Potential Applicability of Slab Impulse Response (SIR) in Geophysical Investigation of Pavement Structures

Masrur Mahedi¹; MD Sahadat Hossain²; Ahmed N. Ahsan³; Asif Ahmed⁴; Mohammad Sadik Khan⁵; and Kelli Greenwood⁶

¹Graduate Student, Dept. of Civil, Construction and Environmental Engineering, Iowa State Univ. E-mail: mmahedi@iastate.edu
²Professor, Dept. of Civil Engineering, Univ. of Texas at Arlington. E-mail: hossain@uta.edu
³Project Manager, Geotech Engineering and Testing, Houston, Texas. E-mail: ken@geotecheng.com
⁴Graduate Student, Dept. of Civil Engineering, Univ. of Texas at Arlington. E-mail: asif.ahmed0@mavs.uta.edu
⁵Assistant Professor, Dept. of Civil and Environmental Engineering, Jackson State Univ. E-mail: mohammad_sadik.khan@jsums.edu
⁶Dept. of Civil Engineering, Univ. of Texas at Arlington. E-mail: kelli.greenwood@mavs.uta.edu

Abstract

Proper functionality of pavement structures can be ensured with adequate quality assurance and quality control during construction. By monitoring pavement health throughout its design life, authorities can reduce structural damages, and achieve subsequent reduction in maintenance cost and time. Geophysical investigation is growing significantly as a tool of QA/QC of pavement structures. The increased use can be attributed to (i) decreased time consumption, (ii) reduced expense, (iii) lower variability of test results compared to laboratory tests, and (iv) the non-reduction of structural integrity and serviceability of pavement compared to destructive testing. The current research work evaluated the applicability of the Slab Impulse Response (SIR) method in pavement health monitoring by conducting in-situ test results at four different locations of a construction project in Dallas, Texas. The dynamic cone penetrometer (DCP) and Geogauge were utilized alongside SIR to determine the resilient and elastic modulus of the pavement layers. Field investigation results indicated that SIR can be useful in identifying damages associated with low stiffness, such as delamination, honeycombing, cracking, and voids below the slabs-on-grade. Comparisons presented in this paper demonstrated the effectiveness of SIR as an alternative tool to conventional methods of pavement health monitoring.

Introduction

The United States of America is comprised of 4,064,000 miles of public road network. The total length of paved roads is 2,646,000 miles, and the remaining 1,418,000 miles are unpaved (Greene and Wegener, 1997). The satisfactory performance of the road network highly depends on the quality assurance and quality control (QA/QC) during the construction process (Mahedi et al. 2017b). Proper QA/QC measures are needed to be adopted during construction to ensure the design requirements. Moreover, proper design life can be ensured only if proper quality control is maintained throughout the construction process.

Traditionally practiced test methods for QA/QC have been proven unreasonable in terms of time, cost, reliability, and applicability (Graveen 2001). Laboratory tests are often time consuming, and sometimes are not practical during construction work. The use of in-situ techniques that can efficiently evaluate the material properties through simple and less time-consuming procedures would be ideal (Mahedi et al. 2017a).
As a part of QA/QC, the use of non-destructive testing (NDT) for the estimation of in-situ strength and stiffness parameters of pavement layers has been accepted as a new technique of pavement evaluation. In recent years, NDT has gained popularity in the evaluation of existing pavement in terms of strength and stiffness (Plati et al. 2010). Traditional destructive testing methods could reduce structural integrity, reduce serviceability, and cause significant economic loss (Hola and Schabowicz 2010). NDT is used as quality assurance of the pavement during construction and to ensure the usefulness, integrity, and safety after construction. There are two basic types of non-destructive testing methods (Graveen 2001). The first type may be termed as semi-destructive as they cause some minor surface damage. Penetration resistance, pullout, maturity, and brake-off testing methods fall into this category. Slab impulse response, parallel seismic, impact echo, stiffness gauge, ground penetration radar fall into the second category of truly non-destructive methods. These testing methods use indirect methods of measuring mechanical properties to prevent the destruction of pavement. There are several advantages and disadvantages of each test. For example, experience is required to interpret the frequency data in impact echo test. Additionally, this method is based on digital sampling and digital signal analysis, where inherent systematic error is common when determining wave speed and plate thickness (Carino 2001).

During this study, the potential applicability of Slab Impulse Response (SIR) method was evaluated for use in the QA/QC of pavement structures. To accomplish this, two construction sites were selected in the Dallas, Texas area for pavement health monitoring. At the conclusion of the study, field investigation results indicated that SIR can be useful in identifying damages associated with low stiffness, such as delamination, honeycombing, cracking, and voids below the slabs-on-grade. To verify the results obtained from SIR, dynamic cone penetrometer (DCP) and Geogauge were utilized.

**Methods**

**Description of Slab Impulse Response (SIR)**

SIR investigations are performed to identify honeycombs, cracking, damage, and voids below slabs-on-grade. The test surface is impacted with an impulse hammer and the response of the slab is monitored by a geophone placed next to the impact point. Both the hammer input and the receiver output are recorded. For ease of data analysis, average mobility, flexibility, mobility slope, and void index are considered as the analytical parameters of the SIR test.

Mobility at a certain point and frequency represents the maximum velocity per unit of applied force. Flexibility, also known as dynamic compliance, is determined by the slope of the initial portion of the mobility plot, typically up to 40 Hz. Thus, mobility of a point is related to the flexibility of that point. Higher mobility indicates a relatively lower velocity resulting from unit applied force. Mobility slope is determined by the best-fit line to the mobility plot for the frequency range of 100 to 800 Hz (ASTM C1740-10). A high ratio of peak to mean mobility indicates poor support condition and deboning of concrete elements. If the support condition is poor or there are locations with delamination, then the upper most layers dominate the response. In these cases, the location shows higher mobility than the average value found within first 100 Hz frequency. A brief description of the controlling parameters is given in Table 1 below.
Table 1. Controlling parameters of Slab Impulse Response (SIR) test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Significant When</th>
<th>Indication</th>
<th>Possible Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Mobility</td>
<td>Higher</td>
<td>Delamination, Cracking</td>
<td>Trapped air and water</td>
</tr>
<tr>
<td>Mobility Slope</td>
<td>Higher</td>
<td>Poor consolidation, honeycombing</td>
<td>Lack of fines</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Higher</td>
<td>Low stiffness, low thickness</td>
<td>Variation in compaction</td>
</tr>
<tr>
<td>Void Index</td>
<td>&gt; 4</td>
<td>Poor support conditions, voids</td>
<td></td>
</tr>
</tbody>
</table>

For the SIR test, NDE-360 system manufactured by Olson Instruments was used. Basic components include a 4-channel NDE-360 for data collection, analysis and display unit; an instrumented hammer; a geophone; grease; and connection cables. The NDE-360 platform is a powerful, small, and easy-to-handle system which allows fast data collection by a single operator. The Windows software WinTFS with several analysis tools were used for data analysis.

Fig. 1. (a) SIR work methodology, (b) SIR equipment, and (c) SIR test conduct at site

© ASCE
**Dynamic Cone Penetrometer Test (DCP) and Geogauge**

The Dynamic Cone Penetrometer Test (DCP), shown in Figure 2 (a), is performed by dropping a hammer of a specific weight from a certain height. This test combines features of both the standard penetration test (SPT) and cone penetration test (CPT). ASTM D 6951-03 standardizes the DCP test. The penetration depth per blow up to a depth needed is measured which resembles the SPT procedures where blow counts are measured using a soil sampler. The Dynamic Cone Penetrometer can provide continuous measurements of the pavement layers and the underlying subgrade without destroying existing pavement. The term DCPI (Dynamic Cone Penetration Index) indicates how much the rod penetrates during each blow. The CBR (California Bearing Ratio) value is correlated with the DCPI value based on a relation developed by US Army Corps of Engineers. Finally, resilient modulus \((M_R)\) was calculated according to a relationship suggested by Huekelom and Klomp that was adopted by 1993 AASHTO Guide for Design of Pavement Structures, shown below (AASHTO 1993).

\[
M_R = 1500 \, \text{CBR} \quad (M_R= \text{Resilient Modulus (psi)})
\]

The Geogauge, shown in Figure 2 (b) and formerly known as a Soil Stiffness Gauge, is a portable device that can effectively measure the in-situ stiffness of compacted layers. Geogauge imparts small dynamic force to the soil through a ring-shaped foot at 25 steady state frequencies between 100 and 196 Hz. The stiffness \((K)\) is determined at each frequency, and the average of the 25 measurements is displayed on the screen. The value of stiffness, \(K\) (in MN/m) obtained from Geogauge has been converted into Young’s Modulus \((E)\) (in MPa) according to a relationship proposed by CAN Consulting Engineers, shown below (Alshibli et al. 2005).

\[
E = \frac{K(1-\vartheta^2)}{1.77R}
\]

Where,

\[
\begin{align*}
E &= \text{Elastic Stiffness Modulus (MPa)} \\
K &= \text{Stiffness measured with Geogauge (MN/m)} \\
\vartheta &= \text{Poisson’s ratio (assumed)} \\
R &= \text{Radius of the Geogauge (2.25 inch)}
\end{align*}
\]

A pavement section across the width of a newly compacted roadway was tested in this study. Figure 2 (c) shows the data accusation pattern from each of the site. SIR date was taken in grid fashion. DCP and Geogauge data points were taken at the middle of each section.
Results and Discussion

In this study, in-situ testing with SIR, DCP, and Geogauge was performed to evaluate the general condition of the pavement, to assess the relative stiffness of unbound and bound layers, and to determine the $M_R$ after compaction. As previously mentioned, SIR was used to evaluate the pavement health, and DCP and Geogauge were used to validate the SIR findings. After that, the data was analyzed for pavement condition evaluation and to assess different strength and stiffness properties. The Nuclear Density Gauge (NDG) test was also performed for Location-1 to evaluate the density of the compacted material with the help of TxDOT officials.

Location 1

Field tests were performed near Jefferson Viaduct Boulevard in Dallas, TX. A 9-ft. by 30-ft. pavement section was selected for SIR data collection. Within the pavement section, six points (labeled P1-P6) located 6-ft. apart were used for the DCP, NDG, and Geogauge tests. The pavement section was consisted of three layers; cement stabilized base (0–6 inch), lime treated subgrade (6–19 inch) and compacted subgrade (19 inch–).

SIR Results

Results of SIR for Location 1 are shown in Figure 3. Generally, higher values of average mobility indicate delamination (trapped air and water) in the pavement section. From the average mobility contour shown in Figure 3 (a), three points in the pavement section can be identified as having higher mobility. Variation in compaction level and higher water or asphalt content in those points are possible reasons for higher mobility. Figure 3 (b) shows the contour of mobility slope of the pavement section. Again, the contour indicates three zones of higher mobility slope in the same locations as the average mobility contour indicates higher mobility. Locations with higher values of mobility slope indicated the possibility of honeycombing at these locations.
Fig. 3. (a) Average mobility (b) Mobility slope (c) Flexibility (d) Void index contour (Location 1)

Higher flexibility at two locations shown in Figure 3 (c) indicates relative low stiffness and a gap between the base and the subgrade. Variation in compaction level or lower thickness of the base
layer are other possible explanations for higher flexibility. Peak to mean ratio, also defined as the void index, indicates poor support condition and the presence of voids when the numerical value of this parameter exceeds 4. Figure 3 (d) indicates that the selected pavement section is satisfactory in terms of void index except in one location, P6. At this location, the low void index could be explained by water-filled voids. Hence, it can be concluded that point P6 is susceptible to voids due to insufficient compaction.

**Comparison with Geogauge Results**

The results obtained from SIR were compared with the results obtained from Geogauge testing for validation. At each point in Geogauge data collection, three close measurements were taken to reduce error. It has been observed that the Young's modulus measured with Geogauge varied from 8,447 psi to 57,737 psi, presented in Figure 4. The lowest modulus was found at one edge of the pavement (P6). The wet density measured with Nuclear Density Gauge varied from 109.6 pcf to 125.9 pcf. A correlation was observed between lower density values and lower modulus values. Point P6 was located at one of the zones of higher flexibility and had the lowest Young's modulus. Young's modulus was highest for point P4, and the point is located at the zone of lowest flexibility. These trends were found to hold for the majority of points. Based on these associations, the Geogauge results validate the SIR results.

![Fig. 4. Variation of Young’s Modulus with wet density at Location 1](image)

**Location 2**

Location 2 was situated on IH-30 near the Tom Landry Freeway and Avery Street. SIR, DCP, and Geogauge tests were conducted on the site. A 35 ft. by 12 ft. section of pavement was selected for SIR data collection. The DCP and Geogauge tests were performed on 6 different points at 7-ft. intervals across the width of the road. SIR results were validated by results obtained from DCP and Geogauge. The pavement section was consisted of three layers; cement
stabilized base (0~6 inch), lime treated subgrade (6~16 inch) and compacted subgrade (16 inch~).

SIR Results

The average mobility contour from the SIR test, as shown in Figure 5 (a), indicates a large zone of higher mobility in the pavement section. It also indicates that a large zone near P4 and P5 and a small zone near P2 are showing higher values of mobility. The same locations are exhibiting a relatively higher mobility slope, shown in Figure 5(b). Higher values of mobility slope indicate possible locations of delamination. To support the findings from SIR tests, these results were compared with DCP and Geogauge results.

![Fig. 5. (a) Average Mobility, and (b) Mobility slope contour for Location 2](image)

From Figure 6, the Young’s modulus values obtained from Geogauge follow a similar trend as the resilient modulus values obtained from DCP. Young’s moduli increase with the increase of resilient moduli and vice versa.

For the location around point 3, DCP penetrations were minimal for each blow and $M_R$ values were maximum. This may indicate a high-level compaction in that zone. A drop of moduli values from both Geogauge and DCP was observed at points 4 and 5. These are the same points where possible delamination was suspected from SIR results. Thus, the SIR profile could be used to delineate the areas of poor compaction. As such, a pavement engineer could easily determine the location of possible honeycombing and delamination, potentially easing the problem of the pavement health monitoring for ongoing construction.
Degrading infrastructure during evaluation leads to a desire for truly non-destructive testing (NDT) techniques for structural health monitoring of pavement system. While there are established methods to test pavement quality, many are expensive and time-consuming. Because of this, the need for a NDT technique that can accurately indicate areas of low pavement quality arises. The NDT technique of Slab Impulse Response (SIR) was investigated at two different locations in the Dallas, TX area. After data collection and analysis, the SIR results were compared to the results from both dynamic cone penetrometer (DCP) and Geogauge for validation. The SIR results obtained for both Location 1 and Location 2 followed the same trends as the results obtained from the DCP and Geogauge. Test results indicating areas of possible honeycombing, delamination, and poor compaction were observed in the same areas for each testing method. Based on these results, SIR testing could become a standard, non-destructive testing method for checking the quality of pavement during construction phases.

**Fig. 6.** Variation of Young's moduli and resilient moduli at Location 2

**Conclusion**

Degrading infrastructure during evaluation leads to a desire for truly non-destructive testing (NDT) techniques for structural health monitoring of pavement system. While there are established methods to test pavement quality, many are expensive and time-consuming. Because of this, the need for a NDT technique that can accurately indicate areas of low pavement quality arises. The NDT technique of Slab Impulse Response (SIR) was investigated at two different locations in the Dallas, TX area. After data collection and analysis, the SIR results were compared to the results from both dynamic cone penetrometer (DCP) and Geogauge for validation. The SIR results obtained for both Location 1 and Location 2 followed the same trends as the results obtained from the DCP and Geogauge. Test results indicating areas of possible honeycombing, delamination, and poor compaction were observed in the same areas for each testing method. Based on these results, SIR testing could become a standard, non-destructive testing method for checking the quality of pavement during construction phases.
References


