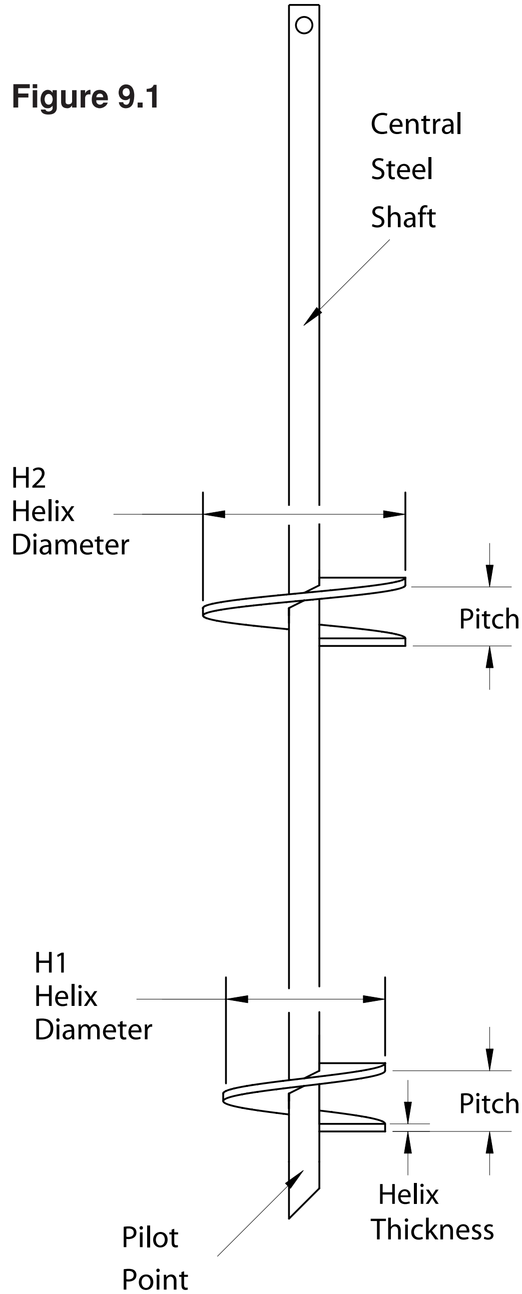
Step 9 – Field Production Control

Helical Screw Foundations - How They Work

By definition, a helical screw foundation is a low soil displacement foundation element specifically designed to minimize disturbance during installation. In their simplest forms, screw foundations consist of at least one helix plate and a central steel shaft. The helix geometry is very important in that it provides the downward force or thrust that pulls a helical screw foundation into the ground. The helix must be a true ramped spiral with a uniform pitch to maximize efficiency during installation. If the helix is not formed properly, it will disturb the soil rather than slice through it at a rate of one pitch per revolution. The central steel shaft transmits the driving energy or torque from the machine to the helix plate(s). The shaft should have a slender size and shape in order to reduce friction during installation. A helical screw foundation functions very similar to a wood screw except that it has a discontinuous thread-form and is made to a much larger scale.

Figure 9.1



Installation Torque/Load Capacity Relationship

Before installation, a helical screw foundation is simply a screw with a discontinuous thread and a uniform pitch. Once installed into soil, a helical screw foundation functions as an axially loaded end-bearing deep foundation. The helix plate(s) serve a two-fold purpose. The first purpose is to provide the means to install the helical screw foundation. The second purpose is to provide the bearing element means for load transfer to soil. As such, helical screw foundation design is keyed to these two purposes - both of which can be used to predict the ultimate capacity.

Design Step 4 detailed how the helix plates act as bearing elements. The load capacity is determined by multiplying the unit bearing capacity of the soil at each helix location times the projected area of each helix. This capacity is generally defined as the *ultimate theoretical load capacity* because it is based on soil parameters either directly measured or empirically derived from sounding data.

This section of the design manual intends to provide a basic understanding of how *installation torque* (or *installation energy)* provides a simple, reliable means to predict the load capacity of a helical screw foundation. More importantly, this prediction method is independent of the bearing capacity method detailed in Step 4, so it can be used as a "field production control" method to verify load capacity during installation.

The installation torque-to-load capacity relationship is an empirical method originally developed by the A. B. Chance Company. Chance has long promoted the idea that the torsion energy required to install a helical screw foundation can be related to the ultimate load capacity of a screw foundation. Precise definition of the relationship for all possible variables remains to be achieved. However, simple empirical relationships have been used for a number of years. The principle is: As a helical screw foundation is installed (screwed) into increasingly denser/harder soil, the resistance to installation (called installation energy or torque) will increase. Likewise, the higher the installation torque, the higher the axial capacity of the installed screw foundation. Hoyt & Clemence [Hoyt (1989)] presented a landmark paper on this topic at the 12th International Conference on Soil Mechanics and Foundation Engineering. They proposed the following formula for the torque/screw foundation capacity relationship:

$Q_{ult} = K_t \times T$ (Equation 9.1)

Where:
Q_{ult} = ultimate uplift capacity [lb (kN)]

K_t = empirical torque factor [ft^{-1} (m^{-1})]
T = average installation torque [lb-ft (kN-m)]

Hoyt and Clemence recommended K_t = 10 ft^{-1} (33 m^{-1}) for square shaft and round shaft helical screw foundations less than 3.5" (89 mm) in diameter, 7 ft^{-1} (23 m^{-1}) for 3.5" diameter round shafts, and 3 ft^{-1} (9.8 m^{-1}) for 8-5/8" (219 mm) diameter round shafts. **The value of K_t is not a constant - it may range from 3 to 20 ft^{-1} (10 to 66 m^{-1}), depending on soil conditions, shaft size and shape, helix thickness, and application (tension or compression)**. For Hubbell/Chance Type SS square shaft helical screw foundations, K_t typically ranges from 10 to 12 ft^{-1} (33 to 39 m^{-1}), with 10 ft^{-1} (33 m^{-1}) being the recommended default value. For Hubbell/Chance Type HS pipe shaft 3.5" (89 mm) helical screw foundations, K_t typically ranges from 7 to 10 ft^{-1} (23 to 33 m^{-1}), with 7 ft^{-1} (23 m^{-1}) being the recommended default value.

Locating helix bearing plates in very soft, loose, or sensitive soils will typically result in K_t values less than the recommended default. This is because some soils, such as salt leached marine clays and lacustrine clays, are very sensitive and lose considerable shear strength when disturbed. It is better to extend the screw foundation beyond sensitive soils into competent bearing strata. If it's not practical to extend the screw foundation beyond sensitive soils, testing is required to determine the appropriate K_t.

Full-scale load testing has shown that helical screw foundations typically have at least the same capacity in compression as in tension. In practice, compression capacity is generally higher than tension capacity because the screw foundation bears on soil below rather than above the helix plates, plus at least one helix plate is bearing on undisturbed soil. Soil above the bearing plates is slightly disturbed by the slicing action of the helix, but not overly disturbed by being "augured" and removed. Typically, the same values of K_t are used for both tension and compression applications. This generally results in conservative results for compression applications. A poorly formed helix shape will disturb soil enough to adversely affect the torque-to-capacity relationship, i.e. K_t is reduced. To prevent this, A. B. Chance Compnay uses matching metal dies to form helix plates which are as near to a true helical shape as is practically possible. To understand all the factors that K_t is a function of, one must first understand how helical screw foundations interact with the soil during installation.

Torque Factors

There are two main factors that contribute to the torque resistance generated during screw foundation installation - *friction* and *penetration resistance*. Of the two factors, friction is by far the larger component of torque resistance.

Friction has two basic parts: Friction on the helix plate and friction along the central steel shaft. Friction resistance increases with helix size because the surface area of the helix in contact with the soil increases with the square of the diameter (Figure 9.2). Likewise, friction resistance increases with pitch size. The larger the pitch, the greater the resistance. This is analogous to the difference between a coarse thread and a fine thread bolt. Basic physics tells us that "work" is defined as force times distance. A larger pitch causes the helix to travel a greater distance per revolution, thus more work is required.

Friction along the central steel shaft is similar to friction on the helix plate. Friction resistance increases with shaft size because the surface area of the shaft in contact with the soil increases as the diameter increases. An important performance factor for helical screw foundations is the *helix to shaft diameter ratio* (H_d/S_d). The higher the H_d/S_d ratio, the more efficient a given helical screw foundation will be during installation. Friction resistance also varies with *shaft shape* (Figure 9.3). A round shaft may be the most efficient section to transmit torque energy, but it has the disadvantage of full surface contact with the soil during installation. When the central steel shaft is large (> 3" [76 mm]diameter) the shaft friction resistance contributes significantly to the total friction resistance. However, a square shaft has only the corners in full surface contact with the soil during installation - thus less shaft friction resistance. ***Friction energy***

Figure 9.2 - Top View of Helix

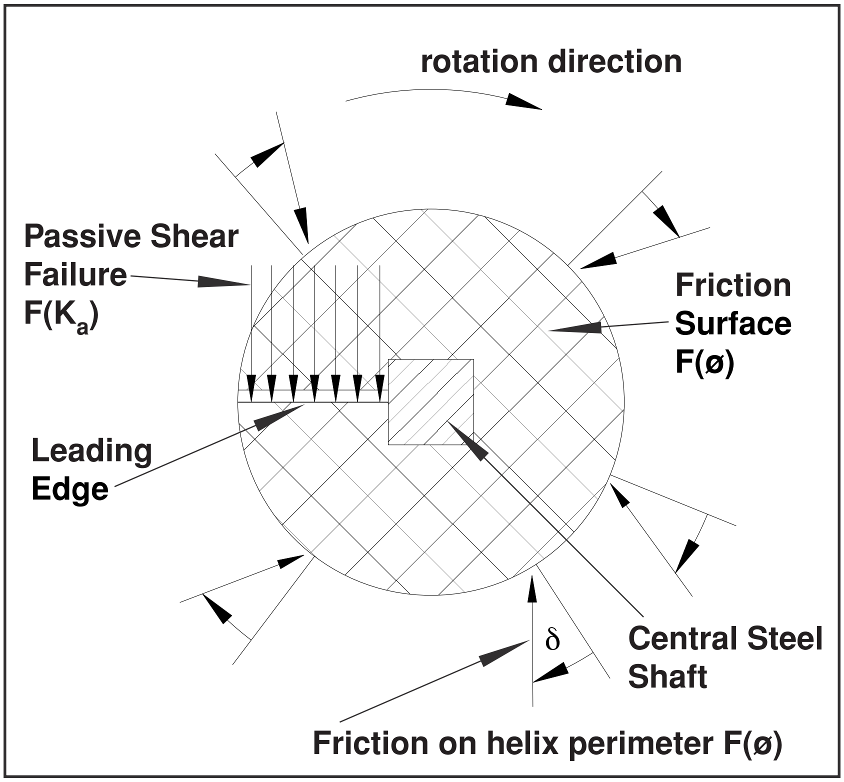
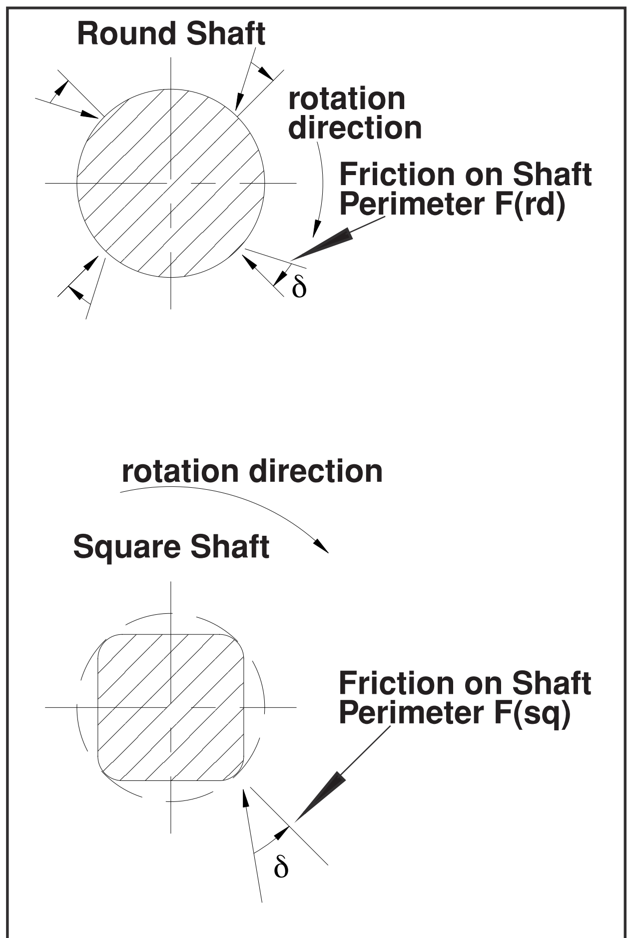


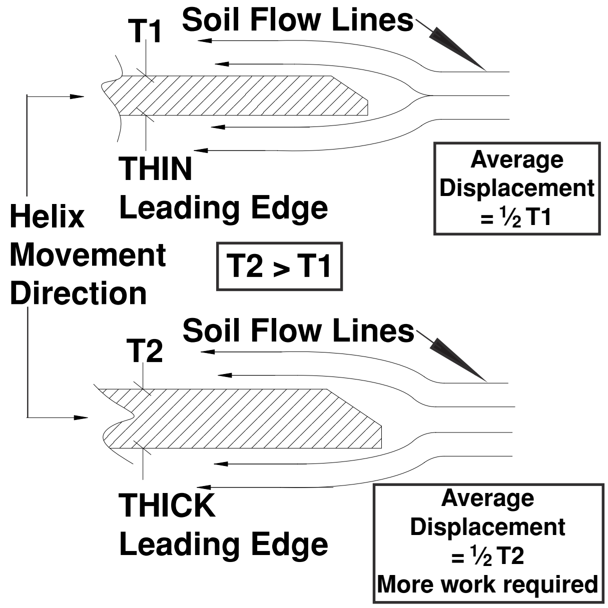
Figure 9.3
Friction Forces Acting on Central Shafts



(energy loss) required to install a helical screw foundation is proportional to the helix and shaft size. The total energy loss due to friction is equal to the sum of the friction loss of all the individual helix plates plus the length of shaft subjected to friction via contact with the soil.

<u>Penetration resistance has two basic parts</u>: Shearing resistance along the leading edge of the helix plate and penetration resistance of the hub pilot point. Shearing resistance increases with helix size because leading edge length increases as the diameter increases. Shearing resistance also increases with helix thickness because more soil has to be displaced with a thick helix than with a thin helix (Figure 9.4). The average distance the soil is displaced is equal to approximately half the helix thickness, so as the thickness increases the more work, i.e. energy is required to pass the helix through the soil.

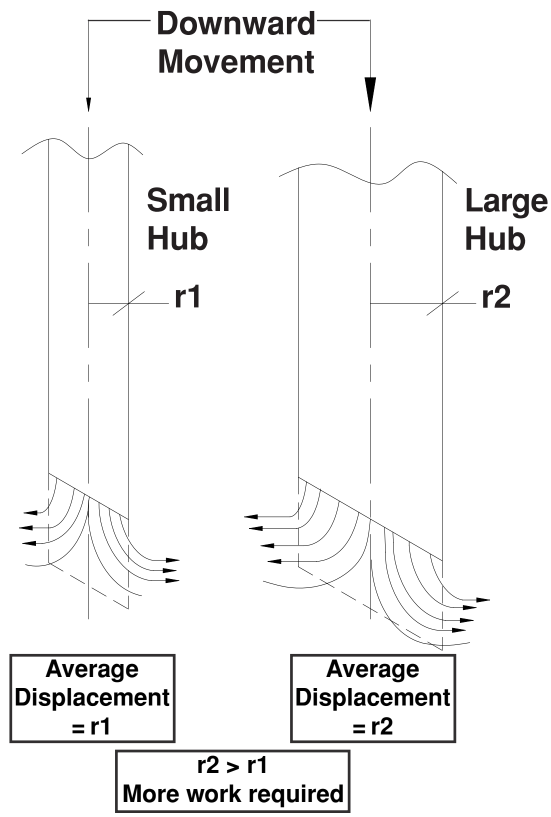
Figure 9.4
Section View of Leading Edge with Flow Lines



Penetration resistance increases with shaft size because the projected area of the hub/pilot point increases with the square of the shaft radius (Figure 9.5). The average distance the soil is displaced is approximately equal to the radius of the shaft, so as the shaft size increases, the more work, i.e. energy is required to pass the hub/pilot point through the soil.

***Penetration energy* required to install a helical screw foundation is proportional to the volume of soil displaced times the distance traveled.** The volume of soil displaced by the screw anchor is equal to the sum of the volumes of all the individual helix plates plus the volume of the soil displaced by the hub/pilot point in moving downward with every revolution.

Figure 9.5
Hub/Pilot Point with Flow Lines



Energy Relationships

***Installation energy* must equal the energy required to penetrate the soil (penetration resistance) plus the energy loss due to friction (friction resistance)**. The installation energy is provided by the machine and consists of two components - *rotation energy* supplied by the torque motor and *downward force* (*or crowd*) provided by the machine. The rotation energy provided by the motor along with the inclined plane of a true helical form generates the thrust necessary to overcome the penetration and friction resistance. The rotational energy is what is termed "*installation torque*." The downward force also overcomes penetration resistance, but its contribution is usually required only at the start of the installation, or when the lead helix is transitioning from a soft soil to a hard soil.

From an installation energy standpoint, the perfect helical screw foundation would consist of an infinitely thin helix plate attached to an infinitely strong, infinitely small diameter central steel shaft. This configuration would be energy efficient because penetration resistance and friction resistance is low. Installation torque to capacity relationships would be high. However, infinitely thin/small helix plates and shafts are not realistically possible, so a balanced design of size, shape, and material is required to achieve consistent, reliable torque to capacity relationships.

As stated previously, the empirical relationship between installation torque and ultimate capacity is well known, but not precisely defined. As one method of explanation, a theoretical model based on energy exerted during installation has been proposed [Perko (2000)]. The energy model is based on equating the energy exerted during installation with the penetration and friction resistance. Perko showed how the capacity of an installed helical screw foundation can be expressed in terms of installation torque, applied downward force, soil displacement, and the geometry of the screw foundation. The model indicates that K_t is weakly dependent on crowd, final installation torque, number of helix plates, and helix pitch. The model also indicates that K_t is moderately affected by helix plate radius and strongly affected by shaft diameter and helix plate thickness.

The important issue is *energy efficiency*. Note that a large shaft helical screw foundation takes more energy to install into the soil than a small shaft screw foundation. Likewise, a large diameter, thick helix takes more energy to install into the soil than a smaller diameter, thinner helix. The importance of energy efficiency is realized when one considers that the additional energy required to install a large displacement helical screw foundation contributes little to the load capacity of the screw foundation. In others words, the return on the energy "investment" is not as good. This concept is what is meant when A. B. Chance Co. engineers say large shaft diameter and/or large helix diameter (>16" diameter) screw foundations are not efficient "*torque-wise*."

If one considers an energy balance between the energy exerted during loading and the appropriate penetration energy of each of the helix plates, then it can be realized that any installation energy not specifically related to helix penetration is wasted. This fact leads to several useful observations. For a given helix configuration and the same available installation energy (i.e. machine):

1. Small displacement shafts will disturb less soil than large displacement shafts.
2. Small displacement shafts result in less pore pressure buildup than large displacement shafts.
3. Small displacement shafts will penetrate farther into a given bearing strata than large displacement shafts.
4. Small displacement shafts will penetrate soils with higher SPT "N" values than large displacement shafts.
5. Small displacement shafts will generate more axial load capacity with less deflection than large displacement shafts.
6. K_t varies inversely with shaft diameter.

Reliability of Torque/Capacity Model

Hoyt and Clemence [Hoyt (1989)] analyzed 91 load tests at 24 different sites with sand, silt and clay soils all represented. All of the tests used in the study were short term; most were strain controlled and included a final loading step of imposing continuous deflection as a rate of approximately 4 inches (102 mm) per minute. This final load was taken as the ultimate capacity. The capacity ratio Q_{act}/Q_{calc} was obtained for each test by dividing the actual capacity (Q_{act}) by the calculated capacity (Q_{calc}). Q_{calc} was calculated by using three different load capacity models 1. cylindrical shear, 2. individual bearing (step 4), and 3. torque correlation. These data were then compared and plotted on separate histograms (Figures 9.6 and 9.7, cylindrical shear histogram not shown)

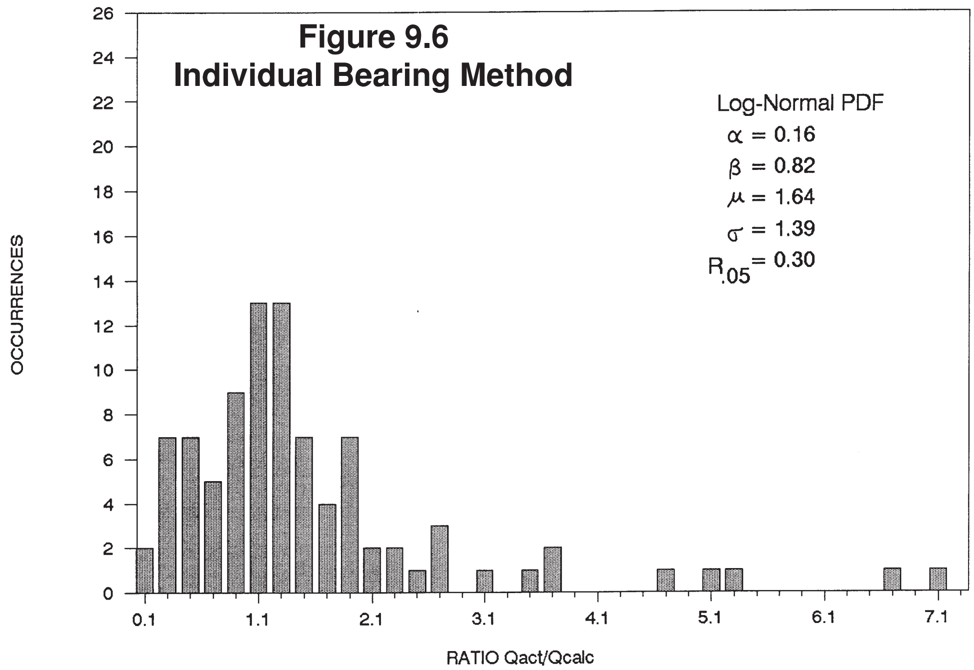


Figure 9.6
Individual Bearing Method

All three capacity models exhibited the capability of overpredicting screw anchor capacity. This would suggest the use of appropriate factors of safety. However, the authors did not discriminate between “good” and”“poor” bearing soils when analyzing the results. In other words, some of the test data analyzed was in areas where the helix plates were located in soils typically not suitable for end bearing, i.e. sensitive clays and loose sands.

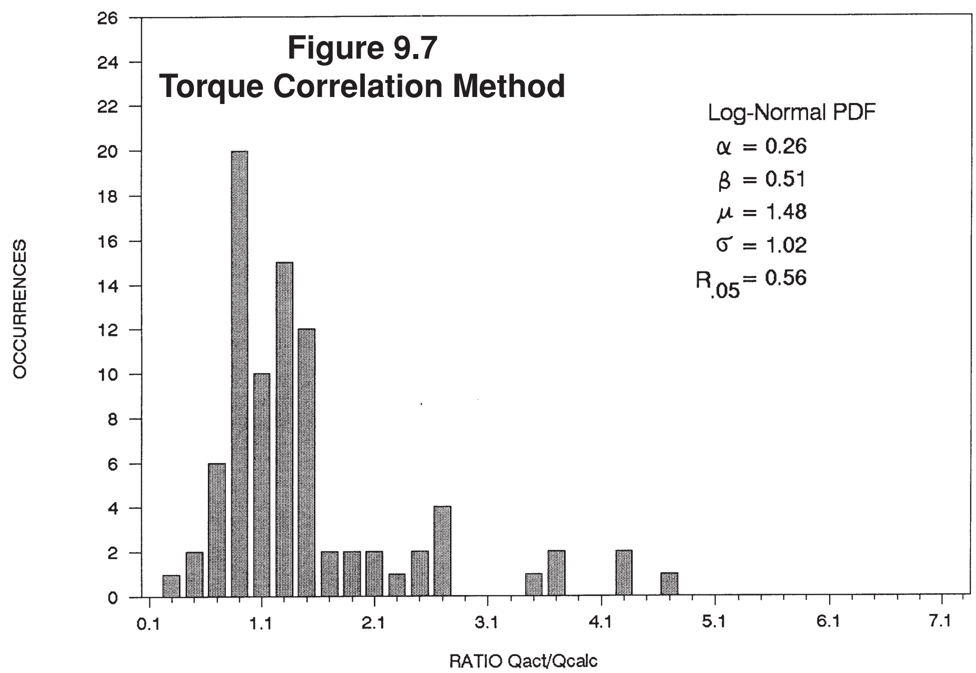


Figure 9.7
Torque Correlation Method

All three capacity models’ mean values were quite close, but the range and standard deviation were significantly lower for the torque correlation method than for the other two. This improved consistency is probably due to the removal of several random variables from the capacity model. **Therefore, the installation torque correlation method yields more consistent results than either of the other two methods.** The installation torque method does have one disadvantage, however, in that it cannot be used until after the helical screw foundation has been installed. Therefore, it is better suited to on-site production control and termination criteria than design in the office.

Measuring Installation Torque

The torque correlation method requires the installation torque to be measured and recorded in the field. There are several methods that can be used to measure torque, and Hubbell/A.B. Chance Company has a complete line of torque indicators to choose from. Each one is described below along with its advantages and disadvantages:

• Shaft Twist

A.B. Chance Company stated in early editions of the Encyclopedia of Anchoring that for standard SS5 anchors, "the most secure anchoring will result when the shaft has a 1 to 1½ twist per 5-foot section." [Encyclopedia of Anchoring (1977)] Shaft twist is not a true torque-indicating device. It has been used as an indication of "good bearing soil" since Type SS screw anchors were first introduced in the mid 1960's. Shaft twist should not be used exclusive of a true torque-indicating device. Some of the reasons for this are listed below.

Advantages

- Simple, cheap, easy to use
- Doesn't require any additional tooling
- Visible indication of torque

Disadvantages

- Quantitative, not qualitative torque relationship
- Not very accurate
- Shaft twist can't be correlated to installation torque on a consistent basis
- Type SS5, SS150, SS175, SS200, & SS225 shafts twist, or wrap-up, at different torque levels.
- Shaft twist for pipe shaft is not obvious without other means of reference

• Shear Pin Torque Limiter

Mechanical device consisting of two shear halves mounted to a central pin such that the shear halves are free to rotate. Shear pins inserted into perimeter holes prevent the shear halves from rotating and are rated to shear at 500 ft-lb of torque per pin. Required torque can be achieved by loading the shear halves with the appropriate number of pins, i.e. 4000 ft-lb = 8 pins. The Shear Pin Torque Limiter is mounted in-line to the torque motor and screw foundation tooling.

Figure 9.8
Shear Pin Torque Limiter

Advantages

- Simple design, easy to use
- Tough and durable, will take a lot of abuse and keep working
- Accurate within ± 5% if kept in good working condition
- Torque limiter - used to prevent exceeding a specified torque
- Relatively inexpensive to buy and maintain
- Easy interchange from one machine to another

Disadvantages

- Point-wise torque indicator, i.e. indicates torque at separate points, not continuous
- Requires constant unloading and reloading of shear pins
- Limited to 10,000 ft-lb
- Sudden release of torsional (back-lash) energy when pins shear
- Fits tools with 5¼" bolt circle only

• Mechanical Dial Torque Indicator

Mechanical device consisting of a torsion bar mounted between two bolt flanges. This tool indicates installation torque directly by measuring the twist of the torsion bar. The dial indicator reads torque directly. The Mechanical Dial Torque Indicator is mounted in-line to the torque motor and screw foundation tooling.

Figure 9.9
Mechanical Dial Torque Indicator

Advantages

- **Never needs re-calibration**
- Simple torsion bar design, easy to use
- Continuous reading torque indicator
- Dial gauge reads torque directly
- Accurate within ± 5% if kept in good working condition
- Fits tools with 5-1/4" and 7-5/8" bolt circles
- Calibrated with equipment traceable to US Bureau of Standards before leaving plant
- Can be used as a calibration tool for other types of torque indicators
- Easy interchange from one machine to another

Disadvantages

- Most expensive torque indicator sold by Hubbell/A. B. Chance
- Tends to be fragile - especially when used in hard, rocky grounds that cause shock and vibration
- Not recommended for applications where bending in the tool string occurs, i.e. tieback anchors
- Not as tough and durable as Shear Pin Torque Limiter

• DP-1 Differential Pressure Torque Indicator

Hydraulic device consisting of back-to-back hydraulic pistons, hoses, couplings, and gauge. Based on the principle that the work output of a hydraulic torque motor is directly related to the pressure drop across the motor. The DP-1 hydraulically or mechanically "subtracts" the low pressure from the high to obtain the "differential" pressure. Installation torque is calculated using the cubic inch displacement and gear ratio of the torque motor. The DP-1 piston block and gauge can be mounted anywhere on the machine. Hydraulic hoses must be connected to the high and low pressure lines at the torque motor.

Advantages

- Indicates torque by measuring pressure drop across hydraulic torque motor
- No moving parts
- Continuous reading torque indicator
- Very durable - the unit is not in the tool string
- Pressure gauge can be located anywhere on the machine
- Analog-type gauge eliminates "transient" torque peaks
- Pressure gauge can be over-laid to read torque (ft-lb) instead of pressure (psi)
- Accurate within ± 5% if kept in good working condition
- After mounting, it is always ready for use
- Can be provided with multiple readout gauges

Figure 9.10 Differential Pressure Torque Indicator

Disadvantages

- Requires significant initial installation set-up time and material, i.e. hydraulic fittings, hoses, oil
- DP-1 requires a hydraulic pressure-to-torque correlation based on the torque motor's cubic inch displacement (CID) and gear ratio
- For two-speed torque motors, pressure-to-torque correlation changes depending on which speed the motor is in (high or low)
- DP-1 requires periodic recalibration against a known standard, such as the Mechanical Dial Torque Indicator
- Sensitive to hydraulic leaks in the lines that connect the indicator to the torque motor
- Relatively expensive
- Difficult interchange from one machine to another

• **In-Line Hydraulic Pressure Gauge**

Hydraulic device consisting of a hydraulic pressure gauge mounted in-line with the high-pressure hose feeding the torque motor. Based on the principle that measuring the pressure in the supply line to the hydraulic torque motor can approximate the work output of the motor. Installation torque is estimated by calibrating the gauge against a known reference - such as a Mechanical Dial Torque Indicator. The gauge can be mounted anywhere on the machine, but the connection to the high pressure line should be as close to the motor as possible.

Advantages

- Simplest, lowest cost, easy to use torque indicating device
- Indicates torque by measuring system pressure on the supply side of the machine's hydraulic pump
- Continuous reading torque indicator
- No moving parts
- Very durable - the unit is not in the tool string
- Analog-type gauge eliminates "transient" torque peaks

Disadvantages

- Least accurate of the torque indicators listed herein
- In-line gauge requires a hydraulic pressure-to-torque correlation based on the torque motor being used
- For two-speed torque motors, pressure-to-torque correlation changes depending on what speed the motor is in (high or low)
- In-line gauge requires periodic recalibration against a known standard, such as the Mechanical Dial Torque Indicator
- Accuracy is a function of gauge location in hydraulic system, oil temperature, hydraulic system backpressure, leaks, age of oil (clean or dirty), age of machine, etc.

Installation Termination Criteria

The engineer of record can use the relationship between installation torque and load capacity to establish minimum torque criteria for the installation of production helical screw foundations. The recommended default values for K_t [10 (33) for A.B. Chance Co. Type SS, and 7 (23) for Type HS] will typically provide conservative results. For large projects that merit the additional effort, a pre-production test program can be used to establish the appropriate torque correlation factor (K_t) for the existing project soils. K_t is determined by dividing the ultimate load capacity by the average installation torque taken over the last 3 feet of penetration into the bearing strata. See Step 11 for more detailed explanation of full-scale load tests. Large-scale projects warrant more than one pre-production test.

Whatever method is used to determine K_t, the production helical screw foundations should be installed to a specified minimum torque and overall depth. These termination criteria should be written into the construction documents. The Appendix to this Design Manual contains a model specification, which contains a section on recommended termination criteria for helical screw foundations.

Tolerances

It is possible to install helical screw foundations within reasonable tolerance ranges. For example, it is common to locate and install a screw foundation within 1 inch (25 mm) of the staked location. Plumbness can usually be held within 2° of design alignment. For vertical installations a visual plumbness check is typically all that's required. For battered installations, an inclinometer can be used to establish the required angle. The Appendix to this Design Manual contains a model specification, which contains a section on allowable installation tolerances for helical screw foundations.

Torque Strength Rating

Torque strength is important when choosing the correct helical screw foundation for a given project. It is a practical limit since the torque strength must be greater than the resistance generated during installation. In fact, the central steel shaft is more highly stressed during installation than at any other time during the life of the foundation. This is why it is important to control both material strength variation and process capability in the fabrication process. Hubbell/A.B. Chance Company designs and manufactures helical screw foundations to achieve the torque ratings published in Table 8.5. The ratings are listed based on product "family," such as SS5, SS175, HS, etc.

The torque rating is defined as the maximum torque energy that should be applied to the screw foundation during installation in soil. It is not the ultimate torque strength, defined as the point where the central shaft experiences torsion fracture. It is best described as an allowable limit, or "safe torque" that can be applied to the helical screw foundation. Some other manufacturers publish torque ratings based on ultimate torque strength.

The designer should select the product family which provides a torque strength rating that meets or exceeds the anticipated torsion resistance expected during the installation. HeliCAP™ Engineering Software (Step 4) generates installation torque vs. depth plots that estimate the torque resistance of the defined soil profile. The plotted torque values are based on a K_t of 10 for Type SS and 7 for Type HS. The torque ratings published in Table 8.5 are superimposed on the HeliCAP™ torque vs. depth plot, so the user can see at a glance when the estimated torque resistance equals or exceeds the torque rating of a given product family.

In some instances, it may be necessary to exceed the torque rating in order to achieve the minimum specified depth, or to install the helical screw foundation slightly deeper to locate the helix plates farther into bearing stratum. This "finishing torque limit" should never exceed the published torque rating by more than 15%. Note that the possibility of torsion fracture increases significantly as the applied torque increases beyond the published ratings. The need to install screw foundations deeper is better accomplished by reducing the size and/or number of helix plates, or by choosing a foundation product with a higher torque rating.

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