Real-Time Spatial Profiling of Subgrade Stiffness for Quality Assurance of Field Compaction

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ABSTRACT
During the inspection of compaction quality for highway roadbeds or railway trackbeds, the selection of a spot for the plate bearing test (PBT) or field density test may frequently invoke conflicts between the construction inspector and construction manager. Furthermore, if compaction quality is not acceptable, a judgment on whether it is attributed to poor material or poor compaction efforts is not straightforward. Consequently, specifications on compaction quality based on a one-point method such as the PBT and field density test would not be a rational approach. As an alternative to the one-point method, this paper proposes a non-destructive surface-wave technique for a spatial distribution of surface-wave velocity (or shear-wave velocity) of compacted material as compaction quality in two dimensions to eliminate the conflicts involved in selecting a test spot. The proposed technique, called the impact-source CSW (ICSW) method, evolved from the conventional continuous surface wave (CSW) method. ICSW method incorporates an impact source rather than a harmonic-signal vibrator. Also, it adopts a new analysis algorithm called the wave-number unwrapping technique, developed to overcome the inherent limitation of the conventional CSW method. To verify validity and feasibility of the proposed ICSW method, field applications were made to construct a 2-D stiffness profile of compacted subgrades and comparisons were made between Young’s moduli from ICSW tests and subgrade reaction coefficients from PBT.

INTRODUCTION
Compaction is a process to increase dry density of soil mass and in turn to increase soil stiffness, and it is an essential process to reduce elastic and plastic deformation caused by traffic loading. In general, a well-designed flexible road pavement would be expected to show a permanent deformation of little more than 20 to 30 mm after a life of 20 years (1). Quality assurance (QA) of compacted subgrade and road base is strictly required in building a safe and healthy pavement. One of the QA procedures adopted in Korea is to ensure field density of compacted material to meet 95% of the maximum dry unit weight by the modified Proctor test. Frequent testing of field density is not practical at a construction site, so the Road Design Criteria of Korea specifies a field density test at every 1000 m$^3$ or at every 400 m per lift (2). If a field density test is not permitted at a complicated site such as a rock debris site, then a PBT should be performed at every 1000 m$^3$ or at every 200 m per two lifts. Since the field density test or the PBT is a one-point method, construction inspectors may often have conflicts with construction managers in choosing a testing spot to represent the 200-m or 400-m section.

An alternative procedure to avoid conflicts involved in field density testing is to make a continuous evaluation of field density or stiffness along a measurement line. Probably the best approach for the continuous evaluation of compaction quality would be surface-wave tests, which are non-destructive, fast and repetitive. Surface-wave tests can be performed by spectral-analysis-of-surface-waves (SASW) method (3, 4), multi array surface waves (MASW) method, refraction micrometer (ReMi) method or continuous surface waves (CSW) method (5, 6). In the case of the SASW method, many researchers have worked for quality assurance and material evaluation of pavement systems including road base, subbase, subgrade and the pavement layer itself. Jones (7) pioneered the use of surface-wave velocity in testing road base, base and subgrade. Later, Nazarian, Stokoe and Briggs (8) and Rix and Stokoe (9) performed further research for evaluating the modulus of pavement subgrade. Also, Bueno et al. (10) specifically
evaluated the compaction of the unbound aggregate base course by the nuclear density gauge and the (SASW). Terrell et al. (11) characterized unbound aggregate base layers using embedded sensors and in situ seismic testing. Recently, Joh et al. (4) proposed a new analysis scheme for the automated analysis of SASW measurements. However, all of these studies on surface-wave velocities focused on the evaluation of shear-wave velocity profiles at a specified measurement location. 2-D visualization of compacted-subgrade stiffness requires continuous evaluation of compaction quality along a measurement array; the CSW method is thus preferred to the SASW method. The CSW method has various advantageous features: it is able to produce global properties of compacted material, analysis for measurements do not require expertise in reducing data, and the analysis time is as short as a couple of seconds. However, the conventional CSW method has inherent limitations: 1. The wavelength measured by the CSW method is mostly in a near-field zone and is not sufficiently short to reveal material stiffness for the topmost lift of compaction. 2. An electro-mechanical vibrator used to generate harmonic surface waves does not produce high-frequency energy for the sampling material of the topmost lift, and is not practical to use at a construction site. 3. The hardware system for the CSW method is not portable, so that frequent testing is not possible for continuous evaluation of compaction quality.

In this paper, a new approach, called the impact-source CSW (ICSW) method, to overcome the inherent limitations of the CSW method is proposed. The approach includes a new analysis theory for determining surface-wave velocities at a small wavelength region and also a new type of source for the generation of broad-band surface waves. For the purpose of verification of validity and feasibility, the proposed approach was applied to several sites in Korea including a natural geotechnical site and a compacted subgrade of National Highway No. 35.

**IMPACT-SOURCE CSW METHOD FOR REAL-TIME EVALUATION OF COMPACTED SUBGRADES**

**Continuous Surface Wave (CSW) Method**

The CSW method (5, 6) is a surface-wave method used to evaluate surface-wave velocities for a series of frequencies using a harmonic source and more than four geophones, as shown in Figure 1. The CSW measurement is performed for a frequency by generating a steady-state vibration of a single frequency and measuring responses at geophones. The measurement is then moved to the next frequency for the typical range from 5 to 200 Hz.

Time histories of particle velocity are transformed to the frequency domain by means of Fourier transform. Phase angles determined at geophones are correlated with offsets of geophones from the source location. The slope of the correlation is a wave number, used to determine phase velocity, as in Eq. 1:

\[ v_{ph} = 2\pi f \frac{\Delta r}{\Delta \phi} = 2\pi f \frac{1}{k} \]

where \( v_{ph} \) is the phase velocity, \( f \) is the source frequency, and \( \Delta \phi / \Delta r \) is the slope of the relationship between the phase angles and receiver locations (or wave number).

The CSW method has advantages over other surface-wave methods in that reliable measurements can be made by steady-state vibration using an electro-mechanical vibrator. Also, deployment of four or more geophones at a measurement array enables global properties of a tested site to be evaluated and minimizes the possibility of falling into local anomaly. However, the CSW method is limited only to the phase angles that are less than 180 deg due to the internal
error in determining the slope $\Delta \phi/\Delta r$, which indicates that only the surface waves with low frequencies (or large wavelengths) can be used. Also, in the operation of the electro-mechanical vibrator, the mobilized frequency is typically limited up to 200 Hz, which is not a sufficiently high frequency to measure surface-wave velocities for the topmost lift of compacted subgrades.

In this paper, an extended approach is proposed to improve the CSW method for quality assessment of compacted subgrades. The approach includes the wave number unwrapping technique to utilize phase angles over 180 deg and the employment of an impulse source for generation of high-frequency surface waves for the topmost lift of compacted subgrades.

**Wave-Number Unwrapping Technique**

In the CSW method, surface-wave velocity is calculated using phase angles of a harmonic wave at different distances from the source. The phase angle is supposed to increase with distance from the source location. However, when the phase angle exceeds 180 deg, the phase angle is folded to a smaller number than 180, due to the inherent limitation of trigonometric arithmetic. Therefore, as shown in Figure 2(a), the numerical instability may cause the phase angle for some receivers to differ from the general trend. The wave-number unwrapping technique, proposed in this paper, is devised to solve the inherent limitation of the CSW method. The wave-number unwrapping technique recovers the wrapped wave number and determines surface-wave velocities using the recovered wave numbers.

Figures 2 and 3 illustrate the procedure of determining surface-wave velocities based on the unwrapping technique. The test site is a compacted subgrade with two 0.2-m thick lifts over bedrock, where stiffness increases with depth. A total of four receivers are deployed at 0.75, 1.0, 1.25 and 1.50 m from source. Phase angles were determined at four receiver locations for 256 frequencies ranging from 0 to 2,500 Hz by forward modeling based on the dynamic stiffness matrix method (12, 13). Firstly, phase angles are unwrapped for folded cases. The wave numbers (or slopes $\Delta \phi/\Delta r$) are then determined to plot wave numbers vs. frequencies. Figure 3(a) is a resulting $f-k$ (frequency-wave number) plot. As shown in Figure 3(a), wave numbers are folded to negative values when the increasing wave number reaches a threshold. In the conventional CSW method, the data for frequencies higher than the folding frequency could not be used. However, the wave-number unwrapping technique proposed in this paper enables all the frequency data to be used for calculation of surface-wave velocities.

Folding of wave numbers (or spatial aliasing) due to the missing cycle of surface waves can be identified easily by checking whether or not the wave-number drop is equal to Eq. 2.

$$\Delta k = \frac{2\pi}{d}$$  \hspace{1cm} (2)

Equation 2 is derived from equating $\Delta \phi$ to be $2\pi$ and $\Delta r$ to be $d$ from Eq. 1. Therefore, the unwrapped wave numbers can be recovered by Eq. 3, where $k^*$ is the modified wave number and $n$ is the number of foldings in the wave numbers.

$$k^* = k + n\Delta k = k + n\frac{2\pi}{d}$$  \hspace{1cm} (3)

For a frequency of 480.4 Hz, there is only one folding in wave numbers, and the unwrapped wave number is 25.13 rad/m. For a frequency of 1,117.6 Hz, there are two foldings in wave numbers, and the unwrapped wave number is 50.27 rad/m. Finally, surface-wave velocities are calculated using unwrapped phase angles, as shown in Figure 3(c).
Use of Impulse Source for CSW Method

An electro-mechanical vibrator is a favorable source for surface-wave measurements because it generates a seismic energy concentrated at a specific frequency. However, a vibrator would not be a reasonable choice for the following cases: 1. when high-frequency energy is required for investigation of shallow stiff material such as compacted subgrades, 2. when real-time measurements and analysis are required at a construction site and, 3. when handy equipment is preferred for portability.

An impulse source such as a hand-held hammer was employed to generate high-frequency energy, to facilitate measurements and to provide portability. Figure 4 is a typical CSW measurement performed at a compacted subgrade. The CSW measurements using impact source can be performed similarly to the SASW measurements. The acquired signals are the phase spectra of transfer function between two receivers. In calculating the transfer function, the first receiver was taken as a reference receiver. As shown in Figure 4, three phase spectra of a sawtooth pattern were determined for the frequency span of 2,500 Hz. Also, for every frequency point, a total of four phase angles from three transfer functions and reference spectrum were put together to determine wave numbers (or slopes $\Delta \phi / \Delta r$), for the two frequencies of 70.13 and 750.0 Hz as shown in Figure 5. To determine wave numbers, phase unwrapping and linear regression techniques were employed for each frequency. The surface-wave velocities could then be determined by Eq. 1. The measurements in Figures 4 and 5 indicate that impulse source is practically an acceptable and effective source for ICSW measurements.

Construction of 2-D Stiffness Profile from ICSW Results

The method used to construct a 2-D stiffness profile from ICSW results is illustrated in Figure 6. As discussed in the previous section, a surface-wave velocity dispersion curve or a shear-wave velocity profile is determined from ICSW measurements based on four or more geophones. A whole set of geophones are then moved to the next segment for the following measurements, which would produce another set of surface-wave velocity dispersion curves or a shear-wave velocity profile. In this way, the measurement line is segmented into several pieces for individual ICSW measurements, which results in a series of surface-wave velocity dispersion curves or shear-wave velocity profiles. The 2-D interpolation scheme and contouring algorithm is then invoked to construct a 2-D contour from the given set of profiles.

FIELD APPLICATIONS

For verification of feasibility and reliability, the proposed approaches were applied to a natural geotechnical site and compacted subgrades. The ICSW test at the natural geotechnical site was performed to verify the validity of the proposed approach. The tests at compacted subgrades were performed to check feasibility of the approach, and the measurements were made at several arrays to construct 2-D contours of shear-wave velocities and surface-wave velocities.

Natural Geotechnical Site at Chung-Ang University

The ICSW method using the proposed algorithm was applied to a natural geotechnical site at Chung-Ang University in Korea to verify validity of the algorithm. For ICSW measurements, an impulse source was adopted with four geophones. The measured transfer functions between the reference geophone and other geophones were used for both ICSW analysis and SASW analysis.
Figure 7 shows the comparison of ICSW measurements and SASW measurements. In Figure 7(a), the results of wave number unwrapping are shown using dark solid symbols. The resulting $f$-$k$ relationship directly leads to the surface-wave velocity plot shown in Figure 7(c). These steps are all automated to reduce analysis time. The automated step includes elimination of messy data by statistical tools. On the other hand, the analysis of SASW measurements includes user-interaction to mask out unwanted signals. Figure 7(b) illustrates the traditional method of masking for SASW measurements. The purpose of masking at low frequency region is to eliminate the near-field data. Masking at high frequency region is required to cut off messy data. The resulting surface-wave velocities by the CSW method compared well with the surface-wave velocities by the SASW method in Figure 7(c). Without a manual interpretation based on expertise, the ICSW measurements could be successfully transformed into a wave-number domain and, in turn, surface-wave velocities.

**Compacted Subgrades of National Highway No. 35, Korea**

Compacted subgrades at national highway No. 35 in Korea were tested at three 10.5-m long segments by ICSW and SASW methods, as shown in Figure 8(a). The tests were performed to investigate the stiffness uniformity of the compacted mass in the spatial domain. To examine the material uniformity of the tested segments, a 2-D resistivity survey was also performed. To facilitate ICSW and SASW measurements, a weight coupler for geophones was employed, as shown in Figure 8(b). Only one to two minutes were sufficient for ICSW and SASW measurements at one segment including measurement setup and data acquisition, and about 20 minutes was sufficient for all the segments at one measurement array. If a rolling device, which is to be developed in the near future, is available, measurement time can be substantially shortened.

For ICSW measurements, four geophones were deployed with a 0.75-m receiver spacing (Figure 8(c)), and an impulse hammer was used to generate seismic energy with a broad-band frequency of up to 2,500 Hz. A total of 14 ICSW measurements were performed for a 10.5-m long measurement array. Surface-wave velocities were determined for each 0.75-m segment and were combined to construct a 2-D presentation in the wavelength domain, as shown in Figure 8(d). Also, for each surface-wave velocity dispersion curve, an inversion analysis was performed to determine the shear-wave velocity profile. Shear-wave velocity dispersion curves were also combined to construct a 2-D profile of shear-wave velocity, as seen in Figure 8(e). As expected, the results of SASW measurements were almost identical to the results of ICSW measurements for surface-wave velocities and shear-wave velocities.

Uniformity of the compacted mass was investigated for the top 0.2-m thick lift at three measurement lines. A distinct difference in shear-wave velocities is observed among the measurement lines. The shear-wave velocity profile of Line 2 shows uniform distribution throughout the measurement line, and the average shear-wave velocity for the topmost lift is 270.8 m/sec. On the other hand, the shear-wave velocity of the topmost lift at Line 1 shows a sudden change along the measurement. The average shear-wave velocity of the top 0.2-m thick lift at 0.0- to 2.0-m section is 177.5 m/sec, and the average velocity for the 2.0- to 10.5-m section is 149.0 m/sec. From the 2-D shear-wave velocity profile, it can be easily observed that a stiff material is localized at the 0.0- to 2.0-m section. A similar trend in lateral variability can be observed in the surface-wave velocity contours shown in Figure 8(d). Similar to shear-wave velocity profiles, the surface-wave velocity contour for Line 1 has a significant stiffness drop at the 2.0- to 10.5-m section, and that for Line 2 is stiff and uniform, similar to the shear-wave velocity profile.
The fact that the surface-wave velocity contour is comparable with the shear-wave velocity contour suggests the possibility of using a surface-wave velocity contour in quality assurance of the compacted material. An alternative use of surface-wave velocity to that of shear-wave velocity implies that time-consuming inversion analyses for determination of shear-wave velocity profiles can be avoided. Therefore, the quality assurance procedure for a compacted material can proceed in real-time at the site.

A 2-D resistivity contour also confirms the results of ICSW and SASW measurements. The contour of Line 1 reveals some localized low-resistivity sections, which indicates the possibility of embedded clayey material. This is because typical resistivity for clayey material is 0 to 100 $\Omega \cdot m$ and the measured resistivity ranges from 20 to 70 $\Omega \cdot m$ at the 1.5- to 10.5-m section. Also, the picture of surface material shows a yellowish color for the same section, which differs from the material at the 0.0- to 2.0-m section. On the other hand, resistivity of the top 0.2-m thick lift at Line 2 is measured to be uniform throughout the measurement line.

**Correlation between Subgrade Reaction Coefficients and Elastic Modulus**

In practice, subgrade reaction coefficient from PBT is used as criteria to judge quality of compaction. Judged from the principle of PBT, subgrade reaction coefficient is clearly an indicator of material stiffness. Shear-wave velocity ($v_s$) is also an indicator of material stiffness, because shear-wave velocity is converted to elastic modulus ($E$) with mass density ($\rho$) and Poisson’s ratio ($\nu$) by Eq. 4.

$$ E = 2(1 + \nu)\rho v_s^2 $$  \hspace{1cm} (4)

Therefore, there must be a reasonable correlation between subgrade reaction coefficient from PBT and elastic modulus from measurements. To investigate if elastic modulus from ICSW tests is appropriate as an alternative or a supplementary parameter for quality assurance of field compaction, PBT, ICSW and SASW tests were compared at highway roadbeds and railway trackbeds under construction. The highway roadbeds located at NamYangJoo in Korea had two test sites, one of which was compacted with rock debris (NYJ-1) and the other was with silty sand (NYJ-2). In the case of railway trackbeds at YangPyung in Korea, two sites compacted with crushed rock were selected. One of the sites has shallow bedrock (YP-1), and the other has deep bedrock (YP-2).

ICSW and SASW tests were simultaneously performed at a 9-m long test array. For ICSW tests, a 3-m section was evaluated with four geophones deployed at 1-m intervals. SASW tests also employ a 3-m section with two geophones at 3-m intervals. Shear-wave velocities resulting from ICSW and SASW tests are plotted in Figure 9(a) and Figure 9(b), respectively. At all of the four test sites, shear-wave velocity contour plots from the ICSW tests compare well with those from the SASW tests. In Figure 10, Young’s moduli were estimated from shear-wave velocities from ICSW and SASW tests and were plotted for comparison. Modulus estimation was based on Poisson’s ratio of 0.3333 and mass density of 1,900 kg/m$^3$. Figure 10 shows a favorable comparison between moduli from the ICSW tests and moduli from the SASW tests. The two comparisons in Figure 9 and 10 verify that ICSW tests are valid and reliable in evaluating shear-wave velocities of geotechnical material compacted.

PBT were also performed at the center of the ICSW test array. A total of 11 tests were performed, and the results are compared with Young’s moduli from ICSW tests. As shown in Figure 11, the subgrade reaction coefficient linearly increases with Young’s modulus, but the relationship between the two parameters is site-specific. The site-specific relationship is mainly
attributed to the inherent feature of PBT, the results of which are affected by material type, moisture content, loading rate and other factors involved in the tests. In fact, PBT at YP sites were performed at a faster rate than PBT at NYJ sites. Also the moisture content of the material at YP sites was much lower than that for NYJ sites. That is, a higher loading rate and lower moisture content led to a steep slope in the relationship between the subgrade reaction coefficient and Young’s modulus.

SUMMARY AND CONCLUSIONS
An algorithm to overcome the limitations of the conventional CSW method was proposed for real-time quality assurance of compacted subgrades or roadbeds. The proposed algorithm is featured to evaluate the stiffness for the topmost lift of compacted material at a production level and also to automate all the analysis steps by eliminating the expertise involved in the analysis of measured data. Some of the findings made through field applications for the proposed CSW algorithm are as follows:

• Surface-wave velocities determined by the proposed approach for the CSW method are practically identical to the surface-wave velocities by the SASW method, which verifies the validity of the proposed CSW approach.
• The 2-D surface-wave velocity contour is comparable with the 2-D shear-wave velocity contour in lateral variability of stiffness for compacted materials at a topmost lift. An alternative use of surface-wave velocity to that of shear-wave velocity enables real-time quality assurance to be performed at the site.
• The 2-D surface-wave velocity contour can contribute to the identification of source for low stiffness of a compacted material. For example, a low stiffness localized in a limited section may indicate that the material used for compaction is not acceptable and does not imply that compaction energy was not sufficient.
• Further development in dedicated hardware may help the proposed CSW approach become a useful tool for ensuring a good compaction such as intelligent compaction equipment.
• Young’s modulus evaluated by the ICSW method has a linear relationship with subgrade reaction coefficient from PBT. However, the relationship is site-specific and dependent upon material type, moisture content, loading rate and other influencing parameters.

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REFERENCES


FIGURE 1  Schematic Diagram of the CSW Method.

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FIGURE 3  Unwrapping of Wave Number and Determination of Surface-Wave Velocities.

FIGURE 4  Phase Spectra Determined at Four Geophones by Impulse Source in CSW Measurements.

FIGURE 5  Phase Unwrapping for Determination of Wave Number and Surface-Wave Velocities from the CSW Measurements Based on Impulse Source.

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FIGURE 8  2-D Profiles of Surface-Wave, Shear-Wave and Electrical Resistivity Determined at Compacted Subgrades at National Highway 35 in Korea: (a) Site View and Measurement Lines, (b) Hardware Devices for ICSW and SASW Measurements, (c) Measurement Configuration, (d) Surface-Wave Velocity Profile, (e) Shear-Wave Velocity Profile, (f) Electrical Resistivity Profile.

FIGURE 9  Spatial Distribution of Shear-Wave Velocity at Compacted Subgrade of Highway and Railway Roadbeds at NYJ and YP in Korea: (a) ICSW Tests, (b) SASW Tests.

FIGURE 10  Comparison of Young’s Moduli Determined by SASW Tests and ICSW Tests.

FIGURE 11  Correlation between Subgrade Reaction Coefficients from PBT and Young’s Moduli from ICSW Tests.
Harmonic-Wave Vibration
(frequency = $f$)

Phase Angle: $\theta$

Distance from Source

Best-Fit Line

Distance from Source, $r$

Phase Velocity:

$$v_{ph} = \frac{2\pi f}{\Delta \phi}$$

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FIGURE 2  Numerical Simulation of the CSW Measurements and Determination of $\Delta\phi/\Delta r$. 
FIGURE 3  Unwrapping of Wave Number and Determination of Surface-Wave Velocities.
FIGURE 4 Phase Spectra Determined at Four Geophones by Impulse Source for ICSW Measurements.
Phase Unwrapping and Linear Regression

(a) Wrapped Phase Angle, deg
(b) Upwrapped Phase Angle, deg

Freq. = 70.31 Hz
Wave Number = 2.344 rad/m
Vel. = 188.5 m/sec

Freq. = 7500 Hz
Wave Number = 6.560 rad/m
Vel. = 253.7 m/sec

FIGURE 5 Phase Unwrapping for Determination of Wave Number and Surface-Wave Velocities from the ICSW Measurements Based on Impulse Source.
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