Capacity of Hydraulically Jacked Piles

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Dr. Perko currently serves on the Board of Directors for Magnum Piering, Inc. In his present role, he directs new product research, design and development, oversees technical support activities, and advises management in technical matters. Dr. Perko has B.S., M.S., and Ph.D. degrees in Civil Engineering and 24 years of professional engineering experience specializing in the design of shallow and deep foundations, excavation shoring, and underpinning.

Magnum Piering, Inc. is a manufacturer of specialty foundation and anchoring devices including jacked piles, helical piles, plate anchors, wall braces and moment frames. Magnum serves customers throughout North America and is celebrating 35 years in business.

Capacity of Hydraulically Jacked Piles

Hydraulically jacked piles are commonly used for underpinning existing structures to arrest settlement or augment the foundation for higher loads. They consist of steel pipe segments coupled together and jacked into the ground using a hydraulic ram. Pipe sections can vary in size from 3" diameter to 18" diameter or larger. Jacking resistance is typically provided by dead loads of existing structures. This type of piling system has been utilized for foundation underpinning, repair, and augmentation for more than 120 years, yet little has been published on the capacity and reliability of these systems. A history of jacked pile technology is presented. Pile load tests from a number of projects are used to derive an empirical formula for capacity and depth prediction. Standards for design of jacked pile systems, reliability, performance, and factors of safety are discussed.

Keywords: pile, foundation, capacity, underpinning, load tests

Introduction

Push pier, resistance pile, steel pier, and jacked pile are some of the tradenames often applied to hydraulically jacked piles used for underpinning. The term ‘jacked pile’ is more common in engineering codes and will be used herein. There are several different manufacturers of jacked piles including Magnum Piering, RamJack, and Atlas Systems. Although jacked piles can be installed using heavy machinery for new construction, this paper is focused on piles used for support of existing structures.

Jacked piles consist of short segments of pipe or structural steel tube that are coupled together and forced into the ground using a hydraulic ram fastened to or beneath a footing, stem wall, or grade beam of an existing structure. In this way, the weight of the structure provides the resistance necessary to force the pile into the ground. A factor of safety is obtained by redundancy, which is consecutively installing more than one pile to carry the dead load. An engineering schematic of an example jacked pile connected to a footing foundation is shown in Figure 1.

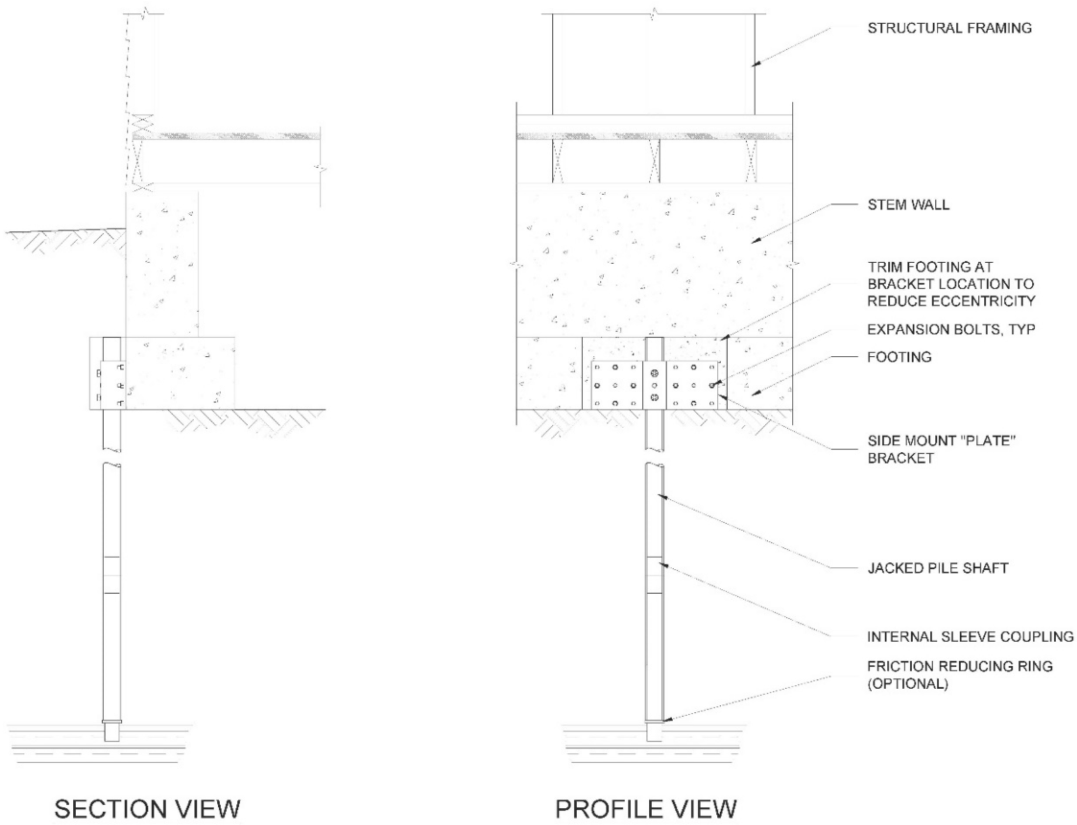


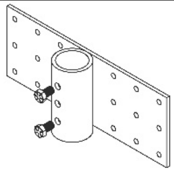
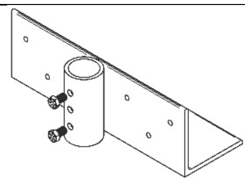
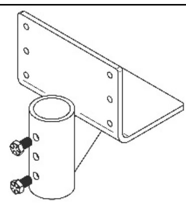
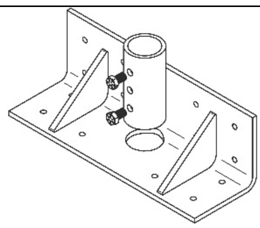
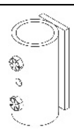
Figure 1. Modern Jacked Pile Engineering Schematic (Courtesy of Magnum Geo-Solutions, LLC)

Figure 2. Examples of Modern Jacked Pile Installation (Courtesy of The Dwyer Company, Inc)

Modern jacked piles typically incorporate a steel bracket. There are many sizes and styles of brackets available. Some categories include plate brackets that bolt to the outside of an existing foundation wall, wide and narrow angle brackets that extend under existing footings, pin brackets for attachment to structural steel, and reverse angle brackets for attachment to footing and wall. Table 1 lists example brackets and their benefits. Jacked piles are driven using a hydraulic ram that temporarily mounts to the bracket. Sections are driven one after another. As the pressure builds, pile advancement slows. Eventually, the pile will achieve the desired negligible rate of advancement at the test capacity. After jacked piles are driven individually and proof load tested, the rams often can be connected hydraulically and used to simultaneously lift and re-level structures, as shown in Figure 2. The fact that each jacked pile is proof load tested during installation provides good quality assurance and reduces pile head deflections upon reloading.

As will be discussed in the next section, jacked pile technology has been used for at least 120 years. Yet, jacked piles remain absent from mainstream foundation engineering texts, academic papers, and most building codes. The goal of this paper is to present a logical design methodology, an empirical method for predicting depth and capacity of these systems, and to discuss the reliability afforded by individual load testing during installation. As a secondary goal, this paper contains standard procedures for installation and testing developed through years of practical experience.

Table 1. Example Jacked Pile Brackets

Image	Type	Benefit	Common Use
	Plate	Low cost, avoid bottom of footing which is rough and pitted, no footing prep or seating grout required	Formed Concrete
	Wide Angle	Distribute load over wider area, helps bridge cracks and reinforce existing foundation	Old Stone and Brick Foundations
	Narrow Gusseted Angle	Less footing prep than wide angle, preferred by contractors	Newer Reinforced Concrete
	Reverse Angle	Supports slabs and walls, less disturbance because it replaces chipping by coring thru footings	Structural Slabs, Tanks, Tilt-up Construction
	Pin	Welds directly to structural steel such as sister beams, needle beams, and embedded plates	Structural Steel

Background

According to a U.S. patent from 1896 by Jules Breuchaud of New York City, hydraulic jacks can be used to drive tubular sectional columns into the ground for the purpose of temporary or permanent support. An image from Breuchaud's original 1896 patent is shown in Figure 3, in which steel needle beams are extended through brick or masonry walls and the protruding ends are used as abutments for hydraulic jacks.

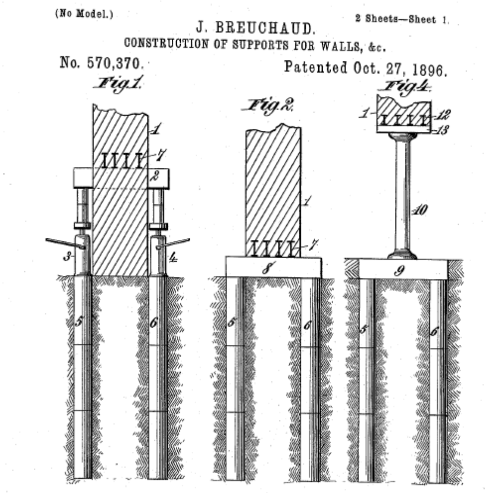


Figure 3. Use of Jacked Piles in 1896

Breuchaud's invention was improved in 1959 by Revesz and Steinsberger of Caisson Corporation and again in 1974 by Paul Cassidy and Company. Both companies worked in the Chicago, IL area. Revesz and Steinsberger's patent, shown in Fig. 4, is very similar to modern jacked piles of today. Their invention shows steel brackets affixed to the foundation, a small hydraulic pump, and shear reduction rings placed at the bottom and arranged along the pile length. Cassidy's invention showed a larger side plate bracket as well as a method to hydraulically connect jacked piles together for proper lifting.

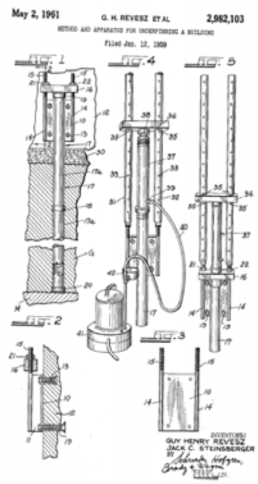


Figure 4. Jacked Piles in 1959

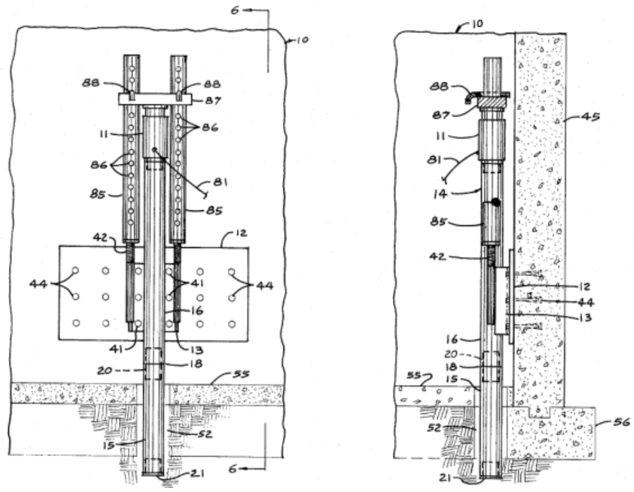


Figure 5. Jacked Piles in 1974

Although jacked piles were originally invented to underpin and stabilize heavy walls of commercial buildings in New York and Chicago, similar methods were adopted for residential underpinning by a number of companies during the 1980’s United States housing boom. Three companies filed patents at nearly the same time for variations and enhancements to jacked pile technology. In July 1987, Langenbach of Perma-Jack in Missouri filed letters of patent for a jacked pile system utilizing displacement disks and a grout column for soft soil applications. In September of the same year, Gregory of Ramjack in Oklahoma filed a patent for a novel componentized jacked pile system. Just two months later, Rippe of Magnum Piering in Colorado patented a high capacity lightweight pile jacking system.

More individuals and companies joined the intellectual property race in the 1990's and early 2000's. Two recognizable systems are the Cable Lock™ method patented March 21, 1995 and a specific angle bracket patented by Earth Contact Products in February, 2001. Most of the companies heretofore mentioned continue to market jacked pile products to installers throughout North America. Fundamental jacked pile technology is now public domain and has been universally available for at least the past 30 years.

Building Code

Although jacked pile technology has been widely used and accepted, it is not specifically addressed in most building codes. Jacked piles are considered “specialty piles” in the International Building Code. By exception, the New York City Building Code, since 1938, provides a short section on, “Piles installed by jacking or other static forces.” This section of the New York City Building code defines allowable pile capacity for permanent applications as 2/3 the installation load if the load is held for 7 hours without measurable settlement, or 1/2 the installation load if the load is held for 1 hour without measurable settlement. For temporary applications, older versions of the New York City Building Code stated that the working load need only be less than or equal to the total jacking force at final penetration. Since 2008, temporary underpinning piles are no longer addressed under this section.

Capacity Requirements

The required capacity of a jacked pile used for underpinning is computed by the same techniques as those used for other deep foundations, with a few special precautions. Jacked piles must have sufficient capacity to support both the dead and live loads of the structure. If a structure is to be lifted and re-levelled, it is essential to add the soil weight above the footing (if any) to the total dead loads computed by conventional means. The adhesion of the soil on the bottom of the footing and/or slab and the friction of the soil along the foundation wall or grade beam also should be considered.

Some contractors only install a sufficient number of jacked piles to lift a structure. While the ability to lift and re-level a structure fixes aesthetic issues, it alone is an insufficient criterion for establishing pile spacing and a jacked pile's required capacity. If foundation underpinning only accounted for loads present at the time of pile installation, most would need further adjustments as loadings change. Therefore, the piling system must be capable of supporting live loads such as snow, wind, earthquake, people, and furnishings that may be added to the structure at a later time. As live loads drive the serviceability limit states, the spacing of jacked piles must be closer than that required to simply lift the structure.

After determining the total dead and live loads, an appropriate factor of safety must then be applied to establish pile spacing and required proof test load. The engineer of record should select a factor of safety suitable for each project and site conditions. Factors of safety used in foundation engineering vary depending on the reliability of soil and subsurface information, the heritage of a particular foundation, and the sensitivity of the structure to movement. The American Society of Civil Engineers Publication 20 96, "Standard Guidelines for Design and Installation of Pile Foundations", explains that a factor of safety of 1.5 is permissible for driven pile foundations since the method of installation provides a means of capacity determination in the field. Installation of a steel jacked pile provides an even more direct means of capacity determination as compared to conventional pile driving. A factor of safety of 1.5 is commonly used in practice for steel jacked pile design. As discussed in a previous section, the current New York City Building Code requires a factor of Safety of 2.0 for jacked piles. The authors believe this requirement is excessively conservative because each pile is proof tested.

Installation

The installation of jacked piles generally involves the following procedures as outlined by Perko (2002):

(1) *An engineer or contractor's technical representative observes the condition of the structure, computes building loads including available dead loads for jacking, and plans jacked pile locations*

(2) *All underground structures and utilities in the vicinity of the piles are located and moved or avoided*

(3) *Foundation access holes are excavated at each pile location*

(4) *Existing foundation is modified to allow connection of brackets as close to the foundation wall neutral axis as possible*

(5) *Piling brackets are mounted to the existing foundation*

(6) *Elevation of the structure at each pile location is measured and a building monitoring program is established*

(7) *Hydraulic rams are temporarily attached to the brackets on the existing structure*

(8) *Piles are jacked into the ground individually until the load used for driving the pile equals or exceeds the required proof test capacity*

(9) *Ram pressure is measured and recorded at 3 foot intervals of jacked pile depth*

(10) *Local building official or special inspector observes pile proof testing for quality assurance*

(11) *After all piles are installed and inspected, the building often can be lifted (if necessary) and re-levelled to the extent practicable*

(12) *The jacked piles are secured to the brackets and the hydraulic rams are removed (*Figure 7*)*

(13) Final building elevations are recorded

(14) Access holes are backfilled and landscaping materials are restored

Figure 6. Typical Jacked Pile Installation Procedure (Courtesy of The Dwyer Company, Inc)

Figure 7. Jacked piles secured to lifting brackets prior to pile cut-off (Courtesy of Hayward Baker)

Proof Testing

To date, no standard method has been developed for completion of installation step 8, which involves field verification of jacked pile capacity. The American Society for Testing and Materials specification D1143 - 81, “Standard Test Method for Piles Under Static Axial Compressive Load” explains routine methods for field performance testing. It is appropriate and sometimes required by local building codes to perform field performance testing on a select number of representative piles to establish the full spectrum of the load deflection characteristic. However, these procedures are time consuming and impractical for proof testing of every production pile. Based in part on this ASTM standard and the standard of care practiced by most engineers and contractors at the present time, the following procedure for proof testing jacked piles is suggested as modified from Perko (2002).

(1) The hydraulic ram used to load the pile shall be fitted with a pressure gauge, shall be capable of delivering the prescribed loads with a sensitivity of at least 5% of the required ultimate capacity of the pile, and shall be calibrated at least annually

(2) Continue pile installation until proof test pressure is achieved, the proof test load shall be at least 150% of the design allowable capacity.

(3) Jacked pile movement relative to a fixed frame of reference shall be measured optically or through the use of a dial gauge

(4) The proof test load shall be maintained until the rate of settlement is less than 1/16 in/hr, not less than 1/2 hr

(5) A field report shall be prepared that at a minimum shall contain pile location, applied proof test load, load duration, and final pile depth

Design Considerations

The following design considerations should be taken into account:

(1) *Proof test load shall not exceed available dead load at jacked pile location. Dead load shall be calculated over maximum unsupported spans on both sides of the planned pile locations using LRFD/ASD factors for temporary construction loads*

(2) *The bracket and ram assembly shall be such that loads are applied vertically and directly to the central longitudinal axis of the jacked pile with eccentricity minimized to the extent practicable*

(3) *The structure to which the bracket and ram assembly is attached shall have sufficient integrity and weight to allow for application of loads to the jacked pile without excessive lifting and without causing damage to the structure*

(4) *If the structure is of insufficient weight to permit the required jacked pile loading, then an earth anchor, ballast weight, or battered pile must be used to provide the necessary reaction or the test load should be downgraded and additional piles added*

(5) *Jacked piles with a minimum spacing less than 2 feet or less than 10% of their average depth should be evaluated for group efficiency*

Theoretical Capacity

In practice, it is seldom necessary to compute the theoretical capacity of a jacked pile, since each pile is proof tested and verified in the field. However, on certain occasions it may be desirable to determine theoretical capacity in order to evaluate the suitability of a particular bearing stratum or to approximate jacked pile depth. In most cases, underpinning the entire structure with steel jacked piles is the recommended course of action.

A steel jacked pile should be treated as a partly friction and partly end bearing pile. According to Meyerhof (1956, 1976), ultimate static pile point capacity can be related directly to Standard Penetration Resistance test blow count by

$$P_{ptu} = 840\, A\, N\, \frac{L}{D} \tag{1}$$

where A = pile tip area (ft^2);

N = SPT blow count (blows/ft);

L = penetration length (ft); and

D = pile diameter (ft)

Meyerhof also specified the criterion that

$$\frac{L}{D} \leq 10 \tag{2}$$

As presented by Perko (2002) the pile tip area should be taken as that of a closed ended pile with the additional diameter provided by the friction reducing ring (if used). Perko (2002) also recommends the standard penetration resistance blow count used in the above equation should be taken as the average value from 3 D below the pile tip to about 8 D above the pile tip. Since Meyerhof's equation is for tip capacity, the penetration length, L, is an indication of the effective vertical pressures that govern the N_q term in the traditional bearing capacity equation. Therefore, it is reasonable to use a fraction of the jacked pile depth.

Perko (2002) assumed that the penetration length, L, is equal to 25% of the depth of the pile minus 1.5 ft to account for the disturbed soil at the ground surface. In terms of mathematical symbols, L is given by

$$L = 25\% \times (L_T - 1.5) \quad (2)$$

where L_T = Total depth of the pile (ft)

It was determined that Meyerhof's equation and the definition of penetration length given above matched field measurements very well.

Since 2002, the authors have gathered and analyzed over 1,500 hydraulically jacked steel pipe pile installation field proof tests. A comparison of the ultimate test load and the bearing stratum SPT N-Value as well as the proof test load and the penetration depth are shown in Figure 8 and Figure 9. The linearity of data indicates that there is a correlation between the three variables.

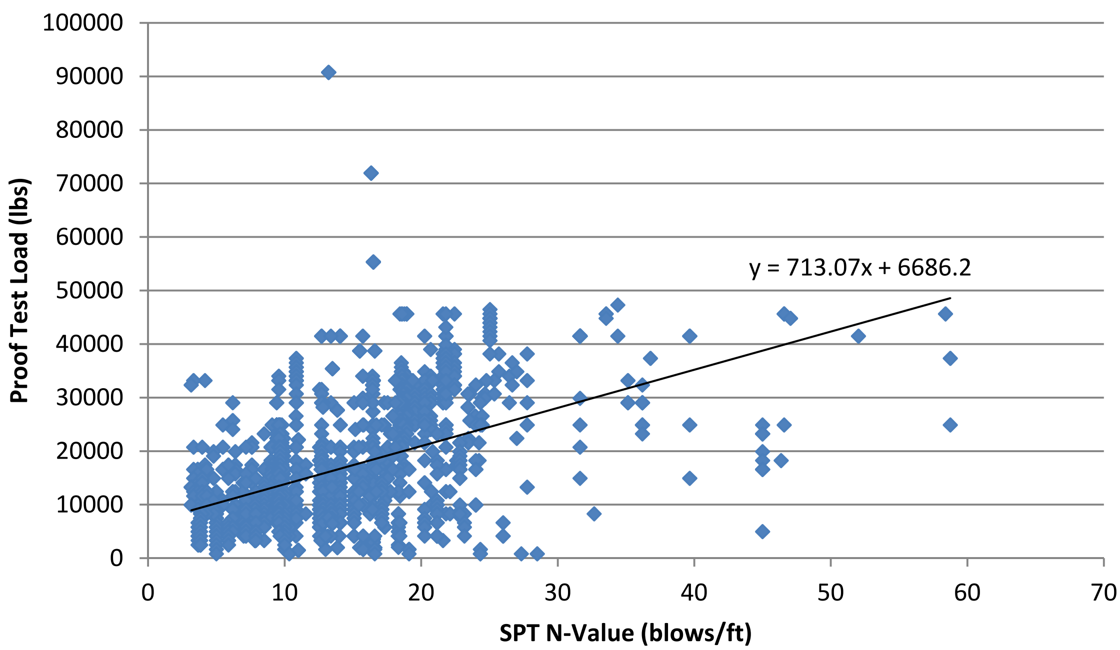


Figure 8. Effect of SPT N-Value on Proof Test Load

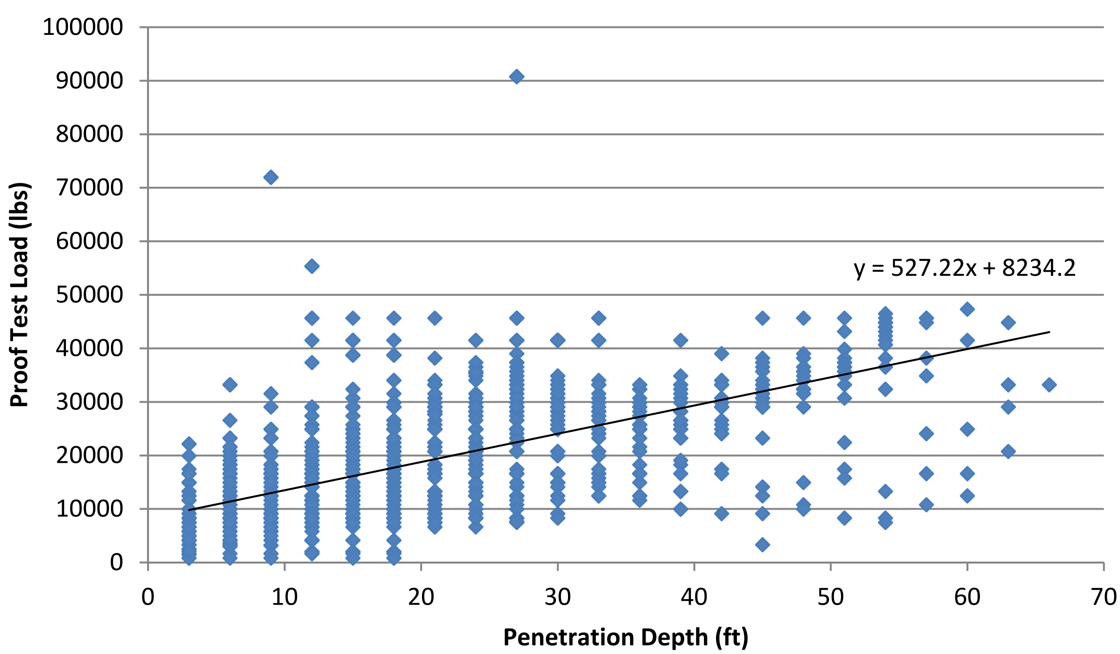


Figure 9. Effect of Penetration Depth on Proof Test Load

The modified Meyerhof equation from Perko (2002) was a good place to start. However, fitting the modified Meyerhof based equation to these data shows poor correlation. These new data from Figure 8 and Figure 9 suggest refinement to capacity and depth predictions is appropriate. Taking the pile tip area as that of a closed ended pile, Equation 1 can be rewritten as

$$P = 840 \left(\frac{\pi D^2}{4} \right) N \frac{L}{D} \tag{3}$$

or

$$P = 210 \, \pi \, D \, N \, L \tag{4}$$

where P = Proof test load (ultimate capacity at depth L)

To solve for a new, more accurate constant, the value 210 in Equation 4 can be substituted for a variable, B_1, and the relationship re-written as

$$P = B_1 \pi D N L \quad (5)$$

This relationship can be further rearranged as

$$\frac{P}{\pi D N} = B_1 L \quad (6)$$

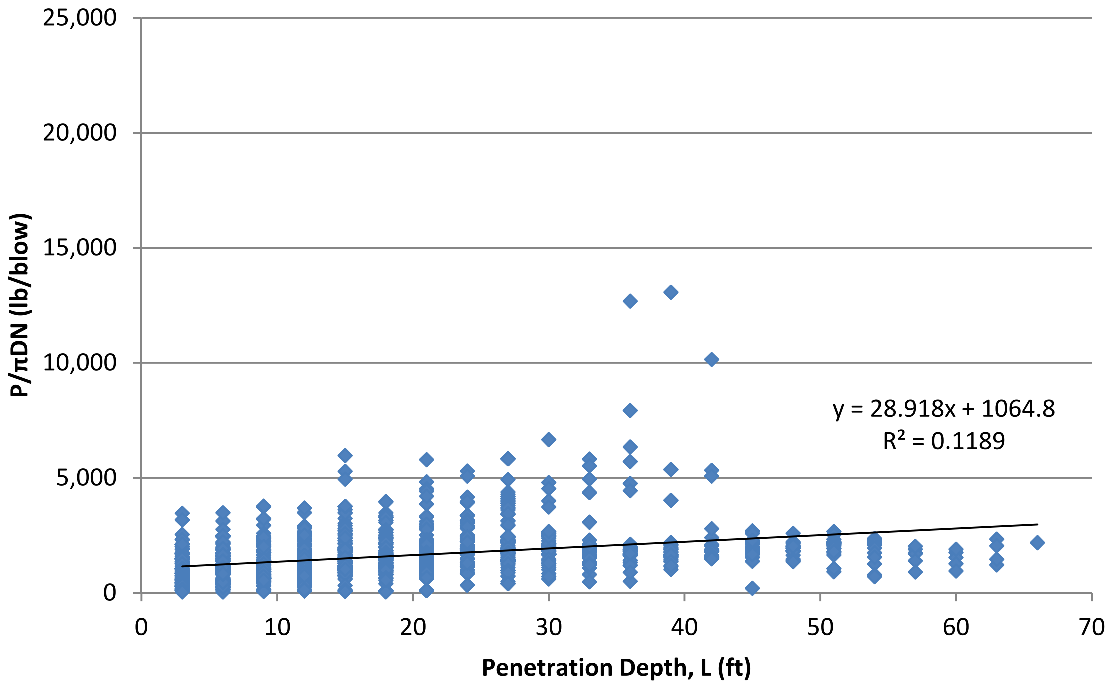


Figure 10. Empirical Fitting Function to Determine B_1 & B_2 Constants

The expression in Equation 6 is plotted versus penetration depth in Figure 10. The fitting parameter, B_1, can be obtained by linear regression analysis. This figure is a plot of all 1,500 proof test data, which includes several soil types. The linear best fit line for the data suggests that an additional y-intercept term needs to be included in the penetration depth term, thus

$$\mathbf{P = \pi D N (B_1 L + B_2)} \quad (7)$$

The B_1 and B_2 terms can be taken directly from the linear best fit line. The R^2 regression is an indication of quality of fit. The low value of 0.1189 is a reflection of the high degree of scatter in the real data. Some of this scatter may be from different installation crews, different soil types, and different test methods.

Predicted proof test load versus the field proof test load is shown in Figure 11. A linear best-fit line shows that there is a better one-to-one correlation between the real and predicted values than would be guessed by the R^2 value of Figure 10. The expression in Equation 7 has an R^2 value of 0.196 in predicting the proof test load based on the pile diameter, bearing stratum SPT N-value and the pile penetration depth. This is a moderately reasonable correlation that should be treated as a fair "first approximation."

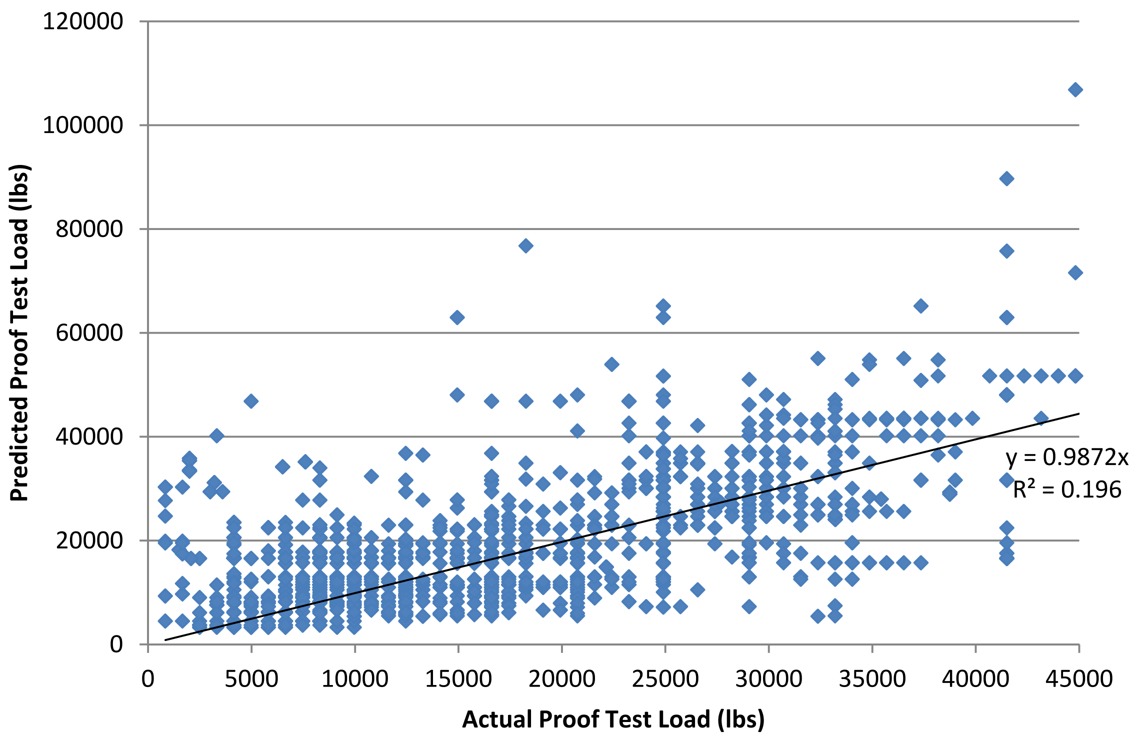


Figure 11. Model Comparison of Predicted Proof Test Load to Actual Proof Test Load

Thus far, the data have not been separated by soil type. To analyze the effect of type of soil on the penetration length, the data were filtered by soil type and fitted similar to that shown in Figure 10. The constants, B_1 and B_2, determined for various soil types are shown in Table 2.

Table 2. Capacity Equation Constants

	B_1	B_2	R^2
All Soils	29	1065	0.12
SP	27	1321	0.1
SM	35	465	0.45
ML	51	376	0.25
CL	25	1338	0.08
Bedrock	23	871	0.14

Using this new Predicted Capacity Equation with the "all soils" constants determined above, a plot of the penetration depth with respect to SPT N-values for various proof test loads can be constructed as shown in Figure 12 and Figure 13 for 3" and 4.5" pile diameters, respectively. These plots can be used to estimate jacked pile installation depths. The charts provide an empirical estimate. The user should keep in mind that the data used to construct these charts has considerable scatter. The estimated penetration depth represents an accurate average. Based on the R^2 value of the linear regression, actual pile depths may vary by +/- 50%.

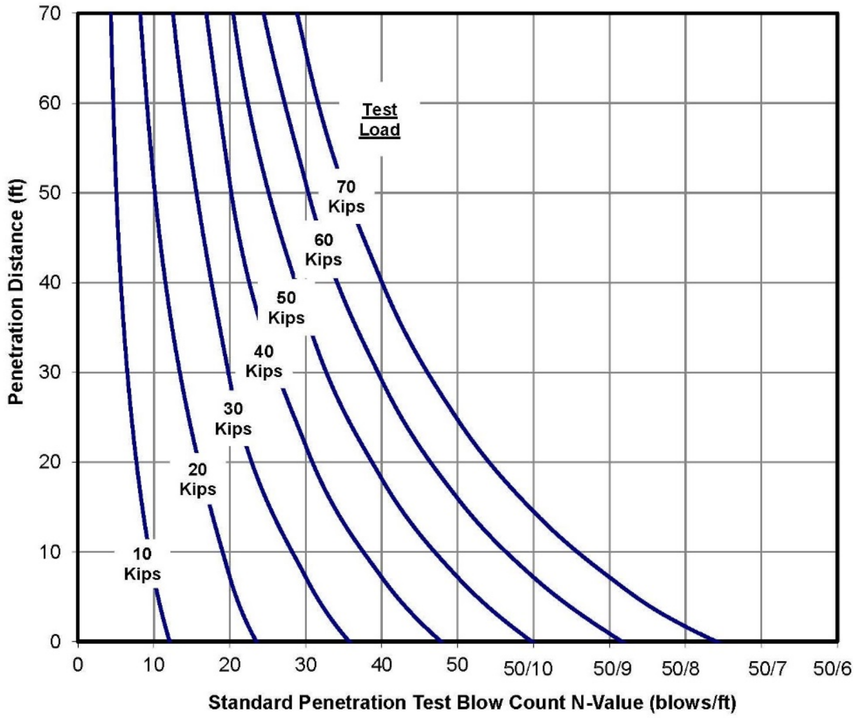


Figure 12. Predicted 3” Diameter Jacked Pile Penetration into Soil and Rock

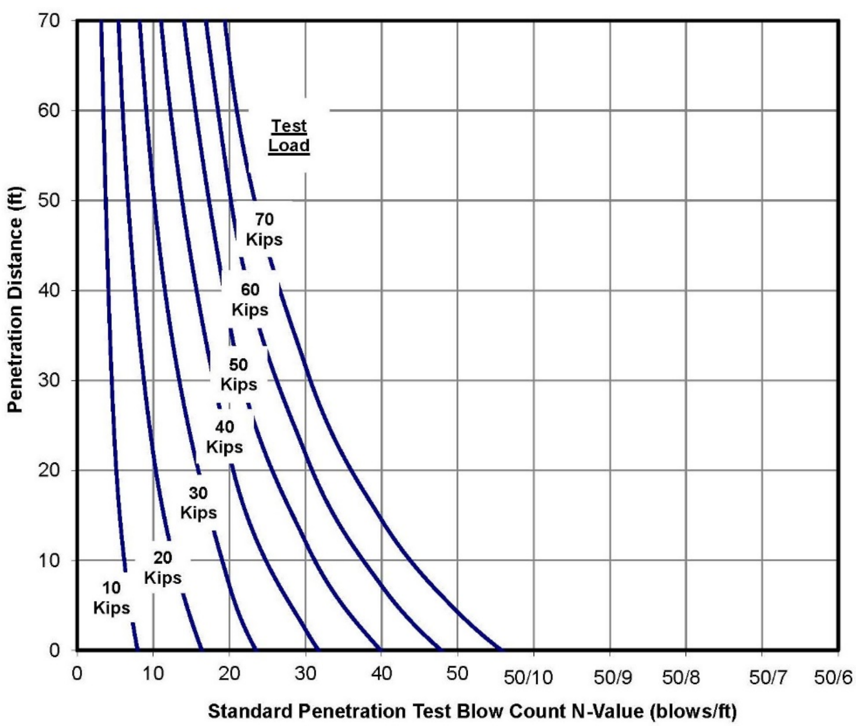


Figure 13. Predicted 4.5” Diameter Jacked Pile Penetration into Soil and Rock

Discussion

In saturated low permeable soils, the installation of jacked piles causes high pore water pressures which substantially reduces soil effective stress. It is standard practice to proof test jacked piles immediately after installation. This procedure is conservative since the capacity of the pile should increase after pore pressures dissipate and effective stresses return to steady state. For this reason, jacked piles must be completely installed in the same day, as even an overnight delay is sufficient to make the obtainment of additional installation depth difficult. In most cases, jacked pile capacity should increase with time. Groundwater fluctuations and corrosion are exceptions that may adversely affect capacity.

Conclusions

1. Hydraulically jacked steel pipe piles have been used to underpin and stabilize foundations for at least 120 years.
2. Dead and live loads shall be considered in the determination of the required jacked pile capacity and an appropriate factor of safety applied.
3. The structure being underpinned shall have sufficient load reaction to drive the piles to the required proof test load without excessive lifting or damage.
4. An empirical equation is provided that relates proof test load, pile diameter, and SPT blow count to the penetration depth. The relationship can be used in conjunction with constants provided in Table 2 to approximate jacked pile installation depth and/or capacity in different soil conditions.
5. The capacity of jacked piles is proof tested by the method of installation. Standard procedures for jacked pile proof testing are provided herein.

6. Design, spacing, and engineering considerations for jacked pile applications are presented and discussed.

References

American Society for Testing and Materials (1994) “Standard Test Method for Piles Under Static Axial Compressive Load” Test Designation D1143, ASTM International

American Society of Civil Engineers (1996) “Standard Guidelines for Design and Installation of Pile Foundations” Publication 20-96, ASCE Press

Meyerhof, G.G. (1976) “Bearing Capacity and Settlement of Pile Foundations”, J. Of the Geotechnical Eng., ASCE, Vol. 102, GT 3, pp. 195-228

Meyerhof, G.G. (1956) “Penetration Tests and Bearing Capacity of Cohesionless Soils”, J. Of Soil Mechanics and Foundation Design, ASCE, Vol. 82, SM 1, pp.1-19

Miller, G.A. and Lutenegger, A.J. (1997) “Influence of Pile Plugging on Skin Friction in Overconsolidated Clay”, J. Of Geotechnical and Geoenvironmental Eng., ASCE, Vl. 123, No. 6, p. 525

Paikowsky, S.G. and Whitman, R.V. (1990) “The Effects of Plugging on Pile Performance and Design” Can. Geotech. J., Ottawa, Canada, No. 27, pp.429-440

Perko, H.A. (2002) “Axial Capacity of Hydraulically-Jacked, Steel-Pipe Micropiles Used for Underpinning,” Push Pier Engineering Manual, Magnum Piering, Inc.

Figures:

Figure 1. Modern Jacked Pile Engineering Schematic (Courtesy of Magnum Geo-Solutions, LLC)

Figure 2. Examples of Modern Jacked Pile Installation (Courtesy of The Dwyer Company, Inc)

Figure 3. Use of Jacked Piles in 1896

Figure 4. Jacked Piles in 1959

Figure 5. Jacked Piles in 1974

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