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Comparison of Impact-Echo with Broadband Input to Determine Concrete Thickness

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Abstract

Existing concrete slabs and pavements often have unknown thickness and condition. Impact Echo technology is frequently used to determine thickness of concrete slabs and pavements. This method uses an impact device to excite the structure, and an FFT analysis to locate a resonant frequency in the response. However, each impact device has its own characteristic input and frequency and depending on the actual concrete thickness, hardness, and texture, affects the frequency content and hence influences the result. New technology uses pulsing crystals (Pulse Echo) to generate a broadband frequency input which excites only the true resonant frequency of the slab or pavement. Requirements for self calibration and testing procedures are discussed. Comparisons for a variety of thicknesses and concrete surface conditions are presented showing the superiority of the broadband method over traditional Impact Echo method.

INPUT CHARACTERISTIC AND FREQUENCY

Impact Echo Method

The Impact Echo method (IE) is based on the use of a short duration mechanical impact to generate transient stress waves within the concrete specimen. The impact duration (contact time), the time that the impact device is in contact with the test surface, is a critical aspect to the success of the Impact Echo method. The impact duration will depend on the size and type of impact device and the condition of the concrete at the point of impact. Typical impact devices are steel balls of various diameters or solenoid devices. As an example, for a given impact device, smooth hard surfaces will result in shorter impact durations than rough soft surfaces.

Pulse Echo Method

The Pulse Echo method (PE) is based on the use of a transmitter/sensor to administer broadband waves to the concrete surface. The sensor is made of piezoelectric crystal (PZT) elements. A short duration high voltage pulse is applied to the PZT elements. The applied voltage pulse induces crystal contraction/expansion. The contraction/expansion produces a pressure pulse which emits a broadband wave field into the concrete. The wave field generated by the crystals, unlike mechanical impact, is independent of the surface condition (hardness and texture). These features are incorporated in the Acoustic Concrete Tester (ACT) by Pile Dynamics used to make all Pulse Echo tests reported in this paper.

Contact Time

Contact time is the most important parameter to excite a concrete specimen for thickness measurement. A wide range of frequency components in the radiated wave field ensures that a frequency corresponding to the concrete thickness is stimulated. The range of frequencies contained in the wave field is proportional to the inverse of the contact time and the amplitude of the frequency components is proportional to the contact time. (i.e. as contact time decreases the range of frequencies increase, but the amplitude of the frequency components decrease).

The contact time can be measured from the initial portion of the waveform. Contact times were determined for both the pulse and impact generated surface waves on specimens with various hardness and texture. Test setup included a broadband PZT sensor to receive the surface wave arrival, a digital oscilloscope to display and analyze the received signal, Pulse Echo test equipment for pulse generated wave input, and Impact Echo test equipment for the mechanical impact generated wave input. Input waves were applied near the broadband receiver. Figure 1 shows the contact time of a waveform generated on a smooth concrete surface by the Pulse Echo and Impact Echo methods. Table 1 lists the measured contact times and corresponding limiting frequency for various surfaces using the same recording equipment.

Table 1 Measured contact time and frequency for pulse and impact methods

Contact Surface	PE Contact Time (μs)	PE Frequency Component (KHz)	IE Contact Time (μs)	IE Frequency Component (KHz)
Smooth concrete	24	42	55	18
Rough concrete	24	42	65	15
Very rough concrete	24	42	75	13
Tiled concrete	24	42	80	12.5
Asphalt	24	42	125	8

As can be seen from Table 1, the frequency components of the Pulse Echo (PE) wave field are independent of the contact surface hardness and texture, whereas, the frequency components of a given Impact Echo (IE) wave field are dependent upon the contact surface hardness and texture. As the contact time becomes longer, the maximum frequency component decreases, thus the ability to measure thin specimens decreases. The Pulse Echo inputs of shorter duration and higher frequency content therefore inherently facilitate better results when testing thinner specimens.

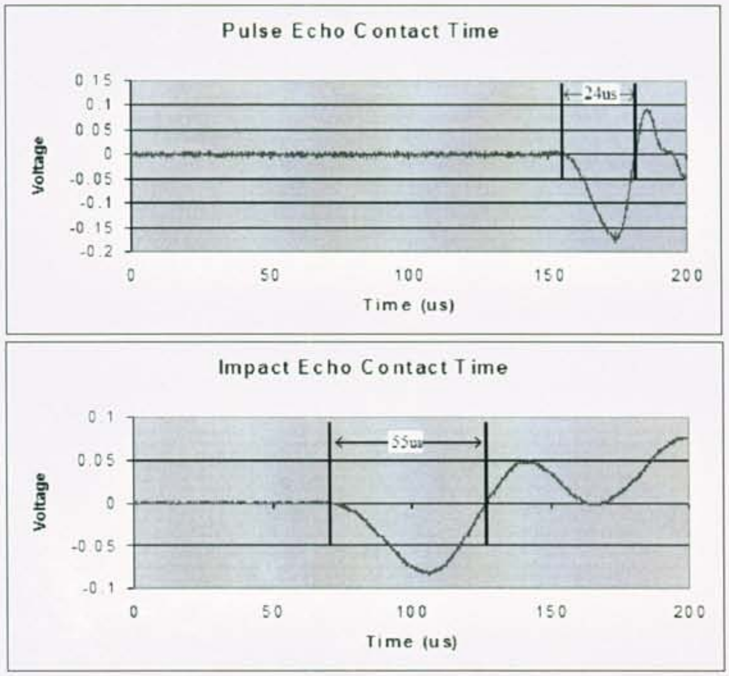

Fig.1 Pulse Echo (broadband crystals) and Impact Echo (solenoid) generated surface waveform on smooth concrete

RESONANCE METHOD

Waves generated by either the Pulse Echo or Impact Echo method can be used to estimate the concrete thickness using the Resonance Method. The wave field generated by the pulse or impact propagates through the concrete. The input sets up a repetitive reflection of many cycles in the relatively thin concrete specimen corresponding to the shortest travel path. A waveform with period T (corresponding to twice the object thickness, TH) develops (Equation 1). Using a high sampling frequency and real time FFT (Fast Fourier Transform) the waveform is transformed into the frequency domain and allows determination of the dominant frequency which corresponds to the background echo reflections (discontinuity due to concrete-to-air or concrete-to-sub-grade interface). In the case of additional discontinuities in the specimen like spalls, delaminations, or horizontal flaws, the frequency spectrum will identify additional frequencies.

Thickness Measurement

For either method (Pulse Echo or Impact Echo), thickness measurements are obtained from the resonant frequency which corresponds to twice the specimen thickness. The specimen thickness is given by the equation:

$$TH = Ws/\{2F\} \quad (1)$$

Where "Ws" is the P-wave speed and "F" is the dominant resonant frequency of the waveform.

Thickness measurement of the Pulse Echo test equipment is best obtained by placing the receiver and transmitter sensors in close proximity on a clean concrete surface and applying the broadband pulse. The tested concrete surface may be painted or covered with bonded floor tile. Figure 2 is the frequency spectrum with dominant peak corresponding to the resultant thickness TH (test location T9).

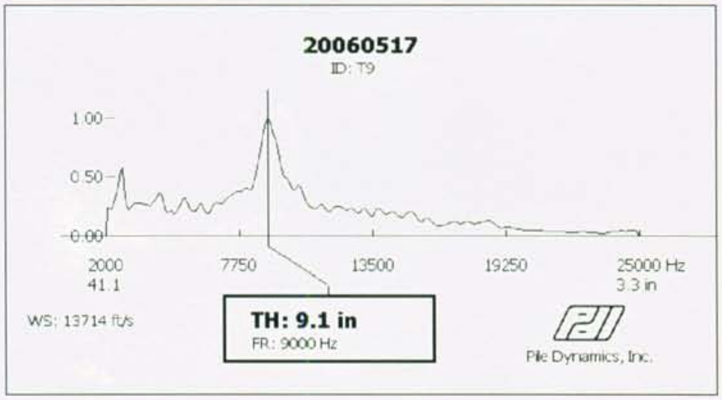

Fig.2 Frequency spectrum with resultant thickness TH - test location T9

Thickness measurement of the Impact Echo test is obtained by placing the receiver sensor on the clean concrete surface and physically applying nearby the mechanical impact (i.e. from a solenoid). The concrete surface may be painted or covered with bonded floor tile. The standard commercial Impact Echo test equipment used did not have the capability to create a hard copy of the resultant frequency response.

Wave speed Measurement

As noted in equation 1, the wave speed (measured or assumed) is used to convert the measured resonant frequency into the concrete thickness. According to ASTM C 1383, the concrete P-wave speed of an unknown thickness can be determined by measuring the direct surface P-wave in the concrete. P-wave speed is then calculated by dividing the distance between two sensors Δd by the arriving time delay Δt. The measured P-wave speed gives a more accurate thickness than an assumed wave speed.

The basic Impact Echo test equipment was not equipped to measure the direct surface P-wave speed of an unknown thickness. If a specimen with a known thickness is available, the wave speed can be "calibrated". If the thickness is unknown, a destructive core could be obtained to determine thickness but usually an assumed wave speed is used (with resulting uncertainty). However, the standard Pulse Echo test equipment (ACT) is equipped to measure the P-wave speed of an unknown thickness. The transmitter and receiver sensors are spaced approximately twenty four (24) inches (610 mm) apart on clean concrete surface. The Δt is measured as the P-wave initiation time (T0) subtracted from the direct surface P-wave initial arrival time at the receiver sensor (T1). Figure 3 shows the resultant P-wave speed measurement (test location T9).

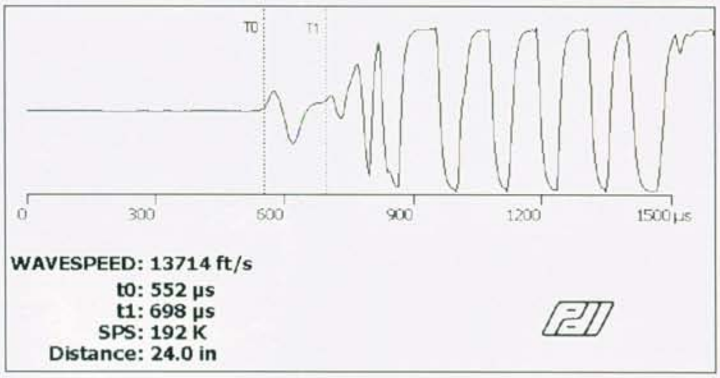

Fig.3 Wave speed measurement test location T9

The measurement of the direct surface P-wave generated by the pulse and impact was investigated. The test included use of two broadband PZT sensors to detect the applied wave field and direct surface P-wave and a digital oscilloscope to display and analyze the signal. Pulse Echo and Impact Echo generated wave fields were both applied six (6) inches (152 mm) from the first receiver. The direct P-wave was distinguishable for the Pulse Echo generated wave field but not for the Impact Echo generated wave field.
The magnitude of the wave field transmitted into the concrete by the Pulse Echo transmitter is significantly greater than the magnitude of the wave field transmitted by the Impact Echo impact device. Magnitude of the wave field is critical to ensure the direct P-wave is received for wave speed measurement. A larger magnitude wave field also provides better operational performance for rough surface and sub-grade (background) conditions.

PULSE ECHO VERSUS IMPACT ECHO CONCRETE THICKNESS MEASUREMENT COMPARISON

Concrete P-wave speed and thickness measurement tests were conducted using both a Pulse Echo system (ACT) and an Impact Echo system. The concrete specimens had various thickness, wave speed, surface condition, support condition, and shape. The concrete specimens tested were categorized as a) Smooth surfaced concrete slabs with sub-grade (actual thickness unknown), b) Smooth surfaced concrete slabs with no sub-grade (background interface is air and actual thickness known), c) Rough surfaced concrete slabs with sub-grade (actual thickness unknown), and d) Smooth surfaced concrete pipe with no sub-grade (actual thickness known).

Thickness measurements by the Pulse Echo method were based on wave speeds determined from measurement of the direct surface P-wave using the Pulse Echo test equipment.

Thickness measurements by the Impact Echo method were based on the recommended default wave speed of 12,000 ft/sec (3657 m/sec) for specimens with unknown thickness and a "calibrated wave speed" for specimens with a known thickness. The "calibrated wave speed" was determined from the known thickness and measurement of the resonant frequency using the Impact Echo test equipment. Since, the calibration determines the unknown wave speed from the known thickness, a thickness "measurement" becomes a self fulfilling prophecy.

Thickness measurements were performed on twelve different test specimens. For each specimen, thickness measurements at four locations spaced 6 inches (152 mm) apart in a square pattern were attempted. There was a maximum of five test attempts to obtain a measurement at each of the four locations. For each test specimen, the average at the four measurement locations was determined and recorded in Table 2.

Test specimens T1, T2, and T3 had smooth surface and were on a sub-grade (warehouse floor). Actual thicknesses were not measurable. For T1 and T2, differences in PE and IE thickness measurement was a result of different wave speeds (i.e. measured P-wave speed by PE, assumed for IE). For T3, the difference in PE and IE thickness measurement was a result of different wave speed and different peak resonant frequency.

Test specimens T5, T6, T7, and T12 had rough surface and were on a sub-grade. Actual thicknesses were not measurable. On the rough surface, the Impact Echo test equipment often required numerous test attempts to obtain a thickness measurement. If a measurement was not obtained after five test attempts, "No Data" was counted for that location (measurements were taken at four locations for each test specimen with a maximum of five attempts per location). There was one "No Data" for T5 (only three locations were used of the four locations), three "No Data" for T6 (result at only one location), and four "No Data" for T12 (no result obtained in any of the four locations). T12 was the roughest surface, a deep brushed sidewalk. The Pulse Echo method achieved a measurement on the first test attempt at all four locations for each test specimen. Where measurements were obtained, differences in PE and IE thickness measurement was a result of different wave speeds (i.e. measured P-wave speed by PE, assumed for IE) and demonstrates the importance of the actual wave speed measurement. The percent error (ϵ) compared with the Design TH is shown in Table 2 for both PE and IE results.

Table 2 Thickness (TH) from Pulse Echo (PE) and Impact Echo (IE) Methods

T	Surface	Design TH	PE TH	PE ϵ	IE TH	IE ϵ	No Data	
		in (mm)	in (mm)	%	in (mm)	%	PE	IE
1	smooth	6 (152)	6.5 (165.1)	8.3	5.9 (149.9)	-6.0	0	0
2	smooth	8 (203)	8.0 (203.2)	0.0	7.6 (193.0)	-5.0	0	0
3	smooth	10 (254)	10.7 (271.8)	7.0	**7.4** (188.0)	-26.0	0	0
4	smooth	8 * (203)	7.9 (200.7)	-1.3	8.0 (203.2)	0.0 *	0	0
5	rough	10 (254)	10.5 (266.7)	5.0	**8.0** (203.2)	-20.0	0	1
6	rough	10 (254)	10.0 (254.0)	0.0	**8.4** (213.4)	-16.0	0	**3**
7	rough	9 (229)	8.8 (223.5)	-2.2	**7.4** (188.0)	-17.8	0	0
8	smooth	19* (483)	19.2 (482.6)	1.1	19.0 (482.6)	0.0 *	0	0
9	smooth	9 * (229)	9.1 (231.1)	1.1	9.1 (231.1)	1.1 *	0	0
10	smooth	7 * (178)	7.0 (178.8)	0.0	7.0 (178.8)	0.0*	0	0
11	smooth	7* (178)	7.0 (178.8)	0.0	7.0 (178.8)	0.0 *	0	0
12	v rough	4.5 (114)	5.3 (134.6)	18	**	**	0	**4**

*** Test specimens with access to top and bottom and actual thickness measured**
**** Thickness measurement and computed error (ϵ) could not be obtained (no signal)**

Test specimens T4, T8, and T9 had smooth surface and were not on a sub-grade. Actual thicknesses of 8 inches (203 mm) for T4, 19 inches (483 mm) for T8, and 9 inches (229 mm) for T9 were measured. Thickness measurements using the Pulse Echo test equipment were within 1.3% of the actual thickness using the wave speed determined by measurement of the direct surface P-wave. Thickness results using the Impact Echo test equipment were within 1.1% of the actual thickness as expected because wave speed was calibrated to the user input actual thickness. Error (ϵ) in thickness measurements was due to wave speed variance at the four test locations and equipment frequency and wave speed resolution.

Test specimens T10 and T11 were concrete pipes with a smooth curved surface and were not on a sub-grade. Actual thickness of 7 inches (178 mm) was measured. T10 was on a 72 inch (1829 mm) inside diameter and T11 was on 86 inch (2184 mm) outside diameter. Thickness measurements for Pulse Echo based on the measured P-wave speed matched the actual thickness. The known thickness was used by the Impact Echo to calibrate the wave speed.

Conclusion

The Pulse Echo method has distinct advantages over the Impact Echo method to determine concrete thickness. The frequency components of the Pulse Echo generated wave field are independent of the material hardness and texture and remain constant. The capabilities to measure thin specimens will not diminish for softer, rougher surfaces as is the case with Impact Echo. The wave field magnitude transmitted into the concrete by the Pulse Echo test method is larger, providing superior thickness measurement and P-wave speed measurement capabilities on rough surface and thicker specimen conditions. Specimens on grade and rough surface conditions presented difficulties for the Impact Echo method, whereas the Pulse Echo method resulted in consistent clear signals.

Standard Pulse Echo equipment (with no additional equipment) allows P-wave speed measurement of a specimen of unknown thickness. This ability dramatically improves reliability of results.

Using measured P-wave speed with Pulse Echo gave accurate thicknesses in cases of known actual thickness. In cases where actual thickness was not known, results using measured P-wave speed with Pulse Echo were more accurate compared with the Design thickness than using a default wave speed with Impact Echo. Pulse Echo results agreed well with design thicknesses in all tested conditions with maximum difference less than 0.8 inches (20 mm). When compared with the Design thickness, differences for Impact Echo were often under reported by 2 inches (51 mm) or more for thicker specimens. Measurement results were generally significantly better for the Pulse Echo compared with the Impact Echo.

REFERENCES

1. ASTM C 1383-04, "Standard Test Method for Measuring the P-Wave speed and the Thickness of concrete Plates Using the Impact Echo Method"
2. ACT Manual, April 2006, Pile Dynamics Inc.