PILE DRIVING VIBRATION ISOLATION USING GEOFOAM

Karthikeyan Radhakrishnan
CH2M HILL, Santa Ana, CA 92707, kradhakr@ch2m.com

Dawit Negussey
Syracuse University, Syracuse, NY 13244, negussey@syr.edu

ABSTRACT

Vibrations generated by pile driving can damage existing structures and utility lines. Induced vibrations may range in intensity from low levels that annoy occupants to higher intensities that can cause structural damage and foundation settlement. Different types of barriers have been tried in the past to absorb or attenuate surface waves generated by pile driving. Such interceptors vary from open or slurry filled trenches, gas cushions to curtain walls. Geofoam is mainly composed of air and is widely used for packaging and cushioning. Numerical modeling and simulations were performed to evaluate the relative effectiveness of geofoam curtain walls for reducing vibration intensities associated with pile driving. The results of the analyses indicate temporary open trench barriers offer the most effective impedance to surface waves. However, open trench interceptors can be hazardous and limited in depth as sections of the side walls can collapse. Simulations of geofoam filled open trenches showed good impedance to vibration waves. Geofoam filled trench walls can extend to larger depths than open trench interceptors and potential sidewall collapse and construction hazard situations would be minimized. Geofoam filled trench walls can remain as permanent fixtures for intercepting vibrations from traffic and for protection against blasting or subsurface explosions.

BACKGROUND

NCHRP Synthesis 253 (Woods, 1997) provides details on mechanisms of vibration generation due to pile driving by impact and vibratory hammers. The decay of vibration amplitudes with distance result from geometric or radiation damping and material or hysteretic damping. Wiss (1981) attempted to model vibration attenuation by coupling energy and distance in a scaled-distance equation. Heckman and Hagerty (1978) also developed an equation relating pile-driving energy to the distance between a target structure and a vibration source. Hunt *et al*. (2002), investigated changes in shear wave velocity in soils due to pile driving. They concluded changes in shear wave velocity represent increases in soil stiffness and improvement in the seismic response of the soil-pile-structure over time (Pestana *et al.*, 2001). Excess pore water pressure generation during pile driving at various depths in sand and clay soils was investigated by Hwang *et al*. (2001). As previously observed by Bozozuk *et al.* (1978), insitu vane shear strengths of sensitive clays decreased by about 15% following pile driving and the cone penetration resistances reduced up to 30%. The strength losses and reduced penetration resistances were partially recovered within three months following pile driving. Lacy and Gould (1985) provided a review of some 19 cases of settlements due to pile driving vibrations.

To reduce vibrations due to pile driving, two methods are usually considered: (i) use of a wave barrier (ii) select an alternative installation method.

Different types of wave barriers have been tried in experimental studies and field applications. Woods (1968) evaluated the effectiveness of open trench wave barriers. Haupt (1995) found solid concrete barriers of appropriate sizes to be effective, but in no case as effective as an open trench barrier. Hayakawa (1998) used precast hollow concrete panels as permanent wave barriers along railroads. Woods (1997) reported use of corrugated pile shells as wave barriers. Though found reasonably effective, corrugated pile shells were considered uneconomical. Massarsch (2005) proposed a gas cushion curtain for vibration isolation. This system has been tried mainly in Europe but has not been widely accepted. Conceptually, open trenches tend to be economical and effective for intercepting vibration induced waves. However, depending on the soil and groundwater conditions, excavation side walls collapse and open trenches can be difficult to maintain. Maximum depths of unsupported open trenches tend to be limited but larger depths can be maintained by slurry filling. Open or slurry filled trenches may have to be covered or fenced off for safety and would not be suitable as a long term solution.

GEOFOAM

Geofoam commonly refers to block molded EPS (expanded polystyrene). Commonly produced EPS grades vary in density from about 11 to 30 kg/m^3. Geofoam is very light and air constitutes over 95 percent of the volume. Air under atmospheric pressure is encapsulated in fused microscopic cells that comprise the rigid cellular bulk material.

A simple analysis example

Two-thirds of the energy due to pile driving vibrations is transmitted by surface or Rayleigh waves. A one dimensional wave transmission through soil and across a geofoam strip is shown in Figure 1. Evaluations of impedance ratios using formulas given by Kramer (1996) indicate significant stress amplitude reduction as waves propagate through the soil and across the geofoam strip. This lends support to a proposition that a geofoam strip would behave like an open trench.

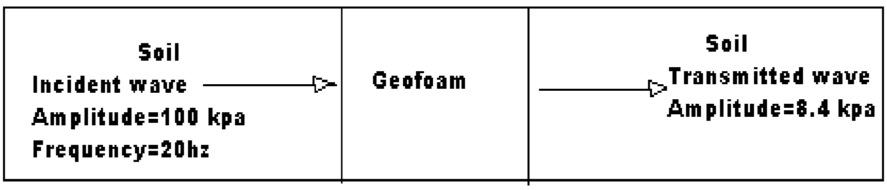

Figure 1: One dimensional wave transmission through geofoam

FINITE DIFFERENCE MODELING AND ANALYSIS

More complicated field conditions were modeled in FLAC (Fast Lagrangian Analysis of Continua) for parametric studies of wave propagation across a geofoam interface. FLAC uses an explicit finite difference scheme to solve equations of motion, using lumped grid point masses derived from surrounding zones (Itasca Consulting, 2008).

Model and meshing

The vibration problem was represented by an axi-symmetric model of a soil layer of 100m width and 30m depth with the axis of symmetry along x = 0. Such large dimensions for the soil mass were to reduce boundary reflection effects, but the zone of interest for monitoring was 30m wide and 10m deep. The main features of the model are given in Table-1.

The grid size for the model mesh was selected as recommended by Kuhlemeyer and Lysmer (1973) to be 1/8 to 1/12 of the wavelength in the direction of propagation. Thus for a calculated representative wavelength of 5.5m, the required grid size at critical segments was 0.5m to 0.7m. Hence, the grid size in the main area of consideration (30m width x 10m depth of the model) was kept at 0.5m x 0.5m. In other areas, grid sizes were varied from 2m x 0.5m to 2m x 2m to reduce run times and utilize computation resources optimally.

Table 1 - Model parameters of the analysis

Modeling Parameters	Initial analysis	Parametric studies
Size of the model	100m x 30m	100m x 30m
Depth of pile driving	10m	10m
Depth of trench barrier	10m	N/A
Depth of geofoam barrier	10m	3m except for depth studies
Distance from source	1m	1m except for distance studies
Width of barrier	1m	1m except for width studies
Monitoring distances	1m to 75m	1m to 75m

Materials and other input parameters

The main materials involved in the analysis were soil and geofoam. Engineering properties and constitutive models used in the analysis are listed in Table - 2.

Table 2 - Material parameters used in the analysis

Material parameters	Values
Soil:	
Constitutive model	Mohr-Coulomb (FLAC in-built)
Type	Uniform coarse sand
Density	2250 kg/m^3
Bulk Modulus	58 MPa
Shear Modulus	27 MPa
Cohesion	0
Friction angle	34°
Geofoam:	
Constitutive model	Elastic Hyperbolic (FLAC add on)
Density	20 kg/m^3
Bulk modulus	5.3 MPa
Elastic modulus	8 MPa
Elastic yield stress	0.1 MPa

Pile driving depth of 10m was used in all models. To further simplify the analysis, driving vibrations induced into the soil along the pile skin were assumed to be constant with depth. The vibration loadings at the pile / soil interface consisted of vertical particle velocities of 1000 mm/s amplitude. The pile / soil interface in the model was at the axis of symmetry.

The variation of particle velocity amplitude with time was described by a simple harmonic wave motion with a frequency of 20 Hz for initial analyses. A parametric study on frequency values was also done. Vibration loadings were applied for 1 second and the particle velocity responses at various points were recorded during loading and up to 9 seconds after the end of load application. The particle velocity responses were monitored at varying distance from the source; both at ground surface and at various depths.

Results

Peak particle velocity (PPV) is usually used to relate vibration amplitudes to damage levels or disturbance levels. Hence, peak particle velocities were monitored at different points in model simulations. The results obtained from various analyses and parametric studies are presented in charts that show attenuation of peak particle velocities and amplitude ratio curves. Amplitude ratio at an observation point in the model is the ratio of peak particle velocity with a geofoam barrier to peak particle velocity without barrier.

PPV attenuation below threshold damage level

A peak particle velocity of 12.5 mm/s (0.5 in/s) is a conservative threshold criterion for limiting vibration induced damage (Woods, 1997). Results from the model studies indicate a distance of about 25m from the source would be required to attenuate vibrations to 12.5 mm/s for cases without barriers (Figure 2). By placing a trench or geofoam barrier of sufficient depth (more than one wavelength), the level of PPV can be reduced below the threshold damage limit at the barrier position. The required distance from the source to the barrier can be as little as 2m. The amplitude ratio of about 85% for an open trench barrier compares reasonably well with the value of 88% reported by Woods (1968). For a geofoam barrier, an amplitude ratio of about 70% was indicated. These simulations considered barriers of 1m width and 10m depth.

Economic constraints and installation difficulties may not favor barriers that extend to 10 m depths. Hence additional analysis considered geofoam barriers of 3.5 m depths. The offset distance required to reduce vibrations below damage limits was about 10m for 3.5m geofoam barrier depth, as shown in Figure 2. Therefore, when no barrier was used, targets located at distances less than 25m from the source may be susceptible to damage. By increasing the geofoam barrier depth, targets at much closer offset distances than 10m can be protected from vibration damage.

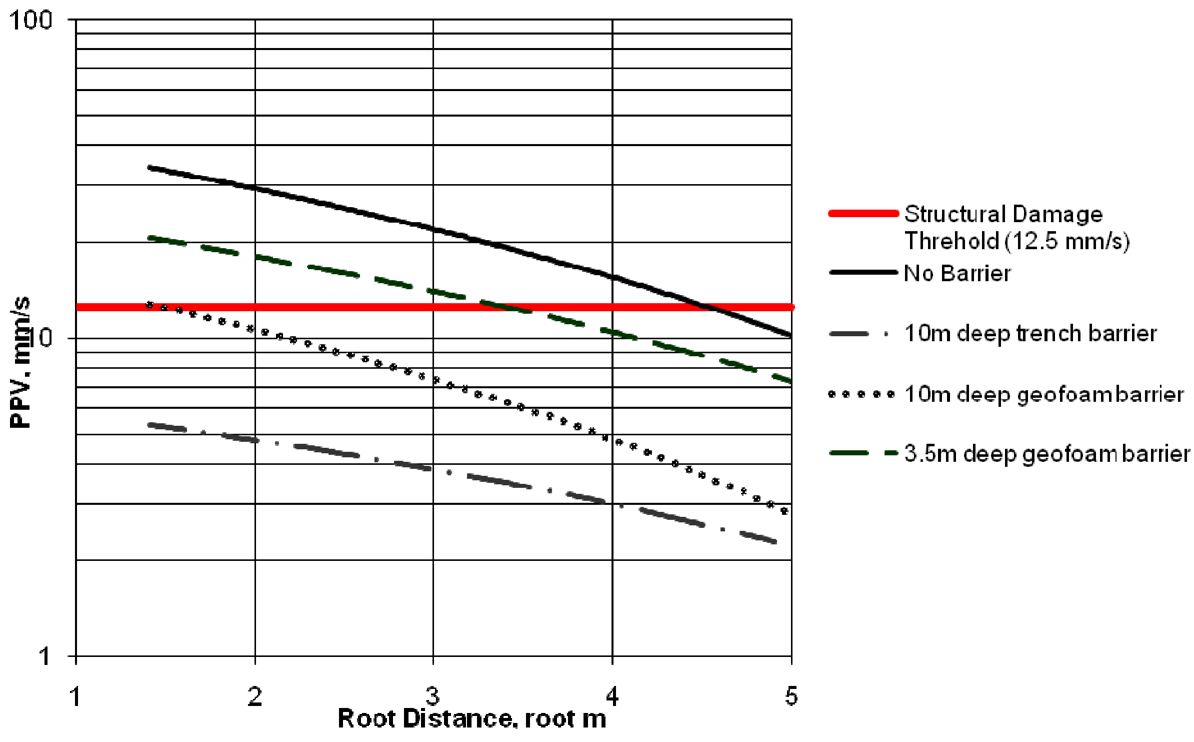

Figure 2: PPV attenuation below threshold damage limit

Parametric studies

Effects of changes in barrier width, depth, distance from the source as well as density of the geofoam and frequency of applied vibrations on attenuation were investigated. Parametric studies simulated changes of each variable within applicable ranges separately. The attenuations improved with barrier depths as shown in Figure 3. For depths of half the wavelength, the reduction in vibration amplitude was about 20 to 40%. Whereas for depths equal to the wavelength, the amplitude reduction became about 35 to 60%. For depths of twice the wavelength, the attenuation improved to about 70% and for 4 times the wavelength, the attenuation reached about 75%. There were significant changes in attenuation improvements with barrier depths. Barrier depths of 1 to 1.5 times the wave lengths can provide attenuation improvements of about 50%..

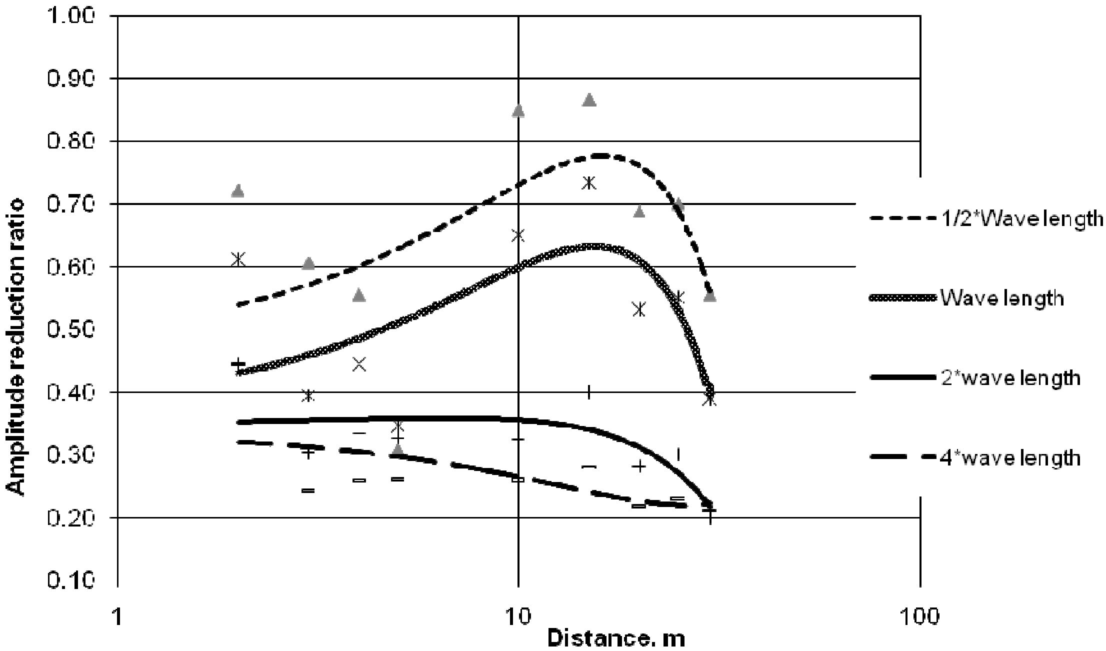

Figure 3: Effect of depth barrier from source on vibration attenuation

Figure 4 shows the effect of placing a 3m deep barrier at different distances from the source. The results indicate the amplitude reduction would best immediately adjacent to the barrier on the protection side. With further distance from the barrier and towards the target, amplitude ratios increase. Placing the barrier adjacent to the target would therefore produce the most protection. A geofoam can also reduce subsurface flow of water and heat in the vicinity of target. Reducing seepage and increasing insulation may be very desirable additional benefits for some applications.

Increasing the width of geofoam barrier reduces the vibration amplitude. The difference in amplitude reduction between a 1m wide geofoam barrier and a 5m wide geofoam barrier can be as much as 20% at shorter distances from the vibration source. However, the amplitude reduction for a 1m wide geofoam barrier placed at 5m from the source was better than for a 5m wide barrier placed near the source. At larger distances from the source, the effect of barrier width was negligible.

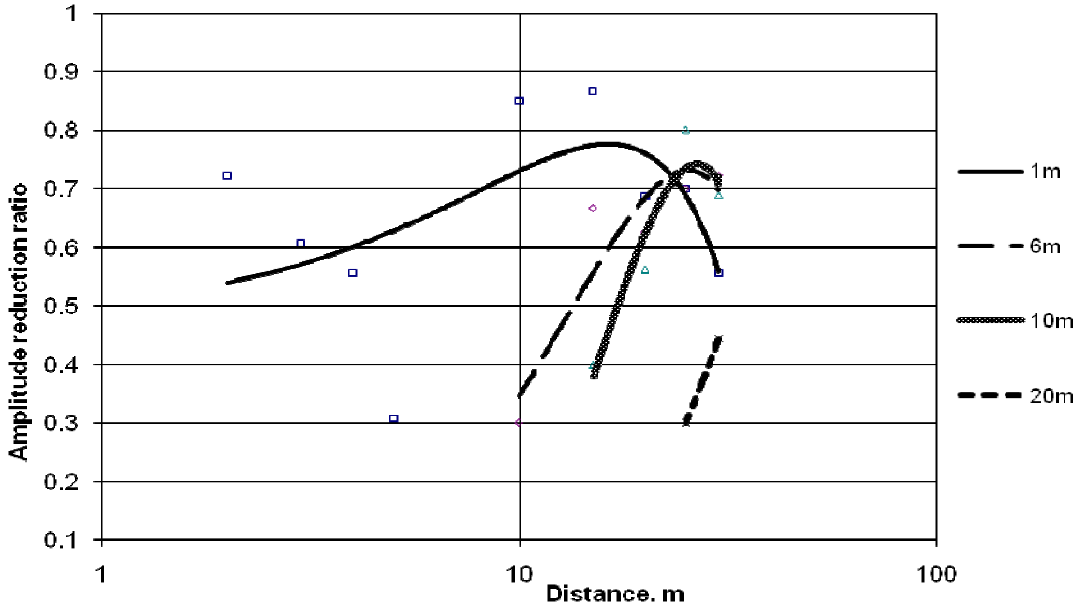

Figure 4: Effect of distance of wave barrier from source on vibration attenuation

Four types of geofoam density grades, as specified in ASTM D6817, were considered. The lowest density geofoam, 11 kg/m^3, provided the most reduction of vibration amplitude. Overall, differences in attenuation with changes in geofoam density were not significant. As the cost of geofoam increases with density, the lowest density geofoam barrier would be preferred for both cost and performance considerations.

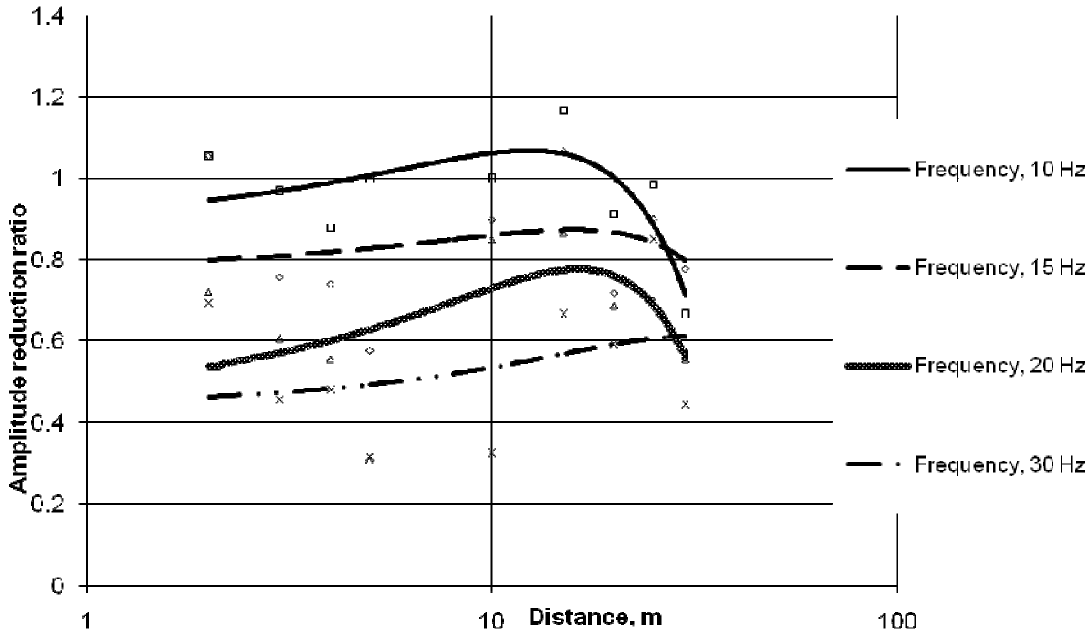

Figure 5: Sensitivity of amplitude reduction to the frequency of vibration

Generally, vibration frequencies associated with pile driving tend to range from 10 to 30 Hz (Woods, 1997). A vibration frequency of 20 Hz was used in the initial analysis and in the parametric studies. A series of simulations were performed in which the vibration frequencies were changed from 10 to 30Hz in steps of 5 Hz for the same vertical peak particle velocity (PPV) of 1000 mm/s at the source. The results shown in Figure 5 indicate geofoam barriers would perform much better in attenuating higher frequency vibrations. This observation can have interesting implications for further studies and possible applications of geofoam barriers for intercepting vibrations from a broad range of sources.

SUMMARY

The foregoing results of model studies indicated open trench barriers would be most effective for intercepting vibrations induced by pile driving. However, depths of open trench barriers would tend to be limited and excavations cannot remain open for extended periods. EPS geofoam barriers would attenuate vibrations effectively as permanent installations. Barrier systems would be designed considering the relative proximity of vibration source and protection target. The barrier depth would be optimized to achieve a desired level of protection. Both the density and width of geofoam barriers did not significantly affect the attenuation performance. The effectiveness of geofoam barriers increased with the frequency of the induced vibration. Barrier positions close to the protection target were more effective than barriers installed close to the source. Further research may be able to identify other suitable applications for geofoam barriers such as for higher frequency vibrations along transportation corridors to high velocity impact loads from blasting or explosions. Where beneficial, geofoam vibration barriers may also be considered simultaneously to reduce seepage and improve insulation. Vibration amplitude reductions of up to 70 percent may be achieved through use of geofoam barriers either for short or long term applications.

REFERENCES

1. Bozozuk et al.(1978), "Soil disturbance from pile driving in sensitive clay", Canadian Geotechnical Journal, Vol. 15, pp. 346-361.

2. Haupt, W.A.(1995), "Wave propagation in the ground and isolation measures", Proceedings: 3rd International conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Vol.2, St. Louis, MO pp. 985-1016.

3. Heckman, W.S., Hagerty, D.J.(1978), "Vibrations associated with pile driving", Journal of the construction division, ASCE, Vol. 104, No. CO4, pp 385-394.

4. Hayakawa, K., Matsui, T. and Woods, R.(1998), "Ground Vibration Isolation by PC Wall-Piles," 4th International Conference on Case Histories in Geotechnical Engineering, St. Louis, MO pp 672-677.

5. Hunt, C.E., Pestana, J.M., Bray, J.D, Riemer, M. (2002), “Effect of pile driving on static and dynamic properties of soft clay”, Journal of Geotechnical & Geoenvironmental Engineering, ASCE, Jan. 2002, pp.13-23.

6. Hwang, J.H., Liang, N., Chen, C.H. (2001), “Ground response during pile driving”, Journal of Geotechnical & Geoenvironmental Engineering, ASCE, Nov.2001, pp 939-949.

7. Itasca Consulting Group, Inc. (2008), FLAC v6.0 Dynamic Analysis.

8. Kramer, S.L.(1996), “Wave Propagation”, Chapter-5, Geotechnical Earthquake Engineering, Prentice Hall Inc., NJ.

9. Kuhlemeyer, R.L., Lysmer, J. (1973), “Finite element accuracy of wave propagation problems”, Journal of Soil Mechanics & Foundation Division, ASCE, Vol. 99(SM5), May 1973, pp. 421-427.

10. Lacy, H.S., Gould, J.P. (1985), “Settlement from pile driving in sands”, Vibration Problems in Geotechnical Engineering, Proceedings of a symposium sponsored by the Geotechnical Engg. Division of ASCE at Detroit, MI, ASCE, New York, pp.152-173.

11. Massarsch, K. R. (2005), “Vibration Isolation using Gas filled cushions”, Keynote lecture, Geofrontiers 2005 – International Conference, American Society of Civil Engineers, January 24-26, 2005, Austin, TX.

12. Negussey, D. (1997), “Properties & Applications of geofoam”, Society of the Plastics Industry, Inc.

13. Pestana, J. M., Seed, R., Riemer, M., Meymand, P., and Lok, M.-H (2001). ‘‘Modeling of soil-pile-superstructure interaction,’’ Geotechnical Engineering Rep. No. UCB/GT/01-06, Univ. of California, Berkeley.

14. Richart, F.E., Hall, J.R., Woods, R.D. (1970), Vibrations of Soils and Foundations, Prentice Hall, Inc., NJ.

15. Wiss, J.F. (1981), “Construction vibrations: state of the art”, Journal of the Geotechnical Engineering Division, ASCE, Vol. 107, GT 2, Feb., pp. 167-181.

16. Woods, R.D.(1968), “Screening of surface waves in soils”, Journal of the Soil Mechanics and Foundation division, proceedings, ASCE, Vol. 94, No.4, July 1968, pp. 951-979.

17. Woods, R.D., Jedele, L.P. (1985), “Energy attenuation relationships from construction vibrations”, Vibration Problems in Geotechnical Engineering,

Proceedings of a symposium sponsored by the Geotechnical Engineering Division of ASCE at Detroit, Michigan, ASCE, NY, pp. 229-246.

18. Woods, R. D. (1997), “Dynamic effects of pile installations on adjacent structures”, NCHRP Synthesis 253, Transportation Research Board, National Academy Press, Washington D.C.