Geometric Effects on Ultrasonic Pulse Velocity Measurements in Concrete Specimens

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Abstract
Ultrasonic Pulse Velocity (UPV) method is a very popular technique used in Non-Destructive Testing (NDT) in Civil Engineering. Major benefit of the method is its simplicity. UPV uses the concept of measuring time of a first arrival of ultrasonic wave from one side of the specimen to another. Moreover, UPV is an ASTM standard test method for concrete specimens. In spite of an easiness of the method obtained results highly depend on the transducers used, coupling quality, and specimen dimensions. In the article the authors focus on the sensor and specimen effects. The results for UPV tests of 9 concrete specimens of different heights and diameters are presented. The specimens are tested with 54 kHz and 850 kHz excitation transducers and the state-of-the-art laser vibrometer (response measurements). This study discusses the laser vibrometer readings and the influence of specimen dimensions (with the dominating factor of length effects in terms of wavelength and specimen length relation) on the measured pulse velocities. Practical recommendations for the minimal dimensions of the test object in order to minimize the error in UPV tests are proposed.

Keywords: Non-Destructive Testing of Concrete, Ultrasonic Pulse Velocity, Laser Vibrometer, Size effects

1. Introduction
Concrete is a popular structural material used in Civil Engineering applications. As for any material, condition of concrete may be affected by the quality of design, manufacturing, loads applied to a structure, character of the loads, environmental deterioration, or aging. Condition of concrete plays a key role for safety of structures [6]. Non-destructive ultrasonic evaluation (NDE) is commonly used for assessment of civil infrastructure and characterization of construction materials. Among the acoustic methods the impact echo, ultrasonic pulse velocity (UPV), and surface waves analysis can be distinguished [8, 10]. The latest trends focuses more on attenuation of wave front [1, 7] and more sensitive methods for detecting changes in velocity (e.g. Coda Wave Interferometry [4, 9, 11]). Wave velocity depends on the medium properties, therefore UPV method is a very popular technique used in NDE in Civil Engineering. Propagation velocity of the longitudinal (P-wave) through the material \( V_P \) can be calculated as:

\[
V_P = \frac{E_d(1-\nu)}{\rho(1+\nu)(1-2\nu)}
\]

where \( E_d \) is dynamic Young's modulus, \( \nu \) is the Poisson's ratio, and \( \rho \) is the density. Major benefit of the UPV is its simplicity. The method is based on the concept of measuring time of a first arrival of ultrasonic wave from one side of the specimen to another. Moreover, UPV is an ASTM standard test method for concrete [2]. The standard specifies the applications of UPV as: assessment of relative quality of concrete, presence of voids imperfections (i.e. voids, cracks, and the effectiveness of its repairs). UPV can be also applied to monitoring changes in the condition of specimen [2]. In spite of an easiness of the method obtained results depend highly on the transducers used, the coupling quality, and the specimen dimensions. In the paper authors discuss those factors by using three kinds of measuring equipment and different sizes of concrete specimens. The use of wave attenuation has been limited, because of the difficulties of obtaining consistent measurements.

2. Methodology

2.1 Calibration of ultrasonic equipment
An initial step in the measurements is the calibration of ultrasonic equipment [5]. It helps to evaluate a time delay introduced by the instrumentation used in UPV tests, and therefore measure the P-wave velocity with a high precision. In this study, the calibration is performed for both groups of ultrasonic transducers with use of steel and PVC rods (four rods of each material).
2.2 First arrival measurements – ultrasonic transmitter / receiver (T/R)

First group of tests is performed in ultrasonic transmitter - receiver configuration. Transducers are kept on the opposite faces of concrete specimens by 3D-printed holders. Thus, constant pressure of transducer application is achieved during each of the tests. The velocity of P-wave through the specimens is calculated by dividing the time of the first arrival by the length of the specimen. The time of flight is read from data recorded with the oscilloscope. Each signal recorded during the test consist of an average of sixteen measurements. The estimation of wavelengths for each type of transducer is presented in Table 1.

Table 1. Ultrasonic transducers and corresponding wavelengths ($V_P = 3760$ m/s)

<table>
<thead>
<tr>
<th>Type of transducer</th>
<th>Wavelength [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequency ($f_c = 54$ kHz)</td>
<td>75.2</td>
</tr>
<tr>
<td>High frequency ($f_c = 850$ kHz)</td>
<td>3.76</td>
</tr>
</tbody>
</table>

2.3 First arrival measurements – ultrasonic transmitter / laser vibrometer (T/L)

In the second group of tests responses are measured with laser vibrometer. Input signals are generated with ultrasonic transducers. The methodology for laser vibrometer tests follows the same procedures as for ultrasonic transmitter-receiver tests. For the case of low frequencies, 500 measurements are used for averaging, while for high frequencies the number of averages was increased to 1000 as the signal-to-noise ratios were low.

3. Methodology

3.1 Specimens

In this study, 9 concrete samples [3] are tested. Specimens were cast from an industrial concrete batch mixed in a concrete mixing vehicle. All concrete specimens were cast at the same time and left to solidify for 5 hours after which the moulds were removed and the samples put in a humidity room for 28 days. Then the specimens were stored in the NDE lab of the University of Waterloo for 8 years, which makes the specimens a unique testing set. A list of all the concrete specimens and their accurate measurements is presented in Table 2 (the names correspond with the rounding of dimensions in cm).

Table 2. Specimen dimensions

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Length [mm]</th>
<th>Diameter [mm]</th>
<th>Sample name</th>
<th>Length [mm]</th>
<th>Diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>cL5D10</td>
<td>49</td>
<td>100</td>
<td>cL5D30</td>
<td>49.6</td>
<td>300</td>
</tr>
<tr>
<td>cL5D20</td>
<td>52.7</td>
<td>200</td>
<td>cL10D30</td>
<td>100.9</td>
<td>300</td>
</tr>
<tr>
<td>cL10D20</td>
<td>98</td>
<td>200</td>
<td>cL20D30</td>
<td>176.5</td>
<td>300</td>
</tr>
<tr>
<td>cL20D20</td>
<td>192.6</td>
<td>200</td>
<td>cL30D30</td>
<td>290.4</td>
<td>300</td>
</tr>
<tr>
<td>cL30D20</td>
<td>289</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Setup - ultrasonic transmitter / receiver (T/R)

Schematic diagram of the test setup is shown in Figure 1 (left). ASTM recommends transducers with a resonant frequency in the range 20-100 kHz in the UPV tests [2]. Therefore, in the first setup US transducers with the resonant frequency: $f_c = 54$ kHz are used. Dynamic signal analyzer (HP 35670A) is used to provide input signal (54 kHz square pulse) to the transmitter, which is amplified to the amplitude of ± 110V. Each specimen is supported on the holder, and the sensors are placed on each face of the cylinder. The readings are taken by Keysight DSO-X 3032T oscilloscope (each signal consist on the average of 16 time traces).

Fig. 1. Ultrasonic transmitter/receiver setup (left), Ultrasonic transmitter/laser vibrometer setup (right).
To generate shorter wavelengths high frequency measurements are also conducted. During the tests Panametrics V-102 transducers (with \( f_c = 850 \text{ kHz} \)) driven by a Panametrics 5052-PR Pulser Receiver in pitch-catch mode are used. The maximum amplification of the hardware is set in order to make the identification of first arrivals easier as the high frequencies attenuates faster.

### 3.3 Setup - ultrasonic transmitter / laser vibrometer (T/L)

The use of laser vibrometer helps to eliminate the impact of transducer’s frequency response on the output reading. Another benefit is that the signal from the laser finally provides physically interpretable vibration units e.g. displacement [m], or velocity [m/s]. In the case of displacement recording, one can distinguish the differences in vibration in nanometer scale. The input part of laser vibrometer experimental setup remains unchanged as in transmitter-receiver tests. The response is read with laser sensor head (LSH) which is connected to the vibration controller (OFV-5000). Laser system is triggered with the input signal, which is also recorded (Figure 1 - right). The response is measured in single, center point of each specimen.

### 4. Results

#### 4.1 Calibration of ultrasonic equipment

The results obtained for the calibration for both low (\( f_c = 54 \text{ kHz} \)) and high (\( f_c = 850 \text{ kHz} \)) frequency transducers are discussed in this section. First, calibration times of flight were plotted against corresponding lengths. Next, trend lines with linear interpolation were added and based on the intercept point of both lines the delay of each system were calculated (Table 3).

**Table 3. Delays of two testing configurations**

<table>
<thead>
<tr>
<th>Type of transducer</th>
<th>Delay [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequency (( f_c = 54 \text{ kHz} ))</td>
<td>2.80E-06</td>
</tr>
<tr>
<td>High frequency (( f_c = 850 \text{ kHz} ))</td>
<td>5.16E-07</td>
</tr>
</tbody>
</table>

#### 4.2 First arrival measurements – ultrasonic transmitter / receiver (T/R)

##### 4.2.1 Length effects

The length effects are studies with signals recorded for specimens: cL5D30, cL10D30, cL20D30, and cL30D30. In this comparison, amplitudes are normalized with the respect to the maximal amplitude observed in each comparative group (except Figure 4 (right) and Figure 6 where traces are self-normalized). Figures 2-4 present the results for 54 kHz transducers.

![Fig. 2. Time traces recorded for the investigation of length effect with 54 kHz transducers: full length (left), zoom (right).](image)

The full time traces show that groups of events in the signals can be distinguished. Figure 2 (right) shows zoomed first event group, which is the main point of interest during UPV test. In case of short samples the separation between P and S-wave is not possible. P-wave reflected from the side is not seen in the signal. In the
signals it is the S-wave which has the highest amplitude and dominates. Therefore, proper characterization of the transducers being used in the test is very important. Moreover, the parameters of acquisition play the key role as the wrong range setting might lead to false characterization of the P-wave as a noise and wrong judgment of S-wave as a first wave arriving. For the longest specimen 2P and 2S waves can be distinguished, which confirms the dominating character of S-wave in the signal.

Next, signals were filtered in time domain so that only P-wave arrival is present. The filtering is not possible for the lengths 5 and 10 mm, as the events of P and S-wave cannot be separated. Therefore, the peak frequency for the cL5D30 specimen is shifted to the left because of S-wave presence. That observation shows that the specimen length has to be longer than one wavelength recommended by the ASTM [2]. Figure 3 shows amplitude spectra calculated for the signals presented above. The observed peaks are associated with the P-wave. A slight effect of an attenuation with increasing length of the specimen can be observed (black line in the figure). The central frequency of the peaks is shifted to the lower frequencies as the length of specimen rises.

![Fig. 3. Fourier spectra for signals in Figure 2](image)

In the Figures 4-5 results for specimens: cL5D30, cL10D30, cL20D30, and cL30D30 tested with 850 kHz transducer are presented. Signals presented in the figure 4 (left) are normalized with the respect to the maximal amplitude observed in the comparative group. The effect of amplitude attenuation with the length of specimens is easily observable. Figure 4 (right) shows signals normalized to each maximal value. In this group of signals P-wave arrivals are dominating. Some small influence of S-wave can be also distinguished. 2P and 2S-waves do not have a distinctive character in the signals. The wave reflections from the sides (half distance) are not visible in the plot.

![Fig. 4. Time traces recorded for the investigation of length effect with 850 kHz transducers: full length (left), self-normalized zoom (right).](image)

In the Figure 5 the spectra for the signals are presented. Again signals were filtered to observe only the event of the P-waves. The effect of S-wave mode on short specimens is less significant than in the 54 kHz transducer and the peaks are narrow. Moreover, the attenuation of high frequencies is clearly observed. The amplitudes of the first arrivals highly attenuates with the specimen length and may lead to limited number of applications. It also explains why the ASTM recommend the use of transducers with a resonant frequency in the range from 20 to 100 kHz.
4.2.2 Diameter effects

Next the effects of diameter on UPV test results are investigated on specimens: cL5D10, cL5D20, and cL5D30. In these tests amplitudes are normalized with the respect to maximal value of each signal. In the Figure 6 (left) the P and S-waves can be distinguished. The 2P and 2S-waves do not have a distinctive character. Figure 6 (right) presents the spectra for this group of signals. Increase of a diameter does not affect the area of the peaks associated with the P-wave in a clear manner. The slight shift in the case of cL5D20 might be caused by surface imperfections of the specimen.

4.3 First arrival measurements – ultrasonic transmitter / laser vibrometer (T/L)

4.3.1 Length effects

This section presents the results obtained with the laser vibrometer. First the results for 54 kHz transmitter-receiver tests are shown. Again the comparison is done for the group: cL5D30, cL10D30, cL20D30, and cL30D30.
The character of recorded signals (Figure 7) corresponds to the one of recorded with ultrasonic transducers. However, in this situation the important benefit is that the responses are measured at single position and have physically interpretative amplitude. In case of displacement, one can observe the vibrations in nanometer scale. In the case of short specimens the separation between P and S-wave is not possible (Figure 7). Dominating influence of the S-wave on signal is present again. P-wave arrival has very small amplitude in the relation to S-wave and might be not identified if acquisition is not carefully designed. The displacement measured with laser vibrometer is more prone to attenuation than when the response is measured with ultrasonic transducer.

4.3.2 Diameter effects

The laser test results with 850 kHz transducer are presented in the Figure 8. Due to the low signal to noise ratio, only the signals recorded for short specimens are presented. In the Figure 8, P and S-waves can be distinguished. The 2P and 2S-waves do not have a distinctive character.

4.3.3 Specimen top face displacement

Finally, top face of the specimen CL30D20 is scanned with laser vibrometer. The localization of 19 measuring lines (with a total of 289 points) is presented in the Figure 9. Each of the recorded signal in this test consist of the average of 150 time signals.
The P-wave sent from the bottom face results in plane and equally distributed displacement for the top face of the specimen. The main energy (associated with the S-wave) results with the major displacement in the central part of the top face. This preliminary test shows that main energy travels nearly in a beam shape from one end of specimen to another.

Fig. 10. Displacement in nanometer scale of the top face of specimen cL30D20 for P-wave arrival at $t = 0.074164$ ms (left), and main energy arrival at $t = 0.13163$ ms (right).

5. Conclusions

Ultrasonic NDE methods are commonly used for assessment of civil infrastructures. UPV is one of the most commonly used ultrasonic methods due to relatively easy application. However, specimen geometry effects such as the length-to-diameter ratio must be considered. These effects are investigated in this study. The ASTM standard [2] for concrete recommends ultrasonic transducers with resonant frequencies between 20 to 100 kHz. These frequencies generate long wavelengths and therefore imply limitation in the dimensions for the specimens. In this work low ($f_c = 54$ kHz) and high ($f_c = 850$ kHz) frequency ultrasonic transducers are used. Moreover, measurements also taken with laser vibrometer in order to reveal physical dimensions of the responses. Authors present the importance of the application pressure for transducers and show how it affect the signals. In case of low frequencies the separation between P and S-wave is impossible for short specimens and therefore, it remains the major limitation of the method. It is extremely important to have knowledge of signals generated by transmitter used in the tests. The authors present the signals in which S-waves have a dominant character and may lead to wrong interpretation of first arriving signal if acquisition is not done carefully (e.g. low number of
bits in the acquisition unit, or too wide measuring range) even for the specimens with valid length criteria [2]. In the case of high frequency transducer one has to take into consideration the effect of attenuation regarding the length of the sample. The authors recommend that the length of test specimen should exceed more than one wavelength recommended by ASTM (thin spectra peaks were obtained for specimens with lengths of three wavelengths). The effects of diameter are also investigated in the paper and seem to have minor influence on UPV results. Finally the real displacements observed for different events on the top face of the specimen are presented. Further work may be conducted, as the averaging due to position for laser vibrometer can be taken into consideration in order to increase the noise-signal ratio.

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References