CHAPTER 4

IMPULSE RESPONSE FIELD TESTING STUDY

4.1 INTRODUCTION

Impulse response testing is commonly used for quality assurance testing of free-head shafts. A field testing study was conducted to evaluate the effects additional structures constructed atop the shaft have on the signal response.

Permission was obtained to perform testing at a construction site where STS Consultants, Ltd. previously completed free-head impulse response testing on several dozen drilled shafts. This provided an ideal situation, because the free-head tests would be available to compare with inaccessible-head tests. Drawings for this site were obtained to determine which of the previously tested shafts were to be covered by additional concrete structures. After this was determined, the shafts were located and tested on several different occasions. In addition to having the free-head results, soil boring logs and field records for all the shafts were also available. This data allowed the measured shaft length to be compared with the actual length and impulse response simulations to be completed using a simulation program.

4.2 FIELD CONDITIONS

4.2.1 Shaft Specifications

A total of 16 shafts were evaluated in the inaccessible-head condition, of which, free-head results had been previously obtained for 12 of the shafts. The shafts ranged from 55.8 to 65.3 ft in length and were nominally 2.5 to 8 ft in diameter. All the shafts had 60° bells at the base which were set in a hard silty clay / dense silt. All shafts were temporarily cased causing approximately the upper 20 to 27 ft of the shaft to be enlarged by at least 0.5 ft. All the foundation concrete used on the project had a specified design strength of 4,000 psi, although actual strengths ranged from 4,700 to 7,100 psi (see Table A3). Table 4-1 provides a summary of the shaft specifications and Sections 4.2.1.1 through 4.2.1.4 provide additional shaft details.

4.2.1.1 Shafts 109, 110 and 111

Free-head and inaccessible-head responses were obtained for these three shafts. The plan view is shown in Figure 4-1 and a profile view for the shafts and soil conditions is shown in Figure 4-2.

Shaft 109

Shaft 109 was nominally 4 ft in diameter, but the upper 24 ft was actually 4.5 ft in diameter due to the presence of the temporary casing. The bell is 10.8 ft in diameter at the base and 5.8 ft high. The overall shaft length is 57.9 ft. A 4 ft thick, 5 x 5 ft cap was constructed above this shaft with two 3 ft wide by 4 ft thick grade beams extending perpendicularly to each other from the cap. The one grade beam extended for 26 ft connecting to shaft 110. The other grade beam extended for 42 ft connecting to another shaft.

Table 4-1. Summary of shaft specifications for field study

Shaft Number	Nominal Shaft Diameter (feet)	Upper Shaft Diameter[a] (feet)	Shaft Length (feet)	Concrete Cap Dimensions[b] [L x W x D] (feet)	Number of Grade Beam Legs	Maximum B[c] (feet)
109	4	4.5	57.9	5 x 5 x 4	2	4
110	3	3.5	57	n/a (4 ft)[d]	3	4
111	5	5.5	58.7	6 x 6 x 5	1	5
210	3.5	4	59.8	n/a (10.6 ft)[d]	2	10.6
244	3.5	4	59.3	n/a (10.8 ft)[d]	3	10.8
277	3.5	4	56	n/a (10.3 ft)[d]	3	10.3
303	3.5	4	62	4.5 x 4.5 x 4	1	4
324	3.5	4	64	4.5 x 4.5 x 4	2	4
325	3.5	4	63.1	4.5 x 4.5 x 4	1	4
336	8	8.5	65.3	9 x 9 x 4	2	4
337	3	3.5	65	5 x 5 x 4	1	4
340	6	6.5	63.6	8 x 8 x 4	3	4
345	3.5	4	60.8	n/a (10.3 ft)[d]	3	10.3
353	3.5	4	60.6	4 x 4 x 4	1	4
425	2.5	3	58.5	n/a (7 ft)[d]	1	7
426	2.5	3	55.8	n/a (7 ft)[d]	1	7

[a] Approximately the upper 20 to 27 ft of the shaft lengths were enlarged due to temporary casing; for the specific casing lengths for each shaft see Sections 4.2.1.1 through 4.2.1.4

[b] [L x W x D] = [Length x Width x Depth]; shafts without caps had grade beams connecting to the shaft head without any section enlargement

[c] B = the depth from the top of the uppermost grade beam to the top of the shaft

[d] Shaft had grade beam connected directly above it with no section enlargement (cap); number in parentheses indicates the depth from the top of the grade beam to the shaft head

Figure 4-1. Plan view of shaft and grade beam locations for shafts 109, 110 and 111

Figure 4-2. Soil and shaft profiles for shafts 109, 110 and 111

Shaft 110

Shaft 110 was nominally 3 ft in diameter, but the upper 23 ft was actually 3.5 ft in diameter due to a temporary casing. The bell is 7 ft in diameter at the base and 3.4 ft high. The overall shaft length is 57 ft. Three, 3 ft wide by 4 ft thick, grade beams intersect above this shaft. One grade beam extends 26 ft connecting to shaft 109. Another extends 14 ft connecting to shaft 111 and the third extends 28 ft connecting to another shaft.

Shaft 111

Shaft 111 was nominally 5 ft in diameter, but the upper 23 ft was actually 5.5 ft in diameter due to a temporary casing. The bell is 10.2 ft in diameter at the base and 4.5 ft high. The overall shaft length is 58.7 ft. A 5 ft thick, 6 x 6 ft cap was constructed above this shaft with one 3 ft wide by 4 ft thick grade beam extending 14 ft from the shaft connecting to shaft 110.

4.2.1.2 Shafts 210, 244, 277 and 345

Free-head and inaccessible-head responses were obtained for these four shafts. All the concrete structures shown in Figure 4-3 and 4-4 were added above the shaft heads before any inaccessible-head testing was completed. The plan view for shaft 210, 244 and 277 is shown in Figure 4-3a. The plan view for shaft 345 is shown in Figure 4-3b. A typical cross-sectional profile of all four shafts is shown in Figure 4-4a. Detailed profiles of shafts 210, 244 and 277 as well as the soil profile are shown in Figure 4-4b. A detailed profile of shaft 345 including its soil profile is shown in Figure 4-4c. Note that the upper 5 ft of the grade beams connecting these shafts is above the ground surface.

Figure 4-3a. Plan view of shaft and grade beam locations for shafts 210, 244 and 277

Figure 4-3b. Plan view of shaft and grade beam locations for shaft 345

Figure 4-4a. Typical cross-sectional view of shafts 210, 244, 277 and 345

Figure 4-4b. Soil and shaft profiles for shafts 210, 244 and 277

Figure 4-4c. Soil and shaft profile for shaft 345

Shaft 210

Shaft 210 is nominally 3.5 ft in diameter, but the upper 23 ft was actually 4 ft in diameter due to a temporary casing. The bell is 8.6 ft in diameter at the base and 4.4 ft high. The overall shaft length is 59.8 ft. A 4.5 ft thick, 5 ft wide foundation girder is connected to the top of the shaft and extends 35 ft until it connects with another shaft. A 6.1 ft thick, 3 ft wide grade beam lies above and perpendicular to the foundation girder. The grade beam extends for 46 ft before connecting to shaft 244.

Shaft 244

Shaft 244 is nominally 3.5 ft in diameter, but the upper 21 ft was actually 4 ft in diameter due to a temporary casing. The bell is 8.5 ft in diameter at the base and 4.4 ft high. The overall shaft length is 59.3 ft. A 4.5 ft thick, 5 ft wide foundation girder is connected to the top of the shaft and extends 35 ft until it connects with another shaft. A 6.3 ft thick, 3 ft wide grade beam lies above and perpendicular to the foundation girder. The grade beam extends for 46 ft before connecting to shaft 210 in one direction and for 36 ft before connecting to shaft 277 in the other direction.

Shaft 277

This shaft is nominally 3.5 ft in diameter, but the upper 21 ft was actually 4 ft in diameter due to a temporary casing. The bell is 8.6 ft in diameter at the base and 4.4 ft high. The overall shaft length is 56 ft. A 4.5 ft thick, 4.5 ft wide foundation girder is connected to the top of the shaft and extends 35 ft until it connects with another shaft. A 5.8 ft thick, 3 ft wide grade beam lies above and perpendicular to the foundation girder. The grade beam extends for 36 ft before connecting to shaft 244 in one direction and for 36 ft before connecting to another shaft in the other direction.

Shaft 345

This shaft is nominally 3.5 ft in diameter, but the upper 23 ft was actually 4 ft in diameter due to a temporary casing. The bell is 8.6 ft in diameter at the base and 4.4 ft high. The overall shaft length is 60.8 ft. A 4.5 ft thick, 4.5 ft wide foundation girder is connected to the top of the shaft and extends 35 ft until it connects with another shaft. A 5.8 ft thick, 3 ft wide grade beam lies above and perpendicular to the foundation girder. The grade beam extends for 36 ft before connecting to another shaft in one direction and for 36 ft before connecting to another shaft in the other direction.

4.2.1.3 Shafts 303, 324, 325, 340 and 353

Free-head and inaccessible-head responses were obtained for these five shafts. A plan view is shown in Figure 4-5 and a profile view of the shafts and the soil conditions is shown in Figure 4-6.

Shaft 303

Shaft 303 is nominally 3.5 ft in diameter, but the upper 22 ft was actually 4 ft in diameter. The bell is 8 ft in diameter at the base and 3.9 ft high. The overall shaft length is 62 ft. A 4 ft thick, 4.5 x 4.5 ft cap was constructed above the shaft. A 3 ft wide by 4 ft deep, 30 ft long grade beam extends from the cap, connecting to another shaft.

Shaft 324

Shaft 324 is nominally 3.5 ft in diameter, but the upper 24 ft was actually 4 ft in diameter. The bell is 8.6 ft in diameter at the base and 4.4 ft high. The overall shaft length is 64 ft. A 4 ft thick, 4.5 x 4.5 ft cap was constructed above the shaft. Two 3 ft wide by 4 ft thick, 30 ft long grade beams extend perpendicular to each other from the cap. One connects with shaft 325 and the other with shaft 340.

Figure 4-5. Plan view of shaft and grade beam locations for shafts 303, 324, 325, 340 and 353

Figure 4-6a. Soil and shaft profiles for shafts 303 and 325

Figure 4-6b. Soil and shaft profiles for shafts 324, 340 and 353

Shaft 325

Shaft 325 is nominally 3.5 ft in diameter, but the upper 22 ft was actually 4 ft in diameter. The bell is 8 ft in diameter at the base and 3.9 ft high. The overall shaft length is 63.1 ft. A 4 ft thick, 4.5 x 4.5 ft cap was constructed above the shaft. A 3 ft wide by 4 ft deep, 30 ft long grade beam extends from the cap connecting to shaft 324.

Shaft 340

This shaft is nominally 6 ft in diameter, but the upper 22 ft was actually 6.5 ft in diameter. The bell is 17.2 ft in diameter at the base and 9.8 ft high. The overall shaft length is 63.6 ft. A 4 ft thick, 8 x 8 ft cap was constructed above the shaft. Two 3 ft wide by 4 ft thick, 30 ft long grade beams run linearly through the cap connecting to shafts 324 and 353. A 2 ft wide by 4 ft thick, 30 ft long grade beam runs perpendicular to the other two grade beams, connecting to another shaft.

Shaft 353

This shaft is nominally 3.5 ft in diameter, but the upper 21 ft was actually 4 ft in diameter. The bell is 8 ft in diameter at the base and 4.3 ft high. The overall shaft length is 60.6 ft. A 4 ft thick, 4 x 4 ft cap was constructed above the shaft. A 3 ft wide by 4 ft thick grade beam extends from the cap connecting to shaft 340.

4.2.1.4 Shafts 336, 337, 425 and 426

Testing for these four shafts was completed after all the concrete foundation structures were constructed above the shaft head. These are the only shafts in this study without free-head results. The plan view for these shafts is shown in Figure 4-7 and shaft and soil profile views are shown in Figure 4-8.

Figure 4-7. Plan view of shaft and grade beam locations for shafts 336, 337, 425 and 426

Figure 4-8. Soil and shaft profiles for shafts 336, 337, 425 and 426

Shaft 336

Shaft 336 is nominally 8 ft in diameter, but the upper 27 ft was actually 8.5 ft in diameter. The bell is 20.3 ft in diameter at the base and 10.6 ft high. The overall shaft length is 65.3 ft. A 4 ft thick, 9 x 9 ft cap was constructed above the shaft. Two, 2 ft wide by 4 ft thick, 30 ft long grade beams extend perpendicular to each other from the cap. One connects with shaft 337 and the other with another shaft.

Shaft 337

Shaft 337 is nominally 3 ft in diameter, but the upper 24 ft was actually 3.5 ft in diameter. The bell is 8.6 ft in diameter at the base and 4.8 ft high. The overall shaft length is 65 ft. A 4 ft thick, 5 x 5 ft cap was constructed above the shaft. A 2 ft wide by 4 ft thick, 30 ft long grade beam extends from the cap connecting with shaft 336.

Shaft 425

Shaft 425 is nominally 2.5 ft in diameter, but the upper 20 ft was actually 3 ft in diameter. The bell is 6.5 ft in diameter at the base and 3.4 ft high. The overall shaft length is 58.5 ft. A 4.5 ft wide by 7 ft thick, 24 ft long transfer beam was constructed above the shaft connecting it to shaft 426.

Shaft 426

Shaft 426 is nominally 2.5 ft in diameter, but the upper 21 ft was actually 3 ft in diameter. The bell is 6.5 ft in diameter at the base and 3.4 ft high. The overall shaft length is 55.8 ft. A 4.5 ft wide by 7 ft thick, 24 ft long transfer beam was constructed above the shaft connecting it to shaft 425.

4.2.2 Testing Conditions

The free-head tests were completed between July and October 1993 by STS Consultant's field technicians. The tests were completed using the equipment described in Chapter 3. Shaft head preparation for the geophone and impact surface was completed using a mason's hammer. The hammer is used to clear away the latency from the top of the shaft and to get a semi-smooth surface. The hammer impact surface was prepared at the center of the shaft, and the geophone surface preparation was completed near the perimeter of the shaft.

The geophone was coupled to the concrete by means of Castrol Water Pump Grease for the free-head tests. This grease is no longer commercially available and a substitute needed to be located before this field study could be completed. This grease had provided successful results for many years. It is known that it is an approximately 30% calcium soap-based grade 5 grease. Several attempts were made to obtain similar samples to the Castrol product from various lubricant producers, but to no avail. An HVAC duct-caulking product was being used by STS Consultants as a temporary replacement for the Castrol grease. This product was found to be unsatisfactory for cold weather use, which is when the majority of the inaccessible-head testing was completed. Lubricant manufacturers provided samples of grade 3 greases which were evaluated. A paraffin-based grade 3 grease called Rykon obtained from Amoco Lubricants was found to provide satisfactory results in both warm and cold weather. This was determined by comparing the results from a test shaft at STS Consultant's lab facility that was originally tested with the Castrol product with the results of a test on the same shaft prepared with the Rykon grease.

In addition to using a different couplant for the tests on the inaccessible-head conditions, the geophone and impact surfaces were also prepared differently. The surfaces were prepared initially by means of the mason's hammer similar to the free head tests, but then were also smoothed by means of a hand-held grinder to obtain a very flat surface. This was determined to be an efficient method for obtaining the "cleanest" results. The geophone and hammer locations were also altered to determine what effect this had on the results. Column anchor bolts and plates were found above most of the structures, usually centrally aligned with the shaft. When column anchor plates were removable, testing was completed by striking the concrete cap/grade beam over what was believed to be the shaft center. The geophone was placed at what was believed to be within 6 inches of the shaft perimeter. Tests were also completed by adjusting the impact location to near the edge of the cap while maintaining the same geophone location. Figure 4-9 illustrates an example of the different impact locations used on Shaft 340. The impact locations that provided the best results are discussed in Section 4.6.2.

Figure 4-9. Different impact locations used for impulse response testing on Shaft 340

4.3 SIMULATION PROGRAM

Simulations of shaft responses were made using the Siminteg Simulation Program developed by CEBTP of Paris, France and revised by STS Consultants. The program is based on axisymmetric shaft conditions with soil layers that extend "infinitely" in the horizontal direction away from the shaft.

The program requires the user to input both shaft and soil parameters. The shaft parameters include length (inches), diameter (inches), concrete density (kg/m^3) and concrete compression wave velocity (m/s). The soil parameters include the shear wave velocity (m/s) and density (kg/m^3). The user is allowed to input up to ten layers for each shaft where each layer can vary by any combination of the above parameters. This is very convenient for simulating complex soil conditions and changes in shaft cross-sectional area.

Shaft parameters were based on the construction records and drawings that were obtained for the site. The only cross-sectional area changes occurred at the depth the temporary casing extended to and near the toe to account for the bell. The concrete density was assumed to be 150 pcf (2,400 kg/m^3) for all the shafts and the compression wave velocity value was obtained from Table A3.

The soil layers were approximated from Figures 4-2, 4-4, 4-6 and 4-8 which were obtained from soil boring logs. The parameters used in the simulation were approximated based on the values from Table 4-2.

Table 4-2. Simulation parameters for soil

Soil Type	Soil Shear Wave Velocity[a] -- ft/s (m/s)	Soil Density[b] -- pcf (kg/m^3)
Organic Clay	330 (100)	100 (1,600)
Soft Clay	330 (100)	106 (1,700)
Medium Clay	490 (150)	113 (1,800)

Medium Dense Sand	650 (200)	119 (1,900)
Stiff Clay	650 (200)	119 (1,900)
Hard Clay	820 (250)	125 (2,000)
Dense Silt	980 (300)	131 (2,100)

[a] Estimated from Richart et al. (1970) and suggested values provided by simulation program author

[b] Estimated from typical values suggested by Holtz and Kovacs (1981)

Recall from equations (2-8) and (2-18) that attenuation and mobility are functions of the input parameters required by the simulation program.

Simulating the free-head shafts is a straight-forward procedure where the user inputs the parameters according to the shaft geometry and the surrounding soil conditions. Difficulty arose in simulating the inaccessible shaft condition. The shaft and soil are modeled exactly as in the free-head condition, but parameters for the concrete grade beams needed to be modeled axisymmetrically. The beams were viewed as elements that restrained the shaft head, not allowing it to vibrate freely and thus increasing signal attenuation. The best method to model this situation, was to add a concrete section equal to the depth of the grade beam to the top of the shaft. More details for each shaft are provided in Section 4.5. To achieve the effect of a restrained shaft head, very stiff soil parameters were used for the top soil layer. The top soil layer parameters used for the shafts were rock-like with densities of 150 pcf (2,400 kg/m^3) and shear wave velocities ranging from 650 to 1,300 ft/s (200 to 400 m/s). Results of simulations are shown in Sections 4.4 and 4.5.

4.4 OBSERVED FREE-HEAD RESULTS

The free-head test results confirm that each of these shafts is continuous from head to toe. Most of the tests had at least six clear toe reflections. A summary of the free-head data is shown in Table 4-3. The table shows the calculated shaft lengths obtained using equation (2-10) and compares them to the as-built shaft lengths.

The lengths were calculated by approximating a concrete compression wave velocity from the concrete compressive strength for each shaft. The error of the length measurements ranges from 0.2% for shaft 110 to 6.1% for shaft 111.

Table 4-3. Free-head shaft length calculations

Free-Head Shaft Number	As-Built Length from Head to Toe (ft)	Calculated Length from Head to Toe[a] (ft)
109	57.9	58.1
110	57.0	57.1
111	58.7	55.1
210	59.8	58.1
244	59.3	56.6
277	56.0	57.2
303	62.0	58.8
324	64.0	61.1
325	63.1	64.5
340	63.6	60.6
345	60.8	60.0
353	60.6	59.7

[a] Length measurements were made based on an approximated concrete compression wave velocities from Table A3 (see Table A2 for complete data)

All the length measurements were made on data that was filtered by the methods shown in Section 3.3.2. Recall, that no measurements are shown for shafts 336, 337, 425 and 426 because they were not tested in the free-head condition. Stiffness values are not compared in Table 4-3 because it is shown in Section 4.5, that stiffness values became very erratic for the inaccessible-head tests. The focus in the subsequent discussions is on calculating lengths between resonant peaks for the toe reflections and on comparisons between theoretical and actual mobilities. Results for shafts 110, 244, 353 and 340 are shown as representative results of the free-head tests. These shafts represent the range of nominal shaft diameters for the free-head testing and all four are analyzed in the inaccessible-head condition. Unfiltered and simulated results along with a detailed presentation of the data processing for the final impulse response plot are presented for shaft 244 to provide a better understanding of the data analysis.

Shaft 110

The impulse response plot for shaft 110 is shown in Figure 4-10a, wherein mobility is plotted versus frequency. Recall that mobility is defined as the velocity divided by the force. The upper corner of the plot contains information about the shaft including the test site, test (shaft) number, shaft type, testing date and the nominal diameter. In Figure 4-10a, the resonant peaks are very clear up to 800 Hz. The mobility slightly increases with increasing frequency for this shaft. The cause of the rise is uncertain, but it could be due to resonance of the geophone housing which has been observed to occur between 1,300 and 1,700 Hz. Another possible cause of the rise is resonance due to fine cracks that result from shaft head trimming. The calculated length of 57.1 ft is very close to the as-built length of 57.0 ft. Also notice the alternating cycle of high/low amplitude response between 100 and 600 Hz. These alternating higher peaks are likely due to reflections from the cross-sectional area change at the depth of the bottom of the temporary casing. This trend is evident for all the free-head tests.

The theoretical N range shown in the figure corresponds well to that observed for the shaft below 500 Hz whereupon the rise begins to affect the signal. The theoretical mobility range was calculated using equation (2-18). The range represents concrete density values from 144 to 150 pcf (2,300 to 2,400 kg/m^3) and compression wave velocities from 11,500 to 13,100 ft/s (3,500 to 4,000 m/s) for the nominal diameter of the shaft. The range is slightly higher than the real response (below 500 Hz) because of the presence of the larger diameter in the upper 23 ft of the shaft which formed as a result of the temporary casing during construction. This result occurred for all the free-head results except for shaft 340 which was much larger in diameter, making its mobility less sensitive to slight increases in diameter.

The first peak at 80 Hz was not chosen because the unfiltered response in Figure 4-10b shows a resonant peak occurring at approximately 100 Hz. The filtering procedures combined the 100 Hz peak with the more dominant peak at 80 Hz.

Figure 4-10a. Free-head result for shaft 110

Figure 4-10b. Unfiltered free-head result for shaft 110

Shaft 244

The impulse response plot for shaft 244 is shown in Figure 4-11a. The resonant peaks are obvious up to 800 Hz. The signal remains flat over the range shown except for a rise that starts around 900 Hz. The calculated length of 56.6 ft is short of the as-built length of 59.3 ft. This length does however correspond to a depth between the bell and the toe. The theoretical N range corresponds well with the observed mobility for the shaft due to the larger diameter of the upper portion of the shaft.

The peaks chosen for averaging also matched very well with the shaft simulation shown in Figure 4-11b. The simulation requires the user to input the shaft geometry,

Figure 4-11a. Free-head result for shaft 244

Figure 4-11b. Simulated and observed response for shaft 244

concrete density and compression wave velocity. The user is also prompted for the soil profile, which is defined by a shear wave velocity and density for each stratum. The soil profile for the simulation was adapted from Figure 4-4b.

The data presented in Figure 4-11a has been filtered. Figure 4-11c illustrates the mobility plot based on unfiltered data. The peaks below 500 Hz are fairly obvious, but above 500 Hz, it becomes difficult to determine which peaks to choose for length calculations. After filtering, as shown in Figure 4-11a, the choice of peaks becomes much less subjective.

The force voltage versus frequency is plotted in Figure 4-12a. This shows the usable frequency range extending to about 1,300 Hz. The input frequency range for all free-head tests varied from 1,000 to 1,400 Hz. Recall, the upper end of the range should have been near 2,000 Hz for the hard rubber hammer. The narrower range of frequencies is suspected to be due to the a softening of the hard-rubber hammer tip from the hot summer conditions under which most of these tests were performed. It could also be a result of fine cracks that occur in the shaft head due to head preparation.

The raw and filtered velocity voltages are plotted versus frequency in Figures 4-12b and 4-12c, respectively. Notice how the lowpass filter eliminated the geophone response above 1,300 Hz. The frequency content of the impact force diminished above 1,300 Hz, so any velocity data received above this frequency is not useful when making a mobility plot and is therefore removed.

The repeatability of the test was checked by means of the coherence function. A comparison is made on Figure 4-13 between signals recorded for two tests completed on shaft 244. Ideally, a 1:1 correlation is expected, but due to random vibrations encountered in the field this is usually not possible. The coherence is a function found by subtracting the difference in mobility at each frequency from 1. Thus a coherence of 1 implies that the same signal has been received. The coherence diminishes above 1,200 Hz and there is a lack of continuity at very low frequencies where the stiffness is calculated. Figure 4-13 is representative of the coherence for most of the shafts tested in the accessible condition.

Figure 4-11c. Unfiltered free-head result for shaft 244

Figure 4-12a. Force voltage versus frequency response for shaft 244

Figure 4-12b. Unfiltered velocity voltage versus frequency response for shaft 244

Figure 4-12c. Filtered velocity voltage versus frequency response for shaft 244

Figure 4-13. Coherence function for shaft 244

Shaft 353

The impulse response plot for shaft 353 is shown in Figure 4-14. The resonant peaks are obvious up to 650 Hz, but the mobility begins to increase at frequencies above 450 Hz. This mobility rise is again suspected to be caused by geophone housing resonance or shaft head preparation.

The calculated length of 58.8 ft is short of the as-built length of 62.0 ft. This does however correspond well to a depth between the bell and the toe. The theoretical N range corresponds well for that observed for the shaft when the large diameter of the upper portion of the shaft is considered.

Figure 4-14. Free-head result for shaft 353

Shaft 340

The impulse response plot for shaft 340 is shown in Figure 4-15. The resonant peaks are obvious up to 750 Hz, but the mobility begins to increase at frequencies above 500 Hz. This rise is again suspected to be caused by geophone housing resonance or shaft head preparation.

The calculated length of 60.8 ft is short of the as-built length of 63.6 ft. This does however correspond to a depth between the bell and the toe. The theoretical N range is within the peaks of the observed response. The theoretical N was expected to be slightly greater than the observed response due to the larger diameter of the upper shaft from the presence of a temporary during construction. The larger upper-shaft diameter, however, had less of an effect on the mobility (relative to shafts 110, 244 and 353) because shaft 340 is a much larger diameter shaft.

Figure 4-15. Free-head result for shaft 340

4.5 OBSERVED AND SIMULATED INACCESSIBLE-HEAD RESULTS

Sixteen shafts were tested in the inaccessible-head condition. Several tests were completed for each shaft and one trend became immediately apparent -- the measured stiffness values were very erratic for the inaccessible-head condition. Table 4-4 shows the average stiffness value and standard deviation of all the tests completed for each shaft. Given the inconsistencies in stiffness measurements, this parameter is not useful for evaluating inaccessible shafts.

The most useful result to be obtained from the impulse response method applied to inaccessible-head conditions is the ability to determine the depth from the top of the concrete cap (beam) to the shaft toe by looking for toe reflections. Satisfactory length determinations were obtained for most of the shafts. Table 4-5 shows the mean and standard deviation of the calculated lengths from the top of the concrete cap to the shaft toe. For most of the shafts, several geophone/hammer contact point were used. The mean length measurements were taken for the contact point that was determined to provided the best results. The results of all the tests can be found in Table A2.

To better quantify differences between the shafts, Table 4-6 was developed. This table separates the shafts by their length to nominal upper shaft diameter (L/D) ratio and the depth of concrete beam(s) to nominal upper shaft diameter (B/D) ratio. It also indicates the number of beams connected to the shaft head.

Simulations of the shafts were made to aid the interpretation of the mobility plots. The simulation program is limited to axisymmetric conditions, necessitating the concrete beams to be input as circular concrete masses surrounded by a semi-infinite soil mass.

Table 4-4. Measured low-strain dynamic stiffness values for inaccessible shafts

Inaccessible Shaft Number	Mean Calculated Stiffness[a] (kips/in)	Standard Deviation of Calculated Stiffness (kips/in)
109	13,530	4,630
110	14,280	4,050
111	17,470	10,280
210	15,760	2,510
244	17,420	1,540
277	15,190	2,510
303	13,530	2,680
324	19,360	4,450
325	16,390	2,400
336	38,310	7,540
337	13,250	2,110
340	24,780	5,650
345	13,300	1,880
353	16,330	5,420
425	14,560	1,540

426	11,650	1,830

[a] All stiffness measurements are based on unfiltered data and averages are based on at least 4 tests except for Shaft 110 which is based on 2 tests (see Table A1 for all data) -- 1 kip/in = 1.75 x 10 $^{-4}$ MN/mm

Table 4-5. Inaccessible shaft length measurements

Inaccessible Shaft Number	As-Built Length from Cap to Toe (ft)	Mean Calculated Length from Cap to Toe[a] (ft)	Standard Deviation of Mean Length (ft)
109	61.9	60.8	2.2
110	61.0	No consistent toe reflections	
111	63.7	63.8	1.7
210	70.4	72.5	1.3
244	70.1	69.7	1.0
277	66.3	63.6	0.4
303	66	65.6	1.1
324	68	65.9	2.1
325	67.1	67.1	1.8
336[b]	69.3	64.5	0.6
337[b]	69	65.6	0.6
340	67.6	63.2	1.2
345	71.1	68.2	1.3
353	64.6	64.9	1.4
425[b]	65.5	63.9	0.4

426[b]	62.8	59.4	2.3

[a] All length measurements completed on data filtered by methods shown in section 3.3.2; Length measurements were made based on an approximated concrete compression wave velocities from Table A3 (see Table A2 for all data)

[b] No free-head data available for these shafts

Table 4-6. Comparison of inaccessible shaft parameters

Shaft Number	D = nominal upper shaft diameter (ft)	L = shaft length (ft)	B = total depth of concrete beam[s] (ft)	L/D	B/D	Number of Grade Beam Legs
109	4.5	57.9	4	13	0.9	2
110	3.5	57.0	4	16	1.1	3
111	5.5	58.7	5	11	0.9	1
210	4	59.8	10.6	15	2.7	2
244	4	59.3	10.8	15	2.7	3
277	4	56.0	10.3	14	2.6	3
303	4	62.0	4	16	1.0	1
324	4	64.0	4	16	1.0	2
325	4	63.1	4	16	1.0	1
336	8.5	65.3	4	8	0.5	2
337	3.5	65.0	4	19	1.1	1
340	6.5	63.6	4	10	0.6	3
345	4	60.8	10.3	15	2.6	3

353	4	60.6	4	15	1.0	1
425	3	58.5	7	20	2.3	1
426	3	55.8	7	19	2.3	1

4.5.1 Concrete Beams Less Than 5 ft Thick

This section focuses on the tests completed for shafts 109, 110, 111, 303, 324, 325, 336, 337, 340 and 353. All these shafts have B/D ratios ranging from 0.5:1 to 1.1:1 and L/D ratios from 8:1 to 19:1. To show typical results and address some of the limitations of the impulse response method applied to inaccessible-head conditions, shafts 353, 337, 110, 340, 336 and 324 are presented.

Shaft 353

The impulse response result for one of the tests completed on shaft 353 is shown in Figure 4-16a. The mobility began to increase at 300 Hz. The calculated length of 65.4 ft is slightly longer than the actual length of 64.6 ft for the beam/shaft. This result was obtained by striking the beam at a point similar to Hammer Location #2 (edge of shaft) in Figure 4-9.

A simulation of the test is shown in Figure 4-16b. Resonant peaks which matched the simulated response were observed up to 600 Hz, though the simulated and actual responses were slightly out of phase over 200 Hz. For the simulated response, the effective diameter of the 4 ft by 4 ft concrete cap above the shaft was calculated and added to the top of the shaft. To obtain the signal attenuation of the simulated response shown in Figure 4-16b, it was necessary to use rock-like parameters for the top soil layer. For the soil adjacent to the cap, a density of 150 pcf (2,400 kg/m^3) and a shear wave velocity of 1,300 ft/s (400 m/s) were used. In contrast to the observed mobility, the simulated response did not increase above 300 Hz. The reasons for this are unclear, although one possibility is that the increased mobility is caused by resonance of the beam which is tied into the shaft. Note that the beam is only approximately included in the simulation as merely a larger diameter section of the shaft and not as a secondary structural member with its own natural frequency.

Figure 4-16a. Impulse response result for inaccessible shaft 353

Figure 4-16b. Simulated and observed inaccessible shaft response for shaft 353

Shaft 337

The impulse response result for one of the tests completed on shaft 337 is shown in Figure 4-17a. Flatter resonant peaks were obtained for shaft 337 than those obtained for shaft 353 (shaft 337 has a greater L/D). The calculated length of 66.2 ft is slightly longer than the actual length of 65.6 ft for the beam/shaft. This result was obtained by striking the beam at a point similar to Hammer Location #2 (edge of shaft) in Figure 4-9.

A simulation of the result is shown in Figure 4-17b. The simulated peaks agree with those used for the length measurement of the real data, though the two responses are slightly out of phase over 200 Hz. For the simulated response, an attempt was made using an effective diameter of the 5 ft by 5 ft concrete cap above the shaft. This result is shown in Figure 4-18. This did not match the observed response, so the effective diameter was decreased for the simulation shown in Figure 4-17b.

The simulation in Figure 4-17b used an effective diameter of 4.2 ft, with the soil adjacent to the cap having a density of 150 pcf (2,400 kg/m^3) and a shear wave velocity of 650 ft/s (200 m/s). With regard to attenuation, these parameters resulted in reasonable computed mobilities for the first 250 Hz. Beyond 250 Hz, attenuation of the observed signal was much greater and secondary structural effects likely caused larger differences between observed and simulated mobilities.

The shaft 337 simulation required a smaller shear wave velocity to be used than that used for shaft 353 for the top "soil" layer adjacent to the grade beam. This reduction was needed because of the smaller sized grade beam restraining shaft 337 (2 ft versus 3 ft wide for shaft 353). Using an effective diameter of the cap did not work for as well for shaft 337 as it did for shaft 353. For shaft 337, the cap area is much greater than the shaft diameter (25 ft^2 versus 9.6 ft^2) as compared to shaft 353 (16 ft^2 versus 12.6 ft^2). Using the smaller effective diameter for shaft 337 yielded a much better result. These results seem to indicate that if the axisymmetric simulation is to be used, then the effective cap size used for simulations should not be much greater than the shaft diameter and more emphasis should be given to selection of the parameters used to model the soil layer adjacent to the cap. However, it is clear that a more sophisticated simulation program should be used to model the inaccessible-head conditions.

Figure 4-17a. Impulse response result for inaccessible shaft 337

Figure 4-17b. Simulated and observed inaccessible shaft response for shaft 337 with a 4.2 ft diameter cap

Figure 4-18. Simulation of inaccessible shaft 337 with a 5.5 ft diameter cap

Shaft 110

The free-head response for shaft 110 was shown in Figure 4-10 to provide a satisfactory result. The impulse response result for one of the tests completed on shaft 110 is shown in Figure 4-19a. Only two marginally-clear toe reflections were obtained between 200 and 400 Hz. These reflection appear to repeat themselves between 650 and 800 Hz. The calculated length from these reflection gives a beam/shaft length of 61.1 ft. This length corresponds well with the actual beam/shaft length of 61.0 ft, but the rather arbitrary choice of peaks casts doubt on the validity of the calculated length.

Figure 4-19b shows a length measurement made between three peaks that occur around 60, 500 and 920 Hz. These peaks are suspected to be reflections from along the grade beam between shafts 110 and 111. The average length calculated based on these peaks is 14.9 ft which corresponds well with the grade beam length of 14 ft.

The frequency change between resonant peaks is not consistent for this shaft, and a valid length measurement is not possible. Recall, this shaft has three beams connected to it, each about as wide as the shaft diameter. The shaft diameter is also one of the smaller ones looked at in this study. These factors likely caused attenuation of the toe reflections and allowed the dominant grade beam reflection between shafts 110 and 111 to occur, which preclude making a reasonable length measurement.

Figure 4-19a. Impulse response result for inaccessible shaft 110

Figure 4-19b. Reflections from waves traveling along grade beams for inaccessible shaft 110

Shaft 340

The impulse response result for one of the tests completed on shaft 340 is shown in Figure 4-20a. Flat resonant peaks were obtained for this test. The calculated length of 65.6 ft is slightly lower than the actual length of 67.6 ft for the beam/shaft. This result was obtained by striking the beam at Hammer Location #1 (center of shaft) in Figure 4-9.

A simulation of the result is shown in Figure 4-20b. This simulation shows good correlation between the peaks used for length measurements from the observed data, though the simulated and actual responses were slightly out of phase. The axisymmetric modeling of the grade beams as a stiff soil layer are difficult for larger diameter shafts such as shaft 340. Several attempts were made to simulate the response. First, the effective diameter of the 8 ft by 8 ft concrete cap was calculated and input at the top of the shaft with a soil density of 150 pcf (2,400 kg/m^3) and shear wave velocity of 1,300 ft/s (400 m/s) as shown in Figure 4-20b. Simulation with this input did not match the observed response, other than giving an indication of the resonant peaks. Several additional attempts were made to optimize the simulation, but to no avail. The top layer soil parameters were increased to different values so that attenuation of the simulated signal would increase, giving resonant peaks similar to the observed response. This change only resulted in minimal increases in the attenuation of the simulated response and produced a much lower simulated mobility than the actual result.

Shaft 340 has three beams connected above it, similar to shaft 110. The diameter of shaft 340, however, is twice as large as shaft 110. The L/D ratios for shafts 340 and 110 are 10:1 and 16:1, respectively. The lower L/D ratio of shaft 340 means that attenuation of the compression wave for this shaft is lower. Shaft 340, unlike shaft 110, does not have grade beams that connect to other shafts at a distance less than 30 ft. These geometry differences decrease the possibility of reflections from waves traveling along grade beams "confusing" the result, similar to that which occurred for the shaft 110 response.

Figure 4-20a. Impulse response result for inaccessible shaft 340

Figure 4-20b. Simulated and observed inaccessible shaft response for shaft 340

Shaft 336

The impulse response result for one of the tests completed on shaft 336 is shown in Figure 4-21a. Good resonant peaks were obtained for this test for frequencies up to 600 Hz. The calculated length of 64.2 ft is shorter than the actual length of 69.3 ft for the beam/shaft. This result was obtained by striking the beam similar to Hammer Location #1 (center of shaft) in Figure 4-9.

A simulation of the result is shown in Figure 4-21b. The simulated peaks shows a good correlation with the peaks used for length measurements from the observed data, though the simulated and observed responses were slightly out of phase. The axisymmetric modelling of the grade beams as a stiff soil layer was also difficult for this larger diameter shafts. Several attempts were made to simulate the response. First, the effective diameter of the 9 ft by 9 ft concrete cap was calculated and input at the top of the shaft with a soil density of 150 pcf (2,400 kg/m^3) and shear wave velocity of 1,300 ft/s (400 m/s) as shown in Figure 4-21b. Simulation with this input did not match the observed response, other than giving an indication of the resonant peaks. Several additional attempts were made to optimize the simulation, but to no avail. The top layer soil parameters were increased to different values so that attenuation of the simulated signal would increase, giving resonant peaks similar to the real response. This change only resulted in minimal increases in the attenuation of the simulated response and produced a much lower simulated mobility than the actual result.

Shaft 336 and shaft 340 have L/D ratios of 8:1 and 10:1, respectively. Shaft 336 only has two beams connected above it, compared with shaft 340 which has three. These two factors combined to explain why much better resonant peaks were obtained for shaft 336 than for shaft 340.

Figure 4-21a. Impulse response result for inaccessible shaft 336

Figure 4-21b. Simulated and observed inaccessible shaft response for shaft 336

Shaft 324

The impulse response result for one of the tests completed on shaft 324 is shown in Figure 4-22a. Good resonant peaks were obtained for this test for frequencies up to 800 Hz. The calculated length of 65.3 ft is shorter than the actual length of 68.0 ft for the beam/shaft. This result was obtained by striking the beam similar to Hammer Location #1 (center of shaft) in Figure 4-9.

A simulation of the result is shown in Figure 4-22b. For the simulated response, the effective diameter of a 4.5 ft by 4.5 ft concrete cap was calculated and input at the top of the shaft. This approach yielded a simulation which matched somewhat with the observed response in that a reasonable correlation was obtained for the peaks used for length measurements from the observed data and the simulated peaks, though the peaks were slightly out of phase. The soil density for the top soil layer was 150 pcf (2,400 kg/m^3) and the shear wave velocity was 1,300 ft/s (400 m/s). This shaft had two beams attached to it, but good resonant peaks were still observed.

Figure 4-22a. Impulse response result for inaccessible shaft 324

Figure 4-22b. Simulated and observed inaccessible shaft response for shaft 324

4.5.2 Concrete Beams Greater Than 5 ft Thick

This section focuses on the tests completed for shafts 210, 244, 277, 345, 425 and 426. All these shafts have B/D ratios ranging from 2.3 to 2.7 and L/D ratios from 14:1 to 20:1. To show typical results and address some of the limitations, shafts 244 and 426 are presented along with a test completed on the grade beam between shafts 244 and 277.

Shaft 244

The impulse response result for one of the tests completed on shaft 244 is shown in Figure 4-23a. Good resonant peaks were obtained for this test through 950 Hz, while mobility noticeably increased beyond 600 Hz. The calculated length of 69.6 ft is slightly shorter than the actual length of 70.1 ft for the beam/shaft. This result was obtained by striking the beam similar to Hammer Location #1 (center of shaft) in Figure 4-9.

A simulation of the result is shown in Figure 4-23b. For the simulated response, the effective diameter of a 4 ft by 4 ft concrete cap was used for the top beam, and the effective diameter of a 4.5 ft by 4.5 ft concrete cap was used for the foundation girder. Soil parameters were input for both grade beams even though the top beam was above the ground surface. This was necessary to model under axisymmetric conditions the restraint that the grade beam has on the shaft head. This approach yielded a simulation which matched the real response up to 600 Hz. Reasonable correlation was obtained for the resonant peaks between the observed and simulated responses, though the peaks were slightly out of phase. For the top soil layer, a density of 150 pcf (2,400 kg/m^3) and the shear wave velocity of 1,300 ft/s (400 m/s) was used. This shaft had three beams attached to it, but still allowed good (though flat) resonant peaks to be observed.

Figure 4-23a. Impulse response result for inaccessible shaft 244

Figure 4-23b. Simulated and observed inaccessible shaft response for shaft 244

Shaft 426

The impulse response result for one of the tests completed on shaft 426 is shown in Figure 4-24a. Satisfactory resonant peaks were obtained for this test for frequencies up to 800 Hz. The calculated length of 61.1 ft is slightly shorter than the actual length of 62.8 ft for the beam/shaft. This result was obtained by striking the beam similar to

Hammer Location #1 (center of shaft) in Figure 4-9.

A simulation of the result is shown in Figure 4-24b. For the simulated response, the effective diameter of a 4 ft by 4 ft concrete cap was used for the beam. This approach yielded a simulation which matched the observed response up to 850 Hz. Reasonable correlation was obtained for the resonant peaks between the observed and simulated responses, though the peaks were slightly out of phase. For the top soil layer, a density of 150 pcf (2,400 kg/m^3) and the shear wave velocity of 1,300 ft/s (400 m/s) was used.

This shaft has a very thick (7 ft) grade beam attached to it almost causing some of the resonant peaks to be almost undetectable, especially the one at 290 Hz (see Figure 4-24a). The trend of the mobility plot indicates a large reflection from the bottom of the grade beam based on the change in frequency between the first resonant peak at 70 Hz and the large peak at 1,000 Hz. Using equation (2-10) yields a length of 7.1 ft for a = 930 Hz. Figure 4-24c shows this result more clearly.

The test shown in Figure 4-24a is one of five tests made on this shaft and represents the best result. The results imply that the geometry of this inaccessible shaft represents an approximate limit of the method. Shaft 426 is one of the smallest diameter shafts tested with a B/D ratio of 2.3:1 and L/D ratio of 19:1. The beam above the shaft is also stiffer (wider and thicker) than those connecting to the other shafts tested in this study. This combination results in a large amount of attenuation that apparently occurred in this shaft response, thus making some of the toe reflections barely noticeable.

Figure 4-24a. Impulse response result for inaccessible shaft 426

Figure 4-24b. Simulated and observed inaccessible shaft response for shaft 426

Figure 4-24c. Reflection from bottom of transfer beam for inaccessible shaft 426

Grade Beam

To show the difference between results where the beam is struck above the shaft and where the beam is struck away from the shaft, a test was conducted along the grade beam between shafts 244 and 277. The geophone and hammer contact points were located on the centerline of the beam. They were approximately 18 ft from either shaft.

The grade beam at this location is approximately 6 ft high without any soil surrounding the top 5 ft. The velocity voltage versus time result is shown in Figure 4-25a. Measurements between the reflected peaks yield a calculated length of 5.9 ft assuming v_c = 13,100 ft/s. To show the difference between this result and one where the beam is struck above the shaft, Figure 4-25b is presented. This shows velocity voltage versus time for inaccessible shaft 244. Note the numerous beams reflections in Figure 4-25a compared to the attenuated response in 4-25b where the majority of the stress wave traveled down the shaft.

Figure 4-26 shows the velocity voltage versus frequency. Four small peaks occur around 50, 200, 450 and 700 Hz. It is not known what these peaks correspond to, but they probably represent reflections off the beam/shaft interfaces. One sharp peak appears at 1,100 Hz resulting from the reflection off the bottom of the 6 ft beam. This length is determined by using equation (2-10) and solving for L. A single, sharp resonant peak such as the one shown in Figure 4-26 was not seen in any of the results performed for the inaccessible shafts.

The calculation based on one sharp resonant peak is the basis for another non-destructive test called the impact-echo method. The impact-echo method is used for evaluating concrete walls and is based on recording one dominant peak. The velocity versus time data is converted to the frequency domain by means of a Fast Fourier Transform. The frequency of the dominant peak is then used in equation (2-10) to solve for L, assuming a concrete compression wave velocity of 13,100 ft/s (4,000 m/s).

Figure 4-25a. Velocity voltage versus time for grade beam between shaft 244 and 277

Figure 4-25b. Velocity voltage versus time for inaccessible shaft 244

Figure 4-26. Impact-echo response for grade beam between shafts 244 and 277

The evaluation of the impulse response together with impact-echo results may be a viable method to identify whether or not deep foundations exist below a footing for a bridge pier. This is given that proper access of the above the shaft axis is available. The problem of unknown foundation types, particularly for older structures has been identified by several state DOT's as one of importance for their bridge management systems.

4.6 DISCUSSION

4.6.1 Free-Head Condition

The free-head results show good responses for the 12 shafts that were tested. The results contained at least one cycle of alternating lower/higher amplitude indicating a reflection from the cross-sectional change due to the temporary casing.

Lengths calculated from resonant peaks were very close to as-built lengths. The minor differences can mostly be attributed to variations in the concrete quality which results in different concrete compression wave velocities. The reason some of the impulse response length measurements were about 3 ft short is probably due to more dominant reflections from the shaft bells.

Most of the signals showed evidence of increasing mobility at the end of the record. This rise was most likely due to resonance of the geophone housing. This resonant peak usually occurs between 1,300 and 1,700 Hz depending on the geophone/concrete bond and the size of the shaft head.

Characteristic Mobility Comparison

Figure 4-27 compares the changes in the characteristic mobility among the free-head results. The data are comprised of the geometric mean of the lowest and highest mobility values taken within the first 500 Hz for each free-head test to preclude the effects of the mobility rise due to the geophone resonance. The data are grouped by nominal shaft diameters with theoretical mobility values shown in light grey for each group.

For the 3 and 3.5 ft diameter shafts, it is obvious that upper portion of all the shafts are oversized. The observed mobility for shaft 110 is slightly lower than the theoretical result for the 3.5 ft diameter shaft. This corresponds well with the construction records which show the shaft to be oversized to 3.5 ft for the upper 23 ft of the shaft. The observed mobility for the 3.5 ft nominal diameter shafts lies between the theoretical results of the 4 ft and 5 ft diameter shafts. The reason for the wide discrepancy between the 3.5 ft nominal diameter shafts is not known, but is suspected to be due to cross-sectional variations that often occur in drilled shafts. Shaft 109 is very close to the theoretical mobility, though it was expected to be slightly lower. The reason for this is uncertain because the construction records show the shaft to be oversized to 4.5 ft for the upper 24 ft of the shaft length and the concrete was shown to be of good quality based on the results of a concrete compression test (see Table A3). The observed mobilities for shafts 111 and 340 are both slightly lower than the theoretical results showing good correlation with the construction records.

Figure 4-27. Observed and theoretical mobilities for free-head shafts

4.6.2 Inaccessible-Head Condition

Low-strain dynamic stiffness varied greatly between tests that were repeated on the same shaft. This variation is believed to arise because the shaft is no longer a thin rod-like structure, as is the assumed in the theory used for testing done on free-head shafts and because the additional restraint and the odd shape of the grade beams render the assumption of axisymmetry invalid.

Most of the tests on the inaccessible-head shafts yielded satisfactory results for determining the toe depth. Some limitations were observed. As with the free-head results, some of the reflections occurred from between the top of the bell and the toe. For some cases, such as shaft 426, attenuation of the signal made it difficult to objectively determine resonant peaks. In cases where attenuation was extreme, for example shaft 110, no reliable length determination was possible. Shaft 110 also exhibited reflections from signals propagating along the grade beam which further confused interpretation of the signal. The grade beam reflections are believed to only be a factor when shorter grade beams connect two shafts (the grade beam between shaft 110 and 111 was 14 ft long).

The greatest effect of the grade beams was to increase signal attenuation. The more rigidly held the shaft head was, the more difficult it became to observe the resonant peaks. The simulation program showed that the beam acted like an extremely stiff soil layer at the head. It did reasonably well in simulating the single-beam-leg shafts, but it became more difficult to accurately simulate the multi-leg and larger diameter shaft cases.

To quantify the grade beam effects, several comparisons are made between the various shafts.

Shafts 110 and 340

Shafts 110 and 340 each have three grade beams connected to their heads. The depth of the beams for both cases is 4 ft. The only difference is in the shaft diameters; for shaft 340, the upper shaft diameter is 6.5 ft, whereas for shaft 110, the upper shaft diameter is 3.5 ft. Consequently, as indicated in Table 4-6, shaft 340 has an L/D ratio of

10:1 and a B/D ratio of 0.6:1, whereas shaft 110 has an L/D ratio of 16:1 and a B/D ratio of 1.1:1. Flat but clear peaks were observed in shaft 340's mobility versus frequency plot which allowed a reasonable length determination. The flatness of the peaks indicate strong attenuation even for this relatively large diameter shaft. No reasonable length determinations were possible for shaft 110 which would be expected given the results of shaft 340 and the fact that shaft 110 had a much smaller diameter than shaft 340.

Shafts 340 and 336

Shaft 336 has two grade beams connected to its head. These grade beams are each 2 ft wide and 4 ft thick, as compared to the three grade beams attached to shaft 340, of which, two are 3 ft wide by 4 ft thick and one is 2 ft wide by 4 ft thick. The presence of the larger beam dimensions and the additional beam leg imply that shaft 340 is much more rigidly held at its head than shaft 336. Shaft 336 has a L/D ratio of 8:1 and a B/D ratio of 0.5:1 while shaft 340 has a L/D ratio of 10:1 and a B/D ratio of 0.6:1.

Shaft 336 had much clearer resonant peaks than shaft 340. The primary reasons for this difference is the increased attenuation caused by the presence of the third leg of shaft 340 and the larger dimensions of the beams attached to shaft 340. The greater L/D and B/D ratios resulting from the smaller shaft diameter of shaft 340 also contribute to the increased attenuation of the signal.

Shaft 336 and 324

Shaft 336 and 324 each have two beams connected at their head. The two beams connecting into shaft 336 are 2 ft wide by 4 ft thick, whereas those connecting into shaft 324 are 3 ft wide by 4 ft thick. The beams connecting to shaft 324 are thus more rigid than those connecting to shaft 336. Shaft 336 has a L/D ratio of 8:1 and a B/D ratio of 0.5:1; shaft 324 has a L/D ratio of 16:1 and a B/D ratio of 1:1.

Peaks were observed in the mobility versus frequency plots of both shafts. The peaks for shaft 324 are not as clear as those for shaft 336 as a result of the larger L/D and B/D ratios and the higher rigidity due to the larger dimensions of the beams connected to shaft 324.

Shafts 353, 337 and 426

These three shafts have only one beam leg attached to them. The L/D and B/D ratios vary, and consequently the responses for the inaccessible shaft conditions are different as well. Clear reflections are obtained in the mobility versus frequency plot for shaft 353 with a L/D ratio of 15:1 and a B/D ratio of 1:1. Shaft 337 has a L/D ratio of 19:1 and a B/D ratio of 1.1:1, similar to shaft 353, but the small increase in L/D ratio is apparently responsible for the flatter (more attenuated) response obtained for shaft 337.

Shaft 426 has a L/D ratio of 19:1 and a B/D ratio of 2.3:1. The response for this shaft contained very flat, and in some cases, questionable peaks. Comparing this response to that of shaft 337, which has the same L/D ratio, it is noticed that an increased B/D affects the signal attenuation even for shafts below single leg beams. The grade beam above shaft 426 is also one of the stiffest grade beams studied herein.

Shaft 244

Shaft 244 was chosen as the representative case for shafts 210, 277 and 345. All these shafts had similar L/D and B/D ratios of about 15:1 and 2.7:1, respectively. Shafts 244, 277 and 345 had one beam leg attached directly to the shaft head, with an additional two legs attached above the beam; shaft 210 had only one additional leg attached above the lower beam. Note the impulse response tests were conducted from atop the upper beams in all four cases.

The results of shaft 244 showed that good resonant peaks in the mobility versus frequency plot were obtainable for these conditions. The peaks were somewhat attenuated, but still clear. Compared to the L/D and B/D ratios of shaft 426 (19:1 and 2.3:1, respectively), these shafts exhibited a much better response due to the lower L/D ratio. Given the high B/D ratio and the three beam legs, an uninterpretable result would have been expected based on the discussion for shafts 110 and 340. The differences between shaft 244 and these other shafts must therefore be examined. For shafts 110 and 340, all the grade beams met at the shaft head at the same elevation, and the grade beams were surrounded by soil. For shaft 244, the lower foundation girder was surrounded by soil and was directly attached to the shaft head. The grade beam was constructed above the foundation girder and extended perpendicularly to it. Thus, the grade beam was effectively above the ground surface. This configuration must have allowed greater signal response to be obtained for the inaccessible-head condition than if the grade beam and foundation girder had met at the same elevation and been entirely surrounded by soil.

This discussion clearly indicates the need to account for stiffness of structural members atop drilled shafts when interpreting results. A simulation program should be developed with capabilities to handle these effects.

Mobility Comparison

Figure 4-28 shows a comparison of the characteristic mobilities for the results of tests for inaccessible-head conditions. The mobility values shown in the figure were found by taking a geometric mean of the highest and lowest mobility value within the first 500 Hz of the response to preclude the effects of the mobility rise due to the geophone resonance.. The results are best discussed in terms of the number of beam legs attached to the shaft head.

Shaft 425 and 426 have one beam leg attached to them. The beam legs for these two shafts are stiffer than the other beam legs. Though they are the smallest diameter shafts, the stiffer beam leg gives shafts 425 and 426 higher or comparable mobilities to the 3 ft and 3.5 ft diameter shafts with one, two or three grade beam legs attached to them.

A comparison of mobilities for shafts 110 and 337 show that the mobility decreases as the number of grade beams attached to the head increases for similar sized shafts. This result is also seen for the 3.5 ft nominal diameter shafts. The stacked grade beam shafts (210, 244, 277 and 345) and the shafts where the grade beams are connected

Figure 4-28. Observed mobilities for inaccessible-head shafts

to the head at the same elevation (303, 325, 353 and 324) will be considered separately. For the stacked beam cases, the three leg beam cases have smaller mobilities than two leg beam cases. The results for shafts 210 and 244 are very close (possibly due to a minor geophone/concrete coupling problem for shaft 244), but the mobility of shaft 244 is still slightly lower than that of shaft 210. For shafts where the grade beams met at the same elevation, there is a clear trend for the two-beam-leg shafts to have lower mobilities than the one-leg shafts. This trend supports the conclusion attenuation increases as the rigidity of the shaft increases, because as the number of beams attached to the shaft head increases, so apparently does the average rigidity of the shaft.

Shafts 109 contains two grade beam legs and has a lower mobility than shaft 324 which also has two beam legs. The reason for this is the smaller shaft diameter of shaft 324. Shafts 111 and 336 show the expected trend of decreasing mobility with increasing shaft size. Shaft 340, with a 6 ft nominal diameter, had a mobility value similar to that of shaft 109 with a 4 ft nominal diameter. The mobility for shaft 340 was expected to be one of the lowest values because this shaft had three beam legs attached to the shaft head, and construction records show the shaft to be of good quality concrete and oversized in the upper 22 ft of the shaft. One possible reason for the relatively high mobility value is that a minor geophone/concrete coupling problem occurred during this test.

Geophone/Impact Location

The geophone for the inaccessible shafts tested was placed on the concrete grade beam directly above the shaft approximately 3 to 6 inches within the perimeter of the shaft. Figure 4-9 showed different impact locations that were used for the tests. The most accurate length calculations were obtained for the tests where the impact to the grade beam was applied directly above the center of the shaft. Tests completed with the impact location near the edge of the shaft typically produced reflections that gave length calculations down to the bell. Exceptions to this were shafts 337 and 353 where better length calculations were obtained by striking the grade beam near the edge of the shaft.

Recall, these two shafts have only one beam leg attached to the shaft head and their upper shaft diameters were approximately the same as the concrete cap/beam width.

4.7 CONCLUSIONS

Results of impulse response tests on the 12 free-head shafts indicated easily interpretable signals when analyzed in the frequency domain. Lengths calculated from the resonant peaks in mobility plots indicated good toe reflections were received and confirmed the shaft length and integrity. Some reflections did occur a few feet short of the toe and this is likely explained as being reflections from the shaft bells.

Good toe reflections were obtained for most of the inaccessible-head shafts, though the results were much more attenuated than their free-head test counterparts. The increased attenuation can be attributed to the additional restraint the grade beams impose on the shaft head and, to a lesser extent, the greater distance the stress wave needs to travel in the concrete medium before being recorded. The inaccessible-head results showed low-strain stiffness measurements not to be a useful parameter for inaccessible-head shaft analysis.

The mobilities of the free-head tests showed a consistent decrease in mobility as the shaft diameter increased, except for shafts 109 and 340 which may have had a coupling problem between the geophone and concrete. The mobilities of the inaccessible-head results are lower than their free-head counterparts. The results also indicate mobility decreases as the shaft head restraint increases.

The simulation program provided satisfactory results for the smaller inaccessible diameter shafts. The programs main limitation is that only axisymmetric shafts configurations can be simulated. For the larger diameter shafts, such as 340 and 336, it became difficult to simulate the inaccessible shaft response with the axisymmetric constraint. To properly simulate inaccessible shafts, a more sophisticated program with the ability simulate the response of secondary structural members in addition to the shaft is necessary.

For the majority of the shafts, the best shaft response is obtained when the concrete beam is struck directly above the center of the shaft. This is similar to the testing procedure for the free-head condition.