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Cyclic Lateral Loading of a Model Pile Group in Clay Soil

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February 1999

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CYCLIC LATERAL LOADING OF
A MODEL PILE GROUP IN CLAY SOIL

Executive Summary

PHASE 2C

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13. ABSTRACT *(Maximum 200 words)*

In certain regions of the world, designing deep foundations to withstand seismic loading is a reality. Seismic loading of structures and foundations reaches its most critical state as a cyclic lateral force. The response of soils and foundations to repetitive lateral forces is highly complex, relegating most design methods to be based on overly conservative rules-of-thumb. The primary objective of this research was to analyze mechanics of seismic loading on pile groups in clay soils. To achieve this, a model testing facility was constructed to house a fully instrumented 1x5 model pile group that was subjected to cyclic lateral loading. An empirically-based method for pile group design is suggested based on results generated from model pile group testing.

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This report is part of an ongoing investigation on the response of individual piles and pile groups to various types of lateral loadings. This research has been undertaken on behalf of the Utah Department of Transportation (UDOT) and the Mountain Plains Consortium (MPC).

Phase 1 of the study, involved the design and construction of a model test facility. A model pile was designed, instrumented, and laterally loaded under monotonic conditions. The final report for Phase 1 has been completed and submitted to UDOT and the MPC.

Phase 2 of the project involved advancing results of the Phase 1 to include cyclic loading on model pile groups. This represented a significant increase in the scope of work over the previous phase and consequently was divided into sub phases. The tasks associated with Phase 2A included the design, construction, calibration, and preliminary test results for a pile group subjected to cyclic lateral loading. Phase 2B of the project involved in-depth analyses and design applications for pile groups subjected to the cyclic lateral loadings developed in the previous phase. The final reports for Phases 2A and 2B have been completed and submitted to the MPC and UDOT.

This report, Phase 2C, is an executive summary of the activity and results of Phases 2A and 2B.

INVESTIGATION OF A CYCLIC LATERALLY LOADED MODEL PILE GROUP

Phase 2C, Executive Summary

ABSTRACT

In certain regions of the world, designing deep foundations to withstand seismic loading is a reality. Seismic loading of structures and foundations reaches its most critical state as a cyclic lateral force. The response of soils and foundations to repetitive lateral forces is highly complex, relegating most design methods to be based on overly conservative rules-of-thumb. The primary objective of this research was to analyze mechanics of seismic loading on pile groups in clay soils. To achieve this, a model testing facility was constructed to house a fully instrumented 1x5 model pile group that was subjected to cyclic lateral loading. An empirically-based method for pile group design is suggested based on results generated from model pile group testing.

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EQUIPMENT AND INSTRUMENTATION

The objective of this research was to more clearly define the response of pile groups in clay soils and ultimately mitigate seismic hazard by increasing the confidence in deep foundation design when cyclic loads are a concern. The cost of testing full scale deep foundations is prohibitively expensive for repeated tests, therefore, a model testing facility was developed at Utah State University to run multiple tests in a cost- and time-conscious manner. This project was funded by the Utah Department of Transportation and the Mountain Plains Consortium.

The model test facility is a large steel tank, approximately 3 x 1 m in plan view and 1.2 m high. This tank was lined with a geomembrane and geofabric. A silty clay soil (CL) was placed into the tank in slurry form and then consolidated using hydraulic rams pushing on overlying steel plates. Excess pore pressure was dissipated through the geofabric and out exit drains. The clay was consolidated to an average undrained shear strength of 40 kPa. The clay was maintained in a saturated state throughout the testing.

The model pile group is composed of five piles arranged in a linear fashion, pinned at the top to a pile cap (see figure 1). A linear pile group allowed for focus on group and shadowing effects. A pinned connection was chosen because it could be modeled precisely. A pile spacing of 3d was chosen for this test (d = outside diameter). The prototype pile (OD = 324mm and a wall thickness = 9.53mm) is a typical closed-end steel pipe pile commonly used by the Utah DOT. Similitude considerations were adhered to when designing the model piles. The piles were fabricated from 6061 aluminum pipe with an OD of 33.4mm and a wall thickness of 3.38mm. The piles are 1.52m long of which 85 percent is embedded into the soft clay.

To measure the pile-soil-pile response to cyclic lateral loading, a sophisticated measuring system was devised. Each pile was instrumented with 14 pairs of foil strain gages spaced evenly throughout the length of the piles. Each strain gage pair was diametrically mounted on the inside wall of the aluminum tube and epoxied in place using a unique installation tool designed and built by the USU Civil Engineering Shop. Strain gage load cells were mounted on the pile cap between each pile to measure load distribution. Master load cells were located at each end of the pile cap to measure the total group load. Two LVDT's (Linear Variable Differential Transformers) were used to measure the pile top displacement and slope. With the addition of a sixth pile to compensate for temperature changes and electrical noise, the measuring system was comprised of 182 channels of output.

A highly specialized data acquisition system was designed and built in-house to acquire 182 channels of information in an expedient manner. The four main components of the system were a PC, A/D board, power supply, and acquisition hardware. There is a full Wheatstone bridge for each strain gage — one strain gage in a pile accompanied by three resistors located on their respective circuit boards. Fourteen circuit boards were needed to acquire all 182 channels of information. The acquisition system is controlled by LabVIEW software, which also controls the loading system in a closed loop format.

Cyclic lateral loading of the pile group was accomplished via hydraulic rams. The hydraulic rams were mounted horizontally in plane with the pile cap. Loading force was provided by a hydro-pneumatic tank and regulator. The actuation of the loading force was controlled by a solenoid switch, which was in turn controlled by LABVIEW. The program was written using LABVIEW software, which gave real time analysis of group load, pile top deflection and slope, bending stresses in each pile, and the maximum stress in any one pile during the test.

TESTING

A load scheme was designed after generating predictions using FLORIDA-PIER and Com624P software, and trial and error testing in the lab. The pile group was laterally loaded from zero to 2000N and back to zero in approximately one minute while the acquisition system recorded data at the rate of four samples a second. That is 182 channels recorded in 0.25 seconds; acquired continuously throughout the loading. The group was then loaded in the same manner but in the opposite direction, thus completing one cycle. This was carried out for 50 cycles of loading. The complete test yielded 52 megabytes of data, read continuously for every cycle, encompassing loads from 0 to 2000N for each cycle.

Load, as opposed to strain or hertz, was chosen as the control for testing. During an earthquake, a structure and its foundation will experience forces at some peak level. The force level applied to the pile group was approximately 65 percent of the yield stress of the aluminum model piles. The peak load value was achieved every cycle, this premise based on previous research on clays experiencing cyclic loading (Seed and Chan, 1966)[1].

The loading scheme was designed to look at the mechanics of cyclic lateral loading of pile groups, not dynamic responses involving inertial or kinematic effects. This phase of the research targeted soil degradation due to load and cycle, and a comparison of these results with predicted results from design software. Undrained conditions were maintained throughout the test to simulate soil conditions during a seismic event. During ground shaking, a clay soil has no time to dissipate excess pore pressure generated by the seismic motion. Although the cycle rate used in these model tests were of low frequency, it is assumed that maintaining undrained conditions significantly minimizes frequency as a variable when considering deflection, maximum bending moment, moment distribution, load distribution, pile shadowing, group effects, and other mechanical interactions between the pile group and the surrounding soil.

Upon completion of the cyclic load test a final calibration test was necessary to determine exact correlation between measured voltages and bending stresses. This was done using the cyclic load testing set up with the program slightly modified for calibration. A known load was applied to the piles at a known location and then the measured output was compared to the theoretical bending stresses. A linear regression was done on the comparison. The result was a calibration factor for each gage, which fine tuned the raw output.

For a full description of equipment, instrumentation, testing, and a complete catalogue of the results see Caliendo and Anderson (1996)[2], Caliendo et al. (1996)[2], Rawlings (1997)[3], and Moss (1997)[4].

APPLICATION OF MOMENT AND DEFLECTION RESULTS

Moment distribution and load vs. deflection were two groups of results that were generated. Figures 2 and 3 are plots of group moment distributions for cycles 1 and 50 at a lateral load of 2000N. The curves are shown for all five piles, loaded in one direction and then the other. The outer curves are the lead piles and all subsequent curves are from their respective pile row positions; the lead piles taking the majority of the load in all cases and exhibiting the highest bending moment. These two plots show a progression of maximum bending moment traveling down the length of the piles as the number of cycles increases. This is due to the gapping that occurs at the clay surface. Figure 4 is a moment distribution plot of a single pile showing the slight increase in maximum bending moment as the number of cycles increase. Figure 5 is a plot of load vs. pile top deflection. The gapping can be seen in this plot as the initial offset of each curve after cycle one.

To use these results in a full scale design scenario the information was normalized and presented in a dimensionless form (see figures 6 and 7). The dimensionless variables used for plotting the deflection and bending moment results include all pertinent variables (EI = pile stiffness and D = pile diameter). To use these normalized curves, one would enter into them with a design load (P) induced at the pile cap, and specific pile properties (EI and D). The expected pile top deflection and maximum bending moment in the lead pile can then be predicted. At this time, the results only are valid for similar clay soil profiles and stickup length (ie. CL with an average undrained shear strength of 40kPa). Also, these predictions likely are conservative for any loads corresponding to model loads less than the maximum test load. Further testing is underway to cover a wider spectrum of clay strengths from soft to exceptionally stiff and for various locations of applied load. In addition, the loading procedure will be modified to account for consequences of the pile being subjected to a load that is higher than the previous cycled load. This initially causes the pile to move through a remolded soil, particulary near the ground surface at the soil gap.

The results of the 1x5 model pile group can be extrapolated to a nx5 pile group under the assumption that group and shadowing effects predominantly are a function of pile row position and not column position as suggested by Brown and Reese (1985)[6]. Therefore, this method allows a designer to predict bending moment and deflection of a 5x5 pile group in a CL soil with similar undrained shear strength. Further testing is in order to encompass different pile group geometries.

UTILITY OF DIMENSIONLESS RESULTS

Currently, designing deep foundations for seismic loading involves using software packages that, in the most part, rely on p-y curves for defining the non-linear lateral response of soils. Some programs use a finite element approach, which is quite costly and time consuming for large foundations. P-y curves work but are a highly generalized solution to a complex phenomena. The use of p-y curves for clays often fails to account for increased degradation of the soil with an increase of cycles. The default p-y curves provided by software packages have an option of either static or cyclic, but typically do not account for the permanent deformation that occurs with each increasing cycle.

The normalized curves presented in this paper are the first step toward an empirically-based design method that eliminates the use of p-y curves. Upon further testing for various soil strengths, soil profiles, and pile group geometries, a software package can be written for use in design. This design method shows promise because of its simplicity and ease of use.

ADDITIONAL OBSERVATIONS

The moment and deflection results were reduced to provide further insight into other group trends. Figure 8 is a plot showing the relationship of the maximum bending moment to the number of cycles. The abscissa is the ratio of the maximum bending moment in the lead pile at cycle one to cycle n. The maximum bending moment increases non-linearly with cycles and starts to taper off somewhere after cycle 25. This trend also was seen in plots of depth to the point of maximum bending moment with cycles. Figure 9 shows the relationship between pile top deflection and the number of cycles. Again the abscissa is a ratio, the ratio of pile top deflection at cycle 1 to cycle n. The resulting curve is much more linear.

FINAL COMMENTS

The objective of this ongoing research is to improve seismic design of deep foundations in clay by creating a model testing facility in which to study pile group response to cyclic lateral loads. The first phases of the testing have been completed and the results are promising both in terms of increasing the body of knowledge about pile groups and producing tools that can be used in practice.

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APPENDIX

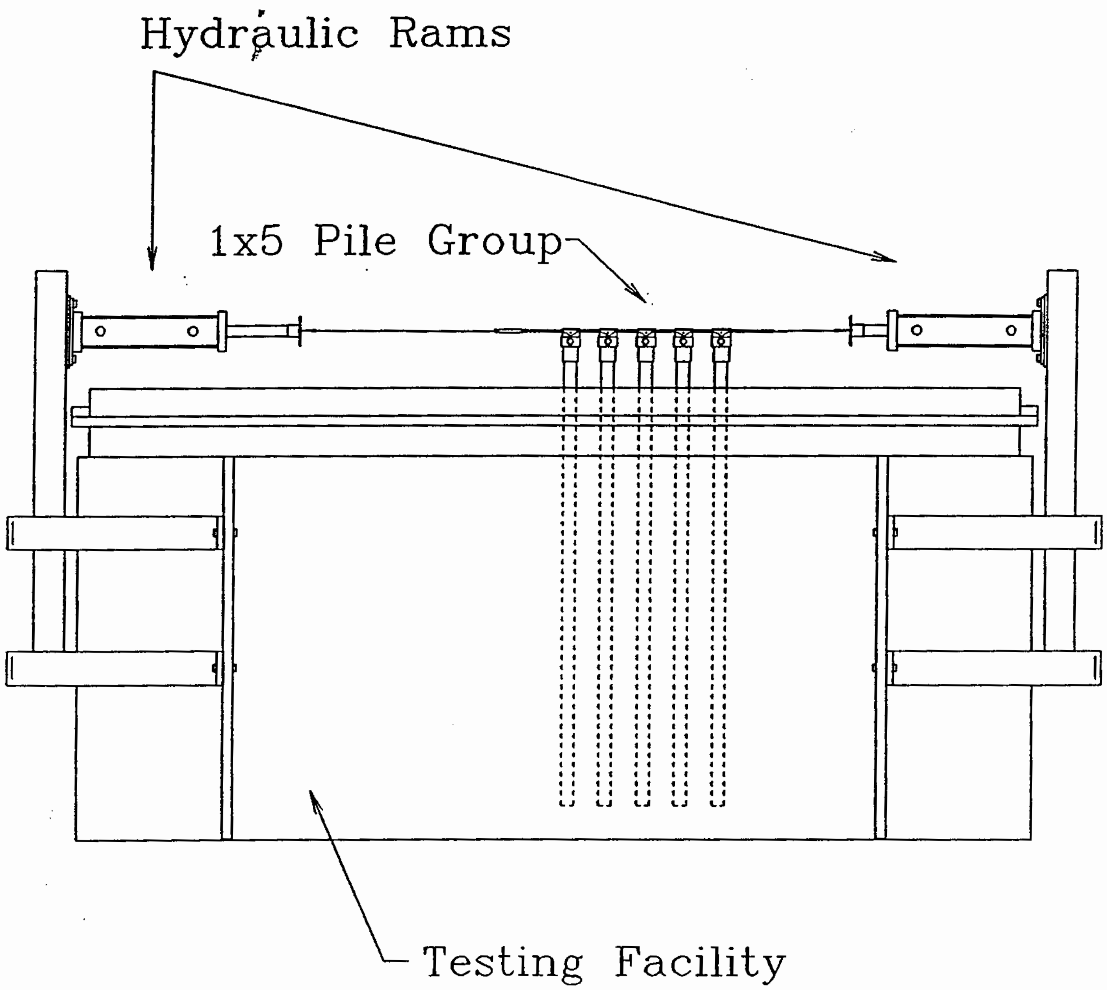


Fig. 1. Model Pile Testing Facility

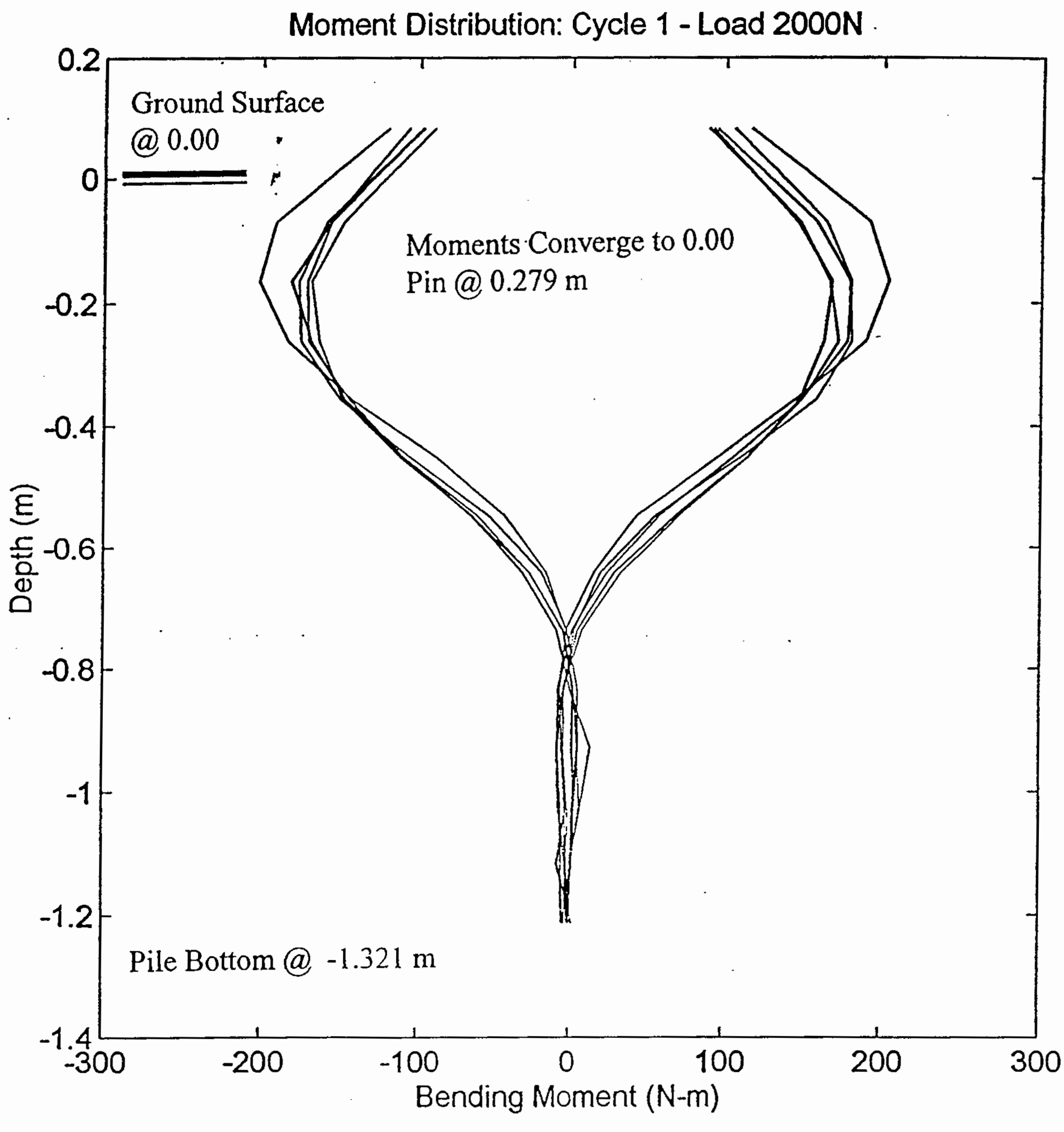


Fig. 2. Moment Distribution for each Pile, Maximum Load, Cycle #1

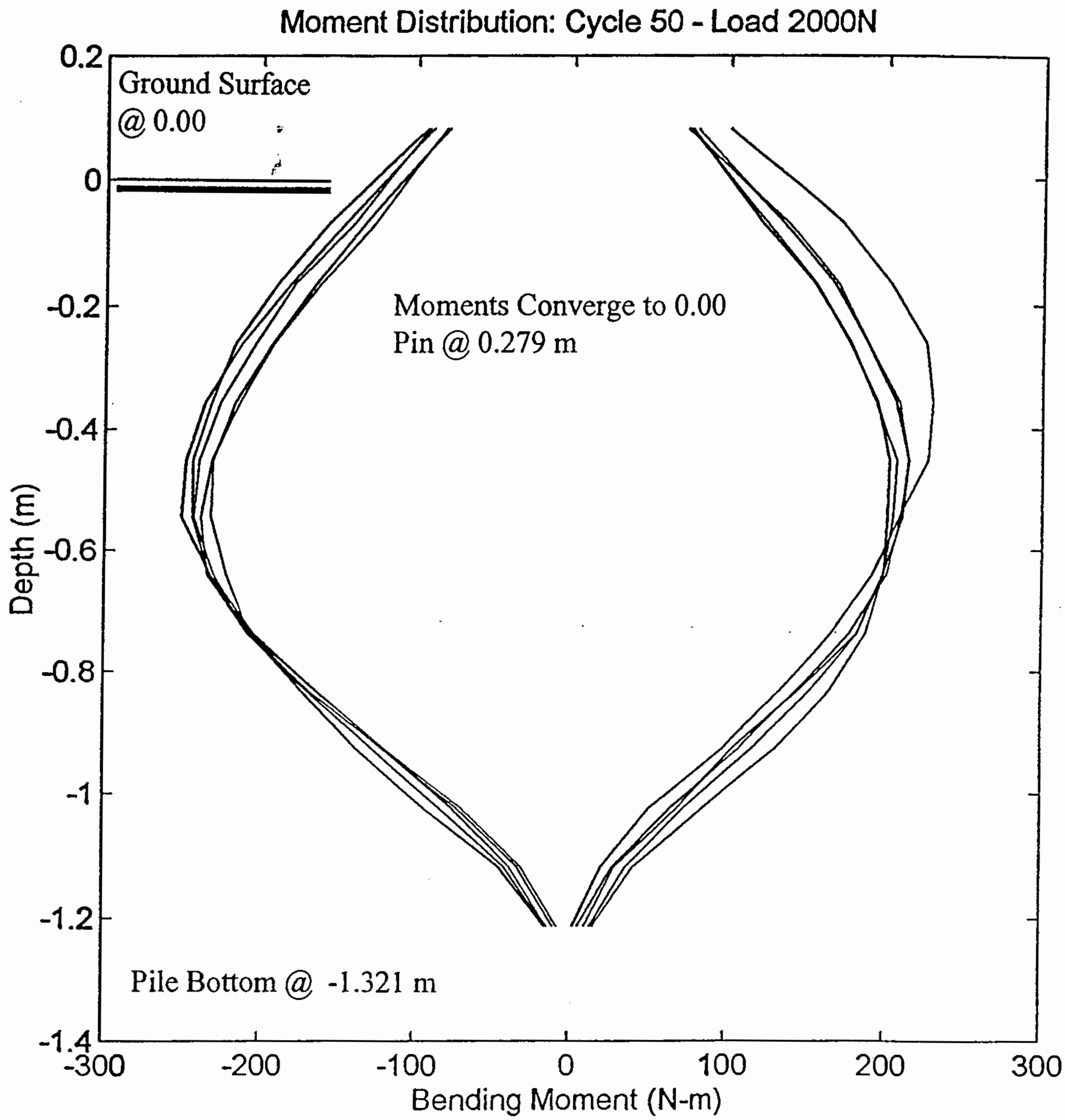


Fig. 3. Moment Distribution for each Pile, Maximum Load, Cycle #50

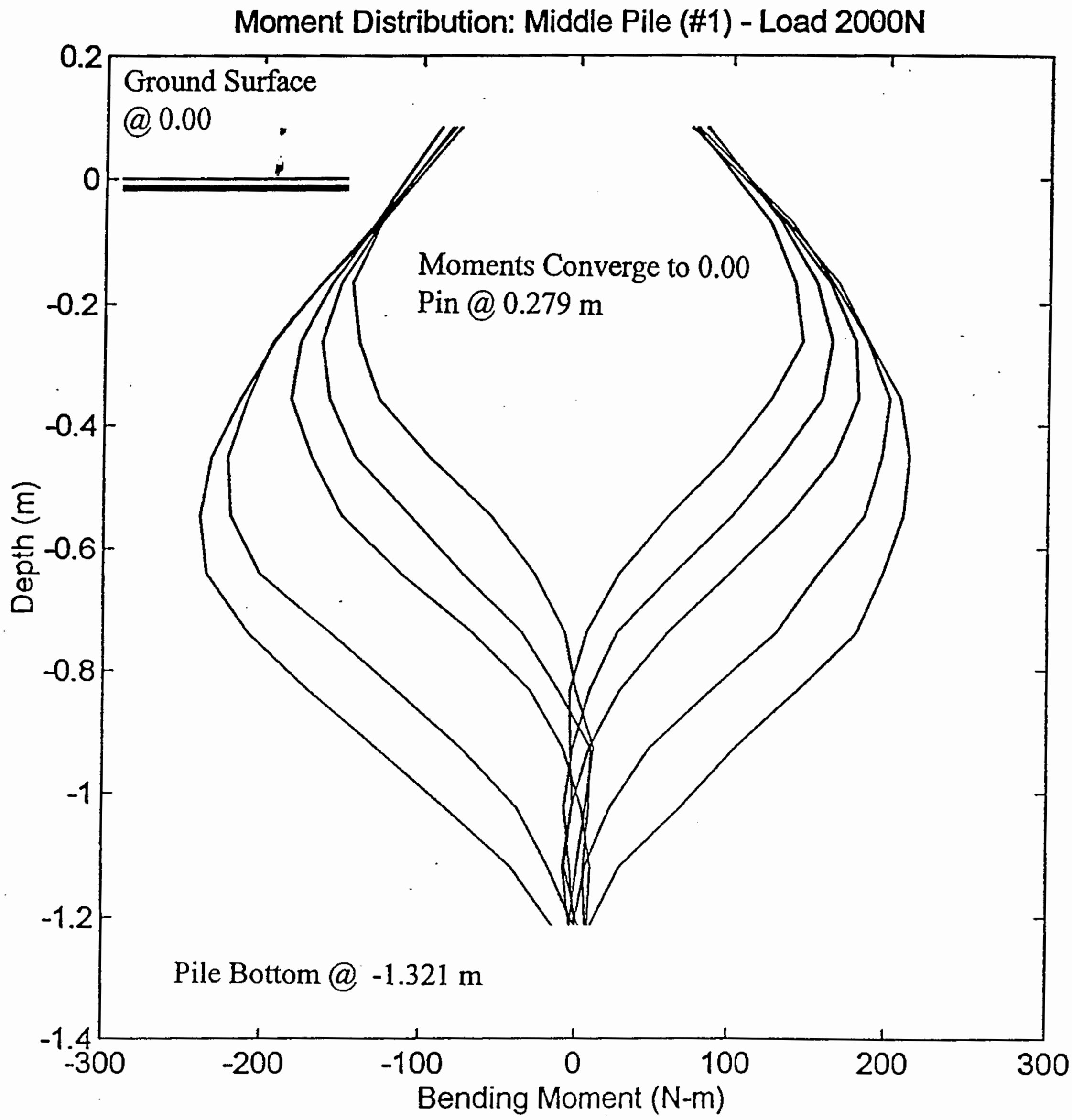


Fig. 4. Moment Distribution, Middle Pile, Maximum Load, Cycles 1 - 50

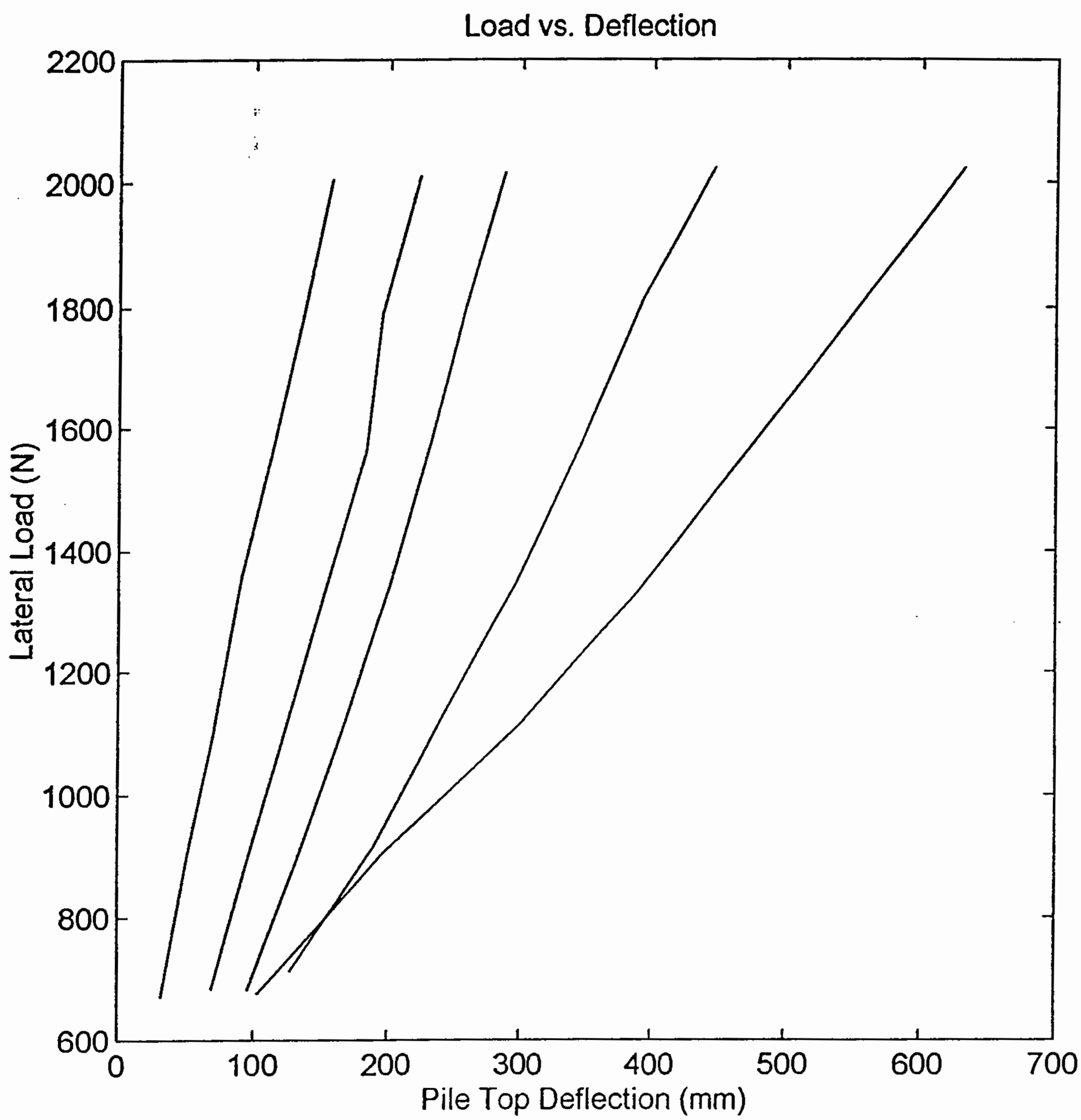


Fig. 5. Pile Group, Top Deflection vs. Applied Load, Cycles 1 - 50

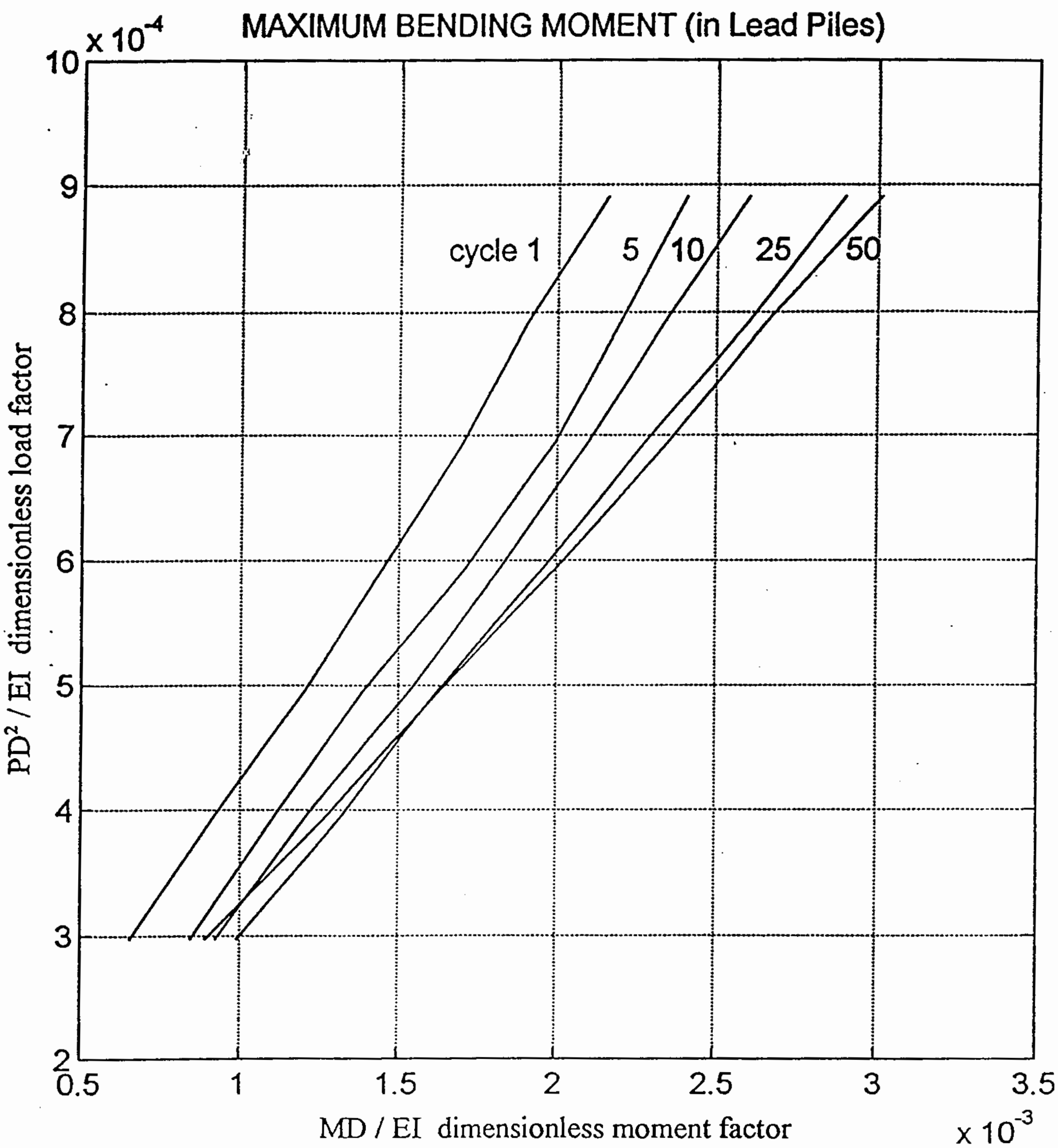


Fig. 6. Dimensionless Factors for Maximum Bending Moment

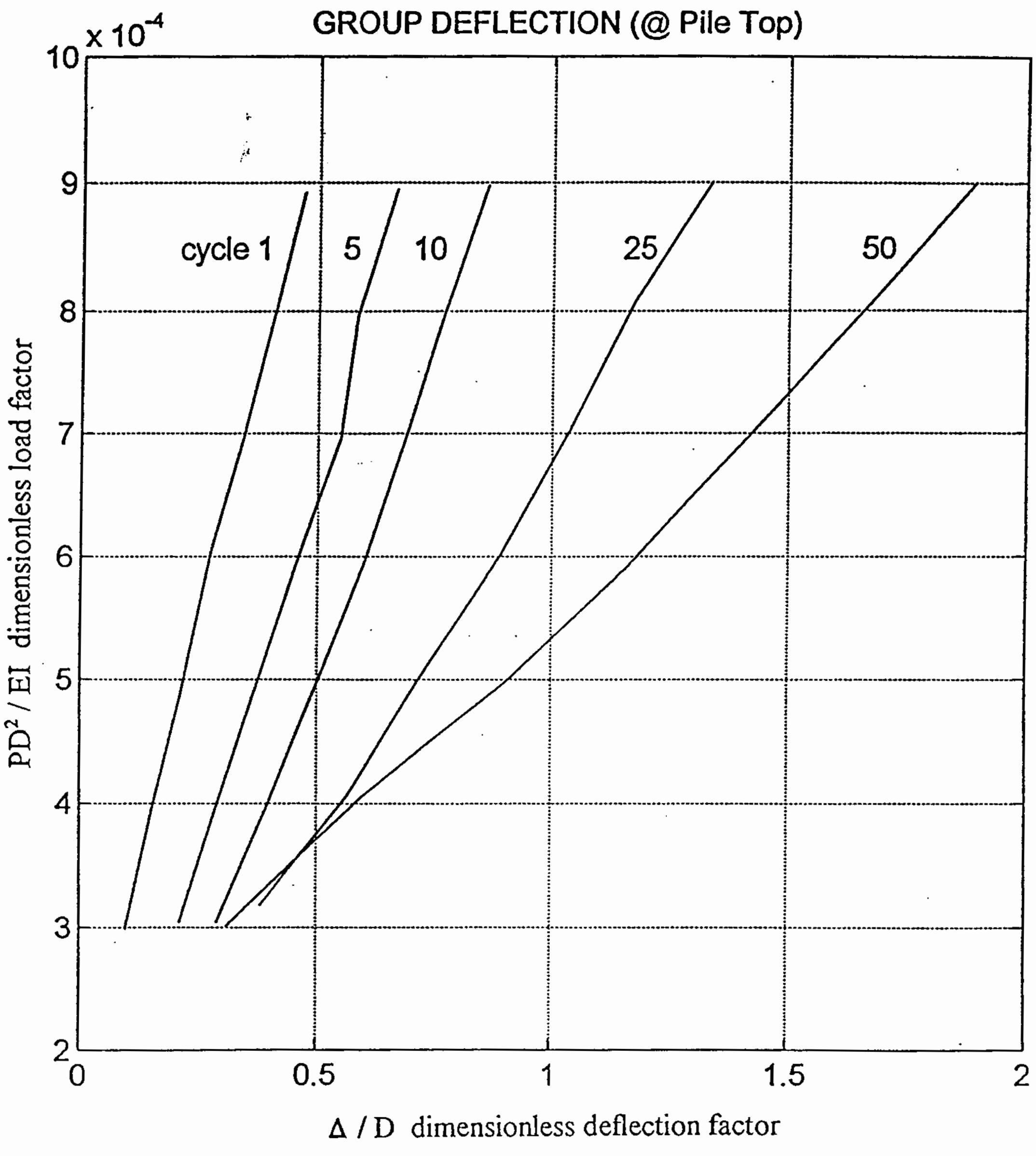
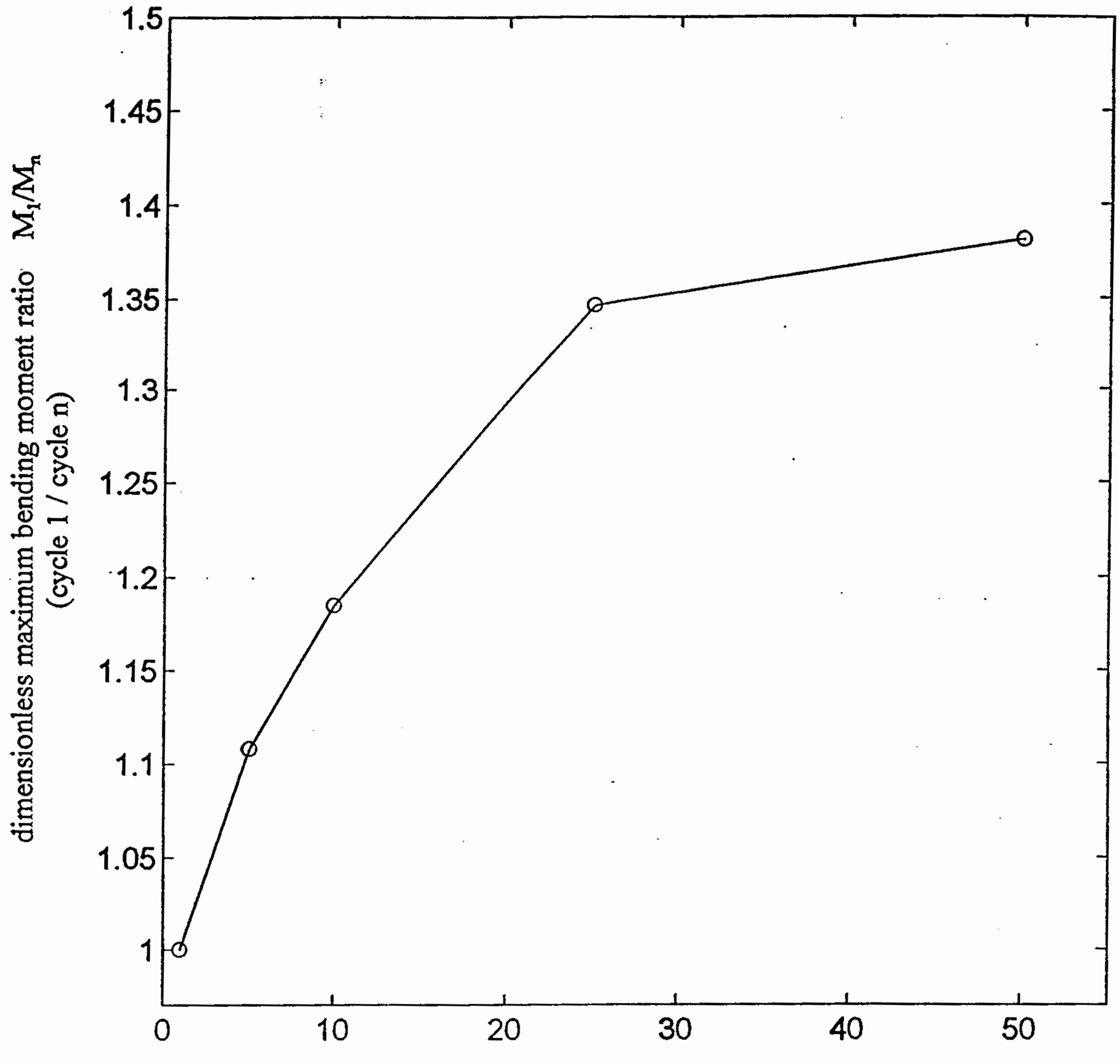


Fig. 7. Dimensionless Factors for Pile Top Deflection

Maximum Bending Moment Ratio for Cycles 1-50



number of cycles

Fig. 8. Maximum Bending Moment Ratio, Cycles 1 - 50

Pile Top Deflection Ratio for Cycles 1-50

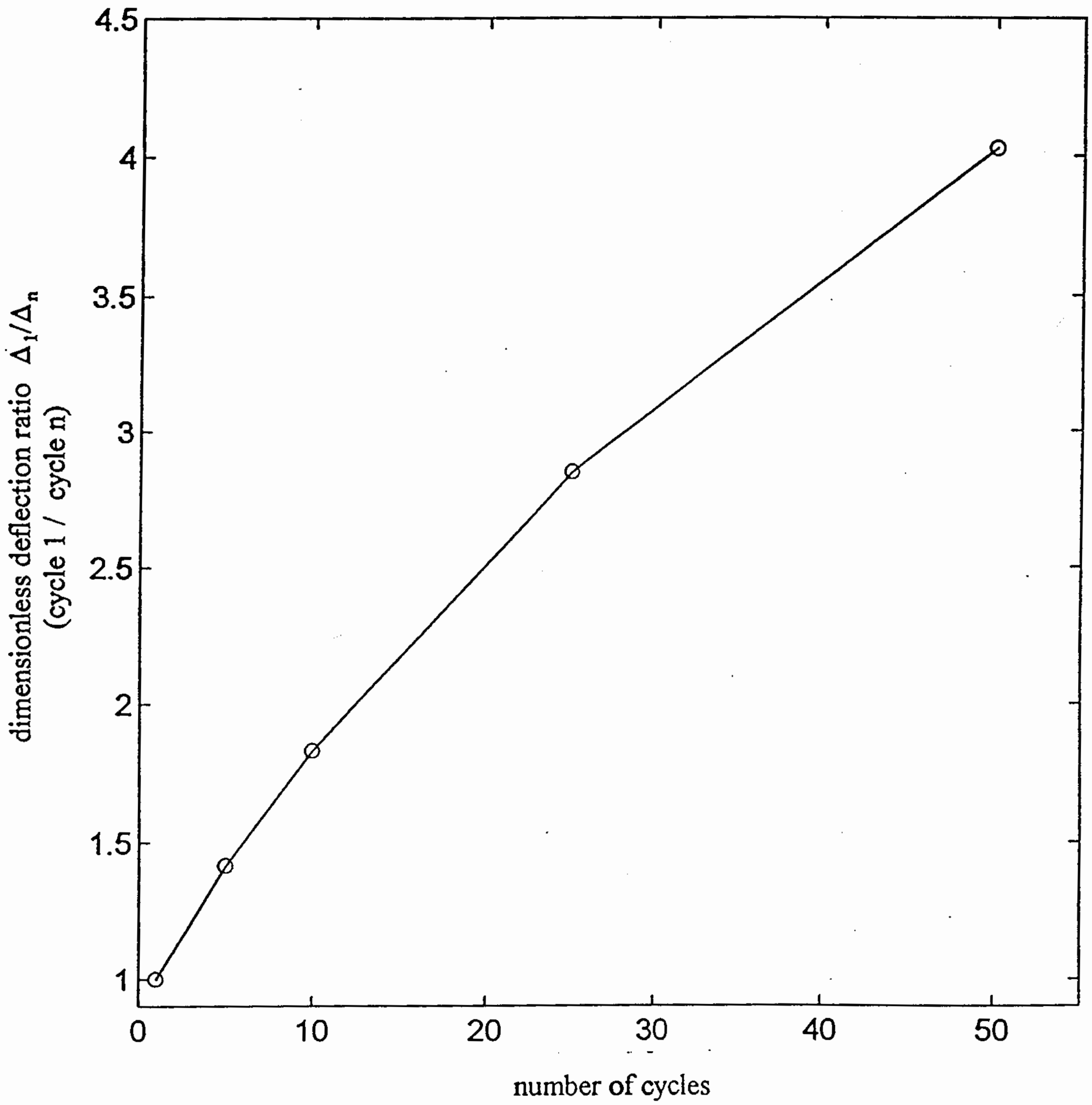


Fig. 9. Pile Top Deflection Ratio, Cycles 1 - 50