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Influence of Lightweight Deflectometer Characteristics on Deflection Measurement

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ABSTRACT: The lightweight deflectometer (LWD) is currently not standardized; as a result, there are a number of commercially available LWD designs that yield different deflection and elastic modulus values. This proves problematic because transportation agencies are beginning to prescribe target deflections and/or elastic modulus values during earthwork construction. This paper presents the results of a comprehensive investigation into the influence of LWD design characteristics on measured deflection. The influence of the sensor type (accelerometer versus geophone), sensing configuration (measurement of plate versus ground surface), LWD rigidity, and applied load pulse were investigated through field testing and finite element analysis. The investigation revealed that the sensing configuration (i.e., the measurement of plate versus ground surface response) is the predominant cause of differences between the Zorn and Prima LWD responses (deflection normalized by peak force). Vertical plate deflection exceeded ground surface deflection by 65 % to 310 % on soils and by 20 % on asphalt. The relative influences of the sensor type (accelerometer versus geophone), plate rigidity, and load pulse each led to relatively small differences (<10 %) between Zorn and Prima LWD responses. The results of this investigation illustrate that each of the two LWD configurations will always produce different deflection and elastic modulus values for the same ground conditions, and that the differences will be difficult to predict.

KEYWORDS: lightweight deflectometer, compaction quality assurance, elastic modulus

Introduction

The lightweight deflectometer (LWD), a device that measures the vertical deformation imparted by a falling mass impacting a plate resting on the ground (Fig. 1), has been used for more than two decades as a quality control/quality assurance (QC/QA) device for earthwork construction (e.g., Fleming et al. 2009; Siekmeier et al. 2009; Vennapusa and White 2009; Mooney and Miller 2009). The device is specifically used in the QC/QA of earthwork and, more recently, asphalt compaction. In the United States, the results of LWD testing, namely, soil deflection or estimated dynamic soil modulus (from Boussinesq analysis of plate loading on an elastic half-space), have been employed in a relative and qualitative sense because acceptance criteria have continued to be based upon dry density and moisture content. More recently, researchers (Steinert et al. 2005; Fleming et al. 1998) and transportation agencies, both in the United States (Kremer and Dai 2004) and internationally, have begun to specify magnitudes of target elastic modulus or deflection values (e.g., Minnesota, Austria, and Sweden). This is an attempt to implement performance-based assessments of designed-for properties such as the resilient modulus.

The move toward specifying magnitudes of deflection and/or modulus suggests a need for standardization. Because there are a number of commercially available LWD models, including the two pictured in Fig. 1, alternative ASTM standards were developed, namely, ASTM E2835-11 and ASTM E2583-07. It has been documented that different LWD designs provide different

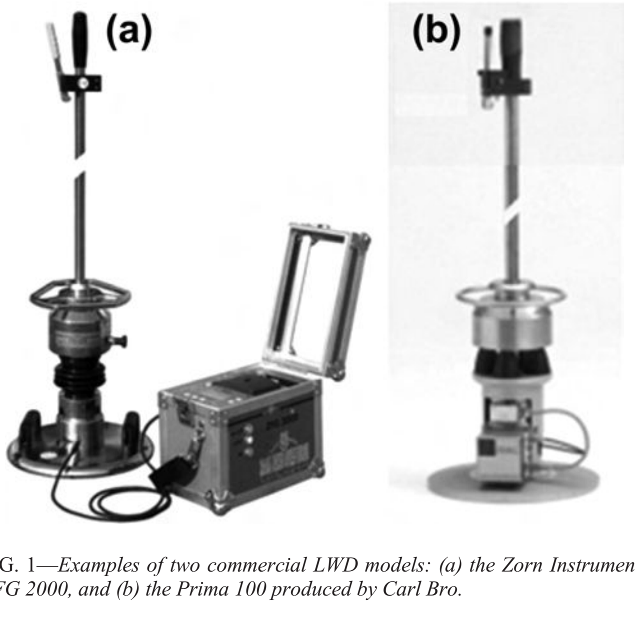

FIG. 1—*Examples of two commercial LWD models: (a) the Zorn Instruments ZFG 2000, and (b) the Prima 100 produced by Carl Bro.*

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measurements of the deflection and estimated modulus for the same soil (Vennapusa and White 2009; Hildebrand 2003; Thom and Fleming 2002; Fleming et al. 2002). These two standards acknowledge the differing results produced by the two devices and identify several major differences in LWD design and operation.

Some researchers have speculated as to the causes of these differing results (Fleming et al. 2002). However, a systematic investigation of the nature of the differences in measured LWD deflection and calculated modulus values has not been published. Such an investigation is critical for the future of the LWD, potential standardization of the LWD, and the proliferation of LWD-based deflection and modulus criteria tied to performance.

This paper presents the results of a comprehensive investigation into the influence of LWD design characteristics on measured deflection and, by inference, estimated dynamic modulus values. The investigation focused on the two LWD designs that are representative of ASTM E2835-11 and ASTM E2583-07. A variety of modifications were made to each LWD design to enable a thorough investigation of the influences of the deflection sensor type (accelerometer versus geophone), sensing configuration (plate response versus ground response), plate rigidity, and nature of the applied load on the measured deflection.

LWD Background

For all LWD tests, a dynamic load is imparted via a drop mass to a plate resting on the ground. A buffer is used to decrease the rise time of the applied loading in order to better match that of vehicle traffic. The measured peak deflection may be employed either directly as a measure of a soil's stiffness or degree of compaction or together with the peak force in the calculation of an estimated dynamic modulus E_{LWD} or E_{vd} of the soil (E_{LWD} is used here). The estimation of E_{LWD} is based on the well-known Boussinesq solution relating the static deflection of an elastic half-space subjected to an axisymmetric surface loading as given by Eq 1, in which A is a stress distribution factor, ν is Poisson's ratio of the soil, w_0 is the peak vertical deflection, F_{pk} is the peak applied load, and r_0 is the radius of the load plate.

$$E_{\mathrm{LWD}} = \frac{A(1-\nu^2)F_{\mathrm{pk}}}{\pi r_0 w_0} \tag{1}$$

The two LWDs used in this study were the Zorn ZFG 2000 and the Prima 100 (Fig. 1). These LWDs represent the two main LWD design philosophies for which ASTM specifications have specifically been developed. The fundamental differences between these LWD designs are illustrated in Fig. 2. The impact force imparted by the drop mass is buffered by elastomeric pads on the Prima LWD and by steel disk springs on the Zorn LWD. The applied force is measured by a load cell on the Prima LWD and reaches levels of approximately 10 kN, and the Zorn LWD assumes a constant applied load of 7.07 kN regardless of ground conditions (i.e., no load cell is used). The accuracy of this assumption is beyond the scope of this paper but is well addressed by Adam et al. (2004).

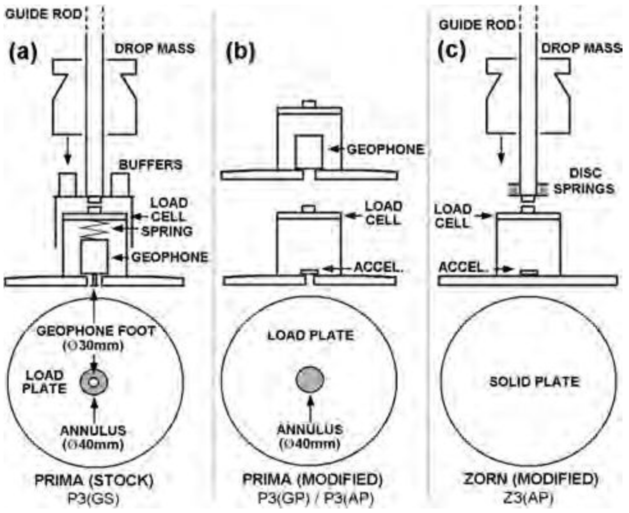

FIG. 2—*(a) Stock Prima 100 LWD, (b) modified configurations of Prima LWD with geophone (top) or accelerometer (bottom) fixed rigidly to the load plate, and (c) Zorn LWD showing modification to include load cell.*

The Prima LWD estimates vertical surface deflection using a geophone in direct contact with the ground through a 40 mm diameter annulus in the plate. The Zorn LWD estimates vertical surface deflection using an accelerometer directly mounted on the solid plate (no annulus). Additionally, the Zorn load plate is more rigid than that of the Prima. The 300 mm diameter Zorn load plate is a solid 19 mm thick disc of steel (the 200 mm version is 40 mm thick), whereas the Prima load plate is a 20 mm thick aluminum plate that tapers slightly to 15 mm in thickness at the edge. The masses of the Zorn and Prima load plates are 13.9 kg and 5.9 kg, respectively.

Data processing differs for each device. Zorn software numerically integrates accelerometer data twice using a trapezoid method to estimate deflection. The time step (0.05 ms) is the inverse of the 20 kHz sampling frequency. The accelerometer used for deflection measurement is a Measurement Specialties 4000A MEMS accelerometer with a nominal sensitivity of 20 mV/g and a natural frequency of 6 kHz (Measurement Specialties 2010). When used in LWD applications, the sensor has a signal-to-noise ratio of approximately 38 dB. A 200 Hz low pass filter is applied to the accelerometer data prior to integration. Prima software low pass filters the raw geophone data (cutoff frequency of 700 Hz) and applies a frequency domain correction for dynamic measurement error introduced by the geophone (Stamp 2012). The velocity is then integrated to displacement using the trapezoid rule with a time step (0.2 ms) equal to the inverse of the 5 kHz sampling frequency. The Prima LWD uses a Sensor Nederland SM-6 geophone with a nominal sensitivity of 27 V/m/s and a natural frequency of 4.8 Hz, giving it a signal-to-noise ratio of approximately 64 dB in LWD applications (SENSOR Nederland bv 2003). Finally, the software in each LWD uses default values for the stress distribution factor A and Poisson's ratio used to estimate E_{LWD}. Zorn software assumes $A = \pi/2$, implying an inverse parabolic plate–ground contact stress distribution (and rigid load plate), and $\nu = 0.212$ for the soil (Matthias Weingart, private communication, March 25, 2011). These cannot be adjusted by the user. Prima software defaults to $A = 2$, implying a uniform plate–-ground contact stress distribution (and flexible plate), and $\nu = 0.50$, but allows the user to adjust these values for specific soil types.

ASTM E2835-11 and ASTM E2583-07 prescribe LWD features directly in line with the aforementioned properties of the Zorn and Prima, respectively, and LWD models similar to these (e.g., the Dynatest LWD is similar in design to the Prima). ASTM E2835-11, developed for the Zorn and similar LWDs, specifies the measurement of LWD load plate deflection (as opposed to soil surface deflection) requires that the "load plate shall be rigid" and allows for parabolic, inverse parabolic, or uniform stress distributions. ASTM E2835-11 does not require the use of a load cell, but it spells out strict procedures for calibration of the applied load. ASTM E2583-07, developed for the Prima and Dynatest LWDs, specifies that deflection should be measured on the ground surface through an annulus at the center of the load plate. ASTM E2583-07 specifies that a load cell is required and states that the load plate shall be "capable of an approximately uniform distribution of the impulse load on the [ground] surface." Neither standard specifies the type of deflection sensor (i.e., accelerometer or geophone); however, ASTM E2835-11 has a much lower tolerance for deflection measurement precision (± 40 μm, versus ± 2 μm in ASTM E2583-07). Both standards acknowledge the difference in calculated modulus that results from using a device in compliance with the other standard.

Lightweight Deflectometer Modifications

To investigate the influence of LWD design characteristics on response, Prima and Zorn LWDs were modified as follows, and as shown in Fig. 2. The Zorn LWD was modified to include a load cell as indicated in Fig. 2(*c*). The introduction of the load cell did not influence the Zorn LWD test. The Prima was outfitted with a geophone and accelerometer to measure the velocity and acceleration of the load plate, respectively (see Fig. 2(*b*)), in addition to the standard geophone-based ground velocity measurement (see Fig. 2(*a*)).

For clarity, each LWD configuration is identified by a four-letter code: (1) LWD model: P for Prima and Z for Zorn; (2) load plate diameter: 2 for 200 mm and 3 for 300 mm; (3) sensor type: G for geophone or A for accelerometer; and (4) sensing configuration: S for contact with the soil/ground or P for plate contact. For example, P3(GS) denotes the standard (stock) Prima LWD with its 300 mm diameter plate and geophone in contact with the soil surface. The modified Prima configurations are designated as P3(GP) and P3(AP), indicating that the accelerometer or geophone was mounted rigidly on the load plate, respectively, rather than in contact with the soil, as shown in Fig. 2. For all Prima configurations, the stock Prima load plate with a 40 mm annulus in the center was used. The same accelerometer and geophone were used for all configurations. For each LWD, data from the on-board sensors were collected by an IOtech DAQ-book and laptop computer. Processing of the data was implemented to replicate each manufacturer's system (i.e., filtering, dynamic measurement error correction, and integration schemes). The geophone data were corrected for dynamic measurement error in the frequency domain; see Stamp (2012) for details. The measured deflection and E_{LWD} from the modified LWDs were validated against the results produced by standard Prima and Zorn LWDs with the manufacturer's data acquisition and processing.

Testing Scheme

LWD testing was performed on 14 test beds at five test sites comprising granular subbase, granular base, lime-stabilized clay subgrade, and asphalt at two construction sites in Colorado. Testing was conducted at each site at different milestones during construction, as the lime-stabilized clay cured and as the layered road structure was built up. Table 1 summarizes the material characteristics of the surface layer of each test bed at each site and lists the LWD configurations used on each test bed. Each test site number indicates a unique spatial area; itemized lines for each test bed reflect different layering or curing time stages. For example, test beds 1–4 at test site 1 involved LWD testing in the same spatial area as each of the four layers was constructed. In this regard, it is important to recall that LWD test results reflect the material response to a depth equal to one to two times the plate diameter. Therefore, many of the test results (e.g., those for granular base and asphalt) convey the coupled response of surface and underlying layers.

Each test bed was established as a reasonably sized sampling area that had a consistent depositional and construction history (i.e., layer thickness, moisture conditioning, compaction passes). Multiple LWD test locations were laid out within each test bed to capture the inherent variability observed in field stiffness measurements via LWD. Several LWD configurations were performed at each test point for direct comparison. Per ASTM standards, the testing at each point involved three seating drops followed by three test drops; results from the three test drops were averaged into a single data record for each point. Significant care was taken to seat the LWD load plates in accordance with the standards.

Influence of Lightweight Deflectometer Configuration

Within each test bed described above, LWD testing was performed at the same set of spatial locations using the different sensing configurations. With a focus on measured quantities rather than computed E_{LWD} values, Fig. 3(*a*) presents the peak deflection normalized by the peak force (w_0/F_{pk}), that is, compliance, measured by the standard Z3(AP) and P3(GS) configurations for an array of locations on four typical test beds. Normalization by force is required because the Prima LWD delivers 20 % to 30 % higher peak forces than the Zorn. It is clear from Fig. 3(*a*) that the deflection measured by the standard Zorn configuration on soil surfaces is consistently greater (50 % to 100 %) than the deflection measured by the standard Prima configuration. The difference is less significant on asphalt. The higher normalized deflections from the Zorn LWD produce lower estimated E_{LWD} values than the Prima,

TABLE 1—*Summary of properties for each test bed.*

Test Bed	Test Site	Number of Points	Surface Material	Thickness, cm	AASHTO/Unified Soil Classification System	Dry Density, kg/m^3	Moisture, %	LWD Configurations Used			
								Z3(AP)	P3(GS)	P3(GP)	P3(AP)
1	1	19	Granular subbase	Variable	A-1-b/GM	2130	8.9[a]	X	X		
2	1	40	Granular base	17[b]	A-1-a/GW	2194	6.0[a]	X	X	X	X
3	1	40	Asphalt 1	4[a]	.	2290	.	X	X		
4	1	40	Asphalt 2	4[a]	.	2290	.	X	X		
5	2	9	Granular subbase	Variable	A-1-b/GM	2156	6.2[a]	X	X		
6	2	12	Granular base	12[b]	A-1-a/GW	2194	6.0[a]	X	X	X	X
7	2	10	Asphalt 2	8[a]	.	2178	.	X	X	X	X
8, 9, 10[c]	3	8	Stabilized clay subgrade (5.0 % QL[d])	31[a]	A-7-6/CL	1810	17.9[a]	X	X	X	X[e]
11, 12[c]	4	12	Stabilized clay subgrade (5.5 % QL,[d] 3 % cement[f])	31[a]	A-7-6/CH	1778	19.2[a]	X[g]	X[h]	X[h]	
13, 14[c]	5	22	Stabilized clay subgrade (5.5 % QL,[d] 3 % cement[f])	31[a]	A-7-6/CL	1826	15.7[a]	X	X	X	X

[a] Nominal design value, not actual measurement.

[b] Survey measurements.

[c] Test bed 8 = cure day 2, test bed 9 = cure day 4, test bed 10 = cure day 8, test bed 11 = cure day 3, test bed 12 = cure day 5, test bed 13 = cure day 2, test bed 14 = cure day 7.

[d] QL, quick lime. QL was added to soil in two mixings: 2.5 % QL mixed with soil, then 48 h mellow; and 2.5 % or 3 % QL mixed with soil, then additional 48 h mellow.

[e] Cure days 2 and 8 only.

[f] Dry cement added the day of compaction prior to remixing.

[g] Cure day 5 only.

[h] Cure day 3 only.

consistent with E_{LWD} trends shown by many researchers (e.g., Vennapusa and White 2009; Hildebrand 2003; Thom and Fleming 2002; Fleming et al. 2002; Fleming et al. 2000).

The deflection results in Fig. 3(*a*) exhibit considerable scatter despite the fact that test beds were identified as areas that experienced spatially consistent treatment (e.g., layer thickness, moisture conditioning, compaction effort). The observed variability is consistent with that reported in the literature for LWD testing (Fleming et al. 2009; Mooney et al. 2008; Abu-Farsakh et al. 2004; Hossain and Apeagyei 2010). In light of the observed scatter, results and conclusions are hereinafter presented and drawn based on statistical means and variances. The means and standard deviations of normalized deflections from each test bed are presented in Fig. 3(*b*). These data convey the difference in normalized deflection (compliance) as measured by the Zorn and Prima LWDs. The magnitude of the difference is generally similar across the three surface soil types and considerably less on asphalt. This is discussed later in the paper.

The ratio of normalized deflections from Z3(AP) to P3(GS) helps to quantify the difference between the standard Zorn and Prima LWD results. The mean (μ), single point standard deviation (s), and standard deviation of the mean (s_{μ}) of these ratios are

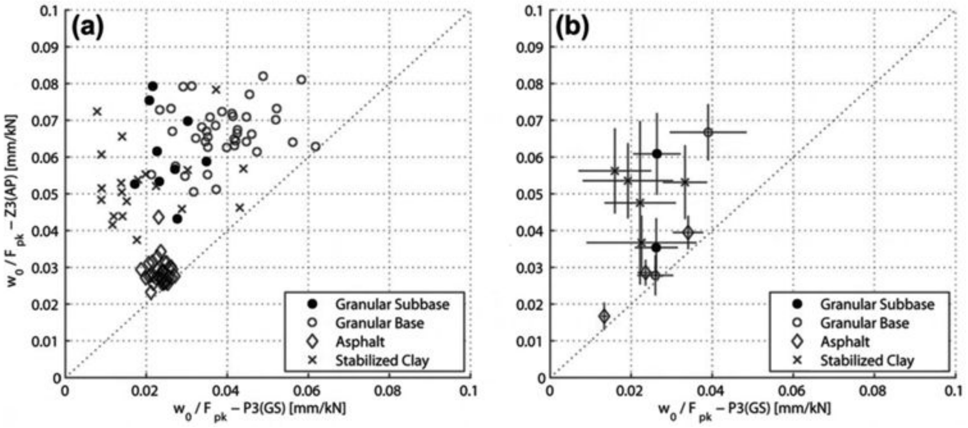

FIG. 3—*(a) Comparison of w_0/F_{pk} from standard LWD configurations Z3(AP) and P3(GS) on four typical test beds. (b) Comparison of w_0/F_{pk} from standard LWD configurations Z3(AP) and P3(GS) on all test beds. Data points reflect mean values, and scatter bars reflect standard deviation.*

TABLE 2—*Mean, standard deviation, and standard deviation of the mean for the ratio of normalized deflection from LWD configurations listed on the left compared to those from configurations listed at the top.*

		P3(GS)			Z3(AP)			P3(GP)		
Compared to:		μ	s	s_μ	μ	s	s_μ	μ	s	s_μ
Z3(AP)	Granular subbase	1.76	0.75	0.33				.	.	.
	Granular base	1.64	0.52	0.23				0.82	0.26	0.17
	Asphalt	1.20	0.20	0.13				0.88	0.13	0.28
	Stabilized clay	3.12	1.87	0.40				1.04	0.27	0.13
P3(GP)	Granular subbase	.	.	.	.	.	.			
	Granular base	1.91	0.60	0.41	1.35	0.44	0.29			
	Asphalt	1.44	0.17	0.42	1.15	0.16	0.36			
	Stabilized clay	3.03	1.81	0.35	1.04	0.32	0.13			
P3(AP)	Granular subbase	.	.	.	.	.	.	.	.	.
	Granular base	1.90	0.66	0.41	1.34	0.45	0.29	1.00	0.18	0.21
	Asphalt	1.47	0.18	0.42	1.20	0.25	0.38	1.04	0.16	0.30
	Stabilized clay	2.74	1.69	0.34	0.84	0.33	0.10	0.86	0.26	0.11

summarized in Table 2 for each surface material type. One's interpretation of these ratios depends upon the consideration of a single LWD test result versus a collective average of test results. For example, when considering the granular base results, the mean w_0/F_{pk} produced by the standard Zorn LWD is 64 % greater than that obtained with the Prima LWD ($\mu = 1.64$). With $s = 0.52$ and assuming a Gaussian probability distribution, a single w_0/F_{pk} from a Zorn LWD test could exceed the Prima w_0/F_{pk} by between 12 % and 116 % (with 1σ or 68 % confidence). With $s_\mu = 0.23$, the average Zorn w_0/F_{pk} could exceed the average Prima w_0/F_{pk} by 41 % to 87 % (68 % confidence). Overall, the standard Zorn configuration yields higher normalized deflections than the standard Prima configuration. The magnitude of the observed difference is dependent on the surface material type.

The influence of the sensing configuration (ground versus plate) and sensor type (accelerometer versus geophone) on the measured deflection was explored using the modified Prima configurations described above. Figure 4(*a*) illustrates the influence of the sensing configuration by comparing data from the standard Prima P3(GS) to data from the modified configuration P3(GP). Here, the only variable is ground versus plate measurement. Figure 4(*b*) illustrates the influence of the sensor type by comparing the measured data from configurations P3(GP) and P3(AP), for which both the accelerometer and the geophone are measuring plate motion. The resulting mean and standard deviation of the normalized deflection ratios are also summarized in Table 2.

Figure 4(*a*) illustrates that GP configuration w_0/F_{pk} values exceed GS configuration w_0/F_{pk} values across all tests. The mean P3(GP) to P3(GS) w_0/F_{pk} values varied from 1.44 ($s = 0.17$) on asphalt to 1.91 ($s = 0.60$) on granular base to 3.03 ($s = 1.81$) on stabilized clay, indicating that plate-based deflections are significantly greater than ground-based deflections. A comparison of these data with the standard Zorn versus Prima configuration results reveals that the sensing configuration (plate versus ground) accounts for the majority of the observed difference between Zorn and Prima results.

Figure 4(*b*) shows that the influence of the sensor type is evident but minimal. The mean P3(AP) to P3(GP) w_0/F_{pk} values

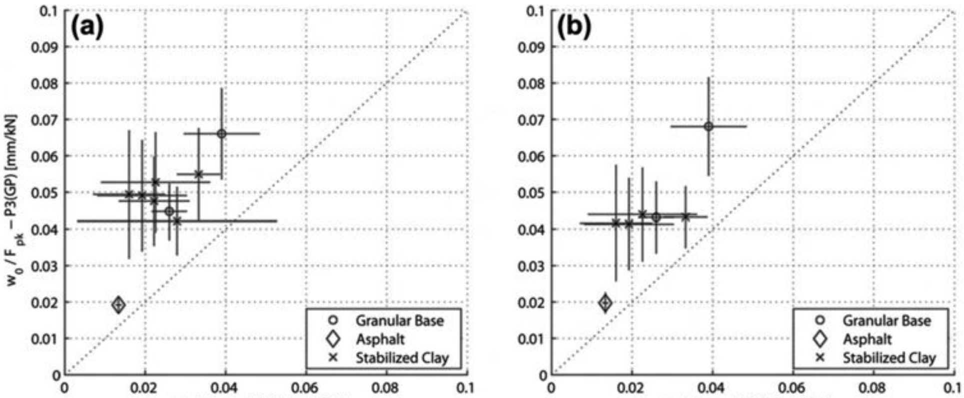

FIG. 4—*Comparison of* w_0 *from LWD configurations (a) P3(GP) plotted against data from P3(GS) at each test point to show influence of sensor location and (b) P3(AP) versus P3(GP) data to show influence of sensor type.*

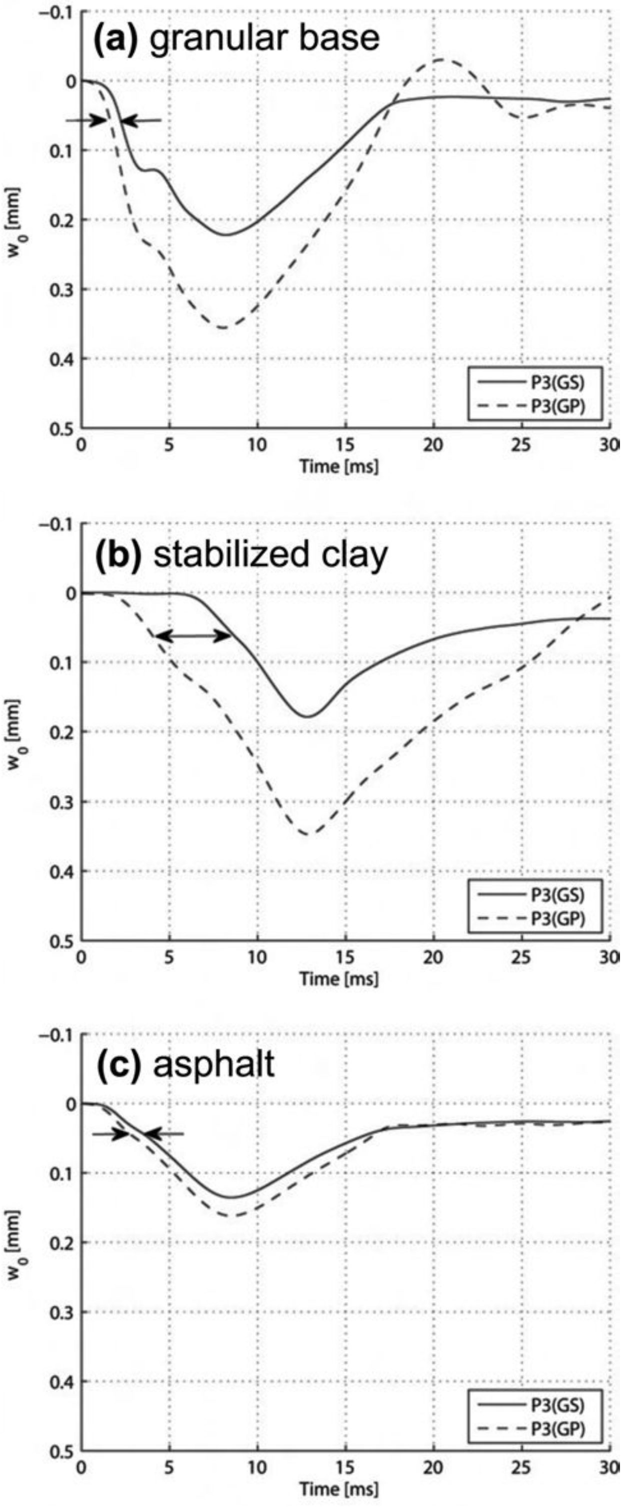

FIG. 5—*Deflection time histories from P3(GS) and P3(GP) configurations for same-location testing on (a) granular base material, (b) stabilized clay, and (c) asphalt. Note the time delay in the initial motion (indicated by arrows) of P3(GS) relative to other records on base and clay soils, but the minimal delay on asphalt.*

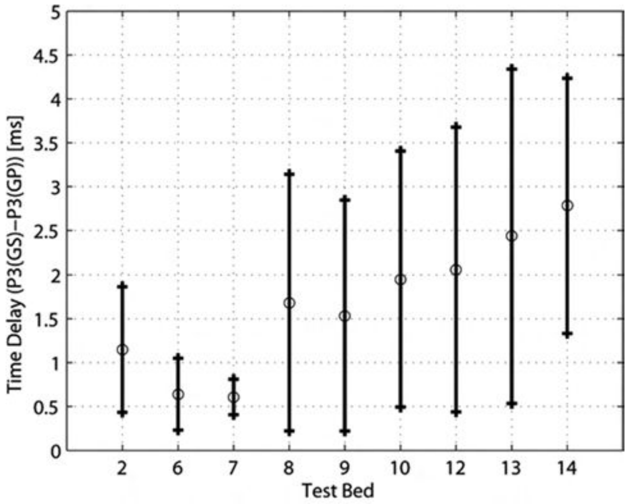

FIG. 6—*Summary of time delay of P3(GS) response compared to P3(GP) response. Open circles indicate mean values, and scatter bars indicate standard deviation. The time difference is calculated when the deflection response for each configuration exceeds a threshold value of 10 µm.*

were found to be 1.00 ($s = 0.18$), 1.04 ($s = 0.16$), and 0.86 ($s = 0.26$) on granular base, asphalt, and stabilized clay, respectively. The difference due to sensor type can be attributed primarily to numerical integration error. The combination of bias offset voltage error and double integration of acceleration data causes a drifting of the estimated deflection with time. The drift error in velocity-based estimates is much less significant, as only a single integration is required. These integration errors are relatively minor in estimated peak deflections but grow considerably if the entire time history is required (e.g., for backcalculation of layered moduli) (e.g., Senseney and Mooney 2010). A complete evaluation of integration error has been provided by Stamp (2012).

The difference in sensor configuration (i.e., ground versus plate deflection) is conveyed in Fig. 5 by measured time histories recorded by the P3(GS) and P3(GP) configurations. These three plots represent typical results from granular base, stabilized clay, and asphalt. The most significant observation, beyond the clear difference in peak deflection, is that the GP-based deflection initiates before the GS deflection. This is most significant in test results on the stabilized clay soils, but it also is noted in records from the granular soils and, to a lesser extent, asphalt. The time delay between the onsets of GS- and GP-based deflections is consistently present but varies across and within material types. Figure 6 summarizes the statistical mean and variance of the time delay observed across all test beds. Stabilized clay test results exhibited the largest average time delay and variation, and the asphalt test results exhibited the smallest time delay and least variation.

Figures 5 and 6 provide some insight into the significant difference between plate-based and ground-based deflections (and the resulting modulus estimates). The results show that the initiation of ground response lags behind the initiation of the plate response. When it does initiate, the GS-based deflection increases at a lower or similar rate (velocity) and tends to peak at the same time as the GP-based deflection. The GS-based deflection therefore cannot "catch up" with the GS-based deflection magnitude. The physical reason for the observed difference is difficult to pinpoint. We revisit this issue later in the paper.

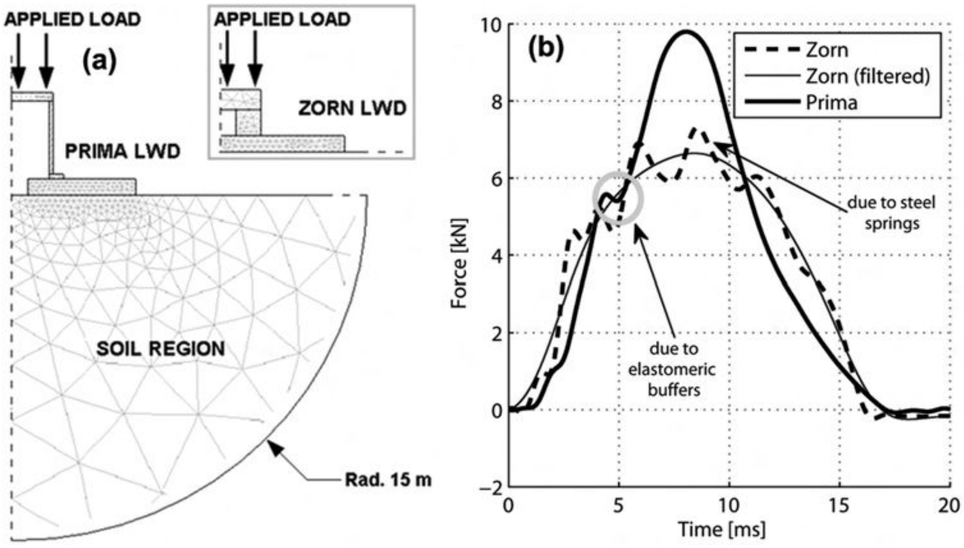

FIG. 7—*(a) Schematic of finite element model used for LWD analysis on homogeneous soil regions in COMSOL Multiphysics. (b) Applied load pulses from Zorn and Prima LWDs. Raw Zorn load data have been low pass filtered at 200 Hz to provide an accurate "max" force for standard LWD calculations per manufacturer practice.*

Influence of Applied Load Pulse and Structural Rigidity

In addition to the differences in their deflection sensor types and configurations, the Zorn and Prima LWDs are different both structurally and in applied load. To investigate the influence of plate rigidity and applied load pulse on resulting deflections, frequency domain-based finite element (FE) analysis was performed in COMSOL Multiphysics[2] using a model previously developed by Senseney (2010). The model is only briefly described here, because of the length restrictions of the paper, and the reader is referred to the work of Stamp (2012) and Senseney (2010) for further details. The FE model is axisymmetric with a radius of sufficient size (15 m) to prevent wave reflections from influencing the results (see Fig. 7(*a*)). Six node triangular elements ranging from 7.5 mm in dimension at the plate–soil interface and graded radially were used. A thorough parametric study was conducted to verify that the model size, element size, and number of frequency components did not influence the problem (Stamp 2012).

All materials were assumed to be linear elastic with material properties as summarized in Table 3. The geometries of the two LWDs were approximated as simplified axisymmetric bodies with 300 mm diameter load plates, as shown in Fig. 7. For both LWDs, the load cell was excluded from this model. The load cell is assumed to deliver a uniform load to the housing below. The Zorn load plate is 19 mm thick, and its housing is 100 mm in diameter by 57 mm tall. A central cavity 36 mm in diameter and 32 mm tall approximates the non-symmetric cavity for the Zorn on-board accelerometer. The Prima LWD's load plate is approximated as a single plate 20 mm in thickness (the slight taper of the actual load plate is considered insignificant), with a central annulus 40 mm in diameter. The Prima housing has a 100 mm diameter cylindrical body with 5 mm thick walls capped by a 10 mm thick plate at the top. The material types of the Zorn LWD (steel) and Prima LWD (aluminum) were modeled accordingly (Table 3).

The force time histories applied by the Zorn and Prima LWDs are shown in Fig. 7(*b*). The observed difference is due to the buffer systems used in each LWD. The Zorn's series of circular steel disc springs (Fig. 2) produces the characteristic ringing behavior. The Prima conical elastomeric buffers produce a smoother load pulse but are responsible for the small hiccup in initial loading visible in Fig. 7(*b*) (Poul-Erik Jakobsen, private communication, August 15, 2011). Using frequency domain representations of the load pulses (up to 450 Hz), both the Zorn and Prima load pulses were applied to each FE model to investigate the influence of both the load pulse shape and the LWD geometry on the resulting soil deflection. Incidentally, the 7.07 kN peak Zorn force was determined after 200 Hz low pass filtering of the measured Zorn load pulse (Matthias Weingart, private communication, March 25, 2011). In this study, the filtered load pulse was used for the determination of the peak load for use in standard LWD modulus calculation and for normalization of the deflection results; for FE analysis, the unfiltered response was used.

A comparison of the FE model response and test bed 6 experimental results for both Zorn and Prima LWDs are shown in Figs. 8(*a*) and 8(*b*). These tests were performed on vertically homogeneous granular base material, and therefore the model assumption of a homogeneous half-space is reasonable. The Zorn and Prima tests were performed at the same location to enable

TABLE 3—*Summary of material properties assigned in FE model.*

Material Property	Soil	Aluminum (Prima)	Steel (Zorn)
Density, kg/m^3	2000	2700	7850
LWD mass, kg	.	5.9	13.9
Poisson's ratio (v)	0.35	0.33	0.28
Modulus of elasticity, gPa	0.05–0.6	69	205
Damping (loss factor, ζ)	0.05	0	0

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[2] COMSOL, Inc., Stockholm, Sweden.

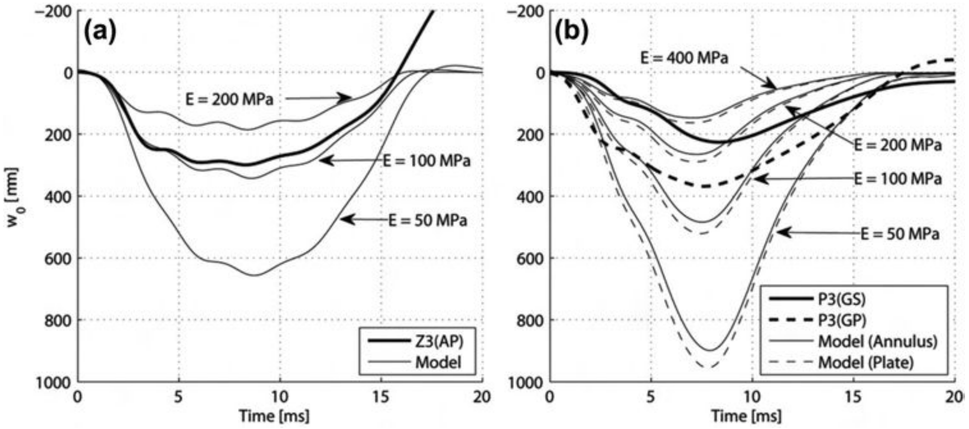

FIG. 8—*(a) Deflection time histories from experimental data for Z3(AP) configuration and FE simulation of Zorn LWD. (b) Deflection time histories from experimental data for P3(GS) and P3(GP) configurations, as well as FE simulations of Prima LWD at the center of the load plate annulus on the ground surface ($r = 0$ m) and near the center of the load plate but measured on the plate ($r = 20$ mm).*

comparison. An FE-modeled response using several Young's modulus values was used to bracket the range observed experimentally and provide a visual representation of the influence of the elastic modulus on the response.

The FE simulation of the Zorn test results mimics the temporal nature of the experimental response, including the loading phase, the time to peak deflection, and the unloading phase until approximately 15 ms, when the plate decouples from the ground surface. Plate–soil decoupling is a complicated problem to simulate with FE analysis. Because this was not of significant interest to the analysis, the appropriate FE modeling of plate–soil decoupling was not pursued. It is worth noting that the experimental deflection time histories are not reliable beyond approximately 15 ms because of integration error. In general, Fig. 8(*a*) illustrates that FE analysis can capture the salient response observed in Zorn tests, including the ringing due to the steel disc springs.

For the Prima LWD, both the GS and GP results are shown in Fig. 8(*b*) together with the FE-simulated response of the plate and ground (within the 40 mm diameter annulus). Again, FE simulations with multiple values of E are used to bracket the measured response. The FE-simulated plate response is consistent with the measured GP response during initial and peak loading. The measured rebound is more gradual than the FE-simulated rebound. Nevertheless, the FE simulated plate response suggests E is between 100 and 200 MPa, consistent with the Zorn FE simulations. This suggests that FE analysis is reasonably capable of capturing Prima plate response even with an annulus present.

The FE simulation of the GS response is quite different. The magnitude of FE-simulated ground deflection within the annulus is less than the FE-simulated plate deflection for all values of E. However, the mild difference between FE-simulated plate and ground responses does not match the significant difference observed experimentally (shown in Fig. 8(*b*)), suggesting that the FE model is not capable of capturing ground response within the annulus. Further, whereas the FE response generally captures the temporal nature of the experimental deflection, the FE-simulated ground response does not emulate the time delay that is observed experimentally. Upon inspection of the 0–2 ms portion of Fig. 8(*b*), one sees that by the time the ground-based geophone begins to record deformation, the experimental plate deflection, as well as all FE-simulated plate and ground deflections, has experienced approximately 200 μm of deflection, a magnitude equivalent to the difference between the ground and plate peak deflections. It is likely that the particulate nature of the soil (e.g., granular flow) instills the observed behavior that cannot be simulated with a continuum-based FE analysis. To this end, the continuum-based FE results cannot be relied upon to analyze GS response (e.g., the FE simulations show that E is between 200 MPa and 400 MPa, significantly higher than the Zorn and Prima plate results). However, the inability of the continuum-based FE simulations to match the observed GS response in and of itself suggests that a complex particulate response is significantly influencing the traditional Prima response. This issue is further addressed in the "Discussion" section.

To characterize the influence of plate rigidity and applied force differences between LWDs, the Prima and Zorn LWD FE models were each subjected to the Zorn and Prima load pulses. The deflected shape of each plate and ground surface at peak deformation (normalized by peak force) is shown in Fig. 9. In Fig. 9(*a*), the FE-simulated responses of Zorn and Prima LWDs are compared (i.e., Zorn plate subjected to Zorn load and Prima plate subjected to Prima load). It is evident that the Prima plate undergoes greater flexure than the Zorn, and that neither LWD appears rigid. The difference in w_0/F_{pk} is less than 10 % and considerably smaller than the 50 % to 100 % difference observed experimentally. The influence of the annulus is evident in the Prima model results; annulus deflections are approximately 10 % less than the surrounding plate deflection. Figures 9(*b*) and 9(*c*) compare the FE-simulated responses of the Zorn and Prima LWDs, respectively, subjected to each load pulse. The Zorn load pulse yields only slightly greater (3 % to 6 %) w_0/F_{pk} values for both the Zorn and Prima LWDs.

The FE simulations suggest that the influence of rigidity on w_0/F_{pk} is minor. However, the full influence of rigidity on modulus estimation is more difficult to assess. Equation 1 utilizes a discrete value of A to characterize the contact stress distribution. The

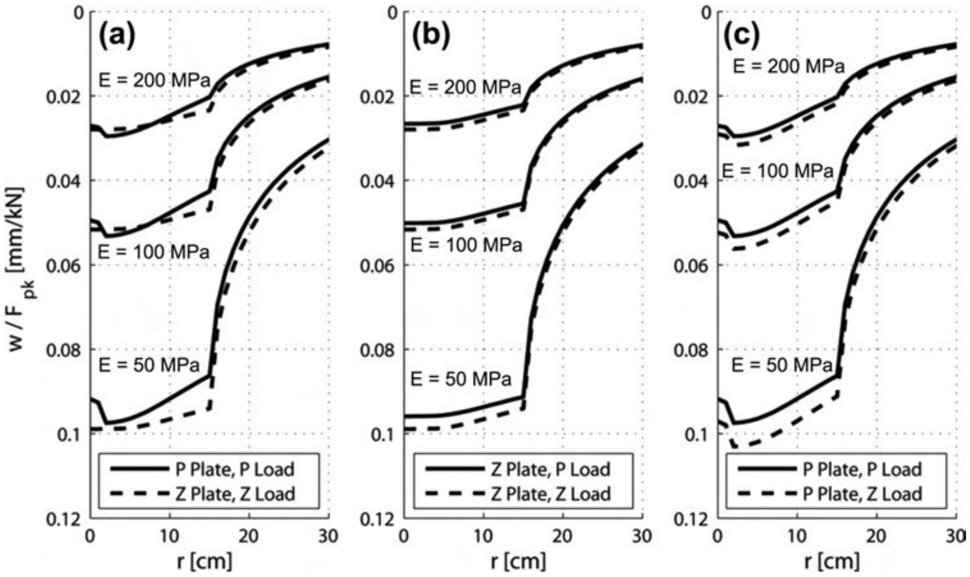

FIG. 9—*Vertical deflection as a function of radius at the time of* w_0 *and normalized by* F_{pk}. *(a) Comparison of results for Zorn (Z) and Prima (P) LWD models subjected to their respective load pulses. (b) Comparison of results for both load pulses (Z and P) applied to the Zorn LWD model and (c) for both load pulses (Z and P) applied to the Prima LWD model.*

contact stress distribution is influenced by the soil type and plate rigidity (e.g., Mooney and Miller 2009; Vennapusa and White 2009). The results in Fig. 9 indicate that the contact stress distributions on the Zorn and Prima LWDs will be different if the plate rigidity is different. Unfortunately, this cannot be fully investigated with FE analysis (Buechler et al. 2012).

Discussion

A number of factors contribute to the difference in measured w_0/F_{pk} values with the Zorn and Prima LWD configurations, including sensor type, sensing configuration (ground surface versus plate), plate rigidity, and load pulse. The most significant contributor to this difference is the sensing configuration; P3(GP) w_0/F_{pk} values from testing on soil exceeded P3(GS) w_0/F_{pk} values by between 44 % and 203 % on average. The respective influences of the sensor type (0 % to 10 % difference), rigidity (<10 %), and load pulse (5 %) are minor in comparison to that of the sensing configuration.

The compilation of experimental and numerical results sheds some light onto the mechanism behind the observed difference due to sensing configuration. The comparison of experimental deflection time histories from P3(GP) and P3(GS) in Fig. 6 reveals a consistent time delay between the initial deflection of the annulus soil and the plate. The plate deflection that occurs during this time delay largely accounts for the difference observed between peak plate and ground surface deflections. This time delay was not present in the FE simulation results. As a result, the FE simulations showed a less than 10 % difference between plate and ground deflections.

There are two likely mechanisms at play that cause the plate versus annulus (ground) deflection difference. First, the material within the 40 mm annulus is not subjected to surface loading and therefore experiences very low confining stress. With load applied everywhere around the annulus, the ground surface within the annulus serves as a stress relief area when a dynamic load is applied to the plate. The underestimation of the ground surface response indicates that the annulus soil experiences upward movement (relative to the plate) associated with this area of stress relief. Second, the plate rests upon soil comprising unbound particulate materials. The surface is smoothed prior to testing and then seated with three impulse loadings prior to testing. Nevertheless, it is plausible that soil particles at the plate boundary undergo initial compression that is not experienced by the surface particles in the annulus. The plate response would capture this initial compression and lead to the deflection differences observed. This second mechanism was suggested by Fleming et al. (2002).

Both possible mechanisms indicate that the particulate nature of the soil is contributing to this difference (e.g., through granular flow). This is further evidenced by the comparatively low difference between plate and ground deflections on asphalt compared to that seen with soil. In addition, the continuum-based FE simulations did not produce the differences observed experimentally. There was no time delay observed in the FE simulations, suggesting that a continuum-based modeling approach does not properly capture the ground response within the annulus. A discrete element modeling approach (beyond the scope of this paper) would provide further insight into localized annulus behavior, as the continuum elastic soil model cannot accurately model the particulate behavior of soil in the annulus of the load plate or at discontinuities such as the edges of the annulus and the plate (Buechler et al. 2012).

Conclusions

An investigation was conducted to determine the influence of LWD design characteristics on the measured deflection and, by inference, estimated modulus. The influence of the sensor type (accelerometer versus geophone), sensing configuration (measurement of plate versus ground surface), LWD rigidity, and applied load pulse was investigated through field testing and FE analysis. The investigation revealed that the sensing configuration (i.e., the measurement of plate versus ground surface response) is the predominant cause of differences between the Zorn and Prima LWD responses (deflection normalized by peak force). Plate measured w_0/F_{pk} exceeded ground surface w_0/F_{pk} by 44 % to 203 % on soils and by 20 % on asphalt. The nature of the difference is linked to a time delay in the experimental plate and ground surface deflection response, a behavior not observed in FE simulations. This experimental/FE discrepancy, combined with the comparison of experimental results on soil and asphalt, suggests that the physical cause is very likely linked to particulate behavior in the annulus and plate–ground contact areas. The respective influences of the sensor type (accelerometer versus geophone), plate rigidity, and load pulse each led to relatively small differences (<10 %) between Zorn and Prima LWD responses.

The results of this investigation illustrate that each of the two LWD configurations will always produce different w_0/F_{pk} and E_{LWD} values for the same ground conditions. Given the multiple factors involved in the differences and the soil dependence in the degree of variance, the overall differences in w_0/F_{pk} and E_{LWD} are likely not predictable. By inference, LWDs built to ASTM E2835-11 and ASTM E2583-07 specifications will always produce different results, and the relationship between these results will be difficult to predict. This will present a significant problem if transportation agencies continue to specify target deflection and modulus values via performance-based specifications. A more tenable solution calls for the standardization of LWDs using a single specification.

This study does not address the question of which LWD parameters yield the best estimate of the soil modulus. This is an important question that can follow from the results presented herein. In such a future investigation, the conventional use of Eq 1 to estimate the soil modulus should be reconsidered for three reasons: (1) it does not account for the inertial and energy dissipation properties of the soil; (2) the lumping of plate rigidity and soil type into a single contact stress distribution parameter is inaccurate (Vennapusa and White 2009; Mooney and Miller 2009); and (3) layering of the subsurface should be considered in most cases (Senseney and Mooney 2010).

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