Discussion of Procedures for the Determination of Pile Capacity

RICHARD L. ENGEL

The Ohio Department of Transportation (ODOT) uses the following methods in determining pile capacity: static analysis, *Engineering News* driving formula, static load tests, dynamic load tests, wave equation program, and Case pile wave analysis program. The ODOT's procedures in using these methods are discussed in this paper along with a case history. A preview of responses from a survey on pile testing and installation practices is also presented. The need to load test and to document load test results is emphasized.

In light of today's technological advancements, which include static analysis and wave equation methods performed by computerized procedures and the use of relatively reliable dynamic-load-testing equipment, why is it still acceptable to support some highway structures on piles having unknown load-resistance capabilities? Why is the *Engineering News* (EN) pile-driving formula still a widely used method for predicting pile capacity (*1*)? Topics relevant to these questions as well as pile foundations as used by the Ohio Department of Transportation (ODOT) are subjects addressed in this paper.

In reviewing pile design and installation procedures as they are currently being used, it can be concluded that there is a need for a knowledgeable organization to prepare updated pile design guidelines and construction specifications. As is the case with most research efforts, the use of quality data obtained from full-scale models is important if accurate mathematical expressions are to be developed. A standardized load-test data base should be developed and made available to all parties interested in pile-resistance prediction methods. Note that much of the information provided herein is being offered not because of its correctness, but rather as documentation of the disarray of existing design and construction methods.

ODOT's PRACTICE

Piles generally used for the support of ODOT's structures are 40 to 70 ft long HP 12 by 53 steel "H" sections or 12-in.-diameter steel pipe piles that are filled with concrete after installation.

The chronological events that are generally followed for the design of a pile foundation are

1. Prepare a subsurface profile from soil sampling and testing information.
2. Determine pile type and estimated length necessary to develop the design load resistance.
3. Provide plan pay items for static load tests and dynamic load tests as per the ODOT guidelines.
4. Install piles to a length that satisfies the specification EN formula.
5. After obtaining initial driving experience at the structure site, decide if static or dynamic load testing, (or both) should be conducted.

Estimated Pile Lengths

The estimated pile lengths provided on project plans are derived by using engineering judgment, "as built" records from similar foundations, and the results of static analyses performed in accordance with the Federal Highway Administration's *Manual on Design and Construction of Driven Pile Foundations* (2). The plan-estimated pile lengths serve two functions: to compute the total bid quantity so a unit price per linear foot can be established through the bidding process and to flag potential problem situations in which pile load tests may be appropriate because there is an excessive difference between driven lengths and estimated lengths.

The contractor is given the responsibility of determining the lengths of piles to be ordered. Since the contractor is not specifically paid for pile splices or unused pile lengths, his or her profits are directly related to the ability to furnish pile lengths compatible with the state inspector's driving requirements.

Guidelines offered in the Standard Specifications by the American Association of State Highway and Transportation Officials (*3*) recommend that the furnishing of piles and the driving of piles should be separate pay items. This may be a more equitable procedure for the contractor and would also give the designer more incentive to be accurate in estimating pile lengths. More emphasis might then be given to conducting static or dynamic load tests (or both) during the early stages of projects for the purpose of obtaining measurements that would be useful in establishing appropriate pile-order lengths and pile-hammer limitations.

Dynamic Driving Formula

All piles that are not driven to refusal on bedrock are required to be installed to a penetration that satisfies the specification EN blow count (Appendix A). The EN blow count criteria may be modified if information is obtained from a load test. Although the EN formula contains a theoretical factor of safety

Ohio Department of Transportation, 25 South Front Street, Room 516, Columbus, Ohio 43215.

of six, it has been found that when the hammer energy is such that the computed required blow count is in the range of 30 to 70 blows per foot, the installed piles often have a failure resistance that is reasonably close to providing a safety factor of two. Piles that are installed in cohesive soils may require time for developing set-up resistance in order to achieve the safety factor of two.

Static Load Tests

Static load tests generally are conducted only on piles for relatively large projects (Appendix B). During the past 20 years, 90 percent of the projects that had static load test pay items provided did not have these items performed during construction. The number of documented static load tests that have been performed on ODOT projects is shown in the barchart in Figure 1. The rationale for permitting the nonperformance of load tests was that the conditions of the pile installations were typical, the expense of the load test could be saved, and the progress of the project would not be delayed.

Dynamic Load Tests

The use of dynamic load testing methods for the prediction of pile capacity has been available to the ODOT since the mid-1970s. A pile-driving analyzer (PDA) became the property of the ODOT at the conclusion of a pile-capacity research project conducted at Case Western Reserve University. In 1982, a PDA (model GA) was purchased by the ODOT with assistance from FHWA.

Typical steps that encompass a dynamic load test (Appendix C) are as follows:

1. The project engineer furnishes an advanced notification of the contractor's proposed pile-driving schedule to the central office construction engineer. This notification is provided to enable the testing personnel to plan their work activities around a potential testing date. Dynamic pile tests are conducted by two engineers in the foundation section of the Bureau of Bridges.

2. After two piles have been installed, the driving logs are reported to the foundation engineer of the Bureau of Bridges. The subsurface conditions are reviewed, and the driven pile lengths are compared to the estimated pile length. If the pile installation behavior is judged to be typical, the dynamic load test is generally nonperformed. For relatively large projects, the dynamic load test is almost always conducted.

3. When a dynamic load test is to be conducted, the project engineer is given instructions for installing the piles that are to be dynamically load tested. If the subsoils are cohesive and it is appropriate to attempt to determine the magnitude of setup, the dynamic testing is delayed as long as is practicable so that the driven piles can gain resistance (setup) before being subjected to a restrike.

4. On the day that the test is to be conducted, the testing team generally arrives at the project site between 9:00 a.m. and 10:00 a.m. The pile-driving logs are examined and a testing scheme is then developed.

5. Piles are made ready for testing by drilling holes at appropriate locations in the piles and, if necessary, threads are cut in the sides of the holes with a tap. Transducers are then attached to the pile after the hammer has been positioned on the pile. Computations are performed using specific pile property values to determine input data for the PDA. The PDA, oscilloscope, and data tape recorder are appropriately situated and all required interconnections are made.

6. As the pile being tested is driven by the contractor's pile hammer, dynamic measurements from the strain transducers and accelerometers are processed by the PDA. The information generated by the PDA is reviewed as the pile is being driven.

7. After three piles are dynamically tested, the test results are assessed and the project engineer is given pile installation instructions, which generally consist of a minimum blow count or a minimum pile penetration requirement.

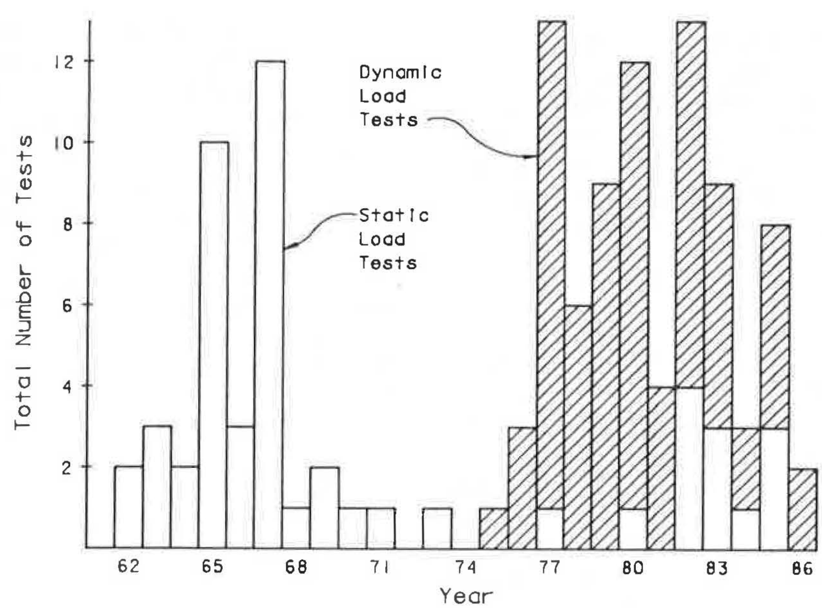

FIGURE 1 Load tests per year.

8. A dynamic load test report is prepared by the Bureau of Bridges' foundation engineer and submitted to the Bureau of Construction.

A common situation that the ODOT has encountered when conducting dynamic load tests is outlined as follows:

1. Piles for a bridge substructure are being installed to a penetration depth that is substantially different from the plan-estimated pile length.
2. In the course of conducting dynamic load tests the piles are driven to a high blow count (over 120 blows per foot).
3. The results of the dynamic load tests indicate that a factor of safety of at least 1.3 can be predicted from the PDA measurements. This predicted pile capacity is probably conservative because the pile hammer is not adequately mobilizing the test pile.
4. The subsoil conditions at this site are such that the pile is expected to gain resistance as time passes (setup).
5. To put this situation in perspective, note that the project is relatively small with only 80 piles, each having a 100-kip design load and estimated to be 45 ft long. If a larger pile hammer is required, the contractor would have to make arrangements for furnishing a larger hammer and mobilizing the hammer to the project site.
6. Is the contractor at fault in any respect or was the type of pile load testing inappropriate? A static load test, or possibly a delayed restrike dynamic load test performed after an appropriate waiting period, may have found the pile resistance to be satisfactory. At this time does this project warrant additional testing of any type?
7. The resolution of these dilemmas has generally been to accept the piles. The rationale for accepting the installed piles is that the factor of safety is 1.3 or more and expected to increase with time. A restrike test could cause delays in production and the personnel performing the tests would be required to return to the project site.
8. The project engineer is instructed to install the piles to an appropriate tip elevation since blow count controls are not relevant.
9. Restricting the hammer size to not less than a specified energy is a means currently being used to reduce the occurrences of some of these awkward testing situations. Potential pile load testing dilemmas should be anticipated and eliminated during the plan design stage by preparation of thorough pile installation specifications. Wave equation controls may be beneficial when attempting to avoid this situation.

Upon reviewing the results of 60 ODOT dynamic load test reports, the following patterns were found:

- On 20 projects, the project engineer was instructed to continue installing the piles as per the specification EN formula. The subsoils at these projects are generally nonplastic.
- On 20 projects, the specification EN pile-driving blow count was required to be increased by 10 to 60 blows per foot. The subsoils at these project locations contain various percentages of cohesive material.
- Most of the remaining projects consisted of restrikes on previously driven piles and a comparison to the testing results of a freshly driven similar pile. Blow count or minimum penetration requirements were then based on measured set-up values.

When consideration is being given to purchasing the PDA and accessories, consideration must also be given to providing personnel for operating the equipment. Usually, an experienced foundation engineer must be present at the site to see that the testing is conducted on piles driven to depths and blow counts that will provide data appropriate for use in establishing driving criteria. The personnel performing the dynamic load tests must have a sincere interest in doing this type of work. Carelessness in conducting dynamic load tests will lead to poor quality measurements. The field portion of dynamic pile testing sometimes requires physical effort that may have to be performed during inclement weather and under dirty working conditions.

The ideal way to perform dynamic load tests is to have trained personnel whose first priority in work assignments is to conduct pile tests. A mobile van or a temporary shack at the test site equipped with shelves, a stool, and a table is suggested for providing a convenient testing environment.

As shown in Figure 1, the ODOT has conducted between 2 and 12 dynamic load tests per year. Approximately 50 bridges are constructed each year that have dynamic load test work items (Appendix D). Most of the load tests are not performed because they are deemed unnecessary or because the testing personnel are unavailable because of commitments to perform their other duties. In an effort to ensure that more dynamic load tests can be conducted, the ODOT is in the process of entering into an annual contract with a dynamic load-testing consultant who will be available as a substitute for the ODOT testing personnel. The consultant would be paid a flat fee (predetermined by bid) per day for testing. The content of the contract will be similar to the plan note provided in Appendix E except that the testing consultant will be reporting directly to ODOT rather than working through the contractor.

Case History

The project that is the subject of this case history is the West Third Street bridge reconstruction located adjacent to Cleveland Municipal Stadium. The foundation for this bridge is 0.25-in.-wall, 14-in.-diameter, closed-end steel pipe piles having a 140 kips design load. The plan-estimated pay length for the piles is 80 ft. The subsoil is very stiff silty clay.

The piles were initially installed to a penetration of 50 ft with a Foundation Equipment Corporation Model 1500 (FEC 1500) pile hammer. At 50 ft of penetration, the blow count per foot was 60. In order to reduce the time of driving and to increase the contractor's ability to install the piles to an appropriate depth, on May 21, 1987, an FEC 3000 was used to install the piles from a penetration of 50 ft to 100 ft. The blow count per foot with this hammer was 35 at 51 ft and 65 at 100 ft of penetration.

After installation of the piles to 100 ft, a static load test was conducted on May 29, 1987, and the failure load was determined to be 200 kips (1.4 factor of safety, 8 days for setup). Piles driven into the silty clay subsoils at this bridge location have a history of gaining strength (setup) during a time period of approximately 2 weeks following pile installation.

On June 3, 1987, a dynamic load test was conducted for the purpose of obtaining additional information that would be used for establishing the appropriate driving requirements. An anchor pile, installed to the same penetration and to a similar blow count as the pile tested statically, was load tested using the dynamic methods. Measurements were obtained while driving the pile from a penetration of 100 ft to 110 ft. The pile's failure load resistance was predicted to be 260 kips at the beginning of restrike and 200 kips at the end of restrike. The 60 kips that were dissipated during the restrike driving are assumed to be an approximate measure of the set-up resistance for a pile in these subsoil materials. A Case damping factor of 1.0 was used by the PDA in the field when determining the pile's static bearing capacity and was later confirmed by the Case Pile Wave Analysis Program (CAPWAP) performed by a consultant.

The measurements found by the static load test and subsequent dynamic load test indicated that approximately 60 kips or more of set-up load resistance should be expected to develop by the piles installed in the subsoils at this bridge site. The contractor was instructed to install all piles to a penetration of 115 ft. The developed pile resistance at this penetration is anticipated to satisfy the required failure load resistance of 280 kips (safety factor of two).

The piston weight for the FEC 3000 is 6,600 lb and the estimated maximum stroke during driving was 4 ft (26,400 ft-lb). The maximum energy transferred to the pile during driving was determined by the PDA to be 19,000 ft-lb (70 percent transferred energy to the pile). The maximum driving stress occurring in the pile at the location of the gauges, as determined from the measured compressive force, was 25,000 lb/in.^{2}. CAPWAP analysis results for a blow occurring at approximately 102 ft penetration found the failure load resistance to be 250 kips (170 kips shaft resistance and 80 kips base resistance).

A similar magnitude of set-up resistance was found at a nearby bridge site having a pile foundation consisting of 200,000 linear ft of 14-in.-diameter closed-end pipe piles. Eight special static load tests had recently been conducted. The static load tests were considered special because each test pile was loaded at 3 days and reloaded 14 days later for the purpose of verifying the amount of set-up resistance. The pile penetrations were approximately 80 ft and the failure loads were approximately 200 kips at 3 days and 260 kips at 17 days.

Hammer Energy

In 1955 the ODOT organized a hammer energy study using full-scale equipment. The study compared the driving capabilities of single acting air-steam hammers with single acting diesel hammers. The conclusion drawn from the comparison of driving similar piles with these hammers was that if 70 percent of the diesel hammer energy, as recommended by the manufacturer, is used for "E" in the EN formula (Appendix A), the predicted pile capacity for both hammer types would be similar at equal pile penetrations. Although this was a crude and limited study, for the past 32 years minimum required blows per foot have been computed by using this reduced hammer energy rating for all diesel hammers.

When conducting dynamic load tests the ability of the pile hammer system to transfer energy to the pile can be determined. The measurements obtained during the ODOT dynamic load tests have found the transferred energy to vary from 25 to 70 percent of the manufacturer's rating.

On two occasions when dynamic load tests were conducted, the energy transferred from the pile hammer was found to be low and inconsistent. The contractor was instructed to replace or repair his pile hammer. After examining the hammers in the shop, the contractors confirmed that mechanical deficiencies were restricting the performance of the hammers. A trained pile inspector may be capable of detecting that a pile hammer is malfunctioning, but generally a confrontation develops when the pile inspector raises questions concerning performance of a contractor's pile hammer. Contractors have not contested a single request by ODOT for hammer repairs or hammer replacement, when measurements are available from the PDA.

During the past 30 years, the ODOT's typical pile design loads have increased from 70 kips up to 120 kips. This increase in design load reflects a need for contractors to provide larger pile hammers that can develop adequate energy for installing piles to greater penetrations for developing the required resistance.

The ODOT has found that the reliability of the specification EN formula (Appendix A) in predicting the correct pile capacity diminishes as the blow count increases beyond 70 blows per foot. At the ODOT it has not yet been decided to undertake the efforts necessary to incorporate the wave equation into the construction program, therefore a plan note specifying a minimum hammer energy rating has been used for the past 2 years as a means to ensure that a reasonably appropriate hammer size will be furnished by the contractor. The required minimum hammer energy is chosen so that its corresponding blow count for the plan pile design load resistance does not exceed 70.

SURVEY

A survey entitled "Pile Testing and Installation Practices" (*4*) has been conducted by the ODOT. Thirty-eight states have furnished their response and a summary of the harvested information is offered herein.

Load Tests

The following list of statements are criteria used for determining when pile load testing should be conducted:

- There must be over 100 piles and the design load must be relatively high.
- There must exist a potential for a cost savings.
- There must be in excess of 10,000 linear ft of piling and the design load must be relatively high.
- At least one load test is to be conducted per structure.
- At least one load test per structure is to be conducted when friction piles are installed in cohesive soils.
- A load test is necessary when soil conditions are such that a static analysis may not be reliable.
- When piles are installed in soils that contain boulders that can damage driven piles, a load test is necessary to verify the integrity of the piles.

- After considering the information in the geotechnical report, the magnitude of the pile design load, previous experiences, the pile proposed length, and tolerable settlement limitations, a determination is made.
- Piles that are installed in rivers must be tested for capacity.
- A load-test data base is available for reference. If a structure is to be built where there are no records of a nearby load test in similar soils, a load test is required to verify capacity.
- Load tests are not specified. However, construction personnel may require load tests when the test is considered to be beneficial.
- Load tests should not be avoided just because there have not been any problems with pile foundations.
- Load tests are needed when the design load is significantly higher than the typical design loads.
- Many states have not developed criteria for requiring load tests.

The goal adopted by most states is to attempt to install piles to a failure resistance equal to twice the design load. In general, pile design loads that are currently being used by departments of transportation vary from 80 kips to 300 kips. Nine of the states sometimes require a safety factor of three. Eight states require the contractor to attempt to load test the piles to failure. Ten states require that a load cell be used to measure the applied load.

Dynamic Load Tests

Nine states indicated that they have purchased the PDA for pile testing. Four other states plan to purchase a PDA in the near future and five states have had piles tested dynamically by consultants.

Typical bridges having pile foundations were described in the questionnaire and each state was asked to indicate its recommended type of load testing, if required. Five states preferred that dynamic load tests be conducted, eight states would perform a static load test, five states would require both types of testing, and twenty states would not require any load testing.

The following is a list of positive and negative comments addressing the use of the PDA:

Positive

- Testing can be performed quickly.
- It is less expensive than a static load test.
- Since static load testing is seldom done, the determination of the capacity of the piles by dynamic load testing will provide confirmation of capacity, which may allow for a reduction of typical pile lengths.
- It is primarily used to ensure that a proper amount of hammer energy is being provided.
- Stresses that occur in the pile during driving can be monitored.
- It is useful on problem projects for aiding in interpreting unusual driving conditions.
- It can be used to obtain field measurements that can be compared with the wave equation analysis of piles output values (WEAP 86).
- Pile damage can be detected during installation.

Negative

- CAPWAP is required in order to get reliable results.
- Predictions are too conservative for hard driving conditions.
- Long-term pile creep data cannot be obtained.
- It is difficult to maintain a staff of trained PDA operators.
- It delays the contractor's operations.
- Personnel conducting the test may sometimes be subjected to hazardous working conditions.
- It is less reliable than a static load test.
- Using CAPWAP delays turn-around time for providing driving criteria to the project personnel.
- There is limited knowledge in the use of damping constants.
- The PDA operator's normal duties are disrupted at short notice when testing is required.

Engineering News Formula

Seventy percent of those responding stated that the EN formula was being used in some manner to control pile installations. Fifty percent agreed with the 1948 Terzaghi-Peck statement regarding the variability of results that can occur with the use of the EN formula and that "the continued use of the EN formula can no longer be justified." The remaining 50 percent defended their use of the formula with arguments such as

- Piles are thought to be installed to a conservative capacity.
- The procedure is relatively easy for field personnel to administer.
- The EN formula is probably as good a method as wave equation or dynamic measurement methods.
- The formula is considered to be relatively reliable.
- When installing piles in granular soils the factor of safety is between 2.0 to 3.0. For cohesive soils the factor of safety is generally 1.1 to 1.4 (may increase with setup), therefore in cohesive soils a minimum tip elevation must be achieved as per a plan requirement.
- The formula is satisfactory provided the person using this method understands its limitations.

Wave Equation

Approximately half of the states responding to this survey have used the wave equation method. Three of the states use the wave equation to determine the required blow count and also to preapprove the contractor's hammer. Most states are presently experimenting with the wave equation to determine to what extent the predictions by the wave equation will affect their current pile installation practices.

DISCUSSION AND CONCLUSIONS

After many years of near stagnation in the development of improved pile foundation design methods to be used by departments of transportation, the past decade has brought about a renewed emphasis in geotechnical engineering. Research projects and workshop programs promoted by the FHWA have been responsible for much of this new activity. Interest is being shown in providing an updated foundation section in the AASHTO Standard Specifications. AASHTO is probably responsible for many of the long-standing policies or lack of policies currently being used by departments of transportation.

Wave Equation

The wave equation is considered to be a more rational approach for determining pile installation blow counts than the EN dynamic formula. On select projects, wave equation blow counts have been determined by WEAP-86 methods (*5*) for evaluating how the wave equation predictions compare to current practice. When the subsoils at a project site consist of granular materials, the wave equation blow count is similar to the blow count required by present methods. Frequently the wave equation results indicate that the pile cannot reasonably be installed to the required resistance by the contractor's hammer (the hammer is too small), although the hammer has been used (successfully?) many times on other similar projects. As shown by the blow counts tabulated in Table 1, it should be expected that if the wave equation controls are not correctly used, the contractors will be required to sometimes furnish larger pile hammers than they have become accustomed to providing. When high blow counts are required by wave equation methods, the engineer must consider if the effects of residual stress (*6*) and setup have been properly addressed.

Dynamic Load Testing

As indicated by the responses to the survey, dynamic load testing is available to 18 of the departments of transportation. If their staffs are interested in performing this type of testing and dynamic load testing is designated as a priority work item, a successful practice can be expected to develop. As more private testing companies obtain the capability to perform dynamic load tests, contracting their services may be a more appropriate avenue for using dynamic load test methods.

Dynamic load testing offers the contractor an economical testing method that can be used as a defense against unreasonable driving requirements. Generally, contractors are at the mercy of the inspector when high blow counts and longer piles are required. As contractors become successful in their rebuttals, it may be prudent for transportation departments to improve their pile design and installation practices.

When dynamic load tests are conducted, the equitable payment units are per hour for the use of the contractor's pile installation equipment and personnel and per day for a testing company that furnishes and operates the PDA and related accessories. The contractor may hesitate to fully cooperate without appropriate compensation. Testing consultants do not have total control over how many piles can be tested per day because they are dependent on cooperation from the contractor and they may be restricted by project constraints.

Load Tests

Advancements in the geotechnical engineering profession are now technologically accelerating; however, some of the fuel being used for these advancements is being extracted from a deficient pile-load-test data base. The load-test data base, which should be the genesis of all theory and correlation studies, must be appropriately developed and made readily available. Although hundreds of load tests are performed each year, those who have put out a call for load-test data reports have received only a few responses consisting of generally incomplete information. There should exist a requirement to furnish a standardized load test report that is considered to be an integral part of the load-test work. Final payment for the load test should not be made until the report has been furnished. Some of the basic topics contained in the load test report should be

- Subsurface soil properties,
- Load versus deformation data,
- Interpretation of failure (preferably by standard methods),
- Pile-driving blow-count logs,
- Pile-hammer system performance information,
- Wave equation analysis,
- Static analysis computations,
- A discussion of set-up resistance,
- PDA prediction of capacity and other pertinent measurements (when available), and
- CAPWAP analysis results (when available).

The format of the report must be developed so that all information can be easily transferred into the standard computerized data bank.

One standard static load test procedure should be used so that consistency is used in determining the load-deformation values. A reasonable attempt should always be made to load the test pile to a plunging failure condition. A reloading of the test pile for determining the magnitude of setup should be done whenever practical. A load cell is needed to measure the

TABLE 1 BLOW COUNTS FROM WAVE EQUATION AND ODOT EN

DELMAG D-12			240 KIPS (SF=2, 60 TON DESIGN LOAD) 14" CLOSED-END PIPE PILE				
MFR'S RATING	ODOT RATING	WEAP-86 RATING	ODOT EN BLOW COUNT	WEAP-86 SMITH DAMPING			
				SIDE = 0.05 TOE = 0.15	SIDE = 0.2 TOE = 0.15		
				SAND	CLAY	CLAY RESIDUAL STRESSES	CLAY 192 KIPS 48 KIPS SET-UP
22,500 FT-LBS.	16,500	18,870	68	68	272	87	88

applied load. Only when a load cell is being used can the accurate calibration of the jack be verified. In the past 5 yr ODOT has experienced two pile load tests using jacking systems that were furnishing totally erroneous loading values. Other load tests have experienced a 10 percent difference between load cell and jack pressure readings.

There should exist some standard rational guidelines for determining when to load test. Basing the need to load test on criteria such as the total number of piles or the number of feet of piles to be installed or the magnitude of the design load permits many bridges to be constructed without load testing controls. Engineers should be capable of producing documentation that offers evidence as to how the pile load resistance was determined for each project.

After a detailed load-test data base has been established, a means then exists for studying the relationships between full-scale pile load tests, static analysis methods, wave equation predictions, dynamic load test predictions, soil strength parameters, and field sampling techniques.

There is a trend toward varying the factor of safety from two to three depending on the confidence level of the controls used for the installation of the piles. When using a safety factor of three for pile designs, the consequences of additional costs that may be encumbered because of a need for a bigger pile section, longer piles, and a larger pile hammer must not be overlooked. Often the use of a load test and a safety factor of two will be the economical procedure for the construction of a pile foundation. Note that conservative methods used in superstructure designs generally will result in extending the life span of the superstructure. Conservative pile foundation designs are a waste of monetary resources because pile foundations are relatively slow to deteriorate.

REFERENCES

1. R. J. Fragaszy, J. D. Higgins, and E. C. Lawton. *Development of Guidelines for Construction Control of Pile Driving and Estimation of Pile Capacity.* Report WA-RD-68.1. Washington State Transportation Center, Washington State University, Pullman, 1985.
2. S. N. Vanikar. *Manual on Design and Construction of Driven Pile Foundations.* U.S. Department of Transportation, 1985.
3. *AASHTO Standard Specifications for Highway Bridges*, 13th ed. Washington, D.C., 1983.
4. R. L. Engel, C. K. Tungsanga, and S. A. Sommers. *A Survey of Pile Testing and Installation Practices.* Ohio Department of Transportation, Columbus, 1987.
5. G. G. Goble and F. Rausche. *Wave Equation Analysis of Pile Foundations—WEAP 86.* Cleveland, Ohio, 1986.
6. J. L. Briaud and L. M. Tucker. *Residual Stresses in Piles and the Wave Equation.* College Station, Tex. 1984.

APPENDIX A
ODOT Specification EN Formula

507.05 Determination of Capacity

The safe bearing value (R) of a driven pile (considered as a single isolated pile) shall be determined by means of the following capacity formula, unless this formula is modified as a result of a static load test or a dynamic load test: For a single-acting, differential-acting, or double-acting, steam (or air-operated) hammer, or a diesel hammer

$$R = 2F/(S + 0.1) \quad (1)$$

where

- R = safe bearing value, in pounds (corresponding with the design load resistance per pile called for on the plans). By using this formula the piles are assumed to be driven to a failure load that is two times the design load.
- W = weight of striking parts of hammer, in pounds.
- H = height of fall of striking parts, in feet.
- F = WH for single-acting steam hammer, in foot pounds, or
- F = approved rated energy of hammer in foot, pounds. For a differential-acting or double-acting steam or air-operated hammer, the manufacturer's rating is used. For diesel hammers, 70 percent of the manufacturer's rating is used.
- S = penetration, in inches per blow (generally determined from the rate of penetration for the last several inches of penetration).

APPENDIX B
When to Furnish Static Load Tests as Bid Items

A static load test item should be included in the structure's estimated quantities if the design load for the piles is 90 kips or more, except as follows:

- A static load test is not necessary if piles are driven to refusal on bedrock.
- A static load test is not necessary if the estimated linear feet of piles is less than 6,000 ft.

Structures that require a static load test item may also require subsequent static load tests as follows:

Estimated Length of Piles (linear ft)	*No. of Subsequent Static Load Tests*
0–10,000	0
10,001–20,000	1
20,001–30,000	2
30,001–40,000	3

APPENDIX C
Construction Specification for Dynamic Load Testing

523.01 Description

This item shall consist of a dynamic load applied by a pile hammer to a pile while transducers obtain measurements for predicting the static capacity of the pile. Waiting periods may be required so that soil set-up and relaxation characteristics can be determined.

523.02 General

The contractor shall notify the engineer of his intent to drive piling at least 3 days before the installation of the first pile. The engineer shall inform the director of the contractor's pile-driving schedule. The director shall determine if the test is to be performed or if some pile-driving experience at the proposed site is to be obtained before a decision can be made. The director will establish a date for the tests and will also determine the location of all piles to be dynamically load tested.

The hammer selected for driving the test-loaded piles shall be used for driving all piles represented by the load-test piles. If the contractor subsequently finds it necessary to use a different hammer, the director will determine if an additional dynamic load test is necessary. Any such test shall be completed at no additional cost to the department.

523.03 Equipment

The contractor shall supply all personnel and equipment required for striking the test pile with the pile hammer. The contractor shall also supply a source of 115-V, 1500-VA, 60-Hz electrical power and extension power cords.

The department will provide the transducers, the Pile Driving Analyzer, and the personnel to install and operate this equipment.

523.04 Test Procedures

Approximately three piles will be tested in one day. Department personnel will drill holes into the piles to be tested so that electronic transducers (two accelerometers and two strain gauges) can be attached. When the transducers have been placed in position and the Pile Driving Analyzer has been made ready to receive the acceleration and strain measurements, the contractor shall strike the pile with the pile hammer as many times as is required to obtain adequate measurements as determined by department personnel.

After the dynamic testing measurements have been obtained and reviewed, the department will provide instructions for driving the piles.

523.05 Method of Measurement

The hours to be paid for under this item will be the sum of the time intervals that the department has requested the contractor to discontinue his normal production pile-driving operation so that the dynamic load tests can be performed. The engineer will measure and record the time needed to perform the tests to the nearest one-tenth of an hour.

APPENDIX D
When to Furnish Dynamic Load Tests as a Bid Item

A dynamic load test item should be included in the structure's estimated quantities if the design load for the pile is 70 kips or more, except as follows:

- A dynamic load test is not required if piles are driven to refusal on bedrock.
- A dynamic load test is not required if the design load is less than 90 kips per pile and the estimated linear feet of piles is less than 1,500 ft.

Estimated Length of Piles (linear ft)	*Estimated Pay Quantity (hr)*
0–5,000	3
5,001–10,000	6
10,001–20,000	9

APPENDIX E
Plan Note for Requiring Dynamic Load Tests by a Consultant

This item is provided to compensate the contractor for using a testing consultant to conduct dynamic load tests on service piles as required by the director. Testing instrumentation and personnel are to be furnished by the testing consultant. The testing consultant's personnel shall have had successful experience in performing dynamic load tests on piles for at least 10 projects. The contractor shall furnish the name of his testing consultant, along with a list of the company's work experiences, at the preconstruction meeting. The director will review the testing company's background and will either approve or reject the contractor's testing consultant.

The testing consultant shall furnish a report summarizing all testing results and stating his conclusions. The report shall be furnished within 1 week after the conclusion of the pile-testing work.

The contractor shall drive piles and assist the consultant during the dynamic pile tests as per Item 523 (Appendix C).

The unit of payment for this work by the testing consultant shall be per day. The testing consultant is expected to test as many piles as practical in an 8-hr workday time period. The testing consultant shall also perform one CAPWAP for each day's work. The contractor will be paid for lapsed time during all dynamic load testing as per Item 523.

Publication of this paper sponsored by Committee on Foundations of Bridges and Other Structures.