Use of Nondestructive Testing To Evaluate Defects in Drilled Shafts: Results of FHWA Research

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Past and current research efforts in the use of nondestructive testing to evaluate the integrity and capacity of drilled shafts containing defects are described. The results of a drilled shaft test program containing both controlled and uncontrolled defects (five shafts at a dense soil site and six shafts at a soft soil site) are presented. The test program was designed to demonstrate in a relative way the ability to find defects, the ability to quantify the location and magnitude of defects, and the correlation of defects with acceptance criteria. Planned defects were created by attaching soil-filled bags to the rebar cages. Uncontrolled defects were created by using improper drilling procedures, such as pulling the tremie pipe out of the concrete, using low slump concrete for portions of the shaft, and using improper slurry control procedures. All shafts contained four preplaced access tubes attached to the rebar cage and were tested using both sonic logging and gamma logging procedures as well as surface reflection techniques (sonic echo test and transient dynamic response test). The approximate costs and relative effectiveness of the different nondestructive techniques in finding and quantifying defects in the shafts are discussed.

Traditional methods for evaluation of defects in drilled shafts include various exploratory methods, some of which are classified as destructive methods. They involve unearthing a portion of the side of the shaft or coring or drilling through the shaft to observe the presence of any defects. Although these methods offer direct observation of the shaft concrete, they tend to be expensive and slow, especially when ongoing construction must be stopped for a period of time. Within the past 20 years, various types of nondestructive testing (NDT) techniques have been developed. They involve either logging of the shaft concrete through preplaced access tubes or using seismic-type methods whereby the shaft is struck on the top with a small hammer. The wave energy travels down the shaft and is reflected from the bottom of the shaft or from defects and is recorded by a geophone or accelerometer on the top. Digital computer advances have allowed refined analysis of the response from both the logging and seismic methods. The results of an FHWA-sponsored project involving the use of NDT techniques to evaluate drilled shafts constructed with planned and unplanned defects are presented.

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PROJECT DESCRIPTION

Site Description and Soil Conditions

For this project, two sites with differing soil conditions were selected in the San Jose, California, area. Five of the 11 shafts were constructed on the property of a California Department of Transportation maintenance yard in Cupertino, California. This site, also known as the "dense or dry" site, had a general subsurface profile consisting of sandy clay to a depth of approximately 3 ft below grade, followed by alternating layers of extremely dense, clayey, and sandy gravels to depths of approximately 33 ft below grade. From 33 ft to depths of at least 40 ft, extremely dense, silty, and clean sands were observed. The groundwater table was located deeper than 40 ft beneath the existing ground surface.

The remaining six shafts were constructed beneath an elevated interchange of State Highway 101 and U.S. Highways 280 and 680 in San Jose, California. This site was known as the "soft or wet" site. The general soil profile indicated approximately 3 ft of stiff sandy clay at the surface, followed by predominantly silty and sandy clays of soft to medium consistency to depths of approximately 50 ft below grade. From 50 to approximately 70 ft, additional deposits of stiff silty clay were observed. The clay was noted to transition from a moist to a wet condition approximately 12 to 15 ft beneath the existing ground surface.

Shaft Construction

The shafts at the two sites were constructed as shown in Figures 1 and 2. Shafts 1 through 5 were constructed at the Cupertino (dense) site, using open-hole drilling "in the dry" procedures. The shafts and underreams were excavated using standard auger drilling methods. Full-length reinforcing steel cages were placed in each shaft, to which were attached 2-in. inside-diameter steel and PVC access tubes (two each) for subsequent downhole logging of the caisson concrete.

The elliptical and neck-in type of defects constructed in Shafts 1, 3, and 4 were created by tying sand-filled geotextile bags in prescribed patterns around the reinforced cages before placement in the shafts. The sizes of the defects were selected to obstruct various percentages of the shaft cross section, typically 15 and 45 percent. The soft bottom conditions in

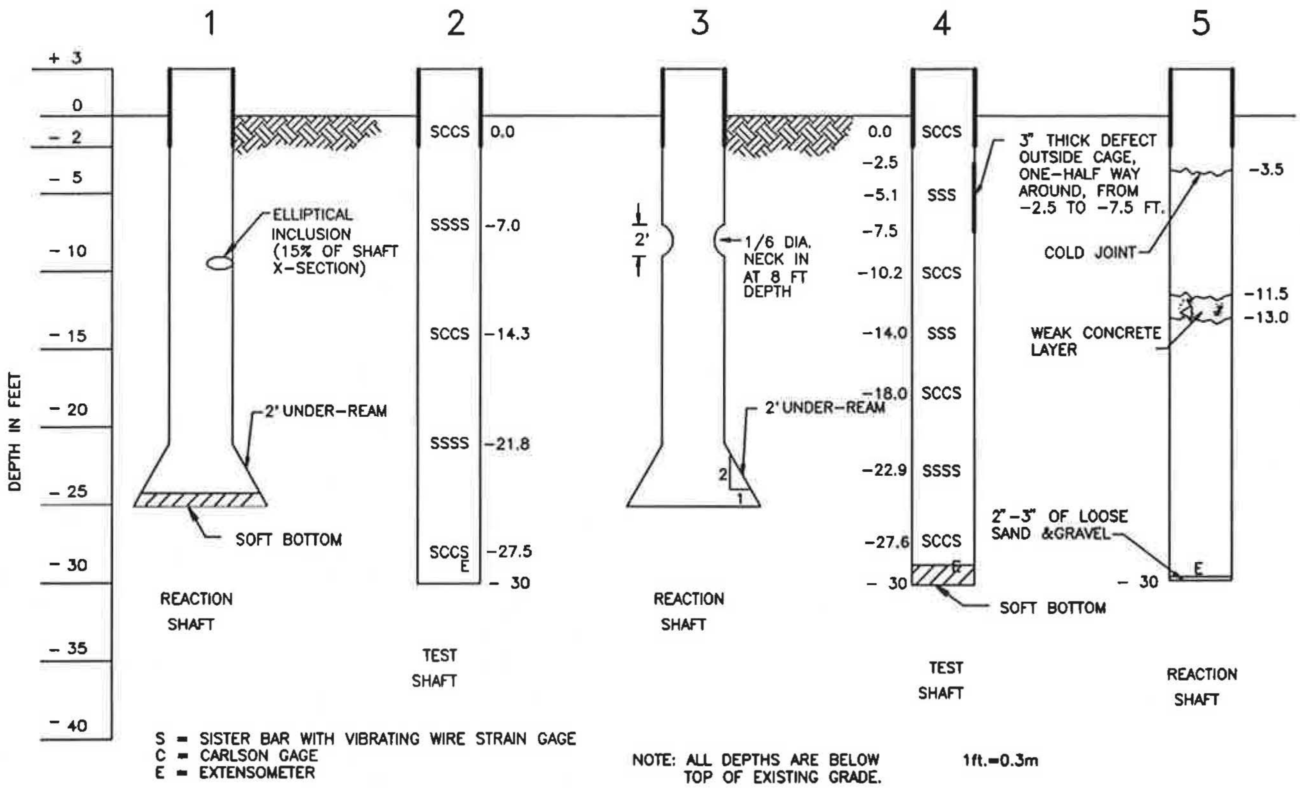


FIGURE 1 Layout of drilled shafts at the Cupertino site.

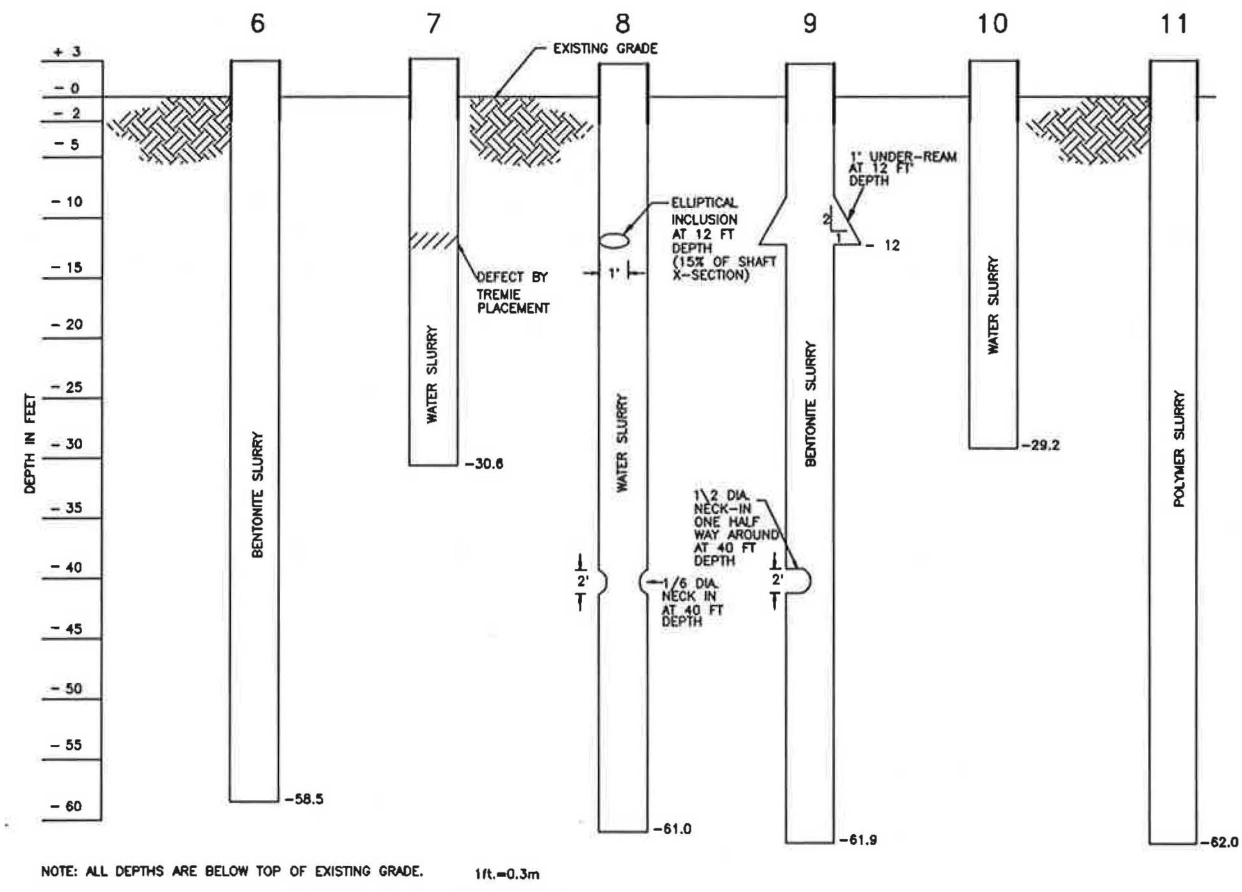


FIGURE 2 Layout of drilled shafts at the San Jose site.

Shafts 1 and 4 were created by placing approximately 1 to 1.5 ft of redwood mulch in the base of the caisson shafts before concreting.

A thin, soft bottom was created in Shaft 5 by disturbing the base of the shaft with the auger without removing the loosened cuttings. Also in Shaft 5, a weak concrete layer was created near the middepth of the shaft by stopping the concrete pour and placing approximately 2 ft of a very weak concrete mix in the shaft. That shaft was then completed up to 3.5 ft below the ground surface and allowed to set overnight. The next day, the shaft was completed to the design grade, thus creating a cold joint. Shaft 2 at the dense site was to be a perfect shaft with no planned defects.

At the San Jose (wet) site, several slurry drilling procedures were used to construct the shafts. Bentonite slurry was used in Shafts 6 and 9; water slurry was used in Shafts 7, 8, and 10; and a polymer slurry was used in the excavation of Shaft 11.

Defects at the wet site consisted of a tremie defect in Shaft 7, which was created during the concrete placement by pulling the pump pipe out of the fresh concrete and allowing the drilling slurry to mix with the concrete intentionally, before replacing the pump pipe in the concrete and completing the shaft. In Shafts 8 and 9, elliptical and neck-in defects were created similar to those at the dense site by tying the sand-filled bags to the reinforcing cages before placement. Also in Shaft 9, a shallow underream was created at a depth of approximately 12 ft below grade during excavation. Shafts 6, 10, and 11 were intended to be perfect shafts with no planned defects. Full-length reinforcing cages were placed in all shafts, with two steel and two PVC access tubes attached to each cage.

At both sites, the shafts were drilled without the use of surface casing, although a cardboard form was used to extend the shafts approximately 3 ft above grade and allow better access for the NDT and large-scale dynamic testing. The concrete at both sites was placed using a concrete pumper truck, with the pipe starting at the bottom of the shafts and progressing upward. The mix design required a minimum compressive strength of 4,000 psi at 7 days. The maximum aggregate size was ⅜ in., with a specified slump of 7 to 9 in. during placement.

As part of the project, electronic instrumentation consisting of sister bar strain gauges and extensometers were attached to the reinforcing cages of Shafts 2 and 4 before concreting. Those instruments were used for subsequent static load tests. In addition, large-scale dynamic tests were completed on all shafts using a 9.75-ton drop hammer and pile analyzer techniques. Those results are discussed by Baker et al. (*1*).

NDT

Methods

On this project, the NDT techniques included gamma-gamma logging, sonic logging, the sonic echo (SE) test, and the transient dynamic response (TDR) test. The gamma-gamma and sonic logging techniques are referred to as direct transmission methods, in that either radiation or sound energy is transmitted and received between parallel coreholes or preplaced access tubes. In the sonic logging method, vibrations are transmitted from one access tube to a receiver in another access tube at the same level while the arrival time and amplitude of oscillation are measured. The shafts are logged continuously, beginning at the bottom and moving to the top. Defects in the shafts are detected through delays or loss of the signal. The transmitter and receiver can be offset in elevation between the tubes to quantify the approximate extent of a defect across the cross section.

In the gamma-gamma logging technique, the radioactive source and counter may be either in separate probes or housed in the same probe. The source is lowered down a preplaced access tube or corehole and raised slowly toward the surface. Lower density zones, such as soil inclusions close to the access tube (within approximately 6 in.), increase the radiation count, because less radiation is absorbed by the defect than in a zone of intact concrete. The advantage of the direct transmission methods is that a continuous record is obtained with depth in the shaft, although defects located more than a few inches beyond the perimeter of the transmission path may not be detected. A primary disadvantage is the requirement for coreholes or preplaced access tubes, which are more expensive than the surface reflection techniques to be discussed subsequently. Typical costs for sonic logging tests are \$0.60 to \$1.00 per ft, not counting the cost of travel expenses or the access tubes.

The SE and TDR methods are referred to as surface reflection techniques and are described by Stain (*2*). In the SE test, the surface of the concrete shaft is struck near the center with a hand-held hammer, thus sending a compression wave down the shaft to the toe or to a major defect. At a transition of cross section or change of material properties, part of the compression wave is reflected back to the surface and is recorded by an accelerometer or geophone. On the basis of the longitudinal wave velocity of the shaft concrete, the distance to the toe of the shaft or to a discontinuity can be calculated. A typical trace is shown in Figure 3. By plotting pile head velocity versus time, the length of the shaft to the toe or from a significant defect is found from the following equation:

$$L = (V_c \Delta t)/2 \quad (1)$$

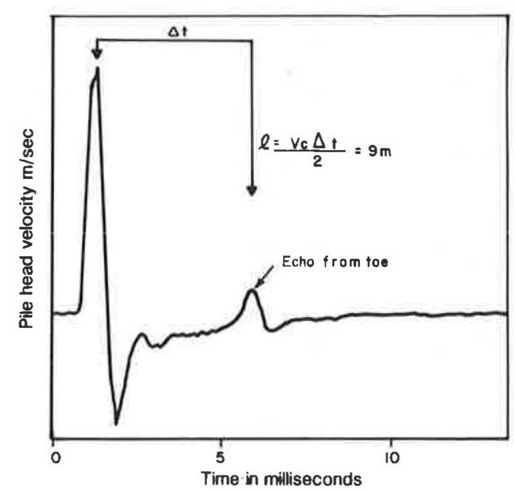


FIGURE 3 Typical response curve from SE test (*2*).

where

L = length of shaft to toe or to a major defect,
V_c = velocity of compression wave in concrete, and
Δt = response time from echo trace.

The TDR test (also known as an impulse or impact response test) is similar to the SE method except that the hammer contains a load cell, which measures the magnitude of the impact force applied to the head of the shaft. Also, the velocity response to the impact recorded by the geophone or accelerometer in the time domain is transformed and reported in the frequency domain. This allows calculation of the length of the shaft to the toe or a major defect and the dynamic stiffness of the upper portion of the shaft, as shown in Figure 4.

In the TDR test, the mechanical admittance or mobility (transforms of velocity/force) is plotted versus frequency. From the characteristic peaks of the trace, the length is calculated as follows:

$$L = V_c/2\Delta f \qquad (2)$$

where Δf is peak-to-peak change in frequency and L and V_c are as defined previously.

An indication of concrete quality in the shaft head can be obtained from the mean height (N) of the resonating part of the trace:

$$N = 1/(f_c\, V_c\, A_c) \qquad (3)$$

where f_c is the density of concrete and A_c is the cross-sectional area of the shaft.

Finally, the stiffness of the upper portion of the shaft (shaft head stiffness) is computed from the inverse slope of the initial portion of the trace in Figure 4. The stiffness (in units of force/displacement) can be compared with results from static load tests.

The main advantages of the surface reflection techniques are that no preplaced access tubes or coreholes are required and testing is rapid. The principal disadvantages are related to masking of a deeper defect by a reflection from a shallower defect and a practical restriction on the length-to-diameter ratio of the shaft ($L/d < 30{:}1$). Also, some minor preparation of the shaft head is required to obtain a clean response from the hammer impact. Excessive reinforcing steel near the center of the shaft can contribute ringing and electrical noise to the signal.

Assuming access to uncontaminated concrete at the shaft head, typical costs for the surface reflection tests are $75 to $125 per shaft, exclusive of travel costs.

For this project, the NDT was performed by four specialty consultants experienced in this type of work. Two of the firms performed TDR testing, three of the four performed SE testing, and two performed sonic logging tests. The gamma logging was performed by one of the coinvestigators of the project.

A first round of testing was performed before the two static load tests at the dense site and before the large-scale dynamic testing. A second round was completed after the large-scale dynamic tests to check for shaft integrity and possible damage, although those results are not discussed here. One consultant was not available for the first round of testing and performed tests approximately 2 months after the large-scale dynamic tests.

Each consultant was provided with information concerning the soil conditions of each site and design drawings similar to Figures 1 and 2 showing the nature of the defects and shaft geometries constructed. A companion phase of this project will be completed at a Texas site in fall 1990. In that phase it is not planned to provide information on the defect location at the outset. Also, the surface reflection tests will be performed before the downhole logging tests.

Results from Surface Reflection Tests

A summary of the defects detected by the TDR and SE tests is given in Table 1. The defects are listed by shaft number, and the consultants are listed as A through D. Although not classified as a defect, an echo or signal return from the base of the shaft is an important record and therefore has been included for each shaft in the table. Of the defects listed, most were planned and were created during construction of the shafts. However, an overbreak was detected by the NDT in Shafts 7 and 11. This was caused by sloughing during excavation of the shaft, resulting in a larger cross section of concrete over a given zone than the nominal shaft size.

Figures 5a, 5b, 6a and 6b display SE test results from Shafts 1 and 8. Data in the "a" and "b" sections were from Consultants C and D, respectively. It is noteworthy that the char-

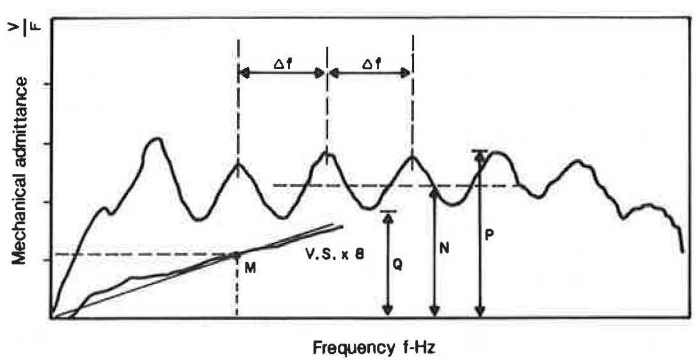


FIGURE 4 Typical response curve from TDR test (2).

TABLE 1 SUMMARY OF RESPONSES FROM TDR AND SE TESTS

Shaft No.	Anomaly/ Depth	(2) B (SL)	(1) A (SL)	(1) (GL)
1	Elliptical/13 ft	-	x	x
1	Bell/26 to 27 ft	-	-	-
1	Soft base/27 ft	-	-	-
2	Base/33 ft	-	-	-
3	Neck-in/11 ft	-	-	-
3	Bell/24 to 28 ft	-	-	-
3	Base/28 ft	-	-	-
4	Perimeter/5.5 to 10.5 ft	-	x	x
4	Soft base/32 ft	-	-	?
5	Cold joint/6.5 ft	-	x	?
5	Weak concrete/14.5 to 16 ft	-	?	-
5	Soft base/ 33 ft	-	-	-
5	Base/33 ft	-	-	-
6	Base/61.5 ft	-	x(soft)	x(soft ?)
7	Overbreak/11 to 15 ft	-	-	-
7	Tremie Defect/15 ft	?	x	-
7	Base/33.5 ft	-	x(soft)	x(soft ?)
8	Elliptical/15 ft	x	x	-
8	Neck-in/43 ft	x	x	x
8	Base/64 ft	-	-	-
9	Underream/15 ft	?	x	-
9	Neck in/43 ft	?	x	x
9	Base/65 ft	-	-	-
10	Base/32 ft	-	x(soft)	x(soft ?)
11	Overbreak/30 to 33 ft	-	-	-
11	Base/65 ft	-	-	?

Notes:

(1) Tests run before large-scale dynamic tests

(2) Tests run after large-scale dynamic tests

(SL) = Sonic Log (GL) = Gamma-Gamma Log

X = Detected - = Not Detected ? = Possible Detection

acteristic response was repeatable by two independent consultants. A clear toe response is apparent on all four figures.

In Figures 7a, 7b, 8a, and 8b, TDR test results from Shafts 1 and 8 (after large-scale dynamic testing) are presented. The "a" and "b" sections were generated by Consultants A and B, respectively. Again, the characteristic response was repeatable by both firms. In Figures 7a and 7b (Shaft 1), the response is from the toe, with no response from the shallow inclusion defect. In Figures 8a and 8b, a response from a shallow defect reported at a depth of 9 to 10 ft is superimposed on the response from a larger defect at 40 ft.

In general, a response from the base or toe of the shafts was the most common response recorded and was caused by the sharp change in modulus and, thus, compression wave velocity between the shaft concrete and the underlying foundation soils. Exceptions occurred in Shafts 8 and 9, which were approximately 60 ft long, constructed under slurry, and had significant defects at approximately 40 ft below grade. Responses from the deeper defect masked the echo from the toe, according to two of the consultants. In terms of defect size, the neck-in defects in Shafts 8 and 9 were the largest, obstructing approximately 45 and 50 percent of the shaft cross section, respectively. The smallest defects were elliptical sandbag inclusions placed in Shafts 1 and 8; they obstructed only 15 percent of the shaft cross section. Significant difficulty in detecting those defects was observed by the consultants, even with knowledge of their presence.

Shaft 5 had the most variation in planned defects, with a thin, soft layer at the base of the shaft consisting of 2 to 3 in. of loosened foundation soils. This "defect" was not detected by the consultants. A weak concrete layer at approximately middepth in the shaft was detected by both TDR and SE methods, but not by all consultants. A cold joint approximately 6.5 ft below the top of the shaft was detected by the SE method, and not by the TDR.

Last, changes in cross section of the shaft typically produced responses from the TDR and echo methods. A shallow underream in Shaft 9 was detected by all but one consultant, and the unplanned overbreaks in Shafts 7 and 11 produced reflections at the change in section for those shafts. The modest 2-ft underreams in Shafts 1 and 3 were noted by two of the consultants.

Results from Direct Transmission Tests

The results of the sonic logging and gamma logging tests are presented in Table 2. The format is similar to Table 1. The defects and locations of responses are listed, along with the notation of whether the defect or response location was detected. In general, the defects must be located between or near the access tubes in the case of the sonic logging test or within approximately 6 in. of the tube in the case of the gamma logging method, to be detected. Table 2 indicates that fewer overall defects were detected than from the impact response tests, although clear evidence of detected defects is presented in the logging traces, such as in Shafts 8 and 9. The sonic logging and gamma logging traces for Shaft 8 are shown in Figures 9 and 10. In the sonic log, the loss of signal at the leading edge of the record gives evidence of the defects. In the gamma log, the defect is indicated by the relative change in the gamma count from the background value.

A general opinion of the consultants regarding the use of steel versus PVC access tubes was that a problem with debonding due to shrinkage of the concrete from the PVC tube resulted in a loss of signal in the sonic logging method, usually in the upper zone of the shaft. This type of debonding was not nearly as common or extensive in the case of the steel access tubes. For the gamma-gamma logging method, the higher-density steel attenuated the signal, although defects located near the tubes could still be detected.

Correlation with Acceptance Criteria

Following completion of the Texas test program, all test results will be correlated with a set of preliminary acceptance criteria, which were developed early in the project. It is hoped that the correlation will warrant future publication.

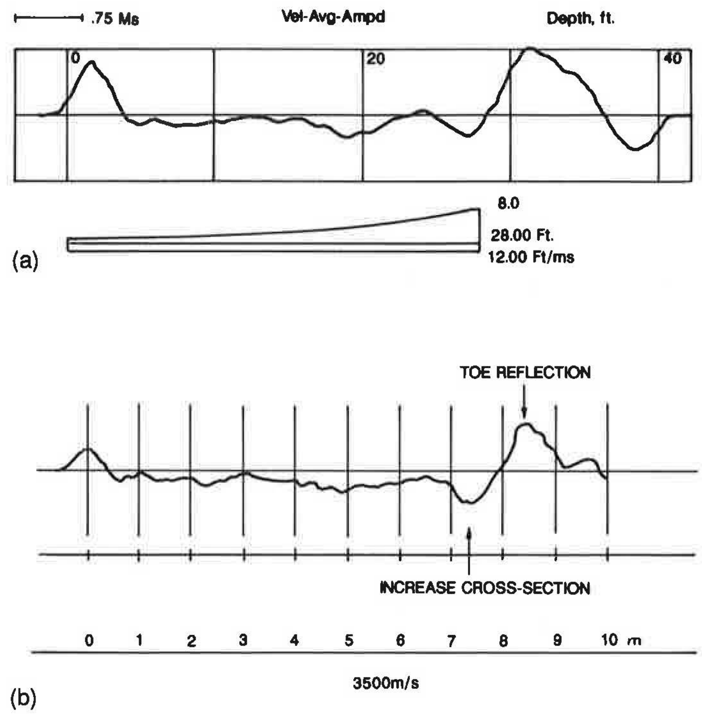


FIGURE 5 Results from SE test of Shaft 1 (*a*, Consultant C; *b*, Consultant D).

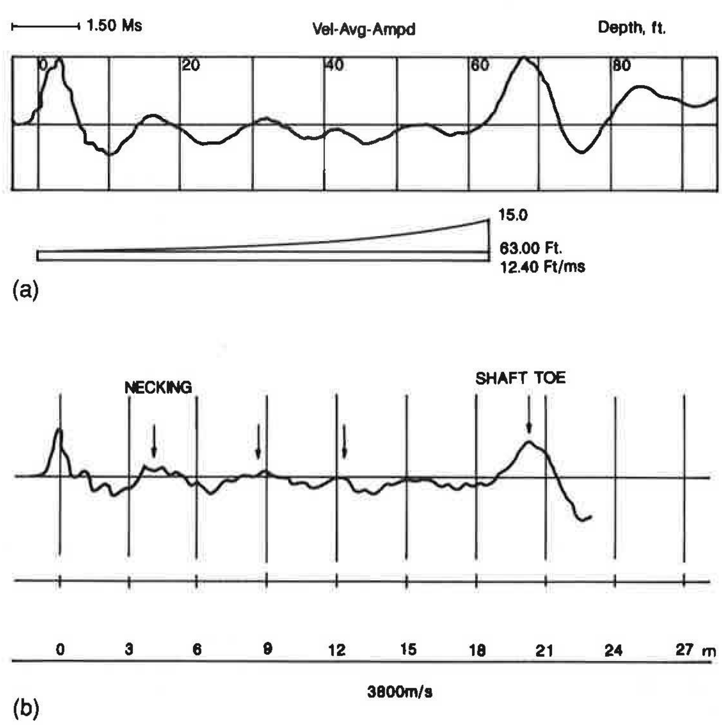


FIGURE 6 Results from SE test of Shaft 8 (*a*, Consultant C; *b*, Consultant D).

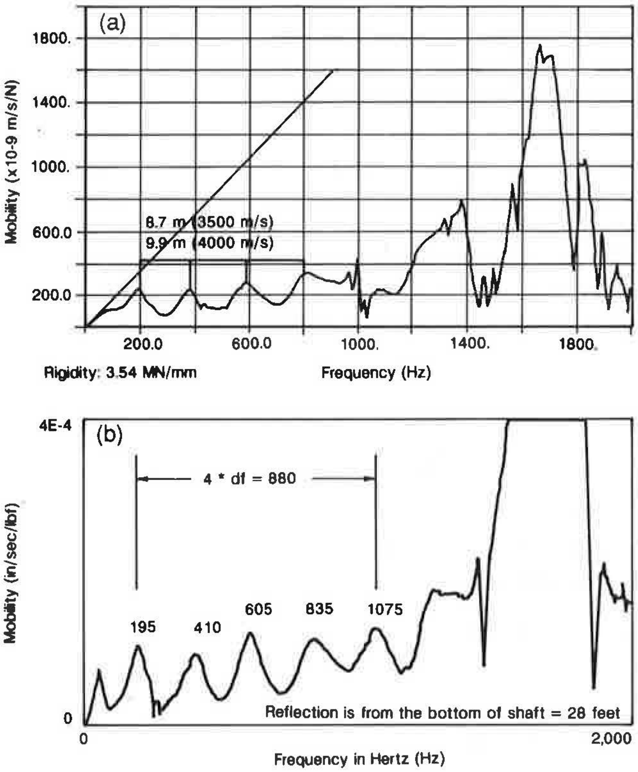
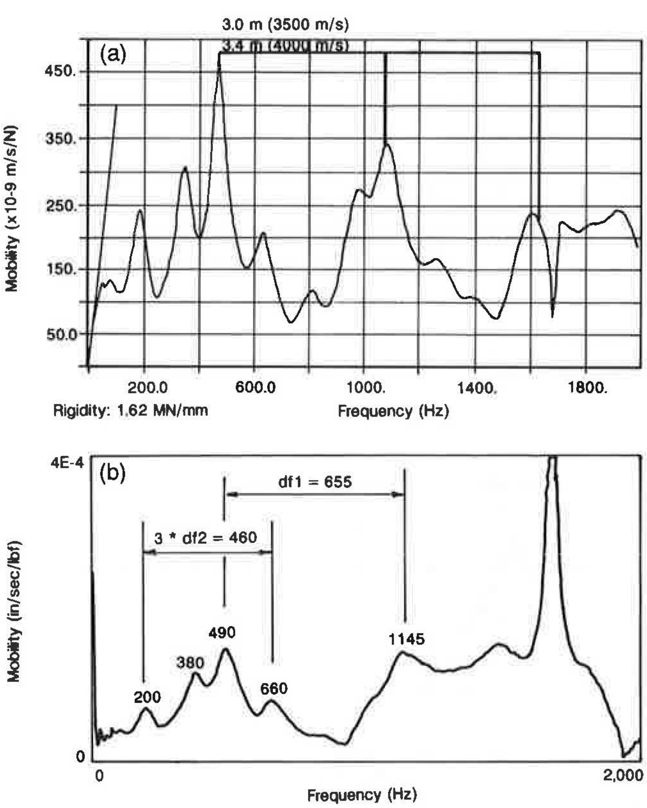


FIGURE 7 Results of TDR test on Shaft 1 (*a*, Consultant A; *b*, Consultant B).



Reflections were from an irregularity at 9.5 feet and a defect at 40.5 feet.

FIGURE 8 Results of TDR test on Shaft 8 (*a*, Consultant A; *b*, Consultant B).

TABLE 2 SUMMARY OF RESPONSES FROM SONIC LOGGING AND GAMMA LOGGING TESTS

Shaft No.	Response/ Depth	(1) A (TDR)	(2) B (TDR)	(2) B (SE)	(1) C (SE)	(1) D (SE)
1	Elliptical/13 ft	-	-	-	-	-
1	Bell/26 to 27 ft	-	-	-	x	-
1	Soft base/27 ft	x	x	x	x	x
2	Base/33 ft	x	x	x	x	x
3	Neck-in/11 ft	-	x	x	x	-
3	Bell/24 to 28 ft	-	-	-	x	x
3	Base/28 ft	x	x	x	x	x
4	Perimeter/					
	5.5 to 10.5 ft	-	x	x	-	-
4	Soft base/32 ft	x	x	x	x	x
5	Cold joint/6.5 ft		-	-	x	x
5	Weak concrete/					
	14.5 to 16 ft	-	x	x	-	x
5	Soft base/33 ft	-	-	-	-	-
5	Base/33 ft	x	x	x	x	x
6	Base/61.5 ft	x	x	x	x	x
7	Overbreak/11 to 15 ft	x	x	x	x	x
7	Tremie Defect/15 ft	x	-	-	-	-
7	Base/33.5 ft	x	x	x	x	x
8	Elliptical/15 ft	?	-	-	x	x
8	Neck-in/43 ft	?	x	x	x	-
8	Base/64 ft	x	-	-	x	x
9	Underream/15 ft	x	x	?	x	x
9	Neck-in/43 ft	x	x	x	-	-
9	Base/65 ft	x	-	-	-	x
10	Base/32 ft	x	x	x	x	x
11	Overbreak/30 to 33 ft	x	-	-	x	x
11	Base/65 ft	x	-	-	x	x

Notes: (Depths are measured from top of shaft)
(1) Test results prior to large-scale dynamic testing
(2) Test results after large-scale dynamic testing
X = Detected - = No detection ? = Possible detection

CONCLUSIONS

On the basis of the results of the study, the following conclusions were drawn:

1. The surface reflection techniques (TDR and SE) could detect the base of the shafts and larger neck-in–type defects. Small or very thin defects, such as the small elliptical inclusion, the cold joint, or changes in concrete properties, were not generally detected. Significant changes in cross section, such as a concrete overbreak or shallow underream, also produced responses from these methods.
2. The direct transmission methods (sonic and gamma-gamma logging) produced clear evidence of defects located near the access tubes, such as the shallow elliptical inclusion defect

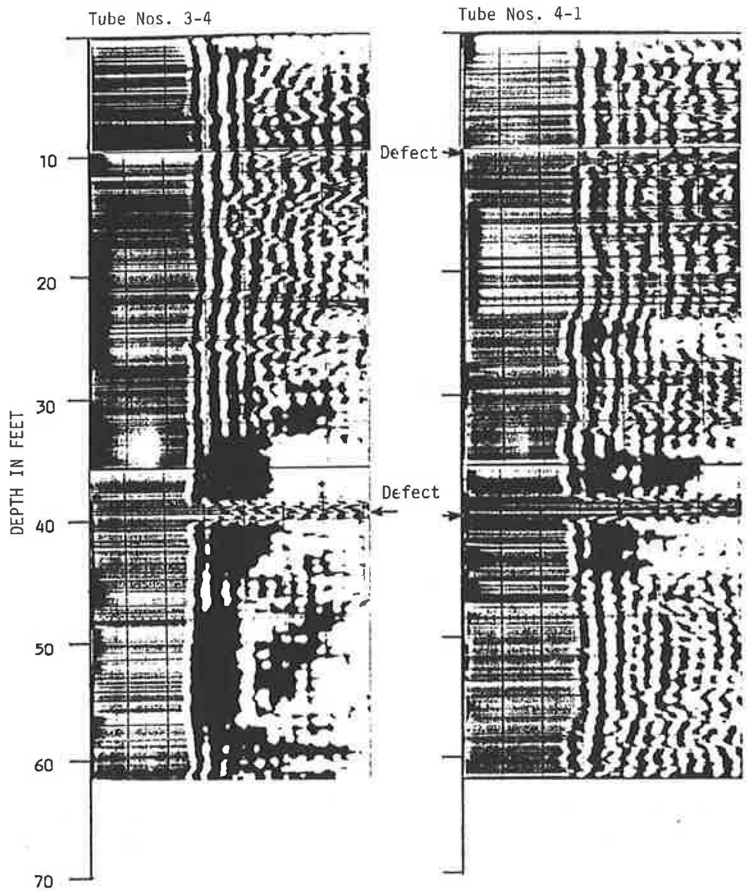


FIGURE 9 Sonic logging record from Shaft 8 (Consultant A).

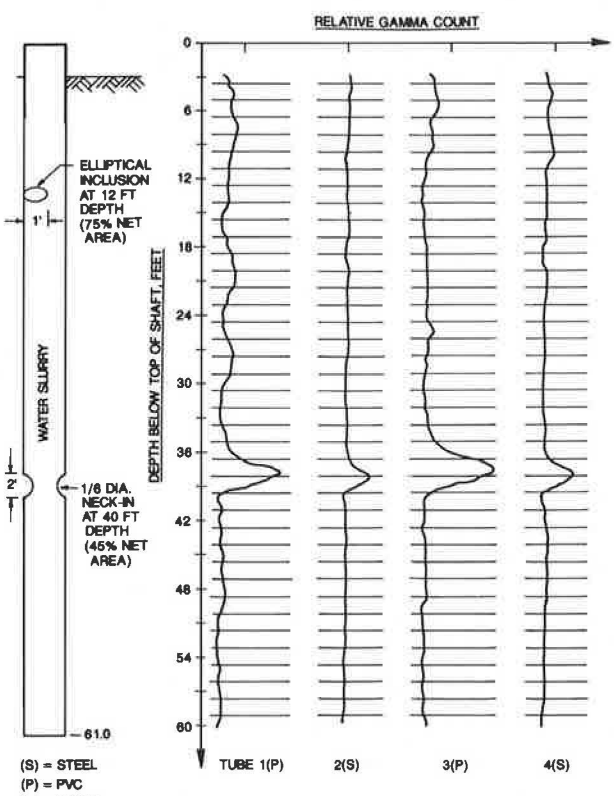


FIGURE 10 Gamma-gamma log from Shaft 8.

and the neck-in defects. For the sonic logging test, use of steel tubes compared with PVC access tubes was shown to reduce the occurrence of debonding between the shaft concrete and tube, thus giving a better signal response.

3. Where different firms used the same testing technique, they reported similar results with regard to depth of a noted defect.

4. NDT techniques, when joined with proper quality control observation during construction, offer a relatively inexpensive method to establish drilled shaft integrity.

ACKNOWLEDGMENTS

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