Quality Control of Diaphragm Walls by Crosshole Sonic Logging

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ABSTRACT The quality of concrete and integrity of deep diaphragm walls in any given project is very important to ensure safety within the excavation and for the long term performance of the structural element. Not only is the structural strength of the wall important, but also its effectiveness in preventing water seepage, which could be compromised by soil or slurry intrusions among other defects. For these reasons, major civil works frequently require thorough testing of deep foundation elements to assure adherence to material quality specifications.

For deep foundations, Crosshole Sonic Logging (CSL) is the most common integrity test measuring the travel time of ultrasonic pulses in the concrete. A low wave speed indicates inferior concrete quality, while a completely missing signal indicates an anomaly or defect. The test is frequently used for the integrity assessment of foundation piles, but is less commonly applied to diaphragm walls.

This paper describes the construction and CSL testing of several tunnel access shafts ranging from 16 to 20 m in diameter, which serve as part of a newly constructed 62 km long wastewater tunnel in Mexico. The diaphragm walls were installed to a depth of up to 45 m, and the individual panels were up to 6 m wide. Because of their great depth and large lateral extent, the maximum possible distance between CSL probes, the verticality of the inspection tubes, and the effect of variable tube distances on the CSL measurements were important questions that arose during the planning stage. This paper presents CSL test results that answer these questions.

1. INTRODUCTION

Crosshole Sonic Logging (CSL) testing has been in use for at least 35 years, and was standardized for the first time in France (AFNOR, 2000). Today, the method is also standardized in the USA (ASTM, 2008) and several other countries. The test

equipment consists of a pair of ultrasonic probes of identical or similar resonant frequencies in the 40 to 60 kHz range. One probe emits a pulse, while the other records the sound waves beginning at the time when the transmitter emits its signal. This technology is a practical tool for the evaluation of concrete quality in deep foundation elements where several tubes (typically with an inside diameter of 35 to 50 mm) are attached to the reinforcement cage prior to installation and concrete pouring. After the concrete has set and/or cured, the tubes are filled with water, probes are inserted to the bottom of two of the tubes, and then retracted to the top while continuously generating and receiving sound waves through the concrete. The depths of the probes are recorded using a digital encoder. The water within the tubes couples the sensors acoustically to the concrete.

Using ASTM D6760 (ASTM, 2008) as a guide, the number of access tubes is usually one for every 0.25 to 0.30 m of diameter, spaced equally around the circumference of the deep foundation element. A minimum of three access tubes is preferred for CSL testing. Therefore, a 1.8 m diameter pile would be equipped with 6 tubes. That is, under the assumption of a 150 mm concrete cover (the tubes are tied to the inside of the reinforcement cage), the distance between tube centers would range from 0.75 to 1.45 m, for the perimeter and main diagonals, respectively. To ensure clear signals at the receiver side, it is generally recommended to limit the distance between tubes to a maximum of 2 m.

Interpretation of CSL records is, at first sight, straightforward: if the time at which the first pulse arrives at the sensor is the First Arrival Time (FAT), and the distance between the tubes is L, then the wave speed is $c = L/\text{FAT}$. If this wave speed is reasonably constant along the length of the pile it is typically assumed that the concrete between the inspection tubes is relatively homogenous and of acceptable quality. On the other hand, if the wave speed at a given depth is suddenly low, then, the results would suggest an anomaly in the concrete between tubes at that location.

Unfortunately, complex situations or difficult-to-interpret signals require further investigation. For example, the tubes are not always parallel and of constant distance, which makes the calculated wave speed inaccurate. In that case, the signal strength at the receiver may be a better indicator of concrete quality. Other limitations exist when a gap between tube and concrete develops, in which case the signals generally do not have sufficient strength to be clearly identified at the receiver. This debonding between the tube and the concrete has been more often observed when the tubes are made of PVC; steel tubes adhere better to the concrete and, therefore, are the preferred material. Because of their tendency to debond more often than steel tubes, it is often recommended when using PVC tubes that the CSL testing be performed no later than 10 days after concrete placement. Another advantage of steel tubes is their sturdiness, which means that they are less likely to collapse in the harsh construction environment. If one tube is damaged, the CSL testing would be limited to only those scans not involving the damaged tube, which can be a severe restriction to the quality assessment of the pile or wall panel.

2. CHALLENGES FOR LARGE DIAPHRAGM WALL PANELS

As discussed, the FAT is related to the material wave speed, c, and, therefore, also to the quality of the concrete. The accuracy of the FAT is affected by the distance between the tubes, L, and a flexible cage might allow the tubes to have a different distance at a given depth than near the top where L is measured as part of the CSL test. For short distances between tubes, a relatively large error in the computation of c would result. On the other hand, for large distances between tubes, the FAT may not give a clear indication of a localized anomaly if the wave can easily choose a path around such a localized irregularity.

The information provided by the Signal Energy (SE) is less sensitive to L, and also provides information on the average concrete quality encountered by the sound wave. Thus, while the FAT may accurately indicate a localized anomaly if L is well known and not too large, the SE is more indicative of the overall soundness of the material between the tube pairs having a large L.

Practice has shown that there is no point requiring that the concrete meets an absolute wave speed requirement because the wave speed varies with strength, age and mix of the concrete. Additionally, the delay in arrival time due to wave travel through the water, tube walls, and uncertain tube/sensor distance can significantly affect the CSL test result. On the other hand, with the exception of the tube location, these effects are similar along the length of the foundation pile or diaphragm wall panel and, therefore, a relative wave speed evaluation is more meaningful than an absolute one. While concrete anomalies affect the wave speed more suddenly (generating a distinct difference in both FAT and SE), possible variations in tube distance can be expected to occur gradually over some distance and with little SE loss. Thus, differentiation between changes in tube distance and a concrete quality problem is straightforward.

The objective of diaphragm wall testing using the CSL method is the need to ensure that the wall has sufficient strength to withstand large bending moments, shear and axial stresses, and is waterproof both within the panels themselves and at the vertical panel joints. The main difference between performing CSL testing for foundation piles and diaphragm wall panels is the shape of their cross section. While it is a simple matter for circular foundation piles, for rectangular panels finding the best locations for the inspection tubes is more challenging. AFNOR (2000) and ASTM (2008) both make recommendations for tube locations within diaphragm wall panels. In any event, for diaphragm wall panels, the benefit of testing in the short dimension of the rectangle is limited because of the small zone of influence that such a test would cover. On the other hand, for a 6 m long wall panel with a thickness of 1 m, testing over the longest possible distance may allow the waves to bypass an anomaly, either vertically or horizontally, thus avoiding discovery. In any event, the objective of the testing is (a) a general assessment of construction quality, and (b) if a major defect is detected prior to excavation, then corrective action can be taken so as not to endanger the stability of the structure and, therefore, the workers. Unfortunately, an assessment of the quality of the vertical joints between adjacent wall panels cannot be

done by CSL because such "cold joints" with potential mud deposits prevent high frequency stress wave propagation.

After wave speeds and signal energies are determined, the engineer has to classify the concrete of piles or wall panels either as being sound or, when reductions in wave speed or signal strength are noticed as containing flaws, anomalies or defects. Likins et al. (2007) have proposed a classification method that is frequently used in North America. However, for piles, these methods of acceptance or rejection are not the same in different jurisdictions, countries, or regions. In addition, while the proposed rules may be applicable to piles with a solid circular cross section, they may not be correct for diaphragm wall panels with a rectangular cross section. For example, automated tomography software, which calculates a 3-dimensional image of wave speeds, is normally set up for circular piles, and cannot be directly applied to rectangular cross sections. Thus, experience and engineering judgment are of paramount importance for record interpretation.

3.   CASE STUDY
3.1 Projection Description

The Tunel Emisor Oriente is located in Mexico City, Mexico, and is a 62 km long wastewater tunnel extending in a northeasterly direction from the intersection of the Gran Canal and Rio de los Remedios avenues in Mexico City to Ejido de Conejos in the State of Hidalgo (Figure 1). Because of its significant length, the tunnel was divided into 6 sections. Twenty-four vertical access shafts (lumbreras) were designed at more or less regular intervals of about 2.5 km. The shafts are cylindrical structures highly stressed due to earth and water pressure. Because of these high stresses, the designers were concerned about the continuity, integrity, and quality of the concrete, which is why they proposed the CSL testing.

Diaphragm wall panels formed circular access shafts (Figure 2) with an inside diameter of 16 to 20 m (Table 1). A single panel was formed by two primary "bites," which were then overcut and joined by a secondary bite. As an example, the wall panel configuration for access shaft L10 is shown in Figure 3. The typical wall panels were 1 m thick, approximately 6 m wide, and, for the three access shafts discussed in this paper, reached depths between 38 and 45 m. In the tunnel sections III and IV, the walls of the access shafts were typically constructed by installing diaphragm wall panels in a circular pattern to depths of 40 to 45 m. Below these depths, as required by the tunnel depth, the wall panels were extended using a conventional lining comprised of shotcrete and circular steel frames.

The testing results and comments for access shafts L10 through L15 are presented and discussed in the following section. The geometry and other information pertaining to the access shafts are shown in Table 1. In each of the six shafts presented in Table 1, three wall panels were tested for concrete quality. An example of three sections of a wall panel and the inspection tube layout is shown in Figure 4.
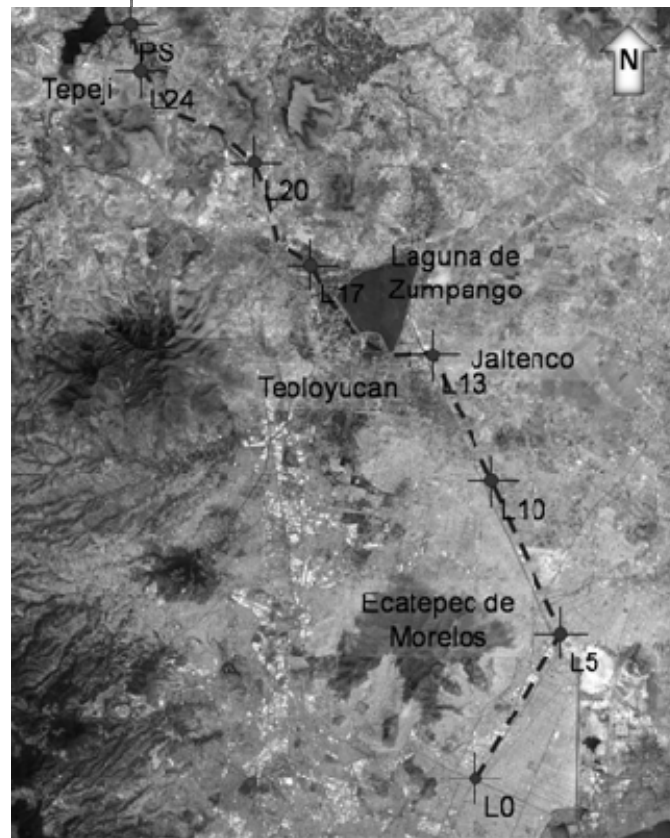
Fig. 1   Map of Tunel Emisor Oriente

Fig. 2   Aerial view of vertical access of the tunnel "shaft", L13

Table 1. Properties of access shafts

Shaft No.	Shaft inside diameter (m)	Total depth of shaft excavation (m)	Diaphragm wall depth (m)	Time elapsed between installation and testing (days)
L10	Upper = 20 Lower = 16	77	45	12 – 27
L11	Upper = 16 Lower = 12	82	38	14 – 22
L12	Upper = 16 Lower = 12	85	42	14 – 22
L13	Upper = 20 Lower = 16	94	45	28 - 34
L14	Upper = 16 Lower = 12	101	38	83 - 102
L15	Upper = 16 Lower = 12	106	40	11 – 38

High quality records where obtained even when access tubes were as much as 4 m apart. Concrete quality was found to be nearly perfect with only small anomalies indicated by sudden reductions in signal strength. After excavating the shafts these findings were later verified (Figure 5). Because of their great depth (45 m), occasional damage to the joints of the steel access tubes occurred, and subsequent obstruction by debris in the tubes limited the amount of data acquired. Furthermore, the vertical alignment of the tubes was not perfect and that limited the usefulness of the absolute value of concrete wave speed with depth. It was therefore more meaningful to base the concrete quality assessment on signal strength rather than wave arrival time. Similar experiences were also made at some other sites in Mexico by the senior author, providing him an experience base for data interpretation at the present site.

For access shaft L10, the three panels M2, M5, and M6, each of which consisted of three sections, were selected for testing and fitted with 6 steel tubes. Testing on the M6 wall panel of L10 was limited because two access tubes (No. 3 and 6) were damaged. This reduced the number of possible and useful scans from the normal 10 to only 3. Each of three of the wall panels within access shafts L11 through L15 were similarly equipped with six tubes each and were tested. The tests were conducted a minimum of 11 days and at most 102 days after concrete pouring. While for PVC tubes, shorter waiting times are often recommended to avoid debonding between the tubes and the concrete, for the steel tubes, even the very long waiting times did not pose a debonding problem.
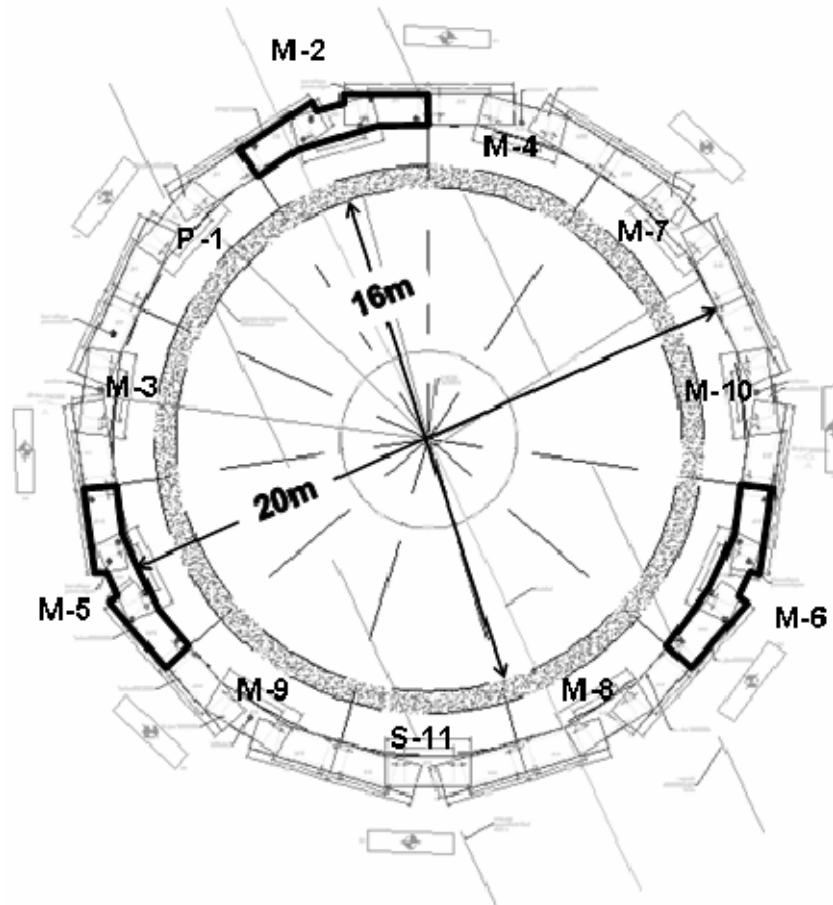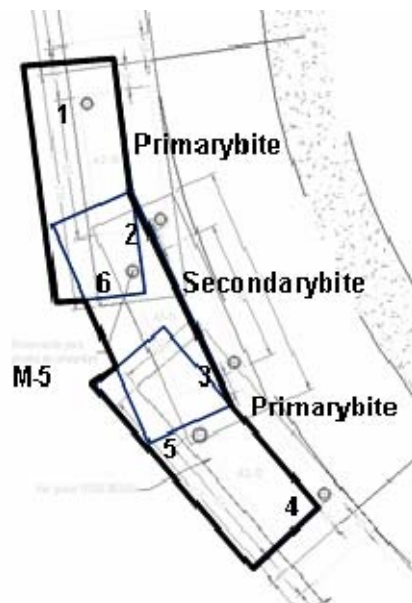
Fig. 3 L10 wall panel configuration

Fig. 4   Location of the six inspection tubes in panel M5 of L10

Fig. 5   Diaphragm wall of the L10

3.2 Test Results

CSL test results obtained by means of the CHAMP equipment and CHA-W software manufactured by Pile Dynamics, Inc. are shown in Figures 6 and 7. The waterfall diagrams of five different scans for wall panel M5 of access shaft L10 are shown in these figures. In a waterfall diagram, positive and negative signal portions are shown as dark and light lines, respectively. The individual signals are normally spaced at a vertical distance of 50 mm. The time origin is usually moved so that only the important signal portion of interest is included, while most of the zero record between transmitter pulse emission and first signal arrival time is omitted. This shift of origin exaggerates the variations in FAT by allowing for an expanded time scale. For the M5 wall panel, 10 different scans were performed, as shown in Table 2. The shortest distance between tubes was 0.83 m and the longest was 2.38 m.

By their color or uniform shading, the waterfall diagrams indicate the strength of the received signal or the magnitude of the signal energy (SE). This characteristic can be automatically quantified by time integration of the square of the signal (Likins et al., (2007)). In the present case, this quantitative result was not shown since the general signal strength was uniform over depth. All 10 waterfall diagrams, even the longest scan of 2.35 m between tubes 2 and 5 (2nd from left in Figure 7), have very clearly defined arrival times and very strong signal content. The only reduced signal strength was noticed in the upper two meters of Scan 2-5, however, not to a degree that would cause concern.
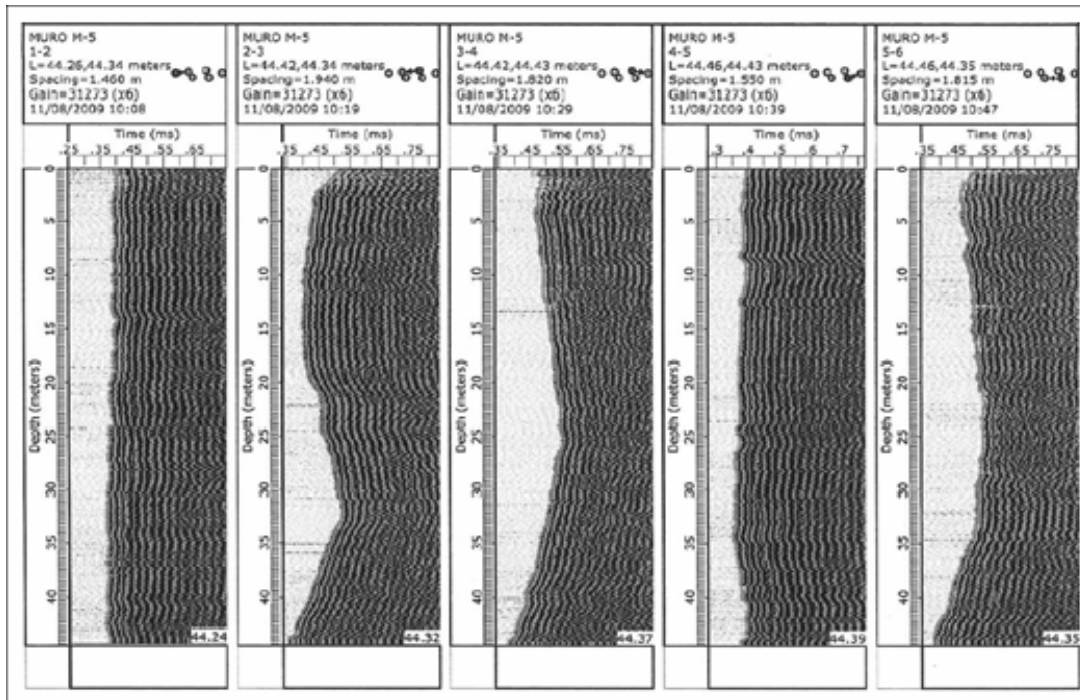
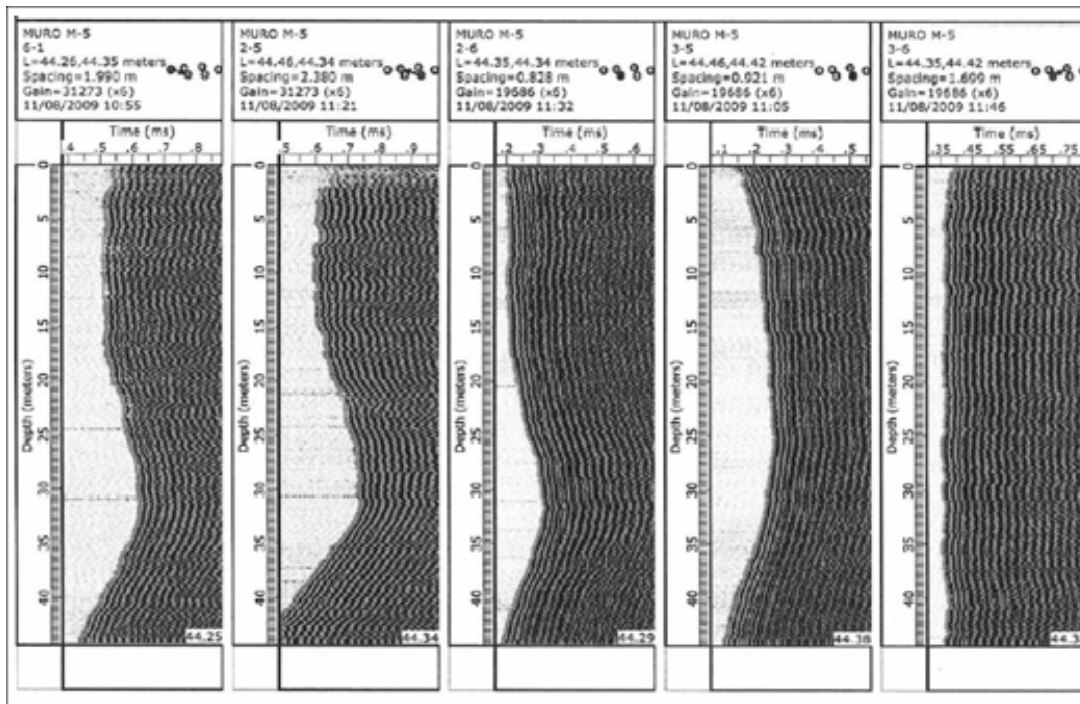Fig. 6   Waterfall diagram for scans L10, M5 1-2, 2-3, 3-4, 4-5 and 5-6

Fig. 7   Waterfall diagrams for L10, M5 scans 6-1, 2-5, 2-6, 3-5 and 3-6

The left-hand waterfall edges represent FAT vs. depth; like SE, FAT can be automatically determined by the CHA-W software using the so-called edge finder. Such automated evaluation makes the analysis more objective than a visual inspection. Furthermore the so-called edge finder determines automatically the wave speed for all signals and the coefficient of variation. Wave speeds can be expected to vary up to 10% for a given mix, depending on age, depth, placement and other conditions.

The waterfall diagrams of Scans 1-2 and 3-6 (extreme left in Figure 6 and right in Figure 7) is what would normally be expected: a relatively constant FAT, and thus a nearly constant wave speed as expressed by a small COV of 3.3% and 2.2%, respectively (Table 2). In fact, the slight reduction of FAT in Scan 1-2 (Figure 6) and the corresponding increase of the wave speed (and therefore strength) with depth can reasonably be expected, because of the high pressures in the concrete at the bottom during curing.

The examples of Figures 6 and 7 were chosen because of their highly variable FAT values. However, even in these cases of apparently high tube distance variations, the average wave speed is a good measure of concrete quality, since both increased and decreased tube distances have to be expected within the same wall panel. While the 3980 m/s average value of Table 2 may be affected by the unusually high values of Scan 2-3 and in particular Scan 3-6, without these two values the average wave speed would be 3,830 m/s which is still indicative of good quality concrete.

Table 2 Wave speeds from measurements in panel M5 of L10

Scan	Tube spacing at top (m)	Wave speed (m/s)	Coefficient of variation
1 – 2	1.46	3840	0.033
2 – 3	1.94	4430	0.090
3 - 4	1.82	3730	0.088
4 – 5	1.55	4180	0.035
5 – 6	1.82	3750	0.095
6 – 1	1.99	3710	0.090
2 – 5	2.38	3810	0.119
2 – 6	0.83	3570	0.162
3 – 5	0.92	4070	0.100
3 - 6	1.70	4720	0.022
Average	**1.64**	**3980**	**0.083**

With the exception of the first and fourth scans (Scans 1-2 and 5-6, respectively) shown in Figure 6 and the last scan (Scan 3-6) in Figure 7, highly variable, yet gradually changing FAT values are evident in the waterfall plots. Since the change of FAT is gradual and since the signal strength is uniform (as apparent from the

relatively uniform waterfall shading), it is most reasonable to conclude that several tubes either incorrectly installed or moved from their intended location during cage placement and/or concrete pouring. Even scans with a constant FAT may have been obtained on dislocated yet parallel tubes. In Scan 2-3, the FAT is approximately 0.41 ms at a depth of 15 m. Assuming a wave speed of 4,000 m/s, the computed tube distance would be L=1.64 m (a shortening of 0.30 m or -15% compared to the top distance of 1.94 m). At a 20 m depth, the FAT is 0.53 ms, which would correspond to a tube distance of 2.12 m (+0.18 m or 9%). Of course, because it is possible that the wave speed also varied, these values are merely estimates, but the magnitudes reflect reasonable tube movements considering the almost 45 m depth of the panel.

The results from L13 are of special interest where one of the scans (Scan 1-3) was taken over a distance of 4.07 m (left of center scan in Figure 8). This is an unusually large distance for ultrasonic pulse propagation in concrete, yet the waterfall diagram shows clear signals and consistent arrival times. Obviously, given modern electronics and signal treatment, the restrictions to tube distances of 2 m, which were reasonable a few decades ago, can now be relaxed.
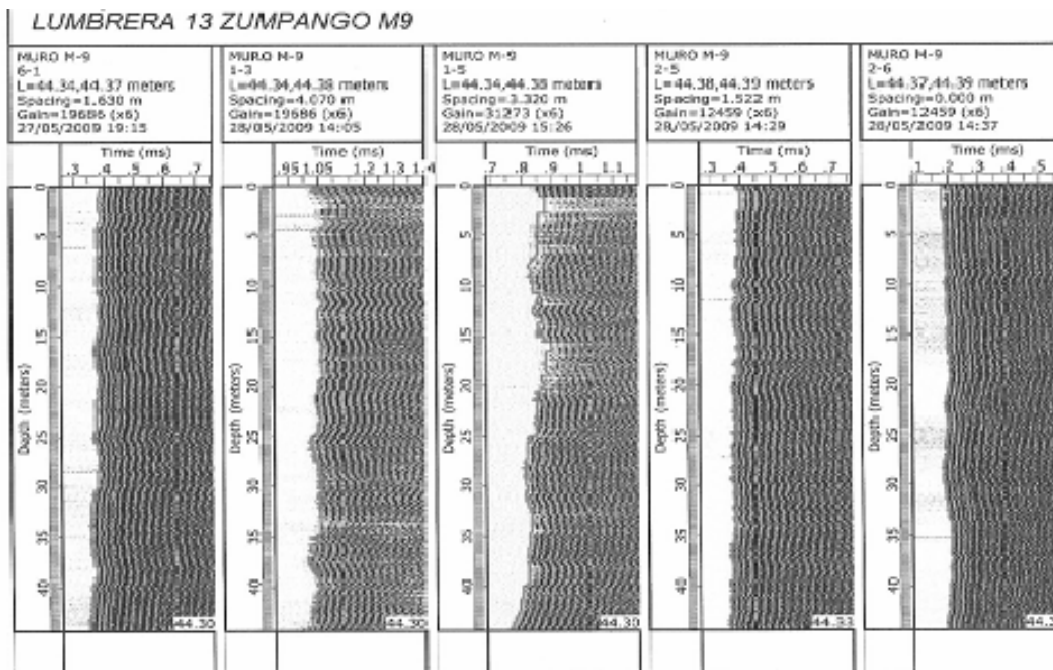

Fig. 8   Waterfall diagrams for L13, M9 scans 6-1, 1-3, 1-5, 2-5 and 2-6

A summary of the computed wave speeds for all 18 wall panels tested is listed in Table 3. Unfortunately, because of the uncertainty with tube locations, these wave speeds do not support detailed studies of concrete quality versus wave speed. However, though scattered, the results do show a consistent tendency of increasing wave speed with concrete age (Figure 9).

Table 3 Average Wave Speed results from all 18 wall sections tested

Shaft No.	Wall panel	Days after Pouring (days)	No. of Scans	Average Wave Speed (m/s)	COV	Maximum distance between tubes (m) (tube-tube)
L10	M2	27	10	4291	0.076	2.68 (3-6)
	M5	12	10	3981	0.083	2.35 (2-5)
	M6	14	3	4005	0.222	2.5 (3-6)
L11	P1	22	9	4238	0.049	2.92 (3-6)
	P2	20	10	4244	0.049	2.87 (3-6)
	P5	14	10	4263	0.061	2.71 (3-6)
L12	P1	22	10	4126	0.080	2.69 (3-6)
	P2	20	10	4184	0.056	2.76 (3-6)
	P5	14	10	4217	0.059	2.93 (3-6)
L13	P5	28	13	4200	N/A	4.04 (1-5)
	M9	34	13	4100	N/A	4.07 (1-3)
L14	M4	91	7	4456	0.035	2.47 (4-5)
	M5	83	9	4202	0.032	2.8 (3-6)
	P1	102	10	4383	0.054	3.0 (3-6)
L15	P1	38	10	4324	0.071	3.05 (3-6)
	P2	37	10	4239	0.049	2.92 (3-6)
	P5	11	10	4233	0.043	3.15 (3-6)
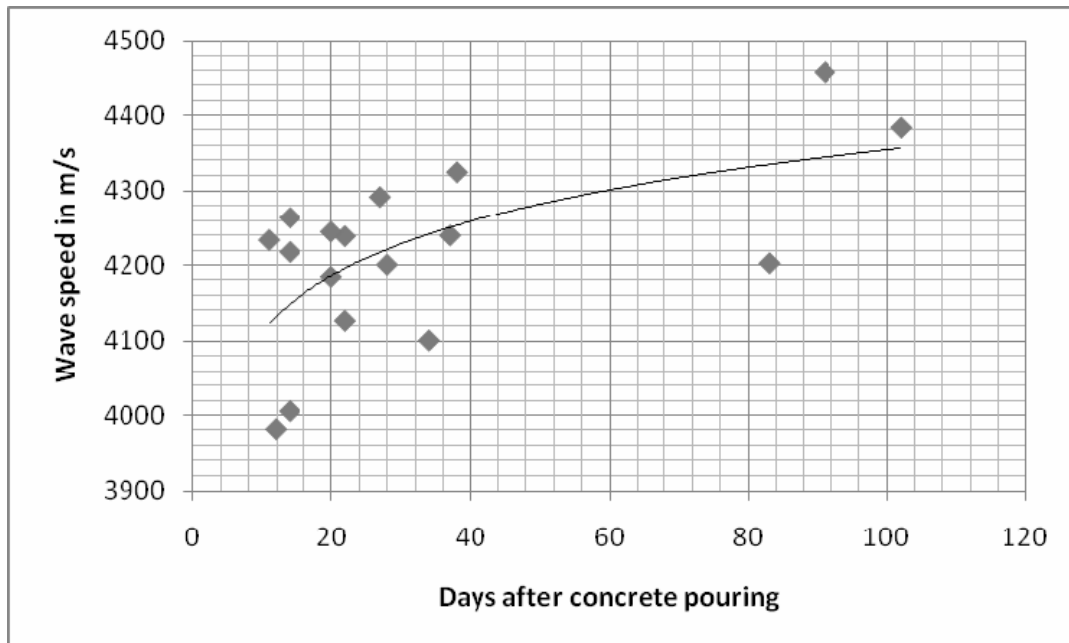
Fig. 9   Average wave speeds vs concrete age

4. EXPERIENCES GAINED AT OTHER SITES

The senior author also had an opportunity to make similar measurements on 35 m deep diaphragm wall panels at a different site. In a verbal communication, the senior author stated that, again, steel tubes were used and the tubes did not suffer any damage. However, tube misalignments similar to those described above were observed. Also at that site, signal strength results supported the conclusion that the concrete quality was nearly flawless. Later excavation confirmed good quality concrete.

5. SUMMARY AND CONCLUSIONS

The case study showed that valuable concrete quality information could be gathered from CSL tests on large diaphragm wall panels. The test results, if they indicate high concrete quality, help assure the construction professionals that they can expect a safe excavation, even though great care still has to be exercised since the tests can only provide a spot check. On the other hand, had flaws been detected, corrective action prior to excavation would have prevented potentially disastrous consequences.

Concrete wave speeds calculated from theoretical tube distances averaged over each scan varied between 4,000 and 4,500 m/s. While a few very higher values may have been caused by calculating with an incorrect tube distance, these wave speed results are indicative of a consistently good quality concrete. Higher wave speeds were generally associated with longer waiting times (between concrete placement and CSL testing).

Clear signals were obtained at tube distances in excess of 4 m. While this may in part be the result of a high concrete quality, it also is due to achievements with modern electronics.

The tubes apparently had shifted from their originally intended position during or after reinforcement cage installation. However, clear and strong signals allowed for meaningful data interpretation.

Concerns regarding the performance of steel tubes and uncertain distances between tubes were found to be overly conservative. The steel tubes did not debond from the concrete even after waiting times of almost four weeks between concrete pouring and testing. However, 2 out of 54 steel tubes suffered damage and prevented complete testing in one wall section.

Mendez and his dedication to family, friends, clients and associates who will always remember his unwavering efforts in providing first class dynamic pile testing and analysis services for the benefit of the profession.

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