In Situ Assessment of the Nonlinear Shear Modulus of Municipal Solid Waste

Évaluation in situ du module non linéaire de cisaillement des déchets solides municipaux

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ABSTRACT: Assessment of dynamic properties of Municipal Solid Waste (MSW) is required for seismic response analyses of existing MSW landfills in areas of moderate to high seismicity. While material properties such as shear wave velocity and unit weight can be readily measured, assessment of nonlinear dynamic properties of MSW has, to date, been restricted to specialty laboratory testing of reconstituted MSW specimens and back analysis of recorded earthquake response. Both approaches have limitations. In this paper, the results of direct in-situ measurements of both small-strain shear modulus and the nonlinear shear modulus reduction relationship are presented. The measurements were performed at a landfill in Austin, Texas, using two mobile vibroseis shakers. In situ tests were performed at two locations. The vertical static load imposed by the vibroseis was varied to evaluate the effect of vertical stress on the dynamic properties of the MSW. Dynamic testing was performed at increasing horizontal loads inducing small to large strains in the MSW. Shear strains ranging from 0.0002% to 0.2% were induced by the shakers allowing the development of in situ shear modulus reduction curves over a large strain range. The effect of waste composition was also assessed in situ.

RÉSUMÉ : L'Évaluation des propriétés dynamiques des déchets solides municipaux (MSW) est nécessaire pour les analyses de réponse sismique des décharges de DSM existants dans les zones de sismicité modérée à élevée. Bien que les propriétés matérielles telles que la vitesse des ondes de cisaillement et poids unitaire peut être facilement mesurée, l'évaluation des propriétés dynamiques non linéaires de DSM a, à ce jour, été limitée à des tests de laboratoire spécialisés de spécimens reconstitués de DSM et de l'analyse inverse de la réponse au tremblement de terre enregistré. Les deux approches ont leurs limites. Dans cet article, les résultats des mesures directes in situ de deux modules de cisaillement a faible contrainte et la relation non linéaire de la reduction du module de cisaillement sont présentés. Les mesures ont été effectuées dans une décharge à Austin, au Texas, utilisant deux gros camions secoueurs vibrosismiques. Les essais in situ ont été effectuées à deux endroits. La charge verticale statique imposée par les camions secoueur a été modifiée afin d'évaluer l'effet de la contrainte verticale sur les propriétés dynamiques de la DSM. Des essais dynamiques ont été réalisés tout en augmantant les charges horizontales qui ont cree des deformations variant entre des petites et des grandes déformations dans le DSM. Des déformations de cisaillement allant de 0,0002% à 0,2% ont été induites par les camions secoueurs permettant le développement de courbes du module de cisaillement in situ et de sa reduction sur une plage de grandes déformations. L'effet de la composition des déchets a également été évaluée in situ.

KEYWORDS: in situ testing, shear modulus, nonlinear dynamic properties, municipal solid waste, landfills

1 INTRODUCTION

Assessment of the dynamic properties of Municipal Solid Waste (MSW) is required for seismic response analyses of MSW landfills in areas of moderate to high seismicity. Dynamic properties in the linear range include shear wave velocity (V_s), the associated small-strain shear modulus ($G_{\max}$) and small-strain material damping in shear ($\lambda_{\min}$). The dynamic properties in the nonlinear range include the (normalized) shear modulus reduction and material damping increase curves. The total mass density of MSW is also an important property in these analyses.

Historically, two approaches have been used to evaluate the nonlinear dynamic properties of MSW: (1) analytical studies that are based on back-calculation of the response of instrumented landfills (e.g., Augello et al. 1998, Matasovic and Kavazanjian 1998, Elgamal et al. 2004) and (2) large-scale laboratory testing of MSW (e.g., Matasovic et al., 1998, Lee 2007, Zekkos et al. 2008, Yuan et al. 2011).

Field measurements of small-strain properties have been restricted to direct measurements of V_s (e.g., Kavazanjian et al. 1996, Matasovic and Kavazanjian, 1998, Sahadewa et al. 2011) and mass density (e.g., Matasovic and Kavazanjian, 1998, Zekkos et al. 2006). This contribution outlines a MSW field testing program that was implemented to directly assess the shear modulus reduction curve of MSW.

2 METHODOLOGY

Field testing was performed at the Austin Community Landfill, in Austin, Texas, U.S.A, following the basic methodology proposed by Stokoe et al. (2006) and the field testing approach proposed by Stokoe et al. (2011). The testing was performed at two representative locations. Shear wave velocity profiling using the Spectral Analysis of Surface Waves (SASW) method was performed first at each location. Two vertical arrays of three-component geophones were then embedded in the waste at four different depths up to a maximum depth of about 1 m. The depth of the sensors was varied at the two locations. A 0.91-m diameter, 0.3-m thick, unreinforced, prefabricated concrete foundation was placed on top of the sensors. Source rods for crosshole seismic testing were placed at a distance of 1.14 m from the first array as shown in Fig. 1. Downhole seismic testing was also performed by striking the side (for shear, S) and top (for compression, P) of the footing and recording arrivals of S and P waves, respectively, at the geophone arrays. Then two mobile vibroseis shakers, Thumper and T-Rex, shown in Fig.2, owned and operated by the George E. Brown, Jr. Network for Earthquake Engineering Simulation at University of Texas (NEES@UT), were used to excite the footing. Thumper was used for the low ground pressure tests and T-Rex was used for higher ground pressure tests.

The mobile shakers were first used to apply a static vertical load increment on the foundation. The foundation settlement during static load application was measured from spanning beams. The vertical load was varied, allowing for an in situ assessment of the effect of vertical stress in the MSW. The sequence of applied vertical loads is shown in Fig. 3. At each vertical load increment, small-strain crosshole and downhole seismic testing was performed. Then, a 30-50 Hz sinusoidal horizontal load at increasing load amplitudes was applied by the mobile shakers and the ground motion was captured by the geophones embedded in the waste. Upon completion of testing, the waste was excavated and in situ unit weight tests were performed as described in Zekkos et al. (2006).

3 DATA INTERPRETATION

The waves generated during cyclic loading by the mobile shakers propagated downwards and were sensed by three-component geophones in each vertical array. Examples of dynamic loading time histories in the horizontal and vertical directions of shaking are shown in Figs. 4a and 4b, repectively. Shear wave velocity was calculated using the travel time of the waves that propagate from the shallower to the deeper sensors. The equivalent shear modulus was calculated using the in-situ measured MSW unit weight. To assess the shearing strain amplitude, the three-component displacement time history was calculated by integrating the recorded velocity time history. A 4-node element was used by selecting pairs of geophones at two different depths (Chang 2002) and the shearing strain time history was then calculated for the element, as shown in Fig. 5. Use of a 2-node approach (one sensor at each depth) or ignoring the vertical displacement component (shown in Fig. 4b) in calculating the shearing strain was found to underestimate the shearing strain.

At each vertical load increment, vertical and horizontal stress distributions were calculated using Foster and Ahvlin (1954). By varying the dynamic load from low to high amplitudes, the shear modulus reduction was evaluated. The effect of confining stress on the shear modulus reduction was evaluated by varying the vertical load increment. Different pairs of geophones were selected to define a 4-node element, as shown in Fig. 6, to allow an in-situ assessment of MSW variability.

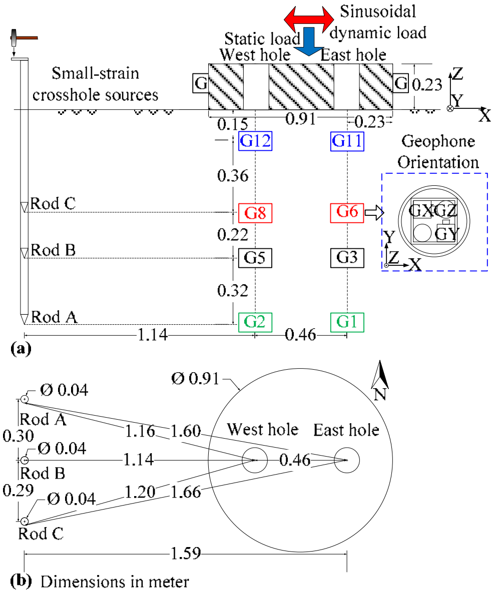


Figure 1: Schematic of the testing setup at location #1: (a) cross-section; (b) plan view.

Figure 2: Photographs of large mobile shakers used to apply static and dynamic loads to the MSW: (a) Thumper and (b) T-Rex.

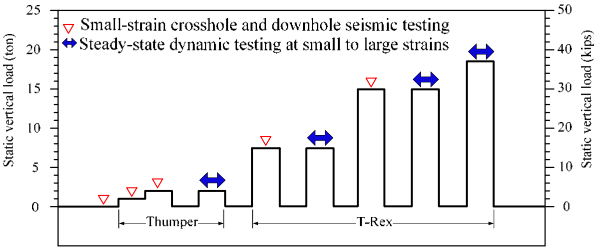


Figure 3. Sequence of static loading and dynamic testing at location #1

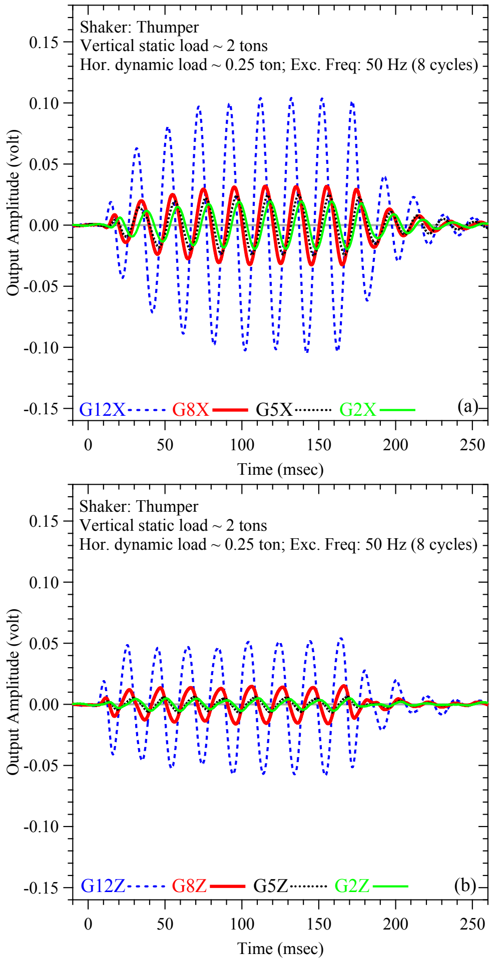


Figure 4. Time-history records from the four geophones (G2, G5, G8, G12) in one vertical array: (a) X axis (horizontal shaking direction) and (b) Z axis (vertical shaking direction).

4 RESULTS

The effect of confining stress on the shear modulus and the normalized shear modulus as a function of shear strain are shown in Fig. 7a and 7b, respectively. The impact of waste composition is eliminated by examining the same set of four geophones. Example results are shown for element A, i.e., the set of geophones nearest to the foundation. As shown in Fig. 7a, $G_{\max}$ increases from 23 MPa to 31 MPa, as average confining stress increases from 14 kPa to 89 kPa. In addition, the $G/G_{\max}$ curve (Fig. 7b) systematically moves to the right, i.e., exhibits a more linear response with increasing confining stress. These trends are consistent with laboratory studies on MSW (Lee 2007, Zekkos et al. 2008, Yuan et al. 2011).

The estimated shear modulus reduction and normalized shear modulus reduction as a function of strain for different sets of geophones (i.e., elements) are shown in Fig. 8. Data shown in Fig. 8 are representative of essentially the same confining stress (11-14 kPa). Elements A, D and F are representative of waste at different depths. Element A considers the four geophones closest to the surface, element D considers the four intermediate geophones and element F considers the four deepest geophones. Significant differences in shear modulus are observed in Fig. 8a and can be attributed to waste variability. The small-strain shear modulus ($G_{\max}$) is on the order of 22 to 27 MPa for elements A and D, but is almost twice of that (~45 MPa) for element F. The variability in waste composition is also demonstrated by the range of normalized shear modulus curves in Fig. 8b. The remaining elements shown in Fig. 8 represent larger elements, with element C being representative of the waste mass that is encompassed by the shallowest and deepest geophones. Thus, element C represents the "averaged" response of the waste mass. Thus, it is not surprising that the value of the estimated shear modulus for this element is intermediate (~30 MPa). The normalized shear modulus reduction curve for element C appears to fall generally on the right side of the range of the data, indicating a generally more linear response.

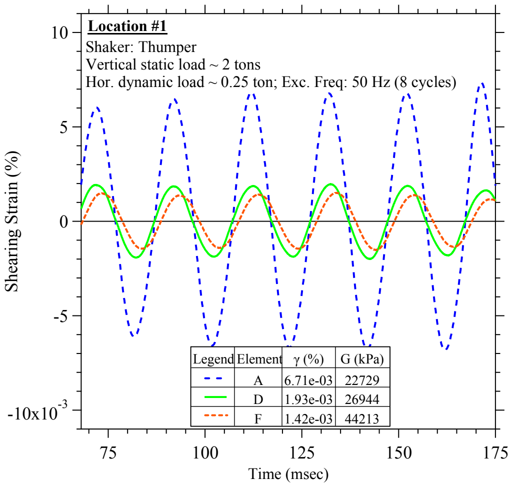
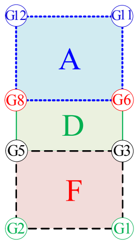


Figure 5. Example shearing strain histories based on 4-node displacement method for the three elements shown in Figure 6.



Element	Geophones/ Nodes
A	G6, G8, G12, G11
B	G3, G5, G12, G11
C	G1, G2, G12, G11
D	G3, G5, G8, G6
E	G1, G2, G8, G6
F	G1, G2, G5, G3

Figure 6. 4-node elements investigated for different sets of geophones.

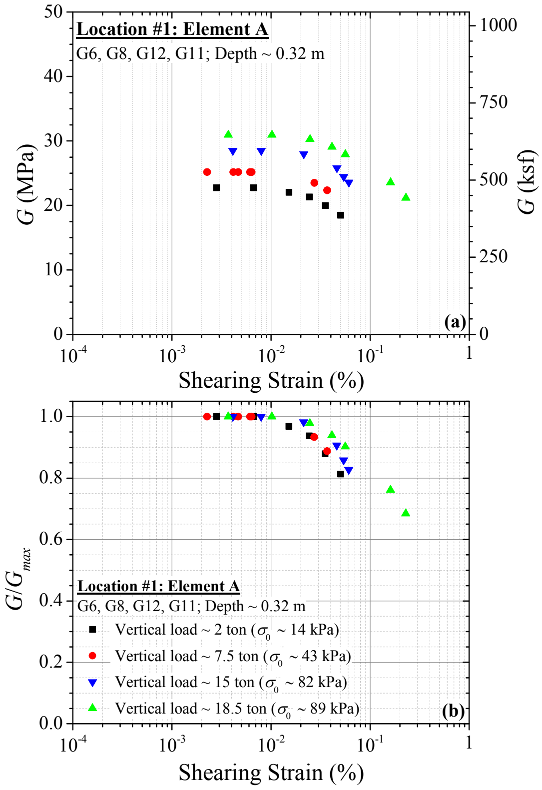


Figure 7. G - log γ and $G/G_{\max}$ - log γ relationships from element A at location #1 at four different confining stresses.

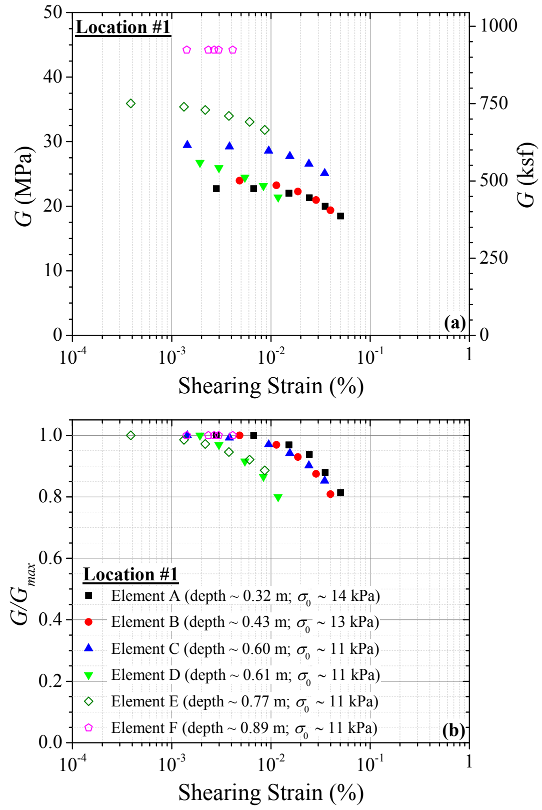


Figure 8. Differences in G - log γ and $G/G_{\max}$ - log γ relationships attributed to different waste composition.

The entire dataset from location #1 is shown in Fig. 9, and exhibits more variability than shown earlier because it includes variations of both waste composition and, to a lesser effect, confining stress. Shear modulus was evaluated for shearing strains ranging from 0.0002% up to 0.2%. Datasets from locations #1 and #2 are shown in Fig. 10 with open black squares and open red circles, respectively. The normalized shear modulus reduction curves are generally consistent, although shear modulus reduction appears to be more pronounced at larger strains for location #2 compared to location #1, which is likely attributed to variability in waste composition.

The field experiment data can be compared to the Zekkos et al. (2008) laboratory-based recommended curves at low confining stresses for variable waste composition. The field data are generally consistent with the laboratory based curves, shown as lines in Fig. 10. Field data for location #1 are consistent with the Zekkos et al. (2008) curves for waste-rich MSW specimens. The $G/G_{\max}$ data from location #2 are generally consistent with these curves for strains up to 0.05%, but at larger strains shear modulus appears to drop off more sharply than recommended by Zekkos et al. (2008).

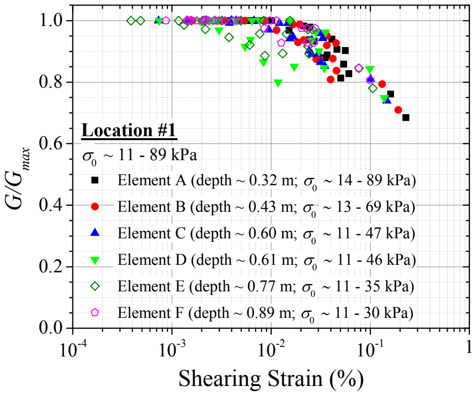


Figure 9. $G/G_{\max}$ - log γ relationships in location #1.

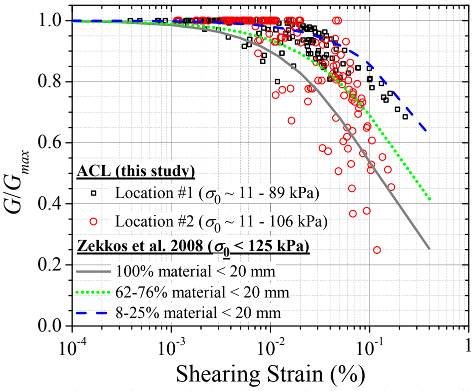


Figure 10. $G/G_{\max}$ - log γ relationships estimated at locations #1 & #2.

5 CONCLUSIONS

In situ data on shear modulus and the normalized shear modulus reduction as a function of shear strain have been generated at a Municipal Solid Waste landfill in Austin, Texas using mobile vibroseis shakers that are operated and maintained by NEES@UT. The methodology described in this paper can be used to evaluate nonlinear properties of MSW in situ over a wide shear strain range (0.0002% to 0.2%).

The impact of waste variability and confining stress on the shear modulus was also assessed in situ. Shear modulus was found to increase with increasing confining stress and to be substantially affected by waste composition. The normalized shear modulus reduction curves were also affected by waste composition and, to a lesser extent, confining stress. The normalized shear modulus also becomes systematically more linear as confining stress increased, similarly to soils.

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