Compaction Evaluation by MASW Surveys (CEMS)

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Abstract

The purpose of the compaction during a road construction is to achieve a necessary stiffness level. Therefore, the compaction evaluation process can be regarded as an in-situ shear-wave velocity (Vs) measurement for top, at most, 1-m thickness of roadbeds. Minnesota Department of Transportation (MnDOT) recently launched a feasibility study to use a seismic surface-wave (MASW) method for this purpose. The first field test, conducted at a 153-m-long test site, used a set of four parallel land streamers (12-channel per streamer) with 1-m geophone spacing and 1.2-m streamer separation. Five surveys were conducted at five different compaction stages during a full-depth reclamation (FDR) road construction. Analysis results of cross sections clearly showed velocity (Vs) variations for, approximately, the top 0.3-m thickness between different stages. In addition, depth-slice (DS) maps created from four parallel cross sections delineated velocity variations not only between different stages, but also between different surface locations. Frequency limitations in surface waves measured by using low-frequency (4.5 Hz) geophones and relatively long (11 m) receiver array for depth of interest (< 1 m) made overall velocities underestimated. Future adjustment in acquisition system and geometry will significantly increase the resolution of the approach.

Introduction

The main purpose of the compaction process applied at various stages of road construction is to achieve the level of stiffness necessary to sustain expected load stress over the entire construction area. In this sense, the compaction evaluation can be regarded identical to in-situ stiffness measurement of road materials.

Stiffness of a material is defined as a measure of resistance to deformation (Sheriff, 2002) and ultimately related to material's elastic moduli that describe the material's behavior under stress. Among the three primary types of moduli—Young's (E), shear (μ), and bulk (β)—the first two (E and μ) are most commonly used because of what they represent. Young's modulus (E) simply dictates the deformation tendency along the axis of stress, whereas the shear modulus (μ) indicates the tendency of shape deformation (i.e., shearing). In reality, deformation always accompanies both transverse and longitudinal changes only at a different ratio. In this sense, the most comprehensive and accurate definition of stiffness should include both moduli of E and μ. According to the theory of elasticity (Sheriff and Geldart, 1982), these two moduli can be defined by a material's density (ρ) and the two seismic velocities (or by Poisson's ratio, ν) of Vp (P-wave) and Vs (S-wave):

$$E = 2\rho Vs^2(1+\nu) \qquad (1)$$

$$\mu = \rho Vs^2 \qquad (2)$$

The two defining equations indicate the heaviest dependency of both moduli on Vs. This is why seismic shear-wave velocity (Vs), the final product from an MASW survey (Park et al., 1999), is often used as a direct indicator of a material's stiffness.

MnDOT recently recognized the potential utility of MASW surveys in compaction evaluation during road construction and launched a feasibility field study to tap into its effectiveness and move toward the goal of making it a routine production method. The pilot study consisted of a series of multiple (five) MASW surveys performed in the same area during a full-depth-reclamation (FDR) road construction; a 153-m long segment on TH56 South approximately 5 miles north of Kenyon, MN (Figure1).

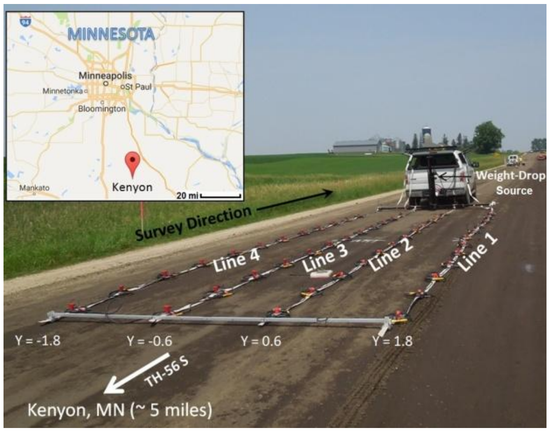


Figure 1. Location map and quadruple land streamers used to acquire MASW data at a test site near Kenyon, MN.

Road Construction by Full-Depth Reclamation (FDR)

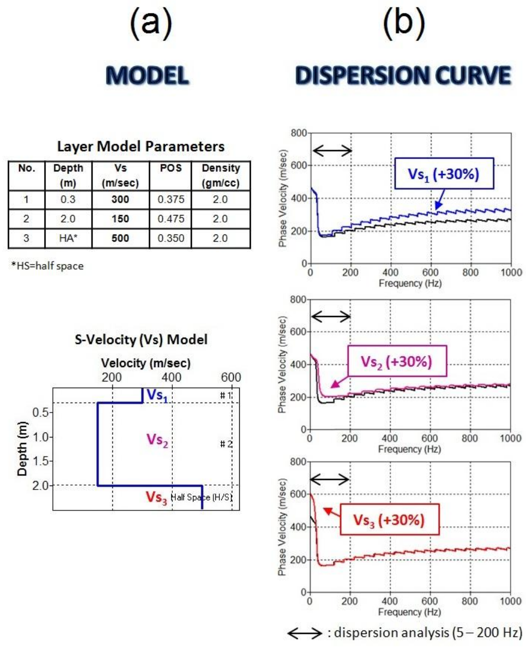
The full-depth reclamation (FDR) rebuilds old worn-out asphalt pavements by recycling the existing roadway. The old asphalt and base materials are pulverized, mixed with stabilizing agent (e.g., cement, emulsified asphalt, or asphalt binder, etc.), and compacted to produce a stabilized base. The new pavement layer of asphalt is then laid on top of the stabilized base. The overall procedure can be divided into three stages; (1) the pre-grind (PG) stage in which existing old pavement and base layers are pulverized, (2) the material is then re-ground and cement, emulsified asphalt, or an asphalt binder is added and this layer is compacted to produce a stabilized FDR (SFDR), subsequently after curing, (3) layer(s) of hot-mix-asphalt (HMA) is placed. During and between each stage, it is important to ensure the necessary level of stiffness is achieved over the entire area of construction. Standard penetration test (SPT) is traditionally conducted for this purpose at selected locations, while more recently Intelligent Compaction (IC) techniques are used. MASW surveys are proposed as a robust QA/QC means that can provide distribution of stiffness in more technically appropriate and spatially continuous form than other approaches can provide.

Data Acquisition

Total five (5) MASW surveys were conducted at the same place during the FDR; one during the pre-grind stage (PG), two during the stabilized FDR stage (SFDR and SFDRb), and two during the final HMA stage (HMA1stLift and HMA2ndLift). The surveys took place during July and August, 2013, by using the existing seismic acquisition system built and used by MnDOT Materials with a minimal modification, a seismic system that employed low-frequency geophones (4.5-Hz) for receivers and was originally built for subsurface investigation at deeper depths of soil and bedrock (e.g., 1-30 m) than the current depth of interest (e.g., 0-2 m). The system consisted of 48-channel acquisition with quadruple land streamers (12 channels/streamer) placed parallel and separated by 1.2-m (Figure 1). A weight-drop source (WD/SASS) generated surface waves 2-m ahead of the closest geophones from the transverse center of the streamers. One impact was delivered to generate one 48-channel field record at one location, and this source-receiver (SR) configuration moved by 1 m each time to produce a total of 154 field records per survey ensuring the coverage of 153-m (500-ft-long) segment of the test site.

Resolution Analysis

Considering the acquisition geometry of receiver array length (L=11 m) and source offset (X1=2 m), the maximum investigation depth (Zmax) is expected to be about 5 m. However, most stiffness changes that will occur during the FDR construction are confined within about the upper 0.3-m thickness. Therefore, it is worth conducting an analysis of how the stiffness variations in this relatively thin layer, as well as other underlying layers, influence the dispersion curve measurement. This analysis is performed by modeling an apparent-mode (AM0) dispersion curve (Gucunski and Woods, 1992) for a velocity (Vs) model that can represent a typical road base (Vs1=300 m/sec) of 0.3-m thickness overlying a subgrade (Vs2=150 m/sec) followed by weathered bedrock (Vs3=500 m/sec) at an arbitrary depth of 2.0 m (Figure 2a). The modeled AM0 curve is displayed (in black) in Figure 2b in comparison to three other AM0 curves that are modeled after changing (increasing) the velocity (Vs) by 30% in each of the three layers; i.e., Vs1, Vs2, and Vs3, respectively. The upper limit of modeled frequency is 1000 Hz where the AM0 curves approach the asymptotic surface-wave velocity of top layer by more than 98%. The curve comparison shown in Figure 2b indicates that velocity (Vs) changes in the three layers result in phase velocity changes mostly at those frequencies higher than 100 Hz (top base), 30-200 Hz (subgrade), and lower than 20 Hz (bedrock), respectively. It is also obvious that the greatest overall change occurs when the top layer changes its velocity, proving the highest sensitivity despite the smallest thickness. These results therefore indicate that, as far as the highest measured frequency (f_{max}) exceeds 100 Hz (and the lowest frequency is lower than 20 Hz), velocity change in any of these three layers will be detected. However, velocity for top layer (Vs1) will be underestimated while f_{max} remains lower than 1000 Hz. Figure 2b indicates that, as f_{max} increases and approaches 1000 Hz, the degree of underestimation will decrease, while the sensitivity in detecting velocity (Vs1) change will increase.



Layer Model Parameters

No.	Depth (m)	Vs (m/sec)	POS	Density (gm/cc)
1	0.3	**300**	0.375	2.0
2	2.0	**150**	0.475	2.0
3	HA*	**500**	0.350	2.0

*HS=half space

Figure 2. (a) Layer model used to generate (b) theoretical apparent-mode (AM0) dispersion curves. The original curve (in black) is displayed in comparison to other curves generated by increasing velocity by 30% for top (Vs1), subgrade (Vs2), and weathered bedrock (Vs3) layers.

Data Analysis and Results

The acquired data set from each survey was split into four (4) subsets of individual lines (1-4) (Figure 1) corresponding to each land streamer of 12-channel acquisition during the pre-processing step. Each subset then went through the normal MASW data analysis sequence to generate a 2-D velocity (Vs) cross section per line.

Different offline offsets of source locations for each line were accounted for during dispersion analysis. Then, dispersion images were generated for a frequency range of 1-1000 Hz (0.5-Hz increment) and a phase-velocity range of 10-1500 m/sec (5 m/sec increment). Dispersion curves were next extracted from these images in an approximate common frequency range of 15-200 Hz. A set of dispersion curves for each line was then used for inversion analysis to produce a 2-D velocity (Vs) map of 2-m depth, which was set intentionally smaller than the optimum depth (e.g., 5 m) to increase the resolution at shallower depths (e.g., ≤ 1 m). A 15-layer earth model of varying thicknesses was used during the inversion. In this way, four (4) cross section Vs maps were produced from each survey for the four (1-4) parallel lines. The Vs cross sections for line 1 are displayed in Figure 3 for all five (5) surveys.

Considering the four (4) lines of 2-D Vs maps being located side by side with an even spacing (1.2 m) between them, it is possible to construct depth-slice (DS) maps by combining Vs data sets from all four lines. In this way, a DS map for 0.0-0.30 m depth range was created for each survey from four (4) lines of 2-D Vs maps. These velocity (Vs) DS maps are displayed in Figure 4 for all five (5) surveys.

Then, these DS maps are converted to Young's (E) and shear (μ) moduli values by using the two equations of (1) and (2). Corresponding DS maps are displayed in Figures 5a and 5b, respectively. A constant density (ρ) of 2000 kg/m^3 and also a constant Poisson's ratio (ν) of 0.4 were used during the conversion.

Conclusions and Recommendations

Although geophones are normally used to investigate a greater depth range (e.g., 0-30 m), they were used in this study mainly to investigate stiffness variations in top about 0.5-m road beds. Despite the reduced resolution in measurement due to frequency limitations in measured data, it seems that results successfully showed relative variations in stiffness that were expected between different stages of FDR road construction as well as between different surface locations. This is an unprecedented approach that deals with the most important property (i.e., stiffness) of road materials through one of the most fundamental scientific approaches; i.e., through seismic-wave propagation.

Considering the possible range of shear-wave velocities for base materials (e.g., 200-500 m/sec) and bituminous pavement (e.g., 1,000-2,000 m/sec), and also possible thickness ranges (e.g., 0.1-0.5 m for base, and 0.05-0.30 m for pavement), the optimum frequency ranges necessary for absolute evaluation of each layer's velocity are calculated, approximately, as 500-5,000 Hz for the base and 5,000-30,000 Hz for the pavement, respectively (Ryden et al., 2004). Therefore, the results (15-200 Hz) from the five (5) field surveys represent underestimated velocities for base and pavement layers, especially for the pavement. A significant improvement in results is expected if a smaller geophone spacing (e.g., 0.5 m) is used. This reduced receiver spacing (dx) by itself will increase the maximum frequency of measured dispersion curves by, for example, two times if dx is reduced by half. In addition, switching to higher-frequency geophones (e.g., 40-Hz phones or 100-Hz phones) will increase overall recording sensitivity at higher frequencies (e.g., 100-1,000 Hz) and can ultimately improve the analysis resolution. However, for absolute velocity (Vs) evaluation of base and pavement layers, accelerometers have to be used that can record surface waves up to 50,000 Hz (50 KHz).

The current data analysis sequence requires an operator's continuous involvement at several different stages of processing. Most of these steps will eventually be fully automated within the analysis software, eliminating the need for operator intervention. This fully-automated software will lead to a complete system in the field that will produce cross sections and depth-slice (DS) maps of stiffness in real-time mode as field survey proceeds.

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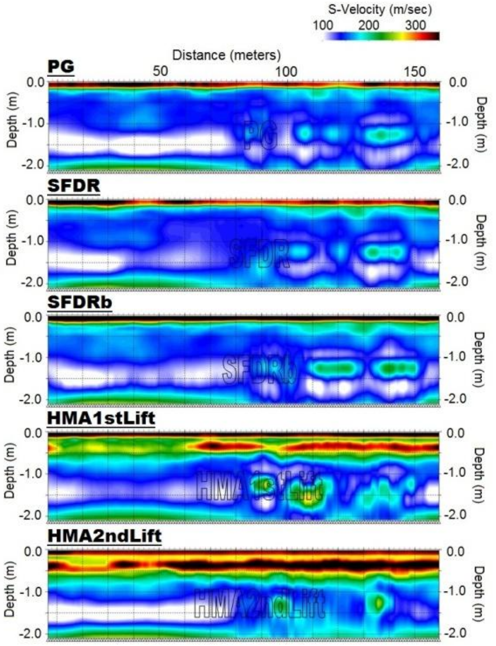

Figure 3. Velocity (Vs) cross sections of line 1 from the five (5) MASW surveys; i.e., PG, SFDR, SFDRb, HMA1stLift, and HMA2ndLift (from top to bottom).

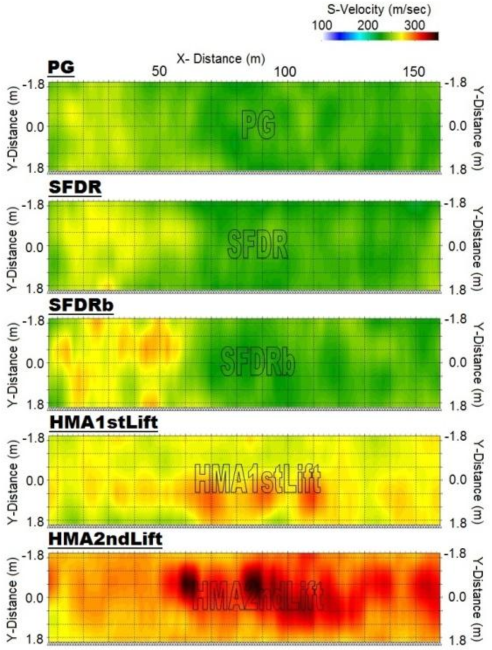

Figure 4. Velocity (Vs) depth-slice (DS) maps from the five (5) MASW surveys for 0.0-0.3 m depth. Each DS map is constructed from four (4) parallel cross sections.

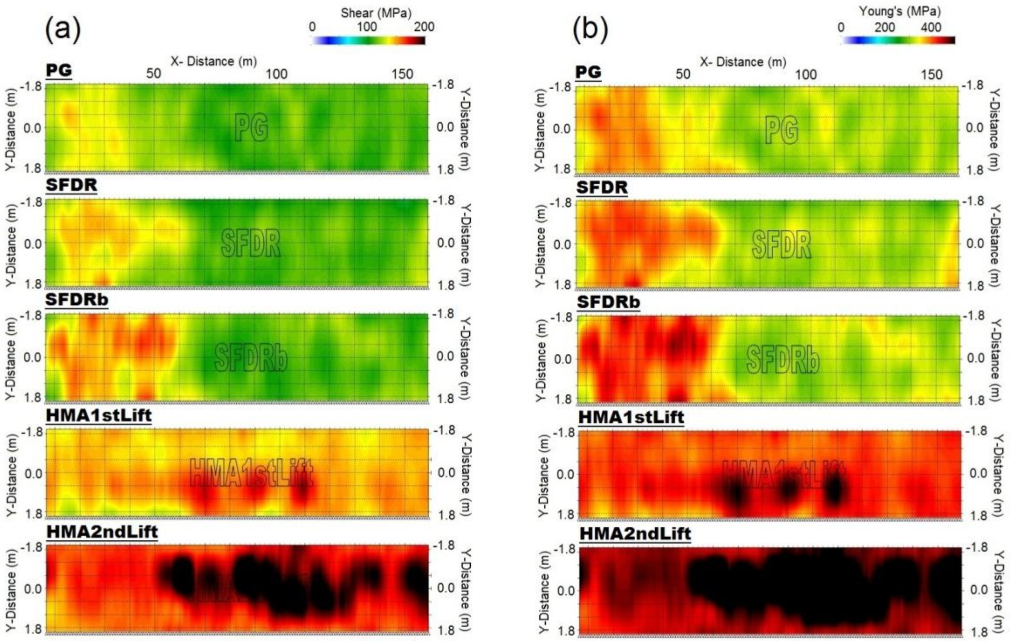

Figure 5. Velocity (Vs) depth-slice (DS) maps in Figure 4 are converted to (a) Young's (E) and (b) shear (μ) moduli maps by using constant values of density (ρ) and Poisson's ratio (ν).