MEASUREMENT OF ULTRASONIC WAVE VELOCITIES

Zahid Khan, University of Waterloo, Waterloo, Canada
Anwar Majid, University of Waterloo, Waterloo, Canada
Giovanni Cascante, University of Waterloo, Waterloo, Canada

ABSTRACT
Pulse velocity measurements require that the specimen size should be large enough to avoid near-field effects. Wave velocity measurements become less accurate as the size of specimen decreases. Different ultrasonic equipment and transducers are used in this study to investigate the propagation of ultrasonic waves in specimens of different sizes and materials (steel, aluminium, and cemented sands). The results indicate that different transducers yield different values of wave velocity because of the differences in the frequency response curve of transducers. A new procedure is suggested to calibrate ultrasonic equipment, which involves the linear curve-fitting of travel time measurements for specimens of different lengths. Results from cemented-sand specimens indicate that wave velocity increases as the cross section of the specimen increases; this increase is attributed to the change in the wave propagation from plane (unconstrained modulus) to spherical (constraint modulus) fronts. Numerical models are used to interpret the results.

Résumé
Les mesures de vitesse d'impulsion exigent que la taille de spécimen doive être assez grande pour éviter les interférences des frontières. Les mesures de vitesse des vagues deviennent moins précises pendant que la taille du spécimen diminue. Différents équipement et transducteurs ultrasoniques sont employés dans cette étude pour étudier la propagation des ondes ultrasoniques dans les spécimens de différents tailles et matériaux (acier, aluminium, et sables cimentés). Les résultats indiquent que les différents transducteurs rapportent différentes valeurs pour les vitesses des vagues en raison des différences dans la courbe de réponse en fréquence des transducteurs. Une nouvelle procédure est suggérée pour calibrer l'équipement ultrasonique, ceci comprend la courbe ajustage de précision linéaire des mesures du temps de voyage pour des spécimens de différentes longueurs. Les résultats des spécimens de sable cimentés indiquent que la vitesse des vagues augmente à mesure que la coupe du spécimen augmente; cette augmentation est attribuée au changement de la propagation de vague d'avants surfaces (module sans contrainte) aux avants sphériques (module avec contrainte).

1. INTRODUCTION

The Pulse velocity method is widely used for the evaluation of elastic properties of materials, the assessment of concrete quality, and the indirect measurement of strength (Popovics et al. 1990, Naik and Malhotra 1991, Popovics and Popovics 1992, and Popovics and Rose 1994). In this method, pulses emitted by a transmitter travel through the material and are detected by a receiver. The travel time of the first arriving pulse is measured with electronic equipment and wave velocity is simply computed as distance over time. A basic requirement for pulse velocity measurements is that the specimen size should be sufficiently larger than the size of the transducer to meet plane wave approximation (Zhang et al. 2002). Thus, the relative size of transducers with respect to the size of specimen affects the wave velocity and attenuation measurements. On the other hand, the distance between transducers should be larger than one wavelength to avoid near-field effects.

In small specimens, variations in the arrival time are magnified in the calculation of wave velocity. When the size of the transducer is smaller than the size of the specimen, the propagating wave front (spherical for circular transducers) approaches the unconstrained boundaries of specimen thus retarding its velocity at the boundaries. These two affects are explored in this study. The main focus of this study is to present simple procedures for the accurate evaluation of wave velocities and the evaluation of Poisson's ratio from velocity measurements in specimens of different sizes.

Wave velocity measurements not only depend on the precision of the equipment but also on the characteristics of the equipment (e.g. response time, frequency response). Thus, different values of wave velocity are obtained if different types of transducers or electronic equipment are used. Since piezo-crystals in ultrasonic transducers have specific frequency response curves, different transducers exhibit different delay times even if the electronic equipment and source function are the same. However, if the specimen is infinitely long, these variations in delay times have negligible effects on the wave velocity measurements.

A new procedure is presented in this study for the accurate evaluation of wave velocity. The technique is based on the use of different-size specimens. The arrival time measured in small specimens is used to extrapolate the results to the case of long specimens. This new technique reduces the variability in velocity measurements obtained with different transducers and ultrasonic equipment.

The dynamic Poisson's ratio can be measured by either the resonance method or by the simultaneous evaluation of at least two types of wave velocities (Whitehurst 1966, Naik and Malhotra 1991); however, there are inherent limitations associated with these methods. The resonance method is a standardized procedure (ASTM C215); however, the use of specimens of different sizes (different resonant frequencies) render different values of elastic moduli and Poisson's ratios for the same material (Kesler and Higuchi 1954, Whitehurst 1966, Malhotra and Sivasundaram 1991). The evaluation of Poisson's ratio from compressional and shear wave velocities is limited because of inherent difficulties in the measurement of travel times when shear waves cannot be generated with the sufficient amplitude.

A new technique is proposed to evaluate the dynamic Poisson's ratio in which only longitudinal waves are used. If the cross-sectional area of the specimen is reduced, the wave front will change from spherical (unbounded medium) to plane (bounded medium). Thus, it is possible to measure the Poisson's ratio (ν) with compressional waves by using different size specimens. Exploratory results are presented for cemented sands.

The following sections present a literature review on specimen-size effects on wave-velocity measurements and methods for the evaluation of Poisson's ratio; then, the experimental methodology followed by results and discussions. Finally, the main conclusions of the study are summarized.

2. LITERATURE REVIEW

Several researchers have studied the effect of specimen size on ultrasonic measurements. These studies show that wave velocity and attenuation are affected by size of specimens. Zhang et al. (2002) analyzed the influence of specimen size on ultrasonic measurements with the pulse echo method. They used poled and unpoled lead zirconate titanate (PZT-5H) ceramics specimens (prisms) of different sizes. The ratio of the lateral dimension of the specimen (T) to the transducer diameter (D) ranged from 0.137 to 4.0. Wave velocity decreased as the ratio T/D increased up T/D = 2.0, larger values of T/D showed constant velocity.

Poisson's ratio ranges from ν=0 (compressible material) to ν=0.5 (incompressible materials). Poisson's ratio in excess of 0.5 is an indication of the material swelling under loading. The dynamic Poisson's ratio can be measured by three methods, (i) from longitudinal, transverse, and torsional resonant frequencies (ASTM, C215), (ii) simultaneous measurements of p-wave velocity and longitudinal resonant frequency, (Swamy, 1971), and (iii) measuring at least two types of pulse velocities i.e. p-wave and s-wave velocities, or s-wave and Rayleigh wave velocities (Achenbach, 1973). The compressional wave velocity in a semi-infinite medium (V_P) is related to compressional wave velocity in a rod (V_L) by:

$$\frac{V_P}{V_L} = \sqrt{\frac{(1-v)}{(1+v)(1-2v)}} \qquad [1]$$

Poisson's ratio can be measured statically or dynamically. Static Poisson's ratio can change during loading (Rüsch et al. 1983). For example when the applied stress is greater than 0.4 times the compressive strength of concrete, Poisson's ratio increases rapidly as the load increases and may exceed 0.5 due to the development of cracks. Dynamic and static Poisson's ratio of concrete depends on mix proportions, aggregate properties, specimen size, and curing conditions (Philleo 1955, Swamy 1971, Malhotra and Sivasundaram 1991). Dynamic Poisson's ratio of concrete varies between 0.2 and 0.3 (Naik and Malhotra 1991), and it is generally higher than the static Poisson's ratio.

Obert and Duvall (1941) found that specimens of same concrete mix but different sizes had different dynamic modulus of elasticity and logarithmic decrement. The natural frequency of a specimen depends on its size and shape; larger specimens have lower resonant frequencies and vice versa. Long et al. (1945) hypothesized that when a wave propagates in a small specimen, the lateral expansion or contraction due to longitudinal strains (Poisson's effect) delays the wave; however in large specimens, the material is constrained and lateral displacements are limited. Therefore, in large specimens (unbounded medium) waves travel at higher speeds than in smaller specimens (bounded medium).

3. EXPERIMENTAL SETUP

The instrumentation for the ultrasonic measurements is shown in Figure 1, which consists of two different pulse generators (Pundit box, and a piezo-driver box), digital oscilloscope (HP 54610B), multimeter (HP 34401 A), power supply (HP 3620 A), load cell (type 50 DBB, capacity 500 N), and data acquisition system (Wavebook 516E). One piezoelectric transducer is used as a source to generate compressional waves (TB50, 50 mm diameter, 54 kHz). Two different receivers of 30 kHz and 60 kHz centre frequencies are also used for comparison purposes (Physical Acoustics R3.0I and R6.0I). Table 1 shows the combinations of equipment and transducers used in the measurements.

Table 1

System	Signal Generator	Source	Receiver
A	Pundit	50 kHz	Broad band
B	Pundit	50 kHz	60 kHz
C	Pundit	50 kHz	30 kHz
D	Piezo-driver	50 kHz	Broad band

Wave velocity is computed using the travel time of a square pulse and the distance between transducers (ASTM C597). A frame fitted with a load cell is used to maintain constant pressure on the transducers during all the tests to improve the repeatability of the results (Fig. 1). Six cylindrical specimens of aluminium and stainless steel are used to determine the delay in the response of the systems given in Table 1. The diameter of the specimens is constant (D= 5 cm), whereas different lengths are used L = 5, 7.5, 10, 12.5, 15 and 20 cm. Cubic specimens of cemented sands of the same lengths are prepared with a gypsum-based cement and tested under atmospheric pressure to study the effect of specimen size on wave velocity and to evaluate the Poisson's ratio of the material using the compressional velocities V_P and V_L. Wave velocity is measured after 56 days when the cemented sand specimens are fully cured.

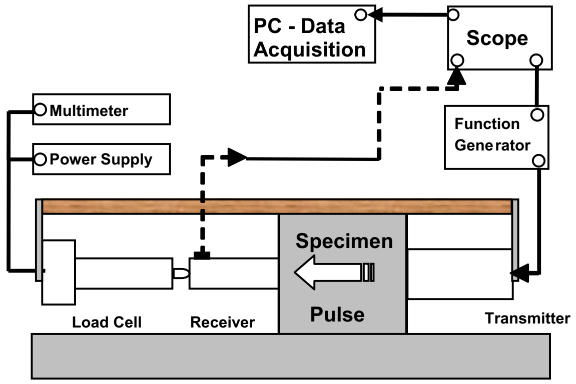

Figure 1: Equipment setup

4. RESULTS AND DISCUSSIONS

Different frequencies for the square pulse are used to study the effect of the frequency content of the excitation function. The excitation frequencies are varied from 5 kHz to 200 kHz. Even though the characteristics of the response signal changes with the excitation frequency, the arrival times are independent of frequency. Thus, arrival times are governed by the high frequency content of the excitation function. Figure 2 shows the variation of wave velocity for the steel specimens with specimen length L; whereas, Figure 3 shows the arrival times. The model lines in Figure 2 are calculated from the regression lines for the arrival times (Fig. 3).

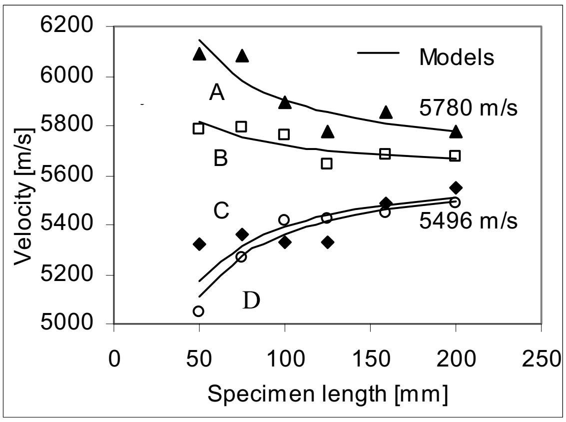

Figure 2: Effect of specimen length and equipment on wave velocity for steel specimens (Table 1).

Figure 3 indicates that the different systems have approximately the same shift in arrival times for all lengths and that the variation of arrival times with length is linear. These shifts (maximum of 2 microseconds) and small variations in arrival times (<0.4 micro-seconds) have significant effect on the wave velocity calculations for small specimens. A velocity change of 21% can be observed for the 50 mm specimen for instance. In spite of the velocity dispersion shown in Figure 2, actual wave velocity can be computed by extrapolating the results of the models to large specimen lengths as shown in Figure 4. The differences in wave velocities among the NDT equipment are reduced to within 0.1% in this figure. The average wave velocity for the steel specimens computed from the slopes of the regression lines is 5640 m/s. Figures 5, 6 and 7 present the results for aluminium specimens, and the average wave velocity is 6320 m/s. The average velocity values are in good agreement with published values (e.g. ASNT 1998).

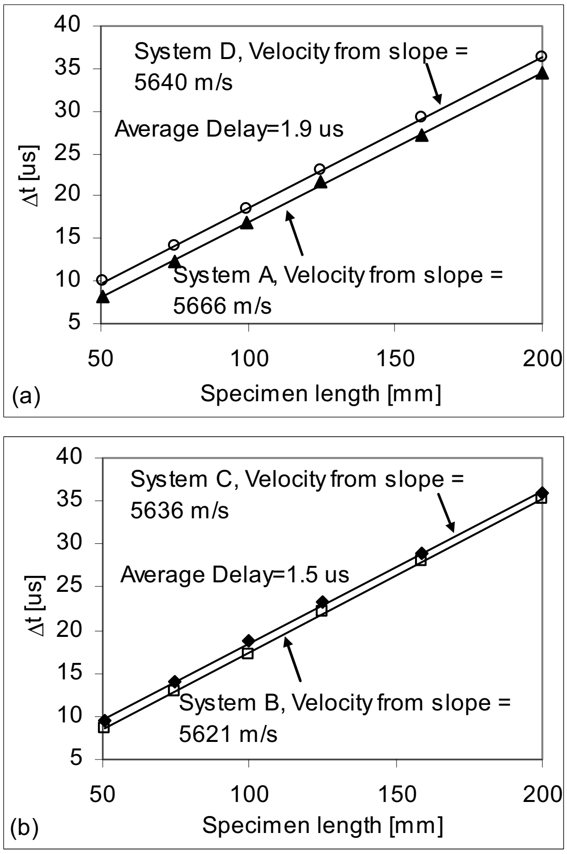

Figure 3: Arrival times for Steel specimens

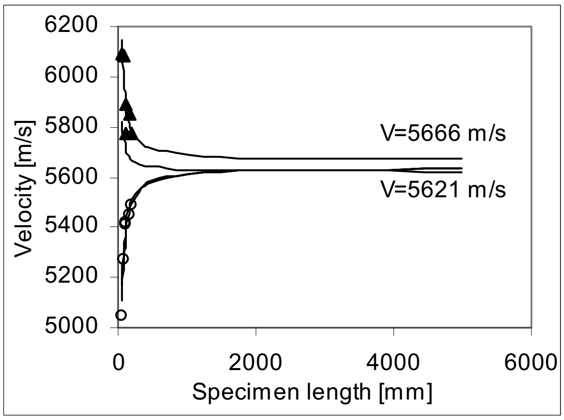

Figure 4: Models of wave velocity in steel specimens extrapolated to larger specimen lengths

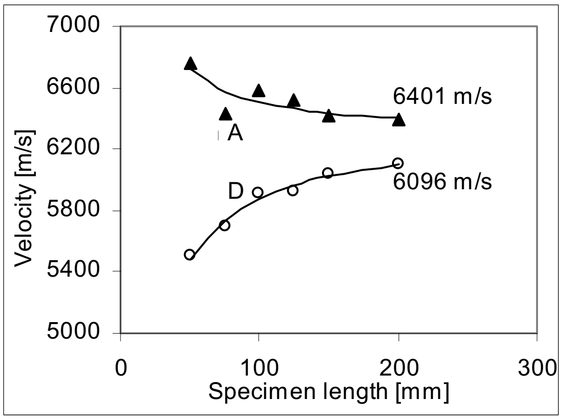

Figure 5: Effect of specimen length and equipment on wave velocity for aluminum specimens (Table 1).

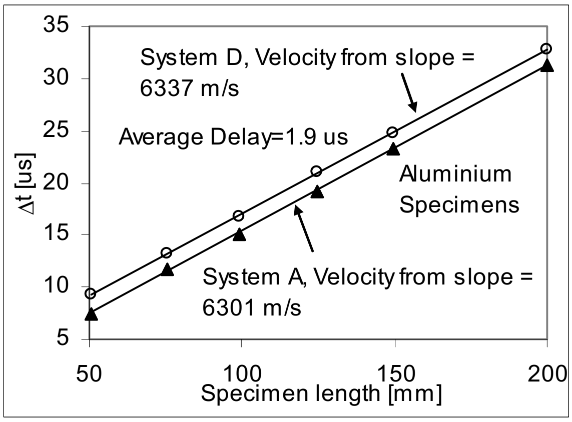

Figure 6: Effect of specimen length and equipment on wave velocity for Aluminium specimens

Figures 8 and 9 present the results for cemented sands (cubical specimens). Since the size of the cemented sand specimens changes with the length of the specimen, wave velocity is affected by the change in length and the cross-sectional area of the specimens as indicated by the mismatching of the extrapolated values of wave velocity (Figure 10).

To evaluate the Poisson's ratio from eq.1, specimens of different cross-sectional area and constant length are used (L= 10 cm). The ratio of the lateral dimension to the length of the specimen is given by the geometrical factor GF (Equation 2). As the geometrical factor approaches the value of one, the wave velocity is considered to be equal to V_P because the wave front is not significantly affected by the boundaries of the specimen. Conversely when the geometric factor is close to zero, the wave propagation can be considered unconstrained and the wave velocity approaches V_L.

$$GF=(T-D)/(2L) \qquad [2]$$

where T is the lateral dimension of the specimen, D is diameter of transducer and L is the length of specimen.

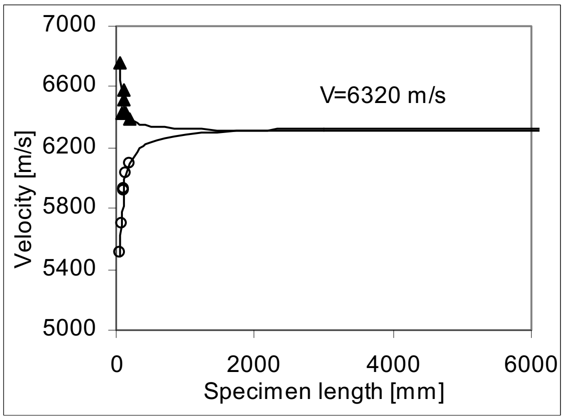

Figure 7: Models of wave velocity in aluminum specimens extrapolated to larger specimen lengths

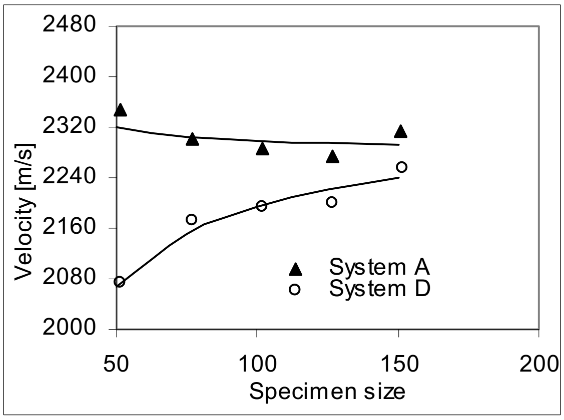

Figure 8: Wave velocity in cemented sand specimens

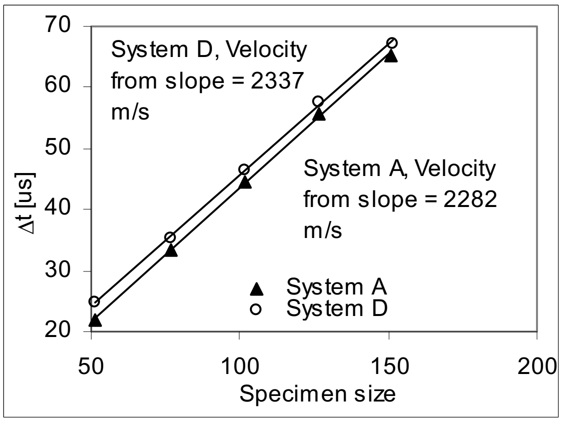

Figure 9: Arrival times in cemented sand specimens

Figure 11 presents the variation of wave velocity with the geometric factor (GF) for systems A and D (same transducers but different signal generator). The Poisson's ratios calculated from Equation 1 are ν=0.22 and ν=0.21 for the two systems.

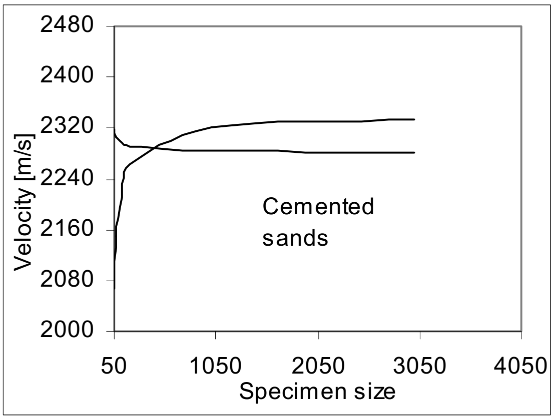

Figure 10: Models of wave velocity in cemented-sand specimens extrapolated to larger specimen lengths

Figure 11 also illustrates the importance of keeping the length constant to keep constant the delay time of the system in the measurements. The two curves are shifted because of the different delay times of the systems used. From the figure, the delay time between systems A and D is 1.9, in agreement with the results for the aluminum and steel measurements.

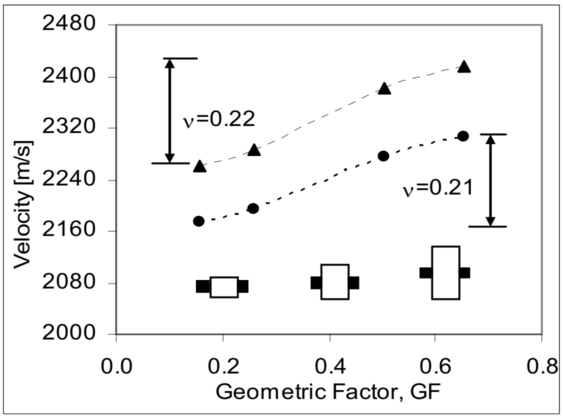

Figure 11: Variation of wave velocity with geometric factor (eq. 2) and evaluation of Poisson's ratio

5. CONCLUSIONS

The pulse velocity method is used to study the effect of different types of ultrasonic equipment and transducers on wave velocity. The main conclusions from this experimental study are:

Wave velocity is not affected by the main frequency of the excitation function when a square pulse is used.

Wave velocity is constant for specimens of different lengths; however, there is an apparent variation in velocity with length because of inherent time delay in the electronic equipment. To compensate for this inherent delay, the wave velocity is computed by extrapolating the arrival times obtained for different length specimens, or by computing the slope of the (arrival time)-(specimen length) plot.

Exploratory results on cemented-sand specimens show that the dynamic Poisson's ratio can be evaluated from different size specimens using compressional waves. However, this conclusion is currently under investigation.

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