How to Select the Most Satisfactory and Economical Pile Foundations

by David Novick

SELECTION of the most satisfactory and economical foundations has plagued foundation engineers for many centuries. Records of construction during the Roman Era indicate that determination of the proper length and type of piles was a vexing problem even then. Much pile foundation knowledge was intuitive or based on individual experience and was not written down for the benefit of new engineers or engineering students. As a result, with the retirement of experienced practical foundation engineers, younger engineers have had to re-learn pile foundation design and construction.

Design Data

A three-step procedure can be recommended for the selection of the type of foundation. In the first step, the engineer should secure preliminary structural design data, including the type, size and function of structure, construction materials, framing system and the controlling site grades. Compressive and tensile design loads, moments and lateral forces at the foundation level are obtained or estimated by the foundation engineer. Several trial structural calculations are made to determine the approximate number of piles for several pile design loads in the normal range of pile loading for timber, concrete or steel piles or subpiers. This article does not cover those structures where shallow spread foundations are economically practicable.

Soils Data

As a second step, the soil borings, laboratory test data and recommendations from the Soils Engineer are reviewed to determine the approximate length of piles in the range of loads under consideration. A preliminary economic study is prepared, using the estimated number and length of each pile type. A determination can then be made of load range which is most economical for the structure under design. If

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THIS SECOND ARTICLE in the series covering "Pile Foundations: Know-How" discusses the importance of knowing how to select pile foundations that will do the most satisfactory and most economical job for the intended purpose. This selection will have to precede any construction at the site and would include taking into careful consideration all available soils test data as well as the driving of the load test piles to determine the type and size of the piles to be used.

No. 3 in the series will be a detailed discussion of "How to Determine Pile Depth Embedment." □

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two or more foundation types are comparable in cost, more refined studies are necessary and bids on alternate types may warrant consideration.

Specs and Supervision

The third step is taken after having selected the pile design load and approximate length. The problem is to insure that the proper pile length will be used, and, by means of the plans, specifications and field supervision, that piles will be driven to the proper depth of embedment so that piles will neither be under-driven, causing settlement and possibly failure, nor over-driven, in which case uneconomical foundations or pile damage may result.

At this stage in the design, an evaluation is made of whether the pile resistance is developed primarily in friction over all or part of the length, bearing at or near the tip, or a combination of both. In an analysis of this kind, consideration should be given to time effects in compressible clay soils which may cause a downward transfer of load from initial friction support to bearing.

For those piles which can be described as friction piles in soft clay or very loose sand, no firm stratum is to be reached and the selection of length is based on foundation soil properties including the shear strength and magnitude of probable settlement at several levels. The use of dynamic formulas is not considered a reliable indicator of friction pile capacity. The length of friction piles in soft clay can best be designated by a specific design tip elevation to which the piles are driven regardless of the driving resistance. Soft clays or organic silt-clays and very loose silts or sands are probably the only situations where true friction pile conditions exist.

Possible Test Load

If the project is large and important, a pile load test program can be initiated, preferably in advance of actual construction. Friction piles should not be tested until at least two weeks after driving and longer periods should be utilized where practicable. Adjustments in pile lengths can be made after analysis of load test results.

Friction Piles

An example of friction piles in soft clay soils for a 100-ft.-high lighting tower foundation in northern Indiana is given in Fig. 1: Subsurface Conditions, Fig. 2: Pile Design Details, and Fig. 3: Construction Specifications. Structural design calculations indicated that if four piles were used at each tower foundation, pile design loads would be 30-tons compression and 5-tons tension with both derived primarily from wind load. Treated timber piles were selected as an economical foundation and the required pile length was calculated to be 50 ft. Contract documents specified "piles shall be driven to the full ordered length of 50 ft. except for an allowance of 2 ft. for pile cap embedment (to account for tensile forces). The length of piles shall not be determined by dynamic formulas."

Pile lengths were determined by the calculations given below using these relationships for frictional and point resistance in soft clay soils:

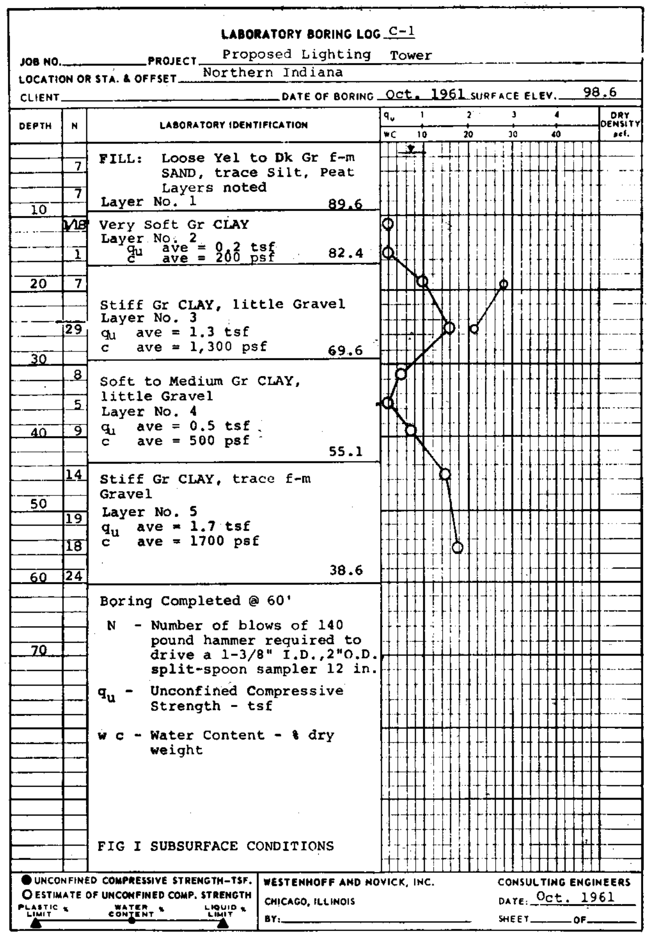

FIG I SUBSURFACE CONDITIONS

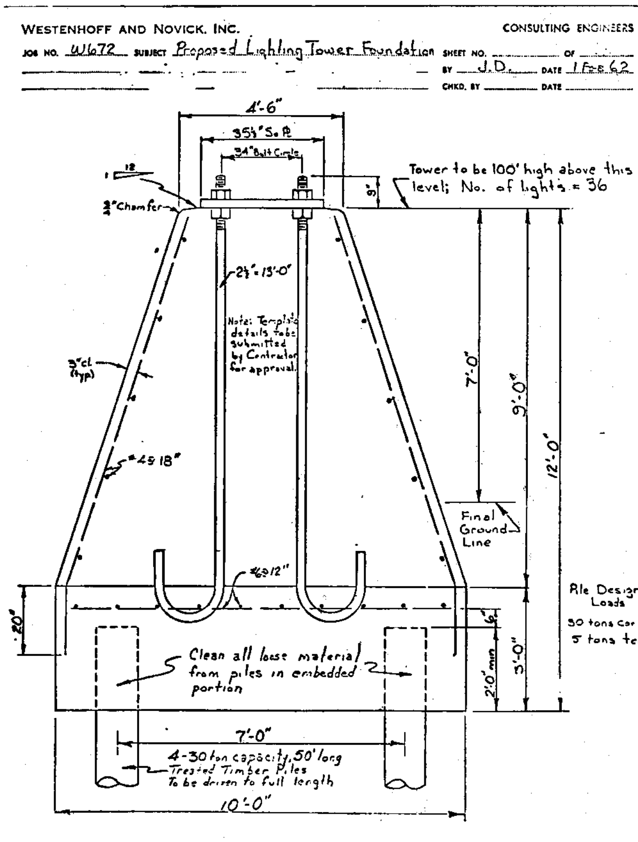

Fig 2
Pile Design Details

$P_f = \Sigma\ c \times r \times h$ where
P_f = ultimate pile capacity due to skin friction—lbs.
c = soil frictional resistance or cohesion, can be taken as equal to one-half of the unconfined compressive strength for soft clay soils—psf (pounds per sq. ft.)
r = average circumference of pile in the soil layer under analysis—ft.
h = height of soil stratum under analysis—ft.
A = area of pile tip—$ft.^2$
In clay soils
$P_p = 7.4 \times c \times A$
P_p = ultimate pile capacity due to point bearing—lbs.
$P_{ult} = P_f + P_p$
P_{ult} = ultimate total pile capacity—lbs.
F.S. = Factor of Safety

$$P_a = \frac{P_{ult}}{F.S.}$$

P_a = Allowable pile capacity at assumed factor of safety.
Calculation of P_f

Layer No. 1	Ignore contribution of loose fill layer	
Layer No. 2	$P_f = 7.2 \times 200 \times r$	1,440 lbs. x r
Layer No. 3	$P_f = 12.8 \times 1{,}300 \times r$	16,640 lbs. x r
Layer No. 4	$P_f = 14.5 \times 500 \times r$	7,250 lbs. x r
Layer No. 5	$P_f = 10 \times 1{,}700 \times r$	17,000 lbs. x r
	$P_f =$	42,330 lbs. x r

Assume average pile diameter = 1.0 ft; r = 3.14 x 1.0 = 3.14 ft.
Assume diameter of pile at tip = 8 in; A = .35 $ft.^2$
$P_f = 42{,}330 \times 3.14 = 132{,}900$ lbs. = 66.5 tons
$P_p = 7.4 \times 1{,}700 \times .35 = 4{,}400$ lbs. = 2.2 tons

It is noted that point resistance is negligible in low strength clay soils and can frequently be ignored.

P_{ult} = 68.7 tons
At F.S. = 2.0; P_a = 34.3 tons;
At F.S. = 3.0; P_a = 22.9 tons
Use P_a = 30 tons at F.S. = 2.3

A factor of safety of 2.0 to 2.5 is generally considered sufficient for calculations of this type, with the actual value a function of the degree of uncertainty in design loads and soil characteristics at each site.

Settlement calculations were not performed for this project since loading was primarily due to wind, and settlement was not a consideration. Piles were spaced sufficiently far apart so that the group effect was not critical.

During construction an inspector called to advise that the piles did not meet the "test requirements" at the ordered length. The term "test requirements" meant ENR resistance. The inspector was instructed to terminate driving at the ordered length. At this site, for friction piles in soft clays, the soil mechanics calculations were considered more reliable than driving resistance. Considerable economy was effected by using a calculated tip elevation. Piles driven to ENR resistance at this site might have been 50% longer without any significant benefit.

End Bearing

For those piles which can be described as bearing piles, a different approach is required. The exact length of bearing piles is difficult to predict accurately due to the great variety in character and consistency of bearing strata. Length predictions are likely to be more accurate for bearing piles driven in sound rock, well defined hardpan or at locations where the pile driving characteristics of the subsoils are well known.

A minimum tip elevation and minimum pile length should be calculated for bearing piles. These calculations should be based on subsoil strength characteristics considering the fact that such piles are normally used to penetrate through a weaker stratum and reach a firm bearing layer. When bearing materials are markedly different in strength from soils providing friction resistance, it is not likely that the peak strength of both soils can be developed simultaneously. The frictional resistance provided by soft clays is likely to be temporary and the pile load transferred to the bearing layer after the passage of time. The peak strength of hard bearing soils may be exceeded before shear strength of soft clays is significantly developed.

Contract specifications should provide that piles penetrate at least down to the minimum tip elevation regardless of the difficulties encountered in driving. This provision will require that the contractor use preboring, jetting or other methods as may be needed to go all the way through hard layers and miscellaneous fills. Below the minimum tip, a dynamic resistance or soil strength can be used to select final tip elevation. The contract plans or design report should call for an estimated length for use in cost estimates and ordering. The *estimated* length must be clearly distinguished from the minimum length.

The driving of test piles is desirable for the initial stage of pile driving on bearing pile jobs. The test piles should be ordered longer than the estimated length in order to provide information on the driving characteristics of the soils below the probable tip elevation. The test piles are driven with the same hammer and equipment as the structure piles so that a plot of driving resistance vs. depth, superimposed on the soil profile, constitute a direct correlation of driving and

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JOB NO. W672 SUBJECT Proposed Lighting Tower Foundation SHEET NO. OF
- Construction Specifications BY WN DATE Feb 2, 1962
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SPECIFICATIONS

Standard Specifications of the Indiana State Highway Department are applicable with these modifications:

Foundation Piles

Treated timber piles shall be driven to the full ordered length of 50 feet except for an allowance of 2 feet minimum embedment in the pile cap. If the embedment in the pile cap is less than 2 feet, special anchorages shall be provided at no extra cost to the Owner. The length of piles shall not be determined by formulas. Steel shoes shall be provided as directed by the Engineer, to penetrate thin hard layers encountered in the borings.

Concrete Foundation - Construction Sequence

Contractor to furnish template to hold position of anchor bolts. After 28 days, or when fc=3000 psi, the base plate and tower can be placed in position. "Embeco" grout is to be placed under base plate after base plate has been leveled, tower plumbed and locking nuts tightened. No lights to be placed on platform until Embeco grout is at least 7 days old or until fc=3750 psi.

Air entrained concrete to be used.

Fig 3 - Construction Specifications

soil characteristics for the particular size and type of pile and the driving equipment.

Analysis of the driving record plot will indicate the relative dynamic resistance provided by different strata and variations in resistance within the bearing layer. Weaker pockets or strata within the bearing layer can be observed. The relative resistance indicated by pile driving records may differ from that indicated by soils tests or soil sampler blow counts.

Where load tests are to be used, e.g., on any large projects, when pile loads are heavy, or when uncertainty exists as to the strength of the bearing layer, the analysis of the soil-driving data plot will enable the selection of the pile or piles to load test. Driving tests then can be used to provide a basis of correlating load test results to structure piles either on the basis of soil strength, driving resistance or both.

To illustrate the process for determining bearing pile lengths and capacities, we will use the case of a refinery plant site in northern Indiana. This same procedure applies to other pile types, including timber.

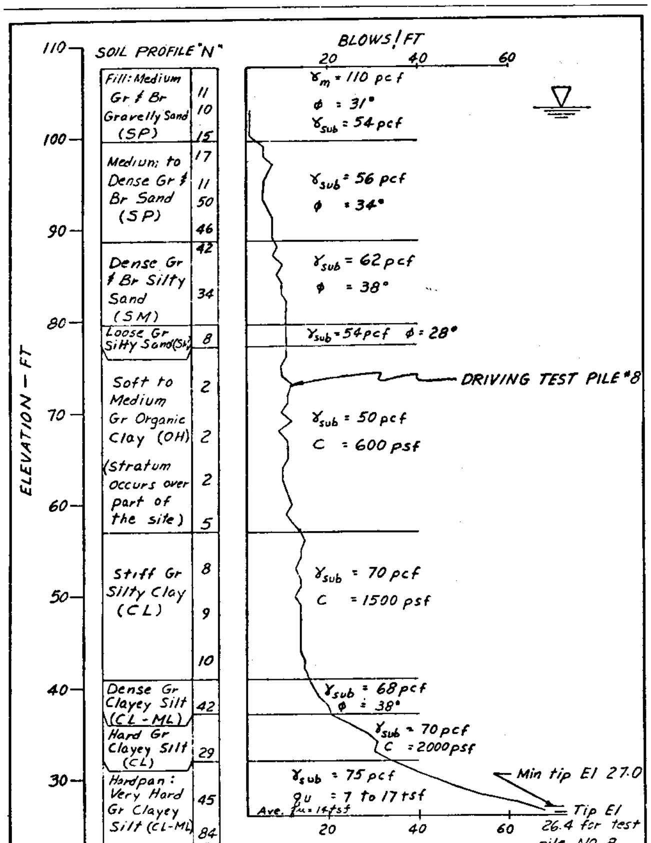
Fig. 4, Typical Combined-Soil Driving Test Plot, illustrates the method of selection of bearing pile lengths for a refinery site in northern Indiana.

Bearing pile lengths were estimated on this basis:

1. Neglect the frictional effect of the soils above the hardpan bearing layer since the stress-strain characteristics of the upper strata and the bearing layer are too different to be developed simultaneously.

2. Assume that the hardpan layer can be analyzed in accordance with the friction and point bearing relationships developed above for soft clay soils. The reasonableness of this assumption is based on the following considerations applied with a substantial factor for judgment and experience:

   a. The hardpan is pre-consolidated to 5 to 8 times the present overburden pressure and therefore is not subject to analyses as a granular soil, e.g., in granular soils confining pressure is a function of depth.
   b. Experience with this Chicago area hardpan layer at many sites in the vicinity of this project indicates that the shear strength relationships are reasonable even though the same formulas are not necessarily reliable for very stiff and hard clays in the same general area.
   c. Additional driving and load testing was provided to supplement the soil mechanics analyses, thus another check on the method.



TYPICAL COMBINED SOIL DRIVING TEST PLOT
REFINERY SITE NORTHERN INDIANA

WESTENHOFF AND NOVICK, INC. CONSULTING ENGINEERS — FIGURE 4

The estimated pile lengths were calculated by the following procedures:

Hardpan layer encountered at EL 32
Pile type: 14BP73 steel pile
Area = 21.46 in.^{2}
r = 2 x 13.64 + 2 x 14.59 = 56.46 in = 4.7 ft.
P_f = 4.5 ft. x 7 tsf x 4.7 ft. = 148 tons
P_p = 7.4 x 7 tsf x 1.39* ft.^{2} = 36 tons
2 | 184
P_a = 75 tons @ F.S. = 2.5
*Assumed bearing area for steel H pile

Based on structure loads and pile driving experience in similar soils, a maximum design load of 75 tons per pile was selected at an estimated penetration of 4.5 ft. into hardpan. The long lengths to the bearing stratum and anticipated hard driving indicated the desirability of high capacity piles which could be driven very hard. The problem can be approached in the same manner, depending upon soil conditions, regardless of what type pile material is used.

The minimum tip elevation was determined to be EL 27, the highest possible elevation at which the piles should be allowed to stop, consistent with bypassing compressible layers, transferring loads to the intended bearing level and giving recognition to the variability of the bearing stratum and the uncertainties associated with soil mechanics calculations in very hard soils.

The above calculations have been presented in simplified form for the purpose of this article. Many projects will justify considerable refinement in procedures.

After a series of driving tests, a load test was performed indicating that the maximum design load of 75 tons per steel H pile could be developed at a driving resistance of 4 blows per inch using a Vulcan 140C hammer. After analysis of the series of combined soil-driving test plots (considering the contractor's driving equipment) and load test data, a driving resistance of 3 blows per inch was specified for pile loads of less than 65 tons and a resistance of 4 blows per inch was called for where design loads were 65 to 75 tons. Structure piles drove only slightly longer than the minimum tip elevation indicating a conservative analysis.

In the bearing pile example, conventional methods could have produced shorter and unsafe piles rather than extra-long, uneconomical piles as in the friction pile example. The problem at this site, or at any site where high loads are to be developed in bearing, is usually to insure that piles are driven to full capacity. ■