A CASE STUDY:
THE IMPACT-ECHO METHOD OF NONDESTRUCTIVE TESTING OF CONCRETE

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ABSTRACT

The Impact-Echo Method of Nondestructive Testing of Concrete was successfully used to determine the thickness' of a severely nonuniform concrete slab floor in Cardinal Hall, a housing complex slated for demolition at the University of Louisville Belknap Campus. This report documents the complete procedure used to accurately measure plate thickness' insitu, with average percent errors of only 2.6% or better, which, represents a true error of 4 mm in a 171 mm slab. The purpose of this paper is to promote the Impact-Echo Methods' wide spread acceptance by professionals, agencies, and the construction industry, thus enabling its full capabilities to be incorporated in practice.

The Rayleigh Surface Wave Procedure, an indirect method for determining P-wave speeds from the propagation speeds of R-waves, was used throughout this project.

INTRODUCTION

Stress wave propagation methods for the purpose of testing solids have existed since the 1940's; however, at the time of inception their practicality was limited to homogeneous solids such as steel. Only during recent advances has technology allowed the testing of a complex heterogeneous solid such as concrete. The reason is simple, high frequency stress pulses created by ultrasonic waves cannot penetrate into concrete, therefore, it was necessary to create an alternate method of introducing stress waves into concrete.

Today, all stress wave propagation methods rely on a mechanical impact of finite duration to introduce the stress pulse into the concrete medium. These transient stress waves create a resonant condition, which causes surface displacements due to multiple reflections from the boundaries and internal discontinuities of the concrete specimen. A displacement transducer located within a close proximity of the impact, then records these surface displacements.

A transient stress pulse is comprised of three independently occurring wave forms. These are most commonly known as compression or P-waves, shear or S-waves, and Rayleigh surface waves or R-waves. The behavior of these wave forms or more appropriately the ability to interpret the behavior of these wave forms is the basis for the Impact-Echo Method for nondestructive testing of concrete.

The Rayleigh Surface Wave Procedure is simply an indirect means of calculating P-wave speeds by measuring the rate of R-wave propagation between two transducers of known finite separation. Since, P-wave speed is the primary piece of data needed for all applications of the Impact-Echo Method; the Rayleigh Surface Wave Procedure will prove to be an invaluable technique to every Impact-Echo user.

THEORY

As mentioned before, there are three types of waves introduced into the concrete by the impact (or stress pulse); compression waves, shear waves, and Rayleigh surface waves. These waves are referred to as P-and S-waves propagate through the object and the R-waves travel across the surface of the concrete.

When the stress pulse is initiated, the P- and S-waves travel through the thickness of the concrete and are reflected by any internal flaws present in the concrete and by the bottom of the slab (or boundary of the specimen). The waves are then reflected by the top of the slab and propagate back through the thickness of the concrete until the stress pulse is fully dissipated. This is known as a transient resonant condition, or in other words, a momentary echoing condition.

In Impact-Echo testing, P-waves are of the most significant importance. This is because reflected P-waves cause displacements of a higher magnitude than do reflected S-waves. P-wave propagation through a concrete slab can be thought of as a person's finger print. Every cured concrete slab exhibits a unique P-wave propagation speed, and can be used to identify the thickness or flaws in the concrete, more or less, in the way that a finger print can identify a unique individual.

Only when the P-wave speed for the concrete is accurately determined, can the Impact-Echo Method be used to determine the thickness, as well as, location and type of flaws within the concrete. Therefore, it is of the utmost importance that great care and ample time is spent determining the P-wave speed of each independent concrete section.

The formula used to determine the P-wave speed can be state as:

$$Cp = 2Tfp \qquad (1)$$

Where Cp is the P-wave speed, T is the thickness, and fp is the frequency of P-wave reflections from the surface. Therefore, once the P-wave sped has been determined, the thickness of the slab or distance to a flaw can be calculated by simply transforming this equation. This again reinforces the importance of an accurate value of P-wave speed. The most factual way to determine the P-wave speed is, to either remove a core from the concrete and measure the thickness, thus reducing the unknowns in equation (1) to only one. This would be considered a destructive procedure and in many cases would disaffirm the benefit of the method. Or, perform an initial test on a portion of the concrete where the thickness is exposed and considered to be flawless. The second procedure will most likely not be practical or even feasible in the field.

Since, either of the aforementioned procedures can not always be considered optimum, and in many cases neither will be possible, it is necessary to introduce an approximate approach that will estimate the P-wave speed independent of the thickness. This is accomplished by measuring the speed of surface wave transmissions between two points located on the top of the concrete object, and using formulae that relates Cp (P-wave speed) to Cr (R-wave speed). This method is known as the Rayleigh surface wave procedure of approximating compression wave propagation, or simply The Rayleigh Surface Wave Procedure (RSWP).

It is important that the details of the following outlined method be mastered before any further testing is performed. It is only through this procedure that the true usefulness of the Impact-Echo Method can be appreciated. According to Lin and Sansalone [1], "Such a procedure increases the power, versatility and ease of use of the Impact-Echo method."

In order to measure the surface wave speed between two points on the surface, there must be two transducers. There are two products currently on the market, specifically designed to address this problem. The first is the Mark II hand held Unit, which also includes a coupler/distance spacer that can be attached to the Mark I unit. The second, is a new P-Wave Speed Distance Spacer, which according to the manufacturer, when used with the new Echo-Blue software has led to more accurate estimations of P-wave speed. This, however, requires the purchase of two Mark II hand held units.

The theory behind this procedure is simple. If the three necessary components for the test, an impactor and two transducers, are located along a mutual line, when activated, the R-waves will travel from the impactor to the first transducer. At the first transducer the wave will be recorded. It then travels to

the second transducer and is recorded. The change in time between the transducers interception of the R-waves divided into the known distance between the transducers will yield the R-wave speed (Cr). From here things become a bit more complicated.

Having determined a value for Cr, the following formula will relate this value to an approximate value for the P-wave sped (Cp), if Poisson's ratio (V) is known. Poisson's ratio is often considered to be between 0.15 and 0.18 for normal strength concrete.

$$Cp= (1 + V)/(0.87 + 1.12V)* \{[2(1 - V)/(1 - 2V)]^{1/2}\}*Cr \quad (2)$$

If Poisson's ratio is considered to be 0.18, the above equation reduces to Cp = 1.76 Cr and if Poisson's ratio is considered to be 0.15, the above equation reduces to Cp - 1.73 Cr. From this, it can be seen that great effort taken to accurately calculate the Poisson's ratio for each test site is unnecessary, because this value introduces very little error into the calculations. When using this equation to test plate-like members it is important to note that the calculated P-wave speed is nearly 96% of the actual P-wave speed in an infinite medium, therefore, when using this equation to approximate P-wave speeds to be used in testing of plate-like members, the P-wave speed obtained from the above equation must be modified by a factor of 0.96.

$$Cp(plates) = 0.96Cp \qquad (3)$$

EXPERIMENTAL PROCEDURE

The data for this article was obtained by the authors from test performed at Cardinal Hall, a residence facility slated for demolition at the University of Louisville, in Louisville, Kentucky. Neither the slab thickness nor the P-wave speed was known for this structure prior to Impact-Echo testing.

Since, most floors were carpeted it was necessary to remove all coverings glue and tack strips from the floor. In many cases, the surface will have to be prepared for testing. It is very important that the surface to be tested is smooth and free from debris.

Next, a 1' x 1' grid was placed on the 18'4" x 12' floor of room 105. This was accomplished by simple chalk lines.

Impact-Echo testing was conducted on specific nodes of the grid. Thereby making it possible to remove cores at the location of the Impact-Echo tests. Once the thickness at nodes had been determined, the floor was cored.

The values which follow confirm that the Impact-Echo system when used with the Rayleigh Surface Wave Procedure to determine P-wave speed can be used to determine slab thickness' with an average percent error of only 2.6%.

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DISCUSSION OF RESULTS

The results shown in Table I were gathered from two days of testing at the aforementioned site. The column, Thickness Obtained from Coring, contains two values based on the variation in the thickness of a 2-in. Diameter core. The average of these two values represents the Average Thickness. Percent Error was calculated from the Thickness Obtained from Impact-Echo and Average Thickness, based on the assumption that the values from Impact-Echo testing were obtained from what became the center of the removed cores.

From these results it can be seen that this floor was placed on a very nonuniform subgrade thus producing a nonuniform slab. In fact, from coring it was later found that the slab varied in thickness form 95 mm to 246 mm. Even under these conditions, it can be seen that the percent error ranged from 0% to 6.75% representing a maximum discrepancy of 16 mm or 0.63 in. In a 237-mm section. The average percent error was 2.6%, which represents a true error of 4 mm in a 171-mm section. Be it also noted, that in 6 of the 18 tests, one third, the percent error was less than 1%, and that in 11 of the 18 tests, nearly two thirds, the percent error was lower than the Average Percent Error.

Sources of error can be contributed to coring procedures, and systematic errors inherent in wave speed and thickness measurements using the Rayleigh wave speed procedure as well as errors inherent with Impact-Echo methods. These systematic errors include; errors in determining R-wave speed, errors in calculating P-wave speed based on R-wave speed measurement and errors associated with the effect of digital resolution on the accuracy of thickness measurements using the Impact-Echo method. A detailed discussion of these results is beyond the scope of this paper. However, according to published literature [2], the above listed errors alone could account for errors of 5.4% to 8.5%. This does not include errors associated with the coring process, which can be a very inaccurate procedure and a possible large source of error in any experiment. In this experiment great care was taken to ensure that the center of the core was the point where Impact-Echo tests were performed. However, due to the variation in the slab thickness in the 2" diameter cores, and the use of the average of two thicknesses of the core to determine the percent error, it is believed that this was the liberal way to calculate the errors. Systematically using the average thickness of the core allowed the authors to be subjective. In other words, any errors due to the coring process are believed to have altered the possibility of

even better results from the Impact-Echo method. Results should improve with experience.

CONCLUSION

In this experiment, the Impact-Echo method was used to determine thicknesses of a concrete slab in correlation with the Rayleigh Surface Wave Procedure for determining P-wave speeds from R-wave measurements. The average percent error was 2.6%, which is considered to be better than current expectations of values calculated using Impact-Echo technology. Hopefully, through on-going tests of this nature, and the probability of even lower error values the Impact-Echo Method will gain acceptance and find its proper place in practice.

This case study has proven that relatively high levels of accuracy can be achieved when using Impact-Echo to determine thickness, as long as great care is taken in determining P-wave speeds. It should also be noted that wave spectra interpretation should be conducted insitu, by an engineer or person well trained in Impact-Echo wave forms. It is believed that this will increase accuracy as opposed to tests being performed by a technician and analyzed in an office.

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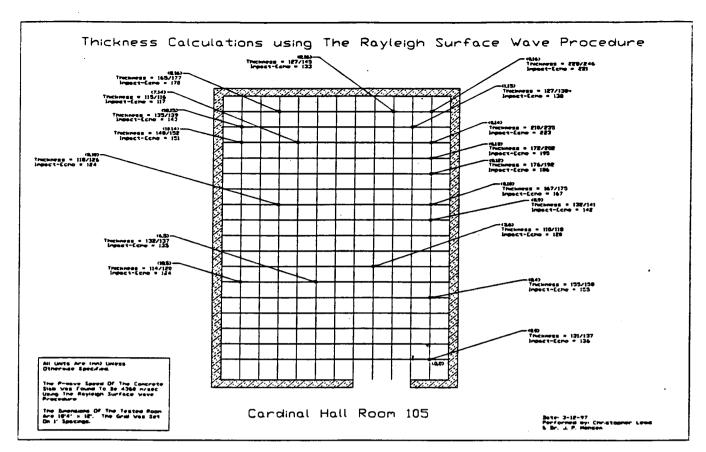
FIGURE I

Location of Test (ft)		Thickness Obtained	Thickness Obtained	Average	Percent
X	Y	from Impact-Echo (mm)	from Coring (mm)	Thickness (mm)	Error
0	0	136	131/137	134	1.49
0	4	155	155/158	156.5	0.95
3	6	120	110/118	114	5.26
0	9	142	132/141	136.5	4.02
0	10	167	167/175	171	2.33
0	12	186	176/192	184	1.08
0	13	195	172/202	187	4.27
0	14	223	210/235	222.5	0.22
1	15	138	127/138	132.5	4.15
0	16	221	228/246	237	6.75
2	16	133	127/145	136	2.20
8	16	170	165/177	171	0.58
7	14	117	115/116	115.5	1.29
10	15	˙143	135/139	137	4.37
10	14	151	148/152	150	0.67
8	10	124	118/126	124	0
6	5	135	132/137	134.5	0.37
10	5	124	114/120	117	5.98

TABLE I - Results from Impact-Echo testing and coring in Cardinal Hall Room 105.

125

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