Construction and Building Materials 188 (2018) 809–819

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

In situ modulus reduction characteristics of stabilized pavement foundations by multichannel analysis of surface waves and falling weight deflectometer tests

Cheng Li [a,b,1], Jeramy C. Ashlock [c,2], Shibin Lin [d,*], Pavana K.R. Vennapusa [e,3]

[a] Key Laboratory for Special Area Highway Engineering of Ministry of Education, China
[b] School of Highway, Chang'an University, China
[c] Department of Civil, Construction and Environmental Engineering, Iowa State University, USA
[d] Rutgers University, USA
[e] Ingios Geotechnics, Inc., USA

HIGHLIGHTS

- A newly improved surface wave method was used to test stabilized pavement foundation.
- Moduli from the surface wave and falling weight methods are compared and discussed.
- Moduli of foundation layers are significantly influenced by testing strain levels.
- A new method was proposed to improve mechanistic-based pavement design methods.

ARTICLE INFO

Article history:
Received 28 April 2018
Received in revised form 11 August 2018
Accepted 25 August 2018

Keywords:
Nondestructive testing
Multichannel analysis of surface waves
Falling weight deflectometer
Multi-layered elastic moduli
Modulus reduction
Stabilization

ABSTRACT

Nondestructive testing methods have been increasingly used to evaluate in situ layered stiffness of pavement systems. However, different testing methods could yield considerable different results, which can bring confusions and difficulties to road agencies when conducting mechanistic-based designs or setting specifications for constructions. This study compares a newly improved multichannel analysis of surface waves (MASW) method and the falling weight deflectometer (FWD) test for estimating in situ moduli of various mechanically and chemically stabilized unpaved road sections, which will serve as foundations for future surface upgrade. The comparisons showed that the trends of MASW moduli generally agree with those of the FWD test for the sections without a geosynthetic layer, but the MASW moduli are much higher than the FWD moduli for the aggregate layers. The discrepancies between the two tests were found to be greatly influenced by the different testing strain levels, which were estimated using the KENLAYER analysis. By combining the MASW and FWD moduli and calculated testing strain levels, in situ modulus reduction characteristics of the various stabilized aggregate layers can also be determined, which provides a better understanding of the in situ mechanistic performances of the different stabilization methods under different traffic loading conditions.

1. Introduction

Performance-based field nondestructive testing (NDT) methods, including falling weight tests and geophysical surface wave methods, have been increasingly studied to evaluate in situ moduli of pavement systems and to collect quantitative inputs for mechanistic-based pavement design methods [1–7]. However, the moduli determined by the different testing methods could be considerable different, which bring confusions and difficulties to both researchers and road agencies when analyzing the test results and setting quality control/quality assurance (QC/QA)

* Corresponding author at: Rutgers University, Piscataway, NJ 08854, USA.
E-mail addresses: cli@chd.edu.cn (C. Li), jashlock@iastate.edu (J.C. Ashlock), shibinlin@gmail.com (S. Lin), pavana.vennapusa@ingios.com (P.K.R. Vennapusa).
[1] Chang'an University, Xi'an, Shanxi Province 710064, China.
[2] 474 Town Engineering Building, 813 Bissell RD, Iowa State University, Ames, IA 50010, USA.
[3] Ingios Geotechnics, Inc., Northfield, MN 55057, USA.

https://doi.org/10.1016/j.conbuildmat.2018.08.163
0950-0618/

specifications for constructions. Geophysical surface wave methods (SWM) including the spectral analysis of surface waves (SASW) and multichannel analysis of surface waves (MASW) methods have been extensively studied for profiling of elastic moduli of pavement systems [5,8–10]. However, the relatively new MASW method has not been applied to testing of pavement foundation layers with a focus on characterizing the elastic properties of both the granular base layers and the underlying subgrade.

In this study, to address these issues, a newly improved MASW method is evaluated and compared with the conventional falling weight deflectometer (FWD) test on various stabilized and non-stabilized test sections. The test sections were constructed along a 3.2-km stretch of granular-surfaced roads using a wide range of geomaterials and chemical additives, including unconventional large aggregates (macadam stones), recycled Portland cement concrete (RPCC), geosynthetics, cement, and fly ash. For comparisons, the MASW and FWD tests were subsequently conducted at the same testing locations within the test sections.

The objectives of this study were to (1) evaluate the feasibility of using the newly improved MASW method for determining multi-layered elastic modulus values of both the granular base and subgrade layers, (2) explain the discrepancies between the MASW and FWD test results, and (3) characterize the mechanistic performances of the various stabilization methods under different traffic loading conditions.

2. Background

The FWD and MASW testing methods employ two different theories (i.e., the theory of elasticity and wave propagation theory, respectively) to estimate the multi-layered elastic moduli of pavement systems. In an FWD test, a large dynamic impact load is applied on the roadway surface, while the resulting deflection basin is measured. A single composite modulus or a multi-layered modulus profile of the pavement system can then be back-calculated using the measured deflection data [11–13]. However, FWD testing has not been widely used by road agencies to set QC/QA specifications for pavement foundation systems due to several limitations including poor agreement between field-determined modulus values and lab-measured results and lack of consistency between different backcalculation methods for the same field-collected data [1].

The MASW employs the phenomenon of dispersion of surface waves in layered elastic media, to infer the layer properties (e.g., thickness and modulus) by matching experimental dispersion curves to their theoretical counterparts [14–16]. In MASW tests, an impact is applied on the ground surface to generate surface waves (e.g., Rayleigh waves for regular profiles with depth-wise increasing stiffness or quasi-Rayleigh waves when the stiffest layer is on the surface), and the surface wave motion is measured using an array of geophones or accelerometers [14]. Based on dispersion characteristics contained in the measured surface motion, the shear wave velocity as a function of depth can be back-calculated through an inversion procedure. However, when applying traditional surface wave analysis methods to pavement systems, several challenges are encountered such as numerical instability when using the transfer matrix method to calculate theoretical dispersion curves at high frequencies, and convergence to a local minimum when using the Levenberg-Marquardt method for inversion [17].

To address these issues, several improvements were made to the dispersion analysis and inversion procedures for the MASW data analysis by Lin [18]. These include a new phase-velocity and intercept-time scanning (PIS) method to improve the resolution and sharpness of experimental dispersion images by minimizing side lobes and aliasing that can be generated by conventional wavefield transformation methods. The side lobes and aliasing can lead to misidentification of apparent higher and lower modes, resulting in errors in the inverted profiles. Compared to the conventional methods, the new PIS dispersion analysis method does not require a complex high-accuracy trigger system, because it eliminates the assumption of that the impact point coincides with the generation point of the Rayleigh waves. The PIS method first converts the field data from the space-time domain to the space-frequency domain by applying a Fourier transform, then uses the slant-stack method to provide a new series of harmonic curves in the phase slowness-time intercept plane, and finally applies another Fourier transform followed by auto-power spectrum analysis to the new harmonic curves to generate the experimental dispersion image. The key differences between the improved PIS and conventional methods are (1) the additional dimension of scanning the intercept time, whereas the conventional analysis assumes an intercept time of zero, and (2) the use of auto-power spectrum analysis, which presents the dispersion image amplitude in terms of power to greatly reduce effects of side lobes and aliasing.

A new hybrid genetic-simulated annealing (GSA) optimization algorithm was also developed by Lin [18] to improve the inversion procedure by enhancing global searching efficiency, thus reducing the risk of the search becoming trapped in a local minimum. The GSA method uses a new combination of the genetic algorithm (GA) and simulated annealing (SA) algorithm, which excel at global and local searches, respectively. The newly improved dispersion analysis method (PIS) and inversion method (GSA) were employed in the surface wave data analysis of this study.

3. Site descriptions and materials

In this study, a 3.2-km stretch of two-lane granular-surfaced road in Iowa, USA was selected to construct the various mechanically and chemically stabilized aggregate surface layers for future surface upgrade. To compare the in situ performance and durability of various mechanical and chemical stabilization methods, a wide range of geomaterials including two unconventional large aggregate materials (also called macadam stones), one RPCC material, three types of geosynthetics, and three chemical additives were used to construct the test sections. Nominal cross-section profiles of the stabilized and unmodified control sections are shown in Fig. 1. The index properties and unified soil classification system (USCS) classifications of the geomaterials used in this study are summarized in Table 1. The design, construction, cost, and freeze-thaw performance for each of the test sections are detailed in Li et al. [19,20].

The dirty and clean macadam stones and the RPCC used to construct the base layers were not bound with tar or bitumen (Fig. 1(a)). The dirty macadam and RPCC material were well-graded with a maximum aggregate size of 125 mm. The clean macadam stone had a maximum aggregate size of 75 mm and was sieved over a 19-mm sieve. For dust control, bentonite and calcium chloride surface treatments were applied on two of the dirty macadam sections. A layer of non-woven (NW) geotextile was also embedded in several of the macadam and RPCC sections to improve subsurface drainage and provide separations (Fig. 1(b)). The 5% bentonite, 15% self-cementing fly ash, and 6% type I/II Portland cement were used to stabilize the three test sections. The fly ash and cement were incorporated into the subgrade (SG) and aggregate (AGG) mixture obtained by mixing the 75-mm thick existing surface aggregate layer with 130 mm of subgrade. Geocomposite, biaxial (BX) geogrid with an underlying NW-geotextile, and the BX-geogrid alone were placed at the interface of the subgrade and granular layer for three test sections to either improve subsurface