Numerical Seismic Approach For Pavement Investigation

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Abstract— geophysical studies, the seismic reflection is one of the techniques adopted for mapping the subsurface profile. The seismic reflection method consists of detecting and processing recorded waves that reflect when meeting the media stiffness changes. Due to the enhancing in the data processing technologies, this method can be adopted with cost-effective for shallow investigation, detection anomalies such as cavity and shallow subsurface profiling. The objective of this study is to evaluate the seismic reflection method for measuring the shallow profile of the pavement layer compared with the conventional impact-echo method and thus able to identify the thickness of the asphalt layer. To ensure the applicability of the seismic reflection approach in various situations, a concrete slab is constructed as an experimental testing site alongside the asphalt pavement. The measurements of the concrete slab and the asphalt pavement thickness are successfully obtained using both the seismic reflection and the impact-echo methods. An attempt was made to detect the time of the waves’ first arrival using Matlab software, combined with a graphical user interface to accelerate and automate the data processing and results’ calculations.

Index Terms: automatic data processing, asphalt pavement, concrete slab, graphical user interface, impact-echo, non-destructive test, Seismic reflection.

1 INTRODUCTION

Over the past few years, the use of geophysical techniques increased in the engineering domain, and this due to the reliable, repeatable and non-destructive nature of the methods. One of the advantages when using geophysical techniques is that it can be easily implemented with high interpretation accuracy [1]. The asphalt pavement tackiness investigations aim to estimate the pavement current status and sufficiency and to estimate the service-life left of the pavement for the rehabilitation decision. The choice of the testing method relies on not disrupting traffic and most importantly, not to cause any damages to the existing pavement and the measurement accuracy. The current non-destructive methods used for shallow material investigations (i.e., ground-penetrating radar (GPR), seismic analysis of surface waves (SASW) then developed to the multichannel analysis of surface waves (MASW)) offers a fast acquisition data process were various sets of data can be recorded at the same location [2, 3, 4]. This gives reliable statistics to the data acquisition aspect. When evaluating an asphalt pavement, the main goal is to estimate the overall strength, one of the parameters that can express this evaluation is the thickness of the asphalt layer. The direct evaluation is visually examining the dogged pits and extracted cores from the pavement; the disadvantage of this evaluation is that it is destructive [5]. GPR is the most used NDT technique in the pavement inspection but the fact that GPR is very sensitive to clay materials and contaminated materials by salt due to the materials high-conductivity. The heterogeneous materials (rocks) can cause limitation to GPR by scattering the electromagnetic signals

and also water tables buried under pavement layers makes the use of GPR in coastal areas questionable [6]. As the layer directly under the asphalt layer is relatively hard bedrock and giving the fact that is closer to the surface can cause some obscurity to the MASW to detect anomalies for both the pavement layer and the layer beneath the pavement alongside with the high testing cost of the MASW survey makes the use of the MASW a less favourable choice [7].

Meanwhile, the seismic reflection method has proven to be an excellent technique to map the under layers of the earth structure as well as resources explorations. Recent research using seismic reflection shows great promising results for shallow targets less than 1 meter in depth [8, 9, 10], also the fact that the difference between the acoustic impedance of the pavement layer and the underlayer gives enormous potential in pavement surveying using seismic reflection. This method shows great potential in overcoming the existing NDT pavement testing methods’ limitations. Currently, numerous studies using the seismic reflection method have shown great promises in the in mapping the shallow surface of the natural soil [11, 12, 13, 14, 15, 16, 17] as it can be cost and time effective. The objective of this study is to develop and adapt the seismic reflection method as a pavement thickness measurement tool and to compare the accuracy of this method with the establish technique, i.e. the impact-echo method. An approach is made to test a pavement asphalt layer. A concrete slab is constructed to assess the influence of the surface and thickness on the overall accuracy of the seismic reflection method. As the seismic reflection method has proved to be a useful tool in shallow soil investigations, Applying the same principle used for the earth’s subsurface profiling to a pavement system is possible. Thus, to identify the thickness of the asphalt layer without the need for coring mechanism, a seismic p-wave is generated by an impact source and sent into the pavement layers. When reaching the surface course and base course boarders, the difference in stiffness and the discontinuity between the two layers will cause the waves to reflect the surface, where it will be recorded by a piezoelectric sensor to be processed later on. This method analyses the first waves arrivals recorded by the sensors at different locations from the impact source. Therefore, the equipment setup has a significant role in the accuracy of the results. A simple wave propagation theoretical calculation is presented in this study to address this issue, where its time effective and with better control than to be investigated on site. Processing
2 METHODOLOGY

2.1 On-site testing procedure

A 0.15 m concrete slab is built in the research center of soft soil on UTHM to investigate the applicability of the seismic reflection method. The similarity in the seismic velocity between concrete and asphalt pavement justify the concrete slab as a coherent substitute for asphalt in physical modelling to be used for both the seismic reflection method and impact-echo. The constructed concrete slab and an existing road pavement at the UTHM campus were used for testing in this study. The coring test shows that the actual thickness of the tested pavement point was 0.09 m (Figure 1).

Figure 1 shows the cored sample on the tested asphalt pavement, where its divided into two layers wearing course and binder course. Due to the resemblance in the seismic p-wave velocity between the two layers [19], both layers are addressed as one surface layer. This method focusses on the arrival of the p-wave in the time domain without using any external data or any material properties assumption. After detecting the first arrival of the p-waves reflecting from the interface, the analysis can be established. A 6 mm in radius ball bearing is used (Figure 2) as a source (impactor), which sends energy in the material as a hemispherical wave in the receivers' direction.

The receivers are piezoelectric sensors that monitor the surface motion and convert it to a voltage signal. Figure 3 represents the configuration setup used for this technique on asphalt pavement. As the p-waves have the highest propagation velocity among the other waveforms, this gives a great advantage to the technique when working in the time domain. In this arrangement, the first motion recorded by the sensor at distance R1 from the impact location is the reflected p-wave arrival. Therefore, using a minimum of three sensors (one trigger and two sensors) named S0, S1 and S2 respectively, giving the times for the first event recorded tp0, tp1 and tp2 respectively, combined with the geometry of the configuration. the thickness of the material and the velocity can be calculated using the following equations;

\[ T_1 = t_{p1} - t_0 \]  
\[ T_2 = t_{p2} - t_0 \]  
\[ h = \frac{R_2^2 T_1^2 - R_1^2 T_2^2}{4T_2^2 - 4T_1^2} \]  
\[ V_p = \frac{R_2^2 - R_1^2}{T_2^2 - T_1^2} \]

Where:
- tp0, tp1 and tp2 respectively are the first even recorded by the sensors S0, S1 and S2 respectively,
- R1 and R2 are the distance between the source and the first and second receiver,
- T1 is the arrival time of the p-wave at the first receiver S1,
- T2 is the arrival time of the p-wave at the second receiver S2,
- h is the thickness of the material,
- Vp is the velocity of the P-wave of the material.

In this study, the conventional method used to measure
concrete slab thickness known as the impact-echo is used for pavement thickness measurement. In the Impact-echo (IE) method, a source and a receiver are located adjacent on the material surface. Figure 4 shows the configuration of the equipment. The impactor used in the seismic reflection technique is also used for this method which is a 6mm ball bearing. The impact of the ball produces a pressure wave (p-wave) which propagate down through the material and reflects from media interface. The difference in density and velocity between the top and the successive layer cause the reflection to rise. In the case of the pavement system, this difference does not always be sufficient, due to the similarities of the asphalt layer’s properties and the subbase layer. However, the bounding limitation of the pavement and the base layer is almost always enough to generate a discontinuity that can give a clear reflection.

From the geometry of the setup, it is known that the distance that the wave propagates in before detected by the sensor is two times the thickness, therefore:

\[ h = \frac{V_p(T)}{2} \]  

(5)

Where \( h \) the concrete or pavement thickness, \( V_p \) is the p-wave velocity in the material and \( T \) is the round-trip travel time. Similar to the seismic reflection method, the p-wave reflects continually from the interface between the two materials and back to the surface, and back ones more to the interface. Contrary to the seismic reflection, it has been shown that the frequency spectrum analysis of the recorded signal of the impact is much more accurate than measuring the time of the first arrival. Figure 5 shows the characteristics of the Fast Fourier Transform of the recorded signal. The thickness resonance is calculated using the frequency peak. It means that the maximum p-waves (\( V_p \)) arrivals per second have been reached. Therefore, the travel time is the inverse of the peak frequency. Consequently, equation (5) becomes:

\[ h = \frac{V_p}{2f} \]  

(6)

Where \( f \) is the frequency corresponding to the peak in the FFT plot.

The ASTM introduced a 0.96 factor to this equation due to the “plate effect” [20]; therefore, equation (6) becomes:

\[ h = \frac{0.96V_p}{2f} \]  

(7)

The Impact-echo method requires to obtain the value of the \( V_p \) independently. Therefore, a concrete cube obtained from the casted concrete and the cored sample from the asphalt pavement are prepared for an ultrasonic test. Thus, the ultrasonic pundit test was used to measure the seismic velocity of the p-waves \( V_p \), as shown in figure 6. Table 1 shows the ultrasonic results obtained from the pundit test, an average value of 3300 m/s and 3301 m/s found for pavement and concrete material respectively.

Fig. 6 Pundit test ultrasonic testing on concrete and pavement samples
Table 1. Result of the ultrasonic seismic wave (Pundit test)

<table>
<thead>
<tr>
<th>Tested sample</th>
<th>Thickness (m)</th>
<th>P-wave velocity (m/s)</th>
<th>Average p-wave velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement core</td>
<td>0.09</td>
<td>3138</td>
<td>3285</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3478</td>
<td>3300</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.15</td>
<td>3384</td>
<td>3300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3220</td>
<td>3301</td>
</tr>
</tbody>
</table>

2.2 P-wave isolation

Multiple source-receivers spacing was used in theoretical calculations to isolate the P-wave arrival from the S-waves generated by the source in the seismic reflection method. The principle applied for this isolation is to calculate the theoretical time needed for the P-wave to travel down the pavement and back using the geometry of the site and the seismic velocity for each wave type, where the ultrasonic test shows that the P-waves travels at a speed of 3300 m/s along a trigonometric course. Meanwhile, the S-waves travels in a direct route at 1800 m/s [19, 21]. Figure 7 shows a plot of both the P-waves and S-waves first arrival time from a 0.15 m concrete slab. When changing the receiver location from the source, it is shown that after a spacing of 0.2m, the p-waves start to arrive sooner than the s-waves.

2.3 Automatic data processing approach

As the detection of the p wave first arrival can be challenging for non-experts in signals processing, where most often the signal recorded is associated with some background noise. An automatic detection using Matlab software is developed in this study to deal with this issue. The code is divided into two sections. First, an artificial neural network is developed as a signal processing technique, then a graphical user interface to ease and speed up the results calculations.

2.3.1 Artificial Neural Network (ANN)

This approach consists of finding starting points for a given dataset using artificial neural network. To accomplish this task 3 principal codes are written in Matlab .m file; first is data saving, where the range of starting points using the average method for a certain .mat file which is exported from the data acquisition software DEWESoft for a given seismic reflection test. The data saving is divided into two parts; first normalizing the given data between 0 and 1. Next, finding the average of two adjacent points. Were the noisy values are rounded to zero, and the peak point of the data plot is viewed (Figure 8).

After getting the range of starting point, the exact value of the starting point must be found. To fulfil this purpose, a Feed-forward neural network has been used to train the model so that it can learn from the given dataset (Table 2). A training of 15 data files is used for this ANN learning, the optimal weight values are saved and will be used to extract the time for an unknown dataset which is not used in ANN training.

Table 2. ANN training parameter set

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter of ANN</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Number of inputs</td>
<td>157</td>
</tr>
<tr>
<td>2</td>
<td>Number of outputs</td>
<td>3 (tp1, tp2 and tp3)</td>
</tr>
<tr>
<td>3</td>
<td>Iterations</td>
<td>5000</td>
</tr>
<tr>
<td>4</td>
<td>Learning rate</td>
<td>0.001</td>
</tr>
<tr>
<td>5</td>
<td>Momentum term</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The successful completion of the data training allows for the ANN to minimize the error to almost zero when the iterations reach 5000 alongside the finding starting points for tp1, tp2 and tp3 matches with the desired ones (Figure 9).
After the completion of the Artificial Neural Network, the primary and last code which consist of the two parts described above is used for detection the first arrival for any given data file obtained from the seismic reflection method automatically. After running the main code on a .mat file The Matlab command code shows the values of tp1, tp2 and tp3 respectively corresponding to the first event recorded of the p-waves for the trigger sensor S0, first receiver S1 and second receiver S3 respectively.

2.3.2 Graphical user interface (GUI)

GUIs (also known as graphical user interfaces or UIs) provide point-and-click control of software applications, eliminating the need to learn a language or type commands in order to run the application [22]. Here a simple GUI is constructed for the data processing part and results’ presentation. The GUI is constructed in Matlab software using an artificial neural network code for first arrival time detection and equations (1), (2), (3) and (4) for results calculations. While using this GUI; the operator needs to input the testing setup configuration and call for the exported .mat file to directly obtain the calculated thickness h and seismic velocity Vp (Figure 10).

3 RESULTS AND DISCUSSIONS

After obtaining the optimum source-receiver spacing distance from the p-wave isolation theoretical calculation, the results are shown in table 3. It was found that the spacing of the sensors equal to two times the targeted depth is the most suitable to isolate the p-waves arrival time from S-waves, also to ensure a sufficient signal to noise ratio to be recorded by the farthest sensor. The results attained from the p-wave isolation for the seismic reflection. A 0.02 m source to receiver spacing for impact-echo to ensure a high-frequency wave propagation. Three tests were conducted for each method to investigate its repeatability. All sensors were connected to a DEWESoft mini data acquisition system and displayed in real-time using the DEWESoftX2 interface. The output data were extracted for MATLAB software for processing.

<table>
<thead>
<tr>
<th>Material thickness (m)</th>
<th>receivers spacing distance (m)</th>
<th>reflected wave Distance (m)</th>
<th>Time of reflected wave (ms)</th>
<th>Time of direct wave (ms)</th>
<th>First arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.100</td>
<td>0.316</td>
<td>0.096</td>
<td>0.056</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>0.150</td>
<td>0.335</td>
<td>0.102</td>
<td>0.083</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>0.200</td>
<td>0.361</td>
<td>0.109</td>
<td>0.111</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>0.250</td>
<td>0.391</td>
<td>0.118</td>
<td>0.139</td>
<td>P</td>
</tr>
<tr>
<td>0.09</td>
<td>0.050</td>
<td>0.187</td>
<td>0.057</td>
<td>0.028</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>0.100</td>
<td>0.206</td>
<td>0.062</td>
<td>0.056</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>0.150</td>
<td>0.234</td>
<td>0.071</td>
<td>0.083</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>0.200</td>
<td>0.269</td>
<td>0.082</td>
<td>0.111</td>
<td>P</td>
</tr>
</tbody>
</table>

Figure 11 demonstrates an example of a recorded seismic reflection method using three receivers. Furthermore, an example of a recorded Impact-echo method was recorded the peak frequency of 18 kHz at the pavement.
The measurements are summarized in Table 5 from both the seismic reflection and the impact-echo methods. Both methods successfully obtain the thickness of both the pavement and the concrete slab. The impact-echo method demonstrates a limitation where the p-wave velocity must be measured with an alternative method, and another limitation arises when testing on a rough pavement surface, which affects the contact time between the impactor and the surface giving errors in the frequency spectrum. In this study, this limitation was overcome by flattening the test points on the pavement. The impact-echo method shows less than 3 % error compared with the seismic reflection at an average of 6 % error.

Table 5. Thickness calculation and errors results

<table>
<thead>
<tr>
<th>Test method</th>
<th>Actual thickness/structure</th>
<th>0.09 m / pavement</th>
<th>0.15 m / concrete slab</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Testing no.</td>
<td>Thickness (m)</td>
<td>Error %</td>
</tr>
<tr>
<td>Seismic reflection</td>
<td>1</td>
<td>0.096</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.088</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.095</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.093</td>
<td>3</td>
</tr>
<tr>
<td>Impact-echo</td>
<td>1</td>
<td>0.087</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.088</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.086</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.087</td>
<td>2</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

The p-wave isolation calculations have confirmed the feasibility of the seismic reflection method. This study shows that the p-wave reflections from the bottom of the asphalt pavement layer can be detected and distinguished from the direct s-wave arrivals. This separation can occur if the arrival measurements are made at the appropriate distance from the source. The seismic reflection directly measured the thickness and velocity of the material without any test location preparation, but less accuracy and low repeatability rate. This is due to the difficulty in detecting the first seismic wave arrival by the receivers. The artificial neural network and the use of the GUIs show high potentials as a fully automatic data processing technique. However, this approach still suffers from some inaccuracy in time detection when changing the sampling time and sampling rate in the acquisition. Thus, further studies and devotion to improving additional data sets in training the ANN are needed which are considered to some extent as destructive.
ACKNOWLEDGMENT
The authors would like to thank the Ministry of Higher Education and Universiti Tun Hussein Onn Malaysia for their financial support on FRGS vot. K049 and TIER 1 vot H183, respectively.

REFERENCES