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Optimizing foundation piling

Empilage de linéarisation de base

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ABSTRACT
The design estimation of the required piling dimensions for a project is a multiple step process that lends itself to optimization. The estimate of required piling dimensions made during the design phase of a project is typically based on published design references. Most commonly, the estimated length of the pile is dictated by the compression load and site subsurface conditions. Although much effort has been devoted to developing equations that optimize the design of the piles, these design phase estimates, in the authors' experience, most often use the engineer's preferred method, and are just the initial steps in the foundation optimization process. The best opportunity to optimize the pile dimensions occurs during pre-production load tests. Based on experience, the authors describe a series of steps used to optimize piling requirements for a project.

RÉSUMÉ
L'évaluation de conception des dimensions d'empilage exigées pour un projet n'est pas une science exacte. L'évaluation des dimensions d'empilage exigées faites pendant la phase de conception d'un projet est typiquement basée sur des références éditées de conception. Le plus généralement, la longueur estimée de la pile est dictée par les conditions de sous-surface de charge et d'emplacement de compression. Bien que beaucoup d'effort ait été consacré aux équations se développantes qui optimisent la conception des piles, ces la phase de conception estime, dans l'expérience des auteurs, emploie le plus souvent la méthode préférée de l'ingénieur, et est juste les mesures initiales dans le processus d'optimisation de base. La meilleure occasion de optimiser les dimensions de pile se produit pendant les essais de charge de pré-production. Basé sur l'expérience, les auteurs décrivent une série d'étapes employées pour optimiser des conditions d'empilage pour un projet.

1 INTRODUCTION

Generally pile load tests are conducted to verify that the pile capacity is at least equal to a prescribed ultimate capacity (usually two times the allowable capacity). For relatively small projects (say, less than 500 piles) minimal effort is normally made to optimize the piling design/installation criteria, and thus the cost of piling. The primary reason optimization is not practical in these cases is because any savings are typically offset by the cost of the load tests. For larger projects, however, the savings can be significant. For example, reducing a 20-m pile by 1.5m on a 3,000-pile project, at $65 per m installed pile cost, can save almost $300,000 for the project, far outweighing the cost of the load tests that are necessary to establish the basis for the reduced pile length.

Based on experience on several large scale projects, the authors describe a series of steps used to optimize piling requirements, including probe piling, instrumentation, load testing, and state-of-the-art interpretation of load test results. Discussion includes optimizing driven piles using a pile driving analyzer (PDA), and load test evaluation and design optimization using tell-tales and strain gauges in the field, and analysis using Davisson's (1973) method and a modified Chin and Vail (1973) method.

2 CANDIDATE PROJECTS

Projects where the piles are installed to a pre-determined depth/elevation or to prescribed driving criteria are candidates for pile length optimization. Projects that have a relatively small number of piles or projects where the piles will be installed (driven or drilled) to refusal on top of rock generally do not leave much room for improvement.

3 PRE-PRODUCTION CONSTRUCTION MEASURES TO OPTIMIZE PILING

Pre-production construction measures that can be used to optimize pile length include the following:

- Probe Piling
- Test Pile Installation
- Load Testing
- Load Test Interpretation

3.1 *Probe Piling*

To understand the behavior of the pile during installation, a set of probe piles can be installed. It is suggested that about 1% to 2% of the production piles be installed as probe piles in areas representative of the whole site. If the piles are driven, the installation of the probe piles must be monitored using a pile driving analyzer (PDA). These probe piles are generally installed to a depth somewhat greater than the anticipated depth of the production pile. The purpose here is to monitor the behavior of the pile during installation and to make a decision on the installation criteria for the test piles. For driven piles, the piles should be re-tapped the following day and monitored with a PDA. The probe piles can be used as production piles after they are successfully installed and/or tested.

3.2 *Test Pile Installation*

Based on the pile length and installation behavior of the probe piles (drilling resistance or blow-counts versus penetration, or PDA results), specific areas of the site can be selected for installing the test piles. Pile lengths/driving criteria are selected based on bearing capacity requirements. The test piles are then installed to the selected installation criteria, and monitored with a PDA, if driven. For the driven piles, the test piles should be re-tapped the following day and, again, monitored with a PDA.

It is recommended that, whenever possible, the piles be installed to several different criteria such as different lengths and/or different blow-count criteria for testing. In many power plant projects, piles of two capacities are utilized. Generally the higher capacity piles range from 80 to 120 tons and the lower capacity piles range from 30 to 60 tons. From a load test standpoint, this automatically provides for two different pile lengths (assuming the same pile type and diameter) for testing.

For driven piles, the PDA is an invaluable tool. Data of capacity versus depth and blow-count can be compared to actual load test results. In the authors' opinion, the accuracy of the results is not very critical as long a "reference" PDA estimated pile capacity – in the field - corresponding to the allowable load can be established. Since the PDA measurements are made directly in the pile, all errors associated with hammer efficiency, helmet, hammer-cushion, etc., are eliminated. Once the PDA is calibrated for a pile type at a project site, it can be used to estimate the pile capacity using other hammers.

The test piles may be used as production piles provided their load carrying capacity has not been compromised by the testing.

3.3 *Static Load Testing*

Static load tests are conducted using ASTM or equivalent national or local standards. The maximum applied load is generally 200% or 250% of the allowable design load. If the reaction load is available, the pile can be reloaded to failure after loading the pile to these limits. This eliminates much of the guesswork involved in load test interpretation. Tests are normally conducted using the required instrumentation per ASTM standards. On various projects, additional instrumentation including tell-tales or strain gauges has been used.

3.4 *Static Load Test Interpretation*

There are various methods available to evaluate the load test results. The instrumentation used during the test can define the method of evaluation. Tests conducted with several tell-tales and/or strain gauges can be evaluated more accurately, although in the authors' experience, the failure rate of strain gauges can be quite high. Most static pile load tests are generally conducted without significant additional instrumentation to that specified in the ASTM procedures.

3.4.1 *Interpretation using standard instrumentation per ASTM*

The standard instrumentation per ASTM yields a load versus deflection curve. Two alternative interpretation methods are discussed below that the authors have utilized frequently on various projects to interpret the load-deflection curve:

Davisson Method: This is probably the simplest method to check the adequacy of a given pile. This method confirms whether the tested pile has the required allowable bearing capacity. For projects where only a confirmation is required on the load carrying capacity of the pile, the Davisson method is used commonly in practice. Several publications have reported that the Davisson method gives a conservative estimate of the ultimate capacity of the pile.

This method makes use of a graph of load versus settlement based on the test results. The elastic deflection of the pile (PL/AE) assuming a purely end-bearing case is drawn on the graph, and then an offset line to the elastic deflection is added. The offset at zero load is computed as:

4 + D/120 mm, where D = pile diameter in millimeters

The authors generally include a PL/2AE plot in the load-settlement graph (see Figure 1) to account for skin friction. Experience indicates that when the load-displacement plot, as shown on Figure 1, is above the PL/2AE line, the applied load is being carried purely by friction. Between PL/2AE and PL/AE the majority of the load is still carried by friction. When the pile intersects the PL/AE line a significant portion of the applied load has reached the tip of the pile.

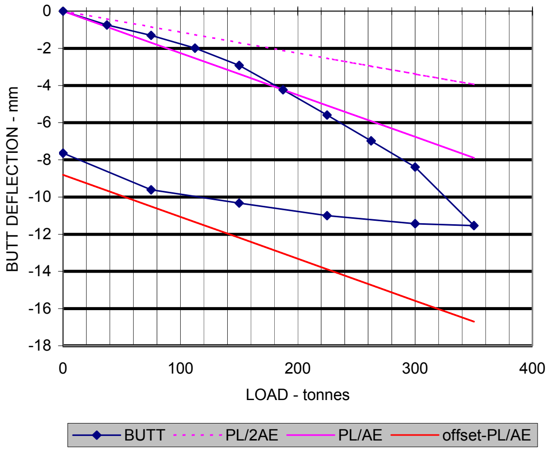

Figure 1. Load-Deflection Curve

Chin and Vail Method: This method has been utilized on various projects to evaluate the load test results when a more detailed analysis is required on the skin friction and end bearing components of pile capacity. It is the authors' opinion that during construction, the Davisson method is simpler and easier to utilize for evaluating the adequacy of a pile to carry the given design load. Chin and Vail, on the other hand, is a useful method to evaluate the pile design parameters such as skin-friction and end-bearing, although the evaluation is more complex.

The Chin and Vail method's stability plot is based on the assumption that the relationship between the applied load, P, and pile head movement, Δ, is hyperbolic, and that a plot of Δ/P versus Δ is linear, as described by the expression:

$$\Delta/P = m\Delta + c$$

where: m = the slope of the straight line, and
c = the intercept on the Δ/P axis.

The Chin and Vail method is particularly useful in evaluating load tests that have not been carried to failure. This is the authors' preferred method for analyzing the load test results in this situation, and it provides a simplified tool to evaluate the design parameters.

The evaluation is performed by plotting Δ/P versus Δ using the load test data (see Figure 2). Provided that the pile does not bear on an incompressible stratum, the stability plot for the early part of a loading test (initial straight line) is a measure of shaft resistance only. At large movements, a second straight line represents the combined effect of shaft and point resistances. The inverse of the slope of the initial straight line ($1/m_s$) is the ultimate skin friction developed in the pile. The second straight line provides the equation to estimate the ultimate total capacity of the pile based on a failure deflection criterion. To be consistent with the "failure criteria", the ultimate load by the Chin Vail method is assumed to be the load at which the curve crosses the Davisson-offset line. The ultimate bearing capacity of the tip of the pile can be estimated by subtraction.

The authors use the Chin and Vail method in conjunction with the Davisson method to evaluate static pile load test data. It is their experience that the Chin and Vail method requires a little modification of the data to adjust for the "zero-error" in a load test. The zero-error is probably due to seating of the loading jack and plates on the pile top. Generally the estimated zero-error is very small, less than 1 mm. However, the initial straight line used to estimate the skin friction on the pile is very sensitive to the zero-error because the pile deflection is very small when the load is being carried purely in friction. Therefore, even a small zero-error can affect the skin friction estimate.

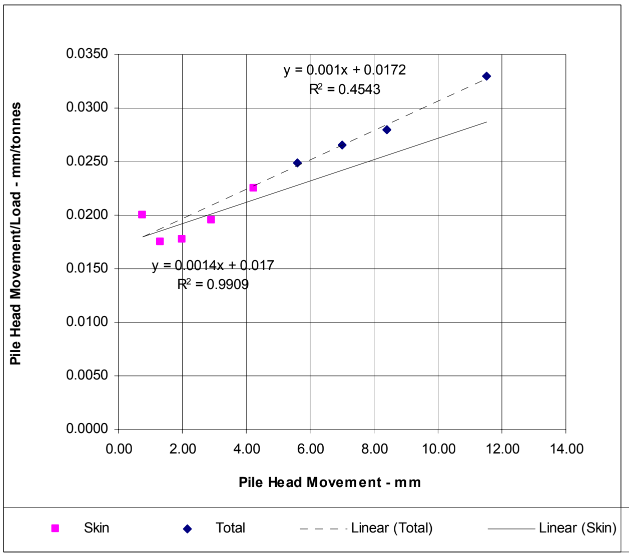

Figure 2. Δ/P versus Δ plot

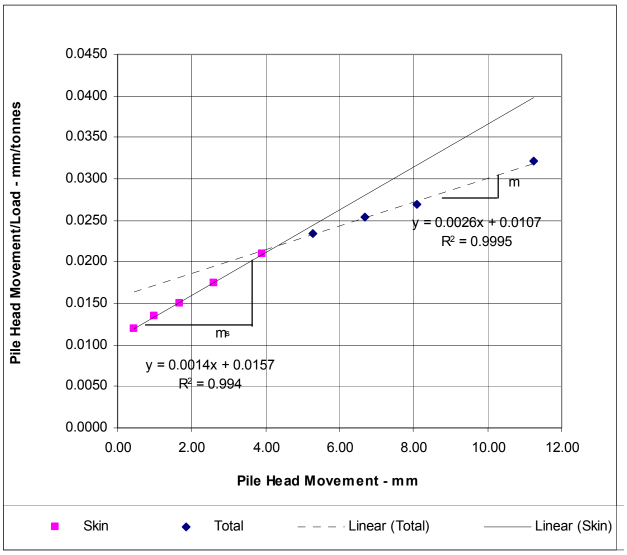

Figure 3. Corrected Δ/P versus Δ plot

The assumption of a hyperbolic load versus deflection curve provides an effective means to estimate the zero-error. By trial and error, the zero-error is adjusted until the initial points of Δ versus Δ/P form a straight line. For most test results, a simple technique uses the first three points, making the slope from point 1 to 2 the same as the slope from point 2 to 3. The zero-error can be easily determined using commonly used spreadsheet software. Figures 2 and 3 show an example of the zero-error. Figure 2 is based on actual test data as shown in Figure 1, and Figure 3 is the corrected data. The correction in this case is only 0.3 mm, but it has significant impact on the initial portions of the curve. As mentioned previously, the Davisson method gives a useful indication of the loads being carried by friction and the loads being carried by friction and end-bearing (see Figure 1). The results from Davisson are compared with the modified Chin and Vail curve. As seen from Figures 1 and 3 both methods indicate that the first five loads are carried primarily in friction.

3.4.2 *Interpretation using tell-tales*

In theory, tell-tales can be used to determine the load distribution in the pile.

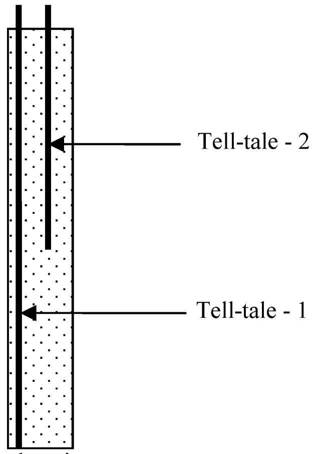

Figure 4. Tell-tale locations

Generally two tell-tales are used, one at the tip of the pile and one in the middle of the pile. For the applied load 'P', the computation is as follows

Tell-tale – 1:
Length = l_1
Measured deflection = D_1
Compressive stress at bottom of tell-tale = P_1

Tell-tale – 2:
Length = l_2
Measured deflection = D_2
Compressive stress at bottom of tell-tale = P_2

Butt of pile:
Measured deflection = D_{total}

$$(P+P_1)/2 = (D_{total} - D_1)AE/l_1$$
$$(P+P_2)/2 = (D_{total} - D_2)AE/l_2$$
$$(P_1 + P_2)/2 = (D_2 - D_1)AE/(l_1 - l_2)$$

where A and E are the pile area and elastic modulus.

The average skin friction developed in each section can be determined. Actual skin friction within each section can only be determined based on the estimated load distribution. The authors prefer to place the second tell-tale at the interface of the bearing stratum. This provides more detailed information of the design parameters in the bearing stratum.

In practice, these tell-tales are very long compared to the measured deflection to 1/100 mm. The flex in the tell-tales can lead to significant errors in the measured readings. The authors generally use the tell-tale data as a check of the load test results. Design decisions and pile optimization are generally not based on these data.

3.4.3 *Interpretation using strain gauges*

The strain gauge serves a similar purpose to the tell-tale in that the measured strains in the pile can be used to estimate skin friction and end-bearing.

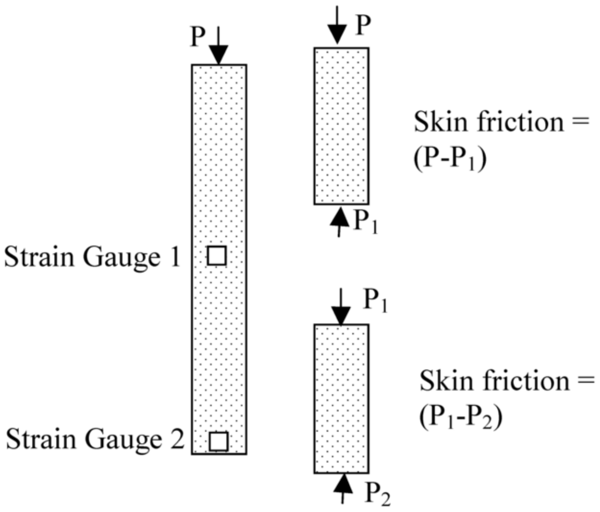

Figure 5. Strain gauge locations

For the applied load 'P', the computation is as follows:

$P_1 = \varepsilon_1 AE$
$P_2 = \varepsilon_2 AE$

where ε is the measured strain at the location of the strain gauge in the pile.

The authors prefer to place the strain gauges at strata interfaces. This provides more detailed information about the design parameters for each stratum. In practice, the authors have experienced a very large number of failures in strain gauges. It is thus preferable to use several strain gauges in each test pile in the hope that some of the gauges produce useful results.

4 OPTIMIZATION

There are several ways to optimize the pile length for a project:

- As noted earlier, the PDA is an invaluable tool for driven piles. Data of capacity versus depth and blow-count can be calibrated using actual load test results. Once the PDA is calibrated for a project, the installation criteria of the production piles can be optimized. This has the added benefit that the production piles can be periodically tested using the PDA for compliance with design requirements. In the authors' opinion, efficient utilization of static load tests and PDA testing is the best approach to optimize the design of driven piles.
- If the PDA cannot be utilized, the load test interpretation information from Davisson and Chin and Vail, as well as instrumentation such as strain gauges can be used to optimize the pile length. This method is particularly useful when the piles are installed to a fixed penetration into a bearing stratum. In the authors' experience, the skin friction and end bearing parameters estimated using the load test results are generally slightly to significantly higher than the values used in design. Therefore, even a conservative approach can lead to some savings in foundation piling. For example, an increase in skin friction from 50 kPa to 55 kPa and the end bearing from 1,500 kPa to 2,000 kPa can lead to significant savings in foundation costs.

5 CASE HISTORY

The authors used this method on a project in Texas where auger-cast piles of length 9.1 m (30 ft), 16.8 m (55 ft) and 18.3 m (60 ft) were tested. The subsurface conditions consisted of about 2.4 m (8 ft) of stiff clays with sand layers underlain by soft clay to a depth of 4.9 m (16 ft) and below 4.9 m (16 ft) stiff clay with layers of sand. Based on borings, CPT and lab test data and using several empirical methods (Neely, 1991 and DM-7.1, 1982) the estimated ultimate skin friction of the bearing stratum below 4.9 m (16 ft) ranged from 29 kPa (0.6 ksf) to 58 kPa (1.2 ksf). An average of 48 kPa (1 ksf) was used in design. The pile was assumed to be bearing on stiff clay with an ultimate end-bearing capacity of 1,500 kPa (31.5 ksf).

The results from the three load tests were in good agreement and slightly better than the estimated values based on borings, CPT, and lab test data. The back-computed ultimate skin friction was 61 kPa, 64 kPa and 77 kPa. The back-computed end-bearing was significantly higher than the assumed 1,500 kPa. Based on a conservative approach, a skin friction of 64 kPa and an end-bearing of 1,500 kPa were used to estimate the length of the production piles. The final length of 15.9m (52 ft) was shorter than the original estimate of 18.3 m (60 ft). Although this is not a large difference in length, with several thousand piles this resulted in savings of several hundred thousands of dollars for the project.

6 CONCLUSIONS

Pile load tests can be expensive and time consuming. For these reasons, on fast paced Projects there is generally a tendency to minimize the number of load tests. In this paper the authors have presented the positive aspects of pile load testing. Careful planning, testing and evaluation can lead to reduction in overall cost to the Project.

In all cases, the authors strongly recommend that a load test be performed to verify the final pile installation criteria. For example, if piles of lengths of 40 ft, 50 ft and 60 ft are tested, then it is preferable to use of the lengths tested for production piling. An extrapolated length of say 55 ft should be used only if the responsible engineer has derived very reliable information from the load tests and the results are within a reasonable range of the design parameters.

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