# Dynamic Load Testing of Drilled Shafts at National Geotechnical Experimentation Sites

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## Abstract

Due to their quick and simple execution, dynamic load testing is a preferred method of Quality Assurance in the United States and around the world for both driven piles and drilled shafts. The test is particularly simple for driven piles, where the loading apparatus, the pile driving hammer, is readily available. To perform the test, strain and acceleration are measured a short distance below the pile top. The strain multiplied by the pile material's elastic modulus and the pile's cross sectional area yields the pile top force. For prefabricated, driven piles the elastic modulus varies only slightly over the cross section, and two strain transducers mounted to opposite sides of the pile usually yield the true average strain.

For drilled shafts, the effort is somewhat more involved because a ram must be brought to the construction site. A crane or free release system must then drop this ram from heights ranging from 0.3 to 3 m.

The acceleration and strain measurements are typically acquired one or two pile diameters below the pile top. Since bored piles without permanent casing often have uncertain cross sectional and concrete material properties, it is generally best to add a pile top extension of a thin steel pipe, one to two pile diameters long and filled with good quality concrete. The sensors are then anchored directly to the concrete after removing the steel from the attachment area. Frequently four strain sensors are utilized to improve the measured average strain because of possible variations in concrete quality and strain magnitudes over the cross section (Figure 1). The steel pipe also acts as external reinforcement and prevents the concrete from spalling due to the impact of the drop weight.

A recent development has combined the measurement system with the dynamic loading system, improving and simplifying the measurements. The acceleration is still measured at the pile top, but the pile top force is calculated from the product of the ram's mass and its measured deceleration. This paper describes dynamic pile tests recently conducted with both strain and ram mounted force measurements at the Federal Highway Administration's National Geotechnical Experimentation Sites in Amherst, Massachusetts

and Opelika, Alabama. It compares the dynamic pile testing results to static load tests and rapid load tests (Statnamic) performed at the sites prior to the dynamic testing.

## Background

Since 1970, dynamic load tests have been routinely conducted on hundreds of construction sites around the world using a Pile Driving Analyzer® (PDA) as a quality assurance measure of preformed, driven piles. Since the end of the 1970s, these tests have also been more and more frequently employed for the bearing capacity assessment of cast-in-place piles and drilled shafts and these results have been correlated to static load tests. A very extensive correlation test series was conducted in 1982 in Melbourne, Australia on 12 shafts of 1.5 m diameter and 60 m length (Seidel and Rausche,1984). After good correlations had been established, approximately 100 additional dynamic pile tests were performed at this site. Further correlations between static and dynamic load test results were presented by Seitz, 1984; Hussein et al., 1992; Wienholz and Huch, 1997; Schau and Weigel, 1997 and others. A standard for performance of the dynamic load test is contained in ASTM D4945.

## Dynamic Load Testing Procedures

For dynamic load testing of driven piles, the loading device is the pile driving hammer and is therefore readily available. For drilled piles this process is more complicated because a ram must be mobilized to the site whose weight, W, must be chosen depending on the magnitude of the required ultimate capacity, Q, to be proven. In general, the following guidelines yield satisfactory results:

$W/Q = 1\%$ for piles embedded in hard cohesive soils or bearing on rock
$W/Q = 1.5\%$ for friction piles in general
$W/Q = 2\%$ for drilled shafts with end bearing in coarse grained soils.

Hussein et al. (1996) discussed this topic extensively and showed that wave equation analysis can be effectively used to select drop weight and cushion thickness for specific shaft and soil conditions.

Accurate measurements are, of course, the most important parameter for good capacity predictions. In general, acceleration measurements are simple because they are independent of the pile material properties. In fact, theoretical studies and experimental results both indicate that even a single accelerometer, attached to the side of the pile, yields the average axial pile motion with sufficient accuracy. Furthermore, the minimum distance between the accelerometers and the pile top can be smaller than for strain measurements, because the acceleration signal is less sensitive to uneven impacts.

Strain measurements on drilled shafts must be conducted with even more care. The sensors have to be attached to clean and sound concrete, since contamination will cause soft concrete and therefore locally higher strains. It is often advantageous to add a concrete extension to the top of the drilled shaft. Ideally this extension would be at least 2 diameters long and encased by a thin walled pipe section which will externally reinforce the extension such that no additional reinforcement is needed. The sensors are installed on the concrete where square windows of approximately 200 mm have been cut into the steel shell. Alternatively, a ring approximately 200 mm wide may be removed from the bottom of the casing to expose a clean and smooth concrete section for sensor attachment. The top surface of the extension should be made even, smooth and perpendicular to the pile axis for the best transfer of the ram energy to the shaft. With an inclined ram guide, inclined piles can also be tested

Of course, when conducting the test, the concrete must have attained sufficient strength and the shaft-soil interface, which is generally disturbed due to the construction process, must have regained its strength such that the test results represent the long term soil strength. For that reason is it generally advisable to perform the tests at least one week after construction.

After the sensors are attached to the pile near its top, a plywood cushion and load distribution plate are placed on the pile top. The dynamic pile test consists of several impacts by the drop weight, normally with increasing drop heights until enough energy has been applied to momentarily activate either the required capacity or the ultimate shaft capacity. During each impact the Pile Driving Analyzer calculates the dynamic compression stresses at the pile top and tension along the shaft for an immediate decision by the test engineer whether or not the test can be safely continued. If necessary, i.e. when the dynamic stresses are too high, then additional cushioning or a reduced drop height may be necessary. Using the simple Case Method formula, the PDA also calculates the pile bearing capacity for a rough estimate of the activated pile capacity.

For the PDA calculations, the dynamic elastic modulus of the pile material must be known. Its magnitude depends on the size and quality of the concrete aggregate and the concrete strength. Frequently, this modulus is already known from tests on comparable sites or can be assumed to be 35 GPa. After the dynamic test, the wave speed in the pile is generally apparent and can be used as a calculate and adjust the pile elastic modulus.

As for all rapid pile or material tests, the maximum load applied by the testing apparatus is not identical to the static strength of the material. For pile tests, the static and dynamic soil response, the ram impact velocity and the elastic properties of the pile material affect the maximum pile top force. It is therefore necessary to calculate the pile bearing capacity from pile top force and velocity measurements.

As mentioned, this can be roughly done on the construction site with the simplified Case Method approach in the PDA; afterwards, in the office, however, the calculation must be refined with signal matching software such as CAPWAP® (CAse Pile Wave Analysis Program). This program performs a system identification by means of signal matching between measured and computed pile top quantities. The program is based on the wave equation and therefore considers both elasticity and mass properties of the pile. The analysis is capable of distinguishing shaft resistance from end bearing and dynamic from static resistance components of the soil. These results can then be used in a static analysis that simulates a static load test. Obviously, this simulated result can be compared with actual static load tests. However, creep or consolidation effects cannot be considered in this calculation. Another draw back, particularly for large shaft diameters, is that static tests may be carried to very large pile top sets with relatively large resistance values while maximum pile penetrations during a dynamic test are generally limited to maximum values of approximately 25 mm.

## **Improvements Using Newton's Law**

Although dynamic pile load testing is very economical, it can be further economized by eliminating the concrete extension at the pile top and making the measurement of the pile top force independent of the pile material properties. One possibility would be to use a pile top transducer for the measurement of the pile top force. However, this has not been found to be practical because different pile sizes would require different transducer sizes and/or adapters would have to be taken to the construction sites.

Fortunately, in the year 1666 Sir Isaac Newton was surprised when a very hard apple hit him on the head. Ingeniously he concluded that it hurt the apple equally much and concluded that action equals reaction. Furthermore, Newton deduced that a force could be determined from the product of the apple's mass and its deceleration. For the same reasons, it is possible to measure the pile top force on the ram as well as on the pile and it is possible to replace the complicated strain measurement at the pile top with the simpler deceleration measurement on the ram. (It is interesting to note that in turn accelerometers work by measuring a force which is proportional to the measured acceleration).

The Newton Concept simplifies the measurement process significantly. For the one mass system which consists only of a ram, cushion and pile, measuring the ram deceleration suffices. Multiplying the ram deceleration with the ram's mass yields the pile top force. It is advantageous for the Newton-test to employ a ram with an impact area large enough to produce an even and uniform impact force over the whole pile top surface. It is also possible to transfer the impact forces to the pile top without a load distributing plate or helmet. The Newton force, $F_N$, which acts on top of the pile, can be calculated from ram acceleration, $a_R$, and ram mass, $M_R$, as follows:

$$F_N = M_R\, a_R \qquad (1)$$

Different from ram force and pile top force which are essentially equal, ram velocity and pile velocity are different due to the cushion deformation. It is therefore necessary to measure the pile acceleration, $a_P$, near the pile top. When integrated, it yields the pile top velocity needed for the calculation of the pile bearing capacity. However, the accelerometers can and should be mounted relatively close to the pile top for a minimal phase shift between force on the pile top and pile top velocity.

The somewhat more complicated two-mass system includes a helmet or a load distributing plate between ram and cushion. In this case, the acceleration of the mass, $M_H$. has to be measured yielding the pile top force as follows.

$$F_N = M_R\, a_R - M_H\, a_H \qquad (2)$$

In general, the measurements include a high frequency component caused by the stress wave that travels up and down in the ram. These frequencies are lower for longer rams. Digital low pass filtering can easily remove these components as long as the ram frequency, $f_R$, is greater than twice the highest pile response frequency, $f_P$, that is of importance for the test evaluation. Generally, 500 Hz is a reasonable upper limit for frequency responses from the pile and using a ram wave speed, $c_R$, of roughly 5000 m/s, the maximum ram length that would allow for a filtering of the pile top force would be:

$$\max L_R = ½\, c_R / 2\, f_P = ½\, 5000/[(2)(500)] = 2.5 \text{ m} \quad (3)$$

Figure 2 shows the measured and filtered force curve for a drilled shaft of 0.9 m diameter and a ram length of $L_R$ = 1.2 m. An obvious difference between the force measurement on the pile and the force on the ram is a time shift due to the distance between their measurement locations. Because the strain transducers must be kept a certain minimum distance below the pile top, the force measured on the pile will include stress wave components which are not present at the very top surface of the pile. For example, the ram measured force can only be compressive while short tension forces are possible at locations below the pile top. Figure 3 shows the results of the two force measurements for a pile from the Amherst site which were taken on the ram and pile with two different Pile Driving Analyzers.

## Testing at the National Geotechnical Experimentation Sites

The FHWA has established several National Geotechnical Experimentation Sites (NGES) in the United States. New construction and test methods are being demonstrated and checked under realistic conditions under varying geotechnical circumstances for their applicability, accuracy and ruggedness.

***Amherst Piles.*** The first such instrumented Newton test was conducted at the NGES in Amherst, Massachusetts. Three bored piles of length 14.5 m and 1000 mm diameter in the upper 6 m and 900 mm in the lower portion of the pile were built in March 2000, and statically and rapidly (i.e. Statnamic) load tested in July 2000 (Iskander, et al. 2000; Iskander, et al. 2001a). The dynamic load testing by the Newton method occurred in September 2000, when each pile was hit three times by the 65 kN Advanced Pile Proof Loader/Evaluator (APPLE) (Figure 4). The ram was dropped freely by hydraulically cutting a short cable loop. In this way, a relatively inexpensive 25 ton hydraulic crane was sufficient for lifting operations. The pile top was protected by a 35 mm thick plywood cushion. A load distributing plate was not needed because the ram had a large, smooth and even impact surface. Drop heights were varied between 250 mm and 1.15 m.

The test frame which provided guiding to the ram was conceived such that the whole system could be setup and moved from one pile to another with a relatively small truck crane. Unloading the test setup, assembling the system, moving the loading device, performing the actual multiple dynamic tests on each of the three shafts and reloading the truck required less than 7 hours.

Figure 3 shows a comparison between force measurements made in the pile and the ram. The maximum force reached 10 MN when the ram was dropped from its highest drop height. This force corresponds to a pile compressive stress of 15 MPa. The transferred energy values calculated from force and velocity measurements ranged between 20 and 40% of the potential ram energy, i.e. ram weight times drop height. The highest efficiency values occurred under the last hammer blow when the cushion had already been compressed and adjusted to the surface of the pile.

The soil conditions in Amherst can be described as soft lake deposits, primarily consisting of Varved Clay below a 4.5 m thick, overconsolidated layer of silt and clay. CAPWAP calculated pile capacities ranged from 850 to 1160 kN. Typical CAPWAP output is shown in Figure 5 for the analysis of Shaft 6 depicting the measured pile top force and velocity, the resistance distribution of the individual resistance forces with the predicted forces in the pile at the ultimate capacity, and the simulated static load-set curve.

Crosshole Sonic Logging (CSL) was also performed at this site using the four access tubes in Shaft 4 to find planned (and unplanned) defects. At the time of testing, the access tubes in Shafts 2 and 6 required for this type of testing were inaccessible, and testing could not be performed. The measured logs of ultrasonic signal arrival times and the associated waterfall plots are shown in Figure 6 for the North-West and North-South tube logs. The planned engineered defects for this shaft were reportedly located at 3 m (insulation outside the cage), 5 to 6.5 m (Pail and tube, outside the cage), 7 m (diameter reduction), 9 m (bucket), 12.2 m (plastic tubing outside the cage), 12.4 to 13.7 m (tube and pail), and 14 to 15.2 m (bucket with insulation). Further information can be found in Iskander, et al. (2001b). The exact planned quadrant location of the defect within the cross section is unavailable. The crosshole sonic logs in Figure 6 clearly show a loss of signal at 3 m and 5.5 to 6 m in the N-W and N-S logs, as well as delayed signals at 7 m (N-S), 9.5 m (NW), 12.5 m (N-W and N-S), 13.5 m (NW), and 14.5 to 15 m (NW).

***Auburn-Opelika Piles.*** A second test series was conducted at the NGES in Opelika near Auburn, Alabama. Beginning a few years prior to the dynamic tests reported here, a variety of pile types had been installed and a number of tests had been carried out. On April 13, 2001 the following eight piles were load tested dynamically:

> Four drilled shafts 0.9 m in diameter and embedded 10 m. Some of these shafts had been constructed with engineered defects. Two shafts were extended roughly 1 m above grade using a corrugated shell, creating a problem for sensor attachment. The other two test shafts had a smooth, circular cross section above grade.
>
> An 18 inch diameter auger cast pile embedded 8.2 m. This pile was not extended above grade and had to be excavated for sensor attachment.
>
> Three pipe piles of 273 mm diameter, 12.7 mm wall thickness and 11.3 m embedment. No results from the pipe pile tests are reported here.

The soils at the site were generally described as a Piedmont residual soil, consisting of 50% sand, 33% silt, plus some clay. SPT N-values averaged approximately 10 with a maximum of around 20. Over the embedment depths of the shafts, undrained shear strength values ranged between 30 and 200 kPa (Brown et al., 1998).

The dynamic loading system again consisted of the same 65 kN ram used in Amherst. It was dropped from between 0.2 and 1.2 m height (see Figure 7). Further test details are included in Table 1.

For the drilled shafts, CAPWAP analyses were performed as for the Amherst tests. Numerical results for all tests are shown in Table 2. In fact, for Shafts 4 and 5 two blows were selected for analysis as a check on the sensitivity of the soils to the dynamic loading.

In both instances, later blows indicated lower capacities even though the energies of impact were higher. The predicted capacities from these four shafts ranged from 1700 to 2150 kN, if the later test blows of shafts 4 and 5 are ignored.

The dynamically tested drilled shafts with corrugated extensions were also subjected to Cross Hole Sonic Logging. For Shaft 9 with four inspection tubes installed, measured logs of ultrasonic signal arrival times and the associated waterfall plots are shown in Figure 8 for data taken between the North-East and North-South access tubes. The planned engineered defects for this shaft were two soil inclusions, one between 4.2 and 4.8 m depth and one between 7 and 7.6 m below pile top. Both defects were located immediately south of the North tube (see Paikowsky et al., 2000) and it is therefore not surprising that the cross hole logs show late arrival times of the ultra sonic pulses in N-E and N-S logs. On the other hand, a minor unintended defect is also noticeable at 2.3 m below the top in the N-S log, and another unplanned defect was observed at 5.7 m below top in the S-E log. Shaft 4 also was fitted with similar defects. These defects covered only between 10 and 20% of the cross section and only the 20% reduction of Shaft 4 showed up as a minor reflection in the dynamic load test records. For defects greater than 30% dynamic load test records would give a more pronounced indication of the defect.

***Capacity Correlations and Load Test Results.*** Table 2 not only shows the results from dynamic load tests (DLT) but also, as much as is available, the results from static tests and from rapid load tests (RLT). Rapid load test is the generic name of the Statnamic test method that was employed at the Amherst site. Static tests were evaluated according to the Offset or Davisson failure criterion for the Amherst tests and for both the offset and D/30 criterion for the Auburn piles. The static results were received only after submitting the dynamic results (Class A predictions).

In Amherst two cycles of static loads were applied in July 2000 and the failure load for both cycles is indicated in Table 2. The RLT conducted in Amherst in July 2000 was evaluated using zero velocity points from measurements along the shaft for static load estimation SuperSAW (Mullins, 2002). This analysis result can then be analyzed by a derived static load-set curves and hyperbolic curve fits. Static load test cycles, RLT and DLT results are shown in chronological order in Figures 9 and 10. Obviously, shaft capacity determination is difficult in this case, even for the static load test method and the capacity of these shafts probably changes with each load cycle applied. The static capacities of the same pile varied from the first to the second load cycle by +12.5 and –8%. For correlation purposes it is probably reasonable to use the first static test cycle as a basis since pore water pressure effects had time to dissipate before the RLTs and DLTs were conducted. On that basis, RLTs overpredicted by +18% to +52.5%, while DLTs differed from static results by –7% and +22%

At the time of the writing of this paper complete information including load set curves was not available on the Auburn static and RLT results, however, we were furnished capacity values based on the offset and the D/30 failure criteria loads (Table 2). The auger cast pile (#14) capacity was predicted within 11% (780 vs 700 kN). The dynamic load test capacities of Shafts 4 and 5 (1820 kN and 2070 kN) were low by 33 and 10% according to the offset criterion results (2700 kN and 2300 kN); these were the highest capacities at the site and apparently were not fully activated dynamically. On the other hand, Shafts 9 and 10 were dynamically overpredicted by 19% and 40% (2145 vs

1800 kN and 1820 kN vs 1300). Since all shafts had the same diameter and depth in virtually the same soil it would be interesting to investigate the loading histories of these piles. For example, it is possible that several loading cycles or soil strength changes since the time of the static testing could have affected the capacities of the piles. In general, it is more instructive to compare predicted and statically measured load set curves.

The difficult nature of the soils is apparent by the ratios of top force loads to dynamically predicted capacities. For the Amherst and Auburn tests these ratios were on average roughly 6 and 4, respectively. Thus dynamic resistance force magnitudes exceeded static ones. The dynamic resistance practically measured by the dynamic test has to be reduced by the damping resistance to yield the static capacity (this is true for either the dynamic load test or the rapid load test.) Where the applied dynamic load is relatively high compared to the static capacity, this can lead to a greater uncertainty in results. The reliability of prediction based on load magnitude warrants investigation.

## Summary

Ram acceleration measurement instead of pile strain measurement allows for improved economy of the already relatively inexpensive dynamic load test. It is easiest and most accurate if no helmet or striker plate is used between ram and pile top, even though a simple correction is possible with an additional measurement of the helmet's acceleration.

The drilled shaft tests conducted in cohesive soils at the Amherst and Auburn National Geotechnical Experimentation Sites helped to further develop and test the APPLE concept. With this method, good Class A capacity predictions were made even under difficult conditions and in a very short time. The results should be further evaluated and should help to further improve the method. For example, in a next step it would be desirable to analyze all blows applied as an aid in judging the sensitivity of the soil.

Experience with this test method for cast *in situ* piles is still limited yet it is very encouraging. Additional correlations are being compiled and further improvements are being made to the field testing equipment and the office analysis methods.

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**Table 1: Summary of PDA Field Results**

| Pile Designation | Pile Diameter | Approximate Penetration | Set per Blow | Ram Drop Height | Transferred Energy | Maximum Force |
|---|---|---|---|---|---|---|
| | (m) | (m) | (mm) | (m) | (kJ) | (kN) |
| **AMHERST** | | | | | | |
| Shaft 2 | 0.9 | 14.3 | 2 | 0.23 | 4.1 | 3603 |
| | | | 4 | 0.53 | 10.8 | 5560 |
| | | | 3 | 0.84 | 17.6 | 7339 |
| Shaft 4 | 0.9 | 14.3 | 2 | 0.53 | 8.1 | 3914 |
| | | | 3 | 0.84 | 17.6 | 6983 |
| | | | 3 | 1.14 | 28.5 | 9741 |
| Shaft 6 | 0.9 | 14.3 | 1 | 0.38 | 5.4 | 3069 |
| | | | 5 | 0.69 | 14.9 | 6316 |
| | | | 4 | 0.99 | 25.8 | 9163 |
| **AUBURN** | | | | | | |
| Shaft 4, Corrug. | 0.9 | | 6 | 0.83 | 14 | 5400 |
| | | 10.1 | 6 | 0.83 | 19 | 7000 |
| | | | 6 (est) | 1.17 | 29.0 | 9080 |
| Shaft 5 | 0.9 | 10.2 | 0 | 0.48 | 10.0 | 4650 |
| | | | 1 | 0.91 | 20 | 6910 |
| | | | 1(est) | 1.17 | 23 | 6680 |
| | | | 1(est) | 1.17 | 36 | 9140 |
| Shaft 9, Corrug. | 0.9 | 10.5 | 2 | 0.91 | N/A | N/A |
| | | | 2 | 0.91 | 20 | 6920 |
| | | | 2 | 1.17 | 31 | 8370 |
| Shaft 10 | 0.9 | 10.1 | 3 | 0.64 | 9 | 3560 |
| | | | 9 | 0.97 | 16 | 5220 |
| | | | 4(est) | 0.97 | 23 | 7740 |
| Auger Cast 14 | 0.46 | 8.2 | 2(est) | 0.58 | 18 | 2730 |
| | | | 2 | 0.58 | 18 | 2330 |

**Table 2: Dynamic Load Test Results and Correlation**

| Pile | Blow Number | Set per Blow | Transfrd Energy | Top Force | CAPWAP Capacity | Static Load Test Cycle 1 | Static Load Test Cycle 2 | RLT SuperSAW Derived Static | RLT SuperSAW Hyperbolic Fit |
|---|---|---|---|---|---|---|---|---|---|
| | | (mm) | (kJ) | (kN) | (kN) | (kN) | (kN) | (kN) | (kN) |
| **Amherst** | | | | | | | | | |
| No. 2 | 2 | 4 | 15 | 5560 | 930 | 1000 | 1125 | 1525 | 1375 |
| No. 4 | 2 | 3 | 24 | 6980 | 1160 | 950 | 880 | 1550 | 1125 |
| No. 6 | 2 | 5 | 20 | 6320 | 850 | **Not Tested** | | 1761 | N/A |
| | | | | | | Offset | D/30 | | |
| **Auburn** | | | | | | (kN) | (kN) | | |
| No. 4 | 1 | 5 | 18 | 5880 | 1820 | 2700 | 2850 | | |
| No. 4 | 3 | 5 | 26 | 8680 | 1580 | | | | |
| No. 5 | 3 | 1 (est) | 23 | 6840 | 2070 | 2300 | 2850 | | |
| No. 5 | 4 | 1 (est) | 37 | 9360 | 1704 | | | | |
| No. 9 | 3 | 1.5 | 31 | 9250 | 2145 | 1800 | 2300 | | |
| No. 10 | 3 | 4 (est) | 20 | 6790 | 1816 | 1300 | 1400 | | |
| No. 14 | 2 | 1.5 | 19 | 2440 | 780 | 700 | 750 | | |

Figure 1: Test preparations with four strain transducers for a small drilled shaft.

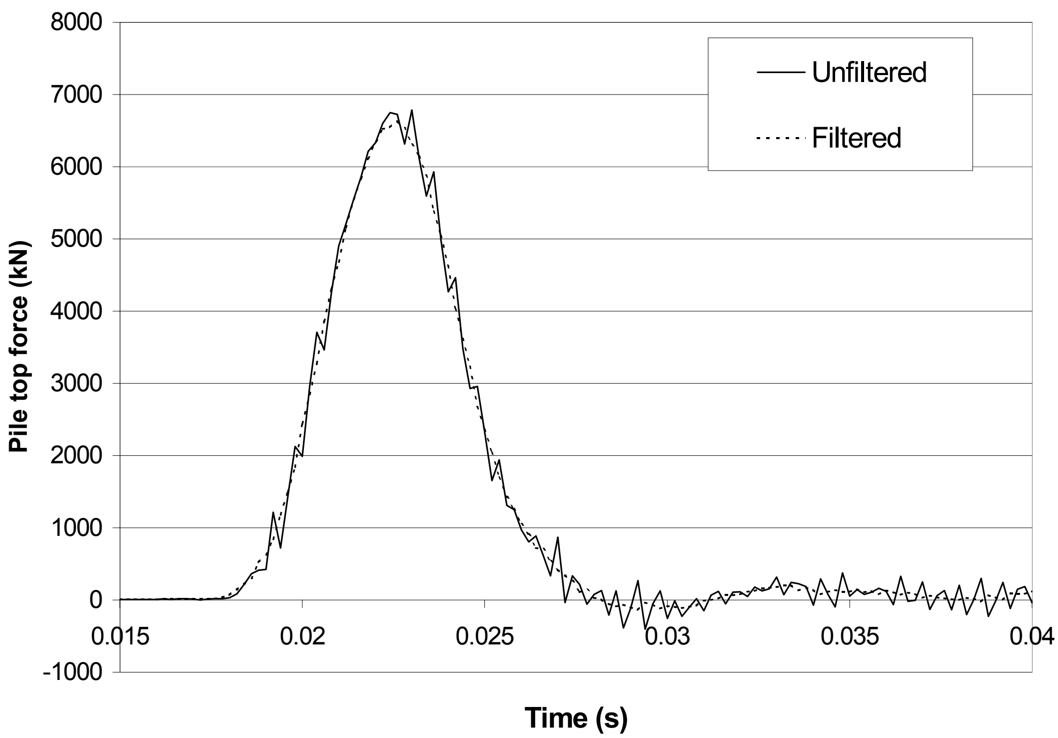


Figure 2: Smoothed and unsmoothed ram inertia force (Amherst, S4, BN2)

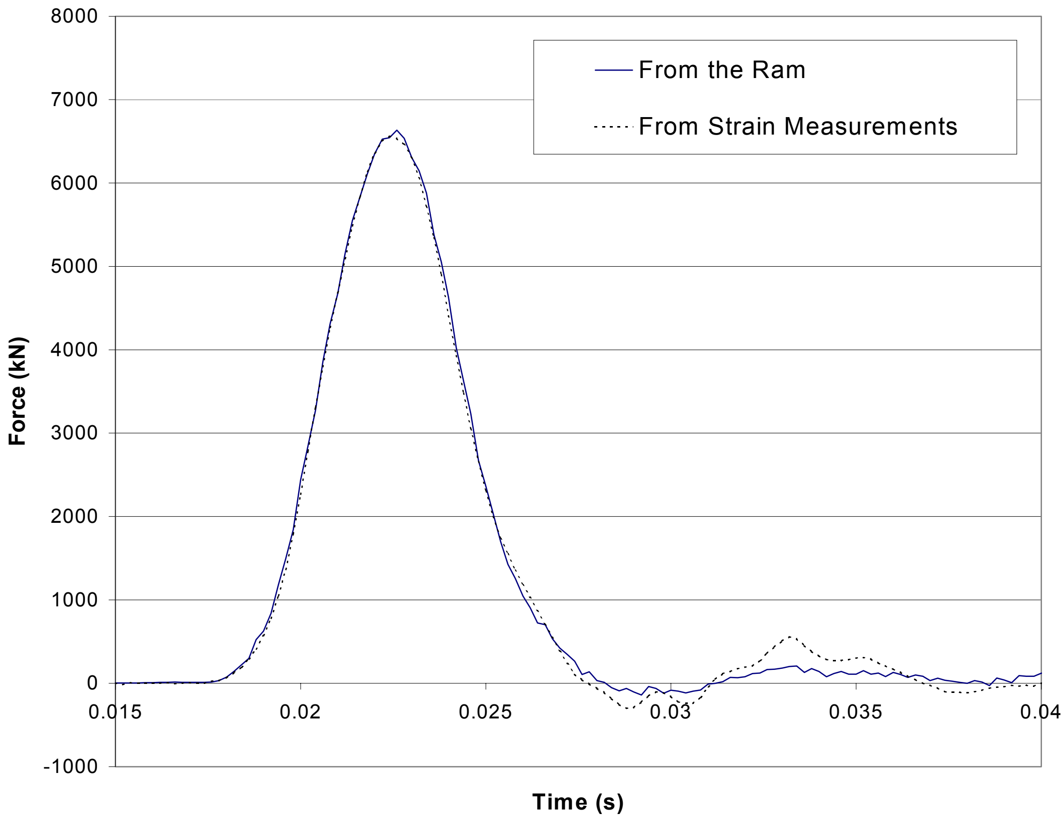


Figure 3: Forces measured on pile and ram (Amherst, S4, BN2)

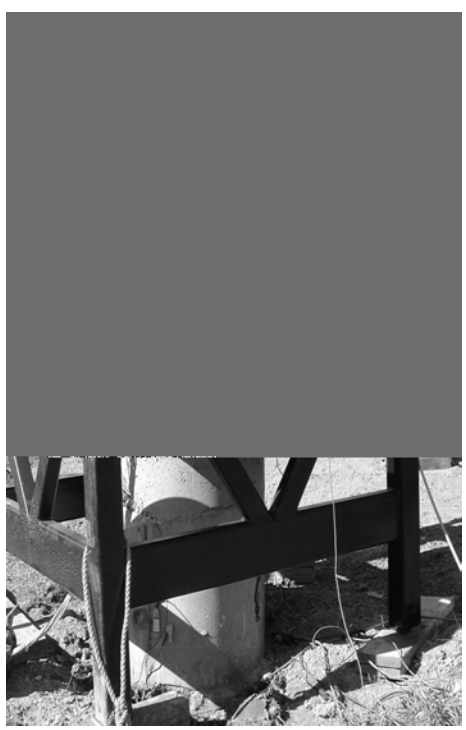

Figure 4: Amherst bored pile test with instrumented APPLE

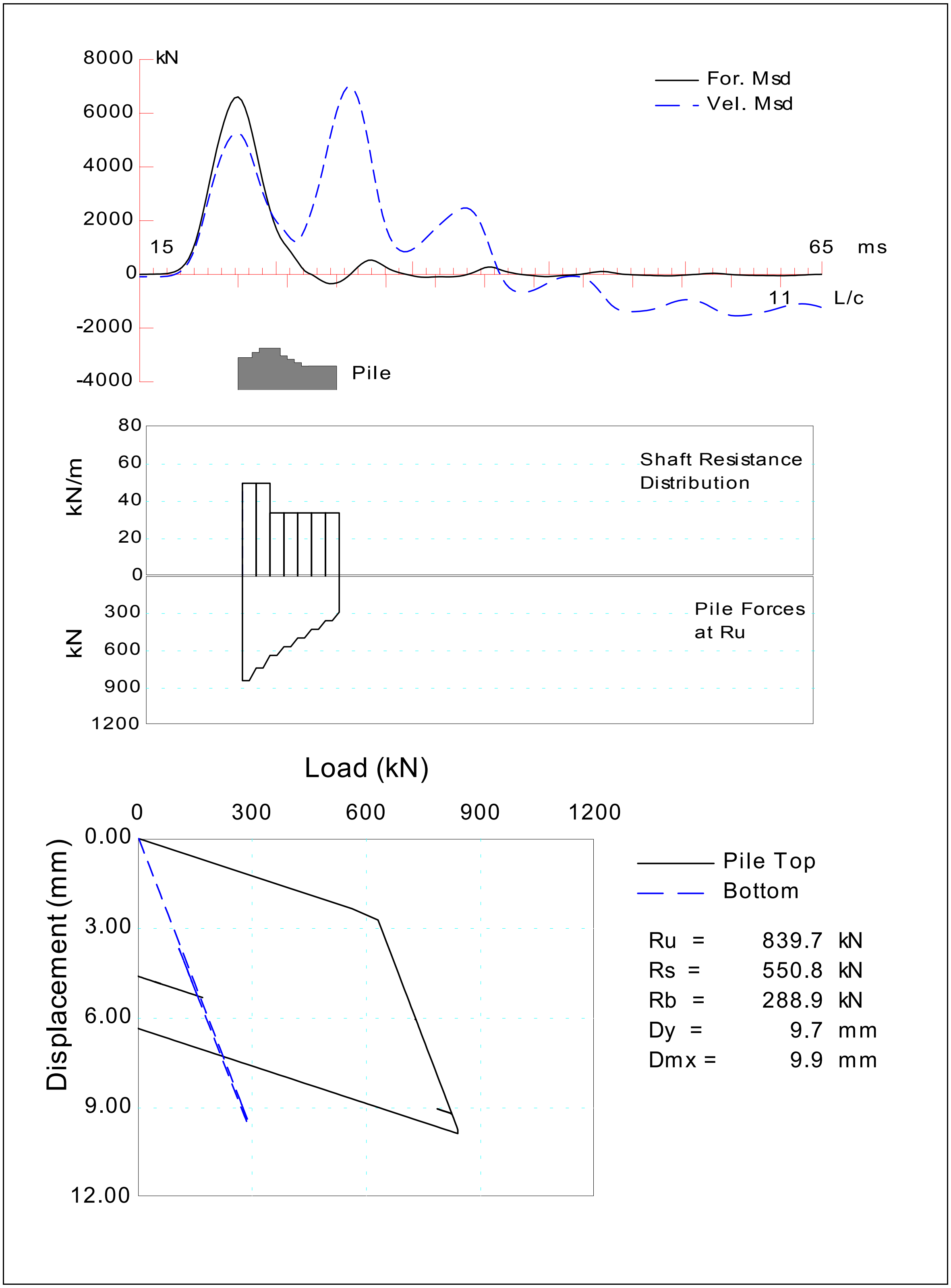


Figure 5: CAPWAP Analysis Result, Amherst Shaft 6

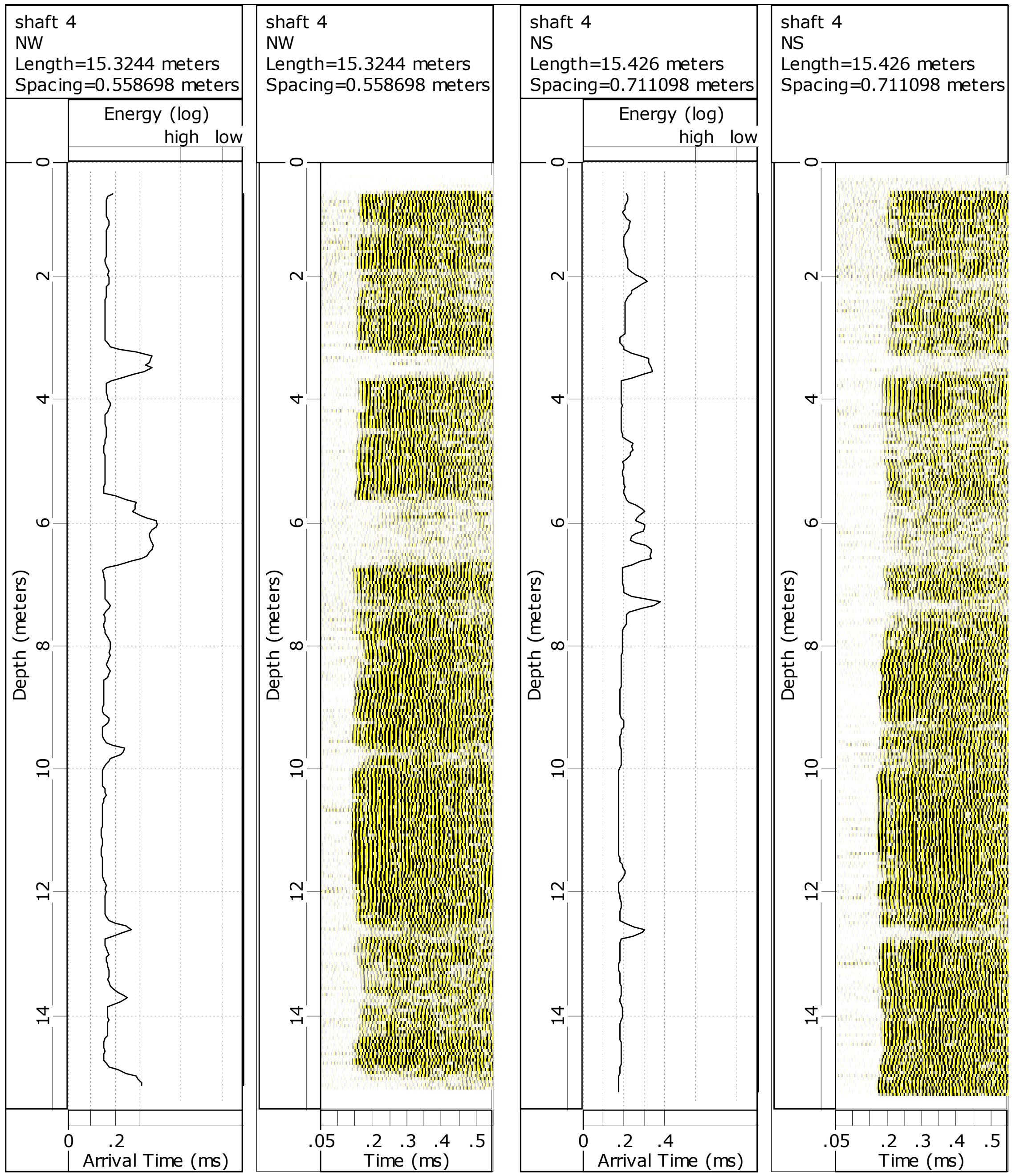


Figure 6 Amherst CSL Results for Shaft 4, North-West and North-South


Figure 7:  Tests on a Corrugated Drilled Shaft at the Auburn Site.

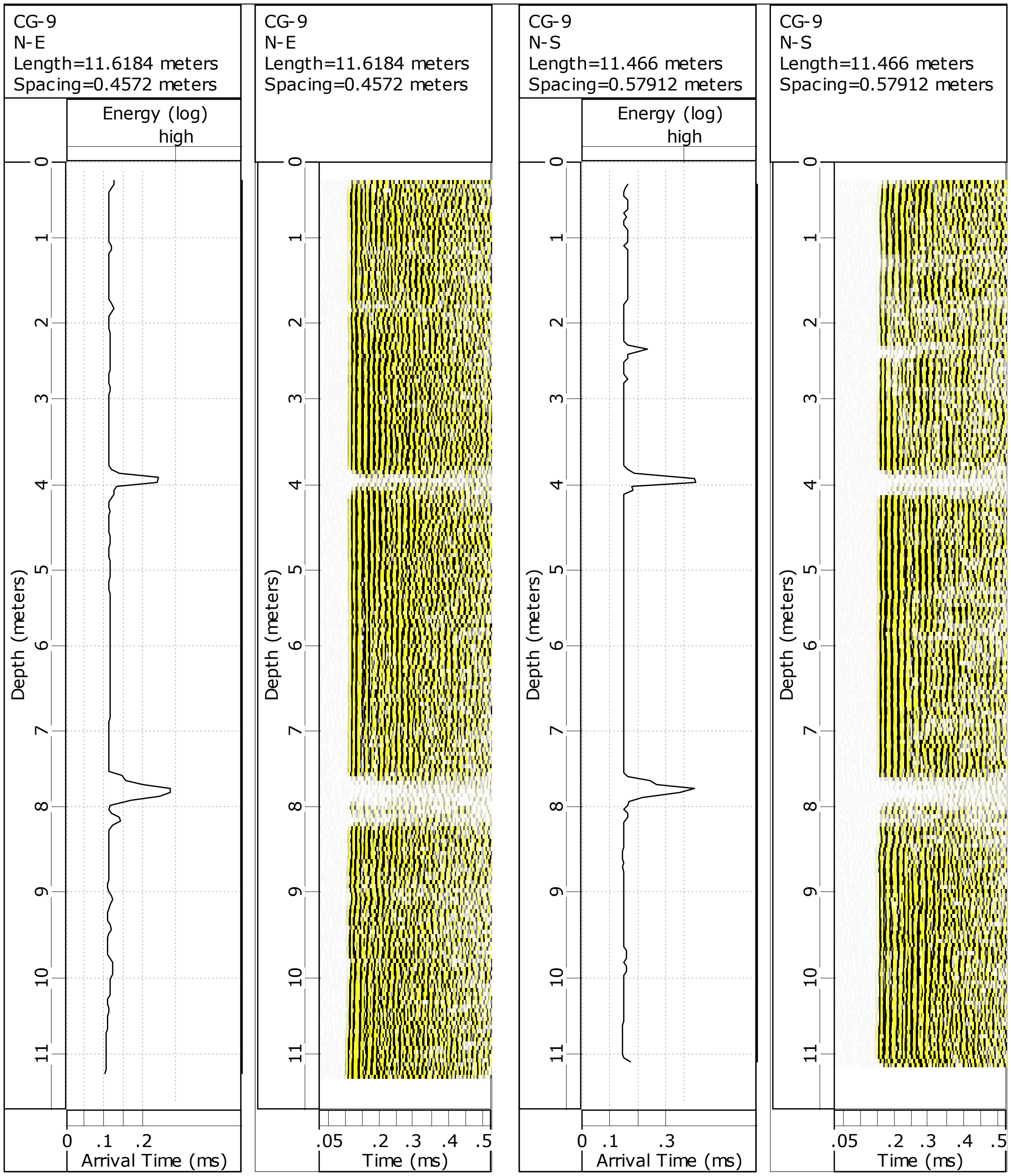


Figure 8 Auburn CSL Results for Shaft 9, North-East and North-South

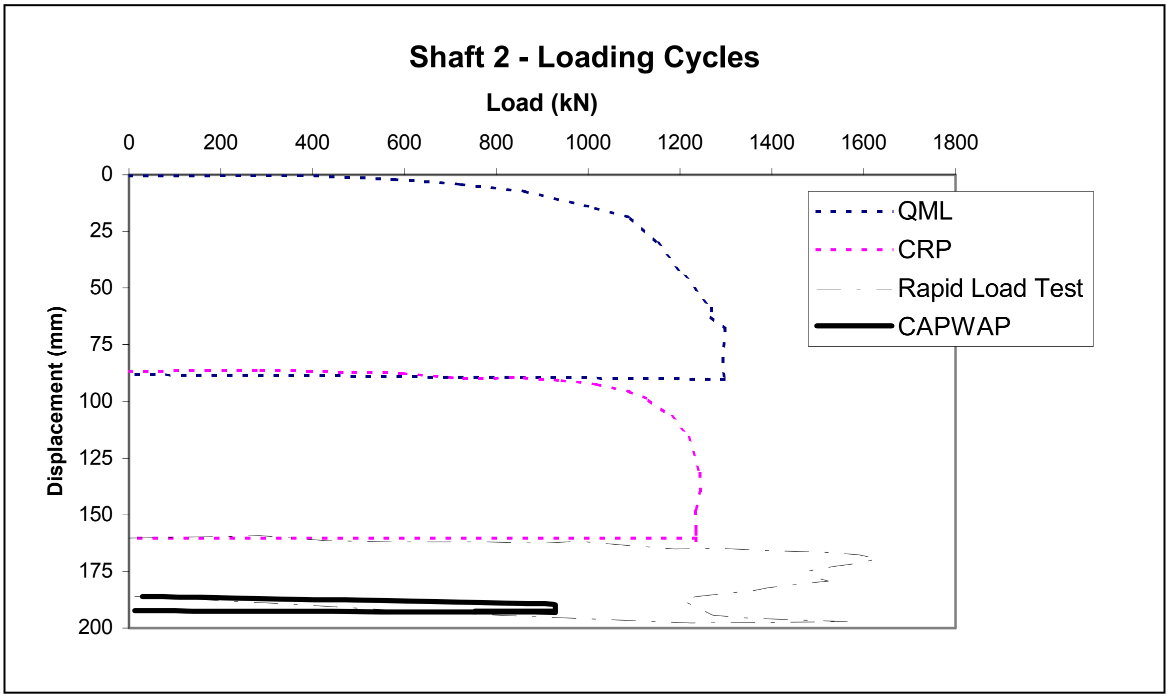


Figure 9. Load Testing Cycle for Amherst Shaft 2.

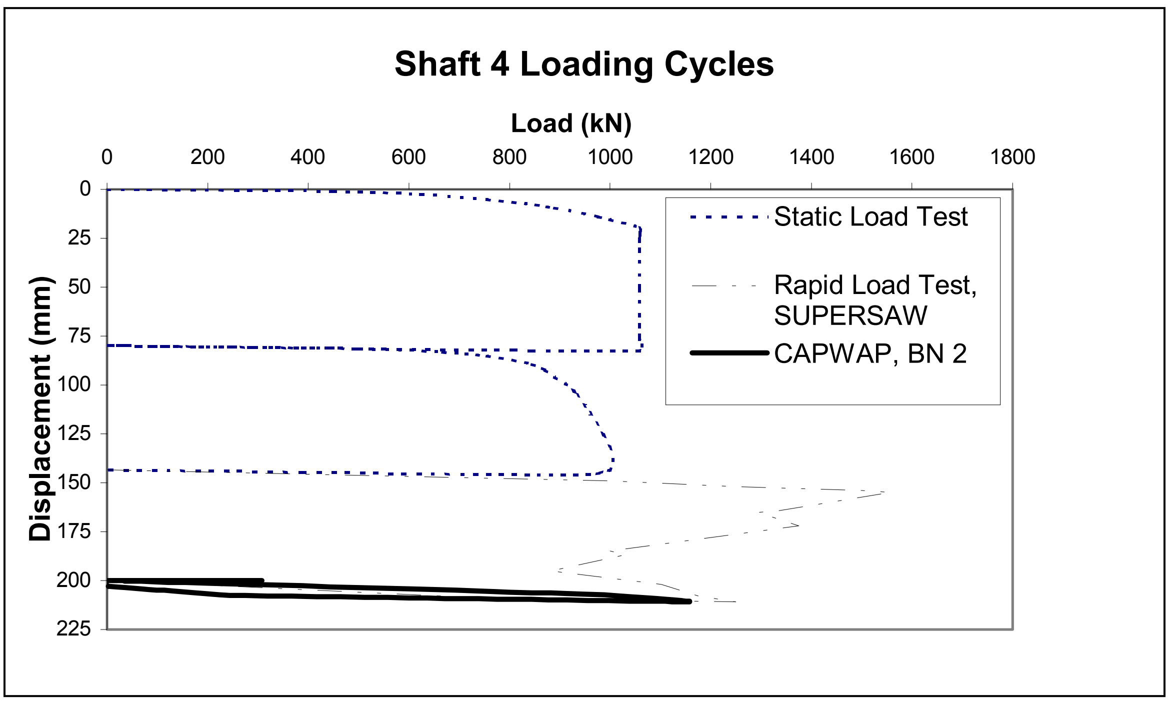


Figure 10. Load Testing Cycle for Amherst Shaft 4.