Rapid Lateral Load Testing of Deep Foundations

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This paper describes a method of conducting rapid lateral loading tests of deep foundations in which the load is applied to the foundation with a time duration of less than one second. For purposes of this paper the loading is applied using a pyrotechnic loading system commonly referred to as Statnamic. However, the method should apply to any lateral loading system which produces a force time history with a loading duration of 20 msec to 1 second. The test provides a measure of the dynamic and static response of the soil/foundation system and must be evaluated as a dynamic loading. Interpretation of the test includes a simple single degree of freedom (SDOF) model which can account for the inertial effects of foundation mass, system damping, and static foundation stiffness. The results of the test measurements are compared with four case histories in which comparative static load test data are available, including pile group foundations and large diameter drilled shaft foundations.

KEYWORDS: load testing, pile foundation, drilled shaft foundation, lateral loading, dynamic loads, pile groups

Many civil engineering works include deep foundations designed for lateral loading. Highway bridges, transmission towers, offshore structures, and buildings are subject to lateral loads from wind, waves, vessel impact, and seismic loadings. Although designers most frequently design for such loadings using static analysis techniques, the actual loadings are most often transient and dynamic, and characterized by rapidly applied loads of short duration. Where site-specific load testing has been performed in support of design for lateral loading, tests have most often been conducted as static jacking tests using hydraulic cylinders and sustained loads.

This paper describes a relatively new method of conducting field lateral loading tests on deep foundations in which the load is applied rapidly, i.e. with a load pulse of less than 1 second. For this paper, the device used to apply this loading uses pyrotechnic combustion to generate gas pressure and is commonly referred to as a Statnamic device. However, the methods used to evaluate the test measurements and interpret the results apply to any rapid test method which is so fast that inertial and damping forces are important, but slow enough that the foundation system moves in a displacement pattern which is similar to a static loading rather than as a bending wave propagation mode. An example of the latter has been described by Briaud and Ballouz (1996) in which a transient impact loading was used to measure the dynamic lateral stiffness of a pile. The Statnamic device produces a much longer wave pulse and has been used to conduct axial loading tests (Janes et al, 1991). The differences in axial loading pulse between the rapid loading produced by the Statnamic and the stresswave produced by a hammer impact have been well documented. The use of the Statnamic device for lateral loading represents an adaptation of the loading device for this purpose.

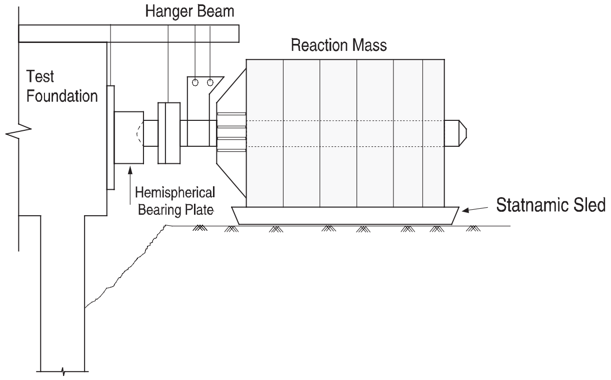
The use of a rapid loading device for lateral load testing offers several potential advantages and limitations. The test can be conducted quickly and efficiently to loads of large magnitude and without the need for a reaction system. Some tests conducted by the author have achieved lateral load magnitudes of 10 MN. Safety is actually enhanced, because there is no hydraulic system loading between two objects with pent-up strain energy and the potential for breakage and quick release due to failure of some component. The dynamic nature of the test provides the additional benefit of measuring the dynamic component of soil resistance, so long as the static component of resistance can be determined reliably. The dynamic nature of the test also represents a limitation, in that rate effects can vary with soil type. Soil creep or displacement due to sustained loading cannot be measured with a rapid test. The dynamic nature of the test requires that inertial components of the system be accounted for and thus the analysis is less straightforward than for a conventional static test. Finally, the measurements must be made using a high speed data acquisition system.

Some early test results have been described by El Naggar (1998), and that paper included his use of a relatively sophisticated Winkler model of a pile on nonlinear spring/dashpot system which operates in the time domain. While the use of such a model provides the means for a very complete description of the problem, the inherent complexity of a dynamic model with many variables makes it difficult to use for routine testing and data interpretation. The techniques used in this paper emphasize analysis using simple dynamic models which can be readily applied and understood and easily compared with static test results. In general, engineers are familiar with static test data and have developed judgement based on such measurements.

The objectives of this paper are to describe the loading system and test measurements and to outline a simple and reliable method for interpretation of the results. Several case histories which include both rapid loading and conventional static loading tests are presented to provide a means of evaluating the interpretation method and of comparing and contrasting the rapid loading system with conventional static tests.

Description of Test Method and Measurements

The Statnamic device, illustrated on Fig. 1, is composed of a reaction mass, a piston in which gas pressure builds to initiate the load, and a connection to the test foundation which includes a load cell and hemispherical bearing to accommodate rotation of the foundation. For lateral testing, the reaction mass resides on a sled which allows the mass to slide across the ground surface or the surface of a barge in the case of over-water tests. The horizontal thrust against the test foundation is produced as the gas pressure builds and accelerates the reaction mass away from the foundation. After the reaction mass has moved some distance off the cylinder, an exhaust port opens and the gas pressure is vented. Typical load pulse duration is around 100 msec, although this can be varied somewhat depending upon the magnitude of the reaction mass and exhaust port location. The magnitude of the load is controlled by the amount of fuel placed within the combustion chamber.



1. Statnamic device is placed against test foundation
2. Pelletized fuel inside piston is ignited
3. Expanding gasses push reaction mass away from foundation imparting an equal and opposite thrust on the foundation

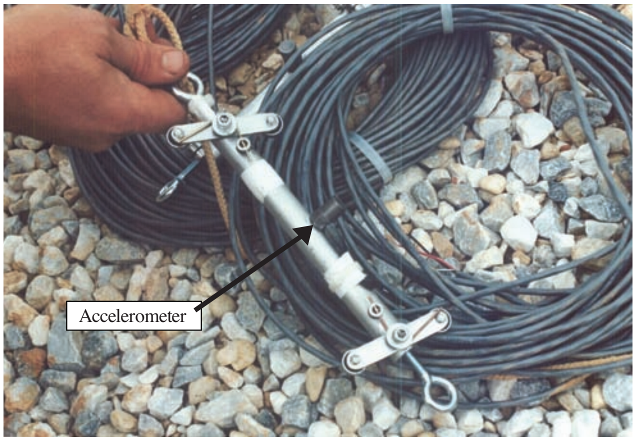
[Fig. 1] Schematic of Statnamic Device for Lateral Loading

The loading test is conducted typically with four progressively increasing load intervals, each of which is a separate rapid loading pulse. Roughly one hour elapsed time is required between load intervals for the device to be reloaded, re-assembled and repositioned against the test foundation. The use of four successive and increasing load pulses has been observed to provide the best means of reproducing the nonlinear load vs displacement relationship with which engineers are familiar from static testing.

Measurements at the top of the foundation include load, displacement, and acceleration. The calibrated load cell provides an accurate and reliable measure of the force applied to the foundation as a function of time. Accelerometers are typically placed at several locations on the test foundation and provide a measure of the acceleration time history and, by twice integration, a displacement time history. Capacitor-type accelerometers are used rather than piezo-crystal type because of their greater stability and reduced tendency for drift over the several seconds of time for which data are gathered. Displacement transducers consisting of long-travel LVDT=s or linear potentiomers are typically mounted on a reference beam to provide a second and redundant measure of movement. It is often difficult to avoid ground-induced vibration of the reference system, although such transient motions are often very small relative to the foundation motion. However, the use of displacement transducers provide the most reliable measure of permanent displacement and the use of these transducers together with the integrated accelerometer measurements provides needed redundancy. An additional accelerometer mounted upon the reference beam is typically used to monitor any vibrations in the reference system.

Measurements are also made below the top of the foundation in order to determine the displaced shape of the pile or shaft and the location of maximum bending stresses. The determination of the displaced shape is made using recoverable, downhole accelerometers, an example of which is shown on Fig. 2.

These are mounted on a guide which is lowered into place at the prescribed elevation within an inclinometer casing. An adjustable mount allows the device to be oriented in the proper direction to align with the load and displacement direction of the test foundation. Double integration of the downhole accelerometer signals allow determination of the displacement time history at each instrument location. For most of the tests performed to date, a string of 8 downhole accelerometers (along with the above ground displacement measurements) have proven adequate to define the displaced shape of the test foundation and the point of plastic hinge formation beneath the surface. Strain gauges are typically used to monitor bending stresses within the pile or shaft. Note that resistance-type strain sensors rather than vibrating wire instruments are required in order to obtain data at the frequency needed for dynamic testing.



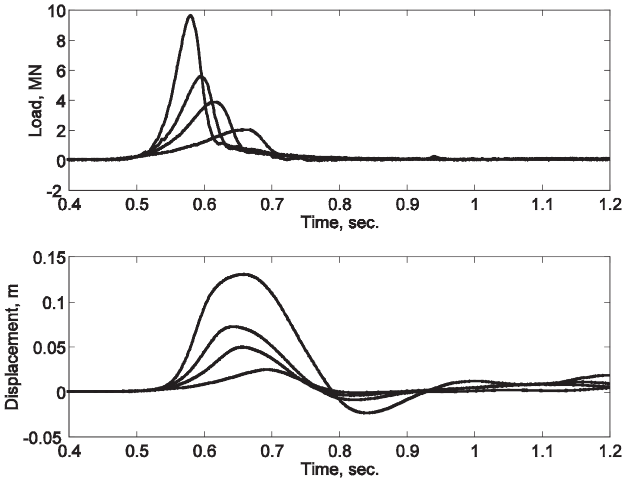
[Fig. 2] Downhole Accelerometer

All of the instrumentation must be monitored using a high speed data acquisition system. A sampling frequency of 1000 samples per second has proven sufficient for the rapid lateral testing of drilled shafts used in this study, although higher frequency sampling may be needed for small piles. Most commonly the system is set to trigger from the load cell and record data from a pre-trigger time of 0.5 seconds to about 4 seconds post-trigger. Most deep foundation systems have a resonant frequency well above 3 Hz, and the data of interest occur generally within the first second after trigger. Some large group foundations over water have produced data of interest for several seconds after trigger.

Test Foundation Response and Data Interpretation

Example Measurements

Although several case histories will be presented later in this paper, it is instructive to utilize some actual data in the process of describing the measured foundation response and proposed method of analysis. Presented on Fig. 3 are the four load time histories for a load test recently conducted in Charleston, SC (Brown and Camp, 2002). This shaft was a 2.6 m diameter by 46 m deep cast-in-place concrete drilled shaft with a permanent steel liner some 25 mm thick in the upper 17 m of the shaft. The soil conditions consisted of soft organic clay within the upper 15 m underlain by a very stiff calcareous clay known locally as the Cooper Marl Formation.



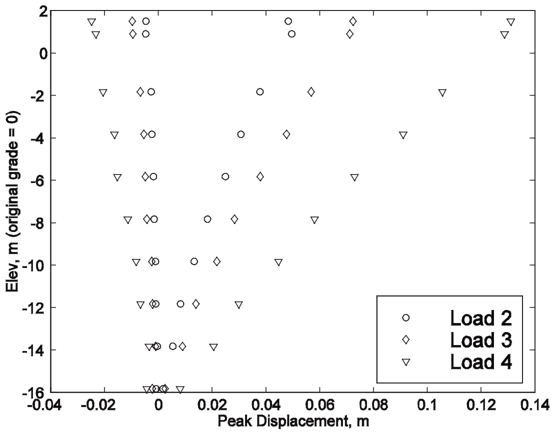
[Fig. 3] Load and Displacement Time Histories for Charleston Test Shaft C-2

Also shown on Fig. 3 are the displacement time histories from these four loadings, measured at the point of loading approximately 1 m above the ground surface. This foundation had large damping, as the oscillations damped out very quickly after the initial peak.

Shown on Fig. 4 are the peak displacements from the downhole accelerometer measurements, plotted as a function of depth below the ground surface, for load events two through four. These measurements indicate very reliably the point of rotation near the top of the Cooper Marl at a depth of around 16 m below grade.

Derived Static and Dynamic Load-Displacement Response

Using a simple single degree of freedom system, an equivalent static and damping response may be derived from the rapid loading lateral test



[Fig. 4] Peak Displacements Below Grade for Charleston Test Shaft C-2

measurements. This model includes a nonlinear static spring resistance, inertia of the shaft rotating about a hinge point below ground, and a viscous damping component. The forces acting on the foundation may be described as follows:

$$F_{meas} = F_{inertia} + F_{damping} + F_{static} \qquad (1)$$

where,

F_{meas} = measured force on the load cell

$F_{inertia}$ = inertial resistance from effective mass of the foundation

$F_{damping}$ = effective viscous damping resistance

F_{static} = effective static soil resistance

The inertial resistance is roughly that of a cylinder rotating about its base, with a diameter equal to that of the test shaft and a height taken as approximately 18 m, based on the observed displacement pattern (16 m below grade plus approximately 2 m above). For such a cylinder of radius r, height h, and mass m, the mass moment of inertia about the base, I_y is:

$$I_y = m\ (\ r^2/4 + h^2/3\ ) \qquad (2)$$

The rotational acceleration of such a cylinder in relation to a displacement x at the loading point z would be $\ddot{x}/z$ and thus summing moments about the base,

$$(F_{inertia})z = (I_y)(\ddot{x}/z) \qquad (3)$$

Therefore, $F_{inertia} = (I_y)(\ddot{x}/z^2) = m_e\ddot{x}$ where m_e may be thought of as the effective mass of the foundation. For this test, m_e would be calculated to be around 85,000 kg. It is normally necessary to increase this value somewhat for analysis purposes in order to include some mass from the passive earth pressure wedge of surrounding soil (which is also suggested by the data) and this value is increased by 20% for this example.

The damping resistance is presumed to be represented by a viscous damper in which the force $F_{damping}$ is proportional to the velocity, $\ddot{x}$, by a constant, c (which is in units of force-sec./length). In order to relate this more meaningfully to a system damping parameter, the damping constant is expressed as a percent of the critical damping, c_c, by

$$D = c/c_c = c/[2(km_e)^2] \qquad (4)$$

where,

k = static stiffness

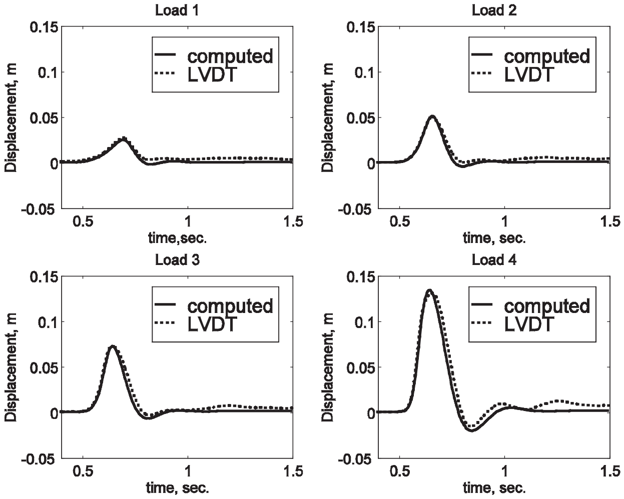
thus,

$$F_{damping} = c = D\ [2(km_e)^2]$$

The static resistance is modeled as a function of displacement, x, using a spring with stiffness k_s. Because the soil response for lateral loading at large strains is known to be highly nonlinear, this spring may be modeled as a nonlinear stiffness which decreases as a function of displacement. For routine analyses, it is normally sufficient that the stiffness has been taken as a constant which is derived independently for each statnamic loading (and is smaller with each successive increased load). It is also possible to assume a stiffness which decreases according to some prescribed mathematical way as a function of displacement.

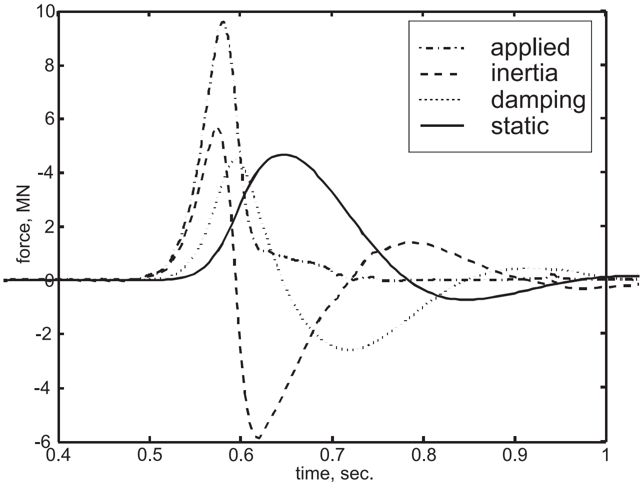
The model is backfitted to the results of the four test measurements to obtain the nonlinear spring and viscous damping parameters which best match the observed behavior, using the measured load vs time as input. This procedure is thus a signal matching process, and the solution is not unique. However, the relatively few parameters constrain the model very well. The static stiffness primarily controls the initial peak displacement with little influence from other parameters. The static stiffness and mass control the frequency of oscillation, and the mass is constrained by the physical attributes of the problem. The damping controls the decay of the peak displacements after the initial peak.

For the Charleston test shaft example, the match of the backfitted model and the measurements is illustrated on Fig. 5. The four test loads are matched using an effective mass of 102,000 kg for each case, a stiffness which is constant for each load case but which decreases from 80 MN/m for the first load to 35 MN/m for the last, and a viscous damping component which is 52% of critical damping for each case. This is a relatively high damping ratio compared to many similar tests, but reflects the large damping which was observed for the test conditions at this site.



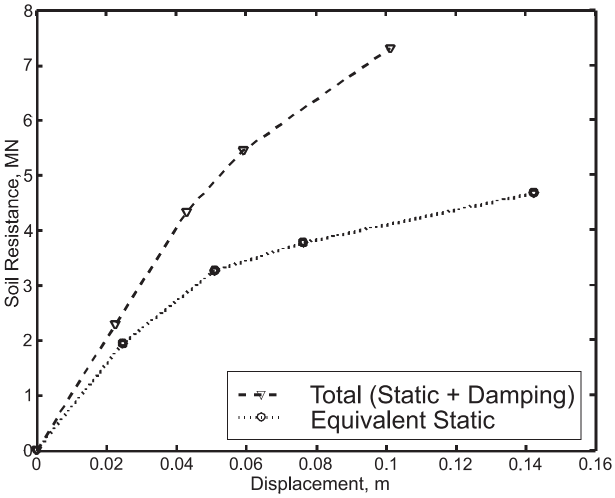
[Fig. 5] Signal Match from SDOF Model for Charleston Test Shaft C-2

The measured, inertial, damping, and static forces are plotted as a function of time for load 4 of this example on Fig. 6. This plot illustrates the development of soil resistance to lateral loading forces during the test. As the rapid loading is applied, this energy is initially used to mobilize the inertia of the shaft. The viscous damping is mobilized as the velocity of the shaft approaches a maximum, then the static soil resistance is mobilized as the displacement reaches a large value. At the maximum displacement, the velocity of the shaft goes to zero, the applied force is already over and the static soil resistance is mobilized to a maximum in order to stop the inertia of the shaft.



[Fig. 6] Forces as a Function of Time from SDOF Model, Load No. 4

As a result of the construct of a model for the test result, the static stiffness can be used to produce a derived static load vs. displacement response as illustrated on Fig. 7. The points shown on that plot indicate the total static soil resistance (static spring force) which is mobilized at the maximum displacement during each of the four loading events. Because the damping is zero at this point, these points are not sensitive to the damping. The points plotted on this figure which are labeled “Total (Static + Damping)” represent the maximum sum of the static + damping forces plotted at the displacement for which this maximum occurs. These forces represent the maximum soil resistance force which was mobilized during the loading event, including the contribution which is attributed to viscous damping. The static resistance is comparable to a static loading test of short duration for which inertial and damping forces are not significant, and for which long term creep from sustained loading is not a major component. The damping contribution represents the effect of the high rate of loading of this soil during the rapid load testing event, which mobilizes a substantial amount of rate-dependent soil resistance in this case. Note also that this dynamic soil resistance is mobilized at a large displacement and a frequency of around 2 to 3 Hz, the damped resonant frequency of the test shaft. This frequency is thought to be reasonably close to that of a seismic load event on a large bridge. Interpretations of dynamic response at other similar but slightly differing rates of displacement or frequency might be inferred from these measurements. Some additional degradation due to gapping and/or reductions in soil shearing strength might be anticipated for many cycles of loading.



[Fig. 7] Derived Soil Resistance vs. Displacement

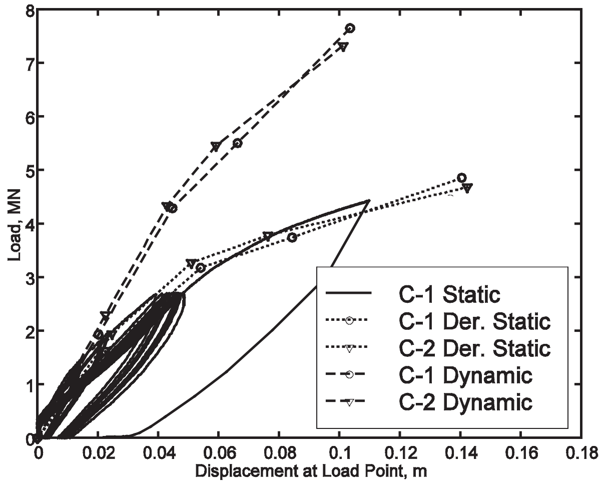
Case Histories

It is instructive to examine those case histories for which the rapid lateral load testing method can be compared with conventional static tests. Several such examples are now available and are reviewed below.

Charleston Test Shafts

The Charleston, SC test shaft C-2 referenced above was part of a major load testing project for a proposed new bridge over the Cooper River. Another identical test shaft, C-1, was located only about 10 m away in nearly identical soil conditions and was also subject to lateral loading. Shaft C-1 was first subject to lateral loading using a hydraulic system so as to produce a slow cyclic lateral loading with a period of around 2 minutes/cycle. After the completion of the cyclic loading, this shaft was subsequently subjected to a rapid loading test in the opposite direction using the Statnamic device.

The results of the slow cyclic and the derived response from the subsequent rapid loading on test shaft C-1 are shown on Fig. 8, along with the rapid loading test results from the identical test shaft C-2 discussed previously. The solid line on this figure representing the cyclic test is seen to match very closely with the derived static response from the two rapid loading tests. The cyclic loading was performed using 10 cycles of constant amplitude force at loads up to about 2.7 MN, followed by a monotonic loading to around 4.5 MN (at which point the pump failed and the test was rapidly concluded!). The derived static response matches quite well with the first cycle loadings (although cyclic degradation was relatively small) and for this monotonic loading to the maximum applied static force. Note that these soft clay soils might be expected to creep under sustained load, but the static (cyclic) test in this case was of short duration. So, the derived static response in this case matches well with a static test of short duration for which long term creep is not a factor.



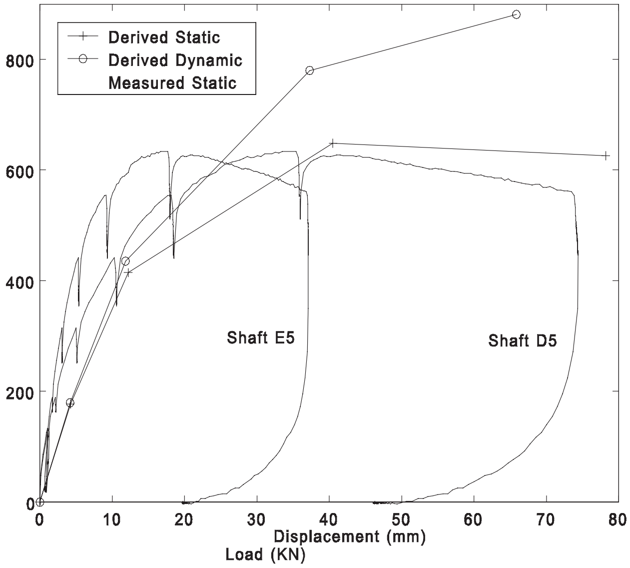
[Fig. 8] Comparison of Static Load - Displacement Response and Two Rapid Loading Tests, Charleston Site

Rock Socket Shafts at Auburn NGES

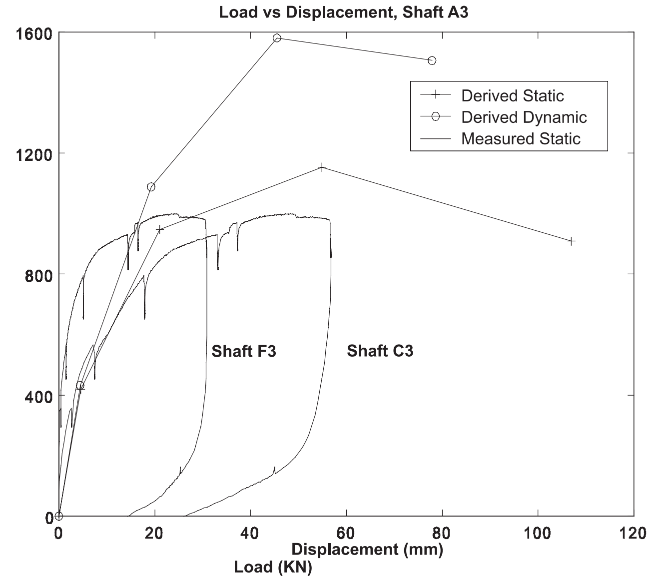
A series of lateral static loading tests were performed on short drilled shafts at the Auburn University National Geotechnical Experimentation Site (NGES) in Alabama (Kahle, 2000). Tests on several similar shafts were performed nearby using the rapid loading method with the Statnamic device. The geotechnical conditions at this site are composed of weathered metamorphic rocks, characterized as hard, fractured quartzite. The overburden soils were stripped away so as to leave the fractured rock formation present immediately below the ground surface. Several shafts of 0.9 m and 1.5 m diameter were constructed into this fractured rock to embedded lengths of up to 2 m.

Conventional geotechnical borings indicate the rock to be hard, but intensely fractured. Coring RQD values were near zero with % recovery generally around 20% or less. Standard penetration test resistance values for the rock typically indicate refusal. Large intact samples of rock taken from the shaft drilling excavation were cored in the lab so as to provide specimens for unconfined compression tests (no suitable samples were obtained from core borings). Unconfined compressive strengths from seven samples ranged from 75 to 185 MPa, with an average value of 130 MPa (19 ksi). This very high strength is virtually irrelevant, as the strength during load testing was dominated by the macrostructure of the formation. The weathered rock at this site represents the type of material for which site-specific field loading tests are most appropriate, as geotechnical characterization of the weathered rock for foundation design purposes is extremely difficult.

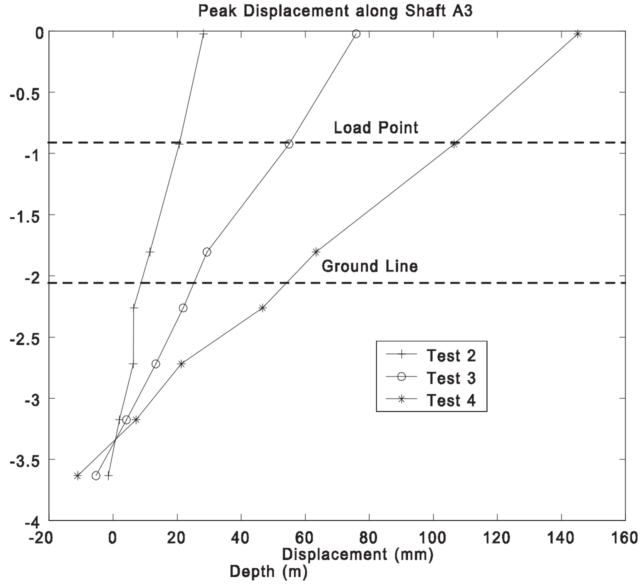
Presented on Fig. 9 are data from two shafts which were pushed apart using a hydraulic loading system (shafts E5 and D5), along with the derived static and dynamic soil resistance from a rapid loading test on a shaft of similar size (B5). These shafts were each 0.9 m diameter and embedded approximately 2 m deep. Presented on Fig. 10 are similar data from shafts which were each 1.5 m diameter and embedded approximately 1.5 m deep. The static loading tests were performed by applying load in increments and holding at constant displacement for periods of around 10 minutes at each increment. The fractured rock did not exhibit a large amount of creep, but did exhibit a strong nonlinear response as a passive earth pressure failure was achieved in each test. Subsurface displacements from integrated accelerometer measurements during the rapid loading tests are provided in Fig. 11, which reveal that this shaft rotated as a nearly rigid-body rotation about a point just above the shaft toe. Inclinometer data from the static tests were similar, indicating a point of rotation about 0.3 to 0.5 m above the toe.



[Fig. 9] **Comparison of Static and Rapid Loading Tests, 0.9 m Diameter Rock Sockets, Auburn NGES**



[Fig 10] **Comparison of Static and Rapid Loading Tests, 1.5 m Diameter Rock Sockets, Auburn NGES**



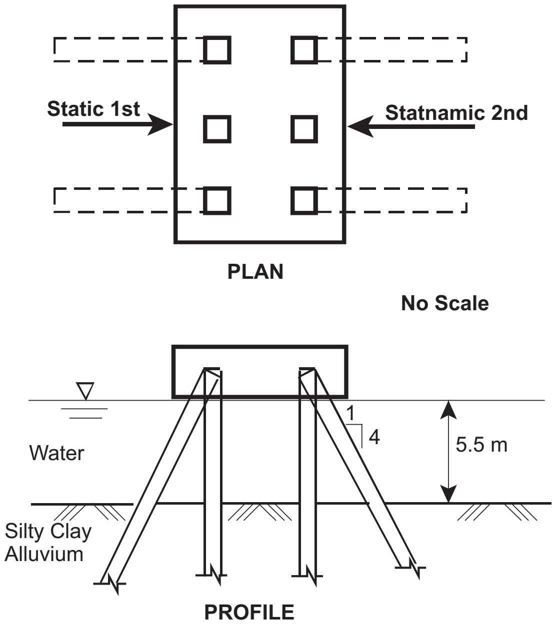
[Fig 11] **Peak Displacements Below Grade for 1.5 m Diameter Rock Socket, Auburn NGES**

The comparisons between the rapid loading and static loading tests for this site suggest that the derived static response agrees quite well with the measured static response from tests on similar shafts, within the range of variability from the site. Most notable was the similarity in the load which produced passive earth pressure failure in this fractured rock formation.

Pascagoula, MS Pile Group

A third and quite different case history is provided by the results of static and rapid lateral loading tests on a group of six prestressed concrete piles. This test was a part of a field test pile program intended to provide guidelines for deep foundation design for a new bridge over the Pascagoula River as well as for other future bridges along the Mississippi Gulf Coast. The site for the testing program is adjacent to the alignment for the new bridge in an area with approximately 5.5 m water depth. The soils are predominantly alluvial deposits of soft to stiff clays above elevation -18 m, with dense sands interbedded with stiff clays below that elevation.

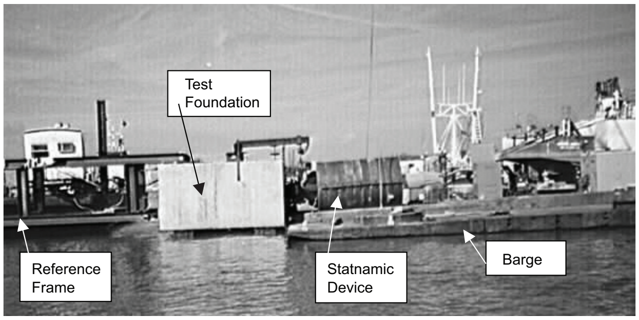
The static lateral load test setup consisted of two foundations to be loaded by jacking each against the other as shown on Fig. 12; additional details of the static load test results are provided by Brown and Crapps, 1998. The static test was performed in increments of load, with the load at each increment maintained for a period of around 60 minutes. The pile group consisted of six square prestressed concrete piles, 0.76 m in width, which are arranged to



[Fig 12] Schematic of Test Foundations, Pascagoula, MS Site

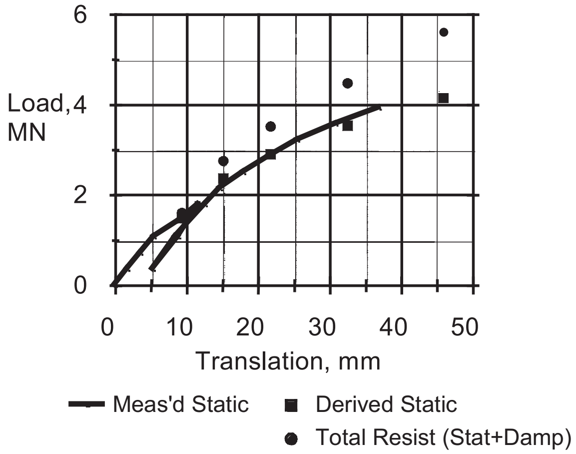
have two vertical piles, two batter piles designed to act in compression, and two batter piles designed to act in tension. The batter piles were installed on a 1:4 batter. The piles were spaced at 3 pile widths at the cap, center to center. The driven piles were embedded 1.5 m into the 2.4 m thick concrete cap to provide sufficient development length on the prestressing strands so that the full moment capacity of the pile was available at the base of the cap. The piles had 24 - 12.5 mm (1/2 inch) diameter strands with 75 mm cover and each strand was prestressed to 144 kN (32.3 kips). A 0.46 m diameter void within the center of each pile was filled with concrete after driving.

After completion of the static lateral load tests, the Statnamic loading was applied from the deck of a barge so as to load each foundation in a direction opposite to that of the static test. The Statnamic testing was performed by applying 5 progressively increasing magnitude loadings using the 14 MN capacity device shown on Fig. 13. Care was taken to ensure that large permanent plastic deformations were not induced in the piles or shafts during the static loading which would affect performance during Statnamic testing. Measurements of permanent displacements taken using the inclinometer device suggest that a permanent lateral displacement after static testing was about 6 mm.



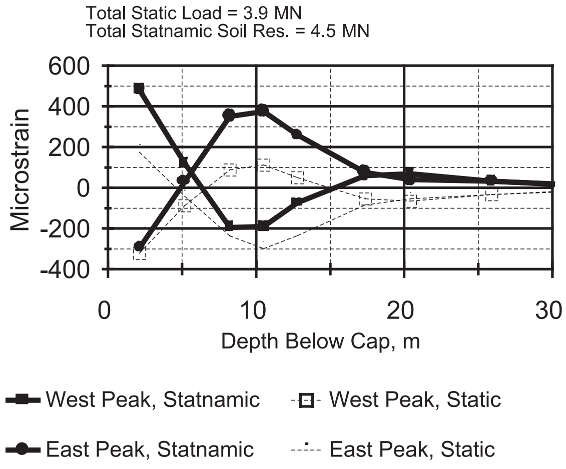
[Fig 13] Photo of Over-Water Statnamic Test, Pascagoula Pile Group

The pile group motions were dominated by lateral translation with very small rotations (as was the case for the static loading). The derived static and damping resistances were computed using a mass equal to the mass of the pile cap plus the contribution of the piles above the mudline. A damping ratio of approximately 30% proved effective in matching the observed displacement time history. Derived static and dynamic resistance as a function of displacement are provided on Fig. 14, along with the static load test measurements. Note that although the static load testing included sustained loading and took about ½ day to complete, the derived static response is seen to match the measured static response quite well. Note also that the derived static curve exhibits the nonlinearity observed in the static test, which was expressed as decreasing foundation stiffness at increased amplitude of motion. The resonant frequency was observed to decrease as the stiffness decreased, as expected.



[Fig 14] Comparison of Static and Rapid Loading Tests, Pascagoula Pile Group

The peak strain gauge data for the statnamic test results generally appeared quite similar to the patterns of strain from the static test. An example of these measurements is provided on Fig. 15 for one of the more well instrumented of the prestressed piles, pile 5 (vertical). This figure illustrates the strains in the pile from the first peak during the statnamic loading; i.e., this is a "snapshot in time" corresponding to that peak strain. For this loading, the total static + damping soil resistance at this point in time is approximately 4.5 MN. The maximum static load applied was 3.9 MN and is provided for comparison. The static and statnamic loads were applied in opposite directions, thus these are "out of phase" with opposite signs. The pattern of strains is seen to be identical, with an offset from the 0 axis of the average between the west and east sides of the pile which reflects the axial load strains superimposed upon the bending strains. Pile 5 for the statnamic loading is put into compression while this pile was in tension during the static loading. The strain gauge data suggest that the piles performed quite similarly during the statnamic and the static lateral loadings.



[Fig 15] Comparison of Peak Strain Measurements, Pascagoula Pile Group

Summary and Conclusions

A method of conducting rapid lateral loading tests of deep foundations has been described, along with a simple procedure for interpretation of the data. The rapid lateral testing procedure is seen to have some advantages in terms of testing efficiency, the capability of inducing very large lateral loads, and the capability of observing dynamic behavior. Several case histories are provided which allow comparisons of the derived static and dynamic response with that of conventional static tests. The simple analytical model described in this paper appears to be capable of providing a reasonable interpretation of the static lateral load response from the rapid loading test and also provides additional information relating to damping. The damping resistance derived from the statnamic loading suggests that the deep foundations tested may have some additional soil capacity available to resist very transient dynamic loading events such as seismic, maximum wind gust, or vessel impact.

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References

1. Briaud, J.L. and Ballouz, M., 1996, "LATWAK: Impact Test for Lateral Static Stiffness of Piles," Journal of Geotechnical Engineering, Vol. 122, No. 6, pp. 437-444, ASCE, New York.
2. Brown, D.A. and Camp, W.F. (2002). "Lateral Load Testing Program for the Cooper River Bridge, Charleston, SC," paper submitted for publication in the Proceedings of the International Deep Foundations Congress, ASCE, Orlando, FL, Feb.
3. Crapps, D.K, and Brown, D.A. (1998). "East Pascagoula River Bridge Test Program", Project Report prepared for Mississippi Dept. of Transportation, April, 1998, Vol's I and II.
4. El Naggar, M. H., 1998, "Interpretation of Lateral Statnamic Load" Test Results. *Geotechnical Testing Journal*, GTJODJ, Vol. 21, No. 3, September, pp. 169-179.
5. Janes, M.C., Bermingham, P.D., and Horvath, R.C., 1991, "An Innovative Dynamic Test Method for Piles," *Proceedings*, Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, pp. 252-256.
6. Kahle, K., 2000, *Performance of Laterally Loaded Drilled Sockets Founded in Weathered Quartzite*, MS thesis presented to Auburn University, Dec., 2000, p. 227