Dynamic Testing of Drilled Shafts

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Concerns about the construction of drilled shafts lead to the need for further testing. To confirm the basic design, a static test is often performed to verify capacity. The ultimate capacity will be the lesser of the soil resistance and the structural strength, affected by the integrity of the shaft. Because of the high costs associated with static tests, however, they cannot be justified economically to verify integrity. Several integrity testing techniques exist, but many require substantial preparation, which translates into extra cost. Lower-cost alternatives to static testing and integrity inspection are presented that can be applied to any drilled shaft or driven concrete pile selected for testing after construction. The capability of this technology on a true Class A prediction event is demonstrated.

Dynamic testing of drilled shafts for bearing capacity (*1*,*2*) and integrity (*3*,*4*) provides a reliable and economical alternative to static load testing. These methods have been used worldwide for many years because of their low costs and time-saving advantages. Integrity testing using the low strain pulse-echo method is particularly fast and cost-effective, allowing the method to be used for essentially all shafts on a site. If bearing capacity needs to be confirmed, high strain testing methods involving dropping a weight on the shaft are used. The speed of this test and its relatively low cost allow a much larger percentage of the shafts to be tested than with any other method.

The case history reported here (*5*,*6*) was initiated by the Association of Drilled Shaft Contractors, Inc. (ADSC), and the Florida Department of Transportation and was conducted at and under the supervision of the University of Florida in Gainesville. To promote the use of drilled shafts, ADSC has supported efforts to demonstrate the reliability of dynamic testing methods as an affordable method for verification of the adequacy of the shafts. A load test shaft and two reaction shafts were monitored dynamically for integrity evaluation. The test shaft was also subjected to high strain dynamic testing and then to a full-scale static load test for comparison of capacity.

SITE DETAILS

Both the north and south reaction shafts (NRS and SRS, respectively) were 30 in. in diameter and 44 ft long. The load test shaft (LTS) was constructed with a 28-in. OD casing to 20 ft and then advanced to 45 ft with a 24-in. auger (area reduction to 73 percent of the 28-in.-diameter section). This detail was not communicated to the testing engineer until after the integrity test revealed this "defect." All shaft details are shown in Figure 1 along with a representative soil boring. The soil profile consisted of 30 ft of sand (SPT N values 6 to 13) over an approximately 6-ft clay layer ($N \approx 10$) under which limestone (unconfined compression strength q^u = 13.6 tsf) was encountered.

LOW STRAIN INTEGRITY TESTS

All three shafts were tested before the static test (the LTS was also tested after the high strain tests) to evaluate structural integrity using the pile integrity tester (PIT) and so-called low strain methods. In this test, a small hand-held hammer was used to strike the shaft and generate a low force or low strain stress wave. An accelerometer was attached to the top of the shaft, and the signal was amplified and digitized for further analysis using the PIT software. Results of several blows were integrated to velocity, averaged, digitally applied exponentially over time, and then plotted. Figure 2 shows the signal before and after amplification for the LTS and demonstrates that reflections from major cross section changes or the shaft bottom were enhanced and more easily interpreted using this amplification function. Figure 3 shows the processed results of low strain tests conducted on the LTS before and after the high strain tests. Since results were similar, it was concluded that the high strain test (discussed subsequently) did not damage the shaft. The test was also performed with an instrumental hammer, allowing computation of both force and velocity. These signals were converted by Fourier transformation to the frequency domain yielding the mobility curve. These results are beyond the scope of this paper. A thorough discussion of the testing method, analysis, and limitations is presented elsewhere (*4*).

The PIT velocity-depth results shown in Figure 1 are prepared by first converting the time scale to a length scale using the typical value of 13,000 ft/sec for the wave speed. After the input pulse, the curve for a uniform shaft should be free of sharp variations until the reflection from the shaft bottom. For the LTS (Figure 1), the positive velocity increase at 23 ft is interpreted as a cross section reduction and matches the designed reduction at the end of the 28-in. casing. The next major velocity increase is at 46 ft, which corresponds approximately to the design length (changing the assumed wave speed from 13,000 to 12,700 ft/sec would change the apparent length to the design value of 45 ft). If the shaft length is accurately known, the wave speed can be calculated if a clear

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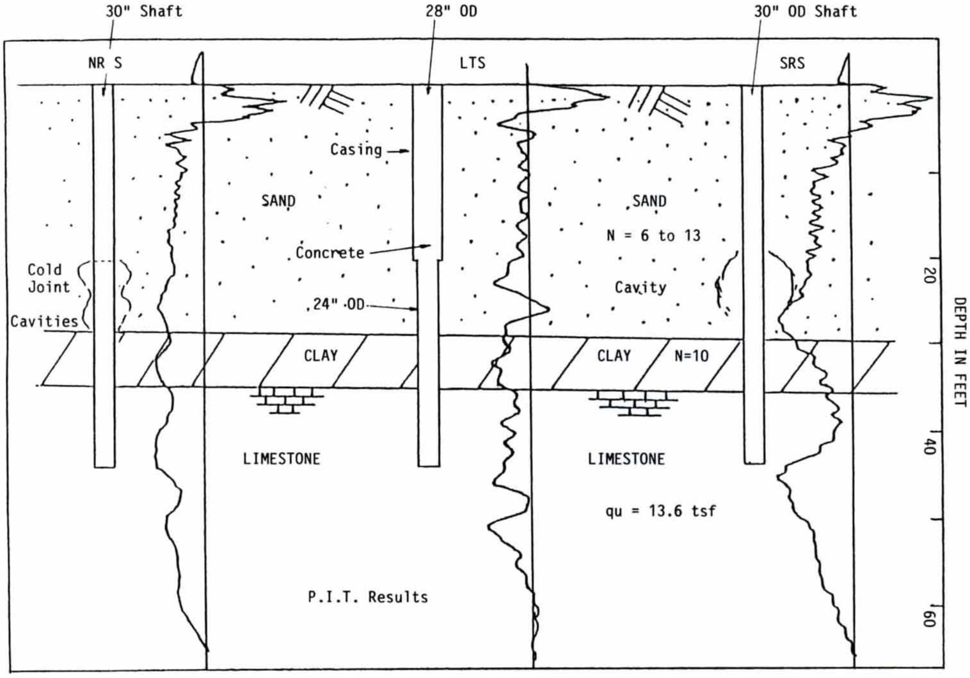


FIGURE 1 Pile and soil profiles along with PIT results.

toe reflection is observed. In this example, the time between impact and toe reflection leads to the previously mentioned wave speed of 12,700 ft/sec, which is well within commonly observed bounds of 10,000 to 15,500 ft/sec. However, this reflection occurs also at twice the depth of the cross-sectional reduction, and the second reflection could be caused by (*a*) reflection from the shaft bottom, (*b*) a secondary reflection from the midlength reduction, or (*c*) a combination of both. The greater negative amplitude near the shaft bottom for the test performed after the high strain testing are indicative of higher soil stiffness (Figure 3). The dynamic loading test cycles apparently compressed the soil under the shaft bottom and produced a stiffer strength response.

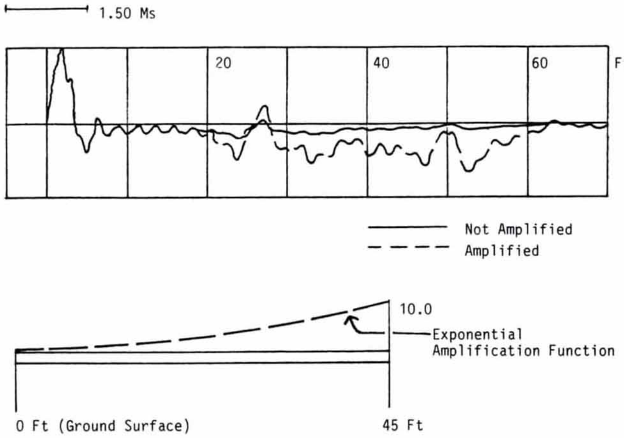


FIGURE 2 *Top*, pile top velocity histories (LTS) showing effects of data amplification; *bottom*, exponential amplification function versus shaft length.

The results of the PIT tests for the uniform reaction shafts also are shown in Figure 1. In neither case do the records indicate sharp cross-sectional reductions. The NRS test result shows a clear reflection from the shaft bottom. The SRS result shows a definite positive change in slope at this location, which for longer shafts with relatively high resistance is often interpreted as positive proof of the shaft length indicator. Although all shafts show some negative reflections, the negative reflection from about 25 ft in SRS was interpreted as a bulge or an increased cross section with subsequent return to the nominal diameter within the clay zone. The larger negative section in the PIT curve for the SRS between depths of 20 and 25 ft corresponds to the depth in which an observed high concrete take occurred during construction. All three shafts show a relative velocity increase near the limestone, indicating perhaps less overage in the shaft diameter due to the strength of this soil material.

HIGH STRAIN CAPACITY TESTS

The LTS was subjected to dynamic testing conforming to ASTM D4945 before static loading. High strain dynamic tests

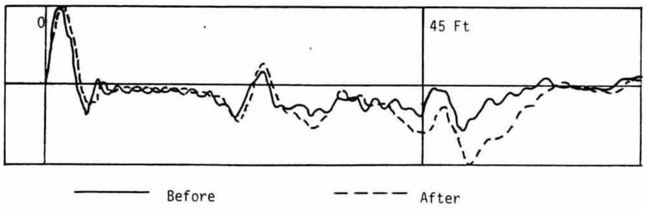
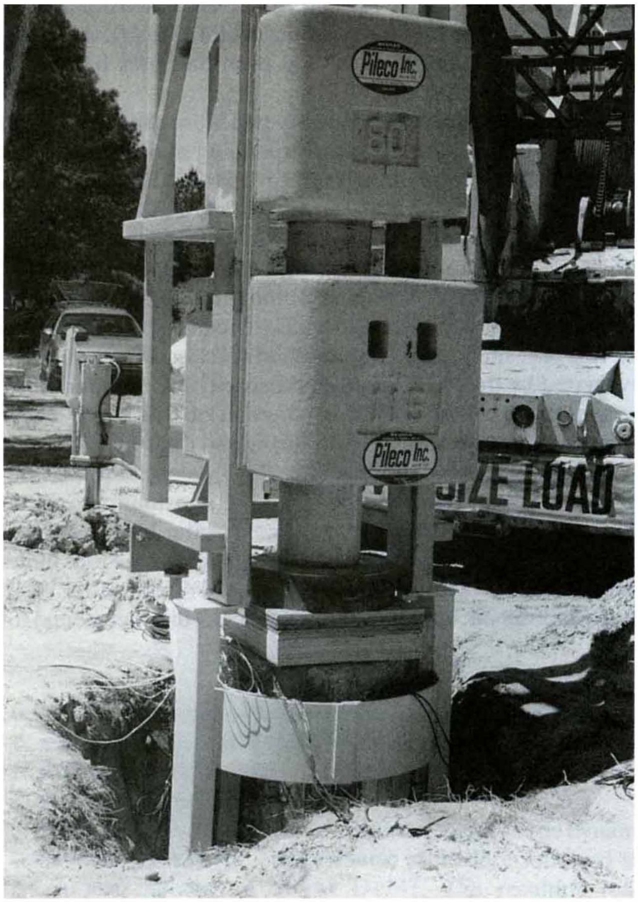


FIGURE 3 LTS velocity histories before and after high strain tests.



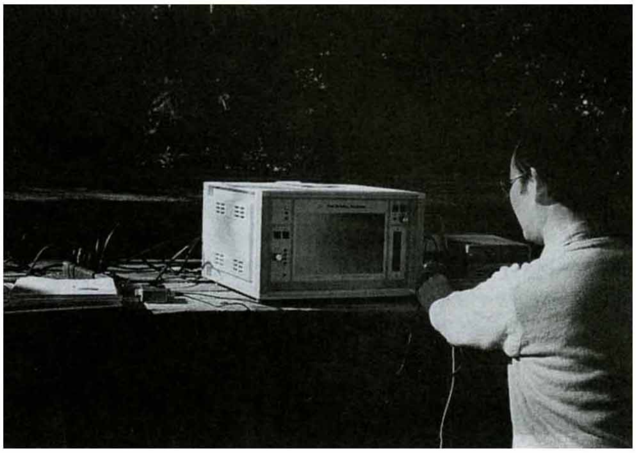


FIGURE 4 Clockwise from top left: Pileco 19.5-kip ram, GCPC Pile Driving Analyzer PIT low strain testing, instrumented pile, and cushion and striker plate.

were accomplished using a 9¾-ton drop weight supplied by Pileco of Houston. The weight was placed in a short set of swinging leads and operated by a small crane. The test consisted of four impacts with 3-, 7-, 8-, and 8-ft drop heights (i.e., with potential energies of 79.5, 136.5, 156, and 156 kip-ft). The weight struck a 3-in.-thick steel striker plate placed on top of an 8-in.-thick plywood cushion covering the top of the shaft. This configuration was designed by wave equation techniques to mobilize the expected soil resistance without causing damaging impact stresses. The impact assembly, cushion, and pile preparation are shown in Figure 4.

Dynamic capacity testing of the LTS involved the measurement of strain and acceleration approximately 3.5 ft below the shaft top. "Windows" were cut into the steel casing and the transducers were bolted directly to the concrete. The signals from the transducers were conditioned and converted to force and velocity by a Pile Driving Analyzer (PDA). The PDA was initially developed in the late 1960s for impact-driven piles and is a field testing and data acquisition system. It has worldwide acceptance in evaluating pile capacity, driving stresses, pile integrity, and hammer performance according to the Case method (*7*). It has also been used to evaluate cast in situ shafts since 1973, with current extensive use on drilled shafts by many organizations worldwide (*8*). A variety of drilled shafts, auger piles, and even barrettes have been tested with the PDA (*1,2*).

The measured force and velocity traces are shown in Figure 5 for the four impacts. The corresponding maximum stresses at the pile top ranged from 0.96 to 1.54 ksi. Energies transferred to the pile top were 7.3, 13.1, 20.4, and 21.9 kip-ft, or up to 14 percent of the potential energies. Clearly, transfer efficiencies improved (from 9 to 14 percent) as the pile top cushion compressed. Substantial amounts of energy were lost because of winch inertia and pulley friction (ram suspended by two-part line). The Case method (a closed form solution evaluated by the PDA) predicted capacity for the four blows ranging from 564 to 679 kips (average of 637 kips). These records were then subjected to further analysis by CAse Pile Wave Analysis Program (CAPWAP) (*9*), a program that calculates the total static resistance and its distribution and, on the basis of these values, a predicted static load-deflection curve for the shaft top. CAPWAP capacities for the four blows ranged from 610 to 665 kips (average 644 kips). CAPWAP also determined average quakes (elastic displacements) of

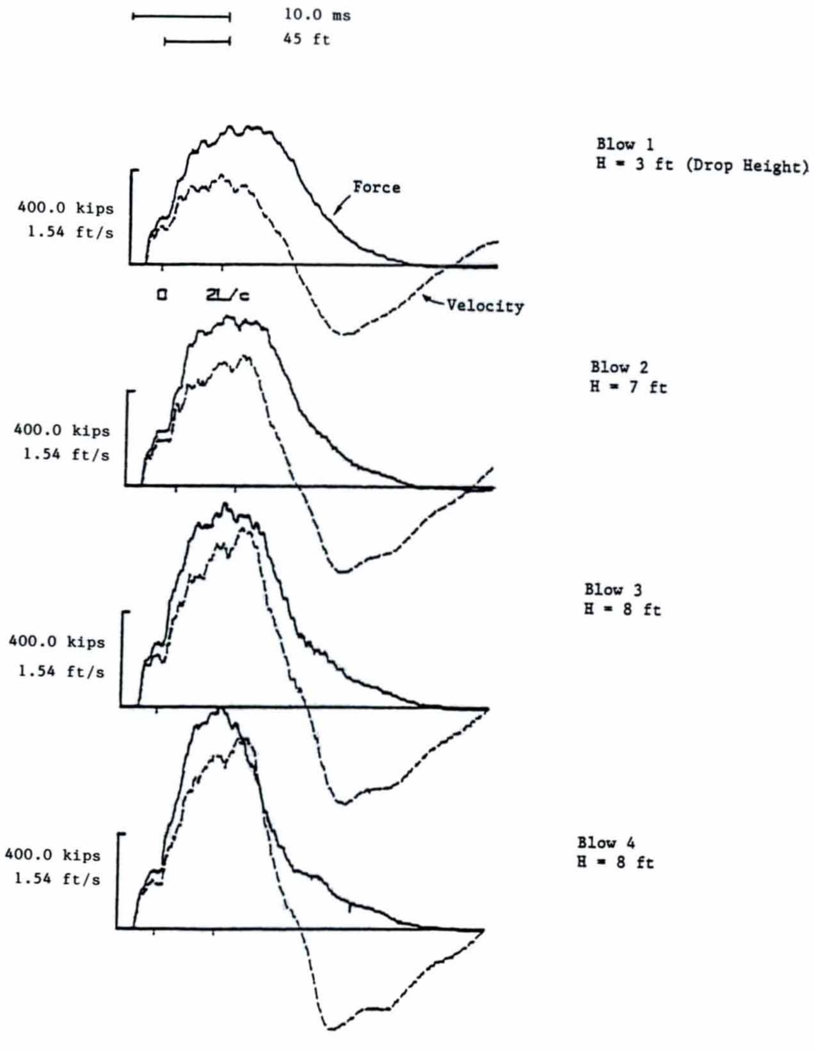


FIGURE 5 Measured pile top force and velocity for high strain capacity tests.

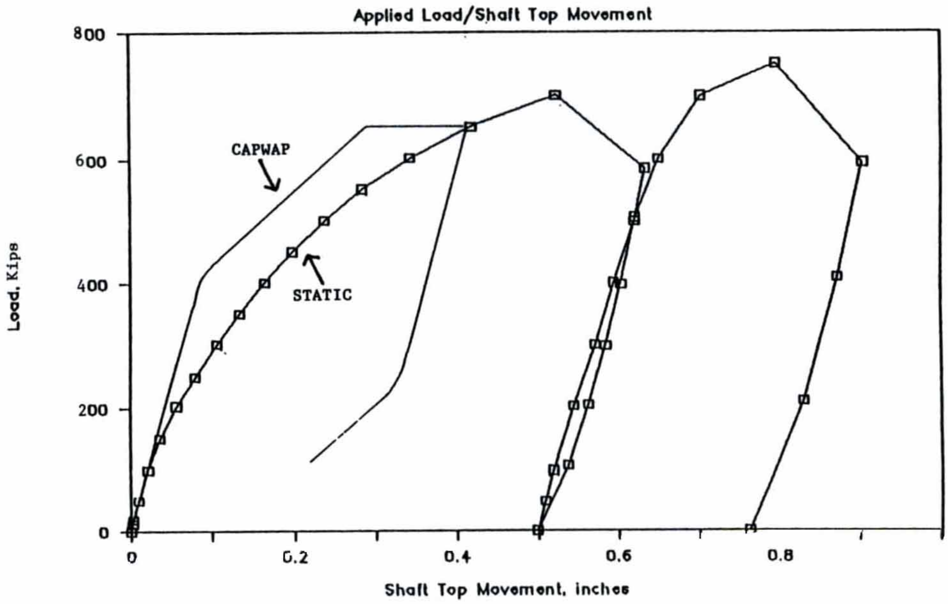


FIGURE 6 CAPWAP versus static load/top movement.

0.06 and 0.18 in. for skin and bottom, respectively, and Smith damping constants of 0.18 and 0.14 sec/ft. These results were reported to the University of Florida before obtaining knowledge of the static test results.

The LTS was subjected to a static load test after the dynamic tests were completed. The load test procedure followed the quick test method of ASTM D1143. The resulting load-deflection curve is shown in Figure 6. The shaft was loaded to a maximum load of 700 kips. If the Davisson limit load criterion is applied, the resulting failure load would be 600 kips. The shaft capacity predicted both dynamically and statically is in close agreement. A second static test cycle was then conducted to a maximum load of about 750 kips. CAPWAP load-deflection curves calculated from all four blows and the two curves from the static tests (after subtracting the creep movements) are combined in Figure 6.

CONCLUSIONS

Dynamic testing using low strain impacts by a hand-held hammer was successful in detecting planned and unplanned area changes in the constructed shafts. These area changes were independently discovered by the test engineer and verified through construction records. Thus, these methods can be of invaluable assistance in the quality assurance of drilled shaft foundations.

High strain dynamic testing for capacity evaluation did not cause damage to the shaft, as evidenced by the low strain integrity tests conducted both before and after the dynamic load tests. This result is not surprising since even the high strain impact stresses were less than 1.6 ksi in compression and 0.1 ksi in tension.

The dynamic loading apparatus performed well. A relatively low percentage (14 percent) of the hammer's potential energy was actually transferred to the shaft, probably because of losses in the cushion and the winch hoisting system. The dynamic pile top records were easily acquired and evaluated with existing equipment and methods already well proven on driven piles. The bearing capacity calculated from the dynamic tests was in good agreement with the results from the static load test. Dynamic testing of drilled shafts has already been applied to numerous cast in situ shafts worldwide with good success and represents a cost-effective, quick alternative to static tests.

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Publication of this paper sponsored by Committee on Foundations of Bridges and Other Structures.