Application: Nondestructive Testing of Drilled Shaft Foundations

Nondestructive tests offer a rapid, economical means of evaluating the characteristics of deep foundations (i.e. drilled shafts, piles, auger-cast piles). There are two broad applications:

- quality control testing of new foundations and
- determining the type and depth of "unknown" foundations.

For the first application, nondestructive tests are used to check for defects in cast-in-place foundations such as drilled shafts. The figures on the next page illustrate two methods of constructing cast-in-place foundations. Defects in the constructed foundation may arise from one of the following problems that could adversely affect the performance of the shaft (O'Neill 1992).

- drilling,
- casing,
- slurry, or
- concreting problems.

Nondestructive tests are ideally suited to use as a construction quality control tool to detect the presence or absence of a void arising from one or more of these problems.

Sonic Echo

Conceptually, the sonic echo method is very simple. The end of the shaft and any defects that exist along its length cause reflections of the seismic waves as they propagate downward through the shaft. By observing the time required for these reflections to return to the top of the shaft, the depth to the reflector can be determined:

$$z = \frac{V_b \Delta t}{2} \qquad (1)$$

where z is the depth to a reflector (a defect or the bottom of the shaft), V_b is the longitudinal wave velocity in concrete, and Δt is the travel time of the reflected wave. Since Δt is a two-way travel time, the numerator in Eq. 1 must be divided by two.

The acceleration time history recorded at the top of a drilled shaft is shown in Figure 1. There is a clearly identified reflection that occurs 9.47 msec after the initial impact. The longitudinal wave velocity of the concrete measured on 15-cm by 30-cm (6-in. by 12-in.)

test cylinders was equal to 3700 m/sec (12,130 ft/sec). Using the observed travel time and compression wave velocity, the depth to the reflector is calculated to be 17.5 m (57.4 ft). The depth agrees well with the design length of 16.9 m (55.5 ft). No other reflections can be identified in the acceleration record.

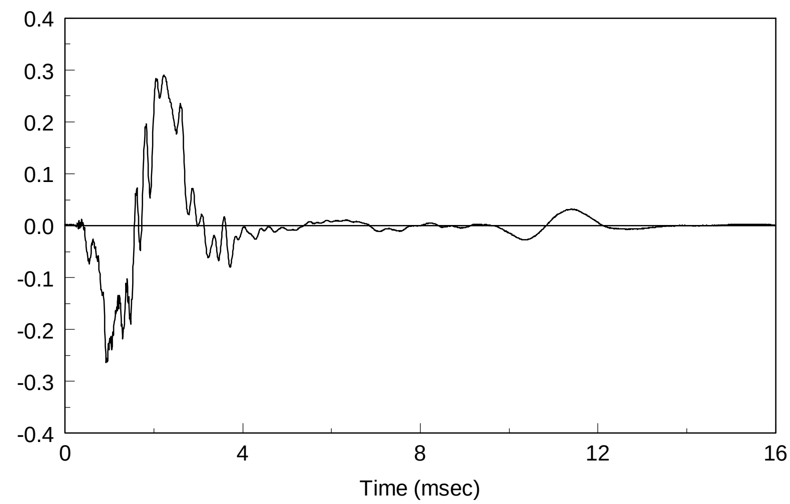


Figure 1 Sonic Echo Test Results

In the absence of a measured value of V_b, it is common to assume the velocity of the concrete using the guidelines shown in Table 1.

Table 1 Suggested Compression Wave Velocity Ratings for Concrete Quality

Compression Wave Velocity (ft/sec)	**General Concrete Condition**
Above 13,500	Excellent
10,800 to 13,500	Good
9,000 to 10,800	Questionable
6,300 to 9,000	Poor
Below 6,300	Very Poor

Sonic Mobility

Theory

Wave propagation in a long, slender foundation can be reasonably modelled using the one-dimensional wave equation. Recall that the one-dimensional wave equation is:

$$\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho} \frac{\partial^2 u}{\partial x^2} \tag{2a}$$

or

$$\frac{\partial^2 u}{\partial t^2} = V_b^2 \frac{\partial^2 u}{\partial x^2} \tag{2b}$$

Consider a rod of finite length L with a free-fixed boundary conditions. This corresponds to a drilled shaft foundation end bearing into rock.

Consider a solution to the wave equation of the form:

$$u(x,t) = U(x)e^{i\omega t} \tag{3}$$

with U(x) of the form:

$$U(x) = A\cos\left(\frac{\omega x}{V_b}\right) + B\sin\left(\frac{\omega x}{V_b}\right) \tag{4}$$

At x = 0 (the fixed end), U = 0 and at x = L, $\frac{\partial U}{\partial x} = 0$. The first boundary condition implies A = 0. The second results in:

$$B\frac{\omega}{V_c}\cos\left(\frac{\omega L}{V_c}\right) = 0 \tag{5}$$

This equation is satisfied only if:

$$\frac{\omega_n L}{V_b} = \frac{\pi}{2} + n\pi \quad \text{for } n = 0, 1, 2, ... \tag{6}$$

$$f_n = \frac{V_b(2n+1)}{4L} \tag{7}$$

To determine the length of the shaft (or possibly the depth to a significant defect), we can rearrange Eq. 7 as follows:

$$L_{fixed} = \frac{V_b(2n+1)}{4f_n} \tag{8}$$

where L_{fixed} denotes the length of the drilled shaft with a fixed end condition. We can derive similar expressions for other boundary conditions. For example, suppose that the drilled shaft is "floating" and relies primarily on side friction for resistance. In this case, the drilled shaft is more accurately modeled as a "free" end. The corresponding equation for this condition is:

$$L_{free} = \frac{V_b n}{2f_n} \tag{9}$$

Clearly, the length is not only a function of the natural frequency of the drilled shaft in longitudinal vibration (and the longitudinal velocity), but also of the end condition. This raises an important practical question because the end (bottom) of the shaft is not perfectly fixed or free and, in fact, may not be known.

To solve this practical problem, consider the *difference* between any two adjacent natural frequencies. For the fixed end condition:

$$\Delta f = f_{n+1} - f_n = \frac{V_b}{4L}\left[2(n+1)+1-(2n+1)\right] = \frac{V_b}{2L} \tag{10}$$

After rearranging, we obtain:

$$L = \frac{V_b}{2\Delta f} \tag{11}$$

For the free end condition:

$$\Delta f = f_{n+1} - f_n = \frac{V_b}{2L}(n+1-n) = \frac{V_b}{2L} \tag{12}$$

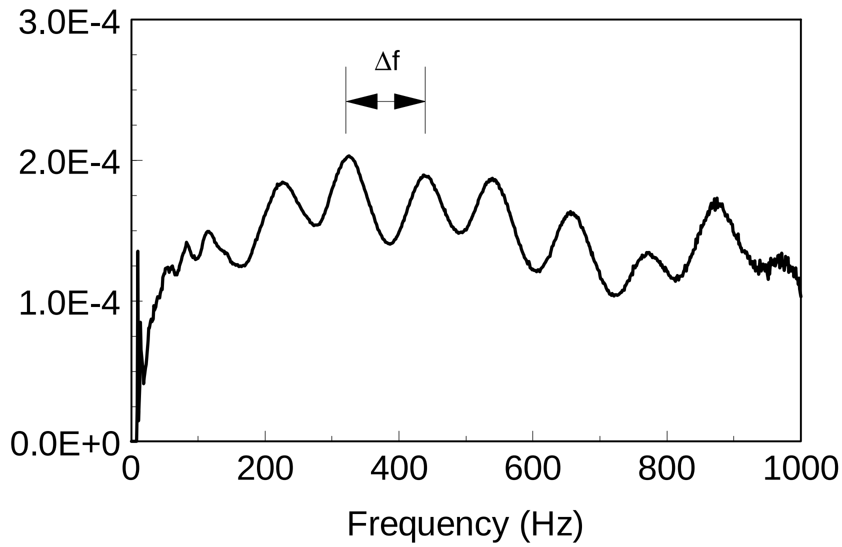
which is the same result we obtained for the fixed end. Thus, although the natural frequencies differ for various boundary conditions, the *difference* between adjacent natural frequencies is the same for different boundary conditions. We can take advantage of this fact to determine the length of a drilled shaft without having to assume or know the boundary conditions at the bottom of the shaft.

Testing Procedure

In the sonic mobility method, the force and acceleration time histories are transformed to the frequency domain using the FFT analyzer. The results are the spectra, P(f) and A(f), of the force and acceleration, respectively. The mobility is a frequency response function defined as the particle velocity observed at the top of the shaft normalized by the force:

$$\text{Mobility} \equiv \frac{V(f)}{P(f)} = \frac{A(f)}{i\omega P(f)} \tag{13}$$

where V(f) is the particle velocity spectrum, $\omega = 2\pi f$ is the circular frequency, and i is $\sqrt{-1}$. The particle velocity spectrum is obtained by integrating the particle acceleration spectrum in the frequency domain as shown in the right-hand term of Eq. 13. The mobility is a complex quantity, but typically only the magnitude is plotted. The figure below shows the mobility curve measured for a drilled shaft. The shaft length and depth to defects, average diameter, and stiffness are determined from the curve using the following interpretive procedures.



The length of the shaft and the depth to any defects are determined from the spacing between peaks, Δf:

$$L = \frac{V_b}{2\Delta f} \tag{11 again}$$

In the figure, the spacing between adjacent peaks is 107.5 Hz. This corresponds to a shaft length of 17.2 m (56.4 ft) which also agrees well with the design length of 16.9 m (55.5 ft). Defects in the shaft would appear as more widely spaced peaks with larger amplitudes. No other peaks are evident in the figure, indicating that the shaft has no major defects.

The average impedance of the shaft can be determined using the average value of the mobility at higher frequencies:

$$N = \frac{1}{\rho_c A V_b} \tag{14}$$

where N is the average value of the mobility at high frequencies, ρ_c is the mass density of concrete, and A is the average cross-sectional area of the concrete. In the figure the average value of the mobility from 200 to 1000 Hz is approximately 1.5 x 10^{-4} mm/sec/N. Using the measured V_b and a measured unit weight of 23.5 kN/m^3 (150 pcf), the average diameter of the shaft is 979 mm (38.5 in.).

The low-strain stiffness is calculated from the slope of the initial portion of the mobility plot:

$$K_{mob} = \frac{2\pi f_M}{\left|\frac{V(f)}{P(f)}\right|_M} \quad (15)$$

where K_{mob} is the low-strain stiffness, f_M is the frequency of a point on the initial slope of the curve, and term in the denominator of Eq. 15 is the magnitude of the mobility at that frequency. The low-strain stiffness varies depending on the frequency used in Eq. 15. For this example, the stiffness varies from 2.0 MN/mm to 2.7 MN/mm (11,421 kips/in. to 15,420 kips/in.) when frequencies from 25 to 50 Hz are used in Eq. 15.

The low-strain stiffness is often several times larger than the working load stiffness because of the difference in strain levels. For this reason, the low-strain stiffness is often used as a relative measurement. Once a typical value is established for the shafts at a site, shafts that have stiffnesses that differ significantly from the typical value can be identified as suspect.