CHAPTER 5
ALLOWABLE LOADS ON A SINGLE PILE

Section I. BASICS

5-1. Considerations.

For safe, economical pile foundations in military construction, it is necessary to determine the allowable load capacity of a single pile under various load conditions.


A structure is designed on pile supports if the soil is inadequate for other types of foundations. The basic principles for pile foundations are that they must be safe against breaking (bearing capacity and shear failure) and buckling and that they must not settle excessively or exceed the soil's bearing capacity. There can be other factors, such as the need to protect a bridge pile from scour.

5-3. Requirements.

The requirements for the preliminary design of a pile foundation follow.

a. Studying soil. Obtain a soil profile resulting from subsurface explorations. This analysis will determine whether the piles will be friction (sand or clay), end bearing (stratum of firm earth), or a combination of both. Local experience can be a useful guide, and sufficient laboratory test data to estimate strength and compressibility of major strata are required.

b. Determining pile length. The most accurate method for determining the length of friction piles is to drive and load test piles. Since the time factor in a theater of operations rarely permits driving and load testing of friction piles, lengths may be calculated from analysis of the soil profile. Uniformity of soil conditions will determine the number of test piles driven at selected locations to verify the computed lengths. On small projects and for hasty construction, dynamic formulas may be used to assess the allowable pile load. If soil conditions are nonuniform and estimating pile lengths accurately is difficult, a pile with an easily adjustable length (timber or steel) should be used. The driving resistance in blows per inch should be used to establish allowable loads by comparing results of nearby piles in similar soil conditions. For deliberate construction, where little experience is available, load tests on selected piles should be performed and interpreted. A minimum of three driving tests (and more if subsurface conditions are erratic) should be
performed. Record driving resistance of test piles and all piles installed. Compare the resistances of the test piles to insure against localized weak subsurface conditions.

Section II. STRUCTURAL DESIGNS

5-4. Structural capacity.

a. Allowable pile stresses. Overstress in timber piles under design loads should not exceed the values given in table 2-2. The allowable stress in steel piles should not exceed 12,000 psi. Estimate possible reductions in steel cross section for corrosive location or provide protection from corrosion. The allowable stress in precast or cast-in-place piles should not exceed 33 percent of the concrete cylinder strength at 28 days.

b. Driving stresses. Do not damage the piles by overdriving. Final driving resistances for various pile types should be limited to the values indicated in [chapter 4].

c. Buckling failures. There is no danger of buckling a fully-embedded, axially-loaded, point-bearing pile of conventional dimensions because of inadequate lateral support, provided it is surrounded by even the softest soils. The ultimate load for buckling of slender steel piles in soft clay is discussed later in this chapter. Buckling may be a problem when piles project appreciably above ground surfaces. In such cases, the unsupported lengths of the pile should be used in column-stress formulas to determine the safe load capacity. The unsupported length, \( l_u \), is computed assuming the pile is laterally supported at 10 feet below ground surface in soft soils and 5 feet in sands and firm soils. This laterally supported point is commonly referred to as a fixed point (see figure 5-1).

d. Lateral loads. Lateral forces on embedded piles may produce high bending stresses and deflections. The behavior of short, rigid piles under lateral loads is discussed later in this chapter. The behavior of relatively flexible piles extending appreciably above ground surfaces and subjected to lateral loads is beyond the scope of this manual.

5-5. Column-stress formulas.

a. Slenderness ratio.

(1) Timber piles. The slenderness ratio \( (l_u/d) \) is the ratio of the effective unsupported length \( l_u \) to the average pile diameter \( d \). The average pile diameter is measured at a point one-third the distance from the butt of the pile. For the effective unsupported length of a single row of piles unbraced in the longitudinal direction, \( l_u \) is 0.7 of the distance from the fixed point to the top of the piles, as shown in figure 5-1. For a single row of piles adequately braced in the longitudinal direction, \( l_u \) is one-half the distance from the fixed point to the lowest bracing. For piles arranged in two or more rows and adequately braced between rows, the unsupported length is one-half the fixed point to the lowest bracing as shown in figure 5-1. If the ratio \( (l_u/d) \) is less than 11, then a buckling capacity need not be determined. If the ratio exceeds a value of 11, the buckling capacity must be determined. To avoid use of extremely slender piles, the value of \( l_u/d \) should not exceed 40. When the slenderness ratio is less than 11, the allowable load is based on table 2-2. When the slenderness ratio exceeds a value of 11, the allowable concentric axial load is computed as the lesser of the following.

\[
Q_{al} = A \frac{0.3E}{(l_u/d)^2} \quad \text{for } \Box \text{ column}
\]

\[
Q_{al} = A \frac{3.619E}{(l_u/r)^2} \quad \text{for } \phi \text{ column}
\]

\[
Q_{al} = AF_c
\]
Steel piles. The slenderness ratio of steel piles is the ratio of the unsupported length ($l_u$) as described to the least radius of gyration ($r$). Tables and formulas for the radius of gyration are given in TM 5-312. The buckling capacity of steel piles must always be determined regardless of the numerical value of $l_u/r$. For the most economical design, the value of $l_u/r$ should not exceed 120. For steel piles the allowable buckling load is calculated as follows.

where:

- $Q_{all} =$ allowable load on pile in pounds
- $A =$ cross-sectional area of the pile in square inches
- $E =$ modulus of elasticity of wood species in psi (table 2-2)
- $l_u =$ unsupported length in inches
- $d =$ average diameter in inches (measured at one-third of the pile length from the butt)
- $r =$ least radius of gyration in inches
- $F_e =$ allowable compression stress parallel to grain (table 2-2)
Section III. DYNAMIC FORMULAS

5-6. Concept.

Dynamic pile formulas are based on the theory that the allowable load on a pile is closely related to the resistance encountered during driving. The concept assumes that the soil resistance remains constant during and after driving operations. This may be true for coarse-grained soils, but may be in error for fine-grained soils because of the reduction in strength due to remolding caused by pile driving. The formula of principal use to the military engineer is the Engineering News formula.

\[ Q_{all} = A[23,000 - 0.7 (I/r)^2] \]

where:

\[ r = \sqrt{I/A} \]

\[ A = \text{area of steel pile in square inches} \]

\[ I = \text{least moment of inertia in inches to the fourth power} \]

5-7. Engineering News formula

The allowable load on a pile may be estimated by one of the following versions of the Engineering News formula.

- Piles driven with a double-acting air or steam hammer or open-ended diesel hammer.

\[ Q_{all} = \frac{2WH}{s + 1} \]

- Piles driven with a single-acting air or steam hammer or open-ended diesel hammer.

\[ Q_{all} = \frac{2WH}{s + 0.1} \]

where:

\[ Q_{all} = \text{safe load in pounds} \]

\[ W = \text{weight of striking parts in pounds} \]

\[ H = \text{effective height of fall in feet} \]

\[ s = \text{average net penetration or pile set, in inches, per blow for the last 6 inches of driving} \]

(A procedure for measuring the set follows.)

\[ E = \text{driving energy in foot pounds} \]

(This quantity may be obtained from \text{tables 3-1} and \text{3-2}.)


To determine the pile set, attach a piece of heavy paper to the pile at a convenient height (figure 5-2). Place a straightedge close to the paper supported by stakes spaced two feet on each side of the pile. Draw a pencil steadily...
across the straightedge while striking the pile with a series of blows. This trace will show the set of net penetration of the pile for a given blow of the hammer. For example, assume that a timber pile is driven by an 1,800-pound drop hammer with a height of fall equal to 6 feet. During the last 6 inches of driving, the average pile set is measured and found to be 0.25 inch. Using the Engineering News formula applicable to drop hammers, the allowable load is computed as follows.

\[
Q_{all} = \frac{2 \times 1,800 \times 6}{0.25 + 1} = 17,280 \text{ pounds or 8.6 tons}
\]


The Engineering News formula provides conservative values in some cases and unsafe values in other cases. Reasonably reliable results are obtained for piles in coarse-grained soils. Generally, when time is available and the cost is justified, pile load tests should be used in conjunction with the dynamic formulas for estimating allowable pile loads. Using only the dynamic formula should be restricted to hasty construction and to projects where the cost of load testing would be too high in relation to the total cost of piles.
Dynamic formulas are useful in correlating penetration resistance obtained from local experience and in relating the results of load tests to the behavior of piles actually driven.

a. Saturated fine sands. In saturated fine sands, the formula usually indicates the allowable load as being less than that which may develop after driving. If time is available, a friction pile that has not developed its required load should be rested for at least 24 hours. The capacity may then be checked with at least 10 blows from a drop hammer or 30 blows with a steam, pneumatic, or diesel hammer. If the average penetration is less than that required by the formula to give the needed bearing capacity, piles do not require splicing or deeper driving. If the required capacity is not developed after the rest period, the piles must be spliced or additional piles driven, if the design of the foundation permits.

b. Jetting. The formulas do not apply to piles driven by the aid of jetting unless the pile is permitted to rest after jetting and then driven to final position without jetting. Data from the final driving may be used in the dynamic formula after resting the pile. The formulas do not apply to end-bearing piles driven to rock or other firm strata.

Section IV. STATIC FORMULAS

5-10. Driven piles.

Static pile formulas are based on the shear strength of the foundation soils. These formulas compute the ultimate bearing capacity and allowable load. Static pile formulas apply to piles in clay (figure 5-3) and to piles completely or partially embedded in cohesionless soil (figure 5-4). The shear strength must be determined from laboratory tests on undisturbed samples or estimated from correlations with the standard penetration test. The latter method is generally more reliable for cohesionless soils. Typical values of the undrained shear strength of cohesive soils are shown in table 5-1. The ultimate capacity of piles in cohesionless soils is influenced by the position of the groundwater table. Depending on the certainty with which subsoil conditions are known, the ultimate bearing capacity should be divided by a factor of safety from 1.5 to 2.0 to obtain the allowable load. For a given allowable load, the static formulas (figures 5-3, 5-4) also determine the required length of piles, the pullout capacities of piles, and the ultimate load buckle of slender steel piles in soft clay.

5-11. Drilled piles.

The allowable load on drilled piles is based on soils shear strength data and from formulas similar to those for driven piles. In clays, the average undisturbed shear strength over the depth of the pile should be multiplied by an empirical earth pressure coefficient, $K_c$, varying from 0.35 to 0.75 to account for softening. If the hole is allowed to remain open for more than a day or two or if a slurry is used during construction, the lower values should be used. In sands, the coefficient of earth pressure, $K_c$, should be taken as 1.0. The allowable end-bearing capacity, $Q_{ub}$, can also be computed using the standard penetration test results in terms of N blows per foot.

$$Q_{ub} = 1.25 (N - 3) \frac{b + 1}{2b}$$

where:

$N = \text{number of blows per foot}$

$b = \text{diameter of pier in feet}$
\( Q_u = \text{Ultimate Bearing Capacity} \)

\[
Q_u = Q_p + \sum Q_s = qA_p + \sum c_i d_i p
\]

- \( Q_p \): Point Resistance
- \( Q_s \): Shaft Resistance
- \( q \): Unit Bearing Capacity = 9 \( C_s \) Tons/Foot
- \( A_p \): Area of Point = \( \pi R^2 \) for Round Piles (Foot)
- \( = 4B \) for Square Piles
- \( C_i \), \( C_{i2} \), \( C_{i3} \): Undrained Shear Strengths for Various Strata (Tons/Foot)
- \( a_i \): Correction Factor (See Graph Above)
- \( P \): Perimeter = \( \pi R \) for Round Piles (Foot)
- \( = 4B \) for Square Piles

Notes:
- Position of Groundwater Table Has No Effect on Ultimate Bearing Capacity, Unless Cohesion is Changed. Point Resistance Should Be Ignored Except in Stiff or Very Stiff Clays.
- Pullout Capacity = \( T_u = (C_i a_i d_i + C_{i2} a_i d_{i2} + C_{i3} a_i d_{i3})P \) (Tons)
- Ultimate Load for Buckling of Slender Steel Piles in Soft Clay

\[
Q_b = \lambda(C E I)^{1/2} \text{(Pounds)}
\]

- \( \lambda \): 0.8 for Very Soft Clay, 1.0 for Soft Clay (Dimensionless)
- \( C \): Average Undrained Shear Strength of Soil Layer (PSI)
- \( I \): Least Moment of Inertia of Cross Section (Inches²)
- \( E \): Modulus of Elasticity of Steel (29,000,000 PSI)

Note: Heavy Steel Piles, Timber Piles, or Concrete Piles Are Generally Not Subject To Buckling II Embedded in Soil for Their Entire Length.

Figure 5-3  Static analysis of piles in cohesive soils
Effective Overburden Pressure

\[ \gamma = 125 \text{ PCF} \]

\[ \gamma = 62.5 \text{ PCF} \]

- **Q_s** = Ultimate Bearing Capacity
- **Q_v** = **Q_o** = \( qA_p + IA_a \)
- **q** = Unit Bearing Capacity = \( P_eN_a \)
- **A_p** = Area of Point
- \( f \) = Unit Frictional Resistance = \( 0.5K_p\tan\delta \)
- \( \delta \) = Angle of Shaft Resistance
- **N_a** = Bearing Capacity Factor
- **A_s** = Shaft Area = \( 2\pi R D \) for Round Pile
  = \( 4 B D \) for Square Pile
- **\( P_e \)** = Effective Overburden Pressure at Tip of Pile
  = \( \gamma D \) for Groundwater Table (GWT) Below Pile
  = \( \gamma D \) for GWT at Ground Surface
- **K_p** = Earth Pressure Coefficient, Compression Pile
- **K_T** = Earth Pressure Coefficient, Tension Pile

\[ K_p = \frac{1}{N_a} \]

**Note:** \( A_p \) and \( A_s \) based on Minimum Periphery for H-Pile.

\[ \gamma = \text{Unit WGT of Soil (PCF)} \]

\[ \gamma' = \text{Submerged Unit WGT of Soil} = \gamma - 62.5 \text{ (PCF)} \]

<table>
<thead>
<tr>
<th>Description</th>
<th>SPT Number N</th>
<th>Angle of Internal Friction, ( \phi^o )</th>
<th><strong>N_a</strong></th>
<th><strong>( \theta^o )</strong></th>
<th><strong>Steel</strong></th>
<th><strong>Concrete</strong></th>
<th><strong>Timber</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Loose</td>
<td>4</td>
<td>20</td>
<td>22</td>
<td>20</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loose</td>
<td>10</td>
<td>30</td>
<td>30</td>
<td>21</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>30</td>
<td>36</td>
<td>50</td>
<td>25</td>
<td>29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pullout Capacity = \( T_e = A_s f = A_s K_T \frac{P_e}{2} \tan\delta \)

1. Complete Embedment of Piles in Cohesionless Soils

Definitions and Analysis Same as Above except That Effective Overburden Pressure is Computed Midpoint of Embedment Depth in Cohesionless Stratum in Computing \( f \). Also:

\[ f = K_p\gamma \]

\[ f = K_T\gamma \]

\[ P_e = (D-h)\gamma + \left( \frac{h}{2} \right) \gamma' \]

\[ A_s = \text{Shaft Area} = 2R h \text{ for Round Pile} \]

\[ = 4 B h \text{ for Square Pile} \]

Pullout Capacity = \( T_e = A_s K_T P_e \tan\delta \)

2. Partial Embedment of Piles in Cohesionless Soils

Note: Shaft resistance in soft soils may be partly effective for transient loads.

Figure 5-4 Static analysis of piles in cohesionless soils
Section V. PILE LOAD TESTS

5-12. Equipment.

Load tests determine the allowable load, the settlement under working load, or the soundness of a pile. Load tests may be conducted in compression or tension. Lateral load tests are seldom justified. The following considerations must be made.

- The test piles should be of the same type and driven by the same equipment as for construction.

- Test loading should not be initiated less than 24 hours after driving piles in cohesionless soils and not less than 7 days in cohesive soils.

- The load is usually applied by a hydraulic jack reacting against dead weights or against a yoke fastened to a pair of anchor piles (figure 5-5). Anchor piles should be at least 5 test pile diameters from the test pile.

- The test load should be twice the proposed design load as estimated from the dynamic formula, static formula, or other means.
Readings of settlement and rebounds should be referred to a deep benchmark and recorded to 0.001 feet.


The loading procedure may be carried out either by the continuous load method or the constant rate of penetration (CRP) method.

a. Continuous load. The load is applied in seven increments, equal to \( \frac{1}{2}, \frac{3}{4}, 1, 1\frac{1}{4}, 1\frac{1}{2}, 1\frac{3}{4}, \) and 2 times the allowable load assumed for design. The load is maintained constant at each increment until there is no settlement in a 2 hour period. The total test load should remain in place until settlement does not exceed 0.002 feet in 48 hours. The total load should be removed in decrements not exceeding one fourth of the total test load with intervals of not less than one hour. The rebound should be recorded after each decrement is removed. A curve may then be prepared showing the relationship between the load and deflection (figure 5-6). This procedure is most reliable where it is necessary to estimate the settlement of piles under the design load. The allowable load is taken as one half that which caused a net settlement of not more than \( \frac{1}{2} \) inch or gross
settlement of 1 inch, whichever is less. The continuous load method is rarely justified in military construction because of the excessive time requirements.

b. Constant rate of penetration. The pile is jacked into the ground at a constant rate, and a continuous record of the load and deformation is taken. The test proceeds rapidly and requires the services of several observers. Results of the test are not too sensitive to the rate of penetration. The load is increased until the pile fails by plunging or the capacity of the equipment is reached. Results of the test are plotted (figure 5-7). The allowable load is considered to be 50 percent of the ultimate bearing capacity defined by the intersection of lines drawn tangent to the two basic portions of the load settlement curve. The constant penetration rate method, a very rapid test, is particularly suited for military construction.

6-14. Bearing stratum resistance.

Where piles are driven through compressible soil strata into a bearing stratum of sand or other firm material, the allowable pile load is based on the carrying capacity of the bearing stratum without depending on the short-term frictional resistance of the compressible soils (figure 5-4). With pile load tests, it is generally not possible to distinguish between the short-term carrying capacity of the compressible soil and the long-term carrying capacity of the bearing stratum. The capacity of the bearing stratum can be obtained by testing the pile inside the hollow casing or by making a load test on two piles driven about 5 feet apart. One pile is driven to refusal in the bearing stratum while the other is driven to within 3 feet of the bearing stratum. The difference in the ultimate loads for the two piles is equal to the carrying capacity of the bearing stratum.
5-15. Limitations of pile load tests.

Pile load tests do not take into account the effects of group action on bearing capacity unless a group of piles is loaded. The settlement of a pile group is not generally related to the settlement recorded during a load test on a single pile. Settlement must be estimated as discussed in chapter 6 from consideration of soil compressibility within the zone of the influence (figure 5-6).

5-16. Lateral loads resistance.

a. Lateral loads. Vertical piles supporting structures are subjected to lateral forces. For example, a pile bent supporting a highway bridge may be subjected to the forces of wind, current, ice, and the impact of floating objects. Similar forces may act on waterfront structures, such as wharves and piers. Properly designed bracing, supplemented by batter piles and fenders, will usually provide the structure with sufficient stability to resist lateral loads. The piles must be driven deep enough to prevent the structure from overturning. Normally, vertical piles driven deep enough to sustain vertical loads will develop enough lateral resistance to prevent the structure founded on a number of piles from overturning. An exception to this could be a bridge foundation in an area subject to scour during periods of high water. When piles are subjected to lateral loads in excess of 1,000 pounds per pile, it is usually more economical and desirable to provide batter piles. Lateral loads apply to both rigid and flexible piles (figure 5-9).

b. Flexible and rigid piles. It is difficult to estimate the resistance provided by a single vertical pile (or group of piles) to lateral forces. The best method is to conduct field loading tests. If time and facilities for this are lacking, the embedment or lateral capacity may be estimated by the use of charts (figures 5-10, 5-11) that apply to fixed-end and free-head short, rigid piles. The effect of group action is ignored in these charts. For the fixed-head pile, failure occurs when the pile moves as a unit through the soil. For the free-head pile, failure occurs when the pile rotates as a unit through the soil around a point located below the ground surface. Theoretical
analysis has been developed and is available for laterally loaded piles in which the flexibility of the pile is considered.

(1) Rigid piles in clay. Figure 5-10 shows the relationship between the ultimate lateral resistance and length of embedment for fixed-end and free-head piles in clay soils in terms of the undrained shear strength (table 5-1). As the shear strength of the soil near ground surface depends on seasonal variations in water content, it is good practice to reduce laboratory values by one-third to one-fourth. A safety factor from 1.5 to 2.0 should be applied to the design lateral load to compute the ultimate lateral resistance. Continuous lateral loads should be resisted by batter piles.

(2) Rigid piles in sand. Figure 5-11 shows the relationship between the ultimate lateral resistance and length of embedment for fixed-end and free-head piles in sands in terms of coefficient of passive earth pressure, $K_p$, assumed equal to 3.0 regardless of the density of the sand. Safety factors from 1.5 to 2.0 should be applied to the design lateral load to compute the ultimate lateral resistance.
Figure 5-10 Ultimate lateral resistance of rigid piles in clay

\[ P_{um} = \text{Ultimate Lateral Resistance, Pounds} \]
\[ C_u = \text{Undrained Shear Strength, Pounds per Square Foot} \]
\[ D = \text{Diameter or Width of Pile, Feet} \]
\[ e = \text{Eccentricity of Applied Load, Feet} \]
\[ L = \text{Length of Embedment, Feet} \]
**Figure 5-11** Ultimate lateral resistance of rigid piles in sand
<table>
<thead>
<tr>
<th>Descriptive Term</th>
<th>Field Test</th>
<th>SPT* Blows per Foot</th>
<th>Undrained Shear Strength Pounds/Square Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Soft</td>
<td>Squeezes between fingers when fist is closed</td>
<td>0 - 1</td>
<td>0 - 250</td>
</tr>
<tr>
<td>Soft</td>
<td>Easily molded by fingers</td>
<td>2 - 4</td>
<td>250 - 500</td>
</tr>
<tr>
<td>Medium</td>
<td>Molded by strong pressure of fingers</td>
<td>5 - 8</td>
<td>500 - 1000</td>
</tr>
<tr>
<td>Stiff</td>
<td>Dented by strong pressure of fingers</td>
<td>9 - 15</td>
<td>1000 - 2000</td>
</tr>
<tr>
<td>Very stiff</td>
<td>Dented only slightly by finger pressure</td>
<td>16 - 30</td>
<td>2000 - 4000</td>
</tr>
<tr>
<td>Hard</td>
<td>Dented only slightly by pencil point</td>
<td>Over 30</td>
<td>4000</td>
</tr>
</tbody>
</table>

*Standard Penetration Test
(Measured with 1½ inch ID sampler driven 1 foot by 140-pound hammer falling 30 inches)