콘크리트의 응력과 속도 측정을 위한 One-sided technique 개발

Development of Advanced One-sided Stress Wave Velocity Measurement in Concrete

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Abstract

A new procedure for the advanced one-side measurement of longitudinal wave and surface wave velocities in concrete is presented in this paper. Stress waves are generated in a consistent fashion with a DC solenoid. Two piezoelectric accelerometers are mounted on the surface of a specimen as receivers. Stress waves propagate along the surface of the specimen and are detected by the receivers. In order to reduce the large incoherent noise levels of the signals, signals are collected and manipulated by a computer program for each velocity measurement. For a known distance between the two receivers and using the measured flight times, the velocities of the longitudinal wave and the surface wave are measured. The velocities of the longitudinal wave determined by this method are compared with those measured by conventional methods on concrete, PMMA and steel.

Keywords : Concrete, One-sided velocity measurement, Longitudinal wave, Surface wave

1. Introduction

There has been considerable interest in the reliable measurement of the velocity of stress waves in concrete. Elastic constants, such as the dynamic Young's modulus,

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have been determined with velocity measurement since the velocity of stress waves depends on the elastic constants of materials. In addition, many attempts have been made to correlate concrete strength with the measured longitudinal wave (L-wave) velocity.[1] The reliable measurement of stress wave velocity in concrete is required also in other NDE(NonDestructive Evaluation) techniques. The ultrasonic pulse velocity method is a well-known method for L-wave velocity measurement because of its easy application to concrete structures. This technique is most reliable when applied to concrete structures whose opposing and parallel surfaces are accessible.[2] However for some concrete structures such as pavements, opposing and parallelsurfaces of structures are not accessible. Although the ultrasonic pulse velocity method can be applied to concrete structures in one-sided fashion with the indirect transmission method, it has been shown to give unreliable results.[3]

For these reasons, the development of a method for the reliable one-sided measurement of L-and R-wave velocity in concrete is important and necessary. Efforts to develop a method for one-sided measurement of the velocity of stress waves in concrete have been made since the 1940's. Recently, Qixian et al[4] developed a method for one-sided velocity measurement in concrete.

The one-sided method presented in this paper is similar to Qixian's work but our procedure has several advantages. The final objective of this study is the development of a reliable and automated test unit or simultaneous one-sided measurement of the velocity of L- and R-wave in concrete.

2. Experimental Setup

2.1 Principle

As shown in Fig.1, the stress wave source and two receivers are placed along a line on the same surface of the test specimen. A solenoid is used as a source of impact-generated stress waves. The solenoid striker acts as a point source.[5] The L-wave component along the surface is only weakly generated by a point source. On the other hand, the R-wave component is strongly generated by a point source.[6]

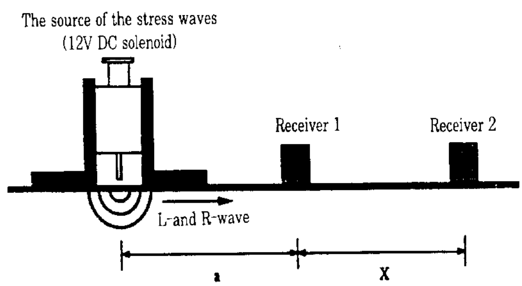

Fig 1. The arrangement of the source of the stress waves and the receivers

In this study, a Labwindows based computer program was developed to automate the entire procedure of the velocity measurement. The program first prompts for the collection of 10 individual time-domain signals. When the solenoid striker impacts on the

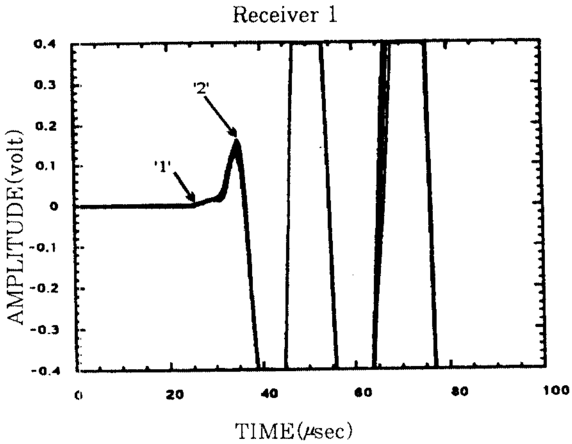

Fig. 2 10 waveforms collected from each receiver before shifting

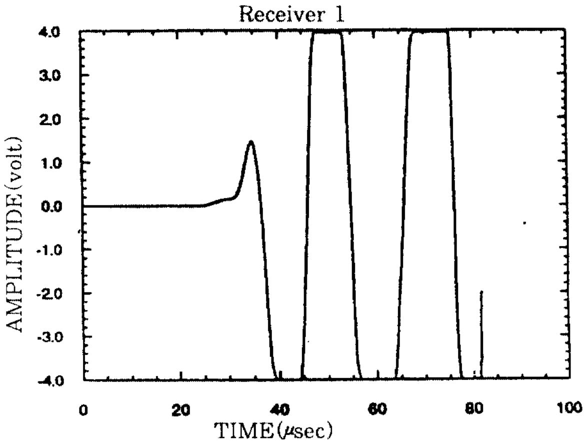

Fig. 3 The resulting waveforms from each receiver after shifting with respect to the average value of the first positive peak and summation

surface and propagating waves are generated, a waveform can be obtained from each receiver. Captured 10 signals are then overlay plotted as shown in Fig. 2. The '1' '2', the first large positive peak of the following waveform, indicates the R-wave arrival. The signals from the receiver closer to the impact point(receiver 1) and the receiver farther from the impact point(receiver 2) are stored in channel 1 and 2 of the digital oscilloscope.

However, large incoherent noise levels in the signal hinder the accurate identification of the L-wave arrival in a signal captured waveform. In order to reduce large incoherent noise levels of each waveform, all 10 signals are shifted along the time axis with respect to the average time value of the point '2' (the first positive peak) and summed. The respective shifted and summed waveforms by this program are shown in Fig. 3.

A threshold noise value for each summed signal is then determined by averaging the maximum value of the first 10 1-μsec spans of the summed signal within which there are no L- and R-wave arrivals. The first approximate L-wave arrival time for each summed signal is then defined by that time when the values of five consecutive signal points are above this threshold noise value. Although the SNR(Signal to Noise Ratio) is improved after the summation process, this approximate L-wave arrival time is slightly in error due to the remaining noise in the summed waveforms. In order to find the L-wave arrival time more accurately, a curve fit method (a linear least squared error fit) is used. A line is fitted to the summed signal about the approximate L-wave arrival time. The average noise level for each summed signal is used to defined the zero-signal level. The average noise is obtained by averaging the signal values in the first 10μsec of the each summed signal. The L-wave arrival time of each summed signal is determined by the intersection of the fitted line and the zero-signal level. Fig.4 shows the more accurate L-wave arrival time for receiver 1.

The R-wave arrival feature is defined as the time value of the first positive peak of each summed signal.

By measuring the flight time of L- and R-wave signal feature between the both receivers, tL,R, and knowing the spacing between receivers, X, velocities of L- and R-waves can be calculated by

$$V_{L,R} = \frac{X}{\Delta t_{L,R}} \qquad (1)$$

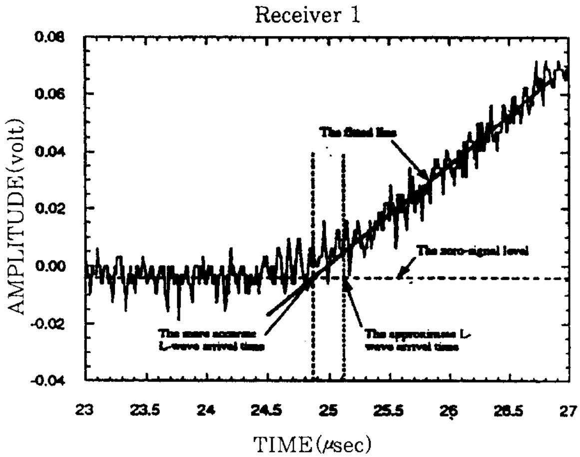

Fig. 4 An illustration of the more accurate L-wave arrival time determined by fitting about the approximate L-wave arrival time for receiver 1

In order to verify the velocities measured with this one-sided method, the conventional methods were used to corroborate the L-wave velocity of all specimens. The L-wave velocity of non-metals(PMMA, concrete) and metals(steel) were measured with the through transmission pulse velocity method, as described in ASTM C597[7], and the ultrasonic pulse-echo method using a 3.5MHz contact transducer respectively. The R-wave velocity of all specimens was estimated using wave propagation theory.[8] The relationship between wave velocities and the elastic constants of an elastic, isotropic solid are:

$$\left(\frac{V_L}{V_T}\right)^2 = \frac{2(1-\nu)}{(1-2\nu)} \qquad (2)$$

where V_L and V_T represent the velocities of the L-wave and T-wave respectively, ρ=mass density, and ν=dynamic Poisson's ratio.

For concrete, the dynamic Poisson's ratio was assumed to be V=0.25.[2,9] The ratio V_T/V_L of all specimens was obtained from the equation(2). The well-known Rayleigh wave equation[6] is

$$\alpha^6 - 8\alpha^4(3-2\beta^2) + 16(\beta^2 - 1) = 0 \qquad (3)$$

where, $\alpha^2 = (V_R / V_T)^2$, $\beta^2 = (V_T / V_L)^2$ and V_R is the velocity of the velocity of the Rayleigh surface wave.

The ratio V_R/V_T of all specimens was then calculated from equation(3). After V_T/V_L and V_R/V_T of each specimen are known, the velocity of the surface wave can be calculated using the L-wave velocity as measured by conventional methods. The consistency of the test was determined from the variability of the repeated tests as measured by the coefficient of variation of the sample.

2.2 Test Specimens and equipment

In this study, Four kinds of specimens were used to verifythe one-sided measurement of the velocity of the L- and R-wave: two plain concrete plates, a PMMA plate(acrylic resin) and a steel plate. The exact composition, casting, and curing conditions of the concretes are unknown. However, it is known that both concrete plates are mature (older than 1 year) and are comprised of a gravel coarse aggregate with a maximum particle size of 9.5mm. One of the concrete specimens is designated as "high quality" concrete because of the surface condition, the measured mass density, and the ultrasonic L-wave velocity as measured with the through transmission pulse velocity method. The mass density of the high quality concrete is 2324kg/m^3. The L-wave velocity of the high quality concrete is 4.72mm/μsec. The size of the high quality concrete specimen is 103×405×195mm in thickness, length and width, respectively. The other concrete specimen is designated as "average quality" concrete. The mass density of the average quality concrete is 2310kg/m^3. The L-wave velocity of the average quality concrete is 4.47mm/μsec. The size of the average quality concrete specimen is 102×600×300mm in thickness, length, and width, respectively. The size of the PMMA plate is 77×630×600mm in thickness, length and width. The steel plate has a circular shape in plan view with a diameter of 414mm and a thickness of 29mm.

Two piezoelectric accelerometers, each with nominal resonant frequency of 75.5kHz, are used as receivers. A digital oscilloscope is used to acquire and display the waveforms. Using the GPIB interface, a computer collects the waveforms from the oscilloscope. A push-type 12V DC solenoid is used as an impact source.

3. Experimental Results

The one-sided velocity measurement technique was applied to a variety of engineering materials: steel, PMMA, and concrete. The average values of 10 L- and R-wave velocities measurement, and the coefficient of variation(C.V.%) are listed in Table 1 for all tested specimens.

For the purpose of the verification of the one-sided velocity measurement method, the ultrasonic L-wave velocity of all specimens was also measured by conventional methods as $V_{L.e}$. The surface wave velocity of all specimens was then calculated from the basic wave propagation theory as $V_{R.e}$. The L-wave velocities of the PMMA plate, the high quality concrete, and the average quality concrete were measured by the through transmission pulse velocity method using a frequency of 150kHz as specified by ASTM C597. Thus, the ratio $V_{T.e}/V_{L.e}$ was 0.577 as given by equation(2) and $V_{R.e}/V_{T.e}$

Table 1 Comparison of L-and R-wave velocity measurement with one-sided and conventional methods

Test material	Conventional Measured velocity(mm/μsec)	Average of one-sided velocity measurement (mm/μsec)	coefficient of variation of one-sided measurement
Average quality concrete	$V_{L,e}$=4.47 $V_{R,e}$=2.37	V_L=4.44 V_R=2.44	1.1% 0.35
High quality concrete	$V_{L,e}$=4.72 $V_{R,e}$=2.50	V_L=4.70 V_R=2.48	1.1% 0.5%
PMMA	$V_{L,e}$=2.73 $V_{R,e}$=1.33	V_L=2.72 V_R=1.27	0.6% 0.2%
Steel	$V_{L,e}$=5.93 $V_{R,e}$=2.99	V_L=5.96 V_R=2.98	0.8% 0.4%

of the high quality concrete and the average quality concrete was 0.924 as given by equation(3). The obtained value of $V_{L,e}$ for PMMA agrees with that published in the literature.[10] Thus, $V_{R,e}/V_{T,e}$ of the PMMA plate is then calculated as 0.930, as given in the literature. The L-wave velocity of the steel plate was obtained by the ultrasonic pulse-echo method using a 3.5MHz contact transducer. The obtained value of $V_{L,e}$ of the steel plate also agrees with that found in the literature.[10] Thus, $V_{R,e}/V_{T,e}$ of the steel plate was assumed to be 0.923, as given in the literature.

As seen in Table1, the one-sided L-wave velocity measurements are in excellent agreement with the verifying measurements. The average values of V_L are 99%~101% of the corresponding $V_{L,e}$ value for all specimens. The values of the coefficient of variation of 10 repeated measurements of V_L are low enough to be acceptable(0.6%~1.1%). The average values of V_R are in good agreement with the corresponding values of $V_{R,e}$ (99.2%~103% of the expected value) for all materials, except PMMA. The obtained value of V_R for PMMA is only 95% of $V_{R,e}$. This discrepancy may be a result of the well know dispersive character of wave motion PMMA.[6,11] The consistency of V_R measurements is very good. The values of the coefficient of variation of 10 measurements of V_R are less than 1% for all specimens.

4. Conclusions

The ability to reliable measure V_L and V_R in concrete is of interest to the technical community. However, the ability to perform such measurements in structures with only one accessible surface is currently limited. In this study, an automated procedure for the one-sided measurement of L- and R-wave velocities in concrete has been developed. The measured velocities with this one-sided method are consistent and n very good agreement with corroborating conventional methods. This automated procedure is unique in that the values of V_L and V_R are determined by a computer program which compensates for high incoherent signal noise levels(signal summing) and signal dispersion(curve fitting). For concrete specimens with thickness greater than 50mm, this technique can be used with confidence for the determination of V_L. The surface wave velocity, V_R, measured in concrete with this technique may be slightly lower than the actual value.

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