.83	43.96
MLU 090	14.83	26.41
MLU 180	16.30	24.28
TO252 EW	5.06	52.50
TO252 NS	5.42	57.92
TO094 EW	8.92	64.77
TO094 NS	7.79	82.76
TO122 EW	9.33	64.57
TO122 NS	8.15	82.14
SC FN	54.30	78.22
SC FP	2.44	110.32

Figure 2 shows the average response spectra for each orthogonal pair of the scaled input ground motion, and the target rock outcrop UHS. As shown in Figure 2, the average response spectrum of the 14 scaled time histories closely matches the target rock outcrop UHS.

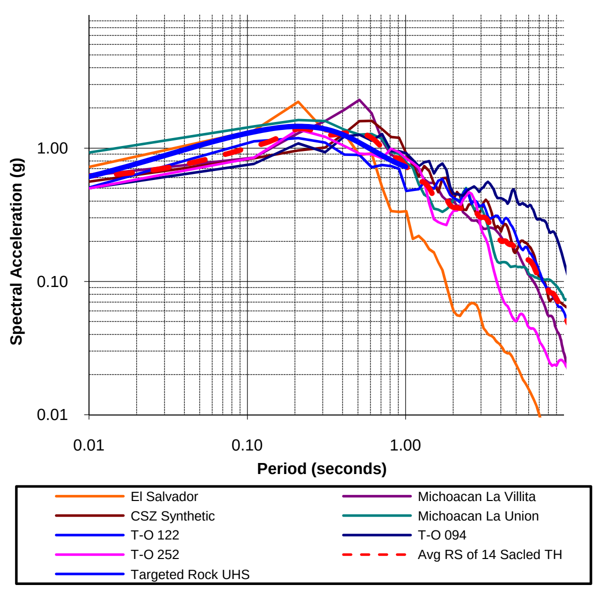

Fig. 2. Average response spectra of scaled input earthquake time histories.

SITE RESPONSE ANALYSIS MODELS

<u>Soil Profiles</u>

A site-response model based on low-strain shear wave velocities was developed for this project. The explorations completed at the project area extend to an approximate maximum depth of 150 feet and were terminated in medium dense to dense sand and gravel. Based on our review of the regional geology at the site, the bedrock was modeled at a depth of 250 feet.

Using the subsurface soil data, we developed two shear wave velocity (V_s) profiles, east and west, for use in our site response analysis. The shear wave velocities of the soil were determined using published correlations based on boring and CPT data. Shear wave velocity below the exploration depth is assumed to increase linearly in accordance with measured values until bedrock is reached at a depth of 250 feet. Figure 3 shows both the east and west V_s profiles used in our site response analyses.

Both profiles are classified as F per 2006 IBC site class definition. The east profile is the softer profile because of the presence of a wood waste layer encountered at depths between 5 and 35 feet in the explorations. Because of space limitations, only the results of the site response analyses completed for the east profile are presented in the paper.

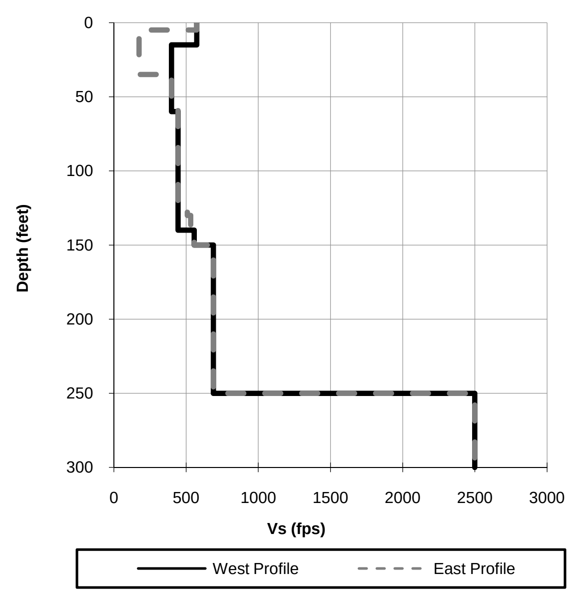

Fig. 3. Shear wave velocity profiles.

<u>Soil Models</u>

In order to evaluate the response of the soil deposits to the ground motion propagation from the bedrock to the ground surface, dynamic properties of the soil layers needed to be defined. Table 5 summarizes the unit weights, reference shear modulus degradation and damping curves used to model the east profile.

Table 5. East Profile Soil Model

Depth (ft.)	γ (pcf)	Modulus Degradation and Damping Curves
0 – 5	130	EPRI (1993)
5 – 35	90	Wehling (2003)
35 – 55	100	Darendeli (2001)
55 – 120	105	Darendeli (2001)
120 – 250	130	EPRI (1993)
> 250	135	Schnabel (1970)

SHAKE2000 Model

The reference shear modulus degradation and damping curves as presented in Table 5 were directly input and used in SHAKE2000. The scaled input time histories were applied as "outcropping" motions in the program.

D-MOD2000 Model

The shear modulus degradation and damping curves used in D-MOD2000 were developed using the Modified Kondner and Zelasko (MKZ) nonlinear stress-strain model. The MKZ model curves were fitted to match the reference curves presented in Table 3. Figures 4 and 5 show an example of the MKZ model curves and the Darendeli (2001) shear modulus degradation and damping curves at depths 35 to 55 feet for the east profile. The full Rayleigh damping option was used and the scaled input time histories were applied as "outcropping" motions with an elastic base.

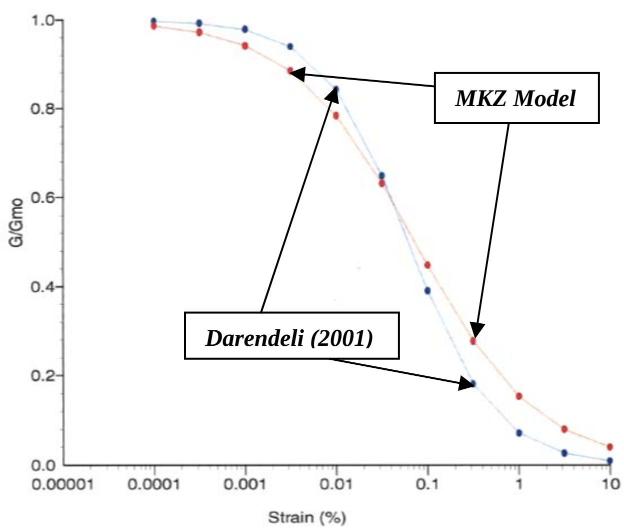

Fig. 4. Modulus Degradation Curves at 35 to 55 feet, East Profile

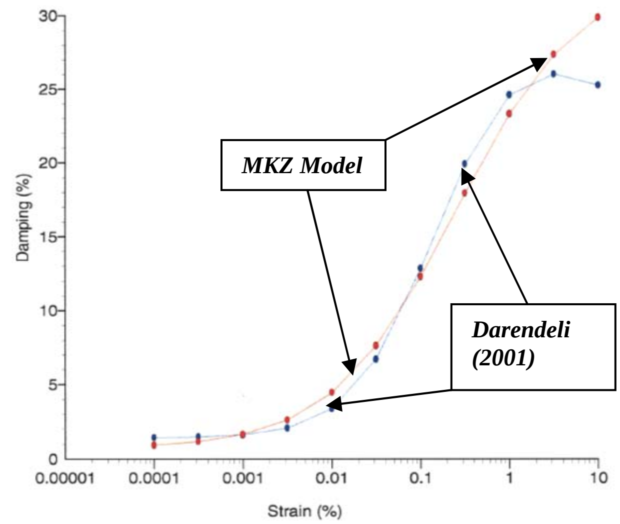

Fig. 5. Damping Curves at 15 to 60 feet, East Profile

SITE RESPONSE ANALYSES RESULTS

The 14 scaled time histories were propagated through the east profile using both the SHAKE2000 and D-MOD2000 models. Site responses including ground surface response spectra, cyclic shear stress and strain within the soil profile were calculated. The following present a summary and comparison of the results calculated with both the SHAKE2000 and D-MOD2000 programs.

Ground Surface Response Spectra

Figures 6 and 7 present the ground surface response spectrum of each scaled time history calculated using the SHAKE2000 and D-MOD2000 programs, respectively. Also shown in Figures 6 and 7 is the average response spectrum of the 14 scaled time histories.

Figure 8 provides a comparison between the average response spectrum and the response spectrum of the SC FN time history (M=9.2, PGA = 0.92) calculated using both SHAKE2000 and D-MOD2000. As shown in Figure 8, the average response spectra calculated by both programs are relatively close to each other. However, the response spectrum of the SC FN time history calculated by D-MOD2000 is consistently higher than that of SHAKE2000.

These results suggest that the equivalent linear code may be unconservative when used to calculate the ground surface response spectrum for a soft site under strong ground motion.

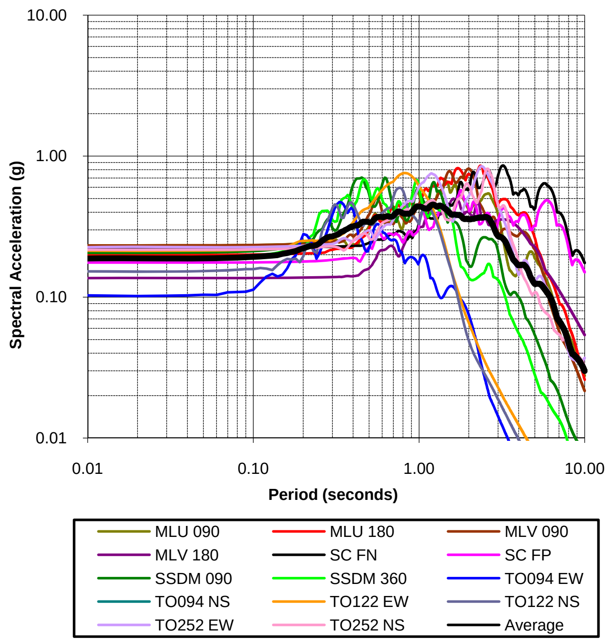

Fig. 6. Ground Surface Response Spectra Calculated using SHAKE2000, East Profile

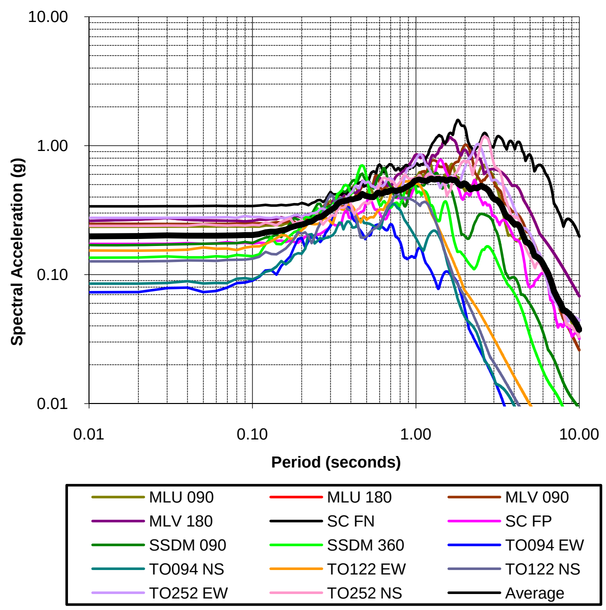

Fig. 7. Ground Surface Response Spectra Calculated using D-MOD2000, East Profile

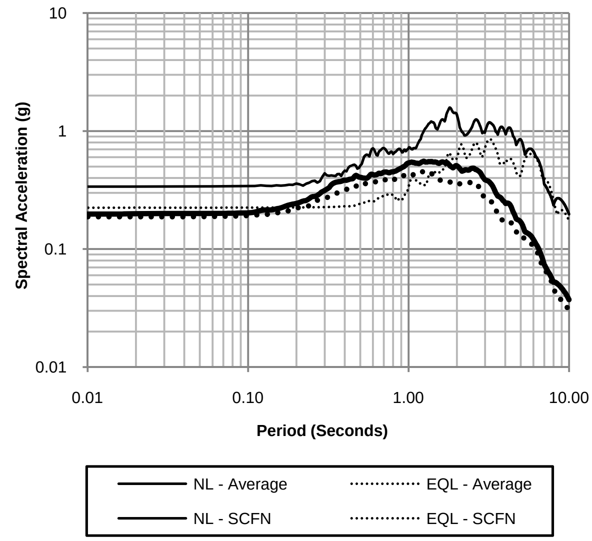

Fig. 8. Comparison of Ground Surface Response Spectra Calculated using SHAKE- and D-MOD2000, East Profile

In order to better evaluate the limitation of the equivalent linear code in the ground surface response spectrum calculation, the results of the 14 scaled time histories were grouped into two categories. The first category contains the results of the time histories with weak to moderate ground shaking intensity, which includes the deep Benioff earthquake and the moderate-size interface earthquake with PGA less than about 0.45g. The second category contains the results of the time histories with strong ground shaking intensities, which includes the moderate to large interface earthquake with PGA higher than about 0.45g. Tables 6 and 7 present the time histories included in both categories.

Table 6. Category 1 – Input Time Histories with Weak to Moderate Ground Shaking Intensity

EQ Type and Magnitude	Time History	Scaled PGA (g)
Benioff, M = 7.6	SSDM 090	0.65
	SSDM 360	0.79
Interface, M = 8.0	TO094 EW	0.44
	TO094 NS	0.32
Interface, M = 8.0	TO122 EW	0.36
	TO122 NS	0.45
Interface, M = 9.2	SC FP	0.19

Table 7. Category 2 – Input Time Histories with Strong Ground Shaking Intensity

Earthquake	Time History	Scaled PGA (g)
Interface, M = 8.1	MLV 090	0.60
	MLV 180	0.66
Interface, M = 8.1	MLU 090	0.68
	MLU 180	0.60
Interface, M = 8.2	TO252 EW	0.44
	TO252 NS	0.57
Interface, M = 9.2	SC FN	0.92

Figure 9 presents the difference of the ground surface spectral acceleration calculated using D-MOD2000 and SHAKE2000 for category 1 time histories. As shown in Figure 9, the difference between the spectral acceleration at the ground surface calculated using the two programs is relatively small, and SHAKE2000 calculated higher spectral acceleration at periods less than about 1 second. This indicates that both SHAKE2000 and D-MOD2000 produce similar ground surface response spectra for weak to moderate motions.

Figure 10 presents the difference of the ground surface spectral acceleration calculated using D-MOD2000 and SHAKE2000 for category 2 time histories. As shown in Figure 10, the spectral acceleration calculated using D-MOD2000 is consistently higher than that of SHAKE2000. These results indicate that SHAKE2000 may be inappropriate and unconservative when used to calculate surface response spectra for a soft site with strong motions.

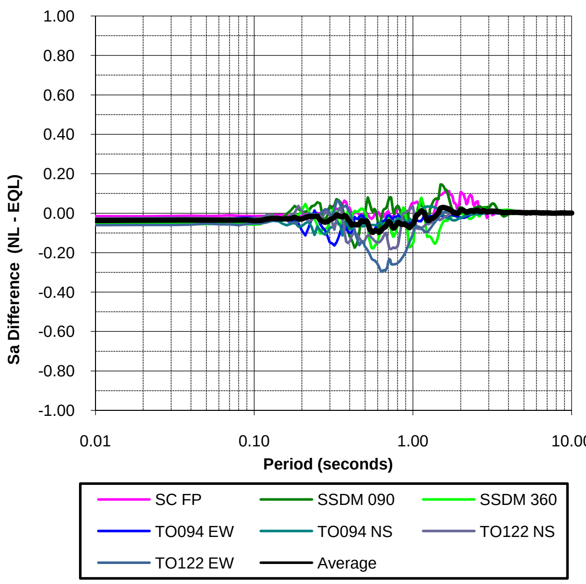

Fig. 9. Difference in Ground Surface Spectral Acceleration Calculated using SHAKE2000 and D-MOD2000, Category 1 (Weak to Moderate Motions)

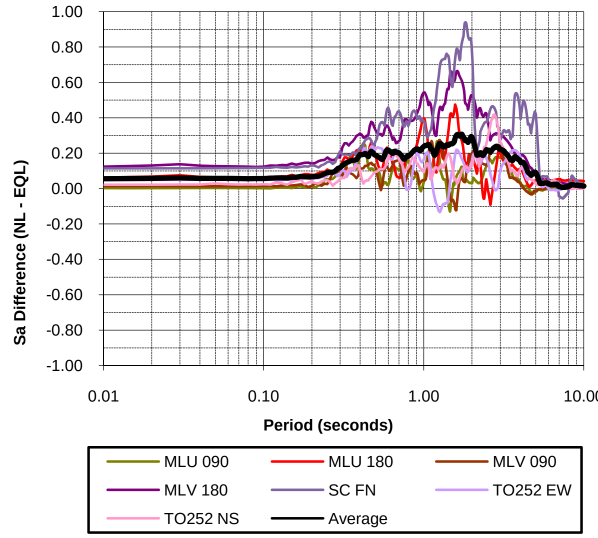

Fig. 10. Difference in Ground Surface Spectral Acceleration Calculated using SHAKE2000 and D-MOD2000, Category 2 (Strong Motions)

Cyclic Shear Stress

Figures 11 and 12 present the cyclic stress ratio (CSR) profiles for each scaled time history calculated with SHAKE2000 and D-MOD2000, respectively.

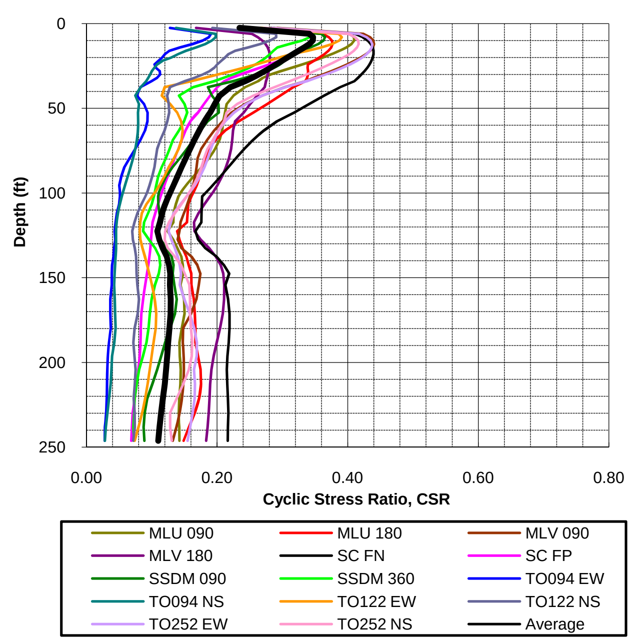

Fig. 11. Cyclic Stress Ratio Profile Calculated using SHAKE2000, East Profile

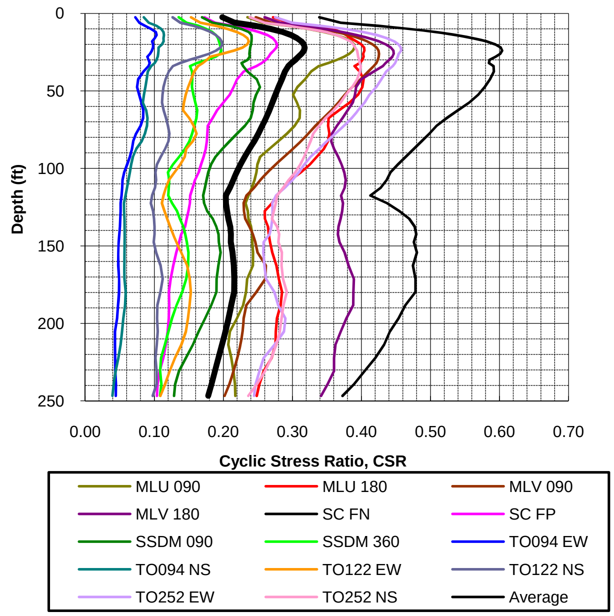

Fig. 12. Cyclic Stress Ratio Profile Calculated using D-MOD2000, East Profile

Figure 13 presents a comparison between the average CSR profile and the CSR profile of the SC FN time history (M=9.2, PGA = 0.92) calculated using both SHAKE2000 and D-MOD2000. As shown in Figure 13, the CSR values calculated by SHAKE2000 differ greatly and are consistently lower than the values calculated by D-MOD2000.

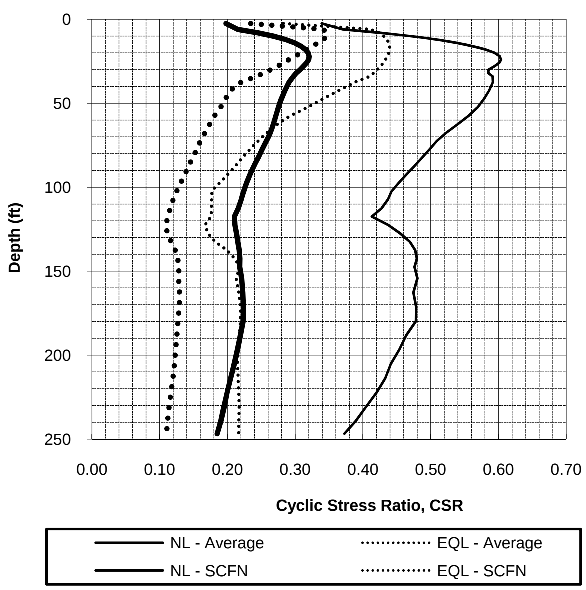

Fig. 13. Comparison of Cyclic Stress Ratio Calculated using SHAKE2000 and D-MOD2000, East Profile

Figure 14 and 15 present the difference of the CSR profiles calculated using D-MOD2000 and SHAKE2000 for category 1 and category 2 time histories, respectively. Although the difference between the CSR values calculated between D-MOD2000 and SHAKE2000 are smaller for category 1 time histories, the difference is significant enough that SHAKE2000 may not be appropriate in soil stress evaluation as it may produce unconservative results. These results also show that nonlinear method provides more reasonable values of soil shear stresses.

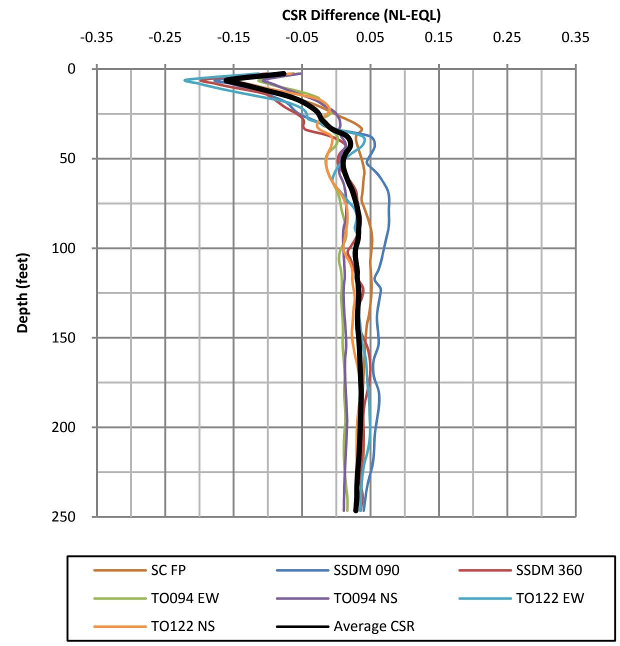

Fig. 14. Difference in Ground Surface Spectral Acceleration Calculated using SHAKE2000 and D-MOD2000, Earthquakes with Moderate Ground Shaking Intensity

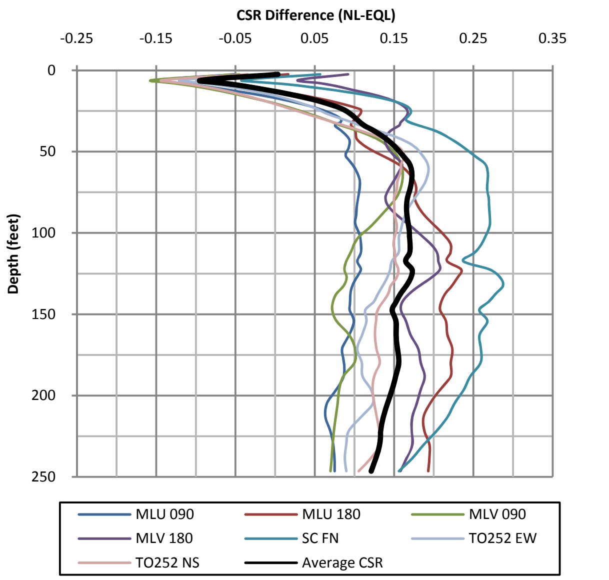

Fig. 15. Difference in Ground Surface Spectral Acceleration Calculated using SHAKE2000 and D-MOD2000, Earthquakes with High Ground Shaking Intensity

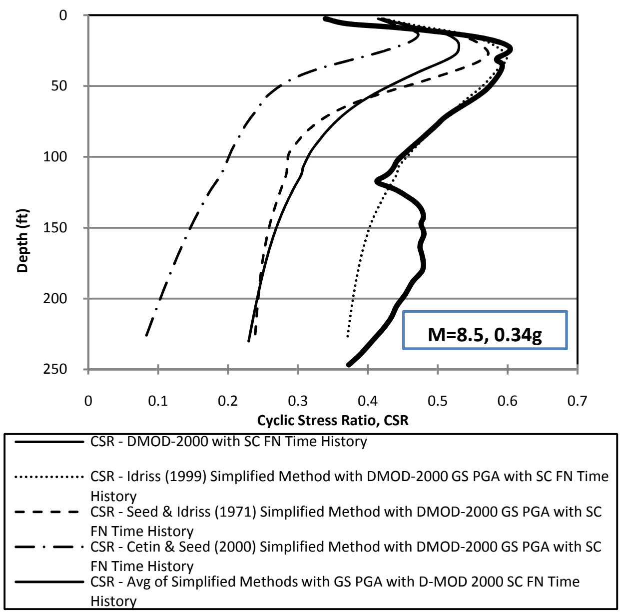

Fig. 16. Comparison of CSR Calculated using Simplified Methods, and D-MOD2000 with SC FN Time History and Output

Comparison to Simplified Methods. The CSR values calculated with both D-MOD2000 and SHAKE2000 are compared to the CSR values calculated with the simplified methods developed by Seed and Idriss (1971), Idriss (1999) and Cetin et al (2000). Four time histories were selected and used in the CSR calculation. The following presents the time histories selected and their characteristics:

1. SC FN – large magnitude, high PGA and long duration.
2. SC FP – large magnitude, low PGA and long duration.
3. SSDM 090 – moderate magnitude, high PGA and short duration.
4. TO 094 – moderate magnitude, moderate PGA and moderate duration.

Figures 16 and 17 present the CSR profiles calculated by D-MOD2000, SHAKE2000 and the three simplified methods with the SC FN time history. Also shown on the figures are the input parameters for the simplified methods.

Figures 18 and 19 present the CSR profiles for the SC FP time history. Figures 20 and 21 present the CSR profiles for the SSDM 090 time history. Figure 22 and 23 presents the CSR profiles for the TO 094 time history.

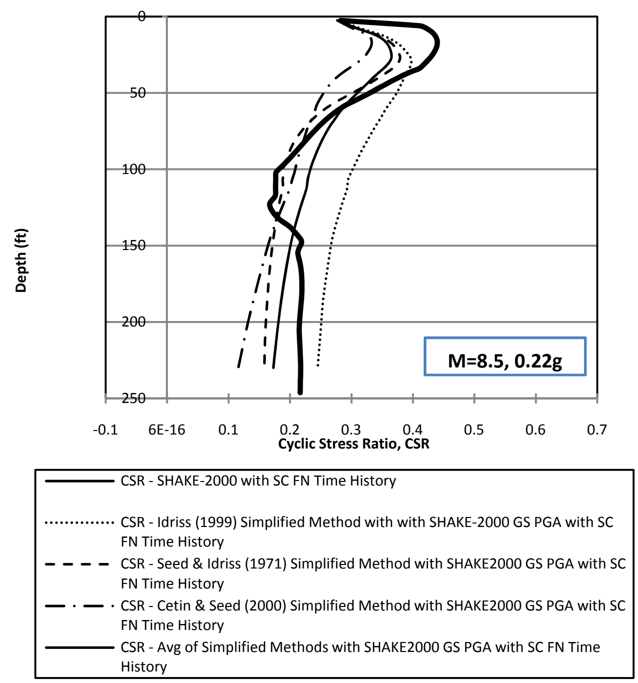

Fig. 17. Comparison of CSR Calculated using Simplified Methods, and SHAKE2000 with SC FN Time History and Output

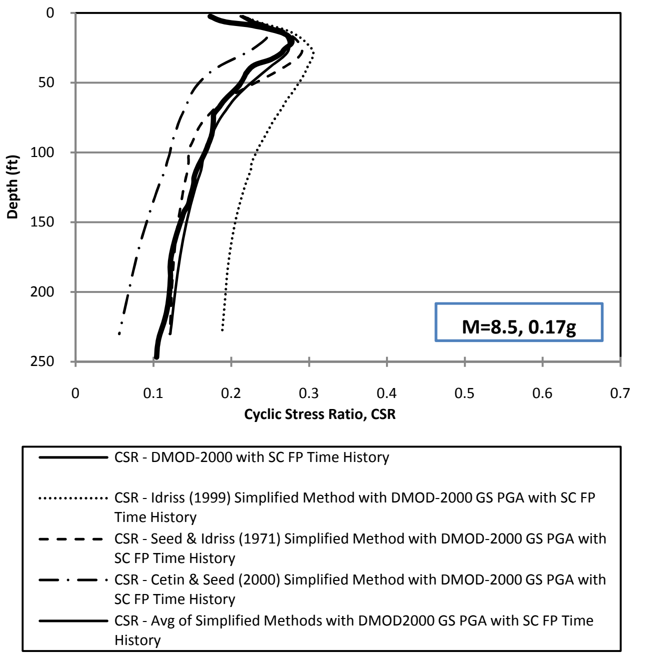

Fig. 18. Comparison of CSR Calculated using Simplified Methods, and D-MOD2000 with SC FP Time History and Output

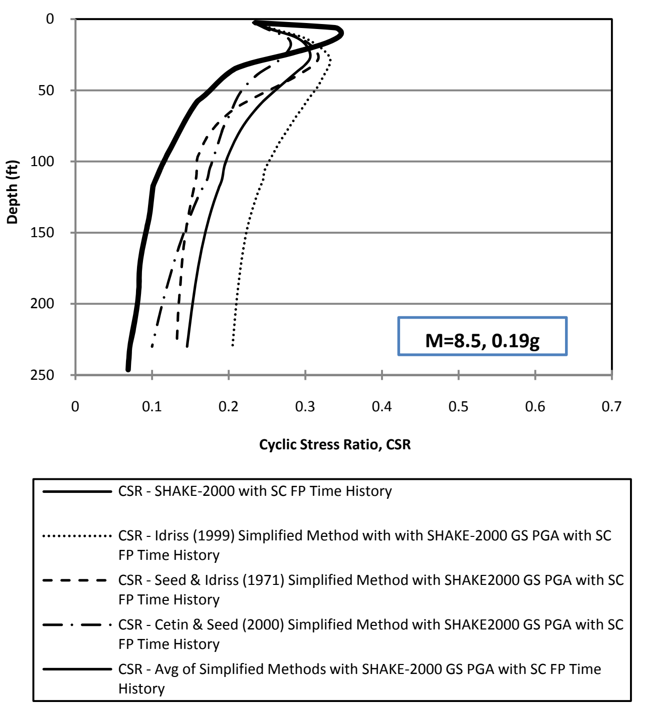

Fig. 19. Comparison of CSR Calculated using Simplified Methods, and SHAKE2000 with SC FP Time History and Output

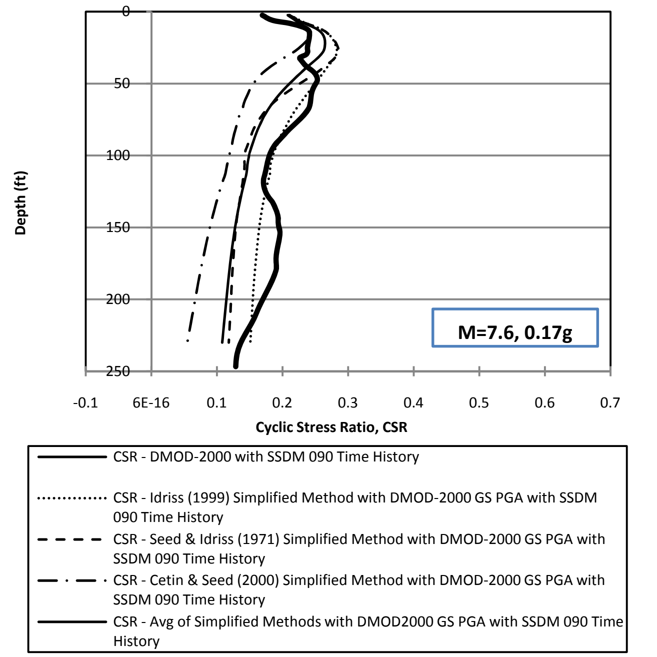

Fig. 20. Comparison of CSR Calculated using Simplified Methods, and D-MOD2000 with SSDM 090 Time History and Output

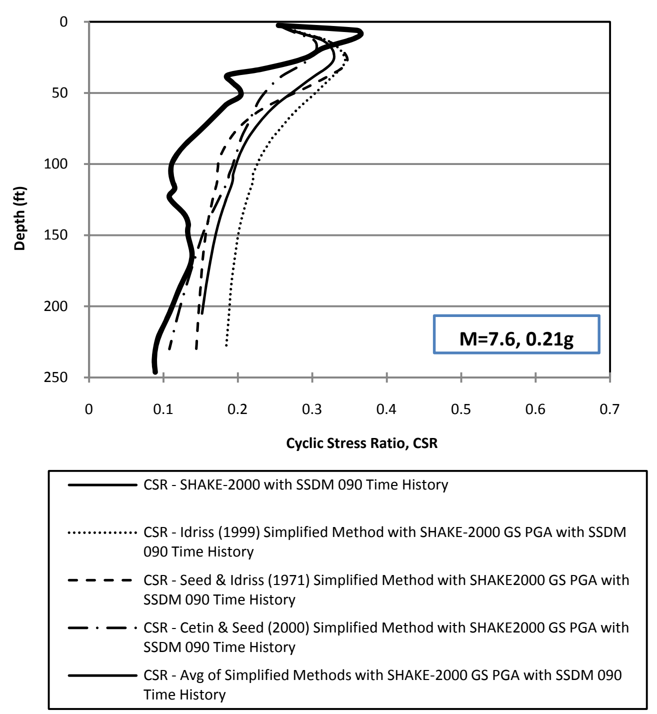

Fig. 21. Comparison of CSR Calculated using Simplified Methods, and SHAKE2000 with SSDM 090 Time History and Output

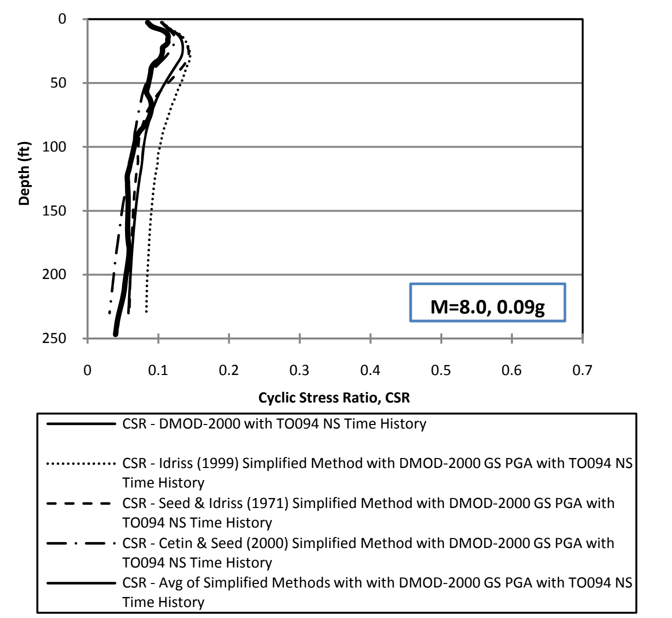

Fig. 22. Comparison of CSR Calculated using Simplified Methods, and D-MOD2000 with TO094 Time History and Output

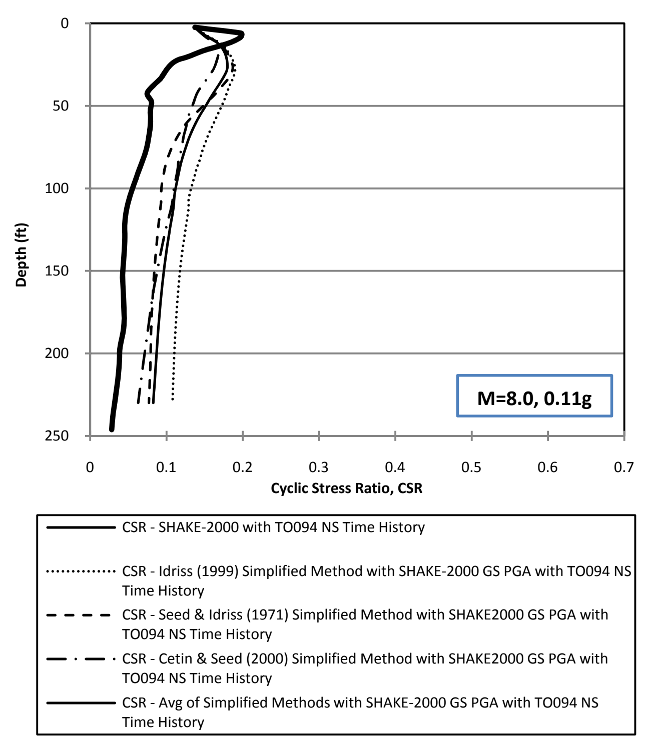

Fig. 23. Comparison of CSR Calculated using Simplified Methods, and D-MOD2000 with TO094 Time History and Output

As shown in Figures 16 through 23, there are significant scatter in the CSR values calculated using the different simplified methods, especially at depth below about 50 feet. For this evaluation, the CSR profile calculated with SHAKE2000 and D-MOD2000 (shown as the thick solid line) was compared to the average CSR profile calculated using the three simplified method (shown as the thin solid line).

Figures 16 through 23 also show that the CSR profiles calculated with SHAKE2000 tend to be lower than the average CSR profile calculated using the three simplified methods. The CSR profiles calculated by D-MOD2000 are more consistent with the values calculated using the simplified methods.

<u>Cyclic Shear Strain</u>

Figures 24 and 25 present maximum cyclic strain profiles calculated using each scaled time history with SHAKE2000 and D-MOD2000, respectively.

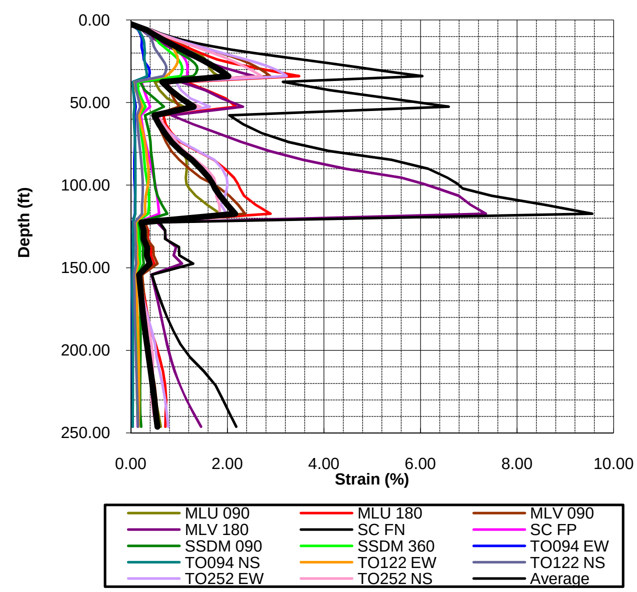

Fig. 24. Maximum Cyclic Shear Strain Profile Calculated using SHAKE2000, East Profile

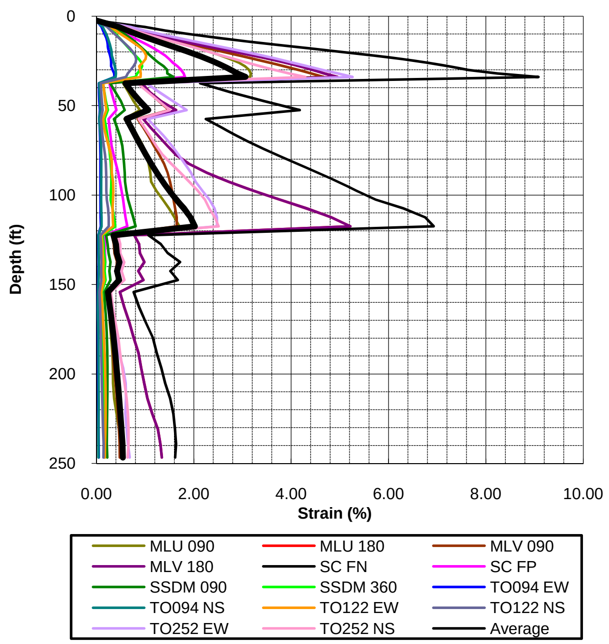

Fig. 25. Maximum Cyclic Shear Strain Profile Calculated using D-MOD2000, East Profile

Figure 26 presents a comparison between the average maximum shear strain profile and the maximum shear profile of the SC FN time history (M=9.2, PGA = 0.92g) calculated using both SHAKE2000 and D-MOD2000.

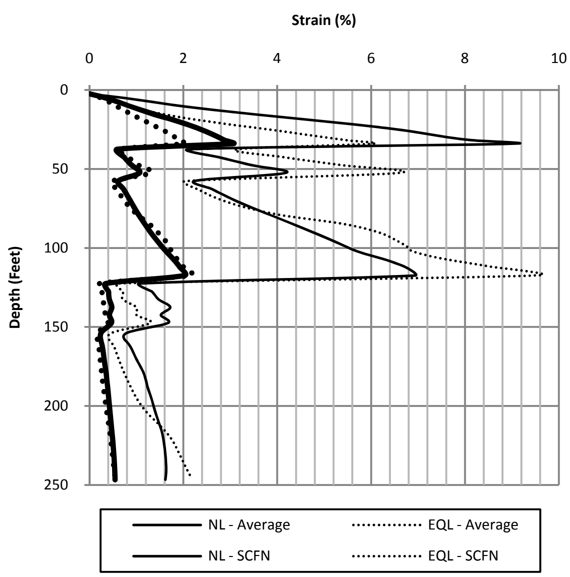

Fig. 26. Comparison of Maximum Cyclic Shear Strain Profile Calculated using SHAKE2000 and D-MOD2000, East Profile

As shown in Figure 26, the average shear strain calculated by both SHAKE2000 and D-MOD2000 is very similar except in the wood waste layer, where SHAKE2000 calculates a lower strain value. In addition, SHAKE2000 predicts the maximum soil strain at the interface between the alluvium and gravel unit. This is inconsistent with what we would expect, because the maximum strain is more likely to occur within the softest soil layer in the whole profile, which in this case is the wood waste layer. This is correctly predicted by the D-MOD2000 results.

CONCLUSIONS AND RECOMMENDATIONS

As presented in this paper, site response analysis can provide practitioners a mean of evaluating the seismic response of a layered soil profile. Although equivalent linear method in performing site response analysis is relatively easy to use and straight forward, there are some limitations that need to be understood.

Based on the site response analysis results presented in this paper, we conclude that:

1. Both the equivalent linear and nonlinear methods provided similar results in ground surface response spectra under the weak to moderate ground motions.
2. For strong ground motions, the equivalent linear method calculated lower surface response compared to the nonlinear method.
3. The nonlinear method provided higher soil shear stresses than the equivalent linear method for the strong motions. The nonlinear method appears to provide more reasonable stresses under these strong motions.
4. The nonlinear appears to provide more reasonable soil strain for the strong motions compared to the equivalent method.
5. The nonlinear method is shown to be more appropriate for use in estimating soil shear stress and strain for soft soil sites and can augment the simplified methods in soil liquefaction analyses.
6. If site response analysis is used for soil shear stress and strain evaluation, it should be done with a suite of earthquake time histories that are representative of the seismic hazard at the site.

ACKNOWLEDGMENTS

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REFERENCES

ASCE [2005]. "*SEI/ASCE 7-05, Minimum Design Loads for Buildings and Other Structures*". American Society of Civil Engineers.

Cetin, K.O., Seed, R.B., Moss, R.E.S., Der Kiureghian, A.K., Tokimatsu, K., Harder, L.F., and Kayen, R.E. [2000]. "*Field Performance Case Histories for SPT-Based Evaluation of Soil Liquefaction Triggering Hazard*". Geotechnical Engineering Research Report No. UCB/GT-2000/09, Geotechnical Engineering, Dept. of Civil Engineering, Univ. of California at Berkeley.

Darendeli, M. [2001]. "*Development of a new family of normalized modulus reduction and material damping curves*". Ph.D. thesis, Dept. of Civil Engineering, Univ. of Texas, Austin, Texas.

Electric Power Research Institute (EPRI) [1993]. "*Guidelines for Site Specific Ground Motions*". Palo Alto, California, Electric Power Research Institute, November, TR-102293.

Frankel, A.D.; Petersen, M.D.; Mueller, C.S.; Haller, K.M.; Wheeler, R.L.; Leyendecker, E.V.; Wesson, R.L.; Harmsen, S.C.; Cramer, C.H.; Perkins, D.M.; and, Rukstales, K.S. [2002]. "*Documentation for the 2002 Update of the National Seismic Hazard Maps*". U.S. Geological Survey Open-File Report 02-420.

Idriss, I. (1999). "An update of the Seed-Idriss simplified procedure for evaluating liquefaction potential". Proceedings TRB Workshop on New Approaches to Liquefaction Analysis, Publication No. FHWA-RD-99-165, Federal Highway Administration, Washington, D.C.

International Code Council [2006]. "*2006 International Building Code*"

Matasovic, Neven and Gustavo Ordonez (2006). "D-MOD2000, A Computer Program Package for Seismic Response Analysis of Horizontally Layered Soil Deposits, Earthfill Dams and Solid Waste Landfills, User's Manual". GeoMotions, LLC; Lacey, WA.

Ordonez, G., (2005). "SHAKE2000, A Computer Program for the 1-D Analysis of Geotechnical Earthquake Engineering Problems, User's Manual," September 2005 Revision. GeoMotions, LLC; Lacey, WA.

Rau, Weldon W. [1986]. "*Geology of the Humptulips Quadrangle and Adjacent Areas, Grays Harbor County, Washington, U.S*". Geological Survey, Map GM-33.

Schnabel, P.B. (1973). "*Effects of Local Geology and Distance from Source on Earthquake Ground Motions*". Ph.D. Thesis, University of California, Berkeley, California.

Seed, H.B. and Idriss I.M. [1971]. "Simplified procedure for evaluating soil liquefaction". Journal of Soil Mechanics and Foundations Div., ASCE 97(SM9), pp 1249-273.

Wehling, T.M., Boulanger, R.W., Arulnathan, R.. Harder, L.F. and Driller, M.W. (2003). "*Nonlinear Dynamic Properties of a Fibrous Organic Soil*". Journal of Geotechnical and Geoenvironmental Engineering, Vol. 129, No. 10, October 2003, pp. 929-939.