ABSTRACT

Title of Document: EVALUATION OF CONCRETE INFRASTRUCTURE QUALITY USING LABORATORY AND ON-SITE TESTING

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The exposure of parking garages to harsh weather conditions and vehicular traffic causes premature deterioration that can compromise structural integrity and pose safety hazards. In order to develop comprehensive and cost-effective strategies for evaluating the condition of their eighteen parking facilities, Montgomery County's Department of Public Works initiated this study. In this phase of the study, a systematic procedure for a robust, automatic, and reliable condition assessment of the concrete slabs of all of the eighteen garages was developed using the nondestructive ultrasonic pulse velocity technique. Computer simulation and laboratory analyses were performed to establish test criteria. Guidelines for conducting the nondestructive tests and analyzing the measured data were provided. The second phase of the study, whereby a performance model will provide a prediction on where the garages are in their life cycles, could be accomplished when the county provides a historical performance of the garages.

EVALUATION OF CONCRETE INFRASTRUCTURE QUALITY USING LABORATORY AND ON-SITE TESTING

By

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DEDICATION

To my sister

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CHAPTER 1 - INTRODUCTION

1.1 RESEARCH NEED

Public parking garages are widely used on a daily basis in both urban and suburban localities. Typically, parking structures experience unusually harsh exposure conditions compared to most other buildings. Because parking garages are usually open structures, they are directly exposed to weather conditions. In cold climates, they are subjected to extreme temperatures, ice, snow, and the corrosive action of deicing salts. These factors, in conjunction with the dynamic loads imposed primarily by moving vehicles, make parking facilities deteriorate more rapidly than other types of building structures. Premature deterioration of exposed concrete surfaces, especially floor slabs, can reduce the structural integrity and pose hazards to the public safety. This necessitates the development of comprehensive and cost-effective strategies for the inspection and condition assessment of parking structures.

Nondestructive methods can be an effective tool in the evaluation of the structural integrity of parking garages. They can provide knowledge about the quality of *in situ* concrete that may be impossible to deduce by the traditional approach of coring and visual inspection alone. Extracted samples, such as concrete cores or reinforcing steel specimens, are very useful. However, removing cores and then making repairs to the sample area is a destructive process that can affect the structural performance of building components. The advantages of nondestructive testing are obvious, but public work departments generally lack guidelines for conducting these tests and for analyzing the resulting measured data.

1.2 RESEARCH GOAL AND OBJECTIVES

The goal of this research was to develop and test a systematic procedure for the inspection and condition assessment of concrete infrastructure using nondestructive test methods. A study was undertaken to assess the condition of eighteen public parking garages in Montgomery County, Maryland, using the ultrasonic pulse velocity technique. The field investigation focused on the concrete floor slabs, which generally experience more deterioration than other structural members and consume the largest portion of the maintenance budget. It is not unusual for the repairs of concrete slabs to require 50% to 80% of the total restoration cost of parking garages (Bhuyan, 1998). With the aim of developing a strategy for the nondestructive evaluation of parking garages, the following specific objectives were studied:

1. To perform computer simulation and laboratory analyses to establish test criteria for a successful implementation of the ultrasonic pulse velocity method when only one side of the structural element being tested was accessible.
2. To develop a method for assessing the test measurements and providing an index as an indicator of uniformity and quality of concrete.
3. To conduct the ultrasonic testing on the floor slabs of the parking garages in a way that meets the criteria established by the laboratory study.
4. To develop a comprehensive procedure for the statistical analysis of the field measurements to obtain a reliable estimate of the velocity data and a more accurate evaluation of the results.
5. To assess the effect of steel reinforcement on ultrasonic pulse velocity measurements when the indirect transmission method is used.

6. To show that the test measurements can be affected for the cases where the surfaces of the concrete slabs are covered by membranes.

1.3 IMPLICATIONS OF THE RESEARCH

The accomplishment of the goal and objectives of this research will provide local governments with valuable guidelines for the inspection and evaluation of concrete infrastructure. The development of a systematic procedure for conducting nondestructive tests and for analyzing the resulting measured data will allow for a robust, automated, and reliable condition assessment.

A comprehensive strategy will enable engineers to nondestructively assess and monitor the quality of concrete over time in parking garages and other concrete structures in a relatively simple, quick, and cost-effective way. The implementation of a technique that may nondestructively and with a relatively low cost assess the condition of structures will result in the reduction of the number of the drilled cores usually required for evaluating the condition of concrete. This will make inspections less costly and less time consuming.

The development of a systematic procedure for conducting the nondestructive testing will increase the speed that test measurements can be performed and therefore will make possible the collection of a significant volume of data in a short time. Thus, larger portions of a structure could be tested which would increase the likelihood of identifying deficiencies and potential problems that can impair the structural integrity. The achievement of accurately evaluating the condition of a structure will enable local governments to take timely corrective action to prevent further deterioration and ensure the safety of public. In addition, the detection of deterioration at early stages will allow for the development of proactive maintenance programs that minimize the cost impact of future rehabilitation and the disruption to the normal operation of facilities.

1.4 ORGANIZATION OF THE REPORT

After the introductory discussion in this chapter, a literature review of nondestructive methods used for the condition assessment of parking and other concrete structures is presented in Chapter 2. In Chapter 3, the ultrasonic pulse velocity method is discussed in detail. Chapter 4 presents the results of the simulation and laboratory studies. Chapter 5 provides the results of the field testing. Chapter 6 discusses the effect of elastomeric traffic-bearing membranes on ultrasonic pulse velocity measurements. Chapter 7 deals with the influence of steel reinforcement on pulse velocity measurements. Finally, Chapter 8 includes a summary of the research, major conclusions, and recommendations for further study.

CHAPTER 2 - LITERATURE REVIEW

2.1 INTRODUCTION

The deterioration of parking garages and other concrete structures is a result of several degradation mechanisms. One of the major factors that affect the durability and service life of parking structures is the corrosion of steel reinforcement due to chloride attack. The exposure of parking garages to the deicing salts transferred by the vehicular traffic or to airborne chlorides in coastal regions is the main contributor to the chloride-induced corrosion. Penetration of sufficient quantities of chlorides in concrete combined with the presence of oxygen and moisture leads to the initiation of corrosion. When the steel reinforcing bars corrode, the volume of corrosion by-products (rust) is generally five to eight times larger than the volume of the original steel (Popovic et al., 2005). As a result, rust expansion exerts pressure on the surrounding concrete and eventually causes cracks and delaminations. As the corrosion process continues and corrosion by-products expand further, a rupture between the delaminated concrete and main component can occur, resulting in spalls and potholes.

While corrosion-induced deterioration is the most dominant and aggressive form of deterioration of parking garages, freezing and thawing can also cause accelerated deterioration especially to the structures that are not adequately air-entrained. Freeze-thaw cycling can cause surface flaking and scaling due to the disruptive forces generated in the concrete paste and eventually lead to the exposure of aggregates in large surface areas.

Visual inspection is the most common method used for the condition assessment of parking garages and involves the detection of signs of deterioration such as cracking, spalling, scaling, and leakage of water through concrete and joints. However, subsurface or internal detects in the body of the structural elements are difficult to evaluate by this method. It is, therefore, necessary the implementation of other methods that can identify problems when the state of deterioration is invisible.

2.2 CONDITION ASSESSMENT OF PARKING GARAGES

Numerous field test procedures are available for the evaluation of concrete including methods that require some removal of the material and nondestructive methods. Some of the commonly used laboratory and nondestructive tests for the condition assessment of parking structures are presented in Table 2.1 (Bhuyan, 2001). The applications of each method are discussed briefly, with the exception of those of the ultrasonic pulse velocity method as it is the main method used in the present research.

Table 2.1 Commonly used laboratory and nondestructive tests for evaluation of parking garages (Bhuyan, 2001).

Tests		Standard Designation
Materials Testing	Chloride ion content	ASTM C1218
	Compressive strength	ASTM C42
	Petrographic examination	ASTM C856
Nondestructive Testing	Delamination survey (chain drag)	ASTM D4580
	Pachometer survey	–
	Radar survey	ASTM D4748
	Ultrasonic pulse velocity method	ASTM C597

Chloride ion content test

The aim of this test is to determine the extent of chloride ion penetration at a certain depth within the concrete, which can indicate the potential for corrosion of reinforcement. High chloride ion concentration at the level of the reinforcing steel bars indicates the presence of active corrosion. Corrosion can start when the chloride ion content reaches a concentration in the range of 0.2% by weight of cement. Concrete powder samples should be taken in at least three different depths within the structure cross-section (Popovic et al., 2005).

Compressive strength test

Concrete core samples are usually removed from selected areas of the structure and are tested in compression to verify that the concrete has the expected compressive strength. Core samples are obtained and tested in accordance with the Standard Test Method ASTM C42 (Bhuyan, 2001).

Petrographic examination

A petrographic analysis involves the examination of concrete core samples microscopically in order to evaluate the quality and durability of concrete. Microscopic examination can identify any material problems or irregularities determining denseness of cement paste, air content, water/cement ratio, aggregate distribution, contaminating substances, depth of carbonation, depth and nature of cracks, and presence of other distress that can affect the integrity of concrete (Bhuyan, 2001; Popovic et al., 2005).

Delamination survey (chain drag)

This method is useful for detecting delaminations in concrete slabs that are usually invisible as they form within the concrete. The technique involves dragging a chain across the surface of the floor slab. When an area of delamination is encountered, a distinct hollow sound is produced. The chain drag method is not totally accurate because of subjective interpretations by inspectors, but it is rapid and inexpensive (Bhuyan, 2001; Popovic et al., 2005)

Pachometer survey

This method involves the use of an instrument referred to as pachometer or covermeter. The pachometer can magnetically locate the reinforcing bars embedded in the structure. Measuring the intensity of the magnetic field produced by the embedded steel, the concrete cover over reinforcement can be determined provided that the size of the reinforcing bars is known (Bhuyan, 2001; Popovic et al., 2005).

Radar survey

Radar surveys are based on the detection of the arrival time and energy level of a reflected electromagnetic pulse. It is an effective method for detecting internal discontinuities, determining concrete thickness, and locating steel reinforcing bars, post-tensioning or prestressing tendons (Bhuyan, 2001; Popovic et al., 2005).

Ultrasonic pulse velocity method

The term *ultrasonics* was given to science and application of *ultrasound*, i.e., sound with a frequency above the human audible range, which is above 20 KHz (Popovics, 1998). Several types of ultrasonic testing have been developed for concrete quality assessment. The ultrasonic pulse velocity (UPV) method has been the most widely accepted method for evaluating concrete quality and has been used for over 60 years. It is based on the principle of propagation of compressional waves, i.e., waves that are transmitted by particles vibrating parallel to the direction of propagation. The basic idea of this test method is the determination of the velocity of wave propagation that requires the measurement of the time taken by a compressional wave pulse to pass from one point of the tested concrete element to another point. The ratio of the distance between these two points to the transit time expresses the velocity of propagation of the ultrasonic pulse.

The first report of velocity measurements of mechanically generated pulses through concrete appeared in USA in the mid-1940s. As indicated by Nawy (1997), a proposed ASTM method was published by Leslie (1955), but it was not until 1967 that it finally became a tentative test method (ASTM C597).

The pulse velocity method may be used to assess the uniformity and relative quality of concrete, detect the presence of voids and cracks, and estimate the depth of cracks. It is also useful to detect changes in concrete that may occur with time or through the action of fire, frost, or chemical attack (Naik et al., 2004).

The pulse velocity of compressional waves through a material depends primarily upon its elastic properties and is almost independent of geometry. The following relationship provides the pulse velocity, V, through concrete as a function of its elastic properties and density (ASTM C597, 2003):

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{2.1}$$

where E is the dynamic modulus of elasticity, μ is the dynamic Poisson's ratio, and ρ is the density.

Numerous studies have been performed with the aim of using pulse velocity as an indicator of quality control. Whitehurst (1951) suggested a general rating for the concrete quality as a function of pulse velocity and is presented in Table 2.2. The classification of the quality of concrete was established experimentally for normal concrete that had a unit weight of approximately 150 lb/ft^3. Whitehurst underlined that this classification may be satisfactory for indicating the general quality of concrete; however, the lines of demarcation could not be sharply drawn. The degree to which a particular concrete will fall into a category (Table 2.2), would depend upon the type of aggregate in the concrete, the mix proportion, and the condition of curing. Therefore, the investigator is advised to have a thorough knowledge of the concrete tested before making conclusions concerning concrete quality based on velocity test results.

Table 2.2 Classification of the quality of concrete on the basis of pulse velocity (Whitehurst, 1951)

Quality of Concrete (General condition)	**Pulse Velocity (ft/s)**
Excellent	>15,000
Good	12,000-15,000
Fair	10,000-12,000
Poor	7,000-10,000
Very Poor	<7,000

Several experimental investigations have been conducted to estimate the compressive strength of the concrete based on the pulse velocity measurements. The general outcome of these investigations was that the relationship between concrete strength and pulse velocity is not unique (Popovics, 2001). This can be attributed to the fact that the factors that affect the strength may affect the pulse in a different way. Some of the factors that influence the relationship between compressive strength and pulse velocity include the aggregate size and type, water-cement ratio, concrete composition, cement type and content, moisture content, curing conditions, and concrete age (Abdel-Jawad and Afaneh, 1997). Many investigators (Sturrup et al., 1984; Swamy and Al-Hamed, 1984; Popovics et al., 1990) have shown that the effect of type and amount of aggregate on pulse velocity is particularly important. Research findings demonstrated that for the same concrete mixture at the same compressive strength, concrete with rounded gravel exhibited the lowest pulse velocity, crushed limestone resulted in the highest pulse velocity, and crushed granite had a velocity between these two. In addition, concrete with a higher aggregate content provides a higher pulse velocity (Popovics, 2005).

Turgut (2004) summarized the findings of previous laboratory studies undertaken by eighteen investigators who attempted to determine the relationship between concrete strength and pulse velocity. The experimental works were performed on concrete specimens of various concrete mixtures and generally of the same age (28 days). The eighteen laboratory investigations provided eighteen different relationships between concrete strength and pulse velocity. This indicates that the relationship concrete strength – pulse velocity is not unique and is affected by the concrete mix. Therefore, the estimation of the compressive strength of a component being tested based on pulse velocity values is possible only when pre-established correlations between compressive strength – pulse velocity have been obtained for the particular type of concrete. Based on the data obtained by the eighteen laboratory studies, Turgut (2004) derived the best-fit curve representing the correlation between compressive strength and pulse velocity as follows:

$$S = 0.0872e^{1.29V} \tag{2.2}$$

where S is the compressive strength in *MPa* and V is the pulse velocity in *km/s*.

CHAPTER 3 - THE ULTRASONIC PULSE VELOCITY METHOD

3.1 INTRODUCTION

In this chapter an in-depth study of the ultrasonic pulse velocity method is presented, while focusing on its implementation when only one surface of the element being tested is accessible. A thorough description of the method and the criteria that should be fulfilled for a successful application are discussed.

3.2 DESCRIPTION AND USE OF TESTING APPARATUS

The equipment for the pulse velocity method, as shown schematically in Figure 3.1, consists of a pulse generator, two transducers (receiver and transmitter), an amplifier, a time measuring circuit, a time display unit, and connecting cables. A complete description of the testing apparatus is provided in ASTM Test Method C 597-97 (ASTM, 2003).

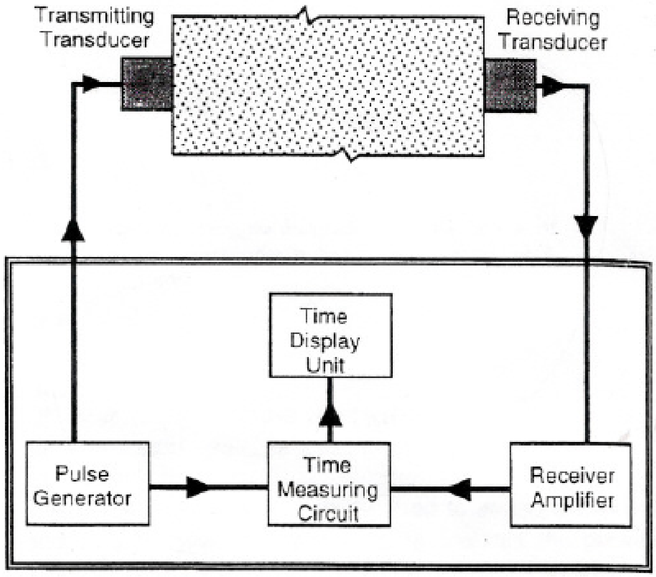

Figure 3.1 Schematic of Pulse Velocity Apparatus (ASTM C 597-97, 2003)

The pulse generator consists of circuitry for generating pulses of voltage. The electrical pulses are transformed into wave bursts of mechanical energy by the transmitting transducer. This is accomplished by a piezoelectric crystal inside of the transducer. The applied voltage causes deformation and the vibrating crystal converts the electrical energy into a mechanical vibration of ultrasonic frequency. The reverse process occurs when the ultrasonic waves are received by the crystal that the receiving transducer includes, i.e., the mechanical energy is converted back to electrical pulses of the same frequency. The voltage generated by the receiver is amplified to produce triggering pulses to the time measuring circuit. In other words, the function of the amplifier is to ensure that any signal from the receiver arrives at the time measuring circuit. Subsequently, the time measuring circuit measures the time interval between the onset and reception of the pulse and this is displayed on the time display unit as a digital readout.

The transducers must be in full contact with the concrete surface; otherwise, the indicated transit time is subjected to error. The elimination of air pockets between the transducers and concrete surface is essential because only a negligible amount of wave energy can be transmitted through air. To assure that the ultrasonic pulses generated by the transmitter pass into the concrete and then are detected by the receiver, a layer of a viscous couplant is placed between the contact surface of the faces of the transducers and the surface of the concrete. Many couplants available in the market can be used to avoid entrapped air such as oil, petroleum jelly, grease, or kaolin/glycerol paste. The couplant layer should be as thin as possible. When the concrete surface is very rough, thick grease should be used as a couplant or the surface where the transducers are applied should be smoothed. A constant pressure should be applied on transducers until a stable transit time is displayed. The pulse velocity is calculated as follows:

$$V = \frac{L}{t} \tag{3.1}$$

where V is the pulse velocity in *ft/s*, L is the distance between transducers (from center to center) in *ft*, and t is the transit time in *sec*. The distance between transducers and the transit times should be measured to an accuracy of about ± 1%.

If a wave encounters a crack or void, the direct passage of ultrasonic pulses is prevented. The wave is diffracted around the discontinuity with the result that the travel time will be longer than that in a sound concrete. The pulse velocity is higher in the case where the concrete if of a better quality.

3.3 TRANSDUCER SELECTION AND ARRANGEMENT

3.3.1 Transducer selection

A certain frequency is optimum for a material. As the frequency increases, it is possible to detect smaller defects in the material. On the other hand, the acoustic energy loss (attenuation) increases with higher frequencies. Because attenuation is high in concrete due to the composite and elastoplastic nature of the concrete, the pulse frequency used for testing concrete is much lower than that used in the testing of metals. A range of frequencies between 20 KHz and 200 KHz is the most optimum for concrete. (Popovics, 1998). The most commonly used transducers have a natural frequency of 54 KHz with a flat contact surface of 2 inches diameter.

Another factor that is likely to require the selection of an alternative transducer frequency is the dimensions of the member being tested. The least lateral dimension of the member must exceed the wavelength of the ultrasonic vibrations (ASTM C 597-97, 2003). It is known that the following relationship is also valid for ultrasonic waves:

$$V = f \times \lambda \tag{3.2}$$

where V is the wave velocity in *ft/s*, f is the frequency of the wave in *Hz*, and λ is the wavelength in *ft*.

This means that, if a decrease in the wavelength of the vibrations is desirable, then the selection of a transducer with higher frequency is an alternative.

3.3.2 Transducer arrangement

The transducers may be arranged, as shown in Figure 3.2, in the following three basic ways:

(a) Opposite faces (direct transmission method)

(b) Adjacent faces (semi-direct transmission method)

(c) Same face (indirect or surface transmission method)

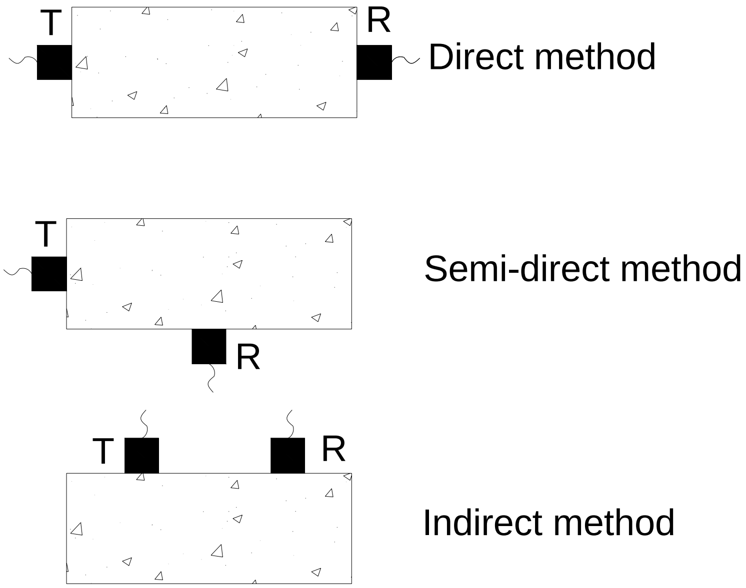

Figure 3.2 Arrangements of transducers (T = transmitter, R = receiver).

Wherever possible, the direct transmission arrangement should be used for assessing concrete quality. It is the most satisfactory arrangement because maximum energy of the pulse is transmitted and received with this arrangement. This occurs because the maximum pulse energy is transmitted at right angles to the face of the transmitter and in the direct transducer arrangement the receiver is directly opposite to the transmitter. The semi-direct method, which is useful in avoiding concentrations of reinforcements, is less energy efficient than the direct method due to the geometry of the transducer arrangement. The indirect method is the least satisfactory, since the amplitude of the received signal is significantly lower (less than 3%) than that received by the direct transmission method (Naik et al., 2004). As a result, the indirect velocity is invariably lower than the direct velocity on the same concrete element. British Standards (as indicated by Yaman et al., 2001) state that this difference may vary from 5 to 20%, depending mainly on the concrete quality. Furthermore, pulse velocity measurements are usually influenced by the surface layer of concrete, which may not be representative of the concrete in deeper layers. They provide information for the quality of concrete down to a depth corresponding approximately to the length of the generated ultrasonic wave.

In addition, the direct method is the most reliable method because the path length is clearly defined and can be measured accurately. In the semi-direct method, the path length is less clearly defined than that of the direct method, but it is generally regarded as adequate to take this from center to center of transducer faces. In the indirect method, the point from which the pulses start to propagate from the transmitter and that of the point at which they are picked up by the receiver is uncertain. According to Krautkramer (1990), as indicated by Yaman et al. (2001), the uncertainty in wave path length is because of the fact that the distribution of excitation over the cross-section of the piezoelectric crystal of the transducer may not be uniform. As a result of this nonuniform and indeterminate deformation of the crystal surface, the points of excitation and reception of pulses can vary between the inner and outer rims of the transducers. Galan (1990) attributed the uncertainty in the path length to another factor: to the quality of concrete at points of application of transducer faces. Invisible microcracks, pores and flaws, and aggregate or clusters of aggregate under the surface layer affect the position of the points of onset and reception of the pulses and consequently introduce uncertainty in the path length. Although the indirect method is the least efficient of the three methods, it is useful in situations where only one surface of a structure is accessible, such as floor slabs, bridge decks, and pavements.

3.4 DETERMINATION OF PULSE VELOCITY BY THE INDIRECT TRANSMISSION METHOD

The ultrasonic pulse velocity is given by the theoretical relationship of Equation 3.1. However, because of the uncertainty in the path length when indirect transducer arrangements are used, individual readings are of a little value. A special procedure is necessary to eliminate this uncertainty. The procedure requires a series of measurements and is presented schematically in Figure 3.3. Readings are taken with the transmitter, T, in a fixed position and the receiver, R, moved progressively away from the transmitter in equal increments along a chosen line on the concrete surface. The transit times recorded, t, are plotted against the distance between transducers, L, as shown in Figure 3.4. If all of the points on the graph lie in the same line, then regression analysis can be applied, and the slope of the best-fit straight line drawn through the points provides the pulse velocity. If a discontinuity in the plot exists, it indicates that a crack exists or the concrete is of variable quality. The advantage of the method described is that it provides an average value of the path length and, therefore, reduces the error in the determination of the path length that inevitably accompanies the indirect transmission method. This procedure has been standardized by the British Standards Institution (BS EN 12504-4) as indicated by

(Bungey 2006), and it is the main method that is recommended and used extensively when the indirect transmission method is applied. ASTM C 597-97 (ASTM, 2003), does not provide any standards for indirect pulse velocity measurements, although it recommends the use of the indirect transmission method when only one face of the structure is accessible.

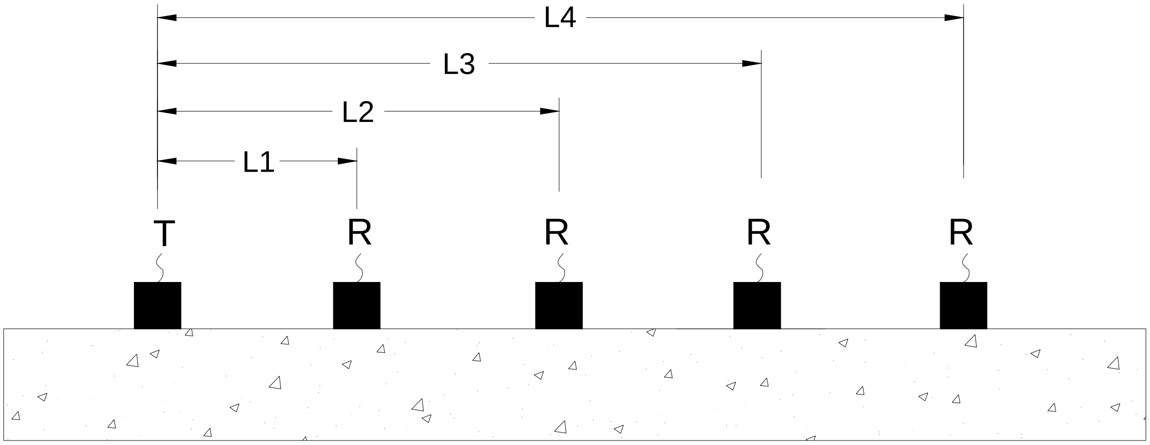

Figure 3.3 Indirect pulse velocity measurements with the transmitter, T, in a fixed position and the receiver moved progressively away from the transmitter in equal increments.

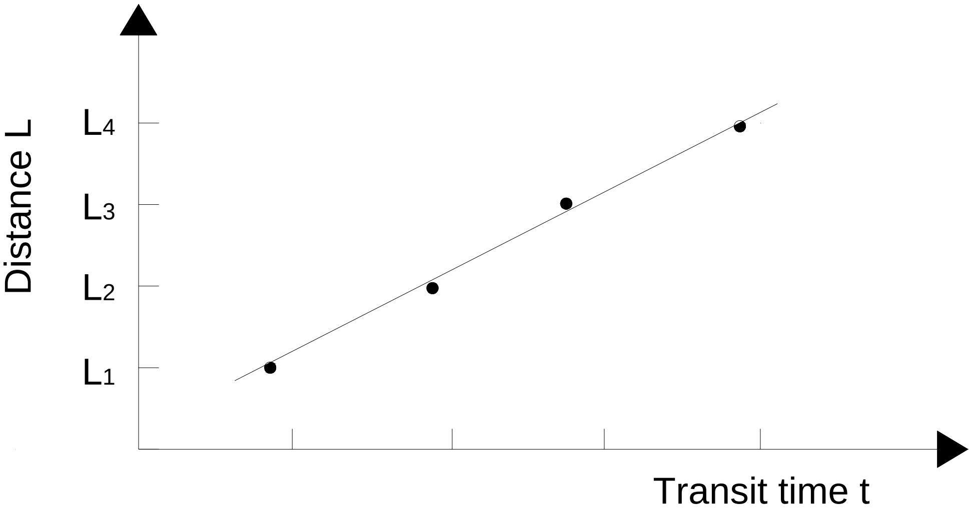

Figure 3.4 Transit time, t, versus the distance, L, between transducers and pulse velocity determination by the slope of the best-fit line.

Pulse velocities can be negatively influenced by the heterogeneous nature of concrete when excessively small path lengths are used. BS EN 12504-4 (as indicated by Bungey, 2006) recommends minimum path lengths of 4 in. (100 mm) and 6 in. (150 mm) for concrete with maximum aggregate sizes of 0.8 in. (20 mm) and 1.6 in. (40mm), respectively. According to Galan (1990) the measurements are admissible if the following criteria are satisfied:

$$L > \lambda \tag{3.3}$$

$$L > 4D_{\max} \tag{3.4}$$

where L is the path length in *in*., λ is the wavelength in *in*. determined from the relationship $V = f \times \lambda$, and D_{max} is the size of the largest aggregate grains in *in.*

As an alternative to the regression method, another method called as the *unit-interval method* is presented herein. The basic idea of this method is the determination of the ultrasonic pulse velocity in each interval computing the individual slopes between adjacent points. The slope between two adjacent points, $S_{i,i+1}$ (*ft/s*), is given by the following equation:

$$S_{i,i+1} = \frac{L_{i+1} - L_i}{t_{i+1} - t_i} \tag{3.5}$$

where L_i, L_{i+1} are the distances, in *ft*, between the transmitter and receiver placed at points i and $i+1$, respectively; t_i, t_{i+1} are the transit times, in *sec*, which correspond to lengths L_i, L_{i+1}, respectively. In Chapter 4, the efficiency of both methods as a tool to concrete quality assessment is investigated.

CHAPTER 4 - SIMULATION AND LABORATORY STUDIES

4.1 SIMULATION STUDY

Simulation is a popular tool in engineering decision making. The basic concept of a simulation is an attempt to model a real-life situation. It involves the representation of a selected physical or abstract system with the aim of understanding how the system works and predicting its behavior. Predictions about the behavior of the system can be made by changing the values of variables. Engineers work with data measured from real systems. However, when data are limited or the cost for their collection is too high, simulation is extremely useful as it can provide solutions and help engineers make decisions. Methods of simulation are based on the generation of random variables, which is usually made by computer programs. Random-number generators produce numbers that have specific statistical characteristics.

The objective of this study is the use of simulation data (1) to compare the pulse velocities determined by the approaches described in the previous section, i.e., the velocities using the regression method and the unit-interval method, and (2) to determine the effective spacing between transducers.

4.1.1 Comparison of the regression and unit-interval methods

It was assumed that UPV measurements were made on a concrete slab with the transmitter, T, in a fixed position and the receiver, R, moved progressively away from the transmitter in equal increments of two inches. The arrangement of the transducers is illustrated in Figure 4.1, with the transmitter location at point 0 and the receiver locations at points 1, 2, …, 6. Three different cases were considered as follows:

Case A: the concrete is of good quality in all intervals

Case B: the concrete is of good quality in all intervals except for interval 4-5, where it is of fair quality.

Case C: the concrete is of good quality in all intervals except for interval 1-2, where it is of fair quality.

The velocities for each interval were generated by the simulation process.

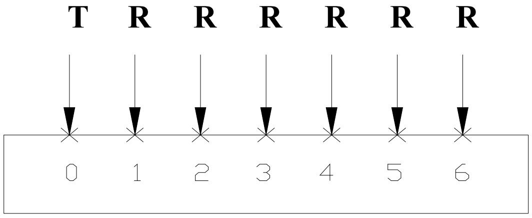

Figure 4.1 Assumed transducers arrangements for simulation (T = transmitter, R = receiver, the numbers 0 to 6 represent the transducer locations).

First, a computer program was used to generate random numbers that had a uniform distribution in the range of (0, 1). Subsequently, these uniform random numbers were transformed into values that followed a normal distribution using the standard normal transformation equation $x_i = \mu + z_i \sigma$, where x_i is the transformed value, μ is the mean, z_i is the uniform random number and σ is the standard deviation. The mean μ for the velocities through good concrete was assumed to be 15,000 ft/sec, while a mean value of 10,000 ft/s was assumed for the fair quality concrete. The standard deviation σ was equal to 2% of the mean μ for both cases.

After the generation of velocities x_i for each interval, the values of the transit time between transmitter and receiver locations were calculated as the ratio of the separation distance to the velocity. The values of the time versus distance between transducers were plotted as shown in Figures 4.2, 4.4, and 4.6 for cases A, B, and C, respectively, and a linear regression line was fitted for each graph. The results of the generated velocities for each interval, which in essence represent the velocities obtained by the unit-interval method, are given in Figures 4.3, 4.5, and 4.7 for cases A, B, and C, respectively.

In Case A, as can be seen in Figure 4.2, all of the points lie in a straight line, which means that the concrete is of the same quality. The slope of the best-fit line yielded an average velocity of 15,162 ft/s. Similarly, the unit-interval method (Figure 4.3) provided a mean value of 15,150 ft/s.

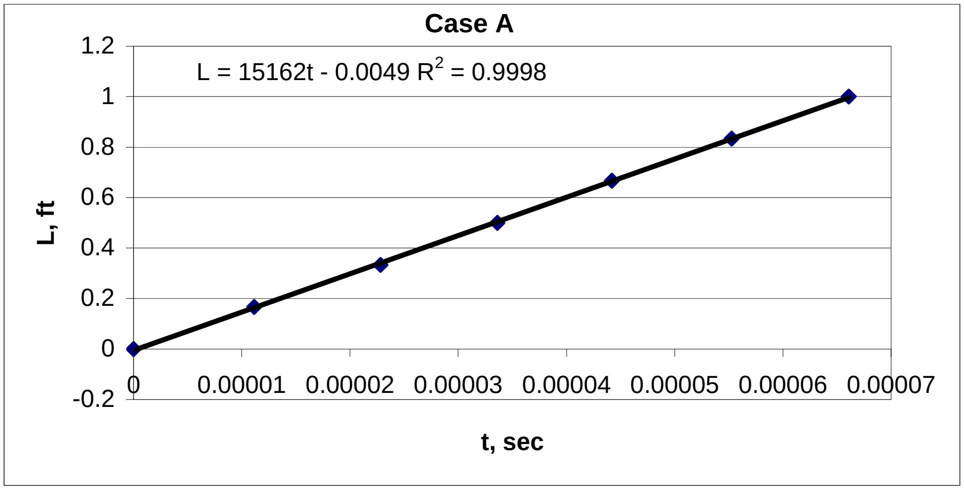

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Figure 4.2 Plot of time versus distance with increments of 2 inches and best-fit line by regression analysis for Case A.

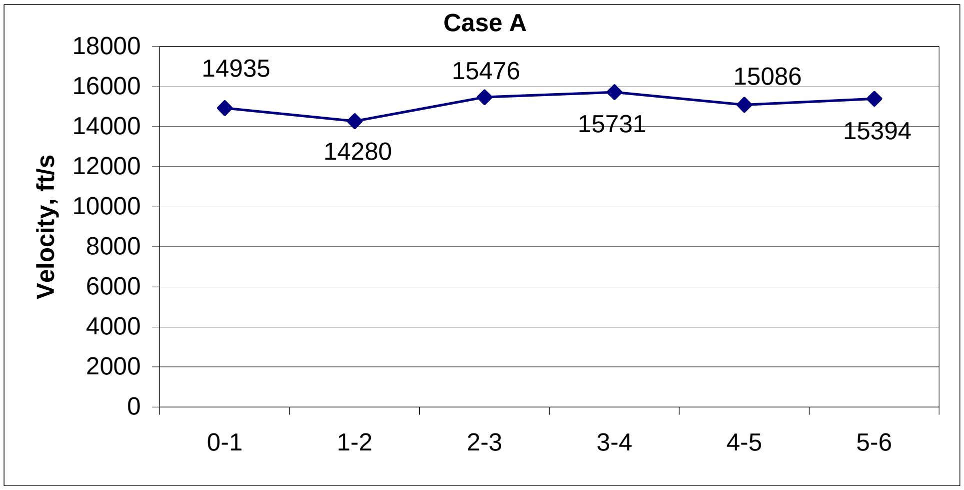

Figure 4.3 Velocities obtained by the unit-interval method with a separation distance of 2 inches for Case A.

In Case B, as shown in Figure 4.4, the points seem to lie in the same line. This indicates such in Case A that the concrete is homogeneous with a mean velocity of 13,866 ft /s, which is untrue, as it is known in advance that the concrete in interval 4-5 was of fair quality. On the other hand, using the unit-interval it is obvious in Figure 4.5 that the concrete is not of uniform quality as the velocity in section 4-5 is 10,057 ft/s. Excluding this value, the average velocity was found to be 15,163 ft/s.

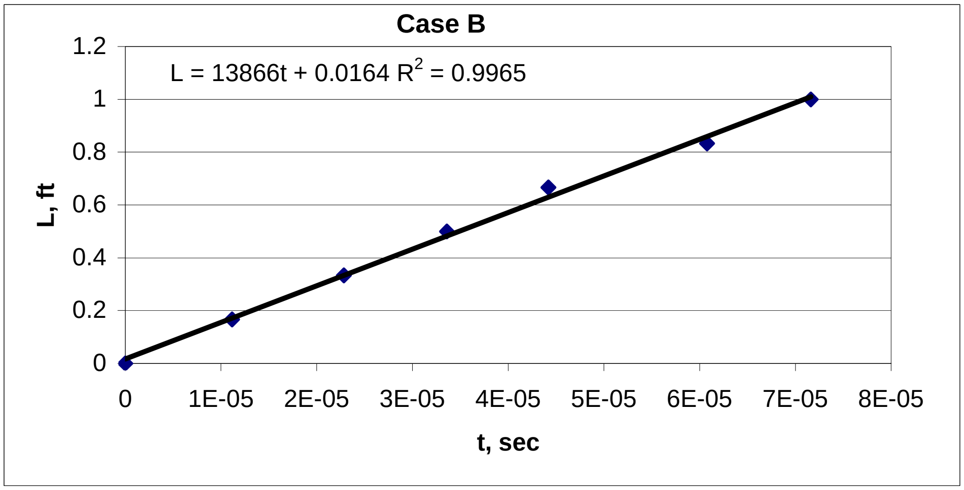

Figure 4.4 Plot of time versus distance with increments of 2 inches and best-fit line by regression analysis for Case B.

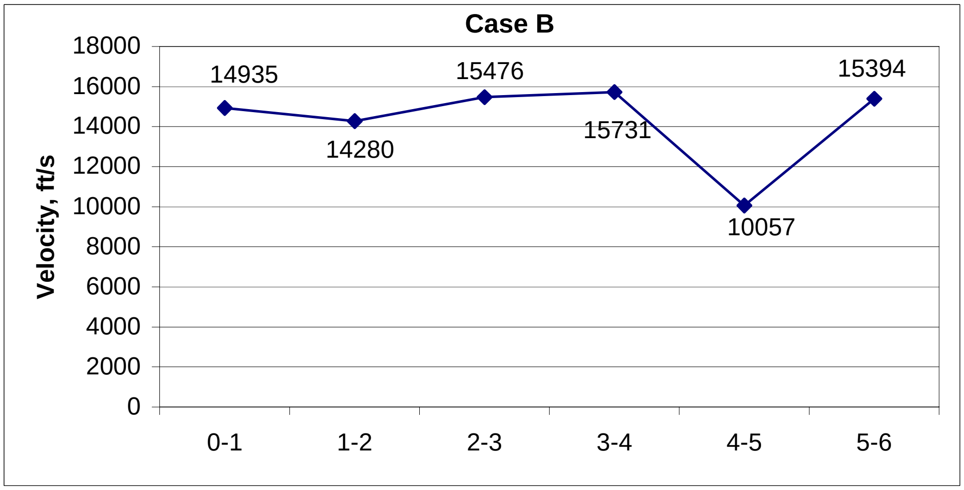

Figure 4.5 Velocities obtained by the unit-interval method with a separation distance of 2 inches for Case B.

The trend shown with Case B was similar to that for Case C. The section of fair quality concrete was distinguished from the sections of good concrete only in the case of the unit-interval method, where the velocity of 9,520 ft/s was low in interval 1-2 (Figure 4.7). With the exception of this value, the mean velocity is equal to 15,324 ft/s, contrary to the average velocity of 13,768 ft/s determined by the regression method.

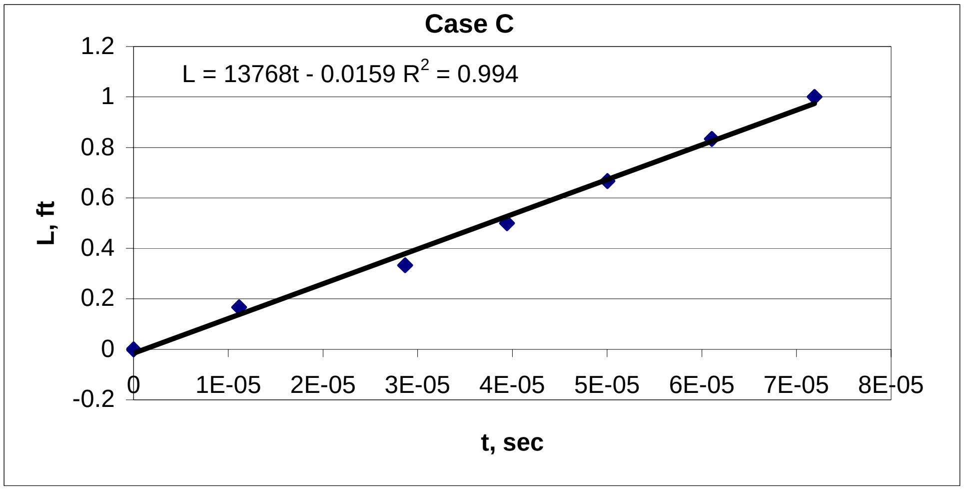

Figure 4.6 Plot of time versus distance with increments of 2 inches and best-fit line by regression analysis for Case C.

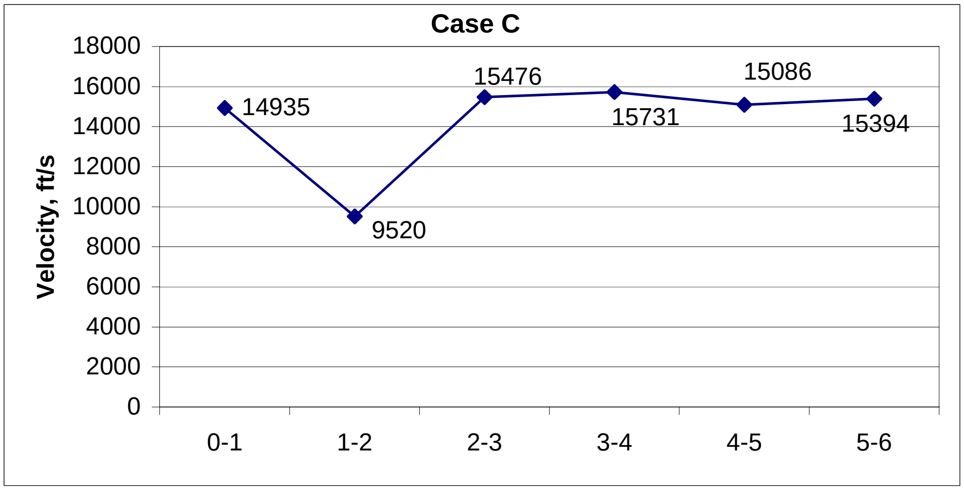

Figure 4.7 Velocities obtained by the unit-interval method with a separation distance of 2 inches for Case C.

For a better understanding and interpretation of the results, the regression approach was applied with increasing successively the number of measurement points. The results are given in Tables 4.1, 4.2, and 4.3, for the cases A, B, and C, respectively. Column 1 of each table shows the receiver locations (see Figure 4.1) where measurements were assumed to be taken, while Column 3 provides the velocities computed by the slope from linear regression analysis. The slope changed as the number of measurement points increased. Columns 4 and 5 contain the intercept of the best-fit line and the correlation coefficient, respectively. For ease of comparison, Column 7 shows the velocities obtained by the unit-interval method.

Table 4.1 Velocities using the regression method with increasing the number of measurement points compared to the velocities obtained by the unit-interval method (Case A).

Regression method					**Unit-interval method**	
Transducer locations (1)	**Number of points** (2)	**Velocity (ft/s)** (3)	**Intercept** (4)	**Correlation coefficient, R** (5)	**Intervals** (6)	**Velocity (ft/s)** (7)
0,1	2	14,935	0	1.00000	0-1	14,935
0,1,2	3	14,598	0.001273	0.99992	1-2	14,280
0,1,2,3	4	14,816	-0.00034	0.99989	2-3	15,476
0,1,2,3,4	5	15,033	-0.00276	0.99983	3-4	15,731
0,1,2,3,4,5	6	15,106	-0.00384	0.99989	4-5	15,086
0,1,2,3,4,5,6	7	15,162	-0.00489	0.99992	5-6	15,394

Table 4.2 Velocities using the regression method with increasing the number of measurement points compared to the velocities obtained by the unit-interval method (Case B).

Regression method					**Unit-interval method**	
Transducer locations (1)	**Number of points** (2)	**Velocity (ft/s)** (3)	**Intercept** (4)	**Correlation coefficient, R** (5)	**Intervals** (6)	**Velocity (ft/s)** (7)
0,1	2	14,935	0	1.00000	0-1	14,935
0,1,2	3	14,598	0.001273	0.99992	1-2	14,280
0,1,2,3	4	14,816	-0.00034	0.99989	2-3	15,476
0,1,2,3,4	5	15,033	-0.00276	0.99983	3-4	15,731
0,1,2,3,4,5	6	**14,025**	0.013327	0.99733	**4-5**	**10,057**
0,1,2,3,4,5,6	7	13,866	0.016374	0.99823	5-6	15,394

Table 4.3 Velocities using the regression method with increasing the number of measurement points compared to the velocities obtained by the unit-interval method (Case C).

Regression method					**Unit-interval method**	
Transducer locations (1)	**Number of points** (2)	**Velocity (ft/s)** (3)	**Intercept** (4)	**Correlation coefficient, R** (5)	**Intervals** (6)	**Velocity (ft/s)** (7)
0,1	2	14,935	0	1.00000	0-1	14,935
0,1,2	3	**11,441**	0.014783	0.99193	**1-2**	**9,520**
0,1,2,3	4	12,158	0.009077	0.99537	2-3	15,476
0,1,2,3,4	5	12,876	0.000388	0.99572	3-4	15,731
0,1,2,3,4,5	6	13,382	-0.01586	0.99641	4-5	15,086
0,1,2,3,4,5,6	7	13,768	-0.01586	0.99699	5-6	15,394

Comparing the velocities determined by the two methods leads to the following conclusions:

- In Case A, the regression method provided velocities similar to those of the unit-interval method. Therefore, it can be concluded that the regression method is efficient when the concrete is of the same quality throughout the slab. It would also be acceptable if all of the concrete was of fair quality.
- In case B, the regression method was not able to clearly identify the location of fair quality concrete. While the regression velocity was lower in this section, 14,025 ft/s, than for the previous calculation, 15,033 ft/s, it was much closer to the 15,000 ft/s value for good quality concrete than to the 10,000 ft/s of fair quality concrete. This result occurs because the regression procedure averages the velocities. Therefore, when the area of the inferior quality concrete is located far away from the transmitter, the regression approach is adequate only throughout the good section.
- In Case C, the problem of the inferior quality concrete, which is located near the transmitter, can be detected by the regression method, as the velocity is low in

that section, 11,441 ft/s, compared to the previous calculation, 14,935 ft/s. However, the velocity increases with an increasing number of measurement points. The problem in this case is that it is difficult to identify whether or not other sections are of fair quality concrete. Because each regression uses data from previous sections, then the velocities for sections beyond the section of fair quality are low, which makes it difficult to decide whether or not these other sections are also of fair quality. Therefore, the presence of an area of inferior quality concrete near the transmitter yields misleading values for the velocities even when the concrete in other sections is of good quality. Thus, it is necessary to take into account many measurement points in order for the regression velocity to approach the actual value of the good concrete.

4.1.2 Effect of spacing between receiver locations

Simulation data were also used to assess the influence of the separation distance between transducers on the velocities obtained using the unit-interval method. The spacing between receiver locations is important because it affects the accuracy of the results. Measurements of time as the wave passes though a section is subject to considerable variation because of the nonhomogeneity of the concrete over very short sections. Thus, for sections of small lengths, e.g., 1-inch, the measured time will vary considerably. This variation is translated into variation of the computed velocity measurements. As the section lengths are increased, the variation due to the nonhomogeneity is averaged, which produces more stable velocity estimates.

Values for the velocities were generated for 26 intervals, each 1-inch long, with the assumption that they were normally distributed. The random normal numbers for good concrete were derived with a mean of 15,000 ft/s and a standard deviation of 150 ft/s. The above procedure was repeated five times for 1-inch separation distance. Subsequently, velocities were computed, with increased spacing from 2 to 8 inches between two receiver locations. The coefficients of variation (COVs) were calculated in each case and the values plotted versus the separation distance. Using mean values for each separation distance, an exponential equation was fitted (see Figure 4.8). Based on the exponential model, it is clear that the coefficient of variation decreases with increasing separation distance. Table 4.4 gives the mean values of coefficient of variation of the velocities for different separation distances and the corresponding values of coefficient of variation derived from the equation.

As the quality of concrete can vary over short distances, it is beneficial to keep short separation distances between the readings. Then the location of poor concrete can be identified. However, with short distances, the concrete variability can give misleading measurements of time. This encourages the collection of data with relatively large separation distances. Based on these competing constraints, Figure 4.8 suggests that the coefficient of variation stabilizes after about 4 inches. Based on this observation, the regression method and the unit-interval method are applied again for the concrete slab used in the first part of the simulation study with a transducer spacing of 4 inches instead of 2 inches. The results are presented in Figures 4.9 to 4.13.

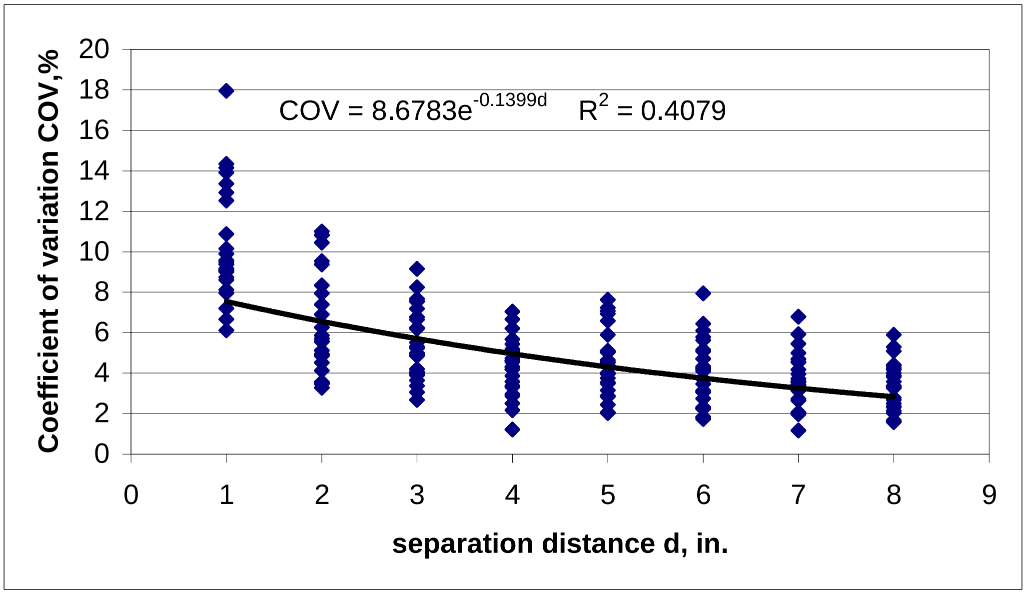

Figure 4.8 Plot of separation distance between transducers versus the COV of velocities obtained by the unit-interval method.

Table 4.4 Mean of COV of velocities with increasing the separation distance and values of COV derived from the exponential equation.

Separation distance d (in.)	**Mean of COV (%)**	**COV= 8.6783e$^{-0.1399d}$ (%)**
1	10.26	7.55
2	6.44	6.56
3	5.46	5.70
4	4.34	4.96
5	4.42	4.31
6	4.00	3.75
7	3.67	3.26
8	3.39	2.83

As can be seen in Figures 4.9, 4.11, and 4.13, the best-fit lines by the regression analyses indicate that the concrete is homogeneous in all cases with a mean velocity of 15,178 ft/s, 14,075 ft/s, and 13,978 ft/s for Case A, B, and C, respectively. In contrast, the unit-interval method was able to reveal the areas of different quality concrete. This is based on the low velocity, 12,166 ft/s, in the interval 4-6 for Case B and 11,628 ft/s in the interval 0-2 for Case C.

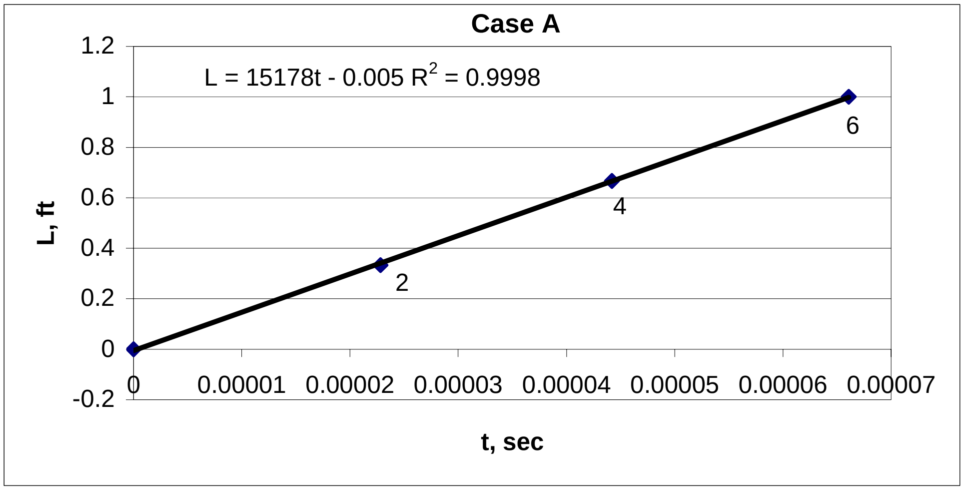

Figure 4.9 Plot of time versus distance with increments of 4 inches and best-fit line by regression analysis for Case A.

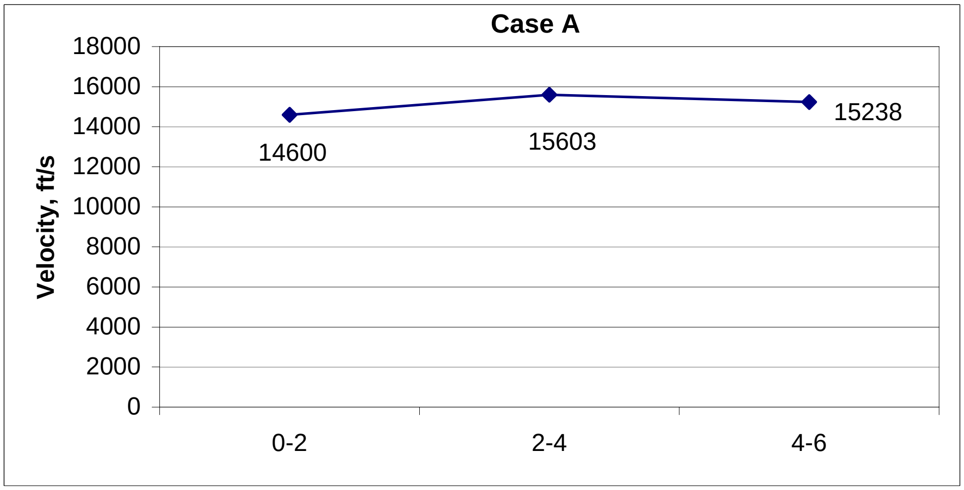

Figure 4.10 Velocities obtained by the unit-interval method with a separation distance of 4 inches for Case A.

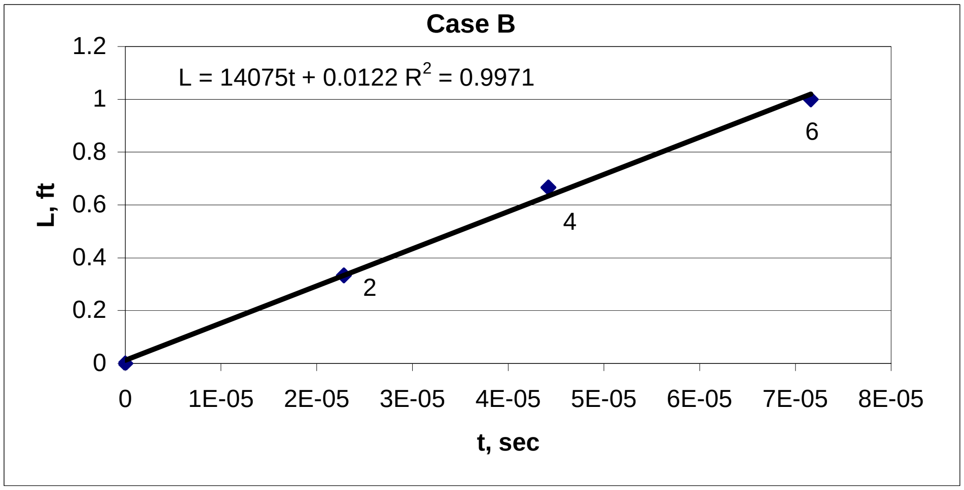

Figure 4.11 Plot of time versus distance with increments of 4 inches and best-fit line by regression analysis in Case B.

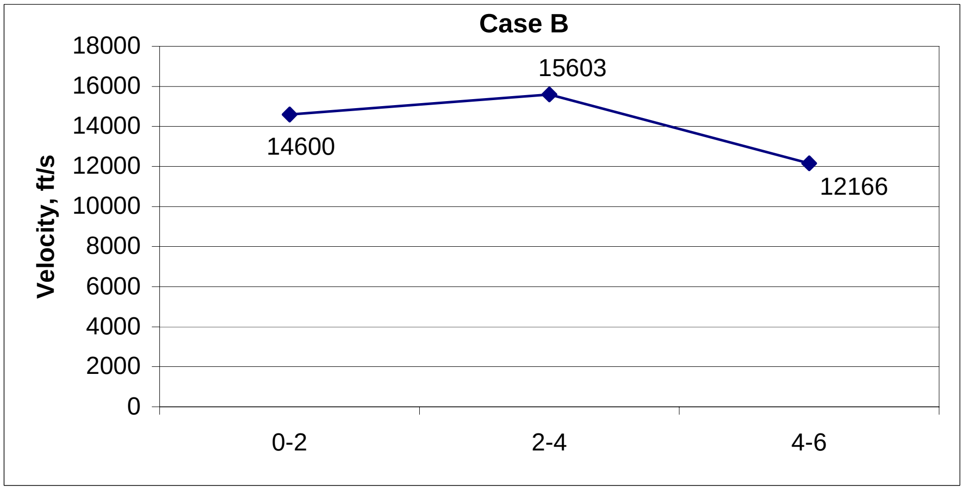

Figure 4.12 Velocities obtained by the unit-interval method with a separation distance of 4 inches for Case C.

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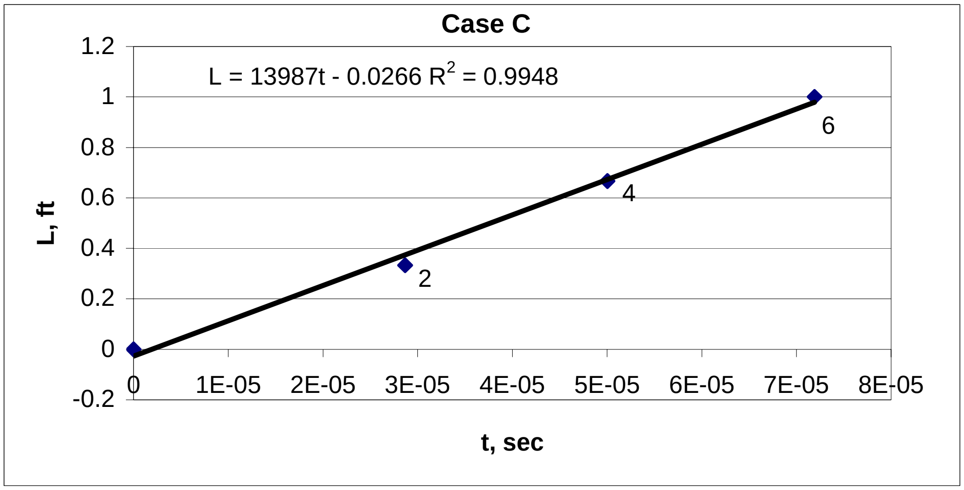


Figure 4.13 Plot of time versus distance with increments of 4 inches and best-fit line by regression analysis for Case C.

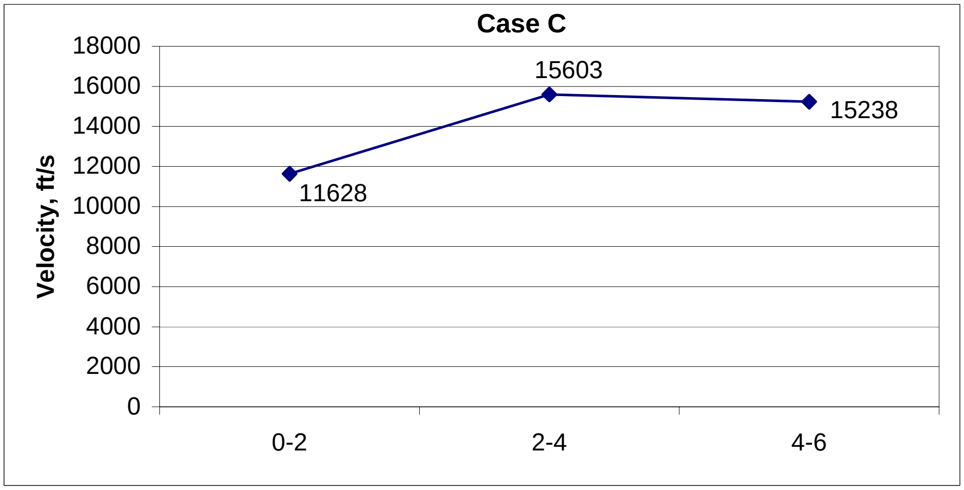


Figure 4.14 Velocities obtained by the unit-interval method with a separation distance of 4 inches for Case C.

4.1.3 Conclusions

From the simulation study it can be concluded that the regression method is efficient when the concrete is of the same quality. Therefore, the regression method is a useful tool when previous analyses have shown the concrete to be of uniform quality.

For the following two reasons the regression method is inadequate in cases where the concrete lacks uniformity: (1) it can not detect sections of different quality concrete when they are located far away from the transmitter, and (2) although it can distinguish a bad area of concrete located near the transmitter if the regression analysis is performed progressively, it results in misleading values for velocities throughout the remainder of the specimen.

The unit-interval method is useful for cases where nonuniformity of specimen quality is potentially present. The method can detect an area of poor quality concrete based on the low velocities obtained in this area. A small portion of poor quality concrete will not bias the estimated velocities of the portions of the specimen of better quality concrete. Thus, if the quality of the concrete is not known, the unit-interval method is the preferred alternative.

Because the heterogeneous nature of concrete can be reflected in short distances between receiver locations and can lead to a considerable variation of the computed velocities, a separation distance of 4 inches is recommended. At this distance, the sampling variation is reasonably small and estimates of the velocity can be made with a reasonable degree of certainty.

4.2 LABORATORY STUDY

The objective of the laboratory study was (1) to investigate the reproducibility of velocity estimates using the indirect transmission method, (2) to compare the regression and the unit-interval methods, (3) to determine the optimum transducer spacing (4) to verify the outcomes produced by the simulation study, and (5) to compare velocity measurements obtained by the direct and indirect transmission methods.

The experimental study involved the measurement of ultrasonic pulse velocities (UPV) using indirect transducer arrangements on two concrete beam specimens. Both specimens had dimensions of 6-in. wide, 21-in. long and 6-in. high. However, they had different concrete mix and additionally a defect existed in one of them.

4.2.1 Indirect transmission method on the specimen without defects

Twenty measurement locations were established along a line drawn on the beam surface, as shown in Figure 4.15, and were labeled as points 1, 2, 3, …, 20. The James Instruments' Ultrasonic Testing System was used. A pair of transducers with a diameter of 2 in. and frequency of 36 KHz was used for the generation and reception of the ultrasonic waves, while a V-meter was used to measure the transit time, i.e., the time it takes for the ultrasonic wave generated by the transmitter to arrive to the receiver. In order to achieve sufficient acoustic coupling, Dow Corning® High Vacuum Grease couplant was applied on the concrete surface. Readings were taken with the transmitter, T, in a fixed position and the receiver, R, moved progressively away from the transmitter in equal increments of 1 in. The transducers were arranged in the followings ways, as shown in Figure 4.16:

- Case A: transmitter location: point 3; receiver locations: points 8, 9, …, 19.
- Case B: transmitter location: point 18; receiver locations: points 13, 12, …, 2.

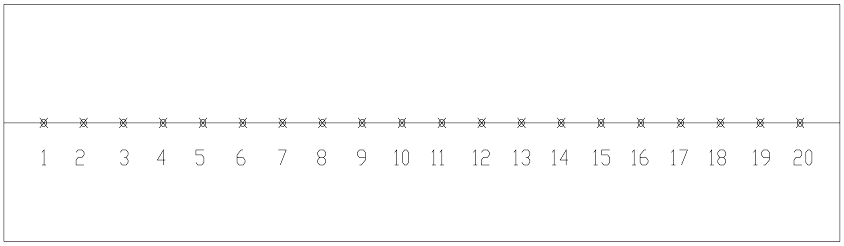


Figure 4.15 UPV measurement locations on the surface of the concrete beam specimen.

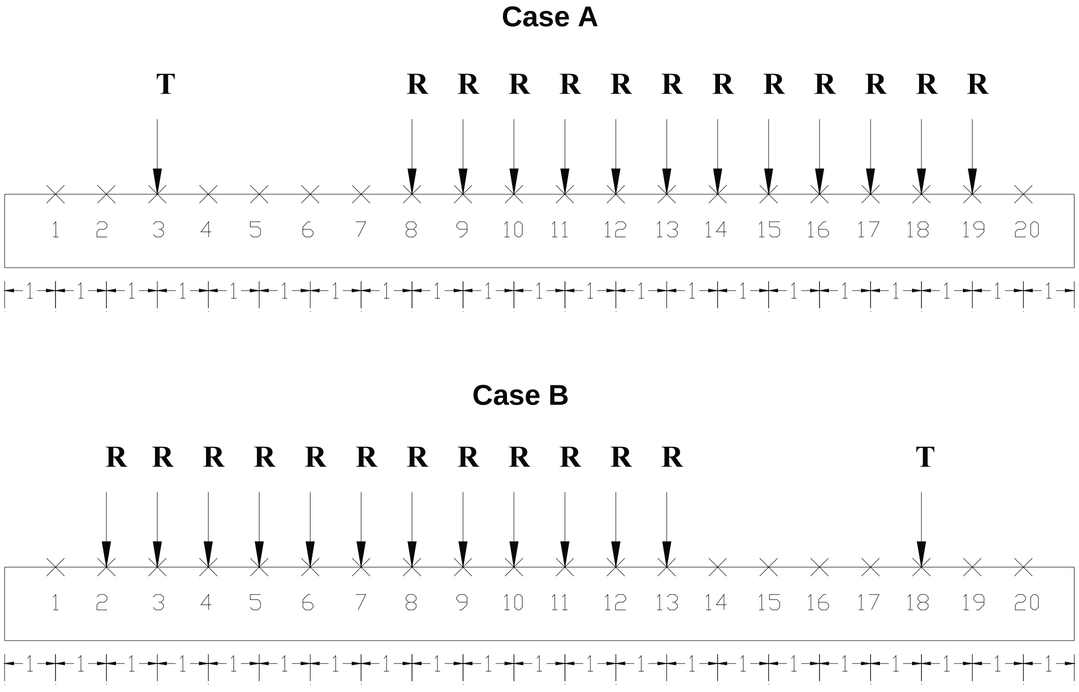


Figure 4.16 Transducer arrangements for Case A and B.

In all cases, five replications were performed at each location in order to check the consistency of the results. In addition, the first measurement was made at 5 in. from the transmitting transducer, because measurements are subject to errors for short path lengths and the requirements described in Chapter 3 should be satisfied. For a concrete with a pulse velocity of 12,000 ft/s and frequency of transducers 36,000 cps, the wavelength, λ, is about 4 inches. This means that the path length, L, should be greater than the value of 4 inches.

The measurements of transit time are given in Tables 4.5 and 4.6 for Cases A and B, respectively. Column 1 of each table represents the transmitter and receiver locations, while Column 2 shows the path length that is the center-to-center transducer spacing. Columns 3-7 provide the measured values of transit time for the five replications, while columns 8 and 9 include the average time t_a, and the coefficient of variation, COV, respectively, of the five measurements for each location. It is obvious from column 8 of the tables that the results are reproduced, given the low coefficients of variation.

Table 4.5 Measured transmit time for Case A with transmitter location at point 3 and transducers spacing of 5 to 16 in. – mean value and COV of five replications.

Points T- R (1)	**L (in)** (2)	**t_1 (µsec)** (3)	**t_2 (µsec)** (4)	**t_3 (µsec)** (5)	**t_4 (µsec)** (6)	**t_5 (µsec)** (7)	**t_a (µsec)** (8)	**COV (%)** (9)
3-8	5	44.5	46.0	44.6	46.8	46.6	45.7	2.39%
3-9	6	55.5	56.2	56.2	56.8	56.6	56.3	0.89%
3-10	7	63.7	62.4	63.6	64.3	64.1	63.6	1.16%
3-11	8	72.0	71.6	71.1	72.6	72.3	71.9	0.82%
3-12	9	77.8	77.3	77.8	78.6	78.3	78.0	0.65%
3-13	10	85.6	85.8	85.1	86.6	86.2	85.9	0.67%
3-14	11	91.5	92.3	91.3	92.0	91.7	91.8	0.43%
3-15	12	98.3	98.0	98.6	98.4	99.3	98.5	0.49%
3-16	13	106.4	108.9	108.4	108.3	106.7	107.7	1.03%
3-17	14	113.8	113.9	114.3	113.8	113.4	113.8	0.28%
3-18	15	117.8	118.6	119.0	118.7	118.7	118.6	0.38%
3-19	16	125.5	125.1	124.6	124.6	126.0	125.2	0.48%

Table 4.6 Measured transit time for Case B with transmitter location at point 18 and transducers spacing of 5 to 16 in.- mean value and COV of five replications.

Points T- R (1)	**L (in)** (2)	**t_1 (μsec)** (3)	**t_2 (μsec)** (4)	**t_3 (μsec)** (5)	**t_4 (μsec)** (6)	**t_5 (μsec)** (7)	**t_a (μsec)** (8)	**COV (%)** (9)
18-13	5	46.4	43.7	45.0	46.3	47.4	45.8	3.13%
18-12	6	55.6	54.7	54.9	53.6	54.3	54.6	1.35%
18-11	7	63.3	62.5	64.1	63.1	63.6	63.3	0.94%
18-10	8	72.5	71.6	71.5	71.1	70.5	71.4	1.03%
18-9	9	78.3	76.7	78.6	78.5	75.0	77.4	2.01%
18-8	10	84.0	84.2	84.7	85.7	85.0	84.7	0.80%
18-7	11	89.4	90.2	91.5	91.6	91.2	90.8	1.05%
18-6	12	95.6	96.6	97.7	98.1	98.2	97.2	1.15%
18-5	13	109.5	107.4	109.3	109.2	109.5	109.0	0.82%
18-4	14	118.9	118.3	117.6	118.2	117.2	118.0	0.56%
18-3	15	121.6	121.7	121.4	121.2	121.1	121.3	0.18%
18-2	16	127.1	127.3	127.3	127.6	127.6	127.4	0.17%

The ultrasonic pulse velocities were determined using the two different approaches described in the previous chapters, i.e., the regression method and the unit-interval method. In the regression method, the transit time, t, for each replication was plotted against the distance between transducers, L, as shown in Figures 4.17 and 4.18. The series 1-5 represent the plots that correspond to replications 1-5, while the series 'a' represents the plot of the average time, $t_{a,}$ of the five replications versus distance. From the regression analyses, the equations of the best-fit straight lines were obtained for each replication and they are included in charts of Figures 4.17 and 4.18. In both figures, the plots for each replication appear to be consistent. This can also be confirmed by the slopes of the regression lines, which range from 11,154 ft/s to 11,851 ft/s for Case A and from 10,984 ft /s to 11,185 ft /s for Case B. This means that the results are reproduced and the values of coefficient of variation are low. Indeed, the coefficient of variation was found to be 1.13% and 0.71% for Case A and B, respectively.

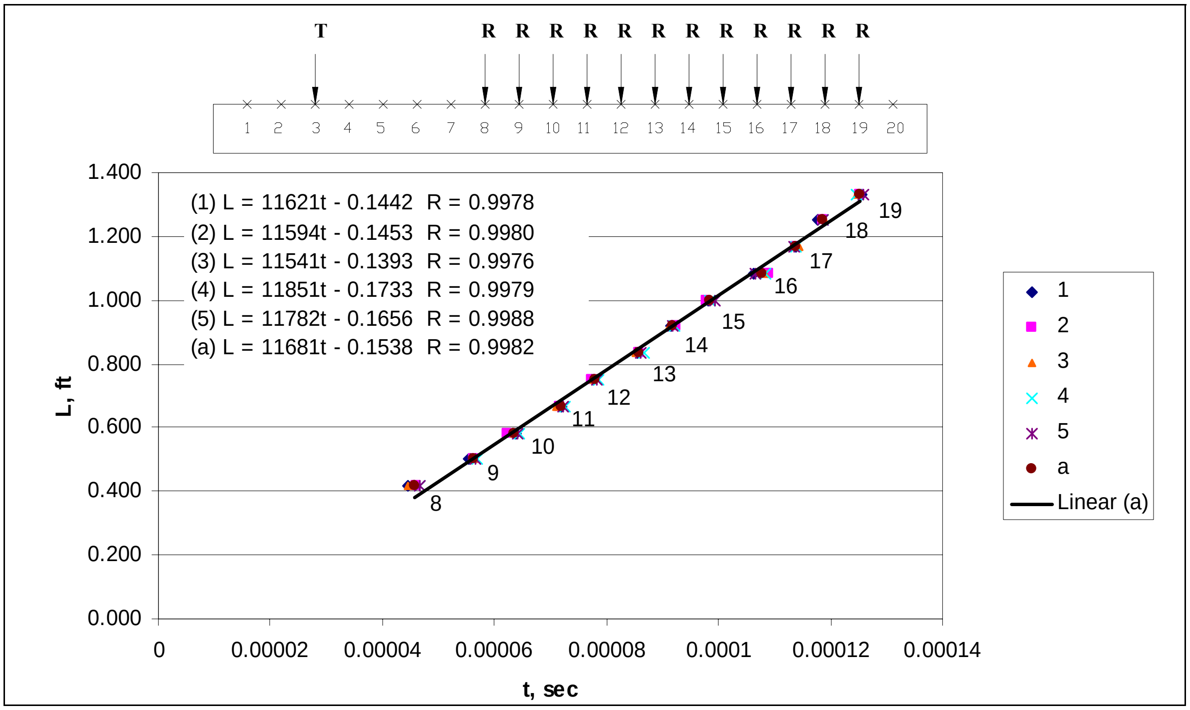


Figure 4.17 Pulse velocity determination by the slope of the best-fit straight line (case A) - transmitter location: point 3; receiver locations: points 8, 9, …, 19.

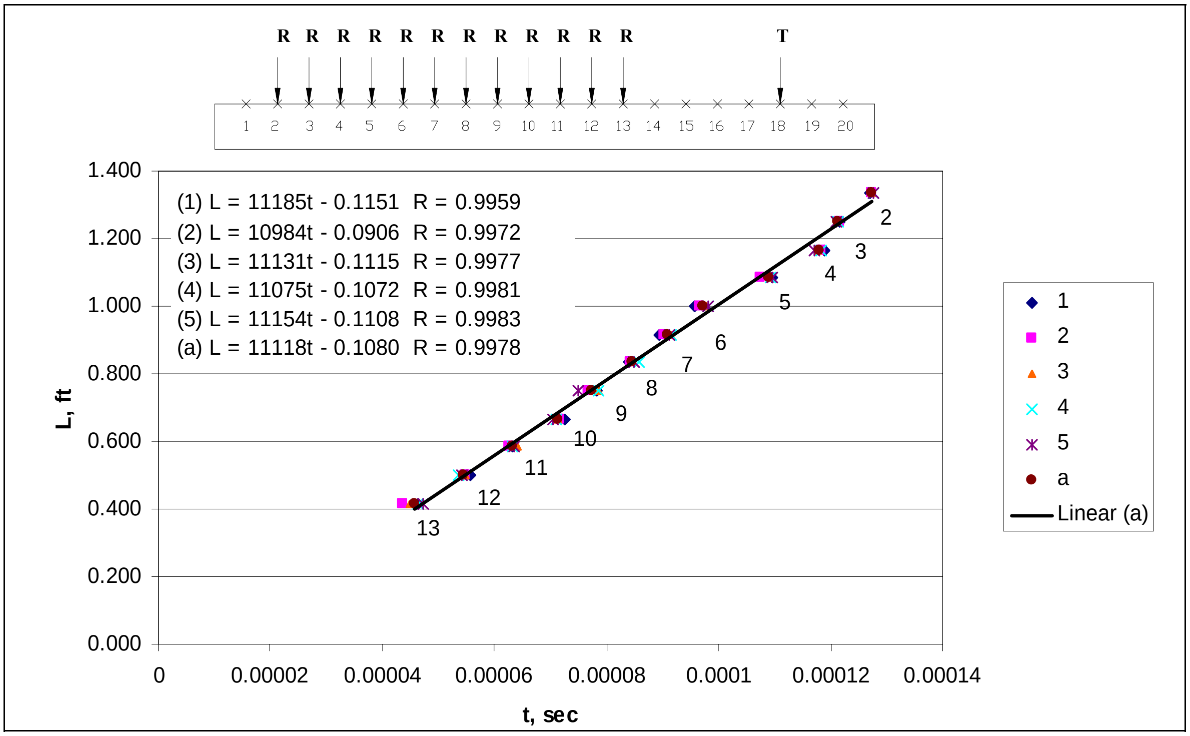


Figure 4.18 Pulse velocity determination by the slope of the best-fit straight line (case B) - transmitter location: point 8; receiver locations: points 13, 12, …, 2.

From the data analysis, it can also be concluded that the different arrangement of the transmitter and receiver (Case A and B) did not have a significant effect on the results. The mean velocity of the five measurements is 11,678 ft/s for Case A and 11,106 ft /s for Case B. In other words, the results are in agreement.

In the unit-interval method, the velocities were determined computing the individual slopes between adjacent points by the mathematical relationship, V= ΔL/ Δt, where ΔL is the difference in distance between two adjacent points and Δt the difference in time between two adjacent points. The results are presented graphically in Figures 4.19 and 4.20.

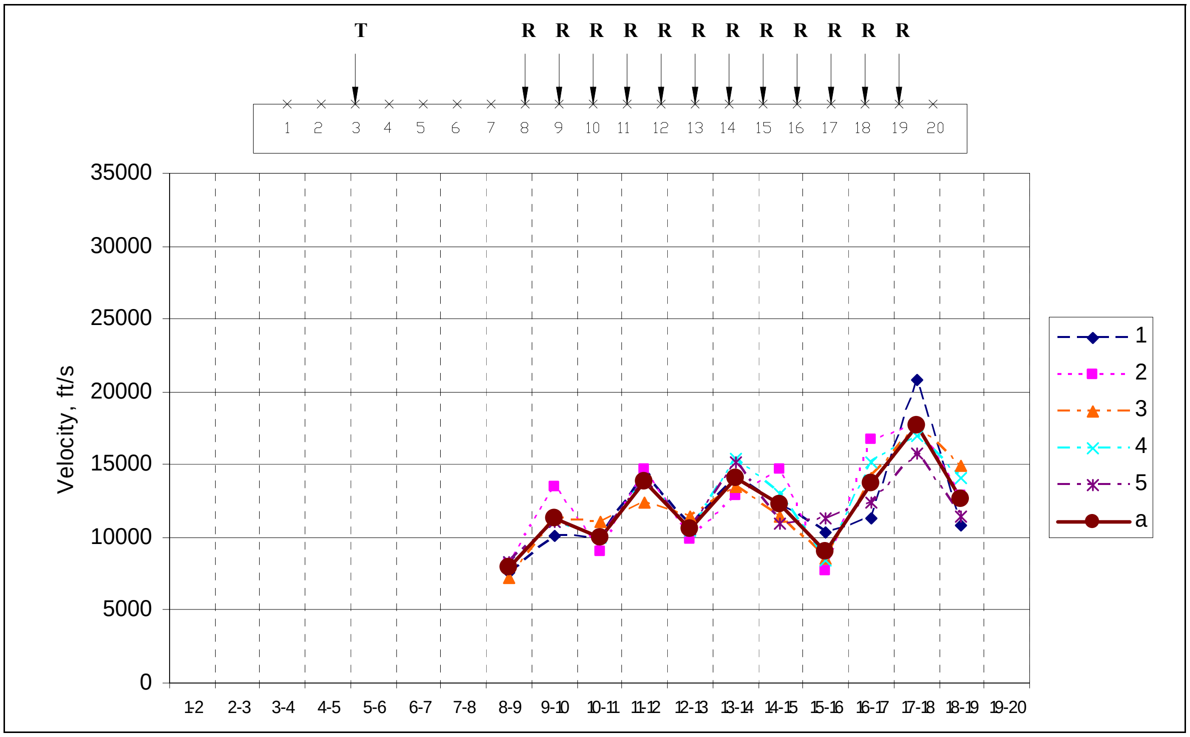


Figure 4.19 Velocities obtained by individual slopes between adjacent points (case A) - transmitter location: point 3; receiver locations: points 8, 9, …, 19.

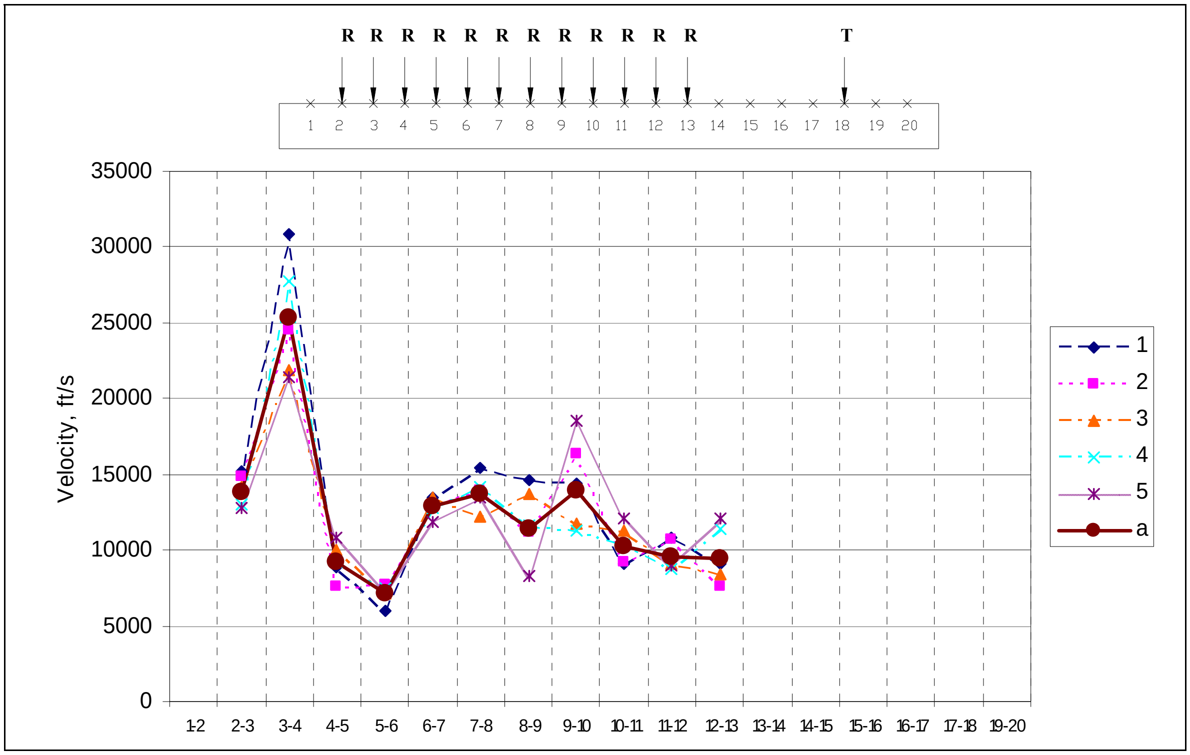


Figure 4.20 Velocities obtained by individual slopes between adjacent points (case B) - transmitter location: point 8; receiver locations: points 3, 12, …, 2.

From the diagrams of these figures, it is evident that the velocity varies in each interval, which has the same distance between two successive receiver locations, i.e., 1 inch. It is evident that variation between adjacent values can be expected. This can be attributed to the heterogeneous nature of the concrete that is reflected in excessively short distances. Because the travel times are so short, a small change in Δt will cause a large change in a computed velocity. For example, an increase of 1μs in Δt results in approximately a 10% increase in velocity when the section length is 1 inch.

To eliminate these problems, it is appropriate to increase the distance between receiver locations. As the distance increases, the error arising from heterogeneity or from any other reason becomes small and the concrete may then be regarded as being statistically homogeneous.

The unit-interval method applied with increasing the spacing between receivers from 1 inch to 2, 3, and 4 inches and the velocities were computed again. In all cases, the coefficient of variation of the velocities produced by the five replications was calculated for each interval, and the values were plotted versus the spacing, as shown in Figure 4.21. Based on the graph, an exponential equation was established. It is obvious that the coefficient of variation decreases with increases of the separation distance. Table 4.7 presents the mean values of coefficient of variation for different separation distances as well as the corresponding values of coefficient of variation derived from the experimental equation. It can be concluded that the separation distance of 4 inches is acceptable for determination of velocities when the unit-interval method is used.

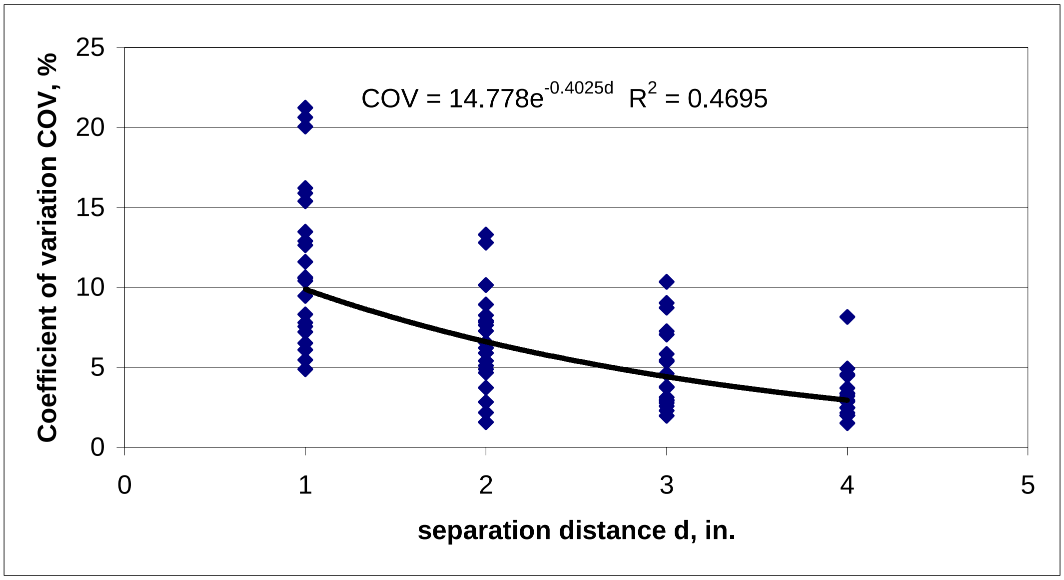


Figure 4.21 Plot of separation distance between transducers versus the COV of velocities of 5 replications obtained by the unit-interval method.

Table 4.7 Mean of COV of velocities and values of COV derived from the exponential equation for different separation distances

Separation distance d (in.)	**Mean of COV (%)**	**$COV = 14.778e^{-0.4025d}$ (%)**
1	11.59	9.88
2	6.65	6.61
3	4.99	4.41
4	3.39	2.95

In order to compare the regression method and the unit-interval method when the transducer spacing is 4 inches instead of 1 inch, the following two transducers arrangements were considered:

- Case C: transmitter location: point 3; receiver locations: points 8, 12, and 16.
- Case D: transmitter location: point 18; receiver locations: points 13, 9, and 5.

The results are presented in Figures 4.22 to 4.25. In Case C, the regression method yielded an average velocity of 10,742 ft/s and a coefficient of variation equal to 2.25 %. Similarly, the mean velocity obtained by the unit-interval method was 10,891 ft/s. In Case D, the results obtained by the two methods were again similar. Using the regression method, the mean velocity for the five replications was found to be 10,535 ft/s and the corresponding coefficient of variation 1.21%. Applying the unit-interval method, the average velocity was 10,582 ft/s. Based on these results, it can, therefore, be concluded that both methods provide similar results when the concrete is homogeneous.

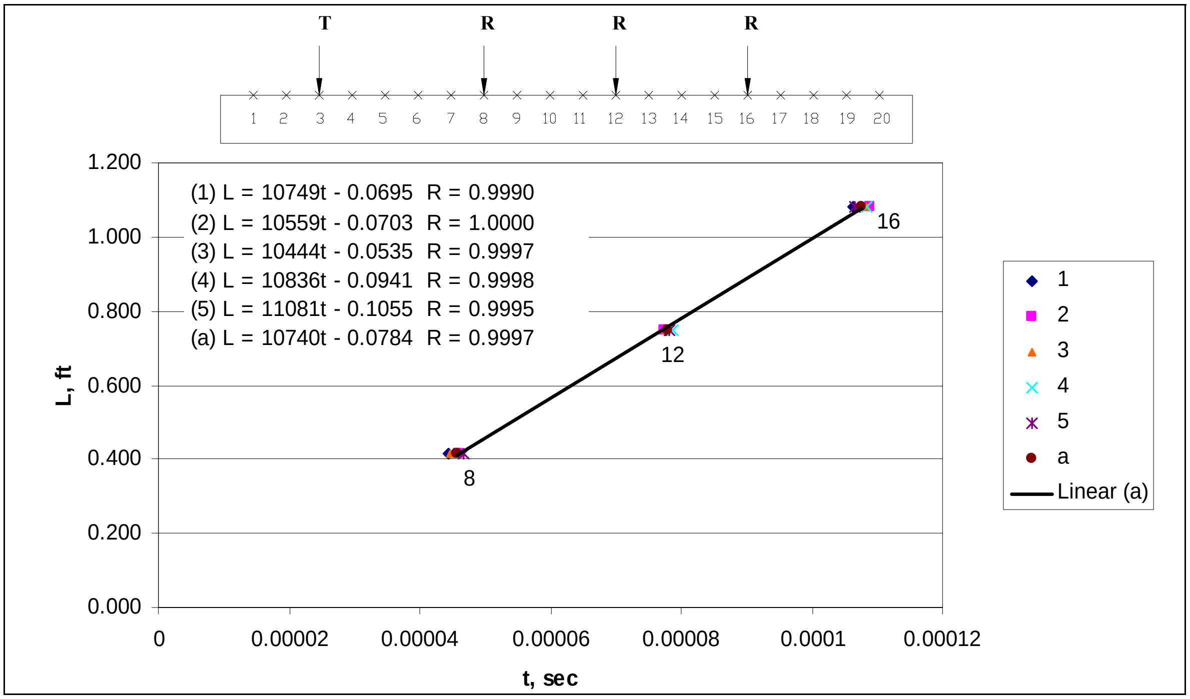


Figure 4.22 Pulse velocity determination by the slope of the best-fit straight line (Case C) - transmitter location at 3 and receiver locations at 8, 12, and 16.

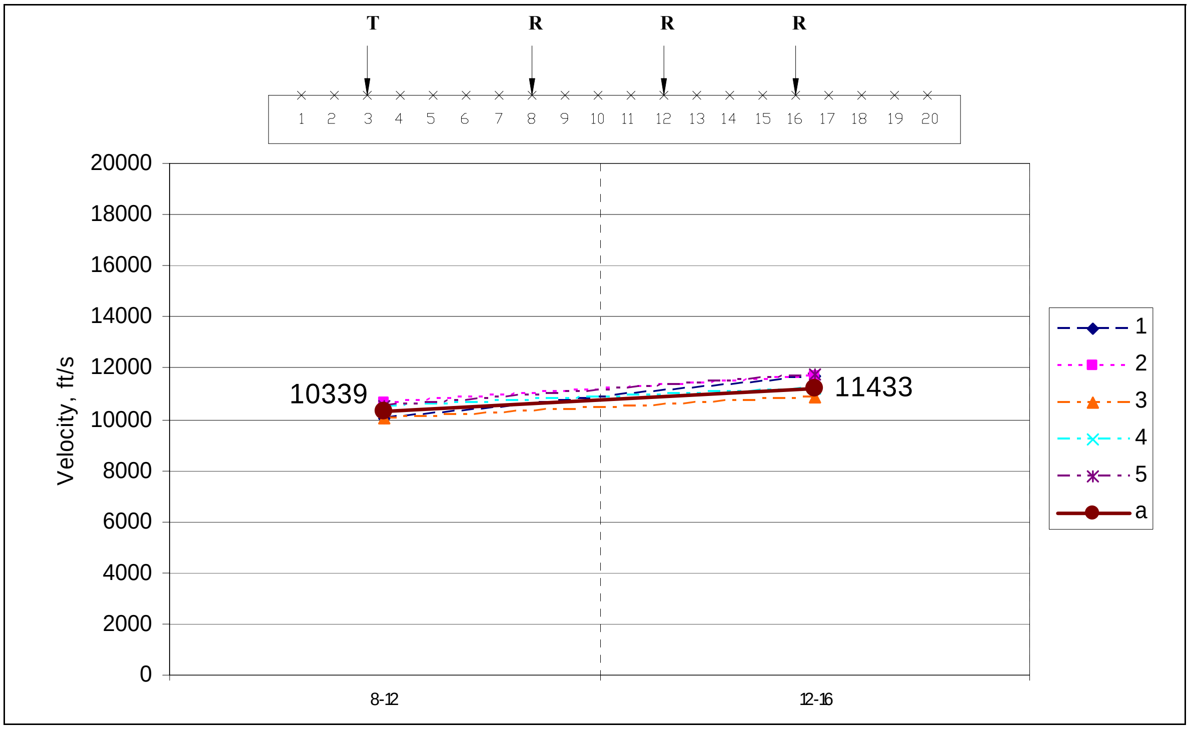


Figure 4.23 Velocities obtained by individual slopes between adjacent points (Case C) - transmitter location: point 3; receiver locations: points 8, 12, and 16.

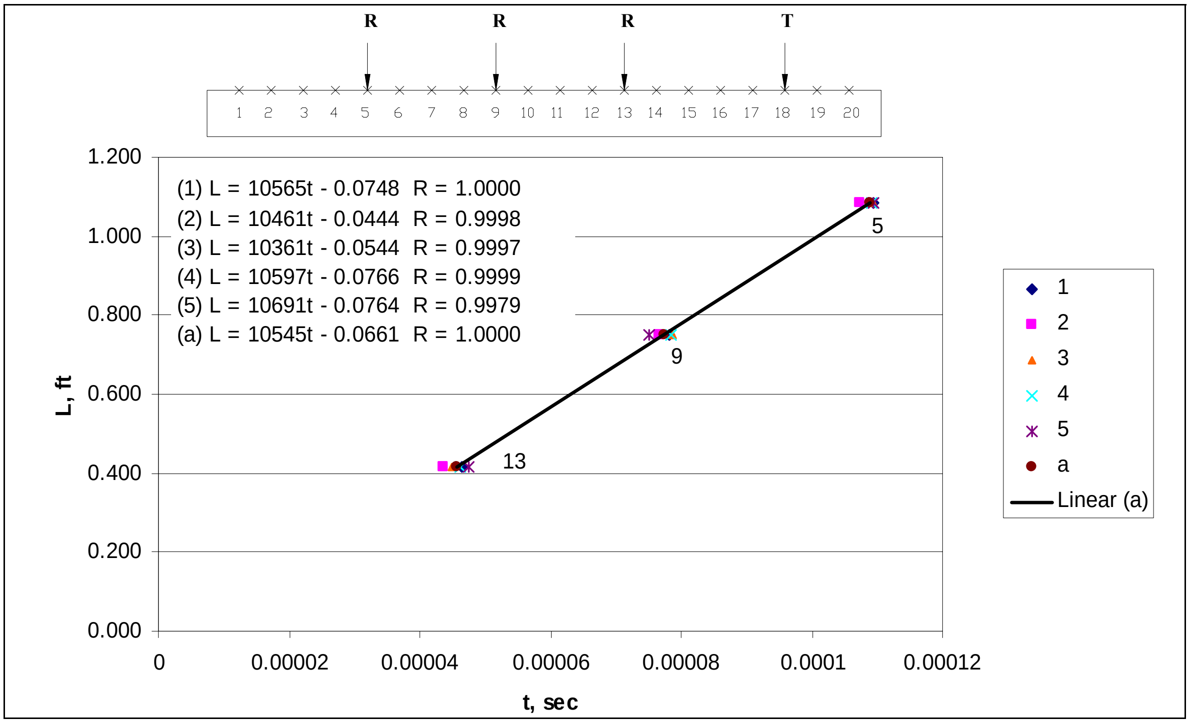


Figure 4.24 Pulse velocity determination by the slope of the best-fit straight line (Case D) - transmitter location: point 18; receiver locations: points13, 9, and 5.

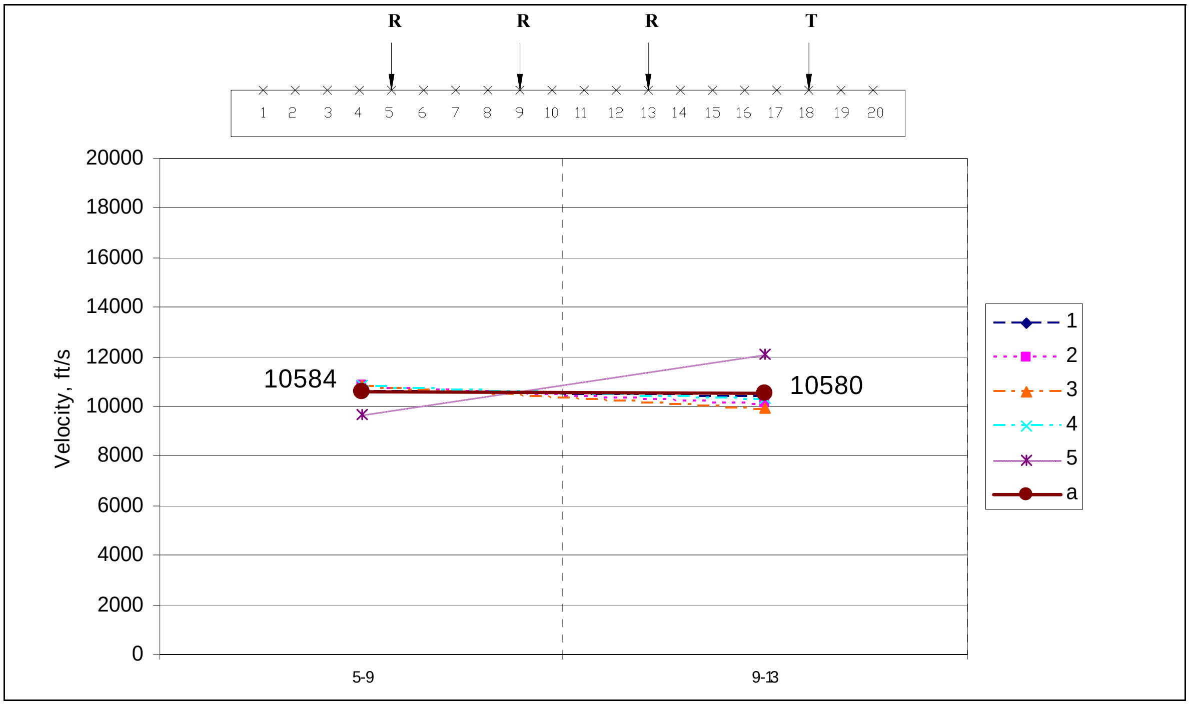


Figure 4.25 Velocities obtained by individual slopes between adjacent points (Case D) - transmitter location: point 18; receiver locations: points 13, 9, and 5.

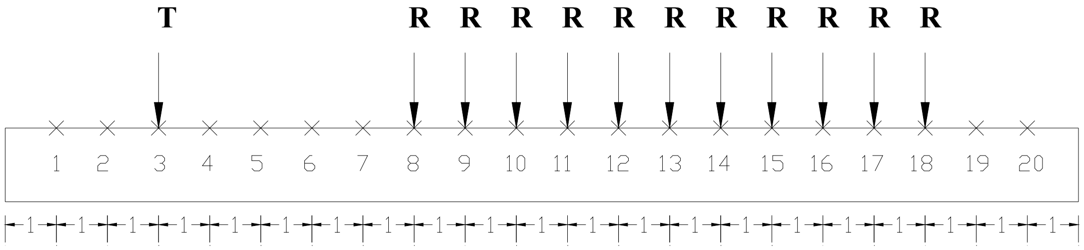
4.2.2 Indirect transmission method on the specimen with a defect

The indirect transmission method was also applied in the same way to another specimen that had a defective section. The transducers were arranged (see Figure 4.26) as follows:

- Case A: transmitter location: point 3; receiver locations: points 8, 9, …, 18.
- Case B: transmitter location: point 18; receiver locations: points 13, 12, …, 3.

The measured values of the five replications are given in Tables 4.8 and 4.9 for Cases A and B, respectively. For each replication, the values of the transit time, t, were plotted versus the distance between transducers, L, as shown in Figures 4.27 and 4.28. From the plots, it is obvious that the points are not coincident. The time interval, Δt, between points 10 and 11 appears to be greater compared to the other time intervals between adjacent points. This indicates that the velocity in this section is lower than the other sections, which is likely due to a defect such as a large void or a crack in this area of concrete. Regression analysis cannot be applied to all points because the nonhomogeneity will yield misleading results. Regression analyses can be applied to points 8 to 10 for Case A and to points 13 to 11 for Case B, but the velocities produced will not be representative of the quality of the concrete because they correspond to small portions of the concrete specimen. The quality of concrete of the specimen can be represented by the velocities provided by regression analyses applied to points 11 to 18 and 10 to 3 for Cases A and B, respectively. The results of the analyses are given in Tables 4.10 and 4.11. Specifically, the tables include the slope and the intercept of the best-fit regression lines as well as the correlation coefficient, R. The average slope of the five replications for the area between points 11 and 18 for Case A was 12,360 ft/s, while for Case B the average velocity was 11,533 ft/s in the interval 10-3.

Case A



Case B

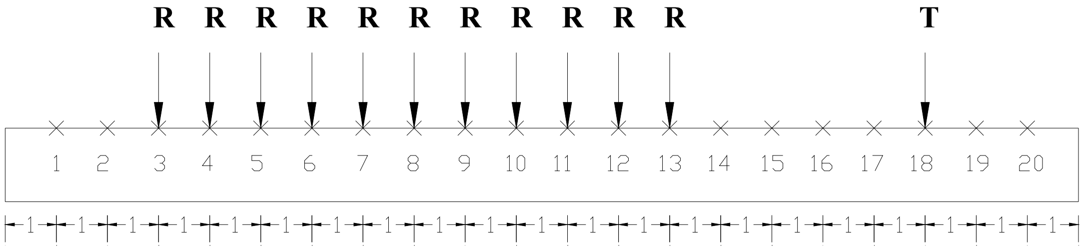


Figure 4.26 Transducer arrangements for Case A and B.

Table 4.8 Measured transmit time for Case A with transmitter location at point 3 and transducers spacing of 5 to 15 in. – mean value and COV of five replications.

Points T- R (1)	**L (in)** (2)	**t_1 (μsec)** (3)	**t_2 (μsec)** (4)	**t_3 (μsec)** (5)	**t_4 (μsec)** (6)	**t_5 (μsec)** (7)	**t_a (μsec)** (8)	**COV (%)** (9)
3-8	5	32.4	31.4	32.3	33.3	33.4	32.6	2.52%
3-9	6	40.4	40.4	41.5	41.4	41.6	41.1	1.48%
3-10	7	48.3	49.3	47.6	48.3	47.5	48.2	1.50%
3-11	8	66.1	63.8	67.1	69.5	70.1	67.3	3.82%
3-12	9	72.6	73.2	75.3	75.9	75.8	74.6	2.07%
3-13	10	78.3	79	80.6	82	80.9	80.2	1.86%
3-14	11	87.3	86.3	87.6	87.6	87.4	87.2	0.62%
3-15	12	91.5	94.7	94.6	94.7	94.7	94.0	1.51%
3-16	13	99	99.6	100.3	101.4	101.7	100.4	1.15%
3-17	14	106.3	107.3	108.4	108.5	108.8	107.9	0.96%
3-18	15	113.5	113.8	115.6	115.3	115.2	114.7	0.84%

Table 4.9 Measured transit time for Case B with transmitter location at point 18 and transducers spacing of 5 to 15 in.- mean value and COV of five replications.

Points T- R (1)	**L (in)** (2)	**t_1 (μsec)** (3)	**t_2 (μsec)** (4)	**t_3 (μsec)** (5)	**t_4 (μsec)** (6)	**t_5 (μsec)** (7)	**t_a (μsec)** (8)	**COV (%)** (9)
18-13	5	34.3	34.3	33.2	32.8	33	33.5	2.17%
18-12	6	40	41.4	39.4	39.3	39.3	39.9	2.25%
18-11	7	45	45.1	44.8	43.6	44.6	44.6	1.35%
18-10	8	66.8	67.3	65.6	65.6	66.3	66.3	1.13%
18-9	9	74.1	75	75.2	75.1	74.7	74.8	0.59%
18-8	10	80.4	80.7	80.1	79.4	78.8	79.9	0.97%
18-7	11	88.6	88.4	88.6	89.2	89.2	88.8	0.42%
18-6	12	94.6	94.6	94.4	93.8	93.2	94.1	0.65%
18-5	13	104.3	104	104	104.3	104.6	104.2	0.24%
18-4	14	111	109.4	110	110.6	110.1	110.2	0.55%
18-3	15	116.6	116.6	116	115.8	115.9	116.1	0.31%

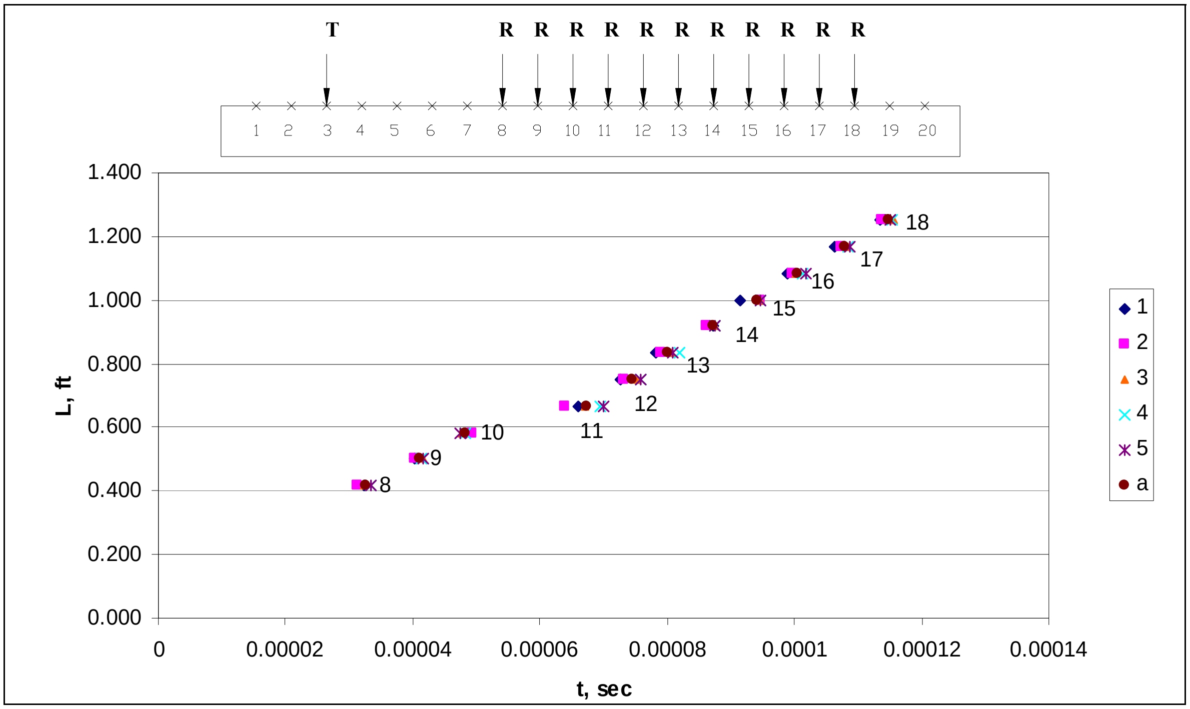


Figure 4.27 Transit time, t, versus the distance, L, between transducers (Case A) - transmitter location: point 3; receiver locations: points 8, 9, …, 18.

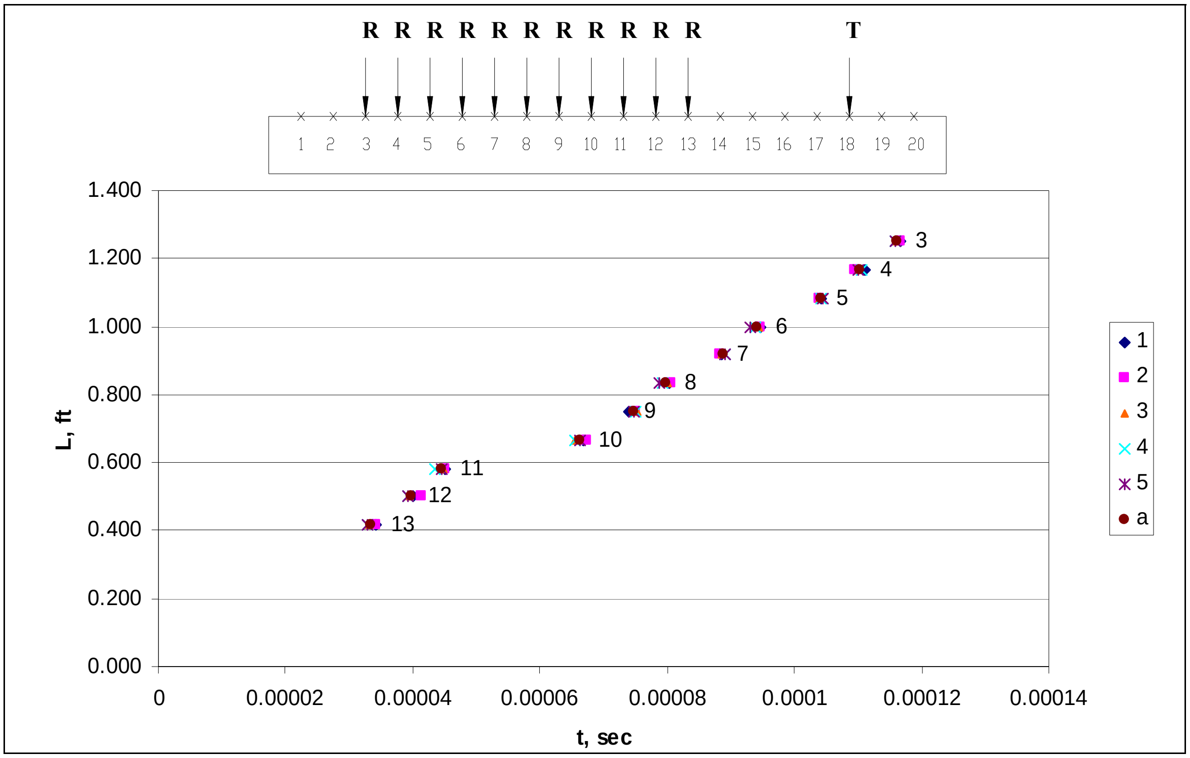


Figure 4.28 Transit time, t, versus the distance, L, between transducers (Case B) - transmitter location: point 18; receiver locations: points 13, 12, …, 2.

Table 4.10 Regression analyses for Case A

Case A	Series	Slope (ft/s)	Intercept	Correlation coefficient, R
Regression analyses for points 8 to 10	(1)	10,482	0.2645	0.9658
	(2)	9,311	0.2257	0.9925
	(3)	10,746	0.2727	0.9734
	(4)	11,087	0.2936	0.9553
	(5)	11,716	0.3049	0.9454
	(a)	10,630	0.2736	0.9678
Regression analyses for points 11 to 18	(1)	12,324	-0.1425	0.9988
	(2)	11,818	-0.1019	0.9986
	(3)	12,237	-0.1576	0.9992
	(4)	12,738	-0.2118	0.9994
	(5)	12,684	-0.2064	0.9987
	(a)	12,370	-0.1647	0.9997
Regression analyses for all points	(1)	10,161	0.0613	0.9914
	(2)	9,986	0.0719	0.9931
	(3)	9,874	0.0696	0.9898
	(4)	9,928	0.0590	0.9872
	(5)	9,906	0.0615	0.9868
	(a)	9,979	0.0640	0.9901

Table 4.11 Regression analyses for Case B

Case B	**Series**	**Slope (ft/s)**	**Intercept**	**Correlation coefficient, R**
Regression analyses for points 13 to 11	(1)	15,554	0.3051	0.9610
	(2)	14,939	0.3014	0.9630
	(3)	14,345	0.2985	0.9781
	(4)	15,222	0.3185	0.9747
	(5)	14,332	0.3081	0.9690
	(a)	14,909	0.3047	0.9696
Regression analyses for points 10 to 3	(1)	11,434	-0.0942	0.9989
	(2)	11,779	-0.1253	0.9991
	(3)	11,542	-0.1005	0.9982
	(4)	11,438	-0.0909	0.9969
	(5)	11,472	-0.0925	0.9962
	(a)	11,552	-0.1023	0.9981
Regression analyses for all points	(1)	9,534	0.0917	0.9906
	(2)	9,671	0.0800	0.9896
	(3)	9,503	0.0979	0.9898
	(4)	9,408	0.1068	0.9889
	(5)	9,485	0.1007	0.9894
	(a)	9,526	0.0951	0.9897

The velocities determined using the unit-interval method were also of interest. However, because the application of the unit-interval method for 1-inch transducer spacing is not acceptable as proved earlier, the following transducer arrangements were considered, in which the separation distance was 4 inches:

- Case C: transmitter location: point 3 and receiver locations: points 8, 12, and 16.
- Case D: transmitter location: point 18 and receiver locations: points 13, 9, and 5.

The regression method was applied again. For Case C, the results of the regression and the unit-interval methods are presented graphically in Figures 4.29 and 4.30, respectively. From Figure 4.29, it seems that the points lie in the same line, which indicates a homogeneous concrete. However, this is contrasted with the conclusions derived from the regression method in Case A. The mean velocity was found to be 9,645 ft/s. On the other hand, the unit-interval method provided different results. A low velocity of 7,937 ft/s occurred in the interval 8-12, but a high velocity (12,900 ft/s) was computed for the interval 12-16. Based on this observation, it can be concluded that a defect must exist in the interval 8-12.

The trend shown in Case C was also observed in Case D. The regression method was not able to detect the defect and yielded an average velocity of 9,339 ft/s (Figure 4.31), while the unit-interval method provided a high velocity equal to 11,330 ft/s in the interval 5-9 and a low velocity of 8,071 ft/s in the interval 9-13, as shown in Figure 4.32. The regression approach smoothes over the difference in the travel times in the different sections, while use of the unit-interval method allows differences in concrete quality to be seen.

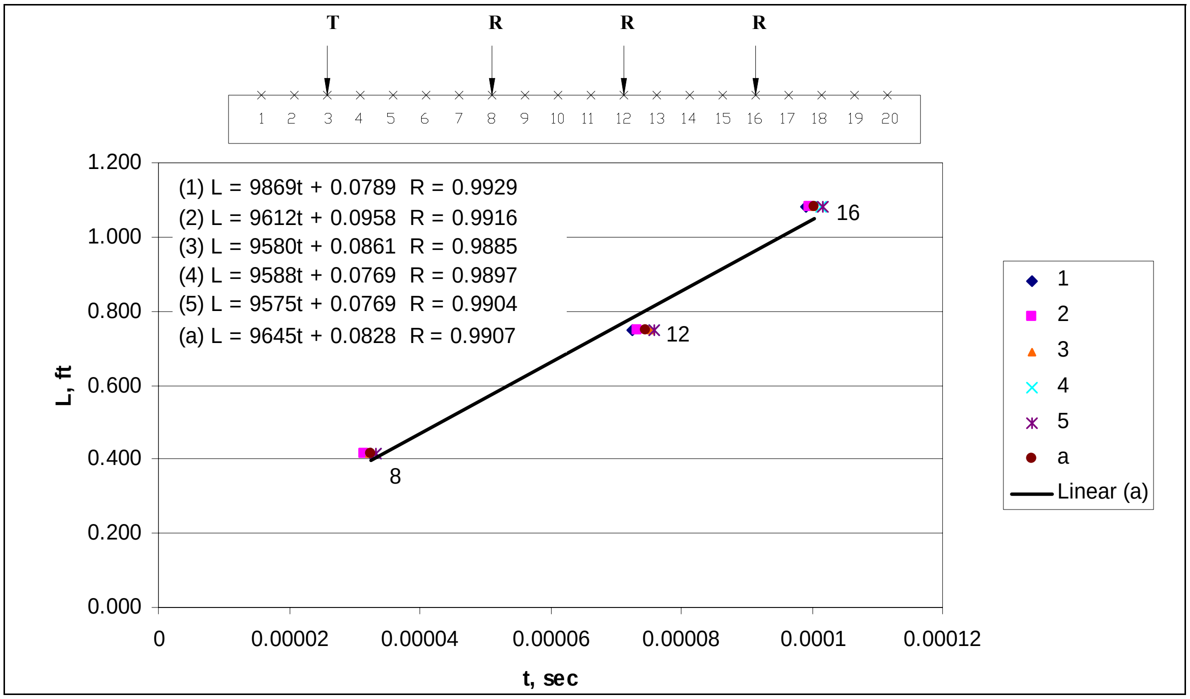


Figure 4.29 Pulse velocity determination by the slope of the best-fit straight line (Case C) - transmitter location: point 3; receiver locations: points 8, 12, and 16.

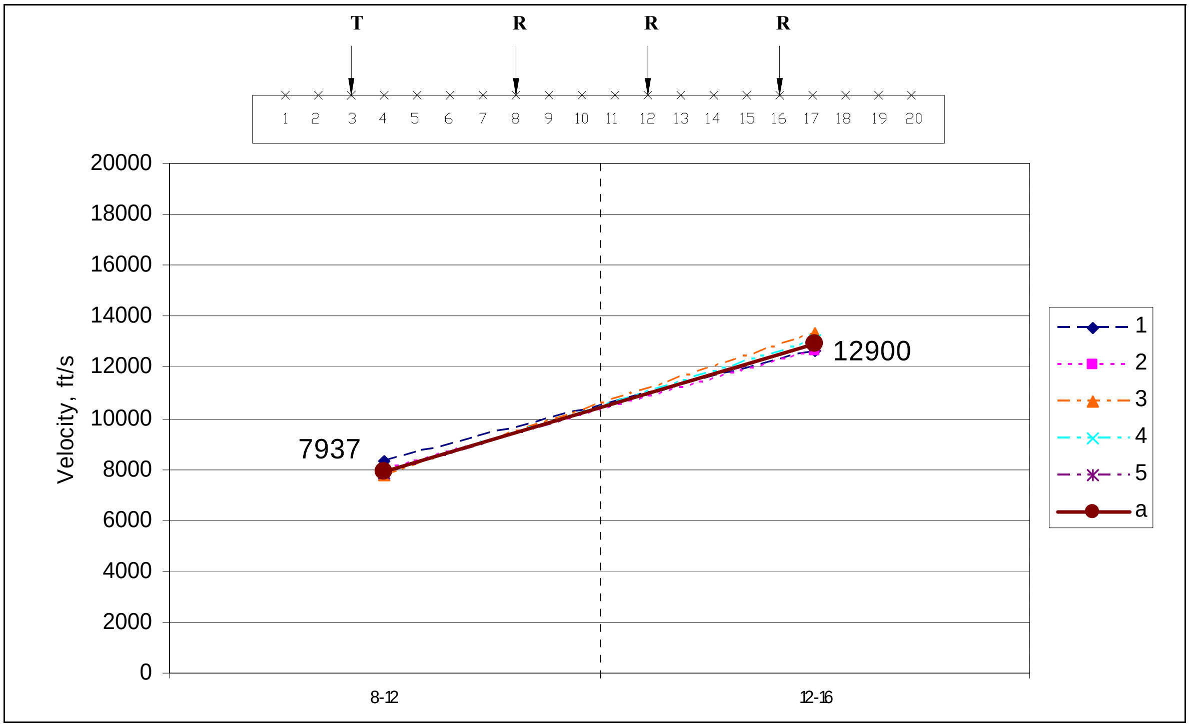


Figure 4.30 Velocities obtained by individual slopes between adjacent points (Case C) - transmitter location: point 3; receiver locations: points 8, 12, and 16.

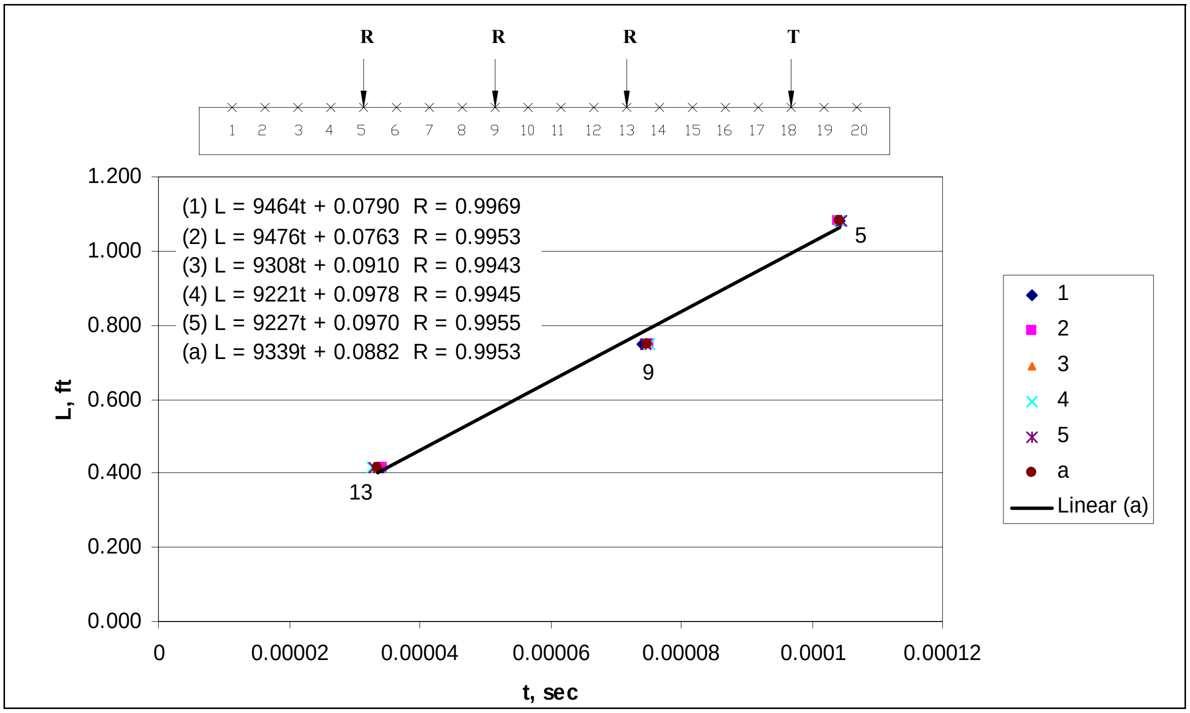


Figure 4.31 Pulse velocity determination by the slope of the best-fit straight line (Case D) - transmitter location: point18; receiver locations: points 13, 9, and 5.

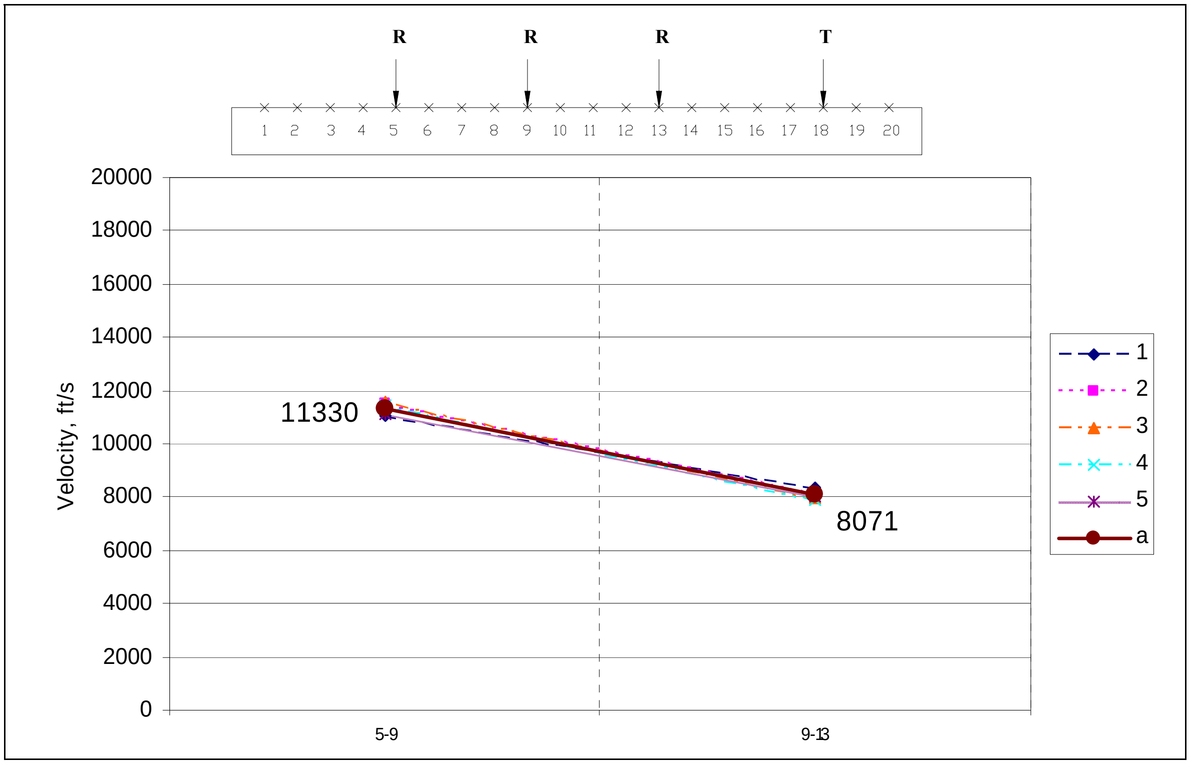


Figure 4.32 Velocities obtained by individual slopes between adjacent points (Case D) - transmitter location: point 18; receiver locations: points 13, 9, and 5.

In summary, the regression method indicated that the concrete is of uniform quality, with an average velocity of about 9,500 ft/s, while the unit-interval method proved that the concrete is generally of better quality with a velocity in the order of 12,000 ft/s but it has heterogeneity somewhere between points 9 and 12. It should be mentioned that the regression method in the case of 1-inch transducer spacing provided an average velocity of 11,947 ft/s, i.e., a velocity close to that obtained by the unit-interval method.

4.2.3 Comparison between direct and indirect velocity measurements

As mentioned in Chapter 3, the velocity from the indirect method is lower than the velocity from the direct method on the same concrete element because the amplitude of the received signal using the indirect transmission method is significantly lower than that received by the direct transmission method. Indirect velocity measurements were performed on the concrete specimen without defects. The transducers were arranged on the opposite faces of the specimen and sixteen measurements were taken in a direction parallel to the width of the specimen. In addition, two measurements were conducted in a direction parallel to the length of the specimen. The measurements were performed at different positions of the beam at two different levels: (i) at distance of 1.5 inches from the surface, and (ii) at a distance of 1.5 inches from the bottom of the beam. The transit times and the pulse velocities are given in Table 4.12. Column 1 shows the length of the direct path. Columns 2 and 3 include the transit times for the measurements taken at the top and bottom level, respectively. Columns 4 and 5 provide the pulse velocities for the top and bottom level, respectively.

Table 4.12 Pulse velocity measurements using the direct transmission method.

L (in) (1)	***t_t (μsec)*** (2)	***t_b (μsec)*** (3)	***V_t (ft/s)*** (4)	***V_b (ft/s)*** (5)
	Top	**Bottom**	**Top**	**Bottom**
6	36.8	36.3	13,587	13,774
6	36.0	34.6	13,889	14,451
6	35.4	34.8	14,124	14,368
6	36.4	35.1	13,736	14,245
6	36.1	35.6	13,850	14,045
6	36.3	35.4	13,774	14,124
6	36.2	35.3	13,812	14,164
6	36.0	35.2	13,889	14,205
21	126.4	124.5	13,845	14,056
Mean Velocity (ft/s)			**13,977**	
Standard deviation			236.6	
Coefficient of variation			1.69%	

The average of all of the velocity measurements was 13,977 ft/s, with a coefficient of variation of 1.69%, as shown in Table 4.12. The average velocity obtained by the indirect method was 11,392 ft/s. It is obvious that the direct method provided a higher velocity than the indirect method. The ratio between indirect velocity, $V_{i,}$ and direct velocity, $V_{d,}$ is equal to:

$$\frac{V_i}{V_d} = \frac{11,392}{13,977} = 0.81 \tag{4.1}$$

Thus, the average indirect velocity was found to be approximately 20% lower than the average direct velocity.

4.2.4 Conclusions

The outcomes provided by the laboratory study are in agreement with those of the simulation study. The regression and unit-interval methods provided similar results when they were applied to the first concrete beam specimen. This means that both methods are efficient when the concrete is of the same quality.

Conversely, in the case of the second specimen, the regression method was able to identify the defect in concrete in the case where the transducer spacing was 1 inch. In contrast, in the case where the separation distance was 4 inches, the regression method failed to detect the problem and resulted in misleading values for the velocities. This means that for a given tested area of concrete, the regression method is more likely to reveal a problem when the number of measurement points increases, i.e., the transducer spacing decreases. However, the performance of many measurements is a time-consuming process, which is not viable in practice.

With regard to the unit-interval method, it was able to detect the defect. In addition, the data analysis showed that the accuracy of the results using the unit-interval method is affected by the spacing between receiver locations. A separation distance of 4 inches was shown to be acceptable for determination of velocity estimates, as it allows differences in concrete quality to be detected and simultaneously the velocities not to be influenced by the heterogeneous nature of concrete.

CHAPTER 5 - FIELD TESTING AND RESULTS

5.1 FIELD TESTING

The field study involved the measurement of ultrasonic pulse velocities (UPV) using the indirect transmission method on the concrete floor slabs of eighteen public parking garages of Montgomery County, Maryland. The name of the parking garages and the year that their construction was completed are given in Appendix A. Because the objective of the ultrasonic pulse velocity method was to provide results that would serve as a reliable source of information on the evaluation of quality of concrete in a parking structure, the measurements were conducted on locations that appeared to be representative of the given structure. For example, the measurements were not performed on defective parts of the structure that were easily identified, such as those characterized by scaling, spalling, or cracking. In addition, they were carried out on locations that were far from the beams of the structure, where densely reinforced zones exist.

After the selection of the test locations, a grid of measurement points over the surface of the concrete slab was drawn. As shown in Figures 5.1 and 5.2, the grid was a system of eight rays labeled as 1, 2, …, 8, and four points marked as 0, 1, 2, and 3 along each ray. A total of twenty-four readings were taken with the transmitter, T, fixed in one position (point 0), which was common for all rays, and the receiver, R, gradually shifted to points 1, 2, and 3, that were at a distance of 4, 8, and 12 inches from the transmitter, respectively. The receiver locations established were denoted as R_{ij}, where the first subscript, i, represents the ray (1 to 8), while the second subscript, j, represents the point (1 to 3). A plastic template was designed to save time and provide precise locations for the transmitter and receiver (see Figure 5.3). Dow Corning® High Vacuum Grease couplant was used in order to assure sufficient transducer contact with the concrete. Measurements were performed using the James Instruments' Ultrasonic Testing System. It was composed of a pair of transducers with a diameter of 2 inches and natural frequency of 54 KHz. In addition, a V-meter displayed the time taken by a wave to travel from the transmitter to the receiver, as shown in Figure 5.4. A set of time data is given in appendix B.

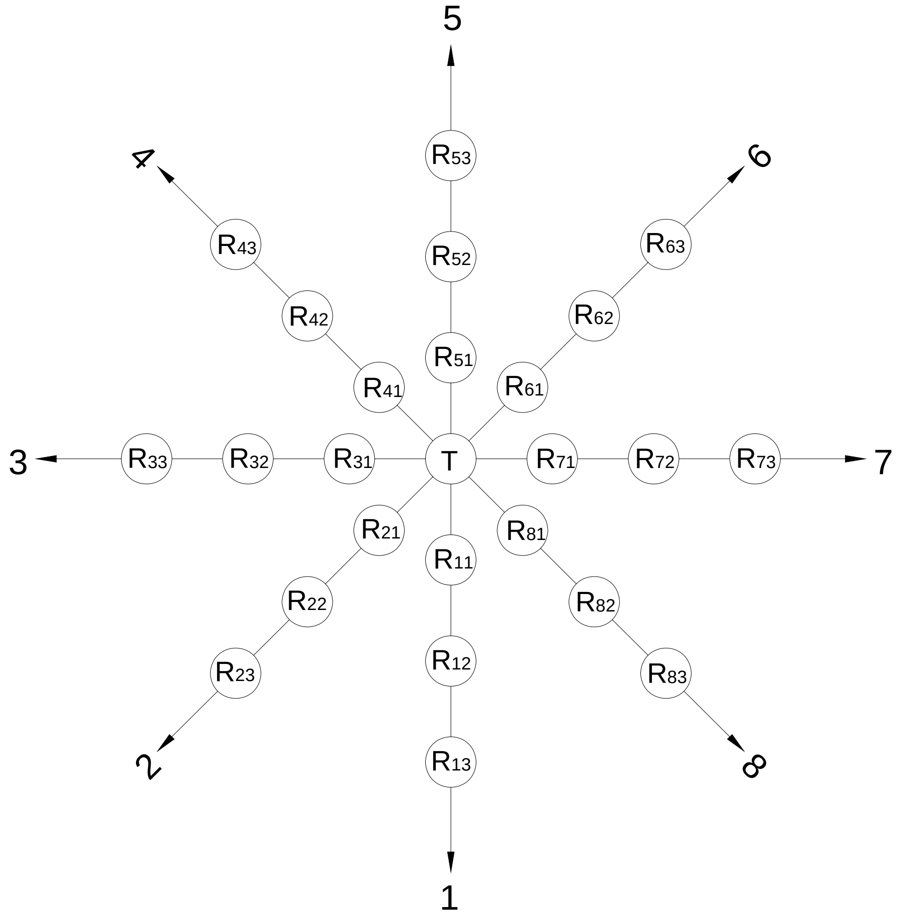


Figure 5.1 UPV measurement locations on the surface of the concrete slab.

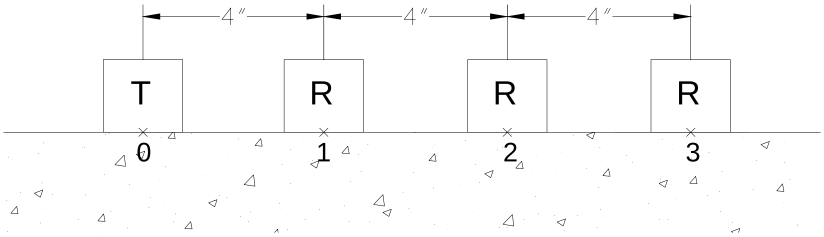


Figure 5.2 Transducer arrangements with the transmitter, T, fixed at point 0 and the receiver, R, shifted successively to points 1, 2, and 3 along each ray.

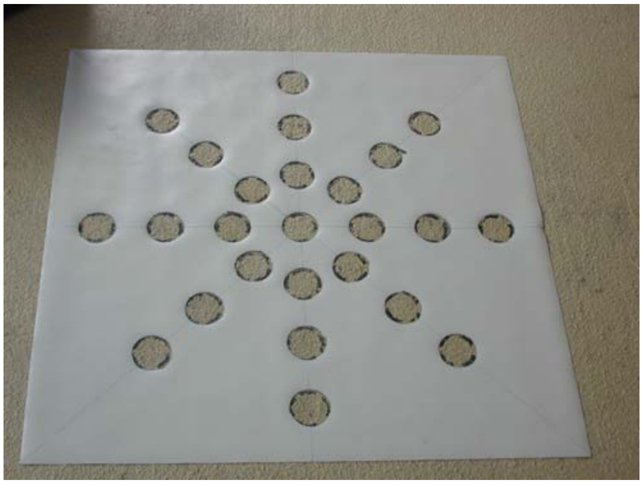


Figure 5.3 Plastic template designed for precisely drawing a grid of measurement points.

Figure 5.4 A V-meter displays the time taken by a wave to travel from the transmitter to receiver at a distance of 8 inches.

5.2 DATA ANALYSIS

Based on the conclusion derived from the previous chapter that the unit-interval method is efficient for the determination of pulse velocities irrespective of the homogeneity of concrete, the individual slopes between adjacent points were computed, which are included in Appendix C. The inner slope, i.e., the slope obtained between points 1 and 2 was denoted as V_{12}, while the slope between points 2 and 3 was denoted as V_{23}. Because it was of interest to compare the unit-interval method with the regression method, regression analyses were made for the points 1, 2, and 3 of each ray and the slopes of the best-fit line, denoted as V_{123}, are also given in Appendix C. To obtain a better interpretation of the results, statistical analyses of the velocity data provided by the unit-interval method were performed according to the following steps, as illustrated in the flowchart of the Figure 5.5.

The first statistical test applied was the t-test for two related samples. This test was intended to check if the inner slope V_{12} was not significantly different from the outer slope $V_{23.}$ The hypothesis for this test was stated as:

$$H_{o\,(1)}: \mu_{12} = \mu_{23} \tag{5.1}$$

$$H_{A\,(1)}: \mu_{12} \neq \mu_{23} \text{ (two-tailed)} \tag{5.2}$$

in which μ_{12} and μ_{23} are the mean values of the velocities V_{12} and V_{23}, respectively. For the cases that the null hypothesis was accepted, which means that the inner and outer slopes were not significantly different, the analysis of variance (ANOVA) test was applied. In contrast, when the null hypothesis was rejected, the next step was the use of the Dixon-Thompson outlier test.

The ANOVA test was a comparison of eight group means. Each of the eight groups included the values of the velocities of each ray. The following hypothesis was used:

$H_{o\,(2)}$: $\mu_1 = \mu_2 = \ldots = \mu_8$ (5.3)

$H_{A\,(2)}$: at least one pair of group means are not equal, (5.4)

in which $\mu_1, \mu_2, \ldots, \mu_8$ the mean velocities of the eight groups. For the cases that the null hypothesis was rejected, the Scheffé test was used to specify which pair or pairs of means were unequal.

The Dixon-Thompson outlier test was intended to examine whether the difference between the inner and outer slopes was due to a measurement subjected to error or because of a localized problem in concrete. The hypothesis for this test, which is only valid for testing one outlier, was:

$H_{o\,(3)}$: all values in the sample are from the same population (5.5)

$H_{A\,(3)}$: the most extreme value in the sample is unlikely to
have come from the same population from which
the remainder of the sample values was drawn. (5.6)

Rejection of the null hypothesis implied that the extreme sample value tested was an outlier. The value detected as an outlier was removed and the t-test for two related samples was applied again. For the cases that the test resulted in the same outcome despite of censoring the outlier value, it was concluded that the cause of the significant difference between the slopes was not due to one measurement but because of a widespread problem related to variable concrete strength.

The t-test for two related samples and the ANOVA test were used to check for homogeneity of velocity, which is translated into uniformity of concrete. A significant difference between the velocities V_{12} and V_{23} indicated a different quality material. However, neither of these tests determined whether the concrete was of good or poor quality. For this reason, the one-tailed lower t-test was used. The hypothesis test was as follows:

$$H_{o\,(4)}: \mu_1 = \mu_o = 8{,}000 \text{ ft/s} \tag{5.7}$$

$$H_{A\,(4)}: \mu_1 < \mu_o = 8{,}000 \text{ ft/s (one-tailed lower),} \tag{5.8}$$

in which μ_1 is the sample mean and μ_o is the population mean. For the value of $\mu_{o,}$ a velocity of 8,000 ft/s was chosen. The criterion of 8,000 ft/s reflects the value of 10,000 ft/s suggested by Whitehurst (1951) and the correction factor of 0.8. The classification of the general quality of concrete suggested by Whitehurst (1951) was based on direct velocity measurements (see Table 2.2 in Chapter 2). Therefore, the suggested classification can be applied to the cases where the indirect transmission method is used only if a correction factor is used to adjust the velocities of Table 2.2. The laboratory study showed that the indirect velocity measurements were approximately 20% lower than the direct velocity measurements, which yields a correction factor of 0.8. The velocity values of Table 2.2 were multiplied by 0.8 and the new boundaries for the different categories of condition of concrete are given in Table 5.1. The acceptance of hypothesis $H_{o\,(4)}$ will imply that the quality of concrete at least does not fall into the category of poor quality concrete.

For the cases that the null hypothesis of the t-test for two related samples and the ANOVA test was accepted, the one-tailed lower t-test was applied to all data velocities

(V_{12} and V_{23}). However, when there was a significant difference between the inner and outer slope, the one-tailed lower test was applied twice, first for the data of velocities V_{12} and then for the data of velocities V_{23}. Further details for the statistical tests are included in Appendix D.

Table 5.1 General rating of the quality of concrete as a function of velocity for the indirect transmission method.

Indirect transmission method	
Quality of Concrete (General condition)	**Pulse Velocity (ft/s)**
Excellent	>12,000
Good	9,600-12,000
Fair	8,000-9,600
Poor	5,600-8,000
Very Poor	<5,600

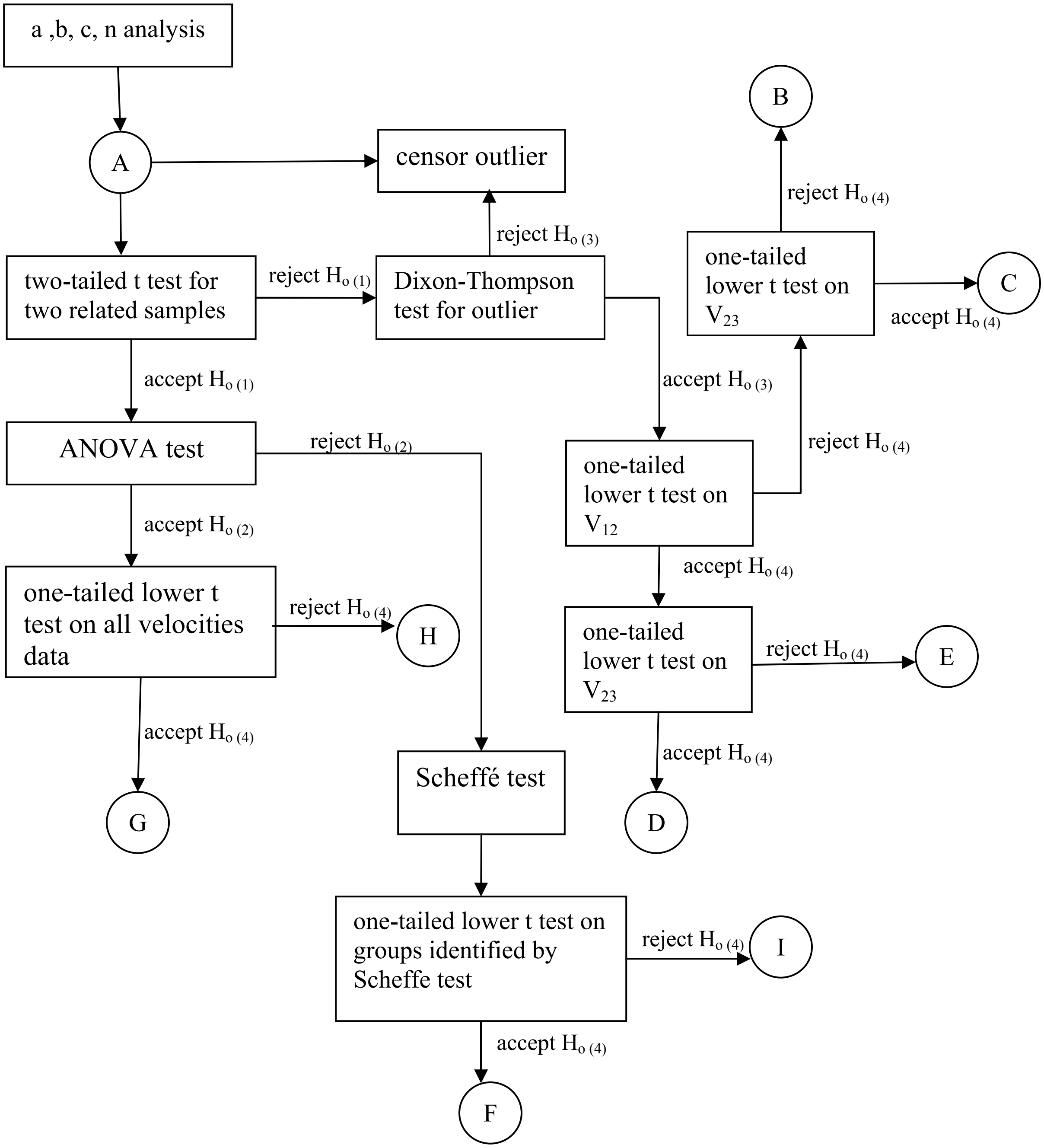


Figure 5.5 Steps of the statistical data analysis.

5.2.1 Selection of level of significance

Selection of level of significance, α, is usually based on convention, and the values of 5% and 1% are mainly used. However, the values chosen for the level of significant should be based on a rational analysis of the physical system being studied because they represent the probability of making a wrong decision with the corresponding implications.

As mentioned earlier, to make a decision about the quality of concrete of the floor slabs of the parking garages, the hypothesis test was used with the null hypothesis $H_{o\,(4)}$: $\mu_1 = \mu_o = 8{,}000$ ft/s and the alternative hypothesis $H_{A\,(4)}$: $\mu_1 < \mu_o = 8{,}000$ ft/s. To make a decision, it is necessary to specify a rejection hypothesis that indicates that the null hypothesis is not accurate. In this case, the decision process used the following rejection hypothesis:

$$H_r : \mu = \mu_r = 4{,}000 \text{ ft/s} \tag{5.9}$$

The distributions for the null and rejection hypotheses are presented in Figure 5.6. The cross-hatched areas indicated with α and β represent the type I and II error decisions, respectively. The concept of these types of error decisions with their corresponding implications are:

- **Type I error (level of significance)**: we conclude that Ho is false when it is true i.e., we decide that the quality of concrete does not meet the standards required for parking garages when it really does. This might lead to the requirement for unnecessary repairs.
- **Type II error**: we conclude that Ho is true when it is not i.e. we wrongly assume that the quality of concrete meets the standards and therefore we fail to identify possible problems on the concrete floor slabs.

The value C is the decision criterion that separates the region of acceptance and rejection. In other words, any computed test statistic value below the decision criterion indicates rejection of the null hypothesis.

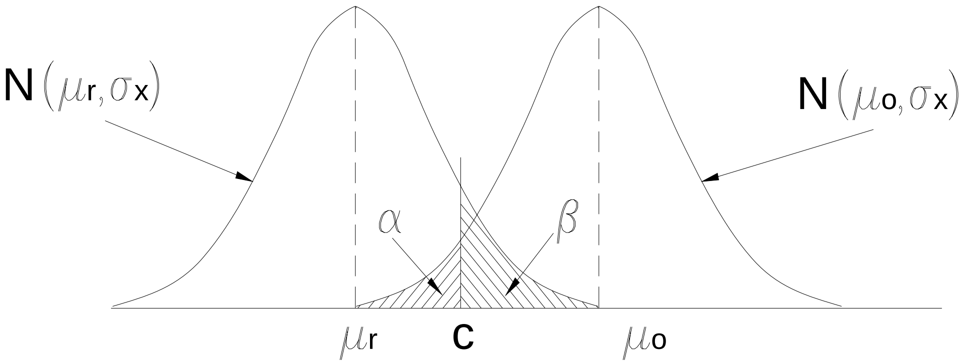


Figure 5.6 Distributions for the null and rejection hypotheses.

The values for the type errors I and II are computed by the following equations:

$$\alpha = \text{P (type I error)} = \text{P } (\mu < \text{C} \setminus \text{H}_o \text{ is true}) = P\left(z < \frac{C-\mu_o}{\sigma_x/\sqrt{n}}\right) \tag{5.10}$$

$$\alpha = P\left(z < \frac{5,600-8,000}{8,000 * COV/\sqrt{n}}\right) = P\left(z < -0.3\sqrt{n}/COV\right) \tag{5.11}$$

$$\beta = \text{P (type I error)} = \text{P } (\mu > \text{C} \setminus \text{H}_r \text{ is true}) = P\left(z > \frac{C-\mu_r}{\sigma_x/\sqrt{n}}\right) \tag{5.12}$$

$$\beta = P\left(z > \frac{5,600-4,000}{8,000 * COV/\sqrt{n}}\right) = P\left(z > 0.2\sqrt{n}/COV\right) \tag{5.13}$$

For sample size, n, equal to 16 and different values for the coefficient of variation, COV, the above equations for α and β yield very small values as seen in Table 5.2. The results by the lab study provided a coefficient of variation of 8.5% for the velocities obtained by the unit-interval method and a transducer spacing 4 inches. It seems reasonable that the coefficient of variation would be greater in the field. However, the results in Table 5.2 show that even though the coefficient of variation is larger, for example 20% the value for the level of significance is very small (0.000000001). For this reason, a value of 0.05% was chosen for the level of significance, which is the smallest available value in statistical tables. For consistency and uniformity, the same level of significance was used for the cases that the sample size was 8. The results in Table 5.2 show that both the α and β values are very small, which provides a high degree of confidence in decisions.

Table 5.2 Type I and II errors for sample size n = 16 and different values for coefficient of variation, COV.

COV	ζ_α	α	ζ_β	β
20%	-6.000	0.000000001	4.000	0.000031671
10%	-12.000	0.000000000	8.000	0.000000000
5%	-24.000	0.000000000	16.000	0.000000000
2%	-60.000	0.000000000	40.000	0.000000000

5.2 SUMMARY OF RESULTS

The results of the data analyses are summarized in Table 5.3. The cases where the surface of the concrete slab was covered by a membrane are not included herein but they are discussed in Chapter 6. The t-test for two related samples showed that for 64 cases the inner and outer slope, i.e., the velocities V_{12} and V_{23}, were not significantly different. The ANOVA test applied to these 64 cases proved that the velocities of the eight groups (rays) were not also significantly different. In other words, the outcomes of the statistical analyses suggest the homogeneity of velocities which is translated into the uniformity of concrete. For 10 cases the hypothesis $H_{o(1)}$ that the velocities V_{12} and V_{23} were not significantly different was rejected. For these 10 cases the Dixon-Thompson outlier test was applied. The application of the Dixon-Thompson test resulted in the detection of an outlier only in one case (Level 3 of Garage 9). Although the outlier was removed, the reapplication of the t-test for two related samples yielded the same outcome. Therefore, for 10 cases the statistical analyses showed that the velocities V_{12} and V_{23} were significantly different which is not attributed to the presence of outliers, but to the fact that the concrete was of variable quality. This result does not suggest that the concrete quality is substandard, only that the inner and outer velocities differed.

The one-tailed lower t test showed that the pulse velocity for all of the cases exceeded the value of 8,000 ft/s, with the exception of only one case (Level 2 of Garage 5). This implies that that the quality of concrete according to the rating of Table 5.1 does not fall into the category of poor quality concrete for all of the 10 cases.

For the 64 cases where the concrete exhibited uniformity, the average values of all data of velocities (V_{12} and V_{23}), were calculated and are included in Table 5.3. These values are also presented in Figure 5.7 in the form of a histogram and are represented by the cross-hatched bars. For the 10 cases where it was found that the concrete lacks uniformity, two mean values for the pulse velocity were computed for each case; one for the velocity data V_{12} and the other for the velocity data V_{23}. The values are also included in Table 5.3. In Figure 5.7, the average of these two mean values is presented for each of the 10 cases and is indicated by the dotted bars.

For each garage the average of velocities obtained in different test locations was computed. The results are presented in Figure 5.7. According to the rating of Table 5.1 the quality of the 20 parking structures fell into the categories that are shown in Table 5.4. However, for the cases where the velocities are close to the boundaries of the different categories, the lines of demarcation should not be sharply drawn. As mentioned in Chapter 2, Whitehurst (1951) emphasized that the lines of demarcation should not be sharply drawn because the degree to which a particular concrete will fall into a category depends on many factors such as mixture proportion and type of aggregate. Therefore, the knowledge of all possible information about concrete will assure a more reliable and accurate evaluation of the condition of concrete of parking garages.

Table 5.3 Results of the data analyses

SILVER SPRING PARKING GARAGES						
Garage 2 (I)		**Level G**	**Level 1**	**Level 2**	**Level 3**	
t-test for two related samples	t	-2.6251	2.2240	-4.2064	-1.0681	
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	
ANOVA test	F	0.338	2.519	0.224	0.448	
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	
One-tailed lower t test	t	2.6105	-2.0653	4.3299	0.8464	
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	
Average Velocity (ft/s)		9,073	7,694	10,679	8,141	
Garage 2 (II)		**Level 2**	**Level 3**			
t-test for two related samples	t	-3.1258	-1.4889			
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$			
ANOVA test	F	0.35	0.054			
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$			
One-tailed lower t test	t	2.8994	3.2099			
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$			
Average Velocity (ft/s)		10,438	9,829			
Garage 4		**Level 1 (a)**	**Level 1(b)**	**Level 2 (c)**	**Level 2(d)**	**Level 3**
t-test for two related samples	t	-0.0020	-1.7367	-1.7006	-0.135	-1.0968
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$
ANOVA test	F	0.339	0.976	0.705	0.431	0.905
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$
One-tailed lower t test	t	-3.7050	3.8192	1.4984	0.6375	-1.1980
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$
Average Velocity (ft/s)		7,674	10,007	8,608	8,277	7,512
Garage 5		**Level G**	**Level 1**	**Level 2**	**Level 3**	
t-test for two related samples	t	-1.5447	-0.1486	-0.6646	0.3963	
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	
ANOVA test	F	0.901	1.245	0.078	1.209	
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	
One-tailed lower t test	t	1.8475	-3.0033	-7.1416	-1.5359	
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Reject $H_{o(4)}$	Accept $H_{o(4)}$	
Average Velocity (ft/s)		8,663	7,162	7,206	7,684	
Garage 7		**Level G**	**Level 2**	**Level 4**	**Level 5**	**Level 6**
t-test for two related samples	t	1.03	-1.6306	1.5944	-0.4228	1.3769
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$
ANOVA test	F	1.219	0.504	0.213	0.535	0.035
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$
One-tailed lower t test	t	9.6986	25.8126	27.3339	23.1277	3.3905
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$
Average Velocity (ft/s)		13,966	12,677	12,715	13,158	10,633
Garage 9		**Level G**	**Level 1**	**Level 2**	**Level 3**	
t-test for two related samples	t	0.9656	-2.9261	1.4309	7.2987	
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Reject $H_{o(1)}$	
ANOVA test	F	0.219	0.042	0.210	–	
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	–	
One-tailed lower t test	t	23.8358	4.8025	5.5731	35.01/2.51	
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	
Average Velocity (ft/s)		12,573	11,629	10,713	13359/8141	
Garage 21		**Level 1**	**Level 2**	**Level 3**		

t-test for two related samples	t	-4.2055	-1.127	1.0708		
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$		
ANOVA test	F	0.64	1.556	0.769		
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$		
One-tailed lower t test	t	2.7019	-0.4048	-1.3777		
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$		
Average Velocity (ft/s)		9,472	7,821	7,501		
Garage 58		**Level G2**	**Level M1**	**Level M2**		
t-test for two related samples	t	-1.1957	1.1581	-1.85		
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$		
ANOVA test	F	0.124	0.785	1.018		
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$		
One-tailed lower t test	t	1.4171	3.2154	2.0048		
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$		
Average Velocity (ft/s)		8,084	9,382	8,638		
Garage 60		**Level B**	**Level 4**	**Level 6 (c)**	**Level 6 (d)**	
t-test for two related samples	t	1.2954	-2.7459	-0.8747	-1.3428	
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	
ANOVA test	F	0.353	0.425	2.969	0.397	
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	
One-tailed lower t test	t	33.8953	38.8001	35.1365	-0.0078	
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	
Average Velocity (ft/s)		12,724	13,699	13,680	7,996	
Garage 61		**Level G**	**Level 4**	**Level 5**	**Level 6**	
t-test for two related samples	t	1.1701	1.2825	-1.1645	-2.8886	
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	
ANOVA test	F	1.76	0.568	0.575	0.009	
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	
One-tailed lower t test	t	20.7061	4.7415	37.4967	3.9368	
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	
Average Velocity (ft/s)		13,081	10,753	13,451	10,753	
BETHESDA PARKING GARAGES						
Garage 11		**Level 3**	**Level 5**			
t-test for two related samples	t	1.0028	0.2405			
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$			
ANOVA test	F	0.129	0.942			
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$			
One-tailed lower t test	t	4.3198	9.9140			
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$			
Average Velocity (ft/s)		12,520	13,270			
Garage 35		**Level G**				
t-test for two related samples	t	-1.5756				
	decision	Accept $H_{o(1)}$				
ANOVA test	F	0.456				
	decision	Accept $H_{o(2)}$				
One-tailed lower t test	t	0.7017				
	decision	Accept $H_{o(4)}$				
Average Velocity (ft/s)		9,464				
Garage 36		**Level G**	**Level 3**	**Level 4**	**Level 5**	
t-test for two related samples	t	0.1848	-4.4535	-14.9239	-8.1725	
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Reject $H_{o(1)}$	Reject $H_{o(1)}$	
ANOVA test	F	0.6515	0.8222	–	–	
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	–	–	

One-tailed lower t test	t	8.9677	7.2948	3.37/16.7	8.71/14.77	
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	
Average Velocity (ft/s)		13,826	12,681	8304/14441	9917/15772	
Garage 40		**Level G(a)**	**Level G(b)**			
t-test for two related samples	t	-1.6478	3.5706			
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$			
ANOVA test	F	0.409	0.16			
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$			
One-tailed lower t test	t	3.2183	1.2118			
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$			
Average Velocity (ft/s)		9,011	8,288			
Garage 42		**Level G1**	**Level G2**	**Level G3**	**Level G3**	
t-test for two related samples	t	-2.0523	-11.4711	-7.9273	0.1733	
	decision	Accept $H_{o(1)}$	Reject $H_{o(1)}$	Reject $H_{o(1)}$	Accept $H_{o(1)}$	
ANOVA test	F	0.034	–	–	0.830	
	decision	Accept $H_{o(2)}$	–	–	Accept $H_{o(2)}$	
One-tailed lower t test	t	4.3190	4.56/18.37	-2.36/9.38	7.8459	
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	
Average Velocity (ft/s)		11,271	8887/13784	7530/12060	12,635	
Garage 47 (I)		**Level G**	**Level 4**			
t-test for two related samples	t	-0.7874	0.93			
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$			
ANOVA test	F	0.611	0.680			
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$			
One-tailed lower t test	t	0.2623	0.4017			
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$			
Average Velocity (ft/s)		8,044	8,168			
Garage 47 (II)		**Level 4**	**Level 5**			
t-test for two related samples	t	0.4603	-7.9393			
	decision	Accept $H_{o(1)}$	Reject $H_{o(1)}$			
ANOVA test	F	0.121	–			
	decision	Accept $H_{o(2)}$	–			
One-tailed lower t test	t	3.0057				
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$			
Average Velocity (ft/s)		9,310	9313/12980			
Garage 49		**Level G**	**Level G1**	**Level G2**	**Level G3**	**Level G4**
t-test for two related samples	t	-1.7984	-14.3463	-3.3348	-5.8754	-9.1738
	decision	Accept $H_{o(1)}$	Reject $H_{o(1)}$	Accept $H_{o(1)}$	Reject $H_{o(1)}$	Reject $H_{o(1)}$
ANOVA test	F	0.99	–	0.159	–	–
	decision	Accept $H_{o(2)}$	–	Accept $H_{o(2)}$	–	–
One-tailed lower t test	t	5.47	16.54/25.33	4.39	4.02/9.89	9.62/15.75
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$
Average Velocity (ft/s)		11,554	9504/12915	11,933	9542/16776	9368/13579
Garage 57		**Level G**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
t-test for two related samples	t	-5.2358	0.2253	-4.6359	-3.5061	0.3248
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Accept $H_{o(1)}$
ANOVA test	F	0.085	1.3512	0.108	0.074	0.292
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$	Accept $H_{o(2)}$
One-tailed lower t test	t	7.5358	30.7841	5.8902	7.2849	0.6341
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$
Average Velocity (ft/s)		12,279	14,133	11,029	11,716	8,094

WHEATON PARKING GARAGES						
Garage 45		**Level G**	**Level 2**	**Level 3**	**Level 4**	
t-test for two related samples	t	-1.976	-0.9707	-10.7754	-1.2665	
	decision	Accept $H_{o(1)}$	Accept $H_{o(1)}$	Reject $H_{o(1)}$	Accept $H_{o(1)}$	
ANOVA test	F	0.459	3.2	–	0.683	
	decision	Accept $H_{o(2)}$	Accept $H_{o(2)}$	–	Accept $H_{o(2)}$	
One-tailed lower t test	t	45.1543	43.1904	5.04/15.54	57.9342	
	decision	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	Accept $H_{o(4)}$	
Average Velocity (ft/s)		15,043	14,368	9250/14403	14,357	

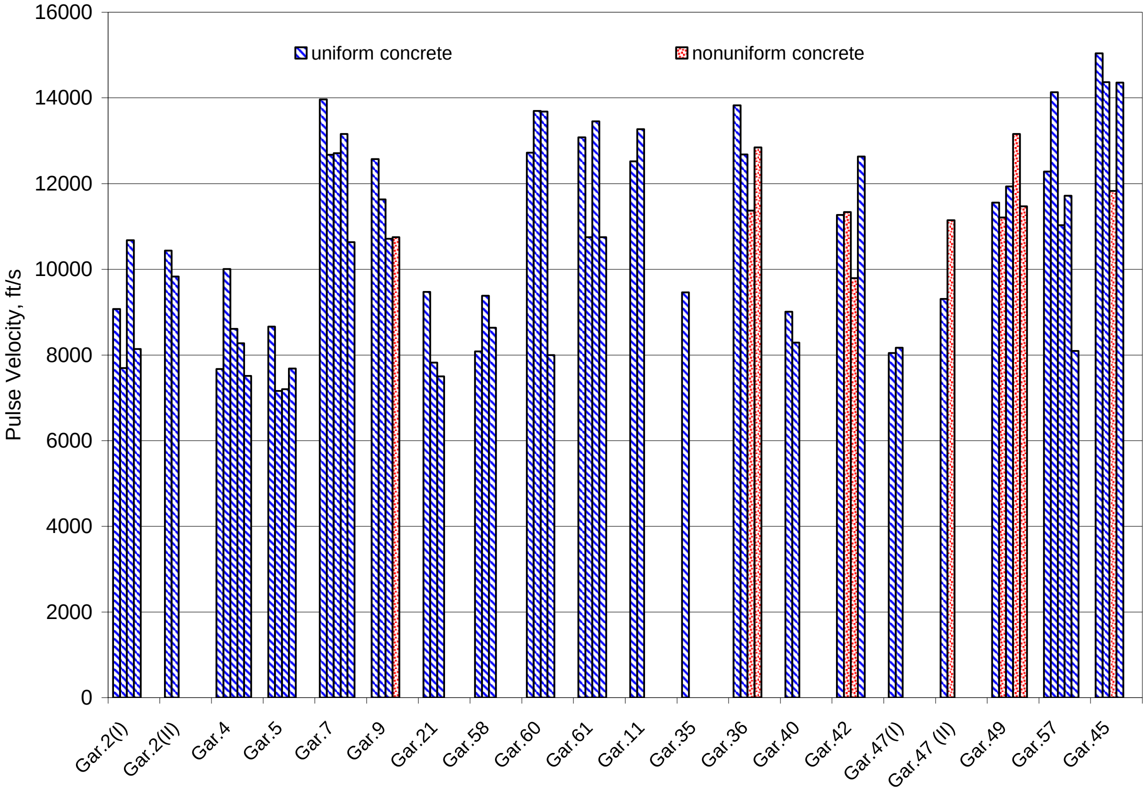


Figure 5.7 Average pulse velocities for each test location.

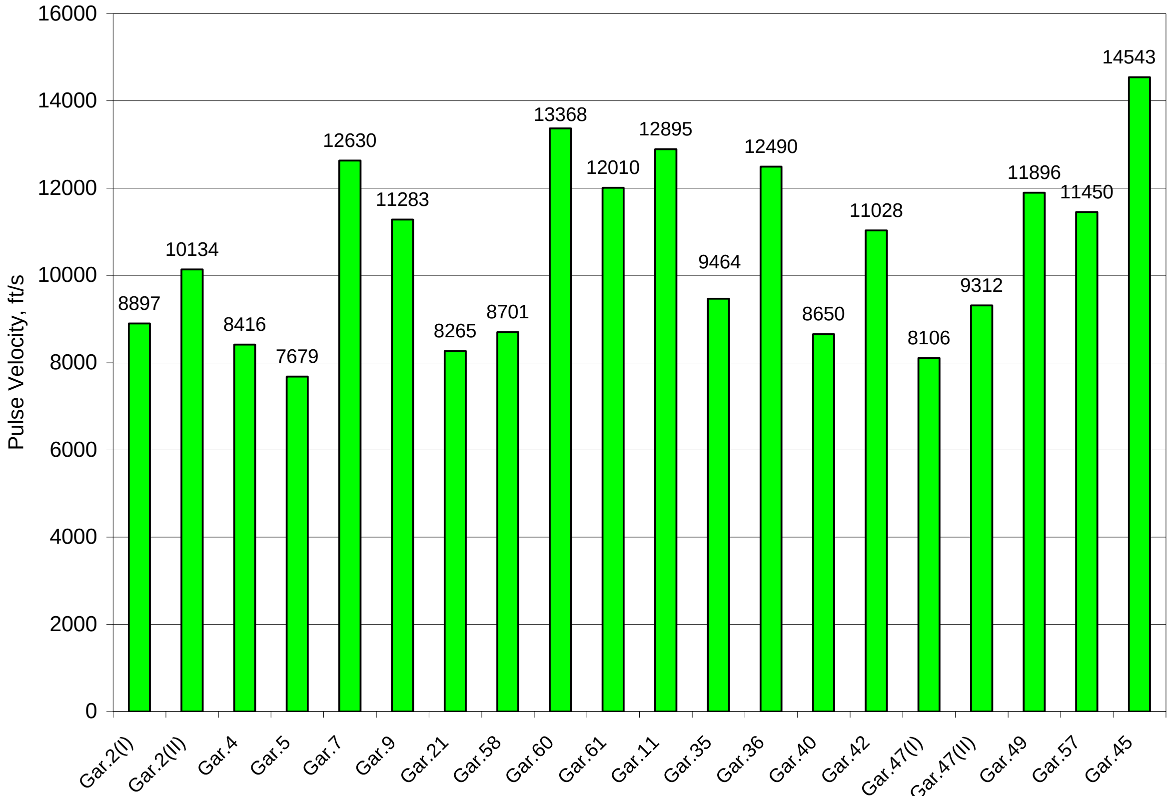


Figure 5.8 Average pulse velocities for each parking garage.

Table 5.4 Condition of the quality of concrete of public parking garages of Montgomery County.

Parking Garages	Quality of Concrete
Gar.7, Gar.60, Gar.61, Gar.11, Gar.36, Gar.45	Excellent
Gar.2 (II), Gar.9, Gar.42, Gar.57, Gar.49	Good
Gar.2(I),Gar.4,Gar.21,Gar.58,Gar.35,Gar.40, Gar.47(I), Gar.47(II)	Fair
Gar.5	Poor
–	Very Poor

CHAPTER 6 - EFFECT OF MEMBRANES ON UPV MEASUREMENTS

6.1 INTRODUCTION

The corrosion of steel reinforcement is the main cause of deterioration of concrete slabs in parking garages. In order to protect the floor slabs against the ingression of water and chloride ions, which are the main contributors to steel reinforcement corrosion, the surface of the slabs are coated with penetrating sealers and elastomeric traffic-bearing membranes. Field experience has shown that membranes have been applied effectively in both bridge and parking decks to reduce the rate of deterioration caused by the penetration of moisture and salts (Mailvaganam, 1986). Penetrating sealers and membranes are more effective when they are installed on a new parking deck or before the deterioration in slab becomes widespread (Popovics, 1994). This chapter provides some information about the properties of penetrating sealers and elastomeric traffic-bearing membranes and investigates specifically the effect of membranes on ultrasonic pulse velocity measurements.

6.2 PENETRATING SEALERS

Penetrating sealers include materials such as silanes or siloxanes. These materials penetrate into the concrete surface and react with cementitious materials to create a layer that repels water and is a barrier to chlorides (Hayes and Tarr, 2006). The depth of penetration varies by the product and with the properties of the concrete on which the sealer is applied. It depends mainly on the size of the sealer molecule and the size of the pores in concrete (ACI 546R, 1996). Penetrating sealers are relatively inexpensive ($1 per square foot) but generally require reapplication every three to five years (Hayes and Tarr, 2006).

6.3 ELASTOMERIC TRAFFIC-BEARING MEMBRANES

Most of the membrane systems used on concrete slabs of parking garages are applied in liquid form in relatively thin layers that are cured to provide a continuous bonded elastomeric surface that is impervious to water and chloride penetration (ACI 362.2R, 2000). Membrane systems have a thickness between 30 mils (0.7 mm) and 250 mils (6mm) and alter significantly the appearance of the concrete surface (ACI 546R, 1996). A cross section of a typical membrane system is shown in Figure 6.1 (Mailvaganam and Collins, 1993). It consists of the following components: (i) a primer or sealer, (ii), a waterproofing membrane, (iii) a wearing course, and (iv) a tie coat. A primer is used to seal the surface of the concrete and promote adhesion of the waterproofing membrane to the concrete. The waterproofing membrane is a flexible base coat that can include urethanes, acrylics, epoxies, neoprenes, or asphaltic products. Due its flexibility, it can bridge effectively small cracks (less than 0.25 mm). The wearing course is a coat that contains aggregates to provide skid and abrasion resistance and prevent wear of the membrane. The tie coat, a polymer material, is used to bond the aggregates firmly to the wearing course (Mailvagnam and Collins, 1993; ACI 546R, 1996). Membranes vary in chemical composition, types of wear-resistant top coats, and methods of application. However, the effectiveness and durability of a membrane system depends not only on its material properties but on how well it is installed (Mailvagnam and Collins, 1993).

Membranes are more expensive than sealers, as they are installed at a typical cost of \$5 to \$7 per square foot (Hayes and Tarr, 2006). However, they provide more effective protection against moisture and chloride penetration. When properly maintained, membrane systems are expected to be effective for 10 years or more in parking garages (ACI 362.2R, 2000). Membranes at high traffic areas, such as entries, exits, turns and ramps require frequent maintenance and can have a reduced service life.

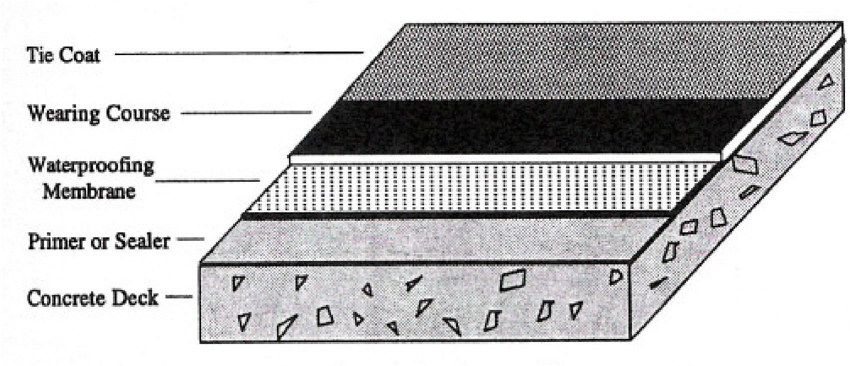


Figure 6.1 Schematic of a typical membrane system (Mailvaganam and Collins, 1993).

6.4 EFFECT OF MEMBRANES ON UPV MEASUREMENTS

Pulse velocity measurements were also performed at locations where the surface of the concrete slabs was covered by an elastomeric traffic-bearing membrane. It should be noted that the measurements were taken at locations where the membranes did not appear to have any signs of deterioration such as holes, tears, blistering or debonding. The computed average pulse velocities are given in Table 6.1. For all of the cases, the velocities were less than the velocities obtained at other locations of garages where the concrete surface was not covered by a membrane. Possible reasons of the decreased values can be: (i) the concrete at these locations is of poorer quality; this is very likely because the membranes due to their high cost are usually installed after the concrete exhibits signs of deterioration; and (ii) the presence of membranes. It seems reasonable that the membranes would cause a decrease in pulse velocity as they are materials that are weaker than concrete.

For a better evaluation of the effect of elastomeric membranes on pulse velocities, measurements were taken at two adjacent locations on Level 2 of Gar.60 where one of the two surfaces was covered by a membrane, as shown in Figure 6.2. The test locations were chosen at an equal distance from the expansion joint. For the site without a membrane, the velocity was 8,736 ft/s, while for the case where the surface was covered by a membrane, the velocity was found to be 8,329 ft/s. This represents a decrease of 5%. Based on the observations of the field investigation, it seems that the presence of a membrane causes a decrease in pulse velocity. However, the data are inadequate to make conclusions. For this reason, an attempt was not made to assess the quality of concrete based on velocity measurements at the locations where membranes were used. Laboratory investigations with controlled specimens with and without membranes are recommended to verify the decrease in pulse velocity and to determine the magnitude of this decrease. The findings of further research will elucidate how velocity measurements are affected by a membrane, and therefore, how the pulse velocity values can be corrected so as to be used as a tool in assessing the uniformity and quality of concrete in cases where the concrete surface is covered by a membrane.

Table 6.1 Pulse velocities at concrete slabs covered by membranes.

Test locations	Pulse velocity (ft/s)
Gar.2(I) – Level 5	7,233
Gar.5 – Level 4	5,645
Gar.60 – Level 7	12,580
Gar.61 – Level 6	8,329
Gar.36 – Level 6	7,922
Gar.40 – Level 1	6,905
Gar.47(I) – Level 2	6,986

Figure 6.2 Locations of test measurements; the concrete surface is covered by a membrane on the left side of the expansion joint.

CHAPTER 7 - EFFECT OF STEEL REINFORCEMENT ON UPV MEASUREMENTS

7.1 INTRODUCTION

One of the significant factors that affects the ultrasonic pulse velocity measurements in concrete is the presence of steel reinforcement. The pulse velocity in steel is 1.4 to 1.7 times the velocity in plain concrete (Naik et al., 2004). Therefore, ultrasonic pulse velocity measurements made in the vicinity of reinforcing bars are higher than those of plain concrete and not representative of the quality of concrete. The increase in pulse velocity depends on the proximity of the point of measurement to the reinforcing bar, the diameter and number of bars, and their orientation with respect to the propagation path (Chung, 1978).

The influence of reinforcing bars oriented perpendicularly in the direction of the pulse propagation is generally insignificant on pulse velocity, especially when the quantity of steel is small in relation to the path length. However, when the reinforcing bars run along or parallel to the path of pulse transmission, the effect of steel reinforcement on pulse velocity measurements is more serious. In general, for concrete with pulse velocities of 4.0 km/s or above, reinforcing bars of 20 mm diameter that run transversely to the pulse path do not have a significant influence on measured velocities values, while bars larger than 6 mm in diameter that run along the path may have a significant effect (Bungey et al., 2006).

The aim of the study presented herein is to investigate the influence of steel reinforcement on pulse velocity measurements conducted on concrete slabs of parking garages. Because the indirect transmission method was used, it is obvious that the case that reinforcing bars oriented parallel to the direction of pulse propagation is encountered.

7.2 EFFECT OF REINFORCING BARS PARALLEL TO DIRECTION OF PROPAGATION

The increase in pulse velocity is apparent when bars run along the direction of pulse propagation, as shown in Figure 7.1, as steel is a stronger material than concrete. The increase in pulse velocity when steel bars run parallel to the direction of pulse propagation occurs because the first pulse to arrive at the receiving transducer may have traveled partly in concrete and partly in steel, as shown in Figure 7.2. Under these circumstances, corrections to the measured pulse velocities are necessary. A correction factor, *k*, was derived by previous research (Chung 1978) and is given by the following relationship:

$$k = \gamma + 2(\frac{\alpha}{L})\sqrt{1-\gamma^2} \tag{7.1}$$

where L is the distance between transducers, α is the perpendicular distance from the line joining the centers of the two transducers to the nearest edge of the bar (see Figure 7.2), and γ is a velocity ratio given by:

$$\gamma = \frac{V_c}{V_s} \tag{7.2}$$

in which V_c is the true pulse velocity in concrete (*ft/s*) and V_s the pulse velocity in steel bar (*ft/s*). Chung (1978) demonstrated that the steel influence occurs when

$$\frac{a}{L} < \frac{1}{2}\sqrt{\frac{1-\gamma}{1+\gamma}} \tag{7.3}$$

and in this case the measured velocity, V_m, should be multiplied with the correction factor k, to obtain the true pulse velocity in concrete, $V_{c.}$. The derivation of the correction factor, k, is illustrated in Appendix E. The equations (7.1)-(7.3) were also adopted by British Standards (BS 1881: Part 203), as indicated by Bungey (2006). The difficulty of applying these equations lies in determining the value for the velocity in steel bar, V_s, because it is affected by many variables.

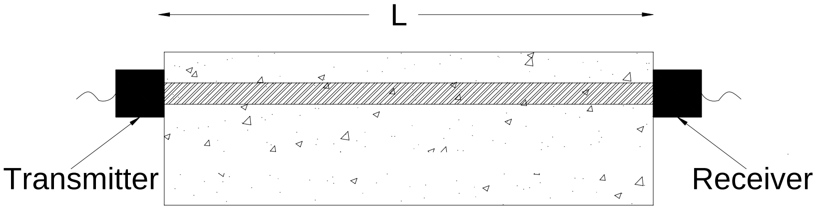


Figure 7.1 Reinforcing bar along to the direction of pulse propagation.

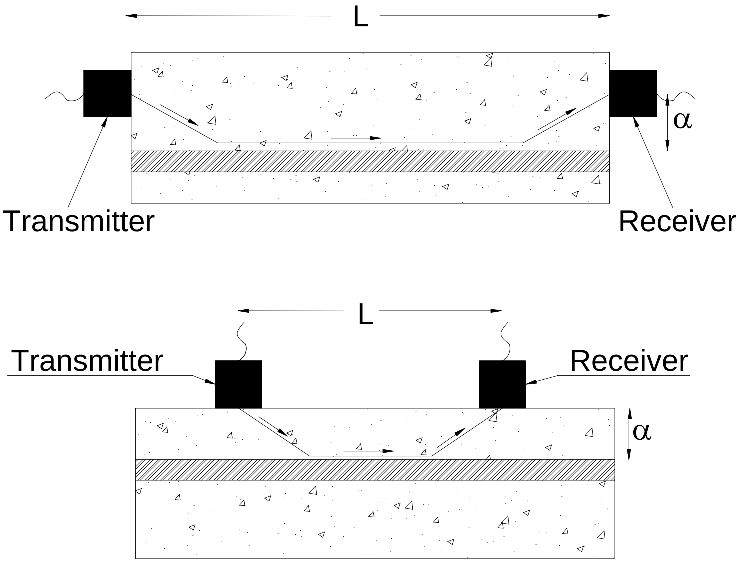


Figure 7.2 Reinforcing bars parallel to the direction of pulse propagation.

The pulse velocity in a steel bar embedded in concrete has been shown to be lower than the velocity in a steel bar in air and much lower than the velocity in an infinite steel medium, and varies with (i) the diameter of the bar, (ii) the pulse velocity of the surrounding concrete, i.e., the quality of concrete, and (iii) the bond between steel and concrete (Chung, 1978; Bungey, 2006). Experimental work carried out by Chung (1978) showed that the pulse velocity in a steel bar in air is different from that in an infinite steel medium (5.9 km/s) and depends on the diameter of the bar. Table 7.1 (Chung 1978) presents the values of pulse velocities obtained by measurements performed in steel bars in air with different diameter. Experiments were also conducted on concrete that contained reinforcing bars, and it was found that the velocity along an embedded steel bar was always higher than the velocity in the plain concrete, but lower than the value obtained by testing the steel bar in air. Based on the test results, the following empirical formula (Chung 1978) for determining of the velocity in a steel bar, embedded in concrete, V_s, was derived:

$$V_s = 5.90 - 10.4(5.90 - V_c)/d \quad \text{for } d \geq 10mm \tag{7.4}$$

where V_c is the pulse velocity in concrete in *km/s* and d is the diameter of the steel bar in *mm*. Chung (1978) underlined that that the test results were obtained with transducers of 50 KHz and this empirical formula may not be applicable to pulse velocity measurements obtained by using transducers of other frequencies.

Table 7.1 Pulse velocity along a steel bar in air (Chung 1978).

Steel bar diameter	6.3 mm	12.7 mm	19 mm	25.4 mm	38 mm
Pulse velocity	5.18 km/s	5.35 km/s	5.48 km/s	5.55 km/s	5.69 km/s

An extensive experimental work was also performed by Bungey (2006) with the aim of deriving the relationship between the pulse velocity in a steel bar embedded in concrete, V_s, the diameter of the bar, d, and the pulse velocity in concrete, V_c. The measurements were performed with transducers of 54 kHz frequency and a plot was provided, as shown in Figure 7.3, for a range of commonly occurring values of V_c and bar diameter.

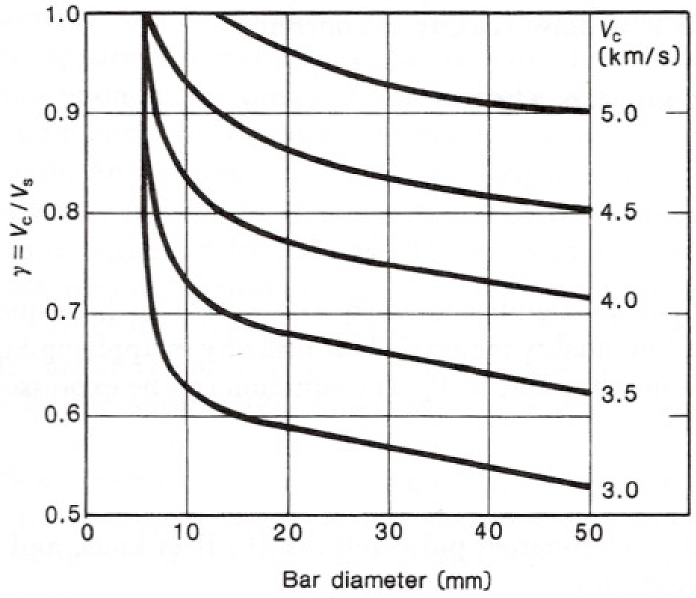


Figure 7.3 Determination of γ as function of bar diameter and concrete quality (based on Bungey, 2006).

An iterative procedure is necessary to obtain a reliable estimate of true pulse velocity in concrete, V_c. First, an assumption is made for the value of V_c. For a known bar diameter, the value of γ can be determined from Figure 7.3. Then, the value of γ is used in equation (7.1) to obtain the correction factor k. Multiplying the measured velocity, V_m, with the correction factor k, should yield a value for pulse velocity in concrete close to the value assumed. The iterative process is continued until the value converges.

It should be noted that the experimental studies carried out by Chung (1978) and Bungey (2006) for determination of value γ were based on the application of direct transducers arrangements (direct transmission method).Therefore, the value of velocity in concrete, Vc, in empirical equation (7.4) and in the plot of Figure (7.3) corresponds to a velocity obtained using the direct transmission method. However, equation (7.1) is applicable for both direct and indirect transmission method.

The determination of correction factors for the measured velocity values for concrete slabs of parking garages was of interest. However, the data used for the determination of correction factors are values for a typical case of a concrete slab in parking structures, as the objective of this study was not to examine each single case, but to provide an overall view of the extent to which the measured velocities can be affected by the steel reinforcement. For the perpendicular distance from the line joining the centers of the two transducers to the nearest edge of the bar, α (see Figure 7.2), the value of 1-½ in. was chosen. This choice was based on the minimum cover requirements provided by ACI 318, Section 7.7 (2005). All floors within an open parking structure should be considered "exposed to weather", and for this case the minimum concrete cover over reinforcement is 1-½ in. The commonly used bars of ½-in. and ¾-in. diameter were considered. The following three cases were considered for the quality of concrete: (i) poor quality concrete, (ii) fair quality concrete, and (iii) good quality concrete. The velocities in concrete for the cases (i), (ii), and (iii) were assumed to be 8,000 ft/s, 9,600 ft/s, and 12,000 ft/s, respectively, using the indirect transmission method. These velocities correspond to values of 10,000 ft/s, 12,000 ft/s, and 15,000 ft/s for the case of the direct transmission method.

Because the transducers used in the field testing were of a 54 KHz frequency, the values of γ were determined by Figure 7.3 and are given in Table 7.2. For the reason mentioned earlier, the velocities related to the direct transmission method were used for the determination of γ. The values of γ were substituted in the second part of equation (7.3) to determine the values of α/L where the steel influence disappears. The results are given in Tables 7.3 and 7.4. Then, the ratio α/L was computed for a distance between transmitter and receiver, L, of 4, 8, and 12 inches. Substituting the values of γ and α/L in Equation 7.1, the correction factors, k, are provided, as shown in Tables 7.5 and 7.6.

Table 7.2 Values of velocity ratio γ for different bar diameter and concrete quality.

Bar diameter, d	$\gamma = \frac{V_c}{V_s}$		
	V_c = 10,000 ft/s (3.0 km/s)	V_c = 12,000 ft/s (3.7 km/s)	V_c = 15,000 ft/s (4.6 km/s)
½ in. (12.7 mm)	0.61	0.76	0.94
¾ in. (19 mm)	0.59	0.74	0.89

Table 7.3 Values of α/L where the steel influence disappears, for ½-in. bar diameter.

Velocity in concrete	γ	$\frac{\alpha}{L} = \sqrt{\frac{1-\gamma}{1+\gamma}}$
V_c = 8,000 ft/s	0.61	0.246
V_c = 9,600 ft/s	0.76	0.185
V_c = 12,000 ft/s	0.94	0.088

Table 7.4 Values of α/L where the steel influence disappears, for ¾-in. bar diameter.

Velocity in concrete	γ	$\frac{\alpha}{L}=\sqrt{\frac{1-\gamma}{1+\gamma}}$
V_c = 8,000 ft/s	0.59	0.254
V_c = 9,600 ft/s	0.74	0.193
V_c = 12,000 ft/s	0.89	0.121

Table 7.5 Values of correction factor, *k*, for ½-in. bar diameter.

L	$\frac{\alpha}{L}$	Correction factor, *k*		
		V_c = 8,000 ft/s	V_c = 9,600 ft/s	V_c = 12,000 ft/s
4	0.375	1.00	1.00	1.00
8	0.1875	0.91	1.00	1.00
12	0.125	0.81	0.92	1.00

Table 7.6 Values of correction factor, *k*, for ¾-in. bar diameter.

L	$\frac{\alpha}{L}$	Correction factor, *k*		
		V_c = 8,000 ft/s	V_c = 9,600 ft/s	V_c = 12,000 ft/s
4	0.375	1.00	1.00	1.00
8	0.1875	0.89	0.99	1.00
12	0.125	0.79	0.91	1.00

The values of the correction factor, *k*, were plotted versus the ratio α/L for bar diameters ½-in. and ¾-in., as shown in Figures 7.4 and 7.5, respectively. From the plots, it is obvious that as the ratio α/L increases, the correction factor, *k*, also increases, which means that the influence of steel becomes less significant. It can also be noticed that for a given ratio α/L the correction factors are increased as the pulse velocity in concrete becomes higher. This indicates that the influence of steel reinforcement on UPV measurements decreases with a better quality concrete. As it was expected, the correction factors were found to be higher in the case of the smaller diameter.

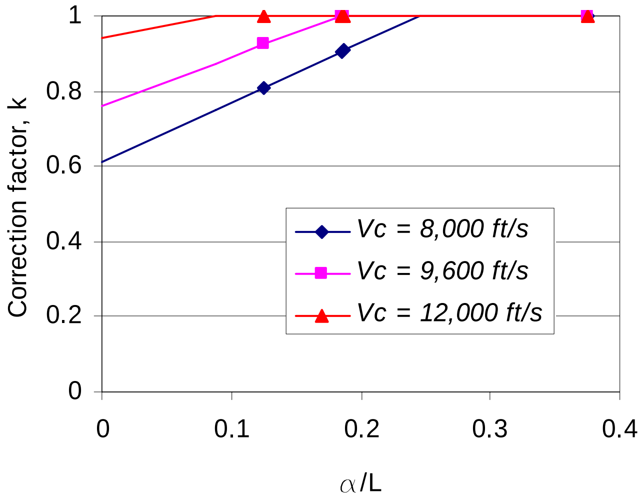


Figure 7.4 Correction factors for ½-in. bar diameter and varying concrete qualities.

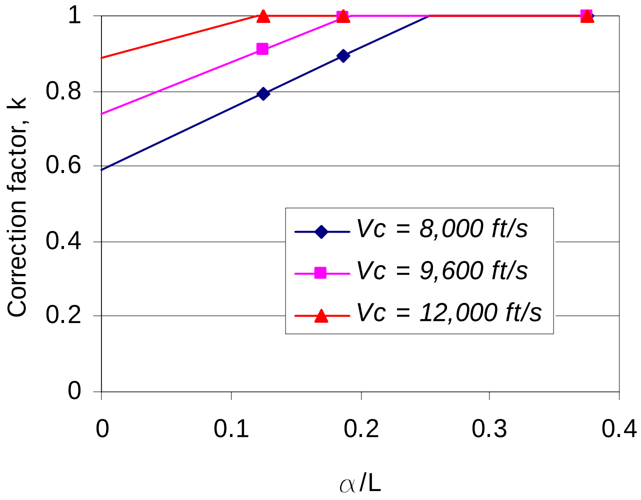


Figure 7.5 Correction factors for ¾-in. bar diameter and varying concrete qualities.

Instead of using the iterative procedure mentioned earlier, we consider that the values 8,000 ft/s, 9,600 ft/s, and 12,000 ft/s are the true velocities in concrete for each case. These values are divided by the corresponding correction factors. The quotients yielded express the expected measured velocities in the field and are contained in Tables 7.5 and 7.6. For a better interpretation of the results, the ratio $(V_m-V_c)/V_c$ was calculated and the computed values are also included in Tables 7.7 and 7.8. Based on the results, it is noticed that in the case where the quality of concrete was good ($V_c = 12{,}000$ *ft/s*), the steel reinforcement did not have an influence on the measured velocities. For the cases of inferior quality concrete, the measured velocities increased by 0.8-23.7 %. The maximum increase occurred in the concrete of the poorest quality. In addition, the measured velocities did not increase when the distance between transmitter and receiver was 4 inches. In the case that the distance *L* was 12 in., higher increases occurred than for an 8-in. distance. In summary, it can be concluded that the steel influence becomes more significant in a poor quality concrete and as the distance between transducer and receiver increases.

Table 7.7 Effect of steel with ½-in. bar diameter on measured pulse velocities.

***d* = ½ in.**	***V_c* =8,000 ft/s**		***V_c* =9,600 ft/s**		***V_c* =12,000 ft/s**	
L (in.)	V_m *(ft/s)*	$\frac{V_m - V_c}{V_c}(\%)$	V_m *(ft/s)*	$\frac{V_m - V_c}{V_c}(\%)$	V_m *(ft/s)*	$\frac{V_m - V_c}{V_c}(\%)$
4	8,000	0	9,600	0	12,000	0
8	8,819	10.2	9,600	0	12,000	0
12	9,900	23.7	10,407	9.2	12,000	0

Table 7.8 Effect of steel with ¾-in. bar diameter on measured pulse velocities.

***d* = ¾ in.**	***V_c* =8,000 ft/s**		***V_c* =9,600 ft/s**		***V_c* =12,000 ft/s**	
L (in.)	V_m *(ft/s)*	$\frac{V_m - V_c}{V_c}(\%)$	V_m *(ft/s)*	$\frac{V_m - V_c}{V_c}(\%)$	V_m *(ft/s)*	$\frac{V_m - V_c}{V_c}(\%)$
4	8,000	0	9,600	0	12,000	0
8	8,961	12.0	9,675	0.8	12,000	0
12	10,103	26.3	10,571	10.1	12,000	0

The implications of the above outcomes on the results of the field testing are that the transit times taken at a distance of 4 inches from the transmitter were not influenced by the presence of the steel, irrespective of the quality of concrete. In the cases of parking garages that the quality of concrete is good, the transit times again were not affected by the reinforcing bars. In the cases that the quality of concrete is fair or poor, the transit times only taken at the distances of 8 and 12 inches might have been influenced. At the distance of 8 inches, the influence would be less significant. These effects on measurements might have occurred only if the axes of the reinforcing bars were coincident with the line joining the transducers, as shown in Figure 7.6 (case C) for rays 3 and 7. The cases B and C are less critical than case C as regards the steel effect. The increase on transit time would result in an increase in the velocities. For example, the velocities V_{12} and V_{23} of the rays 3 and 7 will be higher than the true velocities in concrete. However, because the value of the velocity that represents the quality of concrete of slabs in parking garages is an average of 16 values, the increase due to the steel reinforcement will not affect essentially the overall velocity estimates. In addition, the application of the ANOVA and the Dixon-Thompson tests intended to check the homogeneity of velocity avoids the risk of using a velocity value caused by a significant steel reinforcement influence.

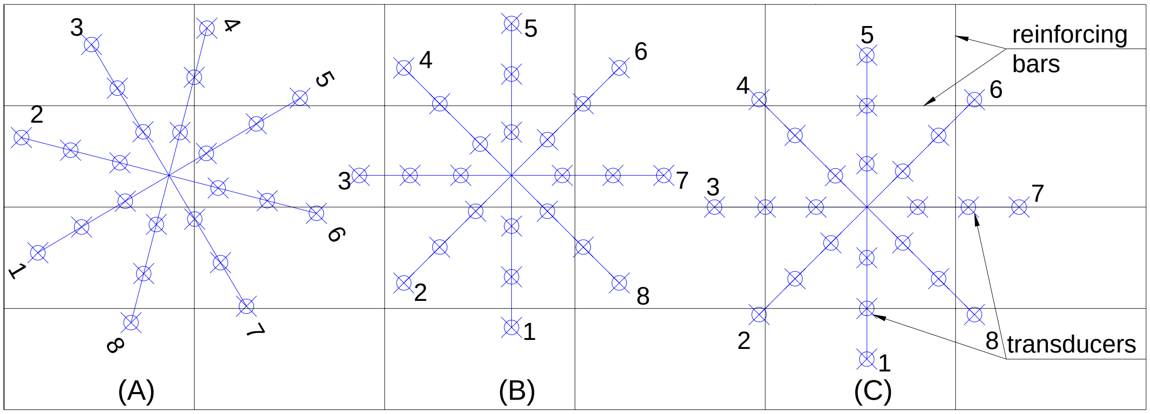


Figure 7.6 Possible locations of transducers with relation to steel bar configurations.

CHAPTER 8 - CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

In the present study, a systematic procedure was developed and tested for the inspection and condition assessment of concrete infrastructure using the nondestructive ultrasonic pulse velocity method. Guidelines for conducting the ultrasonic testing and for analyzing the measured data were provided. This chapter summarizes the major outcomes of this research and recommends areas for further research.

8.2 CONCLUSIONS

The computer simulation and laboratory analyses resulted in the establishment of test criteria for the successful implementation of the pulse velocity method when only one side of the concrete component being tested was accessible. An existing method (regression method) for the determination of pulse velocities when the indirect transmission method is used was evaluated and was compared with a new alternative method (the unit-interval method) developed in the present study. The comparison of the two methods indicated that: (1) the regression method is efficient only when the concrete is of the same quality; in cases where the concrete lacks uniformity, this method was proven to be inadequate, and (2) the unit-interval method is efficient not only when the concrete is of the same quality, but also in case where the concrete exhibits inhomogeneity. This suggests that the unit-interval method can be used as an index for indicating the uniformity and quality of concrete and is preferable to the regression method.

The analyses of the simulation and laboratory data showed that the accuracy of the results using the unit-interval method is affected by the spacing between receiver locations. A separation distance of 4 inches was shown to provide acceptable accuracy for the determination of velocity estimates.

The experimental study indicated that the test results were reproducible when the indirect transmission method was applied in both directions along the specimens. In addition, the velocity obtained by the indirect method was shown to be approximately 20% lower than the velocity obtained using the direct method. This implies that the velocities obtained by the indirect method should be adjusted using a correction factor in order to make assessments for the quality of concrete.

The test measurements in the field were conducted according to the criteria established by the simulation and laboratory studies. The statistical analyses of the field measurements provided reliable estimates of the velocity data and, therefore, reliable estimates of concrete quality. The findings of the field study undertaken with the aim of assessing the condition of the eighteen public parking garages of Montgomery County showed that the quality of concrete tested for almost all of the cases did not fall into the category of poor quality according to the general rating suggested by Whitehurst (1951). However, the condition of the concrete of many parking garages fell into the category of fair quality concrete.

As part of the study, the influence of the steel reinforcement on the pulse velocity measurements was assessed. The analyses demonstrated that the presence of steel reinforcement in the concrete slabs of the parking garages can not affect the pulse velocity measurements when the quality of concrete is good for the given transducer spacing that was used in the field. It also revealed that for a 4-inch distance between transmitter and receiver, the velocity measurements can not be affected, irrespective of the quality of concrete. For a poor quality concrete, the steel reinforcement can cause an increase in pulse velocity for the cases where the distance between transmitter and receiver is 8 or 12 inches. However, because at each test location the measurements were conducted along eight rays, the possible presence of steel reinforcement along one or two rays can not affect essentially the overall velocity estimates.

The second phase of the project was intended to develop a performance model of the parking garages that will provide information on the rate of their deterioration and, hence, a prediction on where the parking garages are in their life-cycles. This can be achieved by a thorough understanding of the current condition of the structures and an extensive review of the existing information about the historical performance of the parking garages. The following materials are considered necessary: (a) original structural drawings, (b) construction documents, such as the quality of concrete specified as well as field inspection reports that will provide detailed information about the type of construction and therefore the expected behavior of the structures, (c) previous condition surveys reports that will show how the structures have performed over time, and (d) maintenance inspection reports and repair documents that will provide information about the repairs that were performed over time and how they affected the rate of deterioration. Based on these data, performance models of the concrete slabs can be developed for each parking garage. The development of the performance models will be useful to estimate the rate of future deterioration and the remaining service life of the parking garages. This phase of the project can be undertaken when the above information becomes available.

8.3 RECOMMENDATIONS FOR FUTURE RESEARCH

In this section, areas for further research are recommended. The recommendations suggested herein are intended to encourage additional research that will aim to maximize the benefits of the ultrasonic pulse velocity method.

The classification suggested by Whitehurst (1951) for the quality of concrete as a function of pulse velocity measurements should not be the sole basis for the interpretation of the results. Knowledge of the mix design, type and size of aggregate, type of cement, age of concrete, and the conditions under which the concrete was exposed during the service life of each parking garage would increase the value of the results. If this information could not realistically be assembled, then additional velocity measurements are recommended at other locations of the parking garages to verify the findings of this research, especially for the cases where the quality of concrete fell into the category of poor or fair concrete.

The use of additional tests at the locations where the pulse velocity measurements were performed would be of a value, especially in the cases where the concrete was shown to lack uniformity. It would be useful to determine the amount of steel reinforcement, if any, at the locations where the concrete was tested for the following reason: the presence of steel reinforcement will indicate (i) a potential source of corrosion by-products (rust), and (ii) an increase in pulse velocity measurements. The use of a covermeter is recommended to determine the location and orientation of the reinforcing bars embedded in the concrete, and the application of the chloride ion content test is recommended to determine the extent of chloride ion penetration at a certain depth within the concrete, specifically at the level of the reinforcing bars. The chloride ion concentration at the level of the reinforcing steel bars will indicate the potential for active corrosion. The use of these tests is recommended because both tests can be performed quickly and with low cost (Bungey, 2006). In the cases where these tests show that steel reinforcement exists at the locations where the pulse velocity method was applied and the concentration of the chloride ions is high, then the presence of active corrosion will be inferred. This implies that the low velocities obtained in these areas that indicate a nonuniform concrete can be attributed to the volume of corrosion by-products (rust).

Cores could be extracted from the concrete floor slabs at the locations where the nondestructive testing test was conducted to confirm the accuracy of the results obtained by the ultrasonic pulse velocity method. It is recommended their direct velocity measurements be taken on the cores before being tested for compressive strength. The relationship obtained between direct and indirect velocities can be compared with those obtained in the laboratory studies. The basis for the calibration of nondestructive testing would be based on a correlation between pulse velocity and compressive strength for a particular concrete mix in the condition in which it exists in the structure. The availability of pre-established calibration curves for each parking garage will allow pulse velocity measurements that will be performed in the future to provide reliable estimates of in-situ strength.

Pulse velocity measurements are recommended to be repeated at the same locations periodically to monitor changes that may occur in the condition of the concrete over time under the influence of various factors. Monitoring changes over a long period of time can provide valuable information on the rate of deterioration of the parking garages. Based on this information, a life-cycle performance model could be developed for each parking garage. Assessing the extent of future deterioration will be essential to choose appropriate maintenance and rehabilitations programs in a cost-effective manner.

APPENDIX A - MONTGOMERY COUNTY PUBLIC PARKING GARAGES

SILVER SPRING	Year Occupied
Gar. 2 (I) Spring – Cameron Garage	1973
Gar. 2 (II) Spring – Cameron Garage	–
Gar. 4 Fenton Street Village Garage	1968
Gar. 5 Bonifant – Dixon Garage	1970
Gar. 7 Cameron – Second Garage	1988
Gar. 9 Kennet Street Garage	1996
Gar. 21 Spring – Colesville Garage	1968
Gar. 58 NOAA Garage	1990
Gar. 60 Wayne Avenue Garage	2004
Gar. 61 Town Square Garage	2004
BETHESDA	**Year Occupied**
Gar. 11 Woodmont Corner Garage	1981
Gar.35 Woodmont – Rugby Garage	1964
Gar. 36 Auburn – Del Ray Garage	2002
Gar. 40 Cordell – St. Elmo Garage	1997
Gar. 42 Cheltenham Garage	2003
Gar. 47 (I) Waverly Garage	1984
Gar. 47 (II) Waverly Garage	1968
Gar. 49 Metropolitan Garage	1991
Gar. 57 Bethesda – Elm Garage	1990
WHEATON	**Year Occupied**
Gar. 45 Amherst Garage	1990

APPENDIX B - ULTRASONIC FIELD DATA

Site: Garage 4 (Fenton Street Village Garage)
8110 Fenton Street, Silver Spring

Date: 07/15/2005

Reported by: C. Stergiopoulou, O. Amer, M. Alshaikh

Location: Level 1
At a, space 1005

Data Sheet 1 out of 5

Points	**Distance** *(in)*	**Time** *(μsec)*	**Notes**
1 - 1	4	54.2	
1 - 2	8	97.3	
1 - 3	12	141.9	
2 - 1	4	56.6	
2 - 2	8	99.7	
2 - 3	12	143.0	
3 - 1	4	55.7	
3 - 2	8	97.5	
3 - 3	12	141.8	
4 - 1	4	54.8	
4 - 2	8	99.8	
4 - 3	12	143.5	
5 - 1	4	52.7	
5 - 2	8	99.9	
5 - 3	12	142.8	
6 - 1	4	53.2	
6 - 2	8	99.8	
6 - 3	12	140.8	
7 - 1	4	55.1	
7 - 2	8	96.5	
7 - 3	12	138.5	
8 - 1	4	54.0	
8 - 2	8	94.3	
8 - 3	12	140.4	

ULTRASONIC FIELD DATA

Site: Garage 4 (Fenton Street Village Garage)
8110 Fenton Street, Silver Spring

Date: 07/15/2005

Reported by: C. Stergiopoulou, O. Amer, M. Alshaikh

Location: Level 1
At b, space 1023

Data Sheet 2 out of 5			
Points	**Distance** *(in)*	**Time** *(μsec)*	**Notes**
1 - 1	4	29.7	
1 - 2	8	64.0	
1 - 3	12	88.7	
2 - 1	4	29.6	
2 - 2	8	67.3	
2 - 3	12	106.0	
3 - 1	4	29.0	
3 - 2	8	66.4	
3 - 3	12	107.2	
4 - 1	4	28.4	
4 - 2	8	64.6	
4 - 3	12	107.3	
5 - 1	4	28.3	
5 - 2	8	64.0	
5 - 3	12	86.4	
6 - 1	4	25.0	
6 - 2	8	63.1	
6 - 3	12	89.9	
7 - 1	4	29.3	
7 - 2	8	65.0	
7 - 3	12	103.4	
8 - 1	4	29.1	
8 - 2	8	64.6	
8 - 3	12	91.2	

ULTRASONIC FIELD DATA

Site: Garage 4 (Fenton Street Village Garage)
8110 Fenton Street, Silver Spring

Date: 07/15/2005

Reported by: C. Stergiopoulou, O. Amer, M. Alshaikh

Location: Level 2
At c, space 2099

Data Sheet 3 out of 5			
Points	**Distance** *(in)*	**Time** *(μsec)*	**Notes**
1 - 1	4	32.8	
1 - 2	8	72.6	
1 - 3	12	123.9	
2 - 1	4	29.0	
2 - 2	8	69.5	
2 - 3	12	102.4	
3 - 1	4	37.0	
3 - 2	8	71.7	
3 - 3	12	104.3	
4 - 1	4	31.0	
4 - 2	8	70.2	
4 - 3	12	103.3	
5 - 1	4	27.2	
5 - 2	8	72.1	
5 - 3	12	102.4	
6 - 1	4	30.3	
6 - 2	8	72.9	
6 - 3	12	122.2	
7 - 1	4	32.4	
7 - 2	8	80.7	
7 - 3	12	122.4	
8 - 1	4	28.0	
8 - 2	8	78.1	
8 - 3	12	107.0	

ULTRASONIC FIELD DATA

Site: Garage 4 (Fenton Street Village Garage) **Date:** 07/15/2005
8110 Fenton Street, Silver Spring

Reported by: C. Stergiopoulou, O. Amer, M. Alshaikh **Location**: Level 2
At d, space 2110

Data Sheet 4 out of 5

Points	**Distance** *(in)*	**Time** *(μsec)*	**Notes**
1 - 1	4	28.5	
1 - 2	8	77.2	
1 - 3	12	112.9	
2 - 1	4	28.6	
2 - 2	8	67.3	
2 - 3	12	100.6	
3 - 1	4	30.0	
3 - 2	8	75.3	
3 - 3	12	107.8	
4 - 1	4	31.6	
4 - 2	8	64.3	
4 - 3	12	125.8	
5 - 1	4	36.7	
5 - 2	8	71.6	
5 - 3	12	114.8	
6 - 1	4	33.3	
6 - 2	8	74.0	
6 - 3	12	128.5	
7 - 1	4	31.3	
7 - 2	8	76.5	
7 - 3	12	105.3	
8 - 1	4	29.8	
8 - 2	8	74.2	
8 - 3	12	126.5	

ULTRASONIC FIELD DATA

Site: Garage 4 (Fenton Street Village Garage)
8110 Fenton Street, Silver Spring

Date: 07/15/2005

Reported by: C. Stergiopoulou, O. Amer, M. Alshaikh

Location: Level 3
At e, space 3016

Data Sheet 5 out of 5

Points	**Distance** *(in)*	**Time** *(μsec)*	**Notes**
1 - 1	4	30.5	
1 - 2	8	81.4	
1 - 3	12	127.3	
2 - 1	4	31.3	
2 - 2	8	78.6	
2 - 3	12	122.3	
3 - 1	4	31.8	
3 - 2	8	67.4	
3 - 3	12	107.1	
4 - 1	4	29.6	
4 - 2	8	79.4	
4 - 3	12	125.0	
5 - 1	4	32.3	
5 - 2	8	84	
5 - 3	12	131.9	
6 - 1	4	34.7	
6 - 2	8	79.9	
6 - 3	12	134.4	
7 - 1	4	33.8	
7 - 2	8	85.1	
7 - 3	12	111.1	
8 - 1	4	34.0	
8 - 2	8	85.2	
8 - 3	12	131.4	

APPENDIX C - CALCULATION OF PULSE VELOCITIES

Table C.1 Velocity in each direction for all levels of Garage 2(I)

<table>
<tr><th colspan="5">REGRESSION METHOD</th></tr>
<tr><th>Velocity V_{123}</th><th>Level G</th><th>Level 1</th><th>Level 2</th><th>Level 3</th></tr>
<tr><td>ray 1</td><td>8910</td><td>7814</td><td>10387</td><td>7470</td></tr>
<tr><td>ray 2</td><td>8220</td><td>8199</td><td>8393</td><td>7820</td></tr>
<tr><td>ray 3</td><td>8948</td><td>7228</td><td>10055</td><td>8422</td></tr>
<tr><td>ray 4</td><td>7685</td><td>7625</td><td>10662</td><td>7978</td></tr>
<tr><td>ray 5</td><td>9806</td><td>7643</td><td>9885</td><td>8160</td></tr>
<tr><td>ray 6</td><td>8870</td><td>7491</td><td>10547</td><td>8503</td></tr>
<tr><td>ray 7</td><td>9077</td><td>8514</td><td>10431</td><td>8057</td></tr>
<tr><td>ray 8</td><td>9033</td><td>6894</td><td>10574</td><td>8337</td></tr>
<tr><td>Mean</td><td>8819</td><td>7676</td><td>10117</td><td>8093</td></tr>
<tr><td>St. Dev.</td><td>628</td><td>513</td><td>746</td><td>342</td></tr>
<tr><th colspan="5">UNIT- INTERVAL METHOD</th></tr>
<tr><th>Velocity V_{12}</th><th>Level G</th><th>Level 1</th><th>Level 2</th><th>Level 3</th></tr>
<tr><td>ray 1</td><td>8032</td><td>8013</td><td>8818</td><td>7199</td></tr>
<tr><td>ray 2</td><td>8313</td><td>8052</td><td>8681</td><td>8460</td></tr>
<tr><td>ray 3</td><td>9083</td><td>7491</td><td>9980</td><td>8052</td></tr>
<tr><td>ray 4</td><td>8013</td><td>7880</td><td>8795</td><td>8396</td></tr>
<tr><td>ray 5</td><td>8110</td><td>7862</td><td>8091</td><td>8210</td></tr>
<tr><td>ray 6</td><td>7770</td><td>8354</td><td>8658</td><td>8013</td></tr>
<tr><td>ray 7</td><td>7955</td><td>8636</td><td>8913</td><td>7752</td></tr>
<tr><td>ray 8</td><td>7559</td><td>6916</td><td>8658</td><td>7407</td></tr>
<tr><td>Mean</td><td>8104</td><td>7900</td><td>8824</td><td>7936</td></tr>
<tr><td>St. Dev.</td><td>454</td><td>524</td><td>529</td><td>453</td></tr>
<tr><td colspan="5"></td></tr>
<tr><th>Velocity V_{23}</th><th>Level G</th><th>Level 1</th><th>Level 2</th><th>Level 3</th></tr>
<tr><td>ray 1</td><td>10101</td><td>7628</td><td>13021</td><td>7770</td></tr>
<tr><td>ray 2</td><td>8130</td><td>8354</td><td>8130</td><td>7294</td></tr>
<tr><td>ray 3</td><td>8818</td><td>6988</td><td>10132</td><td>8842</td></tr>
<tr><td>ray 4</td><td>7391</td><td>7391</td><td>14184</td><td>7610</td></tr>
<tr><td>ray 5</td><td>12970</td><td>7440</td><td>13387</td><td>8110</td></tr>
<tr><td>ray 6</td><td>10515</td><td>6831</td><td>14184</td><td>9083</td></tr>
<tr><td>ray 7</td><td>10753</td><td>8396</td><td>12920</td><td>8396</td></tr>
<tr><td>ray 8</td><td>11655</td><td>6873</td><td>14306</td><td>9662</td></tr>
<tr><td>Mean</td><td>10042</td><td>7488</td><td>12533</td><td>8346</td></tr>
<tr><td>St. Dev.</td><td>1855</td><td>617</td><td>2232</td><td>807</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td rowspan="2">Average Velocity</td><th>Level G</th><th>Level 1</th><th>Level 2</th><th>Level 3</th></tr>
<tr><td>9073</td><td>7694</td><td>10679</td><td>8141</td></tr>
</table>

Table C.2 Velocity in each direction for all levels of Garage 2(II)

REGRESSION METHOD			
Velocity V_{123}	**Level 2**	**Level 3**	**Level 5**[*]
ray 1	9913	9280	8424
ray 2	–	9174	7912
ray 3	10240	9355	4389
ray 4	10191	8872	9839
ray 5	9073	9185	4636
ray 6	8791	9078	4766
ray 7	9172	9497	4357
ray 8	10623	9365	5104
Mean	9715	9226	6178
St. Dev.	698	194	2187
UNIT- INTERVAL METHOD			
Velocity V_{12}	**Level 2**	**Level 3**	**Level 5**[*]
ray 1	8396	7680	10225
ray 2	–	7541	11534
ray 3	7559	11534	5438
ray 4	9132	7788	10384
ray 5	8013	8681	12970
ray 6	7918	11779	12300
ray 7	8190	7576	5777
ray 8	9208	7593	5043
Mean	8345	8772	9209
St. Dev.	620	1819	3271
Velocity V_{23}	**Level 2**	**Level 3**	**Level 5**[*]
ray 1	12484	12255	7278
ray 2	–	12300	6289
ray 3	19608	8013	3750
ray 4	11655	10482	9363
ray 5	10616	9775	3246
ray 6	9980	7576	3364
ray 7	10549	13717	3600
ray 8	12821	12970	5168
Mean	12530	10886	5257
St. Dev.	3292	2294	2225
Average Velocity	**Level 2**	**Level 3**	**Level 5**[*]
	10438	9829	7233

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[*] the surface of the level is covered by a membrane

Table C.3 Velocity in each direction for all levels of Garage 4

REGRESSION METHOD					
Velocity V_{123}	**Level 1 (a)**	**Level 1 (b)**	**Level 2 (c)**	**Level 2 (d)**	**Level 3**
ray 1	7601	11201	7279	7837	6881
ray 2	7716	8726	9050	9242	7322
ray 3	7741	8520	9903	8492	8845
ray 4	7515	8430	9199	6863	6984
ray 5	7394	11277	8755	8504	6690
ray 6	7600	10169	7241	6954	6667
ray 7	7993	8993	7394	8864	8327
ray 8	7704	10662	8241	6879	6839
Mean	7658	9747	8383	7954	7319
St. Dev.	178	1214	1006	959	819
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level 1 (a)**	**Level 1 (b)**	**Level 2 (c)**	**Level 2 (d)**	**Level 3**
ray 1	7734	9718	8375	6845	6549
ray 2	7734	8842	8230	8613	7047
ray 3	7974	8913	9606	7358	9363
ray 4	7407	9208	8503	10194	6693
ray 5	7062	9337	7424	9551	6447
ray 6	7153	8749	7825	8190	7375
ray 7	8052	9337	6901	7375	6498
ray 8	8271	9390	6653	7508	6510
Mean	7673	9187	7940	8204	7060
St. Dev.	433	328	955	1176	985
Velocity V_{23}	**Level 1 (a)**	**Level 1 (b)**	**Level 2 (c)**	**Level 2 (d)**	**Level 3**
ray 1	7474	13495	6498	9337	7262
ray 2	7698	8613	10132	10010	7628
ray 3	7524	8170	10225	10256	8396
ray 4	7628	7806	10070	5420	7310
ray 5	7770	14881	11001	7716	6959
ray 6	8130	12438	6761	6116	6116
ray 7	7937	8681	7994	11574	12821
ray 8	7231	12531	11534	6373	7215
Mean	7674	10827	9277	8350	7963
St. Dev.	280	2797	1928	2256	2063
Average Velocity	**Level 1 (a)**	**Level 1 (b)**	**Level 2 (c)**	**Level 2 (d)**	**Level 3**
	7674	10007	8608	8277	7512

Table C.4 Velocity in each direction for all levels of Garage 5

REGRESSION METHOD					
Velocity V_{123}	**Level G**	**Level 1**	**Level 2**	**Level 3**	**Level 4[*]**
ray 1	6129	6995	7168	6847	4832
ray 2	9235	6359	7104	7593	2964
ray 3	9096	6903	7149	7592	5045
ray 4	9083	7341	7083	7627	6568
ray 5	8457	8606	7183	8090	6010
ray 6	8481	7020	7144	8772	6498
ray 7	8883	6698	7261	7385	6884
ray 8	8612	6674	7308	7150	5591
Mean	8497	7075	7175	7632	5549
St. Dev.	1001	684	76	588	1276
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level G**	**Level 1**	**Level 2**	**Level 3**	**Level 4[*]**
ray 1	7407	7032	7246	7698	4409
ray 2	8230	6173	6859	7508	4444
ray 3	8230	7262	6873	7770	4523
ray 4	10010	7215	6916	7770	6575
ray 5	8190	7246	7663	7246	6523
ray 6	7576	7375	6988	9662	6061
ray 7	7788	7593	7734	7032	6653
ray 8	7680	7062	6562	7440	4946
Mean	8139	7120	7105	7766	5517
St. Dev.	820	421	412	809	1029
Velocity V_{23}	**Level G**	**Level 1**	**Level 2**	**Level 3**	**Level 4[*]**
ray 1	5308	6959	7092	6207	5385
ray 2	10650	6562	7375	7680	2333
ray 3	10256	6588	7457	7424	5767
ray 4	8354	7474	7262	7491	6562
ray 5	8749	10965	6775	9259	5593
ray 6	9747	6707	7310	8071	7032
ray 7	10515	6039	6859	7788	7138
ray 8	9921	6337	8333	6887	6523
Mean	9187	7204	7308	7601	5792
St. Dev.	1766	1578	480	887	1542
	Level G	**Level 1**	**Level 2**	**Level 3**	**Level 4[*]**
Average Velocity	8663	7162	7206	7684	5654

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[*] the surface of the level is covered by a membrane

Table C.5 Velocity in each direction for all levels of Garage 7

REGRESSION METHOD					
Velocity V_{123}	**Level G**	**Level 2**	**Level 4**	**Level 5**	**Level 6**
ray 1	10227	12121	12846	14207	9459
ray 2	15014	12504	12626	13024	9692
ray 3	10226	12232	13013	12736	9215
ray 4	15986	12415	12484	12565	10202
ray 5	14275	12779	12505	12707	9253
ray 6	14398	13096	12594	13101	9691
ray 7	14274	13333	13018	13523	9476
ray 8	14941	12650	12317	12985	9524
Mean	13668	12641	12675	13106	9564
St. Dev.	2196	416	258	534	311
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level G**	**Level 2**	**Level 4**	**Level 5**	**Level 6**
ray 1	13831	11990	14430	14815	14306
ray 2	13495	12920	12484	14065	7880
ray 3	14245	12300	13605	12121	7231
ray 4	17544	11574	12484	11905	14306
ray 5	14368	12034	12870	11990	14684
ray 6	14620	12870	13175	12255	12255
ray 7	14006	13495	13333	13550	11494
ray 8	14430	11779	11862	13661	13947
Mean	14567	12370	13031	13045	12013
St. Dev.	1255	662	792	1115	2968
Velocity V_{23}	**Level G**	**Level 2**	**Level 4**	**Level 5**	**Level 6**
ray 1	8375	12255	11655	13661	7424
ray 2	17094	12121	12771	12165	13333
ray 3	8271	12165	12484	13441	13947
ray 4	14749	13441	12484	13333	8230
ray 5	14184	13661	12165	13550	7153
ray 6	14184	13333	12077	14124	8190
ray 7	14556	13175	12723	13495	8190
ray 8	15504	13717	12821	12392	7559
Mean	13365	12984	12398	13270	9253
St. Dev.	3251	688	405	659	2742
Average Velocity	**Level G**	**Level 2**	**Level 4**	**Level 5**	**Level 6**
	13966	12677	12715	13158	10633

Table C.6 Velocity in each direction for all levels of Garage 9

REGRESSION METHOD				
Velocity V_{123}	**Level G**	**Level 1**	**Level 2**	**Level 3**
ray 1	12191	10030	10018	10188
ray 2	12506	11423	10196	9873
ray 3	12618	10052	9784	9839
ray 4	12662	10151	9981	10079
ray 5	12531	11862	10197	12970
ray 6	13201	11492	10136	9799
ray 7	12202	10191	12624	9842
ray 8	12277	10383	9745	9812
Mean	12523	10698	10335	10300
St. Dev.	330	759	941	1088
UNIT- INTERVAL METHOD				
Velocity V_{12}	**Level G**	**Level 1**	**Level 2**	**Level 3**
ray 1	13605	7937	13228	14065
ray 2	12771	9416	12077	13333
ray 3	12077	7899	12077	13717
ray 4	14006	8271	8569	13123
ray 5	12626	10163	9058	13123
ray 6	13228	9662	12210	12870
ray 7	11696	8503	12920	13123
ray 8	12438	14124	12165	13280
Mean	12806	9497	11538	13359
St. Dev.	774	2048	1739	384
Velocity V_{23}	**Level G**	**Level 1**	**Level 2**	**Level 3**
ray 1	11111	14815	8292	8271
ray 2	12255	15221	8937	8091
ray 3	13228	15152	8375	7955
ray 4	11614	13889	12255	8396
ray 5	12438	14620	11820	12821
ray 6	13175	14684	8795	8130
ray 7	12771	13228	12346	8110
ray 8	12121	8482	8292	8032
Mean	12339	13761	9889	8141
St. Dev.	734	2234	1885	1660
Average Velocity	**Level G**	**Level 1**	**Level 2**	**Level 3**
	12573	11629	10713	13359/8141

Table C.7 Velocity in each direction for all levels of Garage 21

REGRESSION METHOD					
Velocity V_{123}	**Level 1**	**Level 2**	**Level 3[†](c)**	**Level 3 (d)**	**Level 4[*]**
ray 1	8139	5858	11870	6750	14278
ray 2	8402	6091	11267	9293	10097
ray 3	9177	7069	12004	7236	11161
ray 4	8892	8755	11840	7823	9859
ray 5	8387	8452	11256	6546	16309
ray 6	10795	8360	11195	6337	6111
ray 7	11342	7016	12157	6743	8974
ray 8	7614	9418	11943	7648	5598
Mean	9094	7627	11692	7297	10298
St. Dev.	1313	1302	387	962	3671
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level 1**	**Level 2**	**Level 3[†](c)**	**Level 3 (d)**	**Level 4[*]**
ray 1	7508	7062	10482	7576	15504
ray 2	7680	6523	9718	8052	7407
ray 3	7358	6944	10132	7474	14006
ray 4	7047	7541	10549	8375	17094
ray 5	7752	6988	9183	8375	19157
ray 6	9747	7440	9579	8818	4235
ray 7	10684	7680	10352	6301	14493
ray 8	6562	8889	10101	8292	17361
Mean	8042	7384	10012	7908	13657
St. Dev.	1416	715	479	785	5180
Velocity V_{23}	**Level 1**	**Level 2**	**Level 3[†](c)**	**Level 3 (d)**	**Level 4[*]**
ray 1	8937	5081	13889	6127	13280
ray 2	9337	5727	13717	11223	19960
ray 3	13072	7199	15221	7018	9470
ray 4	13072	10684	13661	7358	7440
ray 5	9183	11186	15361	5501	14368
ray 6	12210	9662	13831	5128	19268
ray 7	12121	6485	10352	7278	6901
ray 8	9285	10040	15083	7123	3885
Mean	10902	8258	14395	7094	11822
St. Dev.	1871	2401	1602	1871	5882
Average Velocity	**Level 1**	**Level 2**	**Level 3[†](c)**	**Level 3 (d)**	**Level 4[*]**
	9472	7821	10012/14395	7501	12739

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[*] the surface of the level is covered by a membrane

[†] repaired concrete

Table C.8 Velocity in each direction for all levels of Garage 58

REGRESSION METHOD			
Velocity V_{123}	**Level G2**	**Level M1**	**Level M2**
ray 1	8080	8717	7974
ray 2	8170	7915	10086
ray 3	8003	9253	8492
ray 4	8101	8879	9042
ray 5	8179	11550	8009
ray 6	7963	9157	7706
ray 7	8042	9208	8182
ray 8	8070	8595	8736
Mean	8076	9159	8528
St. Dev.	75	1060	766
UNIT- INTERVAL METHOD			
Velocity V_{12}	**Level G2**	**Level M1**	**Level M2**
ray 1	7955	9980	7974
ray 2	8091	9921	8569
ray 3	8130	10582	7994
ray 4	7663	10384	9390
ray 5	8013	9891	8333
ray 6	8210	9083	7262
ray 7	7955	9158	7262
ray 8	7937	10163	8210
Mean	7994	9895	8124
St. Dev.	165	534	694
Velocity V_{23}	**Level G2**	**Level M1**	**Level M2**
ray 1	8210	7806	7974
ray 2	8251	6720	12626
ray 3	7880	8292	9083
ray 4	8613	7843	8726
ray 5	8354	14245	7716
ray 6	7734	9234	8230
ray 7	8130	9259	9497
ray 8	8210	7541	9363
Mean	8173	8868	9152
St. Dev.	271	2332	1545
	Level G2	**Level M1**	**Level M2**
Average Velocity	8084	9382	8638

Table C.9 Velocity in each direction for all levels of Garage 60

REGRESSION METHOD					
Velocity V_{123}	**Level B**	**Level 4**	**Level 6 (c)**	**Level 6(d)**	**Level 7[*]**
ray 1	12351	13717	13773	6823	16234
ray 2	12508	13549	13222	7053	15646
ray 3	12555	13509	14652	7215	16625
ray 4	12747	13822	14304	8469	16778
ray 5	12844	13224	13305	7462	18291
ray 6	12723	13655	13387	7087	17708
ray 7	12648	14334	13774	8517	17925
ray 8	13230	13596	12933	7838	10839
Mean	12701	13676	13669	7558	16256
St. Dev.	264	319	579	651	2365
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level B**	**Level 4**	**Level 6 (c)**	**Level 6(d)**	**Level 7[*]**
ray 1	13228	13550	13947	8271	20704
ray 2	12531	13387	12771	7524	23810
ray 3	12438	12821	14684	7294	27322
ray 4	12674	13228	14620	7663	25641
ray 5	12626	13605	13072	6614	35842
ray 6	12674	13175	13441	7440	23981
ray 7	12970	14006	13774	12255	35088
ray 8	14306	13021	12300	5931	24691
Mean	12931	13349	13576	7193	27135
St. Dev.	610	372	849	722	5473
Velocity V_{23}	**Level B**	**Level 4**	**Level 6 (c)**	**Level 6(d)**	**Level 7[*]**
ray 1	11614	13889	13605	5900	13661
ray 2	12484	13717	13717	6653	12255
ray 3	12674	14306	14620	7138	12723
ray 4	12821	14493	14006	9551	13123
ray 5	13072	12870	13550	8681	13441
ray 6	12771	14184	13333	6775	14493
ray 7	12346	14684	13774	12255	13175
ray 8	12346	14245	13661	13441	7770
Mean	12516	14049	13783	8799	12580
St. Dev.	441	567	389	2776	2052
Average Velocity	**Level B**	**Level 4**	**Level 6 (c)**	**Level 6(d)**	**Level 7[*]**
	12724	13699	13680	7996	27135/12580

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[*] the surface of the level is covered by a membrane

Table C.10 Velocity in each direction for all levels of Garage 61

REGRESSION METHOD					
Velocity V_{123}	**Level G**	**Level 4**	**Level 5**	**Level 6 (d)**	**Level 6 (e)**[*]
ray 1	13357	9401	13149	9559	11365
ray 2	12674	12277	13251	10500	11340
ray 3	13917	12687	13173	10090	10949
ray 4	14361	12210	13888	9989	11582
ray 5	12944	9522	13300	9525	11968
ray 6	12310	8869	13089	9126	11416
ray 7	11947	8856	13652	9975	8291
ray 8	12844	8597	13937	10205	11339
Mean	13044	10302	13430	9871	11031
St. Dev.	804	1761	344	440	1143
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level G**	**Level 4**	**Level 5**	**Level 6 (d)**	**Level 6 (e)**[*]
ray 1	13021	11111	13280	7843	8150
ray 2	12579	12438	12920	8985	8354
ray 3	13717	13387	13495	8333	7788
ray 4	14948	12210	13661	8032	8396
ray 5	12771	11862	13831	13072	8681
ray 6	13605	7092	12531	7062	8636
ray 7	11990	12121	13072	8210	8396
ray 8	13947	12210	13333	8569	8230
Mean	13322	11554	13266	8763	8329
St. Dev.	925	1909	419	1829	283
Velocity V_{23}	**Level G**	**Level 4**	**Level 5**	**Level 6 (d)**	**Level 6 (e)**[*]
ray 1	13717	8251	13021	12870	25840
ray 2	12771	12121	13605	12970	21930
ray 3	14124	12077	12870	13387	26455
ray 4	13831	12210	14124	14124	24510
ray 5	13123	8110	12821	7752	25253
ray 6	11299	12723	13717	14430	19608
ray 7	11905	7215	14306	13333	8190
ray 8	11947	6901	14620	13072	23810
Mean	12840	9951	13636	12742	21949
St. Dev.	1037	2538	686	2091	5990
Average Velocity	**Level G**	**Level 4**	**Level 5**	**Level 6 (d)**	**Level 6 (e)**[*]
	13081	10753	13451	10753	8329/21949

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[*] the surface of the level is covered by a membrane

Table C.11 Velocity in each direction for all levels of Garage 11

REGRESSION METHOD		
Velocity V_{123}	**Level 3**	**Level 5**
ray 1	9898	13801
ray 2	10438	13717
ray 3	11619	9654
ray 4	11900	10389
ray 5	12284	14519
ray 6	11267	14741
ray 7	10494	13682
ray 8	10620	13523
Mean	11065	13003
St. Dev.	829	1899
UNIT- INTERVAL METHOD		
Velocity V_{12}	**Level 3**	**Level 5**
ray 1	8985	14065
ray 2	14556	13889
ray 3	8913	12870
ray 4	9804	8271
ray 5	18622	15015
ray 6	18416	15361
ray 7	16667	14245
ray 8	15083	13550
Mean	13881	13408
St. Dev.	4105	2219
Velocity V_{23}	**Level 3**	**Level 5**
ray 1	11111	13550
ray 2	8439	13550
ray 3	18939	7955
ray 4	15873	15083
ray 5	9634	14065
ray 6	8636	14184
ray 7	8110	13175
ray 8	8525	13495
Mean	11158	13132
St. Dev.	4055	2173
Average Velocity	**Level 3**	**Level 5**
	12520	13270

Table C.12 Velocity in each direction for all levels of Garage 35

REGRESSION METHOD			
Velocity V_{123}	**Level G**	**Level 1[‡]**	**Level 2[*]**
ray 1	5684	5169	6003
ray 2	5611	5847	6126
ray 3	4019	4838	4452
ray 4	5383	4946	4020
ray 5	7624	4653	4005
ray 6	6622	4612	4816
ray 7	5325	4520	4940
ray 8	6359	6983	3828
Mean	5828	5196	4774
St. Dev.	1064	837	888
UNIT- INTERVAL METHOD			
Velocity V_{12}	**Level G**	**Level 1[‡]**	**Level 2[*]**
ray 1	3845	5640	8439
ray 2	3836	5698	8130
ray 3	3885	5491	6061
ray 4	3659	5537	6006
ray 5	10549	4146	8913
ray 6	6325	4182	4511
ray 7	6072	5537	5942
ray 8	9579	8658	3360
Mean	5969	5611	6420
St. Dev.	2749	1389	1955
Velocity V_{23}	**Level G**	**Level 1[‡]**	**Level 2[*]**
ray 1	30030	4789	4838
ray 2	22222	6006	5058
ray 3	4167	4357	3635
ray 4	24331	4498	3169
ray 5	6184	5368	2881
ray 6	6959	5184	5184
ray 7	4782	3885	4290
ray 8	4998	5963	4523
Mean	12959	5006	4197
St. Dev.	10664	762	874
Average Velocity	**Level G**	**Level 1[‡]**	**Level 2[*]**
	9464	5309	5309

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[*] the surface of the level is covered by a membrane

[‡] the surface of the level is covered by an asphalt layer

Table C.13 Velocity in each direction for all levels of Garage 36

REGRESSION METHOD					
Velocity V_{123}	**Level G**	**Level 3**	**Level 4**	**Level 5**	**Level 6[*]**
ray 1	14488	10156	10063	11884	7946
ray 2	14526	10945	10479	12170	7816
ray 3	11139	14717	10823	11713	8687
ray 4	10767	14459	10219	11644	7680
ray 5	10535	10683	10082	12355	7357
ray 6	15141	14776	10342	12362	7788
ray 7	15361	10583	10215	11212	8118
ray 8	15180	11859	9994	11892	7945
Mean	13392	12272	10277	11904	7917
St. Dev.	2163	2029	271	390	384
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level G**	**Level 3**	**Level 4**	**Level 5**	**Level 6[*]**
ray 1	14065	8460	8271	9980	7955
ray 2	13495	9158	8658	10320	7825
ray 3	9208	14749	8418	9747	8354
ray 4	14556	14184	8292	10482	7633
ray 5	15798	8889	8150	10288	7559
ray 6	14493	13605	8591	10320	7680
ray 7	15432	8818	8190	8569	7918
ray 8	14684	10549	7862	9634	7825
Mean	13966	11052	8304	9917	7847
St. Dev.	2053	2679	255	622	245
Velocity V_{23}	**Level G**	**Level 3**	**Level 4**	**Level 5**	**Level 6[*]**
ray 1	14948	13228	13495	15221	7937
ray 2	15798	14124	13889	15291	7806
ray 3	14749	14684	16835	15291	9058
ray 4	8818	14749	14124	13228	7698
ray 5	8292	13947	14065	16103	7168
ray 6	15873	16260	13550	16026	7899
ray 7	15291	13774	14556	18519	8333
ray 8	15723	13717	15015	16502	8071
Mean	13686	14311	14441	15772	7996
St. Dev.	3196	934	1089	1488	544
Average Velocity	**Level G**	**Level 3**	**Level 4**	**Level 5**	**Level 6[*]**
	13826	12681	8304/14441	9917/15772	7922

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[*] the surface of the level is covered by a membrane

Table C.14 Velocity in each direction for all levels of Garage 40

REGRESSION METHOD				
Velocity V_{123}	**Level G (a)**	**Level G (b)**	**Level 1**[*]	**Level 2**[*]
ray 1	8250	8396	6131	6842
ray 2	8730	8412	6230	6023
ray 3	8699	8161	7455	8978
ray 4	8702	7811	7115	7334
ray 5	9418	7961	7294	6648
ray 6	9822	7754	7409	9486
ray 7	8481	8331	5846	7210
ray 8	8790	8546	6185	6155
Mean	8861	8172	6708	7334
St. Dev.	511	298	669	1263
UNIT- INTERVAL METHOD				
Velocity V_{12}	**Level G (a)**	**Level G (b)**	**Level 1**[*]	**Level 2**[*]
ray 1	8375	8333	5258	5128
ray 2	8091	10070	5350	5216
ray 3	9662	9311	7680	7032
ray 4	8503	8150	7062	7262
ray 5	8292	8271	7391	4983
ray 6	8375	9107	7047	7215
ray 7	8658	8591	4953	5233
ray 8	7716	10010	4968	5200
Mean	8459	8981	6214	5909
St. Dev.	563	769	1180	1049
Velocity V_{23}	**Level G (a)**	**Level G (b)**	**Level 1**[*]	**Level 2**[*]
ray 1	8130	8460	7541	12210
ray 2	9524	7326	7645	7278
ray 3	7955	7326	7246	13661
ray 4	8913	7508	7168	7407
ray 5	11074	7680	7199	11862
ray 6	12210	6831	7825	15949
ray 7	8313	8091	7358	15152
ray 8	10384	7541	8772	7788
Mean	9563	7595	7595	11413
St. Dev.	1539	499	529	3520
Average Velocity	**Level G (a)**	**Level G (b)**	**Level 1**[*]	**Level 2**[*]
	9011	8288	6905	8661

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[*] the surface of the level is covered by a membrane

Table C.15 Velocity in each direction for all levels of Garage 42

REGRESSION METHOD				
Velocity V_{123}	**Level G_1**	**Level G_3 (b)**	**Level G_3 (c)**	**Level G_3 (d)**
ray 1	11176	10845	8975	9990
ray 2	10612	10529	8748	13411
ray 3	9919	11225	9315	12945
ray 4	10105	10137	9806	14124
ray 5	9723	10253	8496	9832
ray 6	10203	10556	9148	13742
ray 7	10529	11193	9047	14313
ray 8	10415	10149	8877	9844
Mean	10335	10611	9051	12275
St. Dev.	454	438	368	2020
UNIT- INTERVAL METHOD				
Velocity V_{12}	**Level G_1**	**Level G_3 (b)**	**Level G_3 (c)**	**Level G_3 (d)**
ray 1	9662	9107	7107	14306
ray 2	9234	9285	6831	13072
ray 3	8503	9470	7974	13072
ray 4	15361	8130	8613	14065
ray 5	7358	8547	7628	7974
ray 6	8071	9158	7610	13387
ray 7	8985	9311	7215	13387
ray 8	8818	8091	7262	12723
Mean	9499	8887	7530	12748
St. Dev.	2473	551	564	1999
Velocity V_{23}	**Level G_1**	**Level G_3 (b)**	**Level G_3 (c)**	**Level G_3 (d)**
ray 1	13550	13889	13228	7994
ray 2	12723	12346	13441	13774
ray 3	12210	14245	11494	12821
ray 4	7918	14430	11574	14184
ray 5	16667	13333	9690	13605
ray 6	15083	12723	11947	14124
ray 7	13072	14620	13072	15432
ray 8	13123	14684	12034	8230
Mean	13043	13784	12060	12521
St. Dev.	2552	890	1222	2817
Average Velocity	**Level G_1**	**Level G_3 (b)**	**Level G_3 (c)**	**Level G_3 (d)**
	11271	8887/13784	7530/12060	12635

Table C.16 Velocity in each direction for all levels of Garage 47(I)

REGRESSION METHOD			
Velocity V_{123}	**Level G**	**Level 2**[*]	**Level 4**
ray 1	7890	5771	9126
ray 2	8090	6340	6739
ray 3	8140	7378	7686
ray 4	7945	6500	6833
ray 5	7946	6864	9388
ray 6	8640	6391	8715
ray 7	7513	7528	7155
ray 8	7862	6554	7649
Mean	8003	6666	7911
St. Dev.	319	575	1037
UNIT- INTERVAL METHOD			
Velocity V_{12}	**Level G**	**Level 2**[*]	**Level 4**
ray 1	7880	6127	11377
ray 2	7937	5963	6231
ray 3	8230	6050	9234
ray 4	8091	6242	5501
ray 5	7862	7032	11299
ray 6	7508	6289	8749
ray 7	7770	5679	8333
ray 8	7880	6423	8013
Mean	7895	6226	8592
St. Dev.	214	397	2106
Velocity V_{23}	**Level G**	**Level 2**[*]	**Level 4**
ray 1	7899	5464	7770
ray 2	8251	6789	7375
ray 3	8052	9950	6680
ray 4	7806	6789	9634
ray 5	8032	6707	8150
ray 6	10384	6498	8681
ray 7	7278	13072	6337
ray 8	7843	6693	7326
Mean	8193	7745	7744
St. Dev.	929	2507	1072
Average Velocity	**Level G**	**Level 2**[*]	**Level 4**
	8044	6986	8168

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[*] the surface of the level is covered by a membrane

Table C.17 Velocity in each direction for all levels of Garage 47(II)

REGRESSION METHOD		
Velocity V_{123}	**Level 4**	**Level 5**
ray 1	8214	10819
ray 2	9221	11502
ray 3	9607	10471
ray 4	8732	10952
ray 5	9364	11887
ray 6	8314	8700
ray 7	9344	10173
ray 8	8838	11158
Mean	8954	10708
St. Dev.	512	976
UNIT- INTERVAL METHOD		
Velocity V_{12}	**Level 4**	**Level 5**
ray 1	11574	9524
ray 2	10417	10040
ray 3	10616	8569
ray 4	7593	10352
ray 5	7628	10320
ray 6	7698	7508
ray 7	11111	8418
ray 8	10040	9775
Mean	9585	9313
St. Dev.	1674	1035
Velocity V_{23}	**Level 4**	**Level 5**
ray 1	6614	12723
ray 2	8333	13717
ray 3	8818	14184
ray 4	10482	11655
ray 5	12821	14306
ray 6	9083	10582
ray 7	8170	13441
ray 8	7955	13228
Mean	9035	12980
St. Dev.	1880	1287
Average Velocity	**Level 4**	**Level 5**
	9310	9313/12980

Table C.18 Velocity in each direction for all levels of Garage 49

REGRESSION METHOD					
Velocity V_{123}	**Level G**	**Level G1**	**Level G2**	**Level G3**	**Level G4**
ray 1	11311	10863	11038	12020	10965
ray 2	11095	11254	9991	10945	10743
ray 3	11412	10766	10950	12721	10762
ray 4	10373	10544	10649	11787	11302
ray 5	10470	10854	10815	11966	11116
ray 6	11176	10744	10903	11071	10898
ray 7	10696	11004	11272	11049	11058
ray 8	11144	11033	11599	11986	10606
Mean	10960	10883	10902	11693	10933
St. Dev.	393	215	470	620	227
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level G**	**Level G1**	**Level G2**	**Level G3**	**Level G4**
ray 1	8865	9390	8130	10787	9183
ray 2	9950	9634	8726	8613	9208
ray 3	9891	9363	8865	10965	9443
ray 4	11001	9285	9285	10040	10132
ray 5	11862	9690	9107	9862	9107
ray 6	9234	9311	8795	8313	9804
ray 7	11990	10070	9311	8150	9058
ray 8	8985	9579	12870	9606	9009
Mean	10222	9540	9386	9542	9368
St. Dev.	1251	263	1457	1085	402
Velocity V_{23}	**Level G**	**Level G1**	**Level G2**	**Level G3**	**Level G4**
ray 1	17182	13175	21368	13717	14124
ray 2	12674	13889	11905	16420	13228
ray 3	13774	12920	15221	15504	12723
ray 4	9833	12392	12723	14684	12920
ray 5	9443	12484	13774	15949	15015
ray 6	14815	12970	15291	19608	12392
ray 7	9718	12210	14948	21231	14948
ray 8	15649	13280	10616	17094	13280
Mean	12886	12915	14480	16776	13579
St. Dev.	2973	549	3252	2511	1002
Average Velocity	**Level G**	**Level G1**	**Level G2**	**Level G3**	**Level G4**
	11554	9540/12915	11933	9542/16776	9368/13579

Table C.19 Velocity in each direction for all levels of Garage 57

REGRESSION METHOD					
Velocity V_{123}	**Level G**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
ray 1	11938	13717	11449	11228	7889
ray 2	12355	14093	10022	10889	7646
ray 3	11991	13097	10290	11301	7811
ray 4	12248	15117	10959	11552	8554
ray 5	12023	13849	10375	10788	8197
ray 6	11939	14545	10027	11666	7936
ray 7	10535	14383	10658	11474	8228
ray 8	11397	14055	11083	11675	8145
Mean	11803	14107	10608	11321	8051
St. Dev.	585	601	520	338	287
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level G**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
ray 1	9747	13605	11038	10288	7770
ray 2	10384	14368	9747	10515	8842
ray 3	10163	12970	8818	9718	8170
ray 4	11779	15221	9083	10753	7994
ray 5	10823	13228	9234	8591	7918
ray 6	11416	15291	8460	10753	7918
ray 7	8726	15291	8613	11299	8842
ray 8	10040	13441	10010	9579	7806
Mean	10385	14177	9375	10187	8157
St. Dev.	965	988	857	856	411
Velocity V_{23}	**Level G**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
ray 1	16260	13831	11905	12438	8013
ray 2	15798	13831	10320	11299	6803
ray 3	15083	13228	12674	13831	7491
ray 4	12771	15015	14430	12531	9234
ray 5	13661	14556	11990	15649	8503
ray 6	12531	13889	12723	12821	7955
ray 7	13889	13605	14881	11655	7716
ray 8	13387	14749	12531	15723	8525
Mean	1386	616	1443	1687	739
St. Dev.	1296	577	1350	1578	691
Average Velocity	**Level G**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
	12279	14133	11029	11716	8094

Table C.20 Velocity in each direction for all levels of Garage 45

REGRESSION METHOD					
Velocity V_{123}	**Level G**	**Level 2**	**Level 3**	**Level 4**	**Level 5[*]**
ray 1	14780	14683	10759	14245	9984
ray 2	15565	14399	10578	13860	9468
ray 3	14748	14460	10426	14609	9001
ray 4	14520	14848	11807	14397	11507
ray 5	15043	14459	11901	14212	9657
ray 6	15182	14524	11341	14552	10352
ray 7	15000	13122	11327	14684	10727
ray 8	15323	14389	10301	14215	10176
Mean	15020	14361	11055	14347	10109
St. Dev.	338	524	623	270	780
UNIT- INTERVAL METHOD					
Velocity V_{12}	**Level G**	**Level 2**	**Level 3**	**Level 4**	**Level 5[*]**
ray 1	14493	14430	8681	14124	8150
ray 2	14881	14430	9208	13889	7698
ray 3	15015	14245	8547	13947	7047
ray 4	14948	14749	9634	14124	10225
ray 5	14556	14749	10582	14556	8354
ray 6	14749	14430	9662	14124	8460
ray 7	14245	13333	9158	14684	9416
ray 8	15015	13774	8525	14245	8271
Mean	14738	14268	9250	14212	8453
St. Dev.	281	487	702	278	982
Velocity V_{23}	**Level G**	**Level 2**	**Level 3**	**Level 4**	**Level 5[*]**
ray 1	15083	14948	15083	14368	13605
ray 2	16340	14368	12674	13831	13021
ray 3	14493	14684	14065	15361	13717
ray 4	14124	14948	16103	14684	13333
ray 5	15576	14184	13774	13889	11696
ray 6	15649	14620	14124	15015	14065
ray 7	15873	12920	15798	14684	12674
ray 8	15649	15083	13605	14184	14006
Mean	15349	14469	14403	14502	13265
St. Dev.	736	696	1166	536	791
Average Velocity	**Level G**	**Level 2**	**Level 3**	**Level 4**	**Level 5[*]**
	15043	14368	9250/14403	14357	8453/13265

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[*] the surface of the level is covered by a membrane

APPENDIX D - STATISTICAL TESTS

The t-test for two related samples

The test is used to compare two sets of data, which is essentially a set of "pairs" of data. The data in one sample (velocities V_{12}) are related to the data in the second sample (velocities V_{23}). The difference, D, between each pair of scores is computed, and subsequently the mean of this difference, $\overline{D}$, is computed. The standard error of the difference between means of two related samples may be estimated by:

$$S_{\overline{D}} = \sqrt{\frac{\sum d^2}{n(n-1)}} \tag{D.1}$$

where

$$\sum d^2 = \sum\left(D-\overline{D}\right)^2 = \sum D^2 - \frac{(\sum D)^2}{n} \tag{D.2}$$

and n is the number of pairs of scores. The test statistic is:

$$t = \frac{\overline{D}}{S_{\overline{D}}} \tag{D.3}$$

The null hypothesis is rejected if $t < -t_{\alpha/2}$ or $t > t_{\alpha/2}$, in which $t_{\alpha/2}$ is the critical value for a two-tailed test and depends on the level of significance α and the degrees of freedom df, where df = n-1. For a level of significance of 0.1% and 7 degrees of freedom, the critical value is ± 5.405 (Ayyub and McCuen, 2003).

Analysis of variance (ANOVA) test

The data of each group are presented in a matrix as follows:

$$\begin{matrix} X_{11} & X_{12} & X_{13} & \cdots & X_{1k} \\ X_{21} & X_{22} & X_{23} & & X_{2k} \\ X_{31} & X_{32} & X_{33} & & X_{3k} \\ \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & & \\ X_{n_1 1} & X_{n_2 2} & X_{n_3 3} & & X_{n_k k} \end{matrix} \qquad \text{(D.4)}$$

The matrix includes k columns, with each column representing a group. If n_j is the number of data values in any group, then the total number of values in all groups, N, is given by:

$$N = \sum_{j=1}^{k} n_j \qquad \text{(D.5)}$$

The mean of the values in each group is calculated. The mean of j group is denoted as $\overline{X_j}$. The average of the group means is the grand mean and is denoted by $\overline{X}$. The test statistic F is the value of a random variable having an F distribution with degrees of freedom of (k-1, N-k) and is computed by:

$$F = \frac{MS_b}{MS_w} \qquad \text{(D.6)}$$

in which MS_b and MS_w are the mean squares between and within variations, respectively. The mean squares are computed by the equations shown in the fourth column of Table D.1, in which SS_b represents the sum of squares between groups and reflects the variation of the group means from the grand mean, $\overline{X}$, while SS_w represents the sum of squares within each group and reflects the variation of the data values, X_{ij}, within the group. The critical value of the F statistic for a level of significance of 0.1% and degrees of freedom (7, 8) is 12.398 (Ayyub and McCuen, 2003). The null hypothesis is rejected if the computed value of F is greater than the critical value.

Table D.1 Summary table for the ANOVA test

Source of variation	**Degrees of freedom**	**Sum of Squares**	**Mean Squares**
Between groups	$k-1$	$SS_b = \sum_{j=1}^{k} n_j \left(X_j - \overline{X} \right)^2$	$MS_b = SS_b / k - 1$
Within groups	$N-k$	$SS_w = \sum_{j=1}^{k} \sum_{i=1}^{n_j} \left(X_{ij} - \overline{X}_j \right)^2$	$MS_w = SS_w / N - k$
Total	$N-1$	$SS_t = \sum_{j=1}^{k} \sum_{i=1}^{n_j} \left(X_{ij} - \overline{X} \right)^2$	–

Dixon-Thompson Test

The objective of this test is to evaluate the data for either a low or a high outlier. The data are ranked from the smallest value, X_1, to the largest value, X_n. The test statistic R and critical value R_c depend on the sample size. For a sample size equal to 8 and a level of significance of 1% the critical value is 0.675 (McCuen, 2003), while the test statistic values are computed by the following equations:

$$R = \frac{X_2 - X_1}{X_{n-1} - X_1} \text{ (low outlier)} \tag{D.7}$$

$$R = \frac{X_n - X_{n-1}}{X_n - X_2} \text{ (high outlier)} \tag{D.8}$$

If the computed R values are greater than R_c, then the null hypothesis is rejected, and the smallest and largest values are low and high outliers, respectively.

One-tailed lower test

The test statistic, t, is:

$$t = \frac{\overline{X} - \mu}{S / \sqrt{n}} \tag{D.9}$$

in which $\overline{X}$ is the sample mean, S the standard deviation, μ the population mean and n the sample size. The null hypothesis is rejected if $t < -t_\alpha$, where t_a is the critical value. For 15 degrees of freedom and level of significance of 0.05%, the critical value is $t_\alpha = -4.073$. For the same level of significance and 7 degrees of freedom, the critical value is $t_\alpha = -5.405$ (Ayyub and McCuen, 2003).

APPENDIX E - CORRECTION FACTOR FOR STEEL BARS PARALLEL TO PULSE PATH

If a steel bar is located close to the direct path between the transducers and runs parallel to it, as shown in Figure E.1, then the first wave to be received might have traveled partly in concrete and partly in steel. The transit time, $t_{1,}$ along the direct path is given by:

$$t_1 = \frac{L}{V_c} \tag{E.1}$$

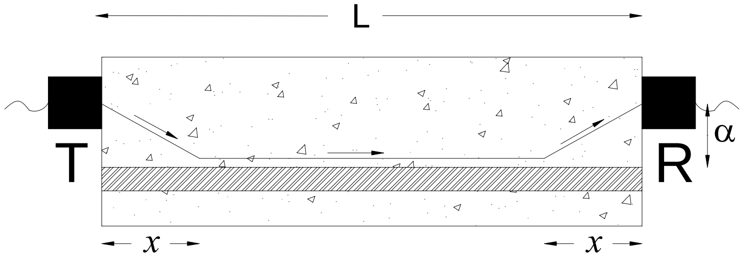

Figure E.1 Steel bar parallel to the direction of pulse propagation (T: transmitter; R: receiver).

The transit time, t_2, along the indirect path is given by:

$$t_2 = \frac{L-2x}{V_s} + \frac{2\sqrt{x^2+\alpha^2}}{V_c} = \frac{\gamma(L-2x)+2\sqrt{x^2+a^2}}{V_c} \tag{E.2}$$

where x is the distance along the steel bar from the concrete surface to the point where the pulse enters or leaves the bar. For minimum t_2 , $\frac{dt_2}{dx} = 0$ .Therefore,

$$x = \frac{\gamma}{\sqrt{1-\gamma^2}} a \,. \tag{E.3}$$

Substituting x in equation (E.2) gives:

$$t_2 = \frac{\gamma L + 2a\sqrt{1-\gamma^2}}{V_c} \tag{E.4}$$

Therefore, if $t_2 < t_1$, i.e., for the case where the transit time along the indirect path is less than that of the direct path, the substitution of equations (E.1) and (E.4) will result in:

$$\frac{a}{L} < \frac{1}{2}\sqrt{\frac{1-\gamma}{1+\gamma}} \tag{E.5}$$

which means that the first pulse to be received have traveled via the indirect path instead of the direct path. The measured pulse velocity should be corrected by multiplying it with the following factor:

$$k = \frac{t_2}{t_1} \tag{E.6}$$

The substitution of equations (E.1) and (E.4) into equation (E.6), gives the following equation for the correction factor:

$$k = \frac{t_2}{t_1} = \gamma + 2(\frac{\alpha}{L})\sqrt{1-\gamma^2} \tag{E.7}$$

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