53:139 Foundation Engineering
The University of Iowa
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Field Estimates of Pile Capacity

1. OVERVIEW

In estimating the ultimate capacity of deep foundations (both driven and cast-in-place), we have considered a number of semi-analytical and/or empirical equations to calculate both the end bearing capacity of a deep foundations, and to calculate the frictional capacity of deep foundations. It should be noted that unless otherwise noted, the methods presented typically apply to both driven pile foundations and cast-in-place pier or drilled shaft foundations. The two alternative methods of estimating the ultimate capacity of deep pile foundations that will be briefly discussed in this handout are:

a. Full scale field load tests; and

b. Pile driving formulas.

2. FULL SCALE LOAD TESTS

In any foundation project there will be at least some uncertainty as to what the subsurface soil properties are throughout the site, even when borings have been taken. In construction projects involving the driving of piles, the uncertainty of the subsurface soil properties can be magnified since the process of driving piles (in particular high displacement piles) can disturb the soils and thus change their properties. One way to deal with these uncertainties is to perform full-scale field load tests on driven piles. The principal benefit of the full-scale field test is that they provide <u>precise</u> information on the capacity of piles at a specific site. This allows designers to use lower factors of safety and can translate to reduced construction costs.

While there are benefits to performing full-scale field load tests on piles, the tests can be both time-consuming and expensive to perform. Thus, they are typically performed only when combinations of the following factors are present:

1. The project is large and many piles need to be driven.
2. Soil conditions at the site are erratic with a high degree of spatial variation.
3. Piles are driven into cohesive soils, whose properties can be greatly affected by the pile driving process.
4. The structure supported on the piles is very sensitive to settlement.
5. The piles will have to resist uplift.

Based strictly on the size of a pile driving project, Engler [1] has proposed the following suggestive guidelines for determining how many (if any) piles should be tested for a given pile driving project.

Total length of piles driven (km)	# of Required tests
0 – 1.8	0
1.8 – 3.0	1
3.0 – 6.0	2
6.0 – 9.0	3
9.0 – 12	4

2.1 Types of Tests

The equipment with which the field tests are to be performed obviously requires the capacity to push down on (load) the piles to test their ultimate downward capacity and the capacity to pull upward on the piles to test their ultimate up lift capacity. Since the capacity of an individual pile can be quite large, the required setup can be quite elaborate, involving anchor piles, cross-beams, hydraulic jacks, and test beams. Assuming that the appropriate loads can be applied to a given pile, and that the displacement of the test pile can be objectively measured, the test is, in principle, quite simple. Loads are applied to the pile and the pile's displacements under the loads are measured. Hence load versus displacement plots can be generated for each pile tested.

One of the difficulties with full-scale field load tests is that the load versus displacement behavior observed will be rate dependent. That is, if the test is performed very rapidly, comparatively small displacements of the pile will be observed. On the other hand, if the test is performed very slowly (which is often most representative of loading conditions under building loads) comparatively large displacements of the pile will be measured. This rate-dependent behavior is demonstrated in Figure 1 and derives from the rate-dependent shear strength behavior of most soils. Recognizing that strain-rate dependence can be an issue, a number of different tests are often performed.

2.1.1 Stress-controlled Tests

Stress-controlled tests are performed by applying vertical loads to the pile and observing or measuring the vertical pile displacement. The load increments are typically: 25, 50, 75, 100, 125, 150, 175, and 200% of the estimated capacity $(Q_u)_{\text{estimated}}$ of the pile, until excessive pile displacement (failure) is observed. Often, these tests are performed either as "slow" maintained load (ML) tests, or "quick" maintained load (ML) tests. The procedure in the "slow" (ML) tests is to

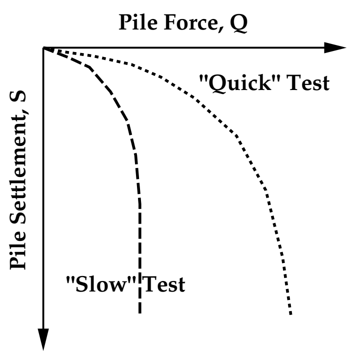

Figure 1. "Slow" and "quick" pile load tests.

apply a load increment and to maintain that load until the incremental settlements cease, or the incremental rate of settlement becomes sufficiently small. This can take several hours per load load increment, and so the "slow" test can require over 24 hours to perform. In "quick" (ML) tests, the load increments are applied for approximately 2–15 minutes and incremented even if the settlement under the current load has not yet completed. The "slow" tests are preferable in that they are more representative of the maintained nature of static building loads. Taking the raw results of "quick" tests without correcting for rate effects can lead to overestimating the ultimate pile capacities and underestimating pile displacements (settlements) under static loads.

2.1.2 Strain-controlled tests

In strain-controlled pile tests, the rate of penetration (extraction) of the pile is fixed, and the force Q required to maintain this rate is measured. Strain-controlled tests, like the stress-controlled tests, yield load Q versus pile displacement curves. The common rates at which these tests are performed are:

a. clays: 0.25 – 1.25 mm/min; and

b. sands: 0.75 – 2.50 mm/min.

These rates are generally quite large, and thus results of these tests are expected to be similar to those from "quick" (ML) tests.

2.2 Ultimate Capacity

Interpreting "quick" (ML) tests and strain-controlled tests that show rate behavior can be tricky, whereas interpretation of "slow" (ML) tests is quite straightforward. In principle, the ultimate capacity Q_u of a pile is the load Q at which the load-displacement curve shows a sharp plunge, and beyond which the pile undergoes dramatic settlement. Practically speaking, however, the allowable capacity $Q_{\text{allowable}}$ of a pile as determined from a full-scale field test is that load Q at which the settlement S equals or exceeds the allowable settlement for the desired application.

3. PILE DRIVING ANALYSIS

3.1 Estimating Ultimate Resistance

The premise behind pile driving analysis and formulas is that the ultimate pile capacity Q_u can be determined by observing the soil resistance to piles during the driving process. In its most fundamental (and simplified) form, the basic idea can be expressed as:

$$H_E = Q_u \Delta S$$

where: H_E is the mechanical energy supplied to a pile by single hammer blow; Q_u is the estimated pile capacity; and ΔS is the incremental advancement of the pile for a given hammer blow. Hence the energy supplied to the pile is equal the work done by the soil to resist the pile's advancement. It is assumed that the resistance force generated by the soil during the driving process is equal to Q_u. Thus if H_E is known and ΔS can be measured for a hammer blow, Q_u can be estimated.

In practice, formulas which are slighly more complicated are employed. In many cases, the complication arises from properly accounting for the actual energy that is imparted to the pile by the driver, and accounting for how much of this imparted energy is available for advancing the pile. Energy imparted to the pile that would be unavailable for advancing the pile is lost to mechanisms such as:

- energy dissipation by irreversible yielding behavior of the pile material;
- elastic waves propagating in the air (sound) and elastic waves propagating in the soil.

Among the formulas that attempt to account for energy loss are the Engineering News Record (ENR) formula which is:

$$Q_u = \frac{W_R h}{S + c}.$$

where: W_R is the weight of the ram; h is the fall height of the ram; S is the measured penetration of the pile per blow; and c is 0.1in if S and h are measured in inches. Alternatively, the Modified ENR formula is:

$$Q_u = \left(\frac{E W_R h}{S + c} \right) \left(\frac{W_R + n^2 W_p}{W_R + W_p} \right).$$

where: E is the rated efficiency of the hammer; n is the coefficient of restitution of the ram and/or cushion material; W_p is the weight of the pile; and c = 0.1in. Standard coefficient values for E and n are as listed below:

Hammer Type	E
single & double acting	0.7 – 0.85
diesel hammers	0.8 – 0.90
drop hammers	0.7 – 0.90

Pile material	Coef. of restitution (n)
concrete or iron	0.4 – 0.5
wood cushion/steel piles	0.3 – 0.4
wooden piles	0.25 – 0.3

Beyond these formulas, numerous others also exist and are sometimes used. Among these are:

- the Michigan State modified ENR formula;
- the Danish formula;
- the Pacific Coast Uniform Building Code formula; and
- Janbu's formula.

There are numerous problems associated with using pile driving resistance to estimate the ultimate static resistance capacity Q_u of a pile. Among these are:

- For soft clay soils, the formulas do not account for the thixotropic behavior of clay. During the actual driving, the clay is highly disturbed and resistance is very small. After recovering, however, the soil "freezes" and regains its strength. One way to account for this behavior in piles driven into clay soils is to allow the soil to recover from the driving process, and then to "retap" the piles or to perform the pile driving test at a later time.
- Pile driving is a very dynamic process. Sands are notorious for showing higher shear strength under dynamic loading than under quasi-static loading. Thus driving analysis of piles in sand could lead to an overestimation of their capacity.
- Estimating the efficiencies of driving hammers can be difficult; and
- Energy absorption properties of piles and cushions can vary significantly.

In summary then, it is possible to *estimate* Q_u from pile driving analysis, but the method does have its recognized difficulties. Due to the uncertainties and inaccuracies associated with pile driving analysis methods of estimating Q_u, factors of safety of 4 to 6 are generally used with ultimate capacities determined in this manner.

3.2 Pile Monitoring During Driving

To avoid material failure and breakage of piles during the driving process, it is best to keep the axial stress in the pile well below the strength of the pile material:

- for wooden piles, keep $\sigma_{\max} \leq 0.7 f_u$, where f_u is the tensile strength of wood;
- for concrete pile, keep $\sigma_{\max} \leq 0.6 f'_c$, where f'_c is the unconfined compressive strength of concrete;
- for steel piles, keep $\sigma_{\max} \leq 0.85 \sigma_{\mathrm{Y}}$, where σ_{Y} is the yield tensile strength of steel;

There are many ways to estimate the maximum stresses in the pile during driving. One simple method is to say that:

$$\sigma = Q_u / A_p ,$$

where Q_u is the estimated resistance capacity of the pile as determined by one of the pile driving formulas, and A_p is the material cross-sectional area of the pile. Thus, if a given pile has been driven to "refusal" such that it barely advances for a given hammer blow, the stresses induced in the pile would tend to be much higher than if the pile were advancing freely into the soil. Piles are most likely to be damaged when they are being driven into stiff soils or rock layers that provide strong resistance.

4. REFERENCES

[1] R.L. Engel (1988) "Discussion of procedures for the determination of pile capacity," *Transp. Res. Record* **1169** 54–61.