Hydraulic Drive Head Performance Curves For Prediction of Helical Pile Capacity

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Abstract

Helical piles often rely on the final installation torque for ultimate capacity verification. When helical piles are designed using traditional bearing capacity equations for deep foundations and field monitored for a specified final installation torque, a factor of safety equal to 2 is often allowed for the design. One of the more common methods of determining torque during helical pile installation is by correlating the differential pressure across a hydraulic gear motor to a torque. Most drive head manufacturers provide multipliers to convert differential pressure to torque for different drive head models. These multipliers are based on theoretical torque equations and vary with the planetary gear ratio, hydraulic gear motor displacement and drive head efficiency. Drive head manufacturers show a linear fit between the differential pressure and output torque with no scaling effect. Previous drive head testing performed by the author has confirmed that the drive head differential pressure to torque relationship is generally linear, however, there is a scaling adjustment needed. This results in a variation of multipliers across the differential pressure range for a given drive head.

Eight hydraulic drive heads from three manufacturers were field tested by Foundation Supportworks, Inc. to compare the torque versus differential pressure curves with varying installation equipment, hydraulic line sizes and hydraulic flow rates. Differential pressure was monitored using three methods including pressure gages, PT-Tracker and an Ashcroft AT-100. Flow and temperature was measured using a Webtech system analyzer. Torque was measured using a Pro-Dig in-line torque transducer, a TruTorque indicator and a Chance Mechanical Dial in-line torque indicator. The current testing indicates that a change in installation equipment and/or a change in hydraulic flow rate may affect the torque versus differential pressure curve of a given drive head. The results of this testing also show that some of the methods for determining torque during helical pile installations may be unconservative, thereby resulting in safety factors less than required.

Introduction

Hydraulic drive heads are used to install helical piles or anchors for many applications including earth retention tiebacks, foundation tiedowns, foundation retrofit underpinning and new construction foundation support. Hydraulic drive heads consist of a hydraulic gear motor attached to one or more sets of planetary gears. The differential pressure across the hydraulic gear motor may be used to predict the torque applied to the helical pile shaft during installation. The hydraulic drive head industry provides gear motor manufacturer recommended gear motor multipliers (GMM_M) to be used in conjunction with the differential pressure reading across the hydraulic motor to correlate installation torque.

The installation torque is used to predict ultimate pile capacity with the torque correlation method. The torque correlation method can use default torque correlations or a site specific torque correlation factor can be determined from field pile load testing (Deardorff 2007). Therefore, for many installations, the differential pressure across the gear motor is used to verify the ultimate helical pile capacity.

Other methods of measuring the torque output of a hydraulic drive head include devices in line with the helical pile tooling such as torque transducers, shear pin indicators or mechanical dial indicators. These systems are considered direct torque monitoring methods and are not influenced by changes in drive head type, hydraulic line size and/or installation equipment since you are measuring torque at the output shaft of the drive head. Unlike direct torque monitoring devices, the use of differential pressure across the gear motor to determine torque can have variable results depending upon the hydraulic flow rate, hydraulic line size and/or installation equipment.

Hydraulic Drive Heads

The torque output of a hydraulic drive head can be determined by the differential pressure across the hydraulic gear motor, the displacement of the hydraulic motor, the planetary gear ratio of the planetary drive system and the drive head efficiency. The theoretical equation to determine torque for a hydraulic drive head is:

$$\text{Torque} = \frac{DP^*CID^*PGR^*\eta}{2^*\pi^*(12in/1ft)}$$

Where:

Torque = the drive head output torque (ft-lbs)
DP = the differential pressure across the hydraulic motor (psi)
CID = the cubic inch displacement of the hydraulic motor (in^3)
PGR = the planetary gear ratio of the planetary drive system
η = the drive head efficiency

The theoretical gear motor multiplier (GMM_T) is simply the torque divided by the DP and can be back-calculated from the above equation as:

$$GMM_T = \frac{CID^*PGR^*\eta}{2^*\pi^*(12in/1ft)}$$

Hydraulic drive head efficiency is dependent upon the losses within the hydraulic motor, planetary gears and final drive shaft. Drive head efficiencies decrease with an increase in planetary gear stages. Larger capacity drive heads may have two or more planetary gear stages while smaller capacity drive heads may have single stage planetary drives. Hydraulic motors are typically either single or two-speed units which allow the drive head to operate in high-speed low-torque or low-speed high-torque modes.

The drive head manufacturers will typically disclose the manufacturers recommended gear motor multiplier (GMM_M), CID and PGR for their drive heads; however they generally do not provide the efficiencies used to determine the GMM_M. The drive head efficiency used by the manufacturer can easily be back-calculated from the above equation. The specifications of the hydraulic drive heads used in this research including the manufacturers published gear motor multiplier (GMM_M) and the back calculated theoretical efficiency (η) are shown in Table 1.

Table 1: Tested Drive Head Specifications

Drive Head Make and Model	Max Torque Rating (ft-lbs)	PGR	Motor Speed	CID	GMM_M	η
Pengo MDT-12K	12000	34.6	High	5.95	2.74	100%
			Low	12.75	5.48	94%
Pro-Dig L5K	5000	19.8	Single	9.76	2.08	81%
Pro-Dig X9K5	9500	15.5	Single	19.22	3.22	82%
Pro-Dig T12K	12000	32	High	5.96	2.24	89%
			Low	12.91	4.85	89%
Pro-Dig T15K	15000	50.5	High	4.97	2.87	86%
			Low	10.92	6.31	86%
Eskridge 5016	7000	16.7	Single	17.10	2.95	78%
Eskridge 78-48	12000	47.7	High	3.19	1.4	69%
			Low	9.56	5.12	85%
Eskridge 75-51	20000	51.4	High	6.38	3.02	69%
			Low	12.75	7.35	85%

The efficiency of a single speed hydraulic gear motor generally ranges from 90 to 95 percent and efficiency losses on the order of 3 to 5 percent per planetary gear stage are typical. Therefore a single-speed hydraulic drive head with a two-stage planetary system would have expected drive head efficiencies of about 81 to 89 percent. Two-speed hydraulic gear motors typically have higher efficiencies in the low-speed high-torque mode compared to the high-speed low-torque mode. The efficiency of a hydraulic motor also varies with the differential pressure; however, drive head manufacturers assume constant efficiencies across the entire differential pressure range.

Test Program

Eight hydraulic drive heads from three manufacturers were field tested by Foundation Supportworks, Inc. to compare the GMM and torque versus differential pressure curves with varying installation equipment, hydraulic line sizes and hydraulic flow rates. Differential pressure was monitored using three methods including standard pressure gages, PT-Tracker and an Ashcroft AT-100. Hydraulic flow and temperature was measured using a Webtech system analyzer. The differential pressure was monitored at the inlet and outlet ports of the hydraulic motor to reduce any line loss effect on the performance curves. Torque was measured using a Pro-Dig torque transducer, a TruTorque indicator and a Chance Mechanical Dial torque indicator. The test results reported herein used the data derived from the Pro-Dig torque transducer and the Ashcroft AT-100 pressure transducer analyzer. The other monitoring systems were used as a backup and for comparative purposes.

The installation equipment consisted of a high flow Case 580 backhoe, high flow Bobcat S250 skid steer or a Bobcat 430 mini-excavator. The Case 580 backhoe was only used to provide the reaction and boom hydraulics for the larger capacity drive heads while the gear motor hydraulics were being fed by the Bobcat S250. The gear motor hydraulic diameters used during the testing were ½, ¾, or 1-¼ inch diameter. The test setups are shown in Table 2.

Table 2: Drive Head Test Setups

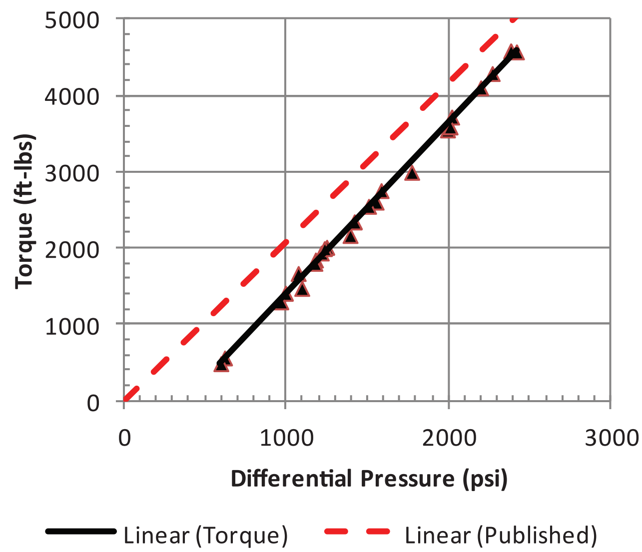
Drive Head Make and Model	Setup No.	Line Diameter (in)	Hydraulic Source
Pengo MDT-12K	1	1-¼	Bobcat S250
Pro-Dig L5K	2	½	Bobcat 430
	3	¾	Bobcat 430
Pro-Dig X9K5	4	¾	Bobcat 430
	5	1-¼	Bobcat S250
Pro-Dig T12K	6	1-¼	Bobcat S250
Pro-Dig T15K	7	1-¼	Bobcat S250
Eskridge 5016	8	¾	Bobcat S250
Eskridge 78-48	9	1-¼	Bobcat S250
Eskridge 75-51	10	1-¼	Bobcat S250

Test Setups No. 2 and 3 were used to evaluate the effect of a change in hydraulic lines size on the torque versus differential pressure curve. Test Setups No. 4 and 5 were used to evaluate the effect of a change in both hydraulic line size and installation equipment on the torque versus differential pressure curve. Test Setup No. 5 was also used to evaluate the effect of varying hydraulic flow rate during installation.

Test Results and Discussion

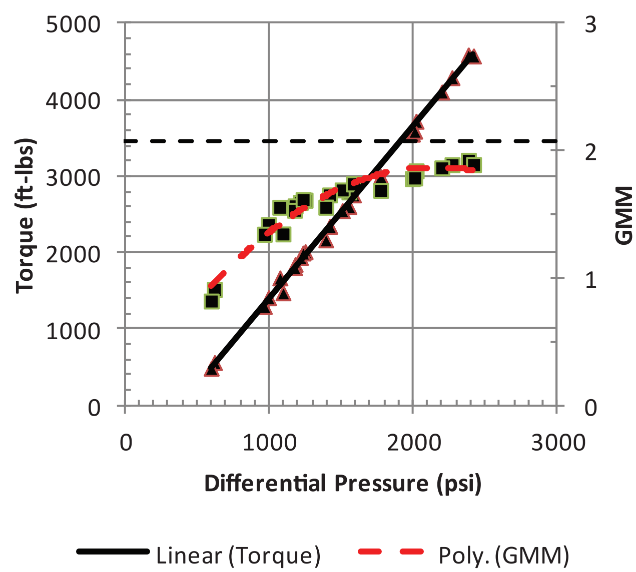
The test data results are shown plotted with torque and the resulting GMM shown on the y-axes and differential pressure on the x-axis. The general trend for all test results is a linear torque curve and non-linear GMM curve. The non-linearity in the GMM curve is introduced primarily due to the x-intercept offset of the linear torque curve from what is published in the manufacturer literature. Specifically, drive head manufacturers show the torque versus differential curve x-intercept at the origin of the axes. For example, the Test Setup No. 2 data shown in Figure 1 illustrates the actual test data curve offset from the manufacturer published torque versus differential pressure curve for the Pro-Dig L5K drive head.

Figure 1: Pro-Dig L5K Test Setup No. 2



The GMM versus differential pressure curve illustrated in Figure 2 is taken from the same test data and shows the variation in actual GMM across the differential pressure range. The horizontal dashed line above the GMM curve represents the GMM_M which is a constant value of 2.08 for that particular drive head.

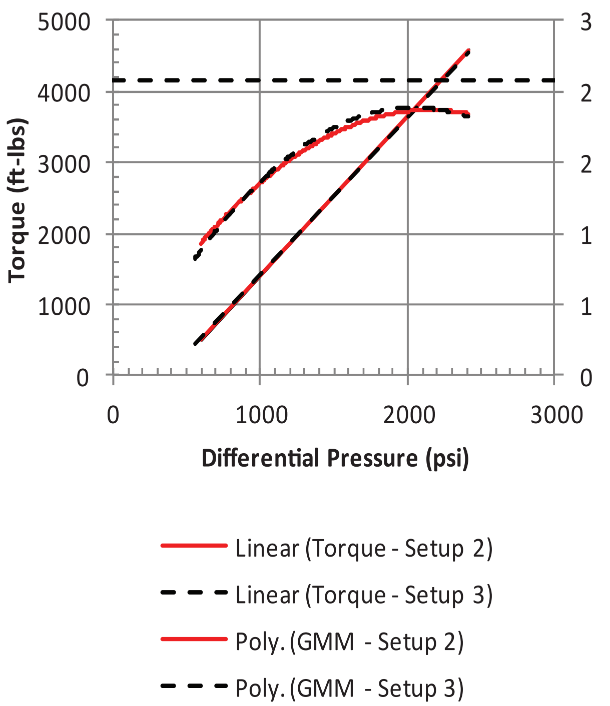
Figure 2: Pro-Dig L5K Test Setup No. 2



The test data shows a significantly reduced GMM at the lower differential pressure ranges and the GMM_M is not achieved during any region of the differential pressure range.

The effect of varying hydraulic line sizes are shown below for the testing performed on the Pro-Dig L5K drive head. Test Setups No. 2 and 3 used ½ and ¾-inch hydraulic line diameters, respectively. The Bobcat 430 was used for both tests with maximum test flow rates of 12 and 15 gpm with the ½ and ¾-inch line diameters, respectively.

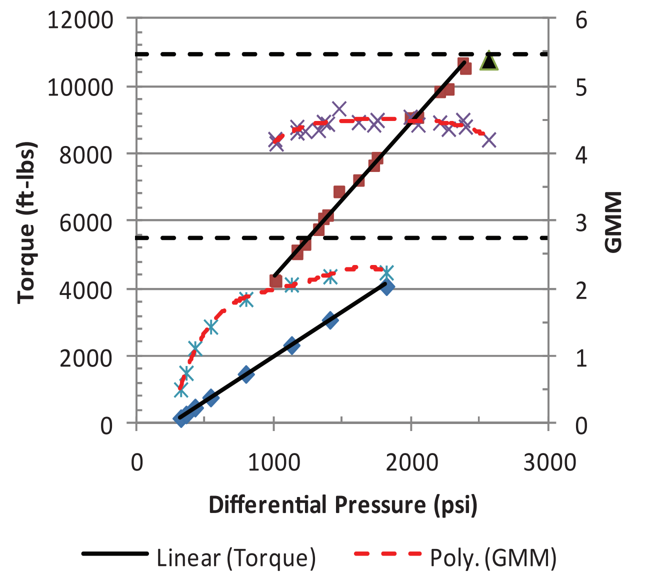
Figure 3: Pro-Dig L5K Test Setup No. 2 and 3



The test results show little variation in the torque and GMM versus differential pressure curve for Test Setup 2 and 3 indicating that a change in hydraulic line size had little effect on the performance curves.

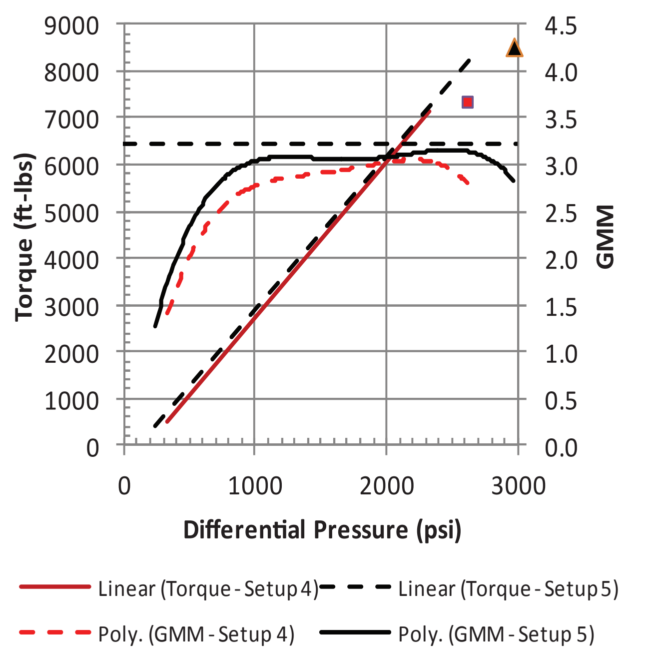
Two-speed drive heads generally exhibit a more non-linear GMM curve in the low-speed high-torque mode than single speed motors. This is illustrated in Figure 4 which shows the results from Test Setup No. 1 with the Pengo MDT-12K drive head. Since this drive head is a two-speed unit, both the high-speed low-torque and low-speed high-torque performance curves are shown. In this test, the gear motor shifted from high to low speed at a differential pressure of about 1800 psi. The test results show a small variation in the GMM in the low-speed high-torque mode with minimum and maximum GMM's of 4.1 and 4.5, respectively. It should be noted that the test GMM's were well below the GMM_M.

Figure 4: Pengo MDT-12K Test Setup No. 1



The effect of varying hydraulic line sizes and installation equipment was evaluated during Test Setups No. 4 and 5 with the Pro-Dig X9K5 drive head and illustrated in Figure 5. Although the test equipment and hose sizes varied between tests, the hydraulic flow rate was kept similar with maximum flow rates of 17 and 18 gpm for Test Setup No. 4 and 5, respectively. The test results show slightly higher GMM's and much higher maximum torque capacity with the larger hydraulic line sizes and Bobcat S250 versus the smaller hydraulic line sizes and Bobcat 430.

Figure 5: Pro-Dig X9K5 Test Setups No. 4 and 5



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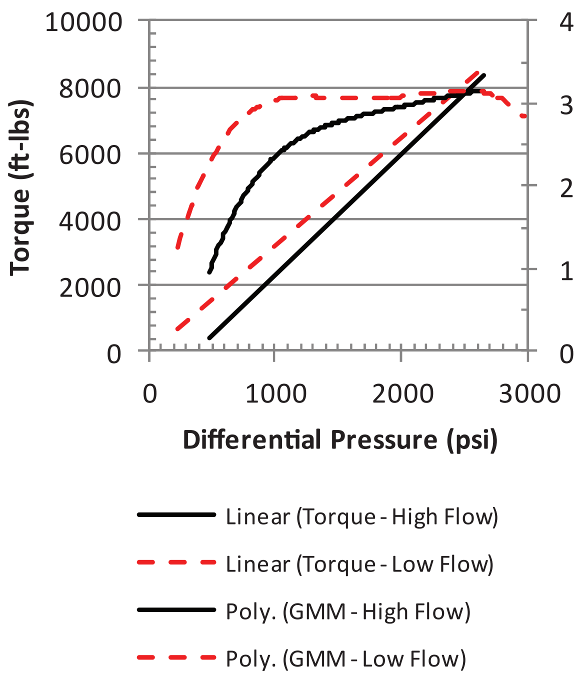
The effect of varying flow rate on the drive head performance curves was evaluated with the Pro-Dig X9K5 drive head in Test Setup No. 5 and is shown in Figure 6. The installation equipment and hydraulic line size was kept constant between the two tests with maximum flow rates of 18 and 38 gpm for the low-flow and high-flow tests, respectively.

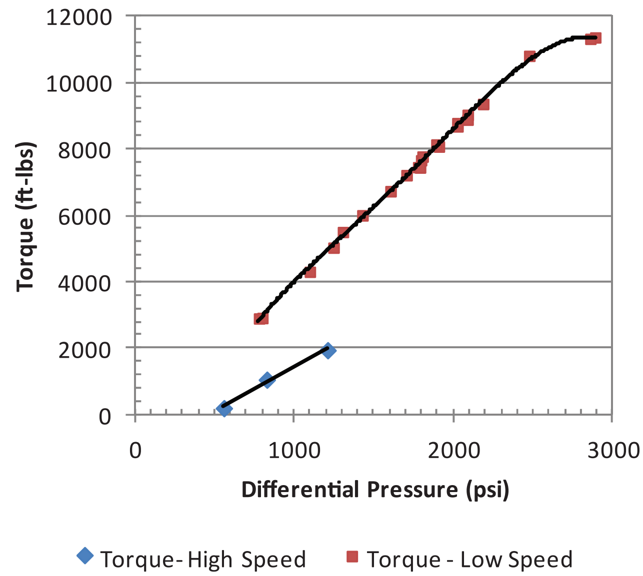
Figure 6: Pro-Dig X9K5 Test Setup No. 5



The test results show a higher GMM and torque versus differential pressure curve for the low flow versus high flow test. The variation is less pronounced at the upper differential pressure range and tends to be equal for both tests at a differential pressure of about 2700 psi. The maximum torque capacity of the drive head was fairly constant between the two tests.

Another characteristic of the torque versus differential pressure curve for most drive heads is the slight drop off of torque at the upper differential pressure range. This drop off in torque is usually right before the motor stalls out. The drop off prior to motor stall out is likely due to loss in motor efficiency at the high end resulting from hydraulic fluid cavitation within the hydraulic motor and/or hydraulic fluid internal slippage through the hydraulic motor components. Most of the data shown previously has ignored the drop off data points at the high pressure range and only the linear portion of the torque versus differential pressure curve is shown in the plots. The GMM curves have included these data points which result in the slight reduction in GMM at the very high end of the differential pressure range. The Pro-Dig T12K test results from Test Setup No. 6, illustrated in Figure 7, show the deviation from linearity at the high differential pressure range for the low-speed high-torque performance curve.

Figure 7: Pro-Dig T12K Test Setup No. 6



The remaining GMM and torque versus differential pressure curves for Setups No. 6 to 10 are shown in Figures 8 to 12, respectively. It should be noted that a high-speed low-torque curve for the Eskridge 78-48 hydraulic drive head is not displayed due to insufficient data points during testing.

Figure 8: Pro-Dig T12K Test Setup No. 6

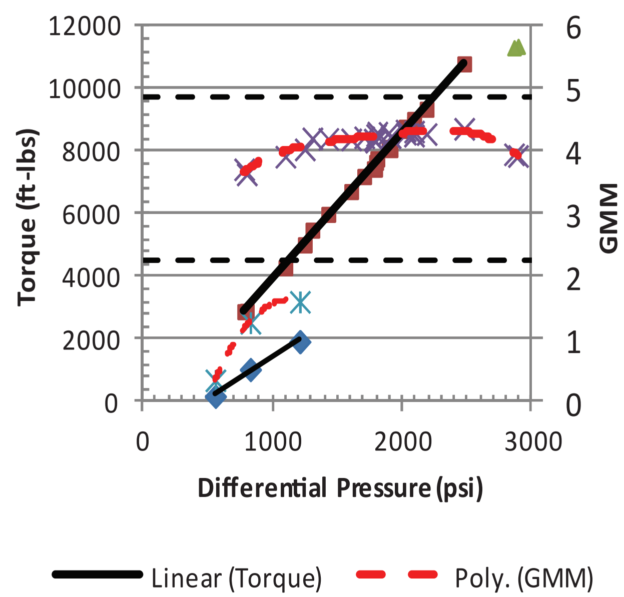


Figure 9: Pro-Dig T15K Test Setup No. 7

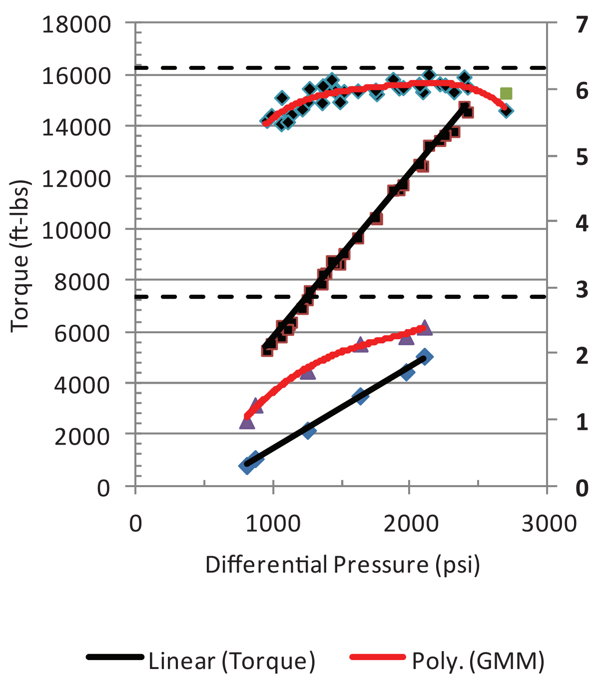


Figure 11: Eskridge 78-48 Test Setup No. 9

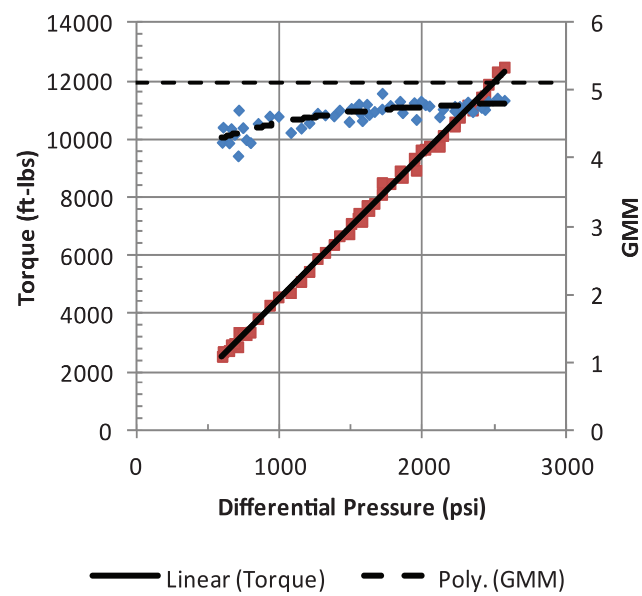


Figure 10: Eskridge 5016 Test Setup No. 8

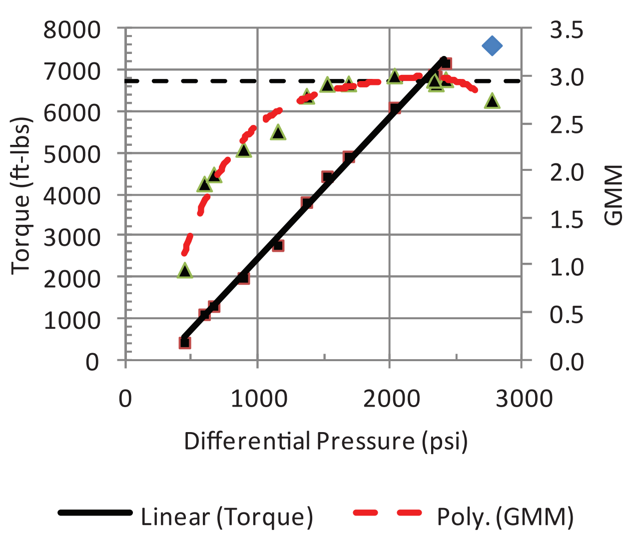
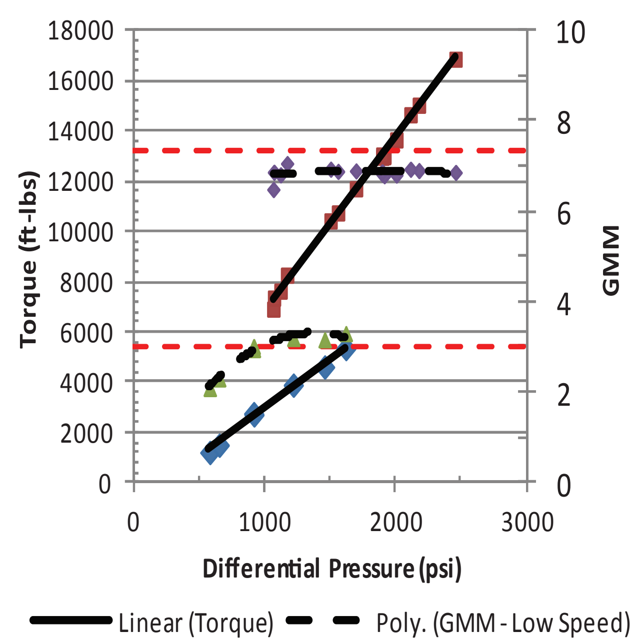


Figure 12: Eskridge 75-51 Test Setup No. 10



The GMM curve is the same shape as the efficiency curve which would vary across the differential pressure range. The test results show a much flatter GMM curve for the two-speed drive heads when operated in low-speed high-torque mode than the single speed drive heads. The maximum test efficiency (η_{test}) for each of the drive heads is compared to the manufacturers' back-calculated efficiency in Table 3. The maximum efficiency ratio included in Table 3 is the ratio of the tested maximum efficiency to the manufacturers' back-calculated efficiency. A maximum efficiency ratio greater than one indicates the tested maximum efficiency exceeds the manufacturers' back-calculated efficiency. It should be noted that the manufacturers assume a constant efficiency across the differential pressure range which is not in agreement with the test results. The maximum tested efficiency of the high-speed low-torque mode for the two-speed drive heads could not be determined due to the motor shifting prior to achieving the maximum efficiency.

Table 3: Drive Head Efficiency Test Results

Motor Make and Model	Motor Speed	Back Calculated Theoretical Efficiency (η)	Test Setup	Maximum Test Efficiency (η_{test})	Maximum Efficiency Ratio (η_{test}/η)
Pengo MDT-12K	Low	94%	1	80%	0.85
Pro-Dig L5K	Single	81%	2	75%	0.93
			3	74%	0.91
Pro-Dig X9K5	Single	82%	4	77%	0.94
			5	80%	0.98
Pro-Dig T12K	Low	89%	6	80%	0.90
Pro-Dig T15K	Low	86%	7	85%	0.99
Eskridge 5016	Single	78%	8	79%	1.02
Eskridge 78-48	Low	85%	9	82%	0.97
Eskridge 75-51	Low	85%	10	81%	0.96

Helical Pile Capacity

The torque correlation method is used to predict and/or verify helical pile capacity during installation. The relationship between torque and capacity is generally predicted by:

$$Q_u = K_t \times T$$

Where:

K_t = empirical torque correlation factor (ft^{-1})
Q_u = ultimate capacity of the pile (lbs)
T = final installation torque (ft-lbs)

The torque correlation factor is highly dependent upon shaft size with the following default values published in the Acceptance Criteria for Helical Foundation Systems and Devices (AC358) by the International Code Council Evaluation Service, Inc. (ICC-ES) for conforming product:

Table 4: Default K_t Values (AC358)

Shaft Type	Shaft Outer Diameter (in).	Kt (ft^{-1})
Square	1.5	10
Square	1.75	10
Round	2.875	9
Round	3.0	8
Round	3.5	7

The ability to accurately predict pile capacity is directly related to the precision of the method used to determine torque in the field. Many helical pile installing contractors currently use the GMM_M and the differential pressure across the gear motor to predict installation torque. The current research shows that the GMM_M is not an accurate predictor of torque and may result in actual safety factors well below predicted. For example, Test Setup No. 1 with the Pengo MDT-12K drive head illustrated in Figure 4 showed a low-speed high-torque GMM ranging from about 4.1 to 4.5 versus the manufacturers published GMM_M of 5.48. The use of the GMM_M versus the actual test GMM could result in pile capacities about 25% less than predicted in the low-speed high-torque mode for this particular drive head.

Conclusion

The test results show two general trends in the torque to differential pressure curve; an x-axis offset from the manufacturers published data and a flattening or slight drop off of the curve at the high pressure range prior to motor stall out. These two characteristics combine to make the GMM curves non-linear across the differential pressure range versus the constant GMM_M values published by the drive head manufacturers.

Other factors that may affect the torque versus differential pressure curve appear to be the installation flow rate and the installation equipment flow capacity. The Pro-Dig X9K5 tests shown in Figure 6 indicate a higher GMM (at the low to mid differential pressure range) when the same installation equipment is used at a low installation flow rate versus a high installation flow rate. The Pro-Dig X9K5 tests shown in Figure 5 indicate that the higher capacity installation equipment in addition to the larger hydraulic line sizes makes a slight difference in the shape of the torque and GMM curves at similar flow rates, however a significant increase in output torque was achieved with the higher capacity installation equipment.

The Pro-Dig L5K tests shown in Figure 3 indicate little variation in the shape of the GMM and torque versus differential pressure curve when the only change is an increase in hydraulic line size.

Drive head efficiency will vary between manufacturer make and model based on the type of hydraulic motor and number of planetary gear stages in the system. The efficiency of a single speed hydraulic gear motor generally ranges from 90 to 95 percent and efficiency losses on the order of 3 to 5 percent per planetary gear stage are typical. Two-speed hydraulic gear motors typically have higher efficiencies in the low-speed high-torque mode compared to the high-speed low-torque mode. The efficiency of a hydraulic motor also varies with the differential pressure; however, drive head manufacturers assume constant efficiencies across the entire differential pressure range.

The ability of a particular drive head to perform near the manufacturers published performance curve at the high differential pressure range could be roughly predicted by evaluating the efficiencies used to develop the performance curves. For example, the Pengo MDT-12K motor has a back calculated drive head efficiency of 100% in the high-speed low-torque mode which is unreasonable given the typical efficiency losses in the hydraulic motor and planetary gear system.

More testing is needed to confirm the effect of flow rate, hydraulic line size and installation equipment variations on hydraulic drive head performance curves.

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