Modulus Reduction and Damping Curves for Landfill Covers

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Abstract

Unlike dynamic properties of municipal solid waste (MSW), the dynamic properties of engineered fill landfill covers at MSW and other landfill sites have not been extensively investigated. The two main reasons for the dearth of research on this topic are: (i) design engineers realize that modern landfill covers are relatively thin (on the order of 1.5 m, or less), and hence, their influence on the overall landfill response is assumed to be small; and (ii) there are readily available sets of dynamic soil properties of cohesive soils that could be assigned to landfill covers soils based upon the results of index testing. However, not all landfill covers are "thin," and the readily available sets of dynamic soil properties may not be applicable for low-plasticity compacted and overconsolidated soils such as landfill covers. At many old landfills and Superfund sites, landfill cover thickness readily exceeds 5 m, and covers can be as thick as 10 to 15 m. These thicker covers may have significant influence on the overall response of landfills, and hence, careful evaluation of cover material properties is warranted. In this paper, results of in-situ nonlinear testing of landfill cover soils was used to develop modulus reduction curves. Shear strains in the cover soils ranging from 10^{-4} % to 2×10^{-2} % were induced by Vibroseis shakers. The material damping curves were estimated from modulus reduction curves by means of a nonlinear constitutive model, Masing rules, and engineering judgement. The modulus reduction and damping curves presented herein may be used for seismic design of landfill covers and other engineered fills constructed of soils of similar plasticity and with similar stiffness (i.e., shear wave velocity) and compaction characteristics.

INTRODUCTION

The complete dynamic characterization of a landfill mass (i.e., landfill cover, waste, and landfill liner) involves evaluation of shear wave velocity (V_s), unit weight, Poisson's ratio, and nonlinear properties of materials in the subsurface profile. Information on unit weight and Poisson's ratio can be readily assumed based upon published information (e.g., Kavazanjian et al. 2013; Zekkos et al. 2006). Nonlinear properties of waste and landfill liner and cover materials may require more rigorous evaluation, especially if fully nonlinear site response models are employed. For most commercial purposes, however, practicing engineers evaluate these properties based upon soil plasticity (i.e., for landfill liner and cover) or as typical values (i.e., for waste).

Figure 1 presents a suite of the Vucetic and Dobry (1991) modulus reduction and damping curves that are widely used for soil covers as part of the seismic design of landfills. These curves relate modulus reduction and damping to Plasticity Index (PI) with no consideration for soil overconsolidation ratio and/or confining stress. Moreover, as stated by the authors of these curves, the PI = 15 – 200 curves are representative of "saturated fine-grained soil deposits." However, landfill covers are constructed as partially saturated (i.e., unsaturated) engineered fills. Furthermore, landfill covers, especially those at older and legacy sites, may be heavily overconsolidated due to multiple drying and wetting cycles and, hence, often classify as stiff soils.

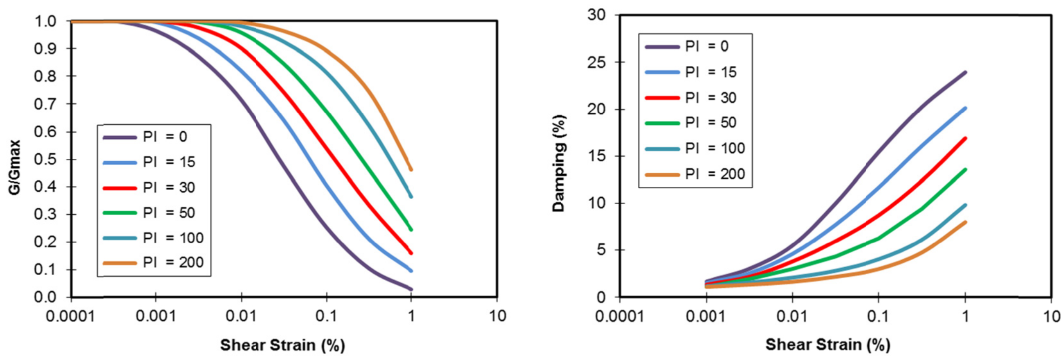

Figure 1 – The Vucetic and Dobry (1991) Modulus Reduction and Damping Curves/

This paper presents the results of in-situ measurements of modulus reduction in a landfill cover. The landfill and its cover soils are representative of numerous landfill sites and engineered fills across southern California and beyond. The corresponding damping curves have been estimated by constitutive modeling and engineering judgement. For soil PI's representative of the given site conditions, the results of measurements are compared to the Vucetic and Dobry (1991) modulus reduction and damping curves. The discrepancy between the subject soils' behavior and that of the published relations is noted and explained, and recommendations for practical applications are made.

IN-SITU MEASUREMENT OF MODULUS REDUCTION

Measurement Technique. The technique for direct (i.e., in-situ) measurement of modulus reduction, as implemented in this study, is presented in Sahadewa (Sahadewa 2014; Sahadewa et al. 2015). Earlier modulus reduction measurement experimental approaches are presented in Stokoe et al. (2006; 2011). Use of this technique for development of modulus reduction curves requires: (i) a relatively powerful source of excitation; (ii) a vertical, embedded instrumentation array; (iii) specialty signal processing equipment; and (iv) specialty reduction of measurement results. The response to excitation is recorded in a form of velocity time history at various depths in the profile. After velocity time histories are numerically integrated to obtain displacement time histories, the 4-node displacement-based method developed by Rathje et al. (2005) is used to calculate the shear strain. Soil stiffness, i.e., strain-dependent shear modulus, G, is calculated at each shear strain increment from the shear wave velocity at that increment and the given unit weight. The shear wave velocity at each shear strain increment is calculated by dividing the vertical spacing between geophones by the associated time intervals between geophones as the waves propagate vertically from the surface towards each of the sensors. The low strain shear modulus (G_{max}) is calculated from unit weight of soil and downhole shear wave velocity measurements that are performed as a part of the nonlinear testing program. The damping curves are developed from modulus reduction curves by means of the nonlinear MKZ constitutive model (Matasovic 1993; Matasovic and Vucetic, 19930 that incorporates Masing rules (Masing 1926).

Site-Specific Measurements. For this study, the required excitation was independently generated by means of two large mobile shakers that are commonly referred to as the Vibroseis shakers (Thumper and T-Rex). These shakers are owned by the University of Texas at Austin (UT) and were operated by the Network for Earthquake Engineering Simulation (NEES) Equipment Site at UT for this project. The excitation was induced by imposing a combination of static (i.e., vertical) and dynamic (horizontal) loads to an array beneath a specially-constructed footing, as shown in Figures 2a and 2b.

Particle velocity was measured during the testing by means of two vertical arrays of three-component geophones placed in an embedded instrumentation array (see Figure 2). Thumper was used for low, ground-pressure tests (up to a vertical load of 36 kN) and T-Rex was used for higher, ground-pressure tests (up to a vertical load of 133 kN). The instrumentation array was set at the top deck of a hazardous waste landfill in southern California. A photo of this array with T-Rex in the background is shown in Figure 2a. A profile through the array, i.e., a schematic of the test setup, is shown in Figure 2b. As shown in Figure 2b, an array installed at the landfill top deck consisted of a 0.91-m-diameter, 0.3-m-thick, reinforced concrete foundation. This foundation was prefabricated and was placed over two vertical arrays of three-component geophones.

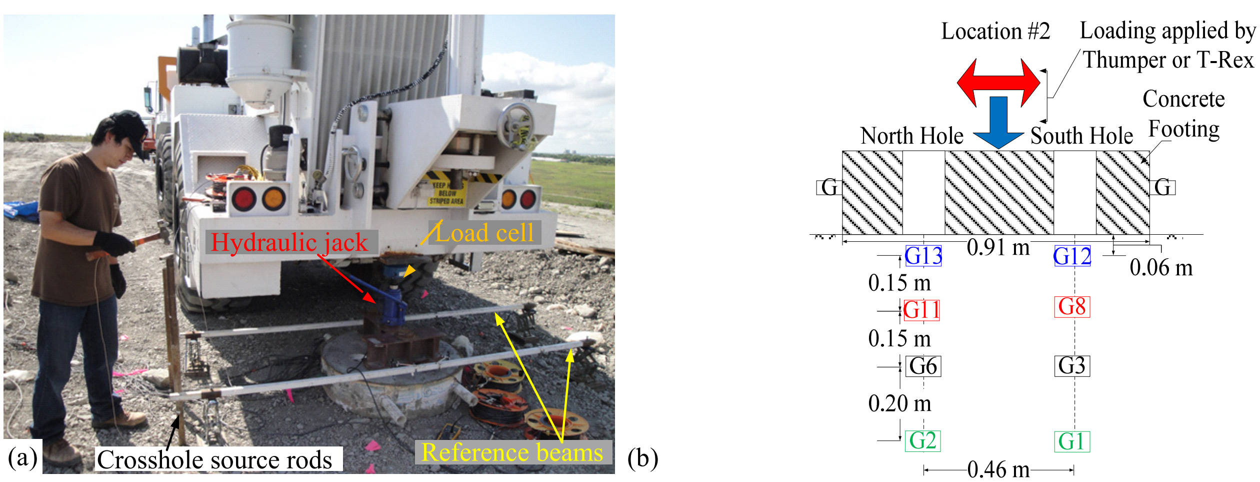

Figure 2. (a) T-Rex applying a Static Load during Small-Strain Crosshole Testing; (b) Cross Section View of Vertical Instrumentation Array (G = Geophone).

The geophones were embedded in the landfill cover soil at four different depths. Upon completion of the testing, pits were excavated at each testing location to recover buried geophones, perform in-situ soil unit weight tests (sand cone), recover bulk soil samples for index testing of soils, and recover relatively “undisturbed” soil samples by thin-walled Shelby tubes for advanced laboratory geotechnical laboratory testing. The advanced laboratory testing consisted of a series of Consolidated Drained (CD) triaxial tests.

Figure 3a shows results from the subject testing combined with other test results available for the given soil cover. These test results reveal that the subject cover soils classify as either CL or ML (Unified Soil Classification System, USCS) with Plasticity Indices (PI) ranging from 19 to 39.

The results of CD triaxial testing indicate that shear strength of these soils can be represented with friction angle of 33 degrees and cohesion of 10 kPa (average of 15 CD tests). The average dry unit weight, average moisture content, and average moist unit weight of cover soils is approximately 14.8 kN/m^3, 20%, and 17.7 kN/m^3, respectively. The average in-situ relative compaction is approximately 92% while, in relative terms, the moisture content is at optimum at the ground surface and increases to 5% above optimum at an approximate depth of 1.5 m.

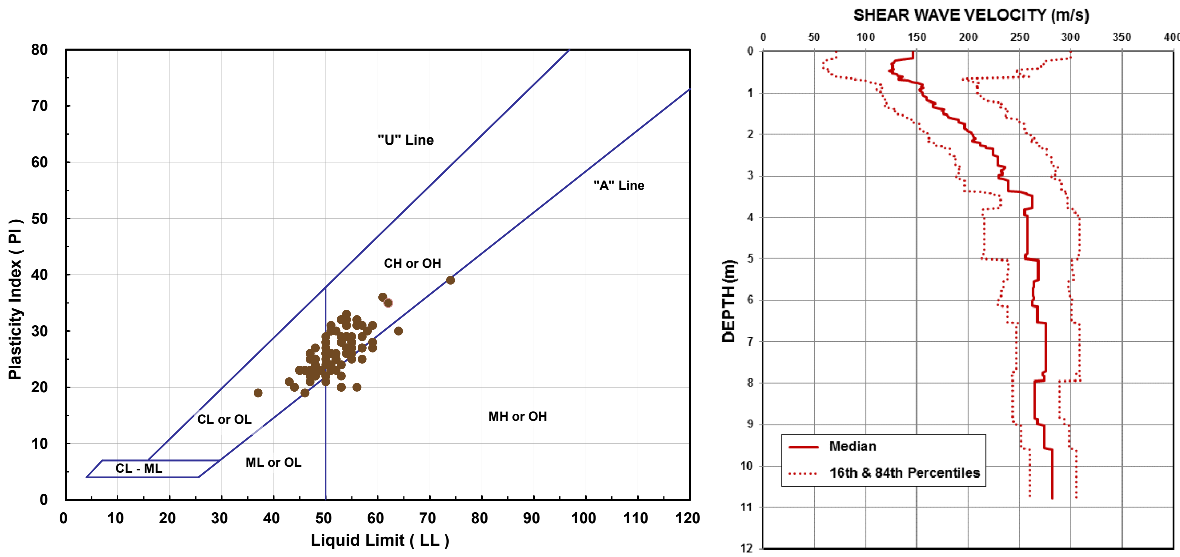

Figure 3. (a) Results of Index Testing of Cover Soils; 3(b) Results of SASW Measurements by University of Texas

The results of Spectral Analysis of Surface Waves (SASW) testing of the cover soils, performed over large area of landfill cover by UT, are shown in Figure 3b. These testing results indicate that, with the exception of a small decrease in the depth range of 0.1 to 0.4 m due to desiccation-related overconsolidation, the average V_s increases with depth. At the ground surface, measured V_s is approximately 150 m/s while at depth of 4 m V_s is approximately 250 m/s.

The modulus reduction curves developed based on the results of nonlinear testing of landfill cover soils that are characterized above (i.e., soils with PI mostly in the range of 19 – 36) are compared to the Vucetic and Dobry modulus reduction curves for PI = 30, 50, and 100 in Figure 4. Although the data collected are for the tested soil material at the top 0.5 m of the cover soil, by increasing the vertical load (static stress) imposed by the Vibroseis prior to dynamic testing, higher confining stresses can be applied. The test overburden pressures of 16, 27, 47, and 83 kPa correspond to the landfill cover thicknesses of 0.9, 1.6, 2.7, and 4.8 m, respectively.

Figure 4 shows a trend of tested modulus reduction curves shifting to a more linear range as confining pressure increases. All of the tested data can be bound with the Vucetic and Dobry (1991) PI = 30 (lower-bound) and PI = 100 (upper-bound) curves. The PI = 50 curve appears to provide a reasonable (i.e., average) representation of all tests data. However, average PI of these data is 27 (PI range of 19 – 39). Furthermore, the Vucetic and Dobry (1991) PI = 30 curve corresponds to the thinnest cover configuration tested herein (1 – 2 m).

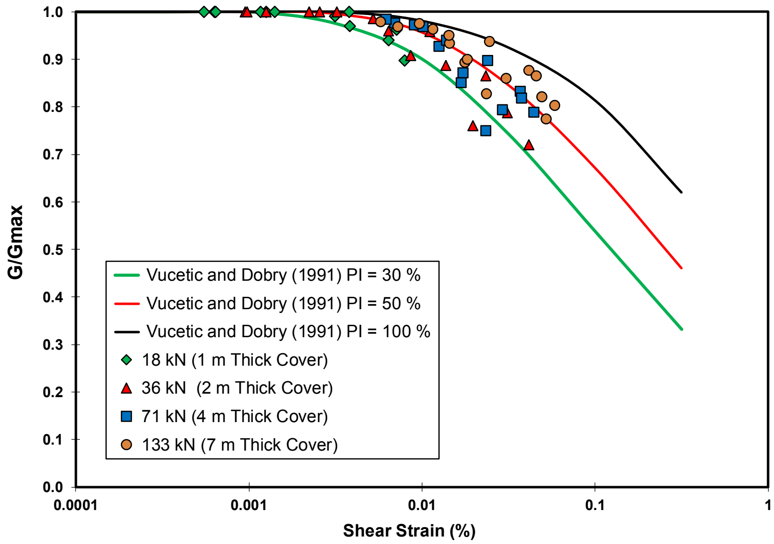

Figure 4. Results of the In-Situ Nonlinear Testing (This Study; PI = 19 – 39) Compared with the Vucetic and Dobry (1991) Curves for PI = 30, 50, and 100.

MODULUS REDUCTION AND DAMPING CURVES OF LANDFILL COVER

As explained above, the Sahadewa et al. (2015) procedure for evaluation of dynamic properties of soils is limited to direct measurement of modulus reduction within an induced range of shear strains. While damping curves cannot be directly measured, they can be estimated based upon engineering judgment and/or calculated from modulus reduction curves by means of constitutive modeling. In this study, we used constitutive modeling to estimate damping curves from measured modulus reduction curves in the low-strain range, and we extended these curves in the large-strain range based upon both constitutive modeling and engineering judgment.

The particular constitutive model employed to estimate damping behavior is the MKZ model (Matasovic 1993; Matasovic and Vucetic, 1993). In its total-stress form, the MKZ model is a modified hyperbolic model that requires only four parameters and allows for accurate fitting of modulus reduction and damping data. The parameters of the MKZ model include G_{max}, reference strain (γ_r), which is defined as a ratio of shear stress and G_{max} at a given shear strain (γ), and curve fitting constants β and s. The Masing (1926) rules are used to define the relationship between the initial loading curve (backbone curve) and cyclic loops. These loops are incorporated in the MKZ model. The same results (i.e., modulus reduction and damping curves) would have been obtained by means of the Darendeli (2001a; 2001b) model. This model is a subset of the MKZ model (the model form, including parameters, is the same, but this model defines the reference strain in a less general manner than the MKZ model, i.e., as a ratio of shear stress and G_{max} at 50% of the shear modulus reduction).

Figure 5 shows our interpretation of the nonlinear test results documented herein in terms of modulus reduction and damping curves for landfill cover soils. As noted above, tested cover soils that served for this interpretation are relatively dense (relative compaction ≈ 92%) and are of relatively low plasticity (PI = 19 – 36). As shown in Figure 5, the lower-bound modulus and upper-bound damping curves correspond to a relatively thin, modern landfill cover (1 – 2.9 m), while the upper-bound modulus and lower-bound damping curves correspond to a relatively thick landfill cover (5 – 7 m) which may be found on some legacy landfill sites.

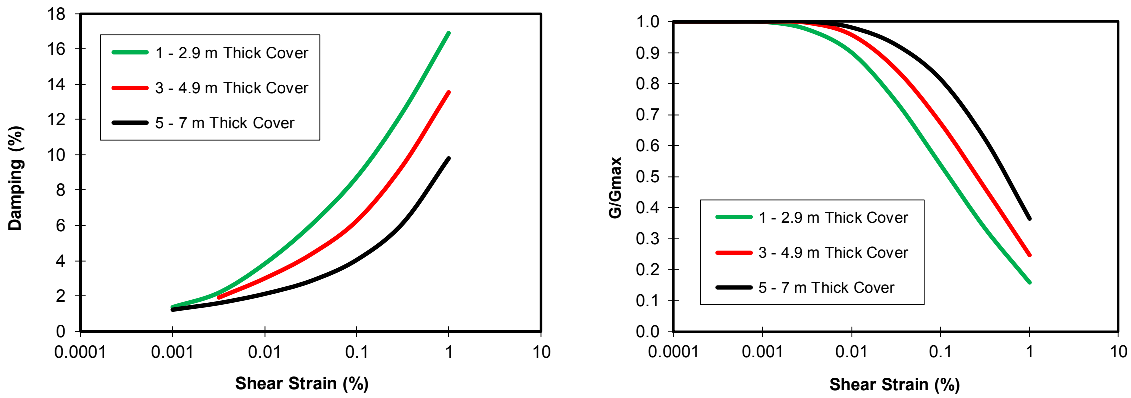

Figure 5. Recommended Modulus Reduction and Damping Curves for Landfill Covers Constructed of Low-Plasticity Soils (PI = 20 – 35; Cover Thickness 1 – 7 m).

SUMMARY, DISCUSSION AND RECOMMENDATIONS

A field experimental program was conducted to investigate the dynamic properties of MSW landfill cover soils in the linear and nonlinear strain range. Crosshole seismic tests at small strains as well as steady-state dynamic testing over a wide shear strain range (0.001% to 0.2%) were conducted at four different static vertical loads. Both vertical and horizontal cyclic loads were induced by means of mobile Vibroseis shakers of NEES@UTexas. An array consisting of two vertical sets of three-component geophones was embedded in the landfill cover and was used to capture the soil response during dynamic testing. Trenching and "undisturbed" sampling was performed to measure in-situ density across the soil profile, and to recover representative soil samples for laboratory testing. The final outcome of the study was in-situ data on the normalized shear modulus reduction as a function of shear strain. The corresponding equivalent viscous damping curve was developed by constitutive modeling and engineering judgment and was further extended by means of constitutive modeling to the strain range required for practical applications.

The results of this study indicate that selection of modulus reduction and damping curves based upon soil plasticity may be un-conservative. This finding is based upon the interpretation of site-specific modulus reduction data shown in Figure 4 that can be approximately represented by the Vucetic and Dobry PI = 50 curve, while the Vucetic and Dobry PI = 30 curve would have been selected based upon the PI range of the tested soils. Depending upon site conditions, including fundamental period of the soil (waste) deposit and characteristics of design ground motions, a larger surface seismic response may be calculated using the Vucetic and Dobry (1991) curves for a higher PI soil.

The observed discrepancy between measured data and published curves as shown in Figure 4 is explained as follows:

1) Landfill covers are typically placed as engineered fills, i.e., in 150-mm thick lifts compacted to 90 to 92 percent of maximum dry density established by the Modified Proctor Compaction Test. Therefore, landfill cover materials are typically denser than soils considered in the Vucetic and Dobry (1991) study. Denser soils are expected to respond in a more nonlinear

manner then their counterparts of the same PI that were deposited (or placed) without compaction; and

2) In arid and semi-arid regions in particular, landfill covers are typically overconsolidated due to desiccation and compaction. Overconsolidated soils are typically stiffer than their normally-consolidated counterparts of the same PI, hence these soils tend to respond in a more linear manner.

Given the findings above, we offer modulus reduction and damping curves shown in Figure 5 for consideration of seismic design of landfills in arid and semi-arid regions where site conditions approach those of cover soils tested in this study.

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REFERENCES

Darendeli, M. (2001a), "Development of a new Family of Normalized Modulus Reduction and Material Damping Curves." *Ph.D. Dissertation*, Dept. of Civil Eng., Univ. of Texas, Austin.

Darendeli, M.B., Stokoe, K.H., II, Rathje, E.M. and Roblee, C.J. (2001b), "Importance of Confining Pressure on Nonlinear Soil Behavior and its Impact on Earthquake Response Predictions of Deep Sites," Proc. *15th International Conference on Soil Mechanics and Geotechnical Engineering*, Istanbul, Turkey.

Kavazanjian, E., Jr., Matasovic, N. and Bachus, R.C. (2013), "11th Peck Lecture: Pre-Design Geotechnical Investigation for the OII Superfund Site Landfill," *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 139, No. 11, 1849-1863.

Masing, G. (1926), "Eigenspannungen und Verfestigung beim Messing." Proc. 2nd International Congress on Applied Mechanics, Zürich, Switzerland, 332 - 335.

Matasovic N. (1993), "Seismic Response of Composite Horizontally-Layered Soil Deposits," *Ph.D. Dissertation*, Civil Engineering Dept., University of California, Los Angeles, 483 p.

Matasovic, N. and Vucetic, M. (1993). "Cyclic Characterization of Liquefiable Sands." *ASCE Journal of Geotechnical Engineering*, Vol. 119, No. 11, 1805-1822.

Rathje, E. M., Chang, W. -J., and Stokoe, K. H. II (2005), "Development of an In Situ Dynamic Liquefaction Test," Geotechnical Testing Journal, Vol. 28, No. 1, 50–60.

Sahadewa, A. (2014). "In-situ Assessment of the Linear and Nonlinear Dynamic Properties of Municipal Solid Waste." A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Civil Engineering) in the University of Michigan.

Sahadewa, A., Zekkos, D., Woods, R. D., Stokoe, K. H. (2015). “Field Testing Method for Evaluating the Small-strain Shear Modulus and Shear Modulus Reduction of Solid Waste.” ASTM Geotechnical Testing Journal, June 2015, 38 (4), 427-441.

Stokoe, K. H., II, Kurtulus, A., and Park, K. (2006), “Development of Field Methods to Evaluate Nonlinear Shear and Compression Moduli of Soil. Proceedings of New Zealand Earthquake,” Geotechnical Engineering Workshop, Canterbury 2006. Christchurch, New Zealand, 56-70.

Stokoe, K. H., II, Zalachoris, G., Cox, B., and Park, K. (2011), “Field Evaluations of the Effects of Stress State, Strain Amplitude and Pore Pressure Generation on Shear Moduli of Geotechnical and MSW Materials,” *International Symposium on Deformation Characteristics of Geomaterials*, Seoul, South Korea.

Vucetic, M. and Dobry, R. (1991), “Effect of Soil Plasticity on Cyclic Response.” *Journal of the Geotechnical Engineering*, ASCE, Vol. 117, No. 1, 89-107.

Zekkos, D. P., Bray, J. D., Kavazanjian, E., Matasovic, N., Rathje, E., Riemer, M., and Stokoe, K. H., II. (2006), “Unit Weight of Municipal Solid Waste,” *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 10, 1250-1261.

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