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An Innovative Dynamic Test Method for Piles

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The system described involves using solid propellant fuels to accelerate a reaction mass off the test pile. The force required to accelerate the reaction mass upwards acts equally downward on the pile. Very high forces may be applied to the pile in a controlled, linearly increasing manner. The duration of the applied load is approximately 100 milliseconds. This rate of loading is slow enough to allow the pile and soil to react together as a composite rigid body. The effects combine to produce pile and soil response no longer dominated by the transfer of force via stress pulse (as with impact). State of the art instrumentation systems are used to obtain test data. Displacement is monitored directly using a laser datum and integrated receiver locatd at the centre axis of the pile. Force is also monitored directly using a calibrated load cell.

INTRODUCTION

Recent trends in foundation practice are to fewer larger diameter, higher capacity cast in place piles. In the last few years the occurrence of high capacity piles carrying over 5.0 MN has increased dramatically. This results in fewer piles supporting a structure and often one pile per column. Each pile now requires significant quality control measures, reflecting the fact that each pile must now carry its load with absolute integrity. The cumbersome static load test procedure does not lend itself well to repeatable testing. Thus a method is required which is capable of loading a pile to failure and is repeatable, mobile, non-destructive and inexpensive. The Statnamic method is introduced as a solution to these and other requirements.

OBJECTIVE

A load test method must establish the elastic pile load deflection behaviour and ultimate capacity. Consistent load deflection behaviour prevents differential settlement while the ultimate capacity is required to ensure economic design. The conventional static load test is the only method presently recognized as providing this in formation, however it is cumbersome, time consuming and expensive. It is recognized that high strain dynamic testing, coupled with a static load test for calibration can provide an economic alternative. However, it is most applicable to driven piles and low capacity concrete piles. When applied to high capacity concrete piles or rock socketed piers, dynamic methods have proven difficult and expensive. Large drop weights and extensive cushioning materials are required, and the danger of pile damage is high. Instrumention has been dictated by what can accommodate the high pile accelerations imposed by the hammer blow. As a result, force and displacements are not measured directly, and are subject to pile material quality and integration error. Finally, the method is unable to provide pile elastic load settlement behaviour which is required to establish overall structural response and prevent differential settlements. A method is proposed, the Statnamic load test, which meets the desired requirements and combines the advantages of both the conventional static and high strain dynamic load test methods. The Statnamic concept is to push on the pile such that it will act as a rigid body. The pile velocity and acceleration are maintained at levels low enough to ensure the pile and soil act as a composite medium, just as they do in a static environment.

STATNAMIC APPARATUS

The Statnamic apparatus consists of a pressure chamber and reaction mass placed on top of the pile. Fuel is burned within the pressure chamber, creating an increasing force which acts against the reaction mass, accelerating it upward. The force required to accelerate the reaction mass upward acts equally downward onto the pile. The reaction mass, generally about 5% of the desired ultimate load, is accelerated to a peak of 20 g. The event lasts approximately 100 milliseconds, with a dominant loading frequency of about 10 hertz. The Statnamic event is well below the typical natural frequency of most pile soil systems at about 50 or more hertz. Pile velocity and acceleration are below 1.0 m/s and 1.0 g. respectively. Thus the Statnamic test is similar to a temporary push on the pile, with dynamic behaviour sufficiently reduced to a level where the influence of stress waves is insignificant.

Figure 1 provides a cross section of the Statnamic device. The pressure chamber consists of a piston and cylinder much like an internal combustion engine. The piston houses a fuel cavity and within its base are load and deflection transducers, thus no further pile alteration or excavation is required. The cylinder with reaction mass carriage and exhaust silencer attached is placed over the piston. Sectional reaction masses are placed upon the cylinder and carriage and clamped together. No portion of the device has a mass greater than 2400 kg (2.5 tons) thus a light hoisting machine may be used for the entire assembly. Finally a casing is placed around the assembly and filled with granular material. The fuel is burned within the pressure vessel forcing the cylinder and reaction masses upward through some predetermined stroke. An exhaust port is then opened and the gasses vent upwards through the silencer. The fuel is designed to burn in a controlled manner with peak pressures of 680 bar (high hydraulic pressure). As the gasses are vented the cylinder and reaction masses continue to rise upward due to the kinetic energy imparted during the pressure stroke. The peak height obtained averages 2.5 m (8 ft). As the reaction assembly rises the granular material fills the void left and arrests its fall.

INSTRUMENTATION

Statnamic instrumentation incorporates state of the art technology combining accuracy and simplicity. A calibrated load cell, housed in the piston base, is used to monitor the applied load. The displacement transducer consists of a light sensitive cell placed at the centre axis of the pile. A remote laser light source is stationed 10 to 20 m (30-60 ft) from the pile and provides a stationary datum isolated from any ground vibrations. Both load and displacement measurements are accurate to 0.1%. Additional instrumentation includes a pressure transducer in the pressure vessel and an accelerometer within the piston base. A rugged field computer and signal conditioner acquires and digitized raw signals at a rate of 4000 hertz, provides immediate load versus displacement plots or time histories and stores the data on disk.

STATNAMIC DEVELOPMENT

The development of the Statnamic load test method was undertaken in 1988 by the Berminghammer Corporation in Hamilton Canada. Research has been conducted on four fronts including: preliminary field testing and instrumentation, laboratory model pile testing, full scale comparative load testing and theoretical modelling and analysis. The presentation of several case studies will be used to discuss the results obtained by the Statnamic load test method.

OTTAWA HUNT CLUB ROAD

A bridge pier for the Hunt Club Road extension in Ottawa Canada was the site of a recent Statnamic load test. The site provided the opportunity to test driven pipe piles on a 1:5 batter. The high strength steel piles are 324 mm diameter (12.75 in) with a 13 mm wall (0.5 in) and approximately 31 m (102 ft) in length. The soil consists of 1 m (3.3 ft) of fill over 1 m of loose to dense silty sand underlain by 10 to 12 m (34 to 40 ft) of over consolidated soft to firm clays. Portions of the clay stratum show a weathered crust 2 m (6.6 ft) thick with shear strengths decreasing from 120 to 20 kPa (17.5 to 3 psi) with depth. The remaining clay stratum has increasing shear strength with depth from 20 to 90 kPa (3 to 13 psi). Beneath the clay stratum lies 8 to 10 m (26 to 33 ft) of interbeded silts, clays and glacial tills in a dense to very dense state. Underlying the glacial till, at an overall depth of 28 to 30m (92 to 98 ft) is limestone bedrock. The piles were driven using a Berminghammer B-400 diesel hammer with a rated energy of 73 kJ (53,750 ftlbs) to 360 bl/300 mm (bl/ft).

A simple lead frame was constructed in one day on site to guide the 240 kN (27 ton) reaction mass as it rode upward at an 11 degree (1:5) angle to the vertical. The Statnamic device was assembled the next morning, the test conducted and then dismantled over a period of approximately 5 hours.

Load deflection results from the statnamic test conducted on pile P2-09 on the west side of the site are provided in figure 2. Static load tests conducted on piles 36 (west side) and 39 (east side) are provided for comparison. The figure shows an

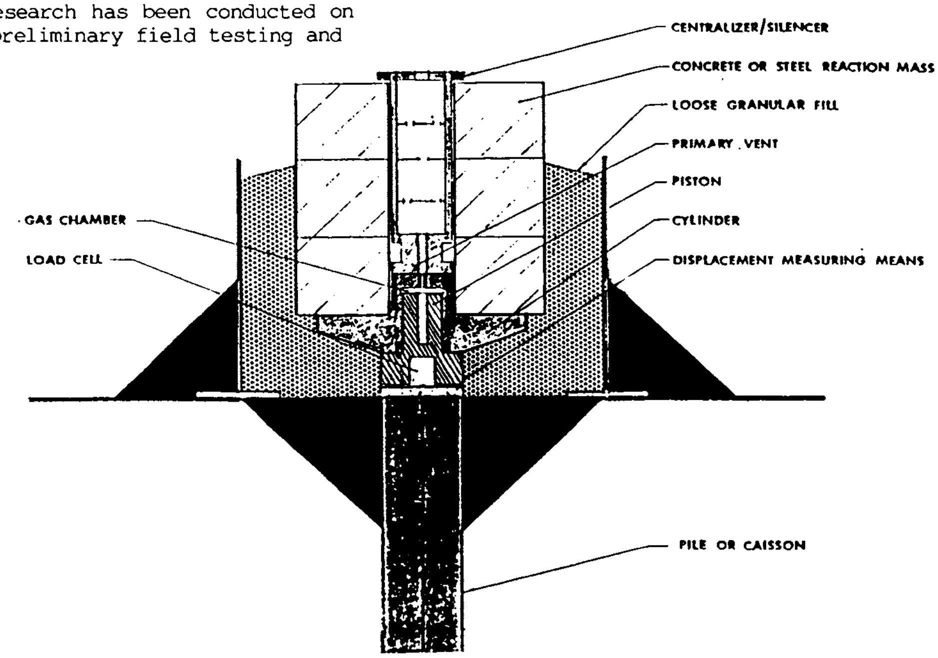


Figure 1: Cross sectional view of Statnamic device

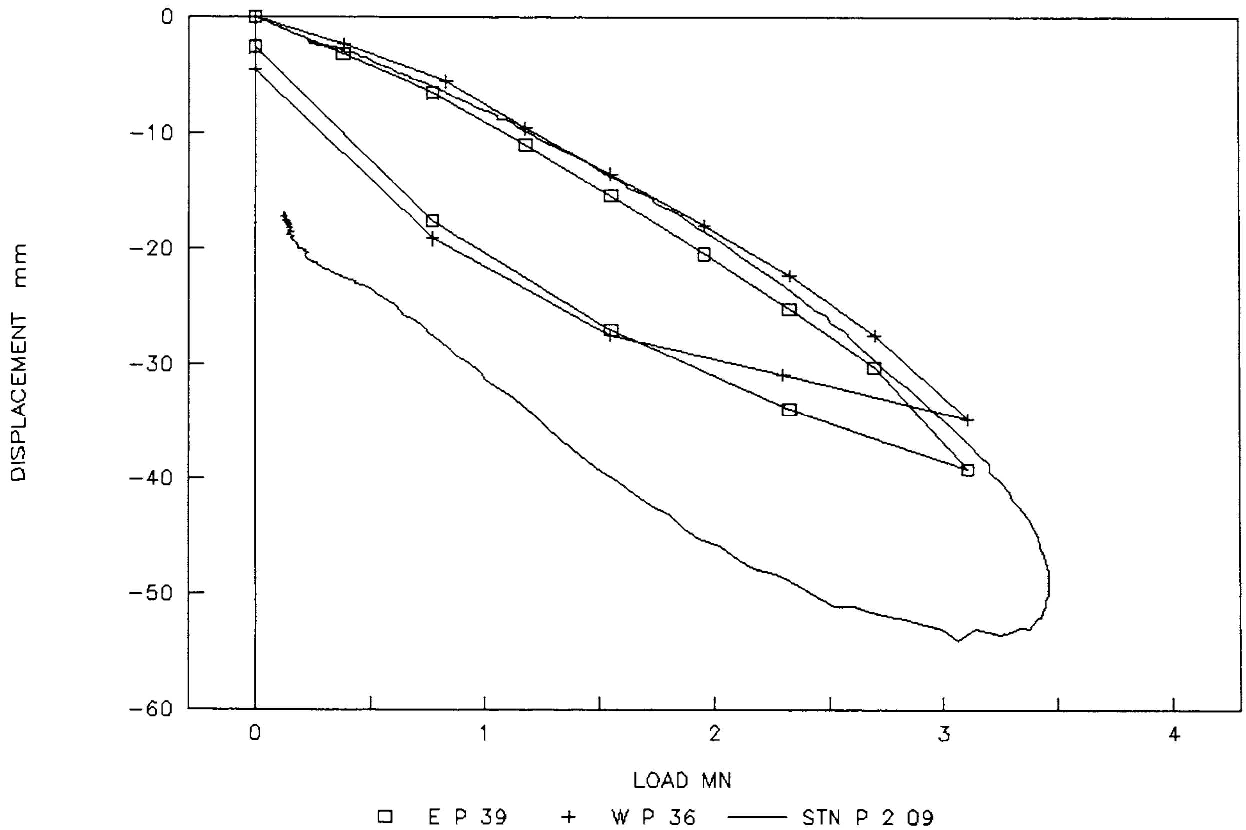


Figure 2: Comparison of Statnamic and preliminary Static Load Test results

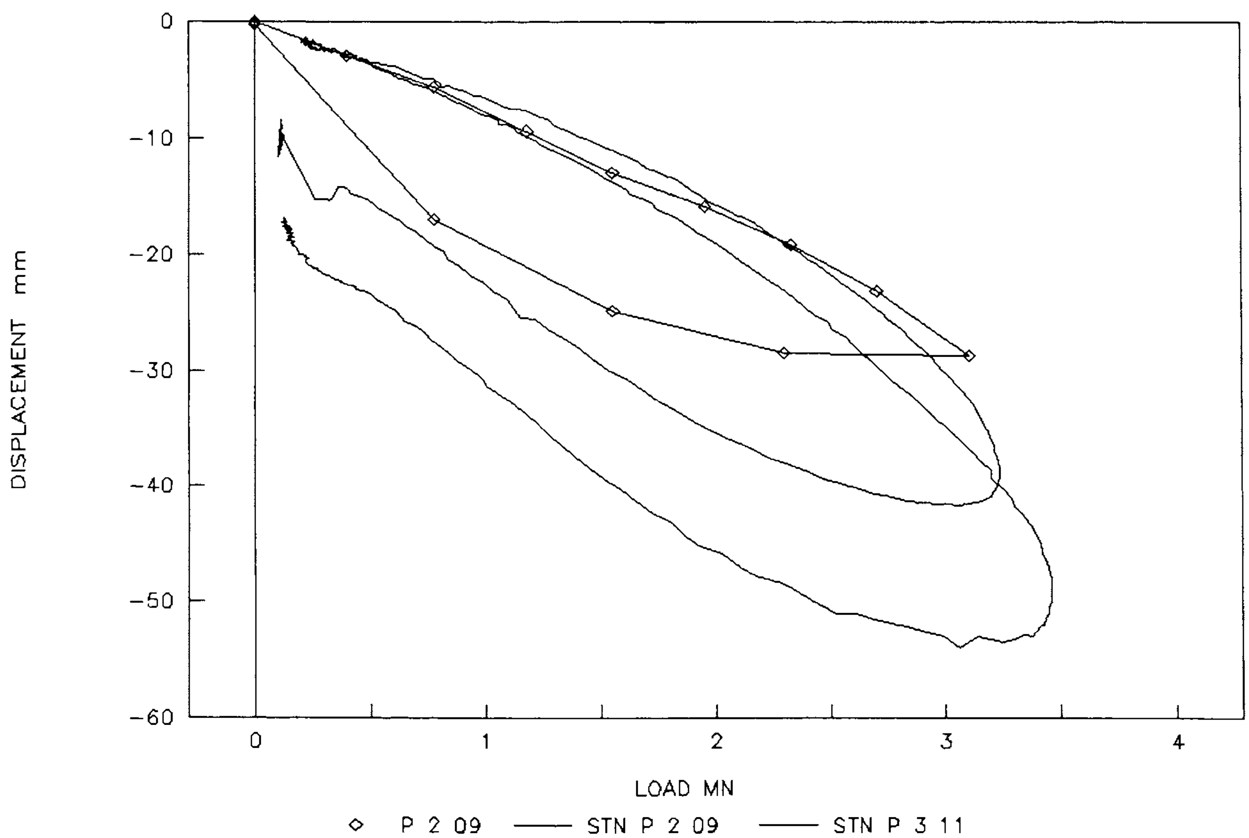


Figure 3: Comparison of Statnamic and Static Load Test results piles P2-09 and P3-11

excellent correlation between statnamic and static behaviour of the piles at both the working load 1.55 MN (175 tons) and twice working load 3.1 MN (350 tons). The Statnamic test mobilized the pile, providing 17 mm (11/16 in) net displacement. This displacement, coupled with the rounded shape of the curve at peak load, indicates failures of the pile soil system has occurred. Figure 3 shows the Statnamic test load deflection behaviour compared to a static load test conducted later on the same pile. The static test required drilling of rock anchors to a depth of 40 m (130 ft) and 2 weeks to conduct. The static result appears stiffer than the Statnamic result. This is expected due to the Statnamic test having driven the pile to a higher set and thus producing a stronger pile. Also provided in figure 3 is a load deflection curve from a second Statnamic test performed on pile P3-11 on the east side of the site. Pile 11 shows a slightly stiffer response. This may be expected as the pile was driven to the same set yet is 3 m (10 ft) shorter than pile 09.

Figure 4 provides a Statnamic load and deflection time history for the test conducted on pile P2-09. The duration of loading is 80 msec with a peak load of 3.6 MN (405 tons). The load increases linearly with time to a sustained peak load prior to venting and a linear release of load. The peak deflection of the pile top of 59 mm may be seen to lag the peak load slightly (3 to 4 msec). This represents the time required for the peak stress to affect the entire length of the pile (or the pile length divided by the wave speed of the pile soil system). However through maintaining the peak load for almost 10 msec, peak loading and displacement will occur in unison.

MCMASTER TEST SITE PROGRAM

A field installation at McMaster University in Hamilton provided the opportunity for several comparative Statnamic and static load tests. The soil profile at the site consists of 3 to 4 m (10 to 13 ft) clayey silt fill with debris, underlain by native subsoils consisting of interbedded silts, clayey silts and silty fine sands to a depth of 17 to 19 m (55 to 62 ft). The water table lies at a depth of approximately 3 m. A dense sand layer overlies weathered shale bedrock below this depth. Eight closed end steel pipe piles were driven using a Berminghammer B-200 diesel hammer (rated energy of 24.4 kJ, 18000 ftlbs). The 178 mm diameter (7.0 in) pipe piles were 18.3 m long (60 ft) with an 8 mm wall (.317 in). The driving resistance averaged 1 bl/300 mm (300 mm = 1ft) throughout driving and increased to 5 to 10 bl/300 mm in the last 2 m (6.5 ft). Four of the piles were instrumented with weldable foil strain gauges at 2/3 and full depth for the purpose of establishing pile load distribution. Half the piles were Statnamically load tested and half statically load tested, and after a suitable time period the procedure was reversed to give comparative load deflection data for each pile. An incremental constant rate of loading method, similar to that employed by Bozozuk et al (1979) and in accordance with ASTM procedures (referred to as quick maintained load (QML) testing) was used for all static tests. Load increments of 20 kN (2.2 tons) were applied at 10 min intervals until pile failure occurred. Statnamic testing was conducted using a 600 kN (66 tons) maximum load device. Four Statnamic load tests were conducted in a single day using 1/20th the reaction mass required for an equivalent static load.

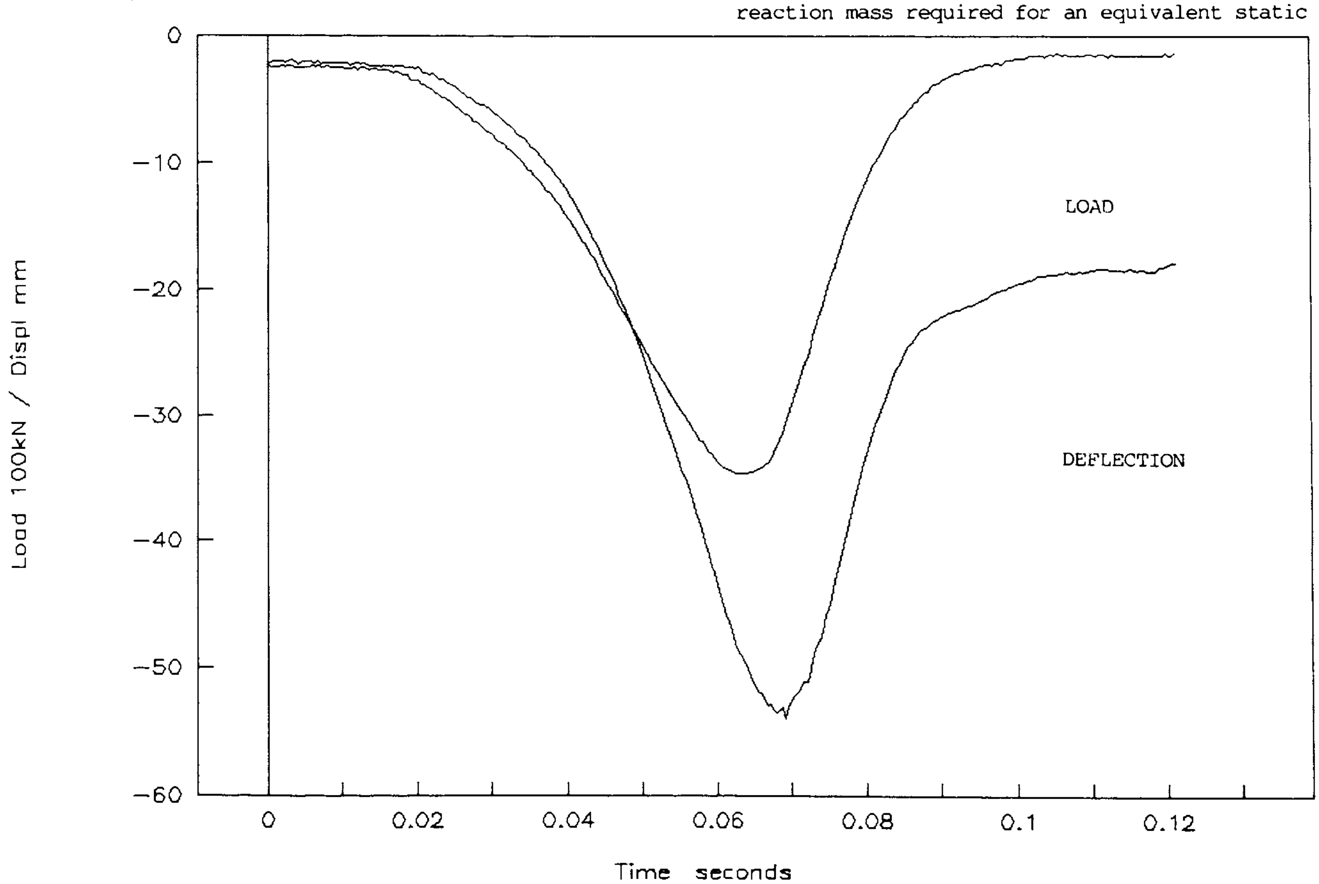


Figure 4: Load and displacement time histories for pile P2-09

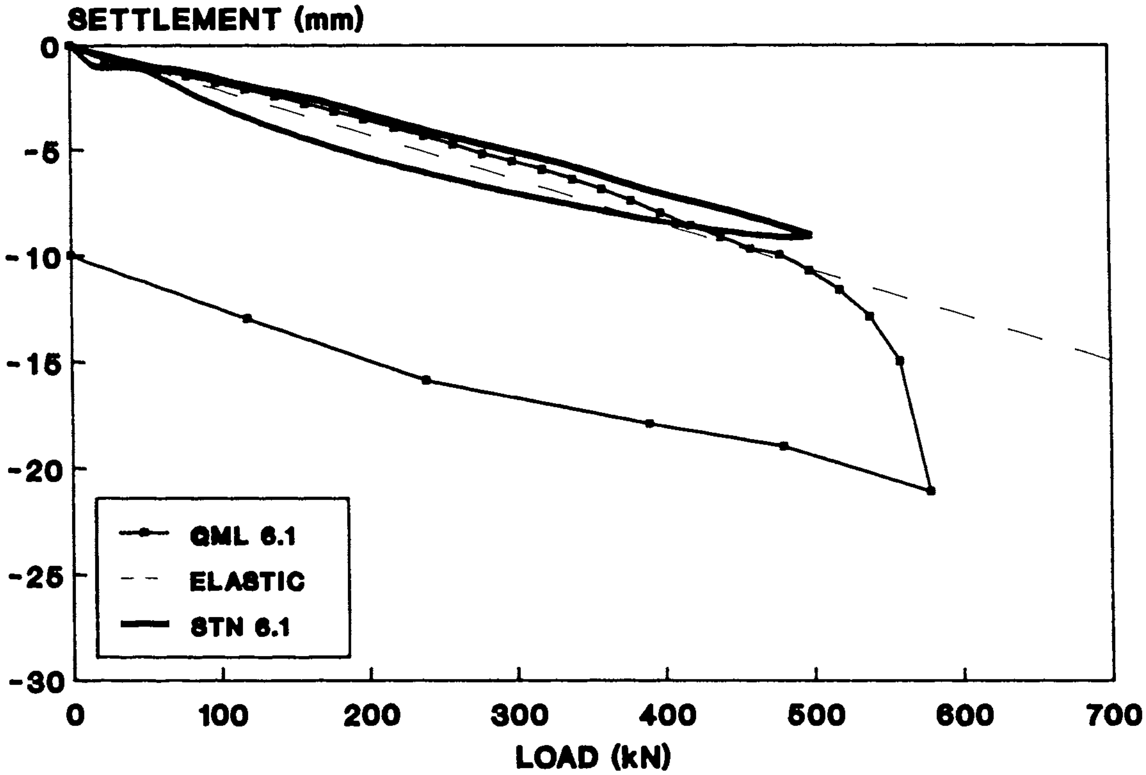


Figure 5: McMaster University comparative load test results pile nr. 6, July 1989

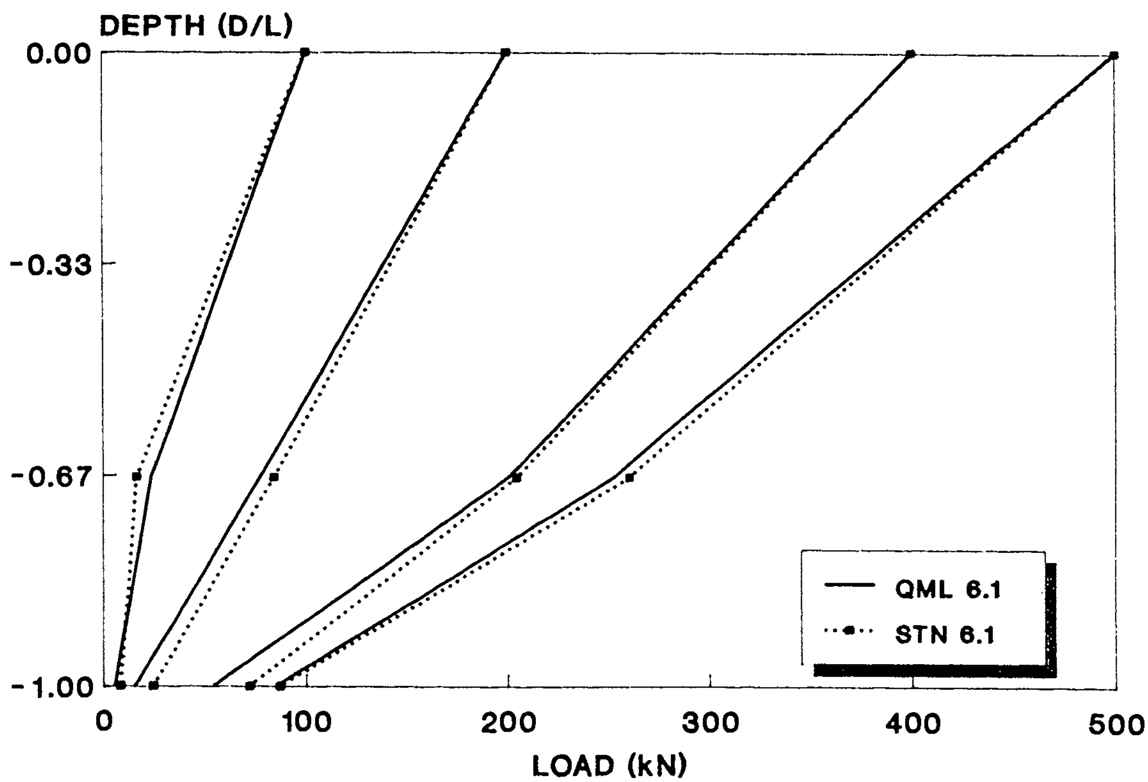


Figure 6: McMaster University pile nr. 6 Statnamic and Static pile load distribution

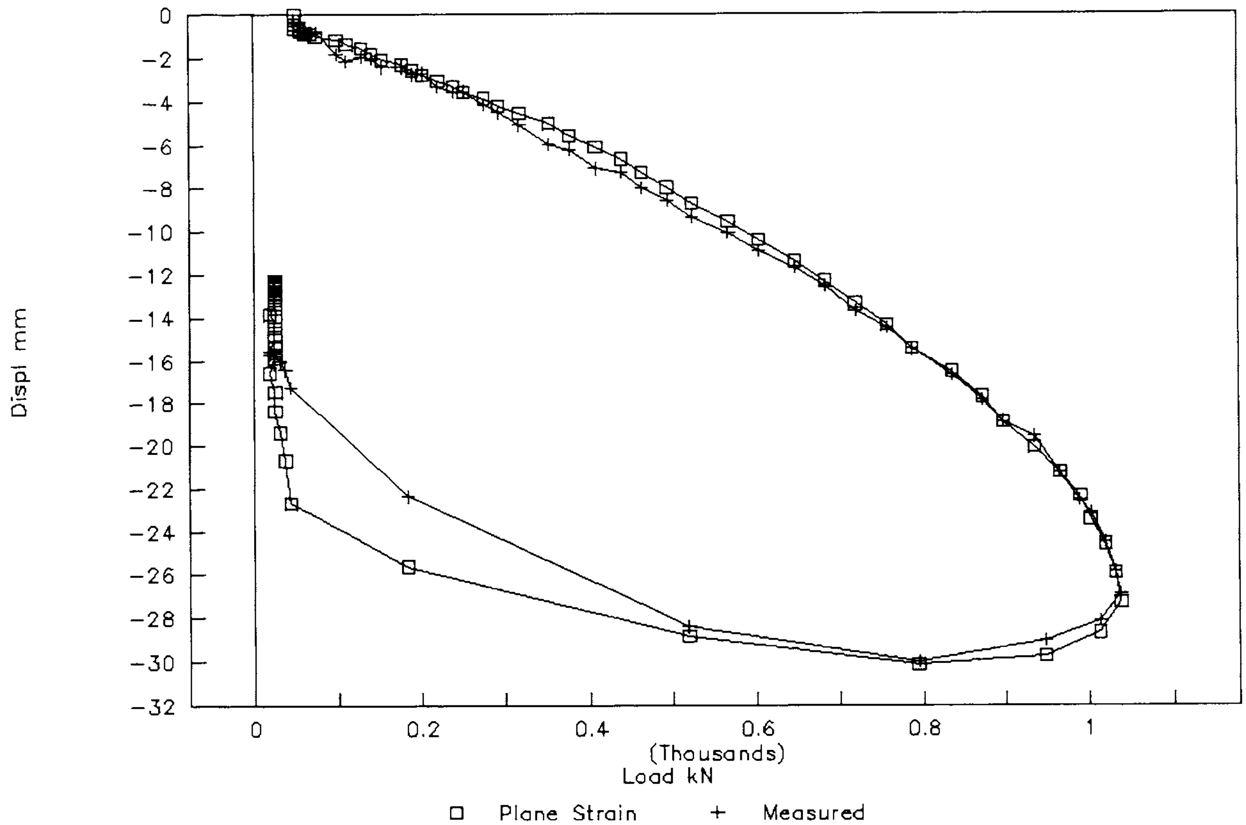


Figure 7: Pile nr. 8, measured and calculated load deflection behaviour

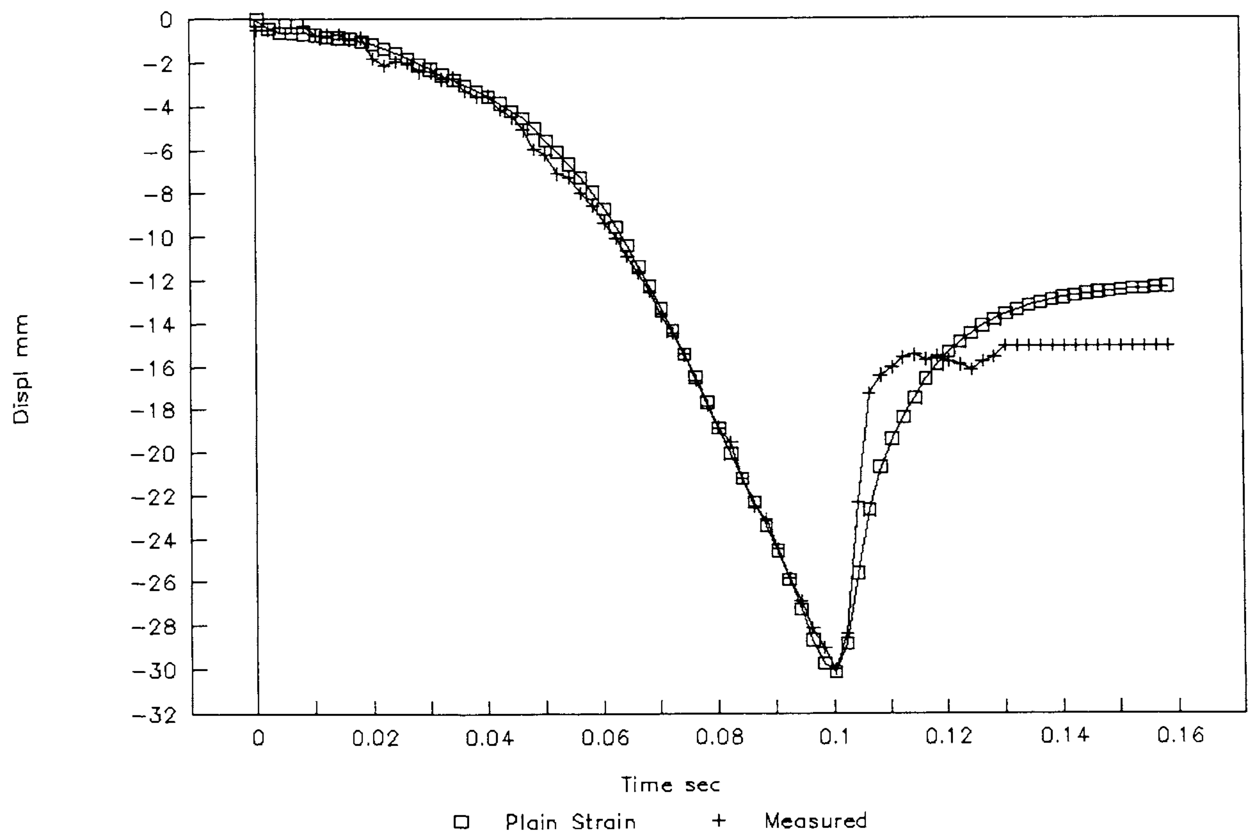


Figure 8: Pile nr. 8, measured and calculated deflection time history

A comparison of the typical load displacement results from each method is provided for pile 6 in figure 5. Also provided is an elastic compression line which depicts pile deflection if the entire load were taken in end bearing. The figure shows a very good correlation between load deflection behaviour for Statnamic and static loading until just prior to pile failure. For a working load of about 275 kN (31.3 tons, one half the estimated failure load by Davisson's) the two methods give virtually the same displacement. No difference in behaviour was perceived for piles loaded first Statnamically as opposed to statically. During the preliminary test stage the Statnamic device was not of sufficient capacity to fail the piles.

Figure 6 provides a comparison between Statnamic and static load transfer behaviour along the pile shaft. The figure shows pile load at the 2/3 point and pile toe equivalent top loads. Thus when the pile was subject to a top load of 500 kN (55 tons) during either the Statnamic or static load test the load in the pile at the 2/3 point was approximately 260 kN (29.5 tons) and at the toe was 87 kN (9.9 tons). This clearly demonstrates the load transfer mechanism from pile to soil is essentially identical between Statnamic and static loading. In addition it proves the Statnamic method loads the pile as a rigid body. It may also be noted the piles derive their strength largely from skin friction with only 17.4% of their capacity derived from end bearing. The piles were tested using a larger statnamic device one year later. Once again the load deflection behaviour of the piles under Statnamic testing closely resembled that of the static tests. The piles were failed using the larger device, however at substantially higher loads than original static failure. The piles may have increased in capacity with the time provided to reset, however it is believed the highly viscoelastic nature of the soft, saturated soils at the site would contribute to the result observed.

Figure 7 provides a Statnamic load deflection curve for pile 8 at the McMaster site for recent testing with a high capacity device. The pile has clearly been mobilized with net displacement of 15 mm (3/5 in) and a peak load of 1.05 MN (115 tons). The curve shows rounding at peak load and a shallowing of the rebound portion, characteristics typical of Statnamic failed pile behaviour. The accompanying curve (boxed points) shows the predicted load displacement from a discretized computer model of the pile soil system. The analysis utilizes plane strain theory to account for inertial and damping effects. It accommodates pile soil slip as well as soil non linearity through the incorporation of a slip element and a weak zone surrounding the pile (Novak and Sheta 1980 and Mitwally and Novak 1988). As may be seen, the program is able to accurately model the pile displacement from the applied top load time history. It should be noted the dimensionless frequencies for Statnamic loading and the piles analyzed to date are within acceptable ranges. Use of the plane strain model will assist in establishing appropriate failure criterion for the Statnamic method for all types of soil.
The displacement time history for the Statnamic load conducted on pile 8 is provided along with the plane strain predicted response in figure 8. The displacement increases linearly with increasing load. Pile velocity and acceleration are below 0.6 m/s (2 ft/s) and 1 g respectively. This is considered ideal pile behaviour. The plane strain displacement model during loading is excellent. This reflects an accurate model of pile soil stiffness and slip. The down loading correlation is not as good which may be due to inaccuracies in the way inertia and soil reattachment to the pile are handled. Future research will eandeavour to improve on the theoretical model through correlation with an expanding data base.

BURLINGTON COMPARATIVE FIELD TESTING

The King Road test site is an old shale quarry in Burlington Canada where six socketed piers were installed and tested in 1980 as part of a research program at the University of Toronto (Horvath et al 1983). The QML method was used to statically test the piers, whose construction provided various forms of rock socketing (smooth and grooved) and end bearing conditions. The original project investigated the load distribution in rock sockets and the effects of contouring the socket wall.

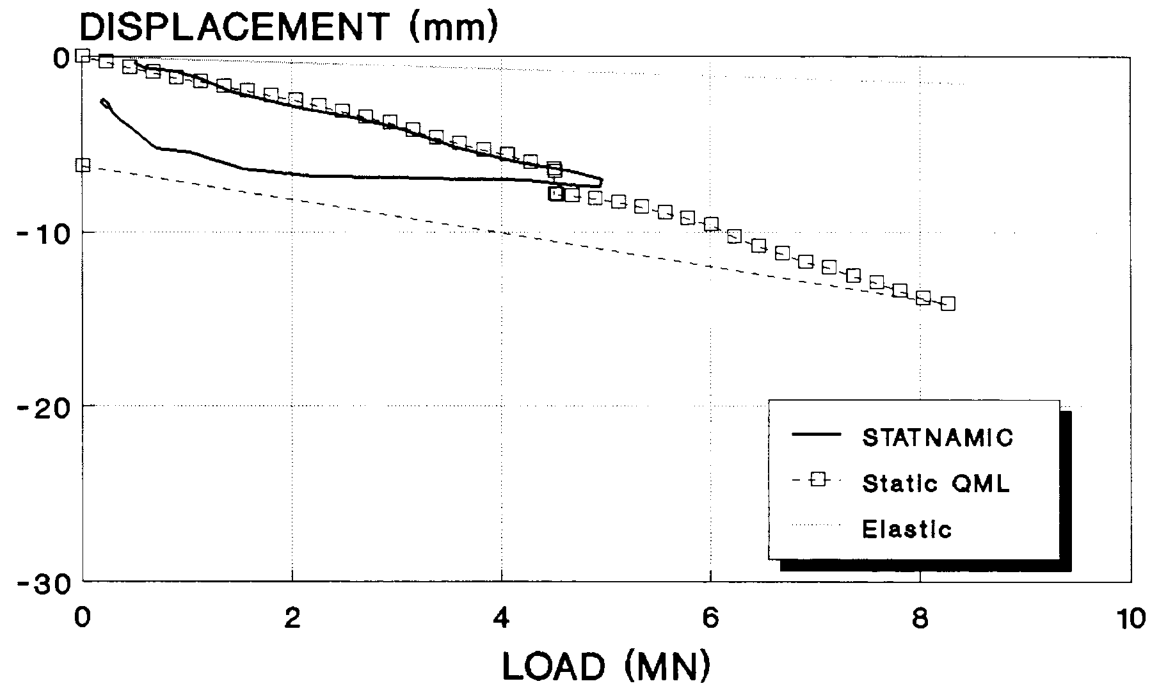
Site rock conditions consist of weathered (isolated from the pile) over competent Queenston shale with an average compressive strength of 6.75 MPa (990 psi) and elastic modulus of 695 MPa (102 ksi). The pier concrete has a compressive strength of 49 MPa (7200 psi) and elastic modulus of 35 GPa (5100 ksi).

Two significantly different test sockets, P1 and P4 were easily accessible (July 1990) for re-testing using the Statnamic device. Test pier P1 was constructed using conventional construction methods (augering) and had a void at the base to eliminate end bearing resistance. Pier P4 was constructed with a grooved rock socket wall and a hydraulic load cell at its base. The initial research program indicated significant increases in shaft capacity with socket grooving.

Vibrating wire strain gauges installed in five of the test sockets as part of the original research program were monitored prior to Statnamic testing. The July 1990 readings were very similar to the 1980 readings indicating the subsurface conditions, in terms of in-situ stresses, did not change significantly.

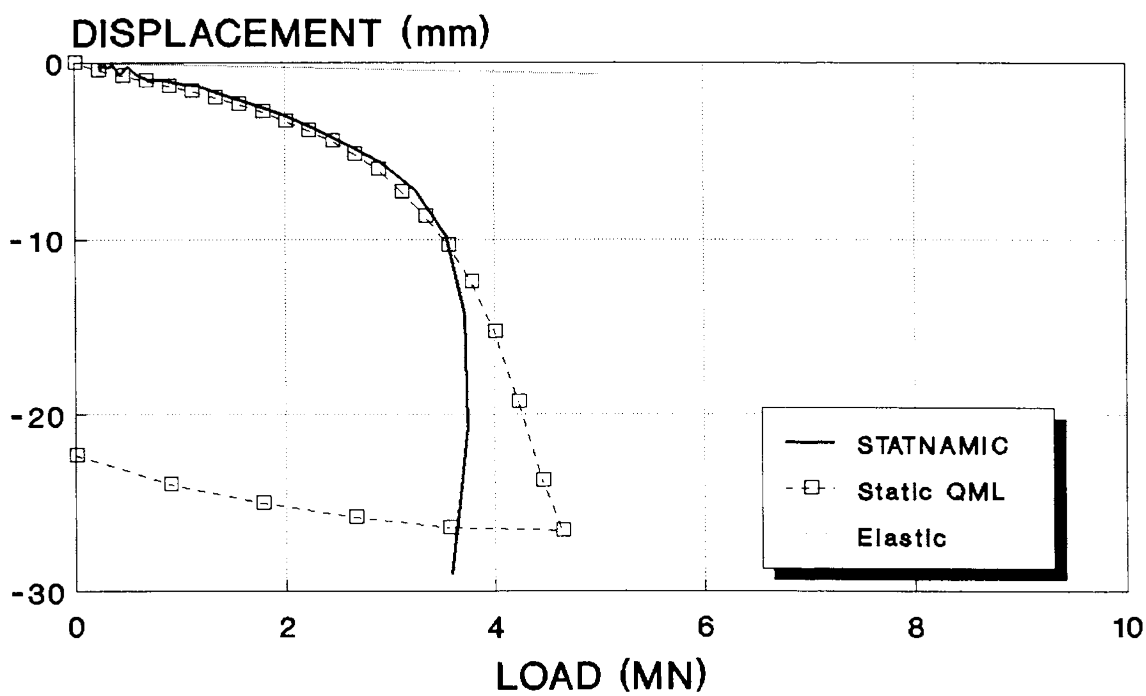
Test pier P1, which supported applied loading through shaft resistance only, failed at 3.4 MN (386 tons) under static loading. Under Statnamic loading, plunging failure was achieved with a maximum loading of 3.7 MN (420 tons). The load displacement curves for the two tests is provided in figure 9. The figure demonstrates the load deflection behaviour of the pier is nearly identical for the two methods of loading.

Test pier P4, which supports applied loading through both a grooved socket and end bearing resistance, did not reach failure under either Statnamic or static loading. The load displacement curves for both test methods are provided in figure 10. The load displacement behaviour of the pile is once again nearly identical for both test methods. The apparent discontinuity in the static load curve at 4.4 MN is due to a load increment being maintained for an extended period of time. It may be seen the curve returns to the elastic line shortly after the loading was increased.



Rock socket: D = 0.710 m, L = 1.37 m
Queenston shale, grooved shaft

Figure 9: Statnamic and static load test results for Burlington rock socketed pier P1.



Rock socket; D = 0.710 m, L = 1.34 m
Queenston shale, conventional shaft

Figure 10: Statnamic and Static load test results for Burlington rock socketed pier P4.

CONCLUSION

The results of comparative Statnamic and static load testing presented in this study reveal several trends. In all cases the correlation of elastic load displacement behaviour of piles subject to the two loading methods is excellent. The deviance at working load is found to be minimal considering the normal deviance which occurs between all piles at a site. The correlation holds very well up to loads equivalent to two times working load, the proof load for most foundations. The ultimate capacity of piles under Statnamic loading is uncertain as a failure criterion has yet to be established. Present results suggest a close correlation exists for piles in stiff soils or in high end bearing conditions as they undergo significant permanent sets at loads equivalent to static failure. Skin friction piles with low end bearing in weak silty or clayey soils with high water contents have shown what may be an over prediction in ultimate load. This trend may be expected in soils whose behaviour is highly dependent upon rate of loading. This remains an area of investigation through laboratory and field testing in addition to theoretical modelling. Overall the Statnamic test may be seen as a remarkably accurate pile load test method with great potential.

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