STRESSWAVE '96

FIFTH INTERNATIONAL CONFERENCE ON THE APPLICATION OF STRESS-WAVE THEORY TO PILES

SEPTEMBER 11 - 13, 1996
ORLANDO, FLORIDA

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Determining Embedment Depths of Deep Foundations Using Non-Destructive Methods

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Abstract

In today's deep foundation industry, non-destructive methods are needed to determine the length of in-service piles. Presently, methods of embedment length determination include, among others, Pile Integrity Testing (P.I.T.), Parallel Seismic Testing (P.S.T.) and core drilling. Core drilling may be used in concrete structures for length and limited integrity evaluation. P.I.T. methods use one-dimensional wave propagation theory and the pile length determination requires that the response from the pile toe is identifiable from measurements of pile top motion. P.I.T. methods have proven to be an invaluable tool for non-destructive length determination and pile integrity evaluation; however, inherent limitations exist and this method may not identify pile length of relatively long piles and/or piles in soils which exhibit relatively high friction.

The P.S.T method requires that a small diameter bore hole be placed near the deep foundation in question. A hydrophone is then lowered into the bore hole and after an impact is applied to the foundation top, the time required for the wave to reach the hydrophone is measured. The speed of wave propagation in both the foundation and the soil along with the wave arrival times for different hydrophone depths are then analyzed for embedment depth determination. This paper gives a description of both P.I.T. and P.S.T. methods and discusses their usefulness and their limitations.

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Background

P.I.T Testing

Low strain pile integrity testing can effectively and inexpensively investigate pile shaft integrity and in-ground lengths of piles. With this method, a pile top is impacted with a hand held hammer generating a compressive wave which travels down the pile. The wave will be reflected at locations of impedance change and also at the pile toe. These reflections are measured at the pile top generally with an accelerometer and evaluated for integrity. The time of observed wave return from the pile toe is used to determine the pile length. The P.I.T. method has been standardized by the American Society for Testing and Materials (ASTM, D5882).

Traditionally, the records of impact pulse and subsequent reflections from P.I.T. testing are analyzed in the time domain by evaluating the velocity at the pile head (Rausche, et al., 1994). This type of test and method of evaluation is commonly referred to as the "Pulse Echo Method" or PEM. In recent years, with the advent of faster analyzers, results from P.I.T. testing may also be evaluated in the frequency domain using Fast Fourier Transform (FFT). This test is often referred to as the "Transient Response Method" or TRM (Rausche, et al., 1991). FFT analysis can also be applied to produce a mobility plot which represents the ratio of the pile's velocity response to a particular excitation force at a certain frequency. To generate a mobility plot, the impact force and the pile velocity have to be measured and both transformed to the frequency domain. Typical records of top velocity, velocity spectrum and mobility are shown in Figure 1.

Utilizing P.I.T. testing for shaft length determination requires that a "clear" reflection be evident from the pile toe. In cases where the pile length is long relative to the pile diameter (typically greater than 30 to 50 pile diameters), especially if the pile is embedded in a soil which exhibits high skin friction, the impact wave may be dampened out before returning to the pile top after toe reflection. It is then impossible to determine the pile length. If the pile top is connected to the superstructure, the reflection from the pile toe may be "masked" by reflections from the superstructure again making it difficult to determine pile length. The pile must also be continuous (mechanical splices may not allow the impact wave to be transferred through the splice).

Pile integrity testing is performed by attaching an accelerometer to the top of the pile or shaft and striking the pile top with a special purpose hand held hammer designed to deliver a relatively sharp impact (*i.e.*, short pulse width relative to the shaft length). If mobility is of interest, the hammer is instrumented to measure the impact force. Impacts from these hand held hammers typically generate accelerations in the 10 to 100 g range and pile strains in the order of 10^{-5}, velocities in the order of 30 mm/s and displacements of 0.03 mm or less. P.I.T testing can be performed to evaluate the integrity of concrete piles (driven piles, drilled shafts, auger-cast), timber piles and concrete-filled steel pipe piles. P.I.T. testing generally does not work with steel piles such as unfilled pipe piles or H-piles.

P.I.T. testing is based on one-dimensional wave propagation where pile impedance variations and soil resistance result in predictable motions at the pile head (Rausche et al., 1988). The time after impact when the reflected waves are measured is directly proportional to the distance from the origin of the reflected wave. When the head of a pile is impacted, a compressive stress wave travels down the shaft at a speed of propagation, c, which is a function of the material elastic modulus, E, and the unit mass, ρ.

$$c = (E/\rho)^{1/2} \tag{1}$$

Pile impedance, Z, is defined as "EA/c" where A is the material cross-sectional area. Therefore variations in impedance indicate changes in shaft cross-section area or concrete quality. For a uniform pile with no soil resistance and a length, L, the input compressive wave reaches the pile toe at a time L/c, reflects as an upwards traveling tension wave and reaches the pile top at a time 2L/c later. Soil resistance or increases in pile impedance, Z, generate upwards travelling compressive waves, while decreases in impedance generate upwards traveling tension waves. A soil resistance or impedance change at a distance "x" below the shaft top will generate a reflection which arrives at the pile head at a time 2x/c after impact. The location (depth) is computed from the assumed wave speed, c.

When the downward traveling compressive stress wave, W_i, created by the hammer impact at the pile head reaches an impedance change from Z_1 to Z_2, a wave reflects upwards, W_u, and another wave continues downward, W_d, such that both continuity and equilibrium are satisfied:

$$\begin{gathered} W_d = W_i\ [2Z_2/(Z_2 + Z_1)] \\ W_u = W_i\ [(Z_2 - Z1)/(Z_2 + Z_1)] \end{gathered} \tag{2}$$

At the pile toe, Z_2 is zero, therefore, the impact compressive wave is completely reflected in tension.

For normal applications, where the pile head is exposed, the accelerometer is attached to the pile top using a gel or wax material usually near the center of the head and a vertical impact is then applied. However, for in-service piles, the hammer impact can often be applied to the concrete cap or beam directly above the pile. It is however preferable to attach the accelerometer to the side of the shaft below the cap or beam, if possible.

The measured pile top acceleration is integrated to velocity and the result displayed graphically on the P.I.T. screen. It helps to average several impacts to remove unwanted "noise" while emphasizing repetitive features. Often, the velocity data is subjected to an exponential amplification with time to amplify reflections (such as from the toe) which are reduced due to pile and soil damping (Rausche, et al., 1992).

A velocity record with an identifiable toe reflection and no major tensile reflections along the shaft indicates a structurally sound shaft (such as in Figure 1). Major tensile reflections above the pile toe indicate significant reductions in shaft impedance from changes in pile cross-section or concrete quality. The velocity may also be transformed to the frequency domain with FFT analysis for assessment of integrity and pile length. In the frequency domain, repetitive peaks occurring at regular intervals of frequency (Δf) are converted to a corresponding depth, x, at which the change in impedance or pile toe occurs from:

$$x = c/2\Delta f \tag{3}$$

Where the length is known and a reflection from the pile toe is indicated, the wave speed is computed from the reflection arrival time. When testing to determine shaft length, the wave speed has to be assumed. The wave speed in concrete may vary by as much as 12% (typically ranges from 3400 m/sec to 4300 m/sec). Therefore, similar variations in computed length are possible.

P.S.T. Testing

The P.S.T. method is a non-destructive method which uses parallel seismic theory to determine the depth of concrete piles or shafts, timber piles, steel piles or wall foundations. A sensitive hydrophone is inserted in a bore hole filled with water adjacent to the unknown foundation element. A low strain wave is then introduced to the pile or retaining wall with a hand held hammer. The wave travels down the shaft and outward through the soil medium and the time required for each impact wave to reach the hydrophone is determined graphically for successive hydrometer depths.

When the hydrophone is below the pile toe and incremently moved up, the time required for the impact wave to reach the hydrophone decreases linearly with the distance from the pile toe to the hydrophone (the distance the wave travels in the soil medium decreases). When the hydrophone is above the pile toe and raised incrementally, the required time for the impact wave to reach the hydrophone decreases at a higher rate since the speed of wave travel in the pile is significantly faster than the speed of wave travel in the soil. The pile depth is determined from the point where the slope of the line intercepting the first time of wave arrival changes with successive depths. This testing procedure is illustrated in Figure 2.

P.S.T. testing is a relatively new method for testing shafts for length determination. The current system described is specifically written for portable IBM PC compatible computers. P.S.T. testing requires that a hole be augered and a PVC pipe be inserted adjacent to the pile or wall foundation in question. Once inserted, the pipe is filled with water. The depth of the pipe should be at least 3 m below the expected bottom of the pile or wall foundation. If the pipe is shorter than the pile, the test may only indicate a minimum length. Generally, the pipe should be located as close as possible to the pile or wall. The likelihood of the wave energy reaching the hydrophone is reduced with increasing distances.

The hydrophone is lowered to the bottom of the water filled pipe and a vertical hammer impact is applied directly to the pile top or to the superstructure if the pile top is not accessible. The instrumented hammer is used to define the impact time and the time to arrive at the hydrophone is measured. The same procedure is performed as the hydrophone is raised incremently. As Figure 2 illustrates, the foundation element depth is determined from the point where the slope of the line intercepting the first time of wave arrival changes with successive depths. The output of the P.S.T. is therefore simply a graph of time dependent signals versus known depth of hydrophone.

In order for this test to be successful, the speed of wave propagation in the soil medium must be significantly less than the wave speed in the foundation element in question. Fortunately, the speed of wave propagation in most granular or fine grained soils is typically 2 to 12 times slower than the speed of wave travel in concrete or timber and 3 to 16 times slower than the speed of wave travel in steel. The speed of wave propagation typically ranges from 3400 m/sec to 4300 m/sec in concrete, 3300 to 3800 m/sec in timber and 5,120 m/sec in steel. Wave speeds in granular and fine grained soils however are much lower and generally range from 300 to 1800 m/sec. Table 1 gives typical speeds of propagation of seismic waves in various subsurface materials. Note that some types of sandstone, shale, granite and basalt may have speeds of wave propagation similar to that of concrete, timber and steel.

indicated a pile length of 8.5 m (28 ft) below the bottom of the concrete cap. As indicated previously, the accelerometer was placed approximately 0.9 m below the cap, therefore the pile length determined from P.I.T testing of 7.6 m (25 ft) compares very well to that determined from coring.

Figure 4 shows the averaged, amplified velocity and acceleration of another pile tested (labeled TP2). The length, assumed wave speed and amplification are also given. A clear toe response indicates a length of 7.8 m (25.5 ft). The impact on this pile was also applied by striking a notched area using a small hammer weighing 1 lb (0.45 Kg). An FFT analysis was performed on this record and the resulting frequency response is shown in Figure 5. The record indicates a repetitive, sinusoidal response indicative of the dominant frequency. Using equation (3) the pile length can be computed from the wave speed and the frequency difference. This computation results in a pile length of 8 m (26.1 ft) which compares very well with the length from the time domain analysis.

P.S.T. Testing

Sample records are shown in Figure 6. The records were obtained from a test performed on a 9.2 m (30 ft) long, 50 cm (20 inch) diameter, drilled shaft. A 12 m deep bore hole was placed approximately 0.5 m from the pile. The hydrophone was first inserted to the full depth of 12 m (40 ft) and then moved upwards using increments of 30 cm (1 ft). Note that the slope of the line indicating the first time of wave arrival changes at 9.3 m (30.5 ft) which confirms the shaft length. Figure 6 also shows the impact force measured with the instrumented hammer. The impact force is used to determine the "beginning" of the impact so that the wave travel time can be measured. This test method is simple to perform and can be performed relatively quickly, although the PVC pipe installation is not trivial.

As indicated earlier, due to the wave speed variances in concrete, the embedment depth may only be accurately determined to within approximately 12% using the P.I.T. method. However, the embedment depth is determined much more accurately using P.S.T. testing irrelevant of the pile or foundation element material since P.S.T. testing does not require any wave speed input (the method is based only on the relative time of wave arrival) since the hydrophone position is always measured and known.

Limitations

Some limitations are inherent to both P.I.T. and P.S.T. methods. With P.S.T., the impact wave must reach the hydrophone so that the time of travel is measured. Similarly, in P.I.T testing, the impact wave must reach the shaft toe and return to the top so that a toe reflection is evident in either the time or frequency domain. For relatively long piles, the impact wave may be dampened out prior to reaching the hydrophone for P.S.T. or reaching the pile top for P.I.T. Of course, any type of mechanical splice which completely reflects the wave at the splice also limits the success of either test. However, these two limitations would still allow for a determination of a "minimum" depth or depth to the splice. Also, because the wave only has to travel downward, P.S.T. testing should be able to measure longer pile lengths than with P.I.T. testing. One additional limitation with P.S.T. would result from testing a shaft which has been "socketed" into a rock which has a wave speed similar to that of the shaft. In that event, the test would not be able to determine the socketed depth.

Conclusion

It may be impractical or expensive to perform destructive type tests such as core drilling to determine pile lengths of existing foundation elements. Core drilling may also give erroneous results if the drilling bit deviates from the shaft axis and exits on the shaft side. Non-destructive methods such as P.I.T. or P.S.T. may be used to determine length of concrete or timber piles (P.S.T. testing can also be used to determine length of steel piles) piles although these methods have some inherent limitations especially for piles which support the superstructure or long piles which exhibit high friction. Sample data from P.I.T. testing has been presented showing the results of testing concrete filled, steel pipe piles supporting a cap and bridge superstructure. One of these piles was also cored for length determination. As shown, both the coring and the P.I.T. testing indicated a similar pile length. Sample data from a P.S.T. test performed on a concrete drilled shaft confirmed the shaft's known length.

Both P.I.T testing and P.S.T. testing offer a practical, inexpensive and reliable non-destructive test method for embedment depth determination. of foundation elements such as shafts, piles or retaining walls. P.I.T testing on concrete piles should be attempted first since this method is generally quicker and less expensive to perform. The alternate P.S.T. test can be attempted where P.I.T testing is not successful.

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Table 1: Speed of Propagation of Seismic waves in subsurface materials.

MATERIAL	VELOCITY m/sec	MATERIAL	VELOCITY m/sec
Top Soils:		Phylite, York Pa.	3050 to 3350
light and dry	180 to 275		
moist, silty	300 to 400	Sandstone:	
clayey	400 to 600	Upper Susquehanna	4270
sandy clay	380 to 650	Panama Canal, Pacific end	2130 to 2750
wet loam	760		
		Colorado-dense, hard and continuous with few seams	2210
Wet, Dense Clay	900 to 1800		
		Colorado-weathered seams and soft areas	1440
Ruble or Gravel	600 to 800	Smoky Hill River, Kansas	1830 to 2290
		Sandstone Conglomerate	2440
Cemented Sand	850 to 980		
		Chalk:	
Cemented Sandy Clay	1150 to 1280	Fort Randall Dam site	
		above water table	1920 to 2130
Saturated Sand	1400	below water table	2440
Sand	1400 to 2550	Granite:	
		Solid and Monolithic	5640
Clay, Clayey Sandstone	2000	Friable and highly decompose	470
		Softened and partly decomp.	3200
Glacial Till			
Upper Susquehanna	1700 to 2250	Badly Fractured and Partly Decomposed	670
		New Hamphshire - badly	
Glacial Moraine Deposit; California		Brocken and weathered	910 to 2440
dry	750 to 1500	Sightly weathered	3050 to 3960
saturated	1500 to 2130	Unweathered, no seams	4880 to 6100
Cemented Lava Agglomerate		Granodiorite	4570
California	1500 to 1830		
Loose Rock-Talus	380 to 760	Basalt - Panama Canal weathered and fractured	2740 to 4270
Weathered and fractured Rock	450 to 3050	Limestone, Dolomite, Metamorphic rocks, Massive rocks	5000 to 6150
Shale:			
Olentangy River, Ohio	2750 to 3350		
Upper Susquehanna	3100 to 3900	Diabase - Broad River South Carolina	6000
Panama Canal Zone	2130 to 2440		
Mancos, Colorado	800 to 880	Greenstone - California	
Romney Shale, weathered	1220 to 2000	tightly seamed	4900
Romney Shale, good	3350	slightly seamed	4050
John Marshall Dam site	880 to 1300		

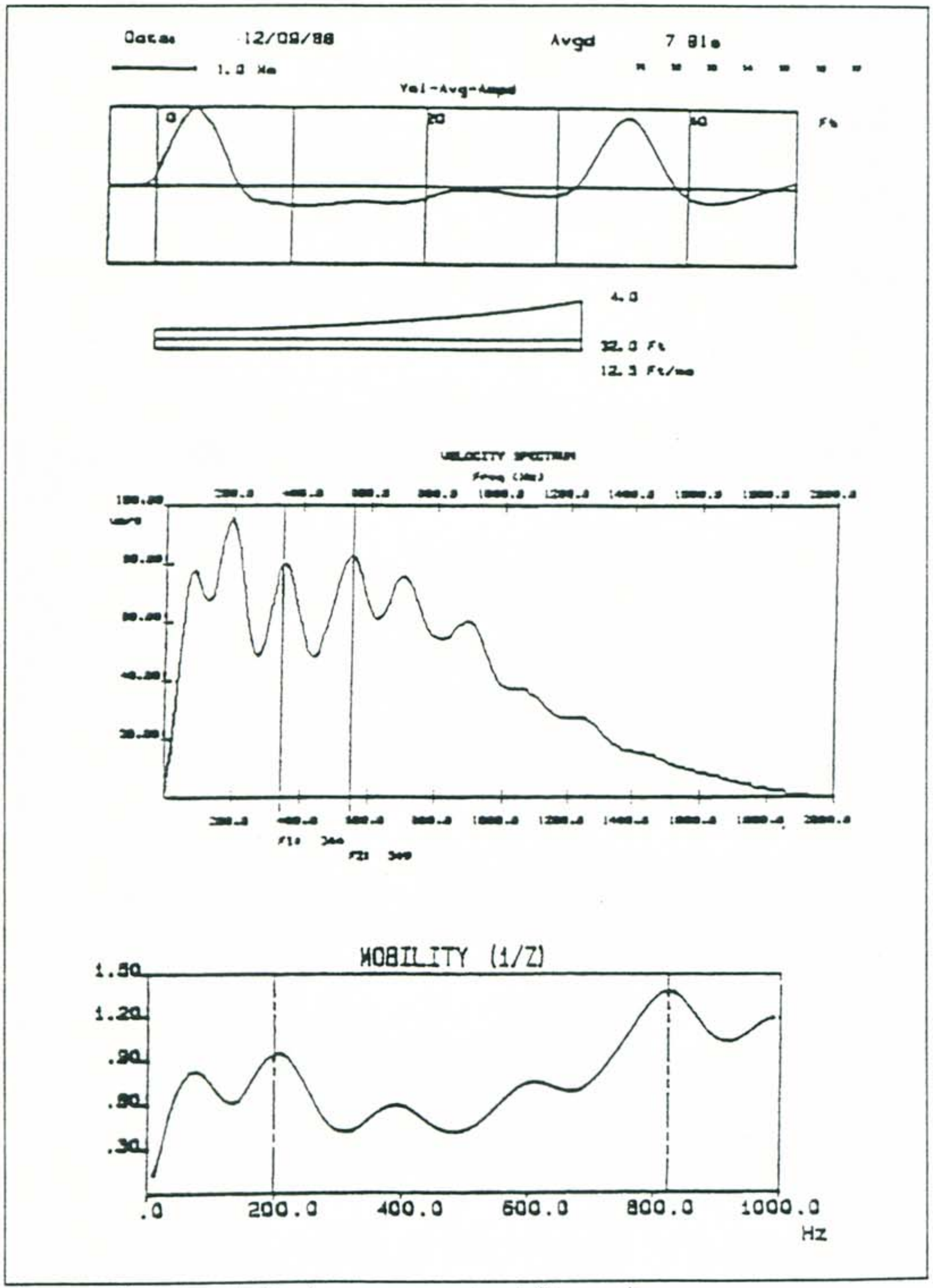


Figure 1: Sample velocity, frequency, and mobility graphs

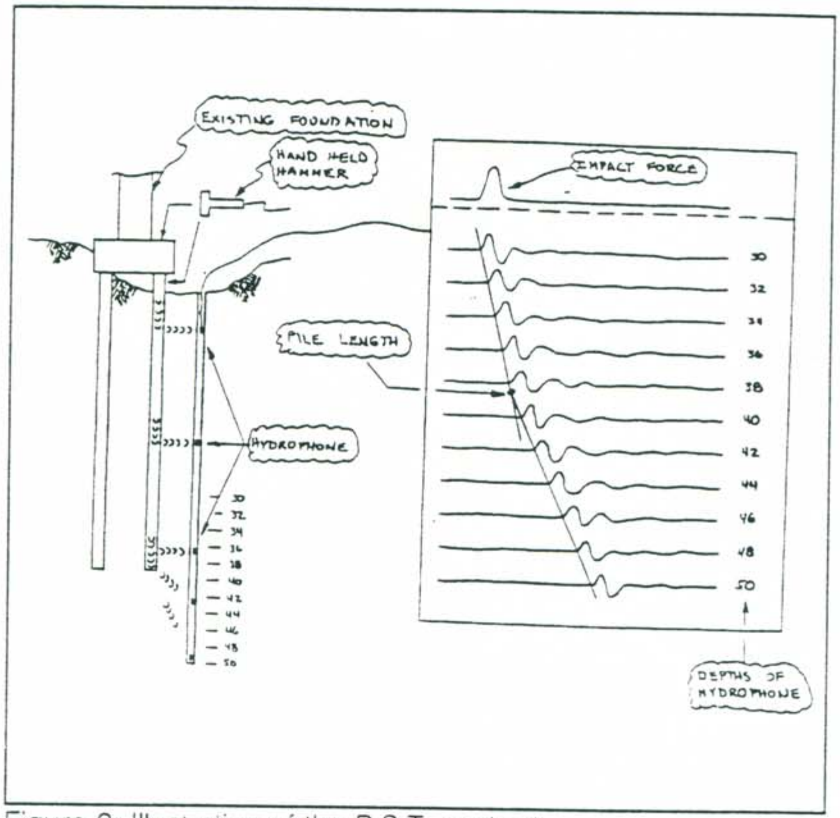


Figure 2: Illustration of the P.S.T. method

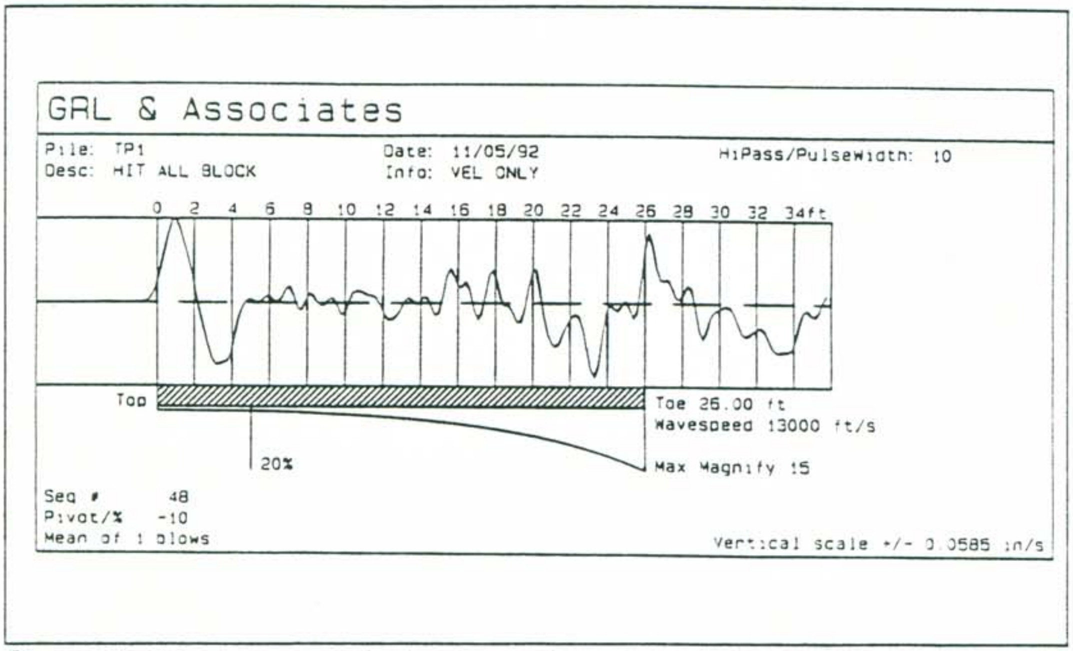


Figure 3A: Velocity record obtained by striking the aluminum block

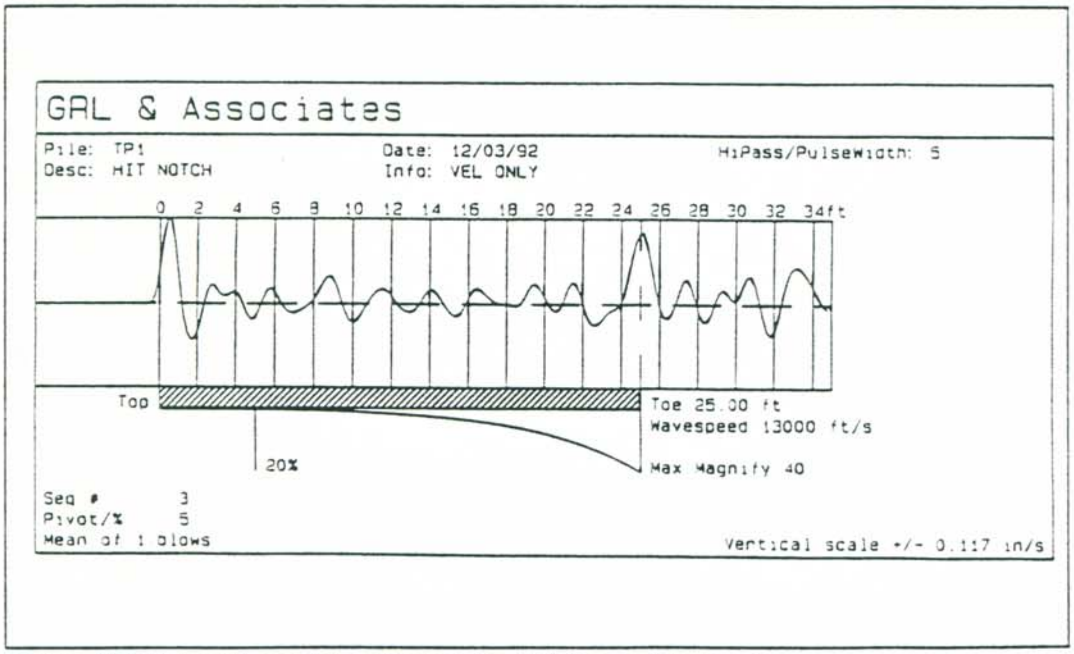
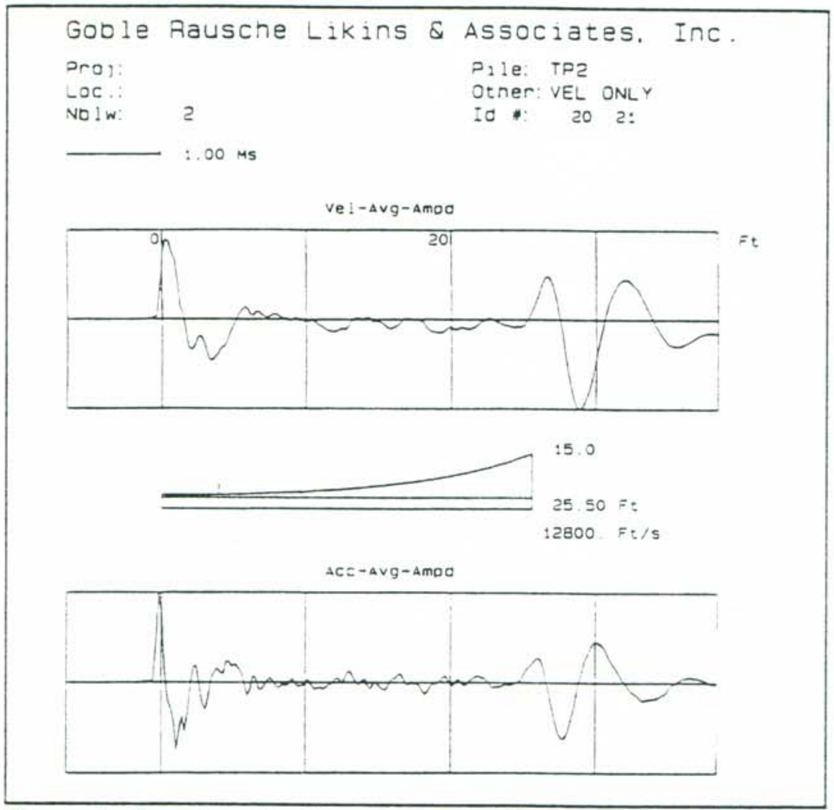


Figure 3B: Velocity record obtained by striking notch in pile



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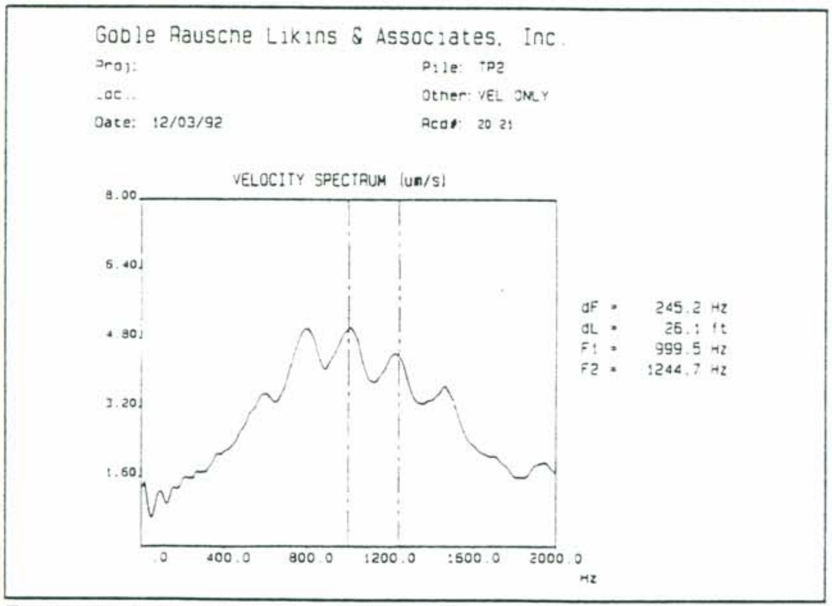
Proj:
Loc.:
Nblw: 2
Pile: TP2
Other: VEL ONLY
Id #: 20 21

Figure 4: Sample velocity and acceleration records for TP2



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Proj:
Loc.:
Date: 12/03/92
Pile: TP2
Other: VEL ONLY
Rcd#: 20 21

dF = 245.2 Hz
dL = 26.1 ft
F1 = 999.5 Hz
F2 = 1244.7 Hz

Figure 5: Velocity spectrum for TP2

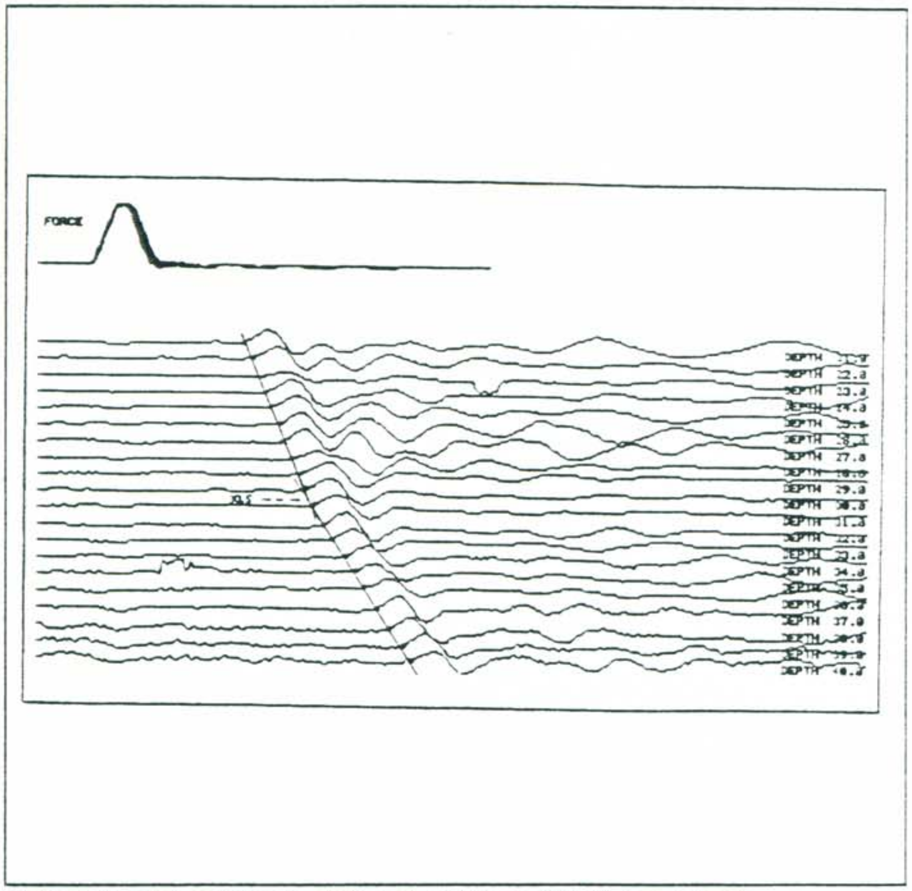

Figure 6: Typical P.S.T. data for a 9.2 m (30 ft) long shaft