Verification of Deep Foundations by NDT Methods

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Presented October 1993

ASCE Annual Meeting
Washington, D.C.

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Abstract

Deep foundations are designed using static analysis techniques and the soil strength and structural integrity are then confirmed by static load tests. However, static tests are time consuming and expensive. Lower cost alternative dynamic tests include high strain testing with large drop weights to estimate soil strength, and low strain testing with small hand held hammers to evaluate integrity. The authors were requested to demonstrate applicability and reliability of dynamic testing on specially constructed drilled shafts. Only after submitting dynamic results were the as built shapes and static test results revealed, making this a true Class A prediction event.

Introduction

Deep Foundations are designed to support large concentrated loads when shallow foundations are inadequate. The design is often based on a static analysis. Because of the uncertainties of soil strength obtained from exploration tests, pile capacity and integrity are traditionally verified

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by static loading of a very small sample of piles, confirming the design assumptions or providing feedback for modifications. Unfortunately, static testing is also time consuming and expensive which in effect reduces the amount of testing. Alternative tests which are relatively quick and low in cost, yet yield reliable results, are desirable. Two dynamic test methods have been subjected to extensive verification testing. For the cost of a single static test, these methods can be quickly applied to many piles making them ideal tools for quality assurance.

Low strain testing with a small hand held hammer produces a measurable pile top motion which is evaluated for shaft length and shape by the Pile Integrity Tester (P.I.T.) system; this technique is widely available in Europe and Asia and has been introduced to the United States. Since this test does not require heavy equipment or expensive access tubes and takes very little time per shaft, conceivably every shaft could be tested. Although capacity is not evaluated, these tests can identify major structural problems. Suspect shafts can then be subjected to high strain or coring tests, and either repaired or replaced.

High strain testing with a large drop weight produces forces and motions which are recorded by Pile Driving Analyzer (PDA) system; this test is now in routine application worldwide on driven piles and has also been frequently applied to drilled shafts. Providing more information than the traditional static testing, PDA tests provide quantitative assessments of hammer performance, driving stresses, and pile integrity, in addition to estimating the static bearing capacity (Goble 1980).

To investigate various non-destructive test (NDT) methods, special test shafts were constructed with known defects at Texas A&M University, sponsored by the Federal Highway Administration. Various organizations were invited to predict shaft length, determine defect presence and location, and estimate static capacity by dynamic test methods. The lengths and shaft shape details were kept secret until after the results were submitted. This was a more severe test than normally encountered (the intended drilled shaft length, installed concrete volume, and other construction observations and design details are usually known). Three of the nine shafts were statically tested by Texas A&M University. Only after submitting all dynamic predictions were the static load test results revealed. In this paper, the authors compare their high and low strain dynamic results with actual static tests and as built shaft profiles. Additional test details may be found in Baker et al. (1993).

Shaft Details

Five shafts were drilled "wet" (under bentonite slurry) at a site consisting of medium dense sand. Four additional shafts were drilled dry at a site with stiff clay. Several "abnormalities" were purposely installed to represent necking, cave in, bulbs, and soft bottoms. The "defects" were created by attaching sand bags to the rebar cages. For Shaft 2, the concrete placement was delayed after drilling, allowing the slurry to harden, producing a mudcake on the entire perimeter.

Low Strain Testing Methods

This test requires attaching an accelerometer to the top of the shaft. The shaft is then struck with a hand held hammer and the force and motion are measured. Due to the impact, a stress wave propagates down the shaft, is dampened by the surrounding soil, and reflects from the toe and also from non-uniformities along the shaft (Rausche et al. 1992). The measurements can be analyzed either directly in the time domain or converted to the frequency domain.

The time domain analysis produces a qualitative evaluation, or can model the shaft by a **signal matching** process, or directly integrate the signal (after allowance for soil effects) to determine a **shaft impedance profile**, reflecting both concrete area and modulus. The records of several blows are averaged to reduce random noise, and/or filtered to reduce low or high frequency components. Because the input pulse has an effective length (about 5 ft, 1.5 m), defects in the upper shaft require comparison of pulse length on several shafts, or simultaneous force and velocity measurement on the tested shaft.

Due to soil resistance, the propagating wave is attenuated as it travels. To compensate, an amplification function is applied to the signal which starts at a value of unity and increases exponentially to a maximum value at the expected time of the wave return from the shaft toe. Amplifying returning signals enhances evaluation of lengths or defects, a major advantage of time domain analysis. Several studies suggest that even with time amplification, stress wave reflections from the toe can only be seen (with 12 bit A/D resolution) for shafts with length to diameter ratios less than 30, unless the soils are very weak. With the now current standard of 16 bit resolution, smaller reflections can be detected allowing higher L/D ratios to be tested. Modern equipment is battery powered, and has very user friendly touch screen graphics. On actual construction sites, shaft lengths and shapes, soil profiles and installation technique are similar; a characteristic response is then generally found and shafts having abnormal response are easily identified.

The traditional frequency domain analysis required actual vibratory force excitation of the shaft through a range of frequencies. The vibrator has since been replaced by an instrumented hammer excitation containing a wide frequency spectrum. The equivalent velocity and force frequency response are obtained by Fourier transformation of the data. The velocity response is divided by the force response to obtain a mobility graph. Because time amplification is meaningless in the frequency domain, this analysis often yields clear results only on shorter shafts with clear length toe reflections before amplification. Furthermore, the frequency presentation does not include phase shift information, making the distinction of increase or decrease in section very difficult. At low frequency, a so called static pile stiffness can be calculated from the mobility graph. However, results are only of relative value and highly site dependent, and highly dependent on the data filtering.

Low Strain Test Results

The first task was to determine the unknown length for all nine shafts. In most cases a clear reflection was observed. Length determination then only depends on the assumed wave speed of the propagating stress wave. Using a value of 14,000 ft/s (4,270 m/s) based on length information given for a single shaft, all other lengths were determined. Of the nine shafts, seven lengths were accurately predicted.

Shaft 1 had a length of 55 ft (16.6 m). The P.I.T. results were initially interpreted as a length of 71 ft (21.6 m), but with a "very strong reduction at 57 ft (17.3 m)" based on a signal matching analysis which estimated a 70 % section loss (in reality the shaft toe). Had the usually available design length been given, then the correct length could be easily confirmed (within assumed wave speed accuracy) from the clear reflection at that depth.

Shaft 6 had a length of 79 ft (24 m; L/D ratio 26) with a major (44%) planned cave-in at 58 ft (17.7 m; L/D ratio 20). The P.I.T. results were initially interpreted as "either defect or toe at 58 ft (17.7 m)." Again, had the design length been available, the length could have been confirmed, and the reflection from 58 ft (17.7 m) properly labeled a major defect.

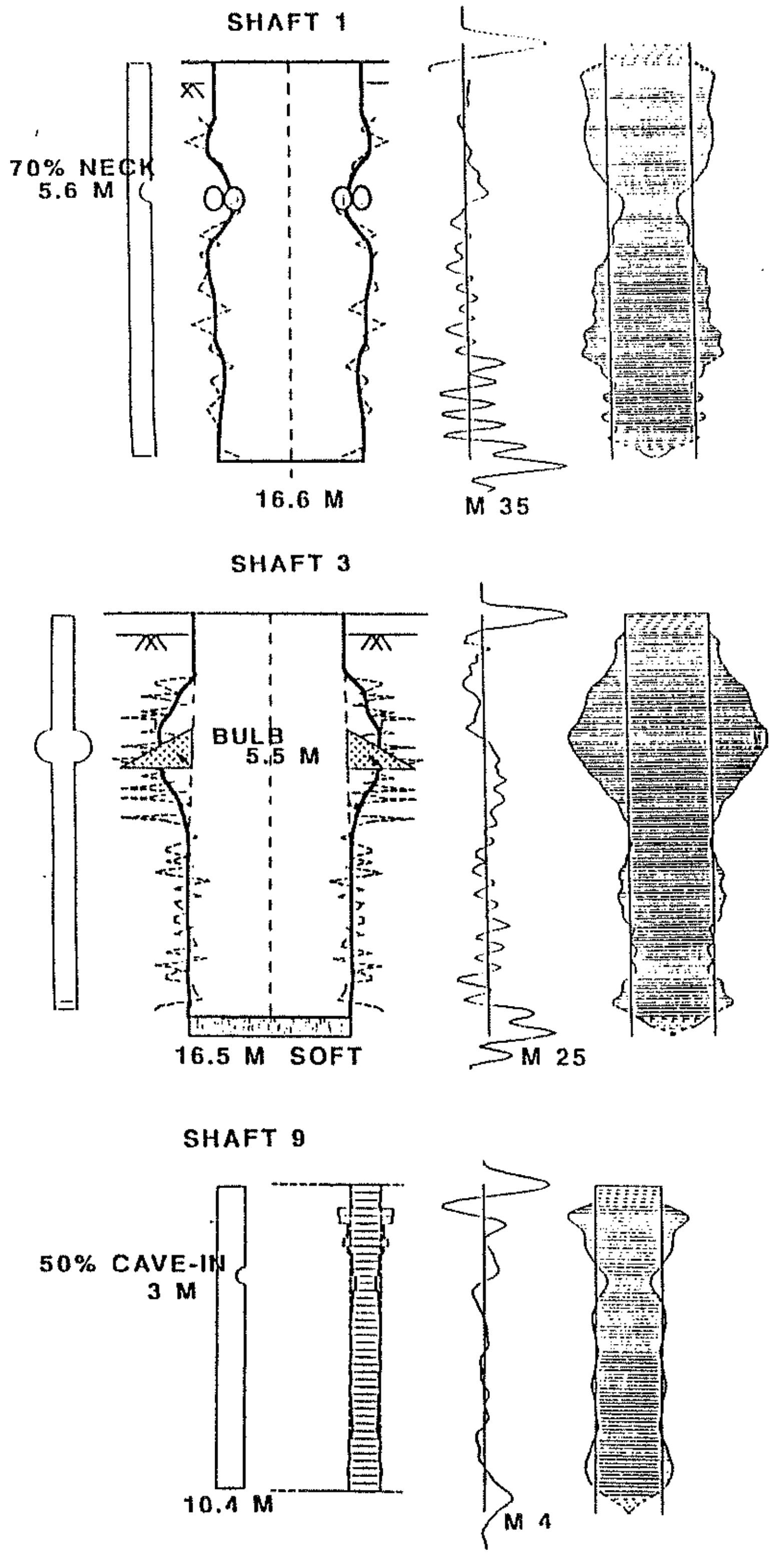

Figure 1. As planned (left), as built (Shafts 1 and 3), PITWAP signal match (Shaft 9), P.I.T. velocity signals (with magnification M), and shaft impedance profiles (right).

As requested by the test directors, further shaft evaluations revealed several additional abnormalities. The main benefit of the low strain test method is finding major defects (the structure is often tolerant of minor defects, and benefitted by enlarged sections). Low strain methods properly identified the five major cross section reductions and also identified most bulges. Minor defects (less than 20% of cross section) and constructed "soft bottoms" went generally undetected by all testing organizations (although it was not clear in the test instructions to identify soft bottoms; in hindsight soft bottoms generally produced larger toe reflections). It is reasonable to conclude that the major defects and lengths of these shafts may be correctly detected by this method.

Further analysis with the PITWAP signal matching program used measured velocity to compute the pile shape; an example result for Shaft 9 is shown in Figure 1 with the planned shape. After the report was submitted, and after the shaft shapes were revealed, the authors determined a shape profile with a technique (then under development) originally proposed by Paquet (Davis et al. 1991). The resulting impedance profiles are given in Figures 2 and 3 along with the planned profiles. The as built shape deduced from the grout takes versus depth log for selected shafts is shown in Figure 1, revealing differences with the as planned design and in general agreement with the calculated shaft profile. It is concluded that the general shaft shape can be estimated from the low strain test, although absolute accuracy is unlikely.

The authors have employed low strain methods under many conditions. On several projects, piles embedded in the pile caps or bridge piers were tested with good success. However, this method does have limitations; such as limited information from deep depths, gaps (cracks, mechanical joints) which the low energy test will not cross, defects at the upper half or third points along the length creating multiple reflections at the time the toe signal occurs, therefore masking the true toe location. Use of the method on H piles, steel shells or sheets is also not promising as the high surface area to volume quickly dampens all reflections. On a positive note, concrete filled pipe piles are easily evaluated and some success is also achieved with timber piles.

High Strain Testing Methods

This test requires a large mass to impact the shaft and mobilize the ultimate soil capacity. In pile driving, the impact generated by the pile driving hammer overcomes the soil resistance during driving. Dynamic testing is today very common and many specifications (*i.e.*, ASTM D4945, 1989) testify to their value. High strain dynamic tests were

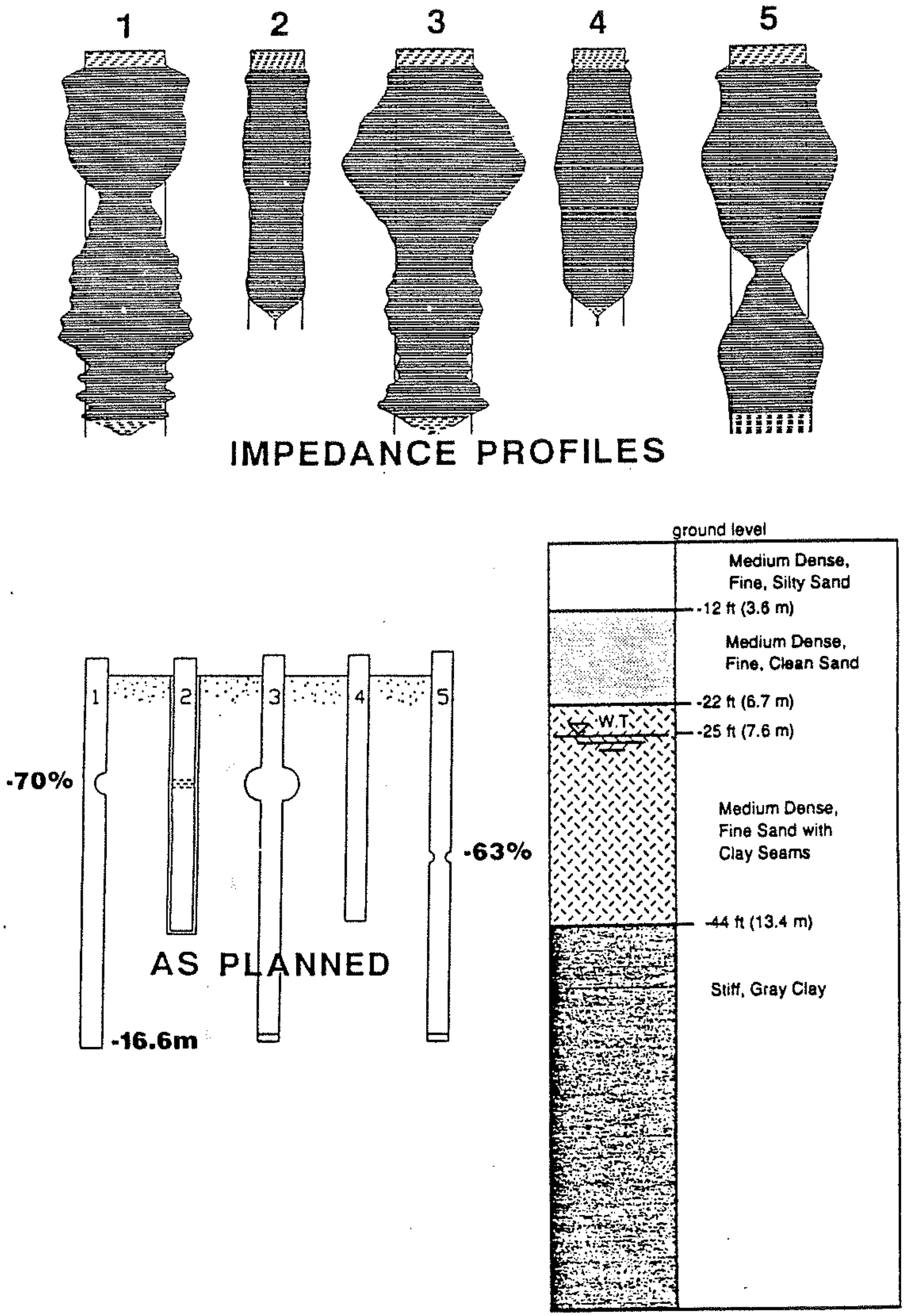

Figure 2. Impedance Profiles versus shaft "As Planned"
(not necessarily as built)

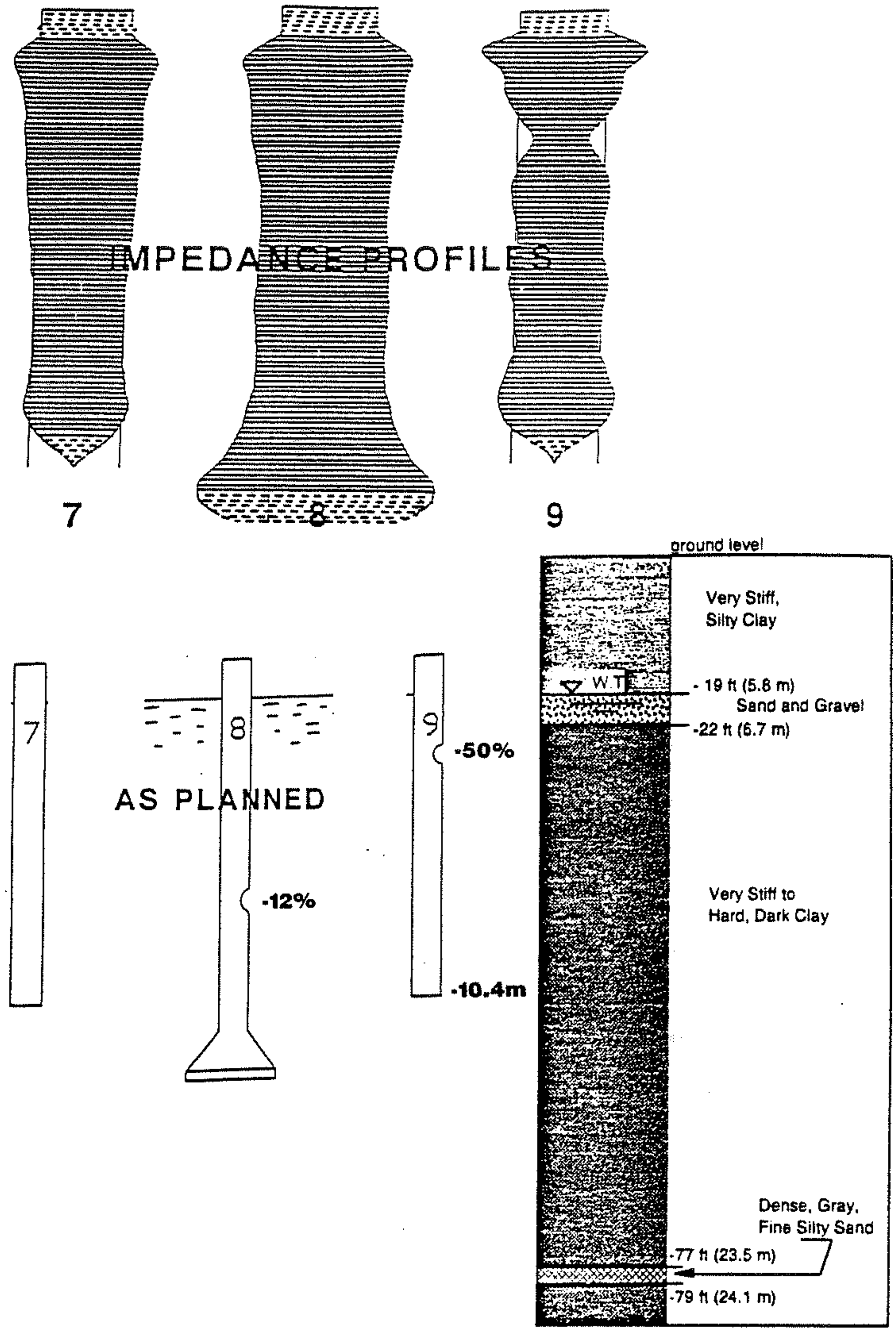

Figure 3. Impedance Profiles versus shaft "As Planned"
(not necessarily as built)

developed to estimate static bearing capacity of driven piles and have been successfully extended to testing drilled shafts. The authors' first test of a drilled shaft was performed in Mexico in 1973. Since that time, numerous successful tests have been achieved by the authors as well as other PDA users, particularly where drilled shafts are the predominate deep foundation solution. The test also calculates driving stresses and energy transferred to the pile; undetected low energy would result in higher blow counts or lower capacity.

Transducers are attached to the shaft at least one diameter below the top; either the top must be excavated or extended (often preferred as it can then be strengthened or reinforced). The impact mass should have a minimum weight of 1.0 to 1.5 percent of the test capacity and can easily test numerous shafts on the same site at low additional cost. In the current test, the ram weight was about 20 kips (90 kN). A drop weight is ideal because it can apply a single blow and can be raised to variable heights if needed, but must be properly guided to prevent eccentric impact. To further reduce potential damage, the shaft top is cushioned with plywood.

When low strain tests indicate an integrity problem, the high strain test could be used to check pile adequacy. High strain testing would detect the defect but may also cause further shaft deterioration. The shaft can be repaired or replaced. The high strain test does have sufficient energy to close small gaps or cracks and is effective in determining the length or integrity of longer jointed piles or H piles.

High Strain Test Results

Of the nine shafts, only three (Shaft numbers 2, 4 and 7) were statically tested (15 minute interval "quick method"). Shaft 2 (installed with interruption, forming a mudcake) failed at a load of 106 kips (480 kN) as defined by the Davisson criteria and was then pushed 6 inches (150 mm). During large additional movement, Shaft 2 exhibited a constant capacity gain with increasing displacement to 280 kips (1270 kN). This static test was followed by a "quasi static" test in which a propellant burns and applies an input force pulse; this quasi static test is still quite rapid (about 0.1 second duration), producing significant velocity dependent soil forces. This test was followed by the high strain drop weight testing after which a second static test was performed which had a Davisson load of 250 kips (1135 kN), a lower limit load evaluation. During the second test, the shaft was pushed an additional 4 inches (100mm), causing further load increase. Placing all tests in chronological sequence as in Figure 4, it is obvious that the Case and

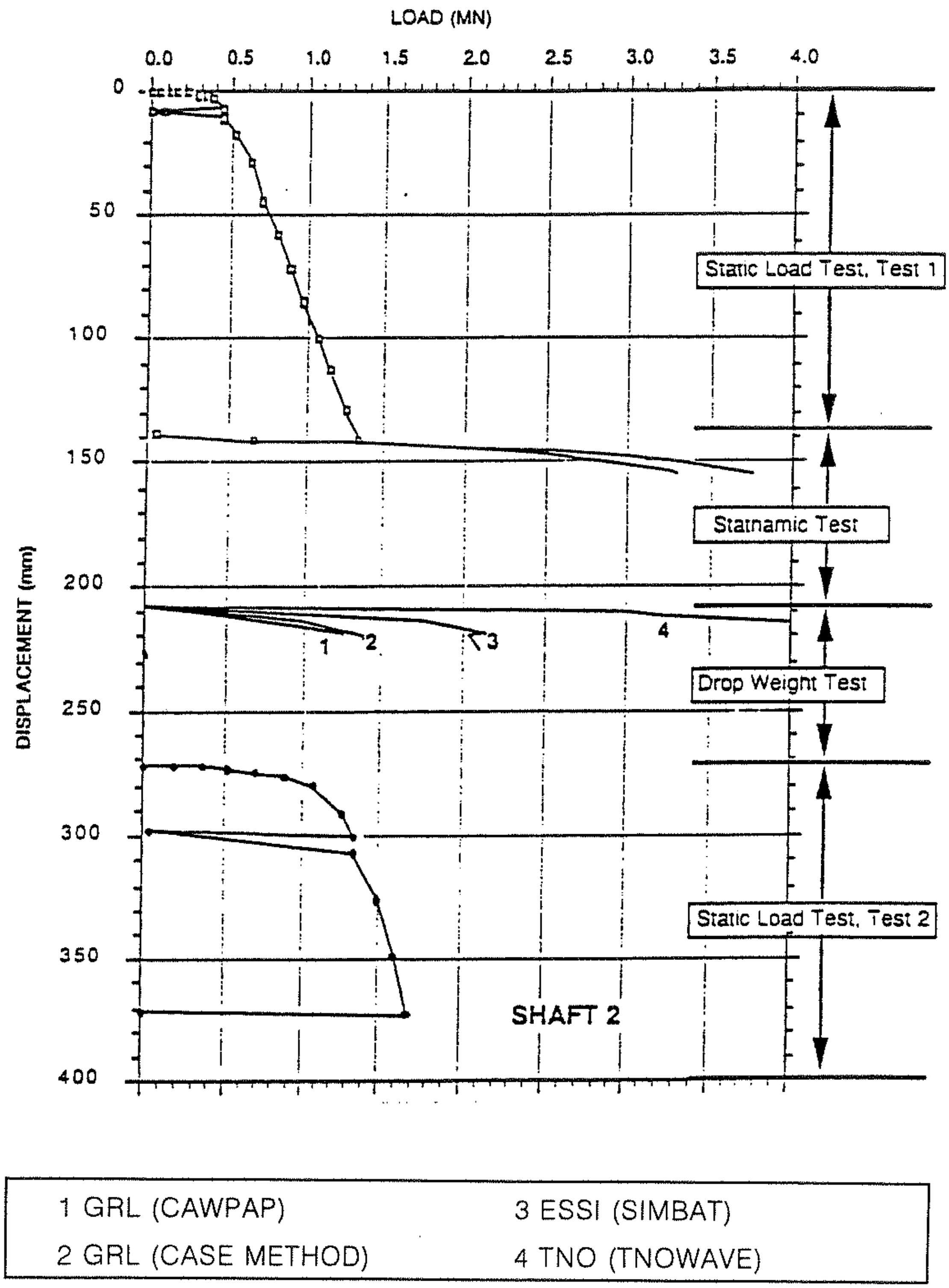

Figure 4. Shaft 2, Load versus Displacement (after Baker 1993)

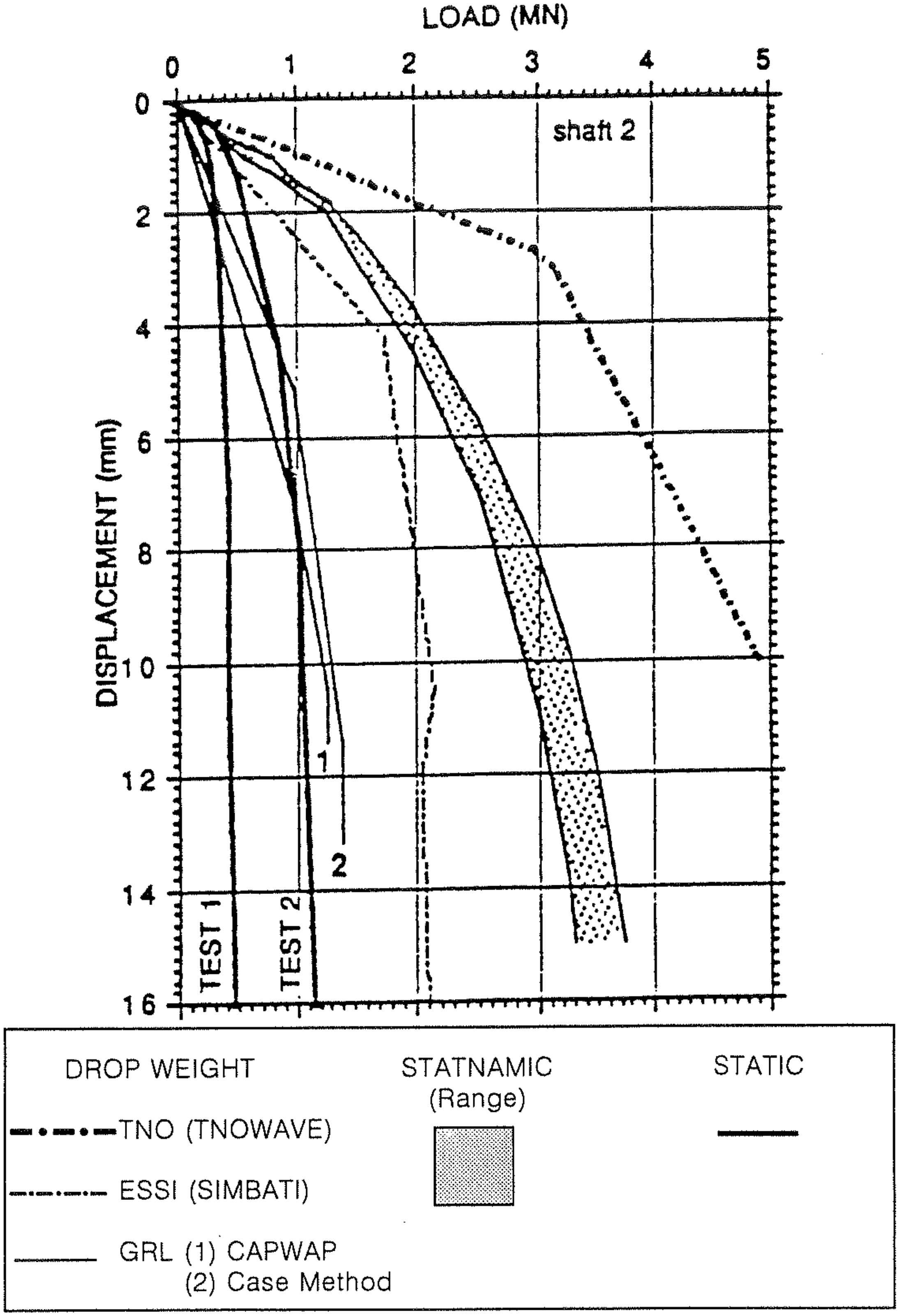

Figure 5. Shaft 2, Load versus Displacement (after Baker 1993)

CAPWAP program results were the only methods to give reasonable correlation relative to the static load at the end of the first static test and/or beginning of the second static test. An expanded graph of the predicted static behavior determined by the quasi static and dynamic test results of different specialists is given in Figure 5.

Shaft 4 had a Davisson capacity of 650 kips (2950 kN), again perhaps a lower limit value. A "break point" in the load settlement curve was observed at about 720 to 750 kips (3270 to 3400 kN). The static curve over the reasonable displacement range is shown in Figure 6 with both Case Method and CAPWAP program results. For all tests, the authors employed a relatively large quake (associated with an experimental radiation damping soil model) in their analysis resulting in larger predicted displacements at low loads; additional experience gained since results were submitted would have greatly reduced this discrepancy.

Ideally the weight is raised and then dropped with a full release mechanism rather than attached to a cable attached to a winch as in these tests. Although the brake was to be fully released, for the first three blows of Shaft 7 at nominally 4, 8 and 10 ft (1.2, 2.4, and 3 m) drop heights respectively, the crane operator did not fully release the brake. A 14 ft (4.25 m) drop height was then applied, unfortunately then also with a fully released brake, resulting in a very high stress. As a result, the shaft top suffered some damage which prevented further dynamic testing of this shaft. The damage affected the authors' strain measurement and hence the computed force and energy (energy for this blow was 50% higher than for other similar drop heights). In hindsight, after the brake problem was detected, the entire test series should have been restarted with low drop heights which are gradually increased, keeping stresses under 3 ksi (21 MPa) to prevent shaft damage.

The static test of Shaft 7 had a Davisson limit of 560 kips (2540 kN) and a maximum applied load of 680 kips (3090 kN). In hindsight, a dynamic result should not have been submitted due to the questionable measurements. However, the CAPWAP program result shown in Figure 7 overpredicted the capacity (unusual for the normally conservative CAPWAP program). The large end bearing, which from a geotechnical view is unlikely for a shaft in clay, was probably caused by a shift in strain measurements late in the blow due to cracking at the shaft top. The shaft resistance of 620 kips (2800 kN) calculated by CAPWAP from the early portion of the record matches the static capacity quite well. The authors' Case Method prediction which also depends only on the early portion of the record (and predicted results by others) did give a reasonable correlation with the static test.

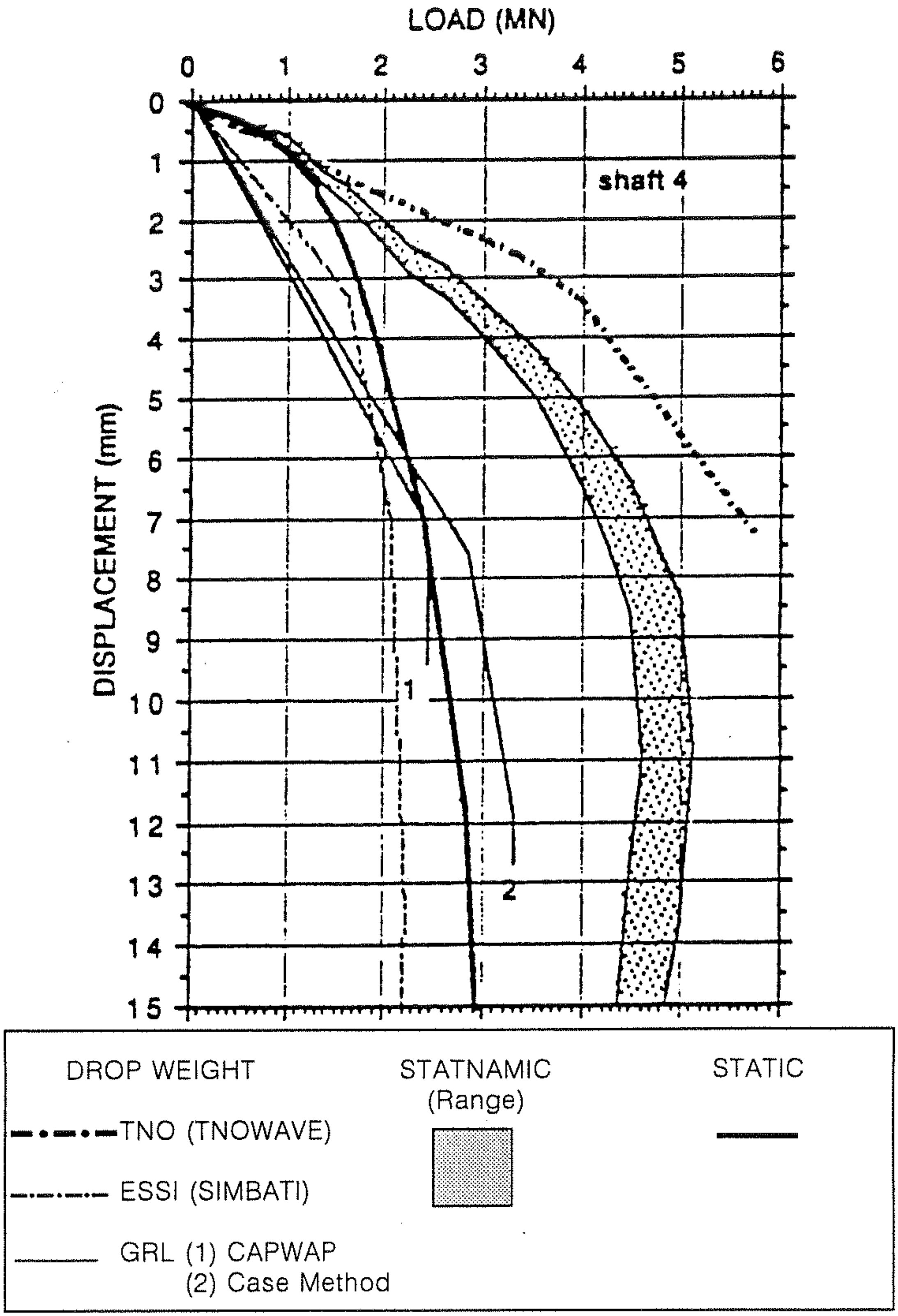

Figure 6. Shaft 4, Load versus Displacement (after Baker 1993)

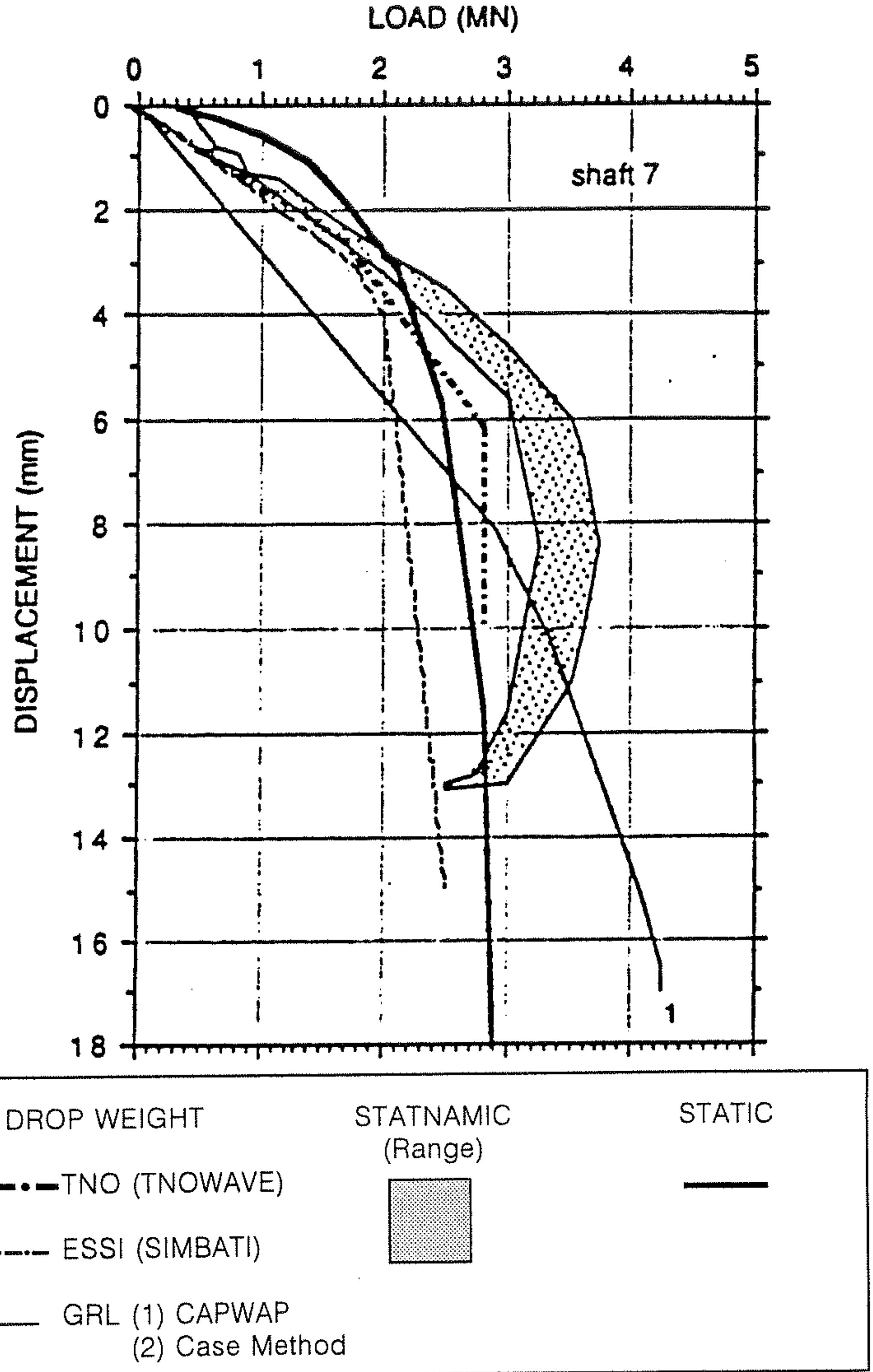

Figure 7. Shaft 7, Load versus Displacement (after Baker 1993)

Summary

Both high strain and low strain dynamic testing are in widespread use around the world. The correlation tests described in this paper demonstrate that dynamic testing and analysis can be used for quality control of drilled shaft projects. The low strain integrity testing detected all major defects in the tested shafts. A reasonable shape profile was obtained from these top impact test methods. Since the test requires no special preparations or access tubes, it is nearly ideal for quality inspection. Shafts with major defects, or which deviate substantially from the norm, can be subjected to further analysis or testing.

High strain testing can further evaluate the integrity of suspect shafts. Many capacity correlation tests have also been performed; the current tests demonstrate that both the Case Method and CAPWAP program developed by the authors produce reasonable results when properly applied. However, care must be exercised during testing to prevent excessive stresses during testing. A guided drop hammer with a free release mechanism is the preferred impact device.

Appendix - References

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