Asphalt Pavement Thickness Measurement Using the Seismic Reflection Technique

Sid Ahmed Remmani, Aziman Madun, Nurul Hidayah Binti Mohd Kamaruddin

Abstract: subsurface profile mapping is achieved using variant geophysical methods, the commonly used method is the seismic reflection. Stiffness change between layers produces reflected waves. Hence the detection of these waves is the concept of the seismic reflection method. The state-of-the-art technologies in signal processing give great advantage to this method, where it can be adopted for shallow investigation cost-effectively to detect anomalies in a non-distractive manner. Measuring the thickness of a paved area using the seismic reflection alongside a conventional method i.e. impact-echo is the main objective in this study. The conventional method to identify asphalt thickness via coring suffers from several limitations, such as damaging the pavement site and the limited number of testing. Due to the similarity between asphalt pavement and concrete in the seismic properties, a concrete slab is used as an experimental testing site for a sole purpose of investigating the applicability of both methods is various site conditions. The thickness of the tested pavement site and the constructed concrete slab are successfully attained using both methods.

Index Terms: asphalt pavement, concrete slab, geophysical methods, impact-echo, non-destructive, seismic reflection.

1. INTRODUCTION

Over the past few years. The use of geophysical techniques in-creased in the engineering domain, and this due to the reliable, repeatable and non-destructive nature of the methods from which it can be easily implemented with high interpretation accuracy after calibrating procedures to the specific objective [1] [2]. The pavement layer thickness is one of the essential factors when investigating the quality of the pavement since the thickness plays a leading role in the pavement life expectancy. Significant focus is now given to the geophysical techniques by the engineering community due to the non-invasive and non-destructive nature of the techniques which can overcome the limitations of the conventional methods (coring) [3]. Currently, numerous studies using the seismic reflection method have shown great promises in the in mapping the shallow surface of the natural soil [4] [5] [6] [7] [8] [9] [10] 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 [11]. An approach is tested on the pavement structure at 9 cm thickness. Besides, a 15 cm concrete slab is constructed to assess the influence of the surface and thickness on the overall accuracy of the seismic reflection method.

2 METHODOLOGY

The seismic reflection method focusses on the arrival of the p-wave in time-domain without using any external data or any material properties assumption. After detecting the first arrival of the p-waves reflecting from the base-pavement interface and the soil-concrete interface, the analysis can be established. Figure 1 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. A 5 mm in radius ball bearing is used as a source (impactor) sends energy in the pavement/concrete slab as a hemispherical wave in the direction of the receivers' direction. The receivers are piezoelectric sensors that monitor the surface motion and convert it to a voltage signal. In this arrangement, the first motion recorded by the sensor at distance R1 from the impact location is the reflected p-wave arrival. Using the geometry analysis of the configuration and a minimum of three receivers (trigger and sensors) the thickness of the medium, h and the velocity, Vp can be calculated using the following equations;

$$h = \left(\frac{R_2{}^2 T_1{}^2 - R_1{}^2 T_2{}^2}{4T_2{}^2 - 4T_1{}^2}\right)^{1/2} \quad (1)$$

And

$$Vp = \left(\frac{R_2{}^2 - R_1{}^2}{T_2{}^2 - T_1{}^2}\right)^{1/2} \quad (2)$$

Where:
R_1 and R_2 are the distance from the source to the first and second receiver, respectively,
T_1 and T_2 are the arrival time of the P-wave at the first and second receiver, respectively,
h is the thickness of the tested medium,
Vp is the velocity of P-wave of the asphalt layer/concrete slab

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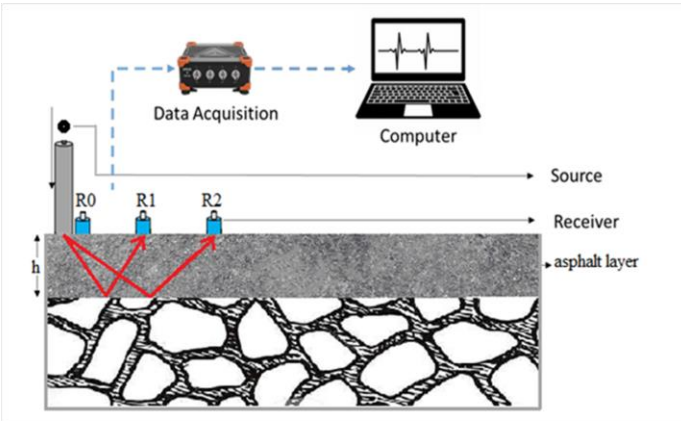


Fig. 1. testing equipment setup.

Meanwhile, in the Impact-echo (IE) method a source and a receiver are located on the pavement/concrete slab surface. Figure 2 shows the configuration of the equipment. The impactor used in the seismic reflection technique is also used for this method which is a ball bearing. The impact of the ball produces a pressure wave (p-wave) which propagate down through the pavement and reflects from media interface. The difference in density and velocity between the top and the successive layer causes the reflection to happen. 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 dis-continuity that can give a clear reflection.

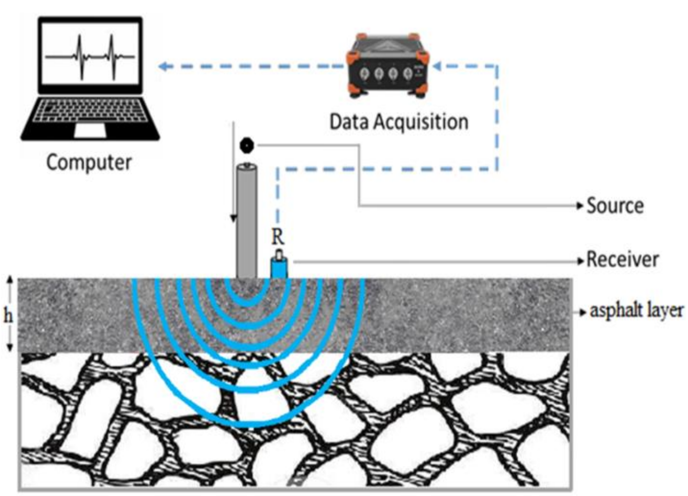


Fig. 2. Impact-echo testing equipment setup.

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

$$h = \frac{Vp(T)}{2}$$
(3)

Where h the concrete or pavement thickness, Vp 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 analysis of the frequency spectrum of the recorded signal of the impact is much more accurate than measuring the time of the first arrival. Figure 3 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 (Vp) arrivals per second have been reached. Therefore, the travel time is the inverse of the peak frequency. Consequently, Equation (3) becomes:

$$h = \frac{Vp}{2f}$$
(4)

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

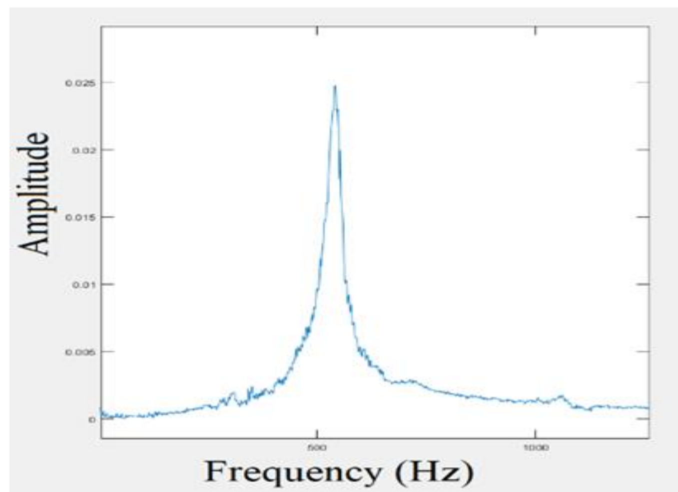


Fig. 3. FFT plot for a corresponding signal recording.

The ASTM introduced a 0.96 factor to this equation due to the "plate effect" [12]; therefore, Equation (4) becomes:

$$h = \frac{0.96Vp}{2f}$$
(5)

3 TESTING PROCEDURE

The existing road pavement at the campus was used as a site for testing. The coring test shows that the actual thickness of the tested pavement was 9 cm. Meanwhile, the concrete slab was constructed at a thickness of 15 cm. The concrete cube was prepared for the ultra-sonic test. The Impact-echo method requires to obtain the value of the Vp independently. Thus, the ultrasonic pundit test was used on samples extracted from the same material to measure the Vp, as shown in Figure 4. Table 1 shows the ultrasonic results. From the ultrasonic pundit test obtained the average value of 3300 m/s and 3301 m/s for pavement and concrete material respectively

Fig. 4. *Pundit test equipment illustration.*

The coring test shows that the actual thickness of the tested pavement is 9 cm. Multiple source-receivers spacing was used and spacing of two times the targeted depth was found to be optimum to isolate the p-wave arrival from the other waves generated by the source in the seismic reflection method and a 2 cm spacing in the impact-echo to ensure a high-frequency wave propagation. All sensors were connected to a DEWESoft mini data acquisition system and displayed in real-time using the DEWESoftX2 interface.

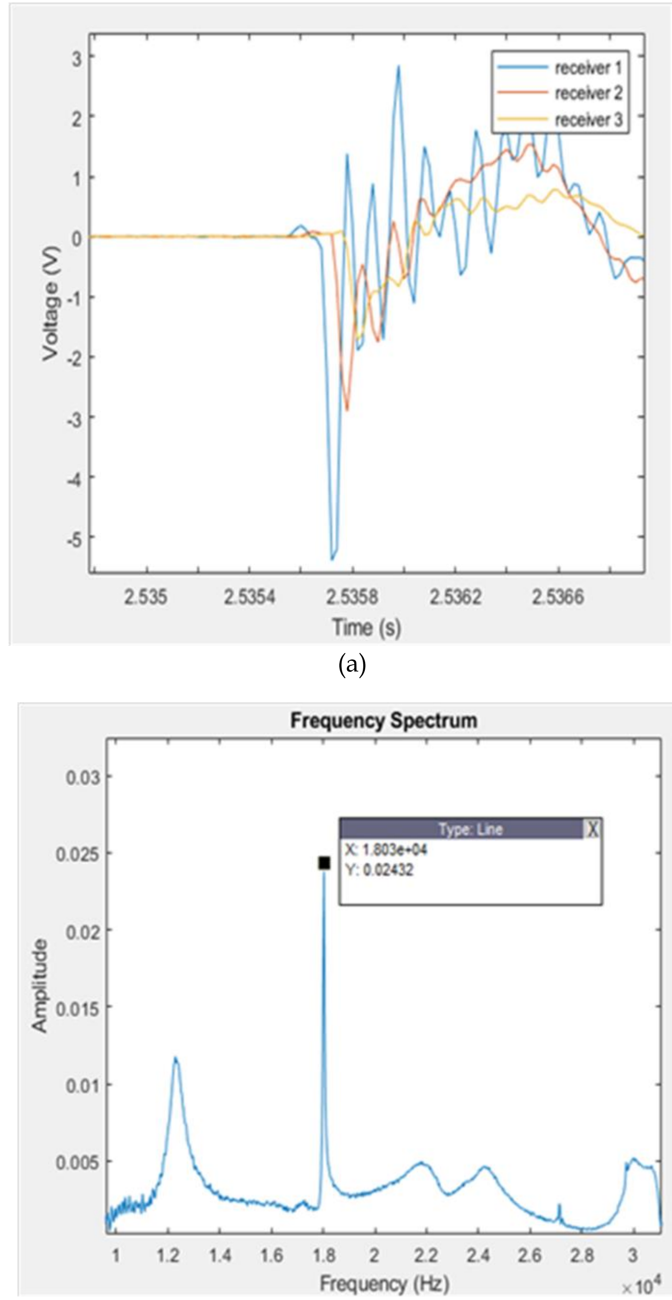
Table 1*: Result of the ultrasonic seismic wave (Pundit test).*

Tested sample	thickness (cm)	P-wave velocity (m/s)		average p-wave velocity (m/s)	
pavement core	9	3138	3285	3478	3300
concrete	15	3384	3300	3220	3301

Multiple source-receivers spacing was used [13] and a spacing of two times the targeted depth was found to be optimum to isolate the p-wave arrival from the other waves generated by the source in the seismic reflection method. Also, a 2 cm source to receiver spacing was used in the impact-echo to ensure a high-frequency wave propagation. All sensors were connected to a DEWESoft mini data acquisition system and displayed in real-time using the DEWESoftX2 interface.

4 RESULTS AND DISCUSSIONS

Three tests were conducted for each method to investigate its repeatability. The output data were extracted for MATLAB software for processing. Figure 5 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.



(a)

(b)

Fig. 5. *(a) voltage amplitude versus time recording of waves on a concrete slab, (b) Fast Fourier transform of a signal obtained on a paved site.*

Table 2 shows the data obtained from the two methods. T1 represents the difference between the time of the first event recorded by receiver 1 and receiver 2, while T2 represents the difference between the time of the first event recorded by receiver 1 and receiver 3. The first arrival time is observed and extracted from the plot of the voltage vs time created by MATLAB. The peak frequency (f) is the frequency that corresponds to the highest voltage amplitude in the FFT plot of the data signal. Using the equations (1), (2) and (5); the thickness of both the pavement and the concrete slab is calculated and tabulated in Table 3.

Table 2. *results from the seismic reflection method and the impact-echo method.*

Test method	Testing no.	Tested structure	Pavement	Concrete slab
		Actual thickness (cm)	9	15
Seismic reflection	1	T1 (ms)	0.07	0.26
		T2 (ms)	0.08	0.28
		Vp (m/s)	2236	1667
	2	T1 (ms)	0.09	0.12
		T2 (ms)	0.0975	0.14
		Vp (m/s)	2309	2402
	3	T1 (ms)	0.07	0.1
		T2 (ms)	0.08	0.11
		Vp (m/s)	2236	3780
Impact-echo	1	f (Hz)	18030	10340
	2	f (Hz)	16750	10120
	3	f (Hz)	15860	10021

The measurements are summarized in Table 3 using both methods. Both methods successfully obtain the thickness of both the pavement and the concrete slab. Given the rugged nature of the pavement surface, the impact-echo method demonstrates a limitation alongside with the fact that the p-wave velocity must be measured with an alternative method, this limitation arises when testing on a rough pavement surface, which affect the contact time between the impactor and the surface giving errors in the frequency spectrum. In this study, this limitation was overcome by flatting the test points on the pavement. The impact-echo method shows less than 6% error compared with the seismic reflection at more than 16% error. Besides, repeatability for the impact-echo test is better than seismic reflection.

Table 3. *thickness calculation and errors result.*

Test method	Actual thickness/ structure	9 cm / pavement		15 cm / concrete slab	
	Testing no.	Thickness (cm)	Error %	Thickness (cm)	Error %
Seismic reflection	1	7.4	18	21.1	41
	2	10.1	12	13.5	10
	3	7.4	18	18.2	21
	Average	8.3	16	17.6	24
Impact-echo	1	8.8	2	15.3	2
	2	9.5	5	15.7	4
	3	10.0	11	15.8	5
	Average	9.4	6	15.6	4

4 CONCLUSIONS

The 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. Meanwhile, this study shows that the impact echo method can provide accurate measurements and reasonable repeatability rate. However, this method required a separated velocity measurement to determine the thickness. Giving the fact that the velocity can change from one location to another, the accuracy of the method is questionable when changing test location along the pavement, which can be in the order of kilometres. This issue should be addressed in future studies. However, discussions with experienced practitioners have indicated that the method is not recommended for pavement investigation due to the crucial role of the contact surface where most often; sites preparations are needed which are considered to some extent as destructive.

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REFERENCES

[1] Pugin, AJ-M, Kevin Brewer, Timothy Cartwright, Susan E Pullan, D Perret, Heather Crow, and James A Hunter, Near surface S-wave seismic reflection profiling–new approaches and insights. First Break, 2013. 31(2): p. 49-60.

[2] Reyes, Carlos Francisco Castro Soto, The crustal and sedimentary structure of the Amundsen Basin, Arctic Ocean, derived from seismic reflection and refraction data. 2018, Niels Bohr Institute, Faculty of Science, University of Copenhagen.

[3] Cui, Peide, Yue Xiao, Mingjing Fang, Zongwu Chen, Mingwei Yi, and Mingliang Li, Residual fatigue properties of asphalt pavement after long-term field service. Materials, 2018. 11(6): p. 892.

[4] Mohanty, Priya R, Numerical modeling of P-waves for shallow subsurface cavities associated with old abandoned coal workings. Journal of Environmental & Engineering Geophysics, 2011. 16(4): p. 165-175.

[5] Sun, Ruixue, A Kaslilar, and Christopher Juhlin. Seismic Imaging of Shallow Groundwater Resources in Glacial Deposits, Sweden. in 25th European Meeting of Environmental and Engineering Geophysics. 2019. European Association of Geoscientists & Engineers.

[6] Buckley, Sean F and John W Lane. Near-Surface VOID Detection using a Seismic Landstreamer and Horizontal Velocity and Attenuation Tomography. in 25th Symposium on the Application of Geophpysics to Engineering & Environmental Problems. 2012.

[7] Zahari, MNH, A Madun, SH Dahlan, A Joret, ZAM Hazreek, AH Mohammad, and RA Izzaty. Shallow Reflection Method for Water-Filled Void Detection and Characterization. in Journal of Physics: Conference Series. 2018. IOP Publishing.

[8] Song, Wenxin, Locating Petroleum Sources Using Dsp Techniques. 2015.

[9] Zahari, MNH, A Madun, SH Dahlan, A Joret, MH Zainal Abidin, AH Mohammad, and AH Omar. Experimental Detection and Characterization of Void using Time-Domain Reflection Wave. in

Journal of Physics: Conference Series. 2018. IOP Publishing.
[10] Remmani, Sid Ahmed, Aziman Madun, and Haroun Benmalek, Shallow reflection method for pavement thickness measurement. J. Fundam. Appl. Sci, 2020. 12(1S): p. 324-334.
[11] Roudari, Sajjad Sayyar, Theophilus Okore-Hanson, Sameer Hamoush, Younho Seong, Sun Yi, Taylor Szeto, and Jean Plummer. Robotic Non-destructive Test of Concrete Structures with GPR, Impact Echo and 3D Vision. 2019.
[12] ASTM, C1383-15, Test method for measuring the P-wave speed and the thickness of concrete plates using the impact-echo method. Annual Book of ASTM Standards, 2000. 1383(04.02).
[13] Metwaly, Mohamed, Alan G Green, Heinrich Horstmeyer, Hansruedi Maurer, and Abbas M Abbas, Combined Seismic Tomographic and Ultra-Shallow Seismic Reflection Study of an Early Dynastic Mastaba, Saqqara, Egypt, in Archaeogeophysics. 2019, Springer. p. 83-99.