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Analysis of surface waves from the light weight deflectometer

Nils Ryden [a,*], Michael A. Mooney [b]

[a] Department of Engineering Geology, Lund Institute of Technology, Box 118, SE-221 00 Lund, Sweden
[b] Division of Engineering, Colorado School of Mines Golden, CO 80401, USA

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ABSTRACT

The combination of high strain modulus from conventional light weight deflectometer (LWD) analysis and low strain modulus from LWD-induced seismic analysis would move the pavement community towards field characterization of non-linear soil stiffness for use in mechanistic-empirical pavement design. This paper explores the experimental and numerical analysis of surface seismic waves during conventional light weight deflectometer testing. Field experiments were conducted on clay, silt and gravel soils to characterize the nature of LWD-induced surface waves and to determine both low and high strain moduli. The usable high frequency limit was found to be 300 Hz for LWD-induced surface waves, enabling the low strain modulus characterization of the top 0.3–0.5-m-thick soil layer. A numerical investigation revealed that modal interference is a significant contributor to near field effects, and that a distance of one wavelength between the LWD center and receiver array center is required to minimize these effects. The LWD-induced surface wave strain levels at a 1 m offset from the LWD were found to be on the order of 10^{-2} to 10^{-3}% compared to the 10^{-3} to 10^{-4}% strain levels associated with conventional small hammer-induced surface waves. The measured low and high strain modulus compares well with published modulus reduction functions.

1. Introduction

Modern pavement design is based on mechanistic analytical models of layered systems. These models are used to predict deformations from a given load based on Young's modulus (E), Poisson's ratio (v), and the thickness of each layer. More recent developments in mechanistic pavement design call for the use of non-linear (stress and strain dependent) modulus functions to better predict deformations in unbound pavement layers [1,2]. A parallel effort has emerged towards the in-situ measurement of mechanistic parameters, e.g., modulus. This has fueled the move away from density based measurement towards devices that assess modulus (e.g., light weight deflectometer, soil stiffness gage, surface seismic, Briaud compaction device) and shear strength (dynamic cone penetrometer).

The light weight deflectometer (LWD) in particular is increasingly being used to assess unbound material properties (e.g., [3] for an overview). A limitation of the LWD in light of the aforementioned use of non-linear modulus is that it provides a single measure of soil modulus. This paper explores the possibility of extracting low strain modulus from the surface waves emanating from a conventional LWD test. Combining this low strain modulus with the high strain modulus determined from the conventional LWD test (10^{-1} to 10^{-2}% per [4]) would help enable the efficient estimation of non-linear modulus functions. We present the results of field experiments and numerical modeling to characterize the seismic wave field generated by the LWD source. Based on these results we propose a seismic wave measurement set-up to minimize near field effects. The combined LWD and "LWD-Seismic" technique was implemented in the field on clay and gravel soils; the results are compared with published modulus reduction functions.

2. Background

2.1. Light weight deflectometer

The LWD is a field device that is increasingly being used for quality control/quality assurance (QC/QA) of compacted unbound materials [3–7]. A falling weight (10–15 kg) impacts a 200–300-mm-diameter (D) base plate and the resulting peak surface deflection (d_0) and impact force are measured. The impact force and base plate diameter is designed to deliver a peak contact stress level (σ_0) of about 100–200 kPa to mimic the approximate stress pulse on a typical subgrade or base layer due to traffic loading on top of a finished pavement. The resulting peak stress and deflection combined with homogeneous, isotropic, linear-elastic half-space theory yields a deformation modulus (E_{vd}) of the soil. In the conventional LWD test a static loading condition is

* Corresponding author. Tel.: +46 46 2227424; fax: +46 46 2229127.
E-mail address: nils.ryden@tg.lth.se (N. Ryden).

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assumed, and Eq. (1) can be used to calculate E_{vd}

$$E_{vd} = \frac{A(1-v^2)\sigma_0 r}{d_0} \tag{1}$$

where A is a shape factor for stress distribution (2 for inverse parabolic (rigid plate) and $\pi/2$ for uniform distribution (flexible plate)), v is Poisson's ratio and r is the plate radius. The measured E_{vd} is influenced by the specific type of device, stress and strain levels in the soil, amount of plastic deformation, surface condition, plate seating, and potential layering within the soil [3,4]. The measurement depth of the LWD is typically $2.0r$–$3.0r$ [4].

2.2. Surface seismic

Seismic wave propagation based methods provide a small strain modulus (maximum modulus) of the material as a function of depth [8–10]. Conventionally, a small hammer is used to generate surface waves which are measured at various distances from the source along the surface. In an elastic half-space, surface waves are non-dispersive and the Rayleigh surface wave velocity (V_R) is only slightly lower than the shear wave velocity (V_S). The relationships between V_R, V_S and compression wave velocity (V_P) are functions of v. The following approximate relation for V_R and exact relation for v are often used [11]

$$V_R = V_S \frac{0.87 + 1.12v}{1+v} \tag{2}$$

$$v = \frac{0.5(V_P/V_S)^2 - 1}{(V_P/V_S)^2 - 1} \tag{3}$$

In a homogenous half-space, the penetration depth of surface waves is approximately one wavelength (λ), hence λ less than the layer thickness will be non-dispersive and propagate with a phase velocity (V_{ph}) equal to V_R. The maximum Young's modulus ($E_{\max}$) can be calculated using

$$E_{\max} = 2\rho V_S^2(1+v) \tag{4}$$

where ρ is the total density of the material. The equations above provide a practical way to estimate $E_{\max}$ from the non-dispersive asymptotic velocity (V_R) of surface waves with λ on the order of the tested layer thickness of a compacted soil layer [8,12]. In the case of a stiff surface layer the asymptotic V_{ph} trend at short λ strictly corresponds to higher modes of surface waves [13]. At longer λ and lower frequencies the measured dispersion curve typically jumps to lower modes of dispersion curves which can make mode number identification and the evaluation of the embedded lower velocity layers challenging. However, at the higher frequencies where λ is on the order of the top layer thickness V_{ph} of all higher modes is known to merge towards V_R of the top layer [13,14]. This property of surface waves makes it easy and practical to estimate V_R of a uniform top layer regardless of the properties of the deeper layers. With this approach, the difficulties related to the inversion of a complete V_S vs. depth profile is avoided and $E_{\max}$ of the top layer can be estimated directly in the field by assuming or measuring ρ and v. Potential difficulties and research questions related to the extraction of V_R of the top layer during the conventional LWD test are therefore not related to surface wave inversion but can rather by summarized as follows: (1) Is the surface wave frequency range from the LWD high enough to resolve thin top layers? (2) How close to the LWD can V_R be accurately measured and how many additional sensors are necessary for this task?

3. Seismic wavefield from LWD

As a first step in this study the seismic wave field over a relatively large distance was analyzed to characterize the nature of waves generated by the LWD. This experiment was performed on a 0.30-m-thick granular base layer overlaying a stiff clay subgrade. Seismic data was collected with a PCB accelerometer (model 393A03) and a custom built LWD [4] as the source. The LWD produces a 17-ms-long force pulse (nominally 8.0 kN) using a 0.30-m-diameter base plate. The accelerometer was fixed at $x = 0$ and the LWD was offset in incremental distances (dx) of 0.20 m to a total offset of 7.0 m (see Fig. 1). At each offset, the surface waves from 4 LWD impacts were recorded and averaged using a sampling rate of 100 kHz.

All recorded signals at 0.2–7.0 m offsets are assembled in a multichannel record in Fig. 2a. The raw data in Fig. 2a is dominated by surface waves propagating with an average velocity of 170–190 m/s. The direct compression (P) wave is visible at 600 m/s in the time domain record (Fig. 2a). Fig. 2b shows the corresponding phase velocity spectrum obtained by using the Multichannel Analysis of Surface Waves (MASW) transformation technique [15,16]. Dark regions in the image correspond to good phase signal to noise ratio (coherence) along the measurement line. The image in Fig. 2b is normalized so that the peak amplitude at each frequency line has unit amplitude regardless of the true signal to noise ratio at this frequency. Surface wave dispersion curves are visible from 10 to 300 Hz (Fig. 2b) with the dominant frequency around 60 Hz (Fig. 2c). At higher frequencies the wave field is dominated by the P-wave and the direct air wave at 340 m/s. Fig. 2c shows the normalized amplitude spectrum from signals recorded at $x = 0.2$, 1.0, and 2.0 m from the LWD.

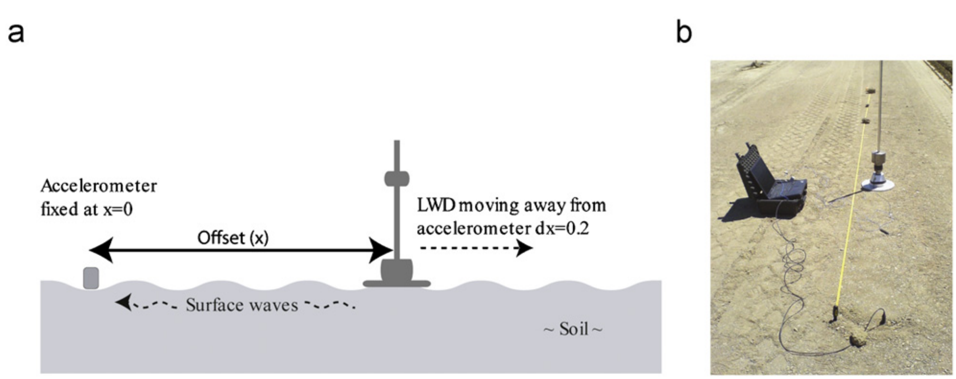

Fig. 1. (a) Schematic and (b) photograph of LWD-Seismic test set-up.