North American Society for Trenchless Technology (NASTT)
No-Dig Show 2011

Washington, D.C.
March 27-31, 2011

Paper A-2-02

QUANTIFYING THE EFFECTS OF LUBRICATION ON JACKING FORCES

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ABSTRACT: The prediction of jacking forces has become a critical component in the planning, design and construction of microtunneling projects. While there are a number of models that can be used to predict jacking forces, quantifying the effects of lubrication on the estimated jacking force can be very difficult. Although it is commonly understood that lubrication can decrease jacking forces to a manageable level during construction, a wide variety of application strategies are used in the field resulting in varied degrees of effectiveness.

While lubrication is frequently used on microtunneling jobs, the effects of lubrication timing, pumping rate, and application strategies are not well understood. This paper seeks to analyze the effects of these factors by examining drives of an 84-inch microtunneling project where lubrication strategies and soil conditions varied by drive. Detailed records of lubrication application, soil type, and jacking force for each drive will be compared to quantify the influence of the lubrication on the observed jacking forces. It is hoped that a better understanding of the effects of lubrication will aid both in jacking force prediction and in the overall planning and design of microtunneling projects.

1. INTRODUCTION

A critical analysis of jacking forces and the effects of lubrication was performed on a project in Portland, Oregon where 84-inch reinforced concrete pipe with a 101.5-inch outer diameter was jacked on a series of five microtunneling drives in varying soil conditions. The designed drive lengths on the project were relatively long, ranging from 1,134 to 1,686 feet, making the prediction of estimated jacking forces an important part of proper shaft thrust wall design as well as intermediate jacking station planning and fabrication quantity. Prior to construction, estimated non-lubricated jacking forces were calculated using a model developed by Staheli (2006). A lubrication reduction factor was then multiplied by the result to obtain the estimated lubricated jacking forces.

During construction, the contractor used an automated lubrication system where the operator had the ability to pump lubrication to any single port within the pipeline for a specific length of time. The pumping rate was controlled by the operator of the bentonite plant. The location of bentonite and the application and volumes that were pumped were evaluated for the first tunnel drive and compared to the jacking forces observed during construction. Based on these observations, the bentonite lubrication application scheme was modified for the second tunnel drive and the subsequent impacts to jacking loads were recorded. This paper explores the effect of the lubrication schemes on the jacking forces observed during the two tunnel drives, and discusses the success of both the original and modified schemes on each of the two drives. The remaining three tunnel drives on the project have not yet been constructed.

2. NON-LUBRICATED PREDICTIONS

The non-lubricated frictional component of the jacking force for each drive was based on an interface friction model developed by Staheli, 2006. This model considers the surface roughness of the jacking pipe and the residual friction angle of the soil through which the pipe is jacked. Staheli (2006) developed interface friction coefficients for a number of different jacking pipe materials over a range of soil residual friction angles, as shown in Table 1.

Table 1. Interface Friction Coefficients for Various Pipe Materials and Soil Residual Friction Angles (after Staheli, 2006).

Residual Friction Angles	**Interface Friction Coefficient between Soil and Pipe**					
	Hobas	**Polycrete**	**Permalok Steel**	**Wet Cast Concrete**	**Vitrified Clay Pipe**	**Packerhead Concrete**
25	0.37	0.40	0.38	0.43	0.42	0.49
26	0.39	0.41	0.40	0.45	0.44	0.50
27	0.41	0.42		0.47	0.46	0.52
27.9 Ottawa 20/30	0.43	0.43	0.44	0.48	0.48	0.53
28	0.43	0.43	0.44	0.48	0.48	0.53
29	0.45	0.44	0.46	0.50	0.50	0.55
30	0.47	0.45	0.48	0.51	0.52	0.56
31	0.49	0.46	0.51	0.53	0.54	0.57
32	0.51	0.47	0.53	0.55	0.56	0.59
33	0.53	0.48	0.54	0.56	0.58	0.60
34	0.55	0.49	0.57	0.58	0.60	0.61
34.6 Atlanta Blasting	0.56	0.49	0.58	0.59	0.61	0.62
35	0.57	0.49	0.59	0.60	0.62	0.63
36	0.59	0.50	0.61	0.61	0.64	0.64
37	0.61	0.51	0.63	0.63	0.66	0.65
38	0.62	0.52	0.65	0.65	0.68	0.67
39	0.64	0.53	0.67	0.66	0.70	0.68
40	0.66	0.54	0.69	0.68	0.72	0.69

Staheli (2006) further developed a model for predicting the non-lubricated frictional component of jacking force as follows:

$$JF_{frict} = \mu_{\text{int}} \frac{\gamma \cdot r \cdot \cos\left(45 + \frac{\phi_r}{2}\right)}{\tan \phi_r} \cdot \pi \cdot d \cdot l$$

Where
JF_{frict} = Frictional Component of Jacking Force [tons force]
μ_{int} = Pipe-Soil Residual Interface Friction Coefficient (from Table 1)
γ = Total Unit Weight of the Soil [tons/ft^3]
ϕ_r = Residual Friction Angle of the Soil [degrees]
d = Pipe Diameter [feet]
r = Pipe Radius [feet]
l = Length of the Pipe [feet]

Once non-lubricated frictional loads were calculated for each drive, a lubrication reduction factor of 0.80 to 0.90 was applied to the non-lubricated estimate based on field observations of lubrication force reduction. Thrust wall design and intermediate jacking station fabrication quantity were based on a 0.80 lubrication reduction factor for conservatism.

3. ANALYSIS OF JACKING FORCES FOR THE FIRST DRIVE

The first drive on the project is shown in profile in Figure 1. The total length of the drive was 1,640 feet and ranged in depth from 34 to 44 feet. A total of seven vertical soil borings were completed for this drive during the design phase of the project along with several geo-probes. The soil along the length of the drive was fairly consistent in terms of composition, but varied significantly in terms of density.

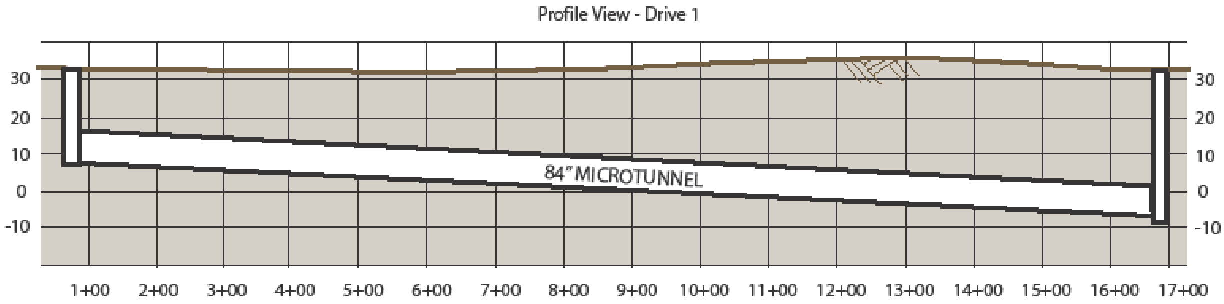

Figure 1. Profile View of Drive 1.

The soil was characterized by the geotechnical engineer as Guilds Lake Alluvium (Shannon and Wilson, 2009) and varied in density from very soft to medium stiff. The soil was described in the Geotechnical Baseline Report (Staheli Trenchless Consultants et al., 2009) as "very soft to soft silt, clayey silt, and clay. Minor constituents in the soft native soil are fine-grained sand in trace amounts and variable amounts of natural leafy and woody material." Prior to construction, jacking forces for the drive were estimated based on the soil properties from the geotechnical investigation. A total unit weight of 100 pounds per cubic foot was chosen to represent the soft clay with a residual friction angle of 26 degrees. Based on the use of wet cast concrete and the values listed in Table 1, an interface friction coefficient of 0.45 was used in the jacking force model to estimate the frictional component of the jacking forces. Figure 2 shows both the predicted and actual jacking forces on Drive 1. A lubrication reduction factor of 80% was applied to the Interface Friction Coefficient to develop the estimated lubricated jacking forces.

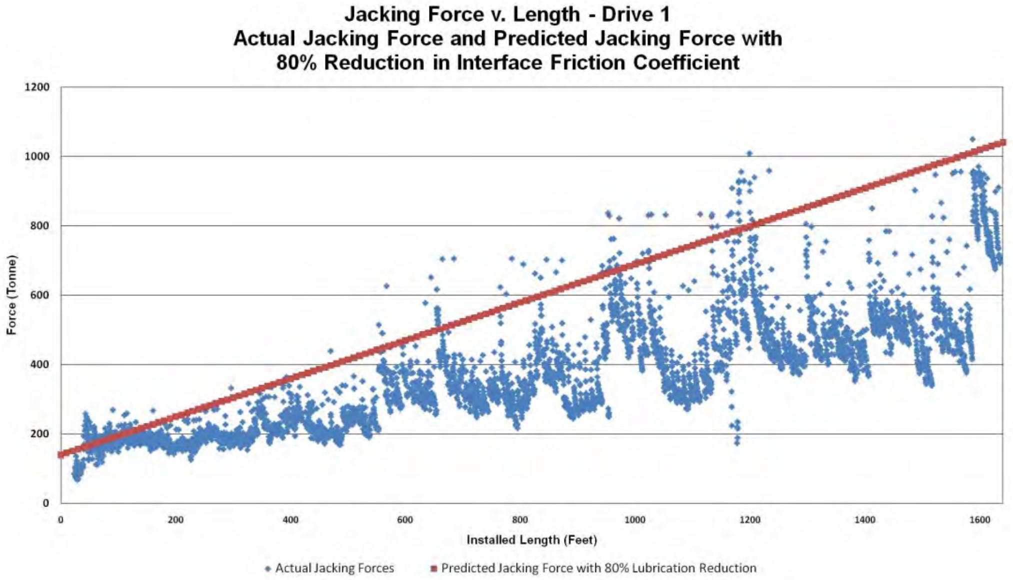

Figure 2. Jacking Force v. Length for Drive 1—Actual Jacking Forces and Predicted Forces using an 80% Reduction of Interface Friction Coefficient for Lubrication.

Since the analysis for the first drive was a “back analysis” that was completed after the drive was completed, the authors had the luxury of having specific soil information along the length of the drive along with the jacking record. This allowed the authors to separate the jacking record into distinct zones for analysis that could be analyzed on an individual basis. The drive was separated into 11 distinct zones that were based on changes in soil composition and distinct changes in jacking forces (i.e. where there were breaks on the slope of the jacking force curve or where the slope of the curve went from positive to negative). Table 2 shows the length and soil properties for each zone. Note that Zones 8 through 11 had the same soil properties, with the zones being distinguished based on distinct changes in the jacking force graph.

Table 2. Analysis Zones for Drive 1 with Total Unit Weight, Residual Friction Angles, and Interface Friction Coefficients.

Zone	Length [feet]	Estimated Total Unit Weight [pcf] (based on GDR)	Estimated Residual Friction Angle [ϕ'_r]	Interface Friction Coefficient [μ_{int}] (Based on Table 1)
1	0-450	95	25	0.43
2	460-640	100	26	0.45
3	650-780	110	28	0.48
4	790-820	110	27	0.47
5	830-880	105	27	0.47
6	890-960	100	26	0.45
7	970-1080	95	25	0.43
8	1090-1200	105	27	0.47
9	1210-1270	105	27	0.47
10	1280-1580	105	27	0.47
11	1580-1640	115	28	0.48

Once these distinct zones were identified, the jacking force graph was broken down into these zones and the jacking force estimates were refined to reflect the parameters within Table 2. A multiplier was then applied to the non-lubricated interface friction coefficient to determine the amount of actual friction reduction that was realized in the zone due to the composite lubrication in the section. Figure 3 shows the graph for Zone 1 (0 to 450 feet into the drive) with the actual jacking forces, the predicted non-lubricated jacking forces, and the predicted lubricated jacking forces. The lubricated jacking forces were back-calculated, adjusting the value for the interface friction coefficient to determine the percent reduction due to the lubrication. For Zone 1, the decrease in friction due to the application of lubrication was 93.5%.

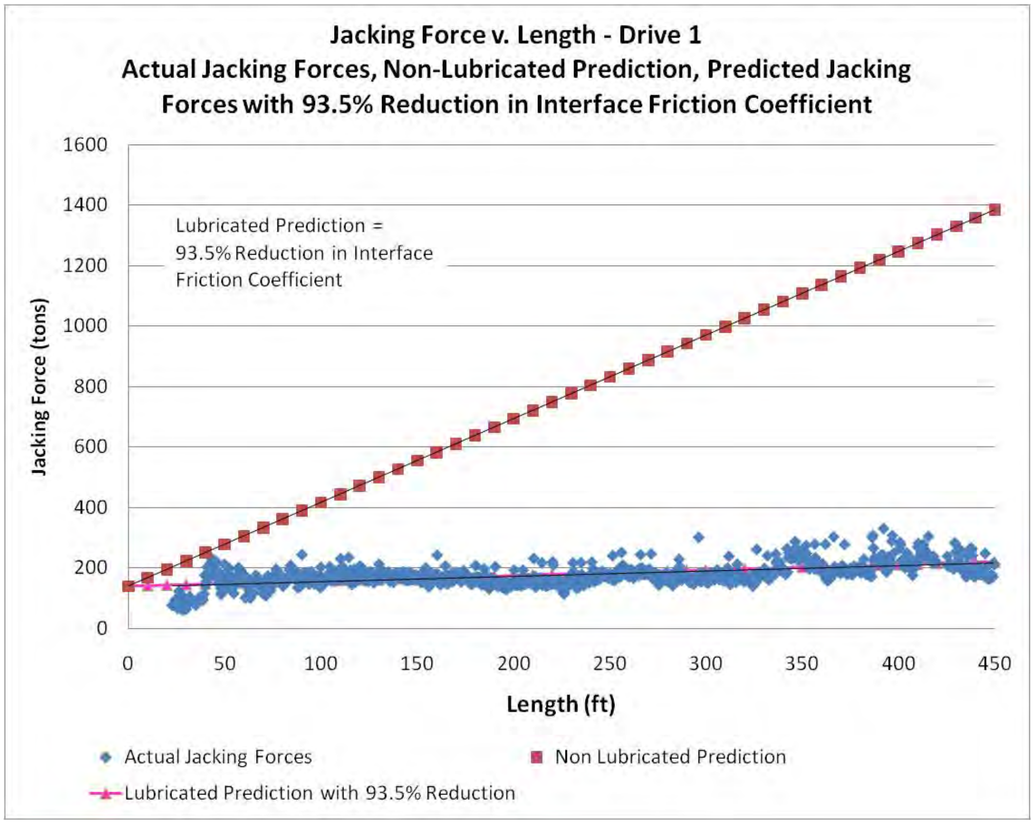

Figure 3. Jacking Force v. Length for Drive 1—Actual Jacking Forces and Predicted Forces from 0 to 450 feet using a 93.5% Reduction of Interface Friction Coefficient for Lubrication.

A similar analysis was carried out for each of the 11 zones of the drive to determine how the lubrication affected the interface friction coefficient. Table 3 shows reduction in interface friction coefficient throughout the various zones of the drive. It is important to note that the reduction in interface friction coefficients is only listed in zones in which the overall jacking force is increasing, comparing the composite interface friction coefficient with the composite non-lubricated friction coefficient through that zone. If one were to use the same analysis in the zones where the overall jacking force was decreasing, the interface friction coefficient would have to be negative, which does not make physical sense. Instead, in those zones where the overall jacking force is trending downward, it is assumed that lubrication is being applied to areas which had not previously been lubricated, or is being more liberally applied to areas that had already had some lubrication, causing the interface friction in those areas to decrease, thus decreasing the total jacking force. Since the analysis is based on the total jacking force using a composite interface friction coefficient as the tunnel progressed through the various zones, the percent decrease is only evaluated in the zones in which the jacking force is increasing.

Table 3. Reduction in Interface friction Coefficient in Zones of Increasing Jacking Forces in Drive 1.

Zone	**Percent Reduction in Interface Friction Coefficient [%]**
1	**93.5**
2	**73**
4	**11**
6	**0**
8	**9**
10	**97**

4. APPLICATION OF LUBRICATION

Due to the wide range of reduction in the interface friction coefficient, it was necessary to analyze the lubrication application scheme to determine the impact on the overall jacking forces. The Contractor used an automated bentonite lubrication system which was programmed to pump at a particular port for a specified length of time and then move to the next port as specified by the operator. The actual pumping rate was determined by the bentonite plant operator and could be adjusted during the installation at the bentonite plant (with or without the microtunneling machine operator's knowledge). For Drive 1, the first bentonite port was located at the machine and all additional ports were plumbed within the pipeline on 40-foot centers. The computer was programmed to pump at the machine for 10 seconds and then pump sequentially down the pipeline at each port for 10 seconds. Once the last port in the pipeline was pumped for 10 seconds, the bentonite would return to the machine for 10 seconds and the process would start over from the beginning. This continued throughout the length of the drive. The overcut on the machine cut a diameter of 104.5 inches for the pipe outer diameter of 101.5 inches. Therefore, the total volume of overcut per foot of length tunneled was 3.37 cubic feet. This would require a total of 25.2 gallons, or 95.4 liters of bentonite to completely fill the annular space around the microtunneling machine.

The microtunneling equipment measured the lubrication in the units of liters/minute and the tunneling rates were measured in meters/minute. Depending on the tunneling speed, the flow rate of the bentonite was adjusted to ensure that the annular space was completely filled by bentonite. However, with the lubrication scheme that was used—moving down the tunnel in 10 second intervals—the further the machine advanced, the less effective the lubrication scheme became.

Table 4. Impacts of Lubrication Scheme on Normalized Jacking Force.

Zone	Length Range [feet]	Normalized Jacking Force [tons/ft^2]	Average Speed [m/min]	Min. Pumping Rate to Fill Annular Space [l/min]	Number of Bentonite Ports in Pipeline	Max Delay between pumping at Head [sec]	Distance Tunneled at Head w/o lubrication [ft]
1	0-450	0.006	0.09	23.4	11	112	0.6
2 & 3	450-780	0.015	0.11	28.6	19	192	1.2
4 & 5	790-880	0.048	0.13	33.8	22	217	1.5
6	890-960	0.073	0.08	20.8	24	240	1.0
8	1090-1200	0.109	0.12	31.2	30	300	2.0

Table 4 shows the average speed of tunneling throughout each zone and the minimum flow rate of the bentonite that was required to completely fill the annular space at the time of pumping. During actual tunneling, the bentonite pumps were set to 30 liters/min which was sufficient to fill the annular space in Zones 1, 2, 3 and 6. However, when the tunneling speed increased to beyond 0.11 meters/min, the pumping rate was not sufficient to completely fill the annular space.

Table 4 shows jacking forces to increase as tunnel length increases. The authors believe that this is largely due to the lubrication scheme that was used. By pumping the ports sequentially, the tunneling machine was allowed to advance a significant distance without any lubrication applied to the leading portion of the excavation. If one considers a full cycle of the lubrication as the tunneling machine advanced through Zone 8 (1090 to 1200 feet into the tunnel), the lubrication was applied at the machine for 10 seconds and then continued down the pipeline for 10 seconds at each port. However, it was a full 300 seconds before the lubrication returned to the head, allowing a full two feet of excavation to take place before lubrication was pumped at the machine again. Adding this to the fact that when they did pump in Zone 8, the pumping rate was below the volume required to fill the theoretical annular space, it is easy to see why the normalized jacking force increased concurrent with the length of the pipe.

5. THE SECOND DRIVE

The second drive on the project was 1,165 feet in length, ranged in depth between 44 and 53 feet deep, and is shown in profile in Figure 4. The soil conditions on the second drive were very similar to those on the first drive in composition; however, they were slightly higher in density. Soils on the second drive consisted of sands and silts ranging from loose to medium dense. For the purposes of estimating jacking forces on the drive, a total unit weight of 125 pounds per cubic foot was used for the silty sand with a residual friction angle of 28 degrees. This resulted in a non-lubricated interface friction coefficient of 0.48.

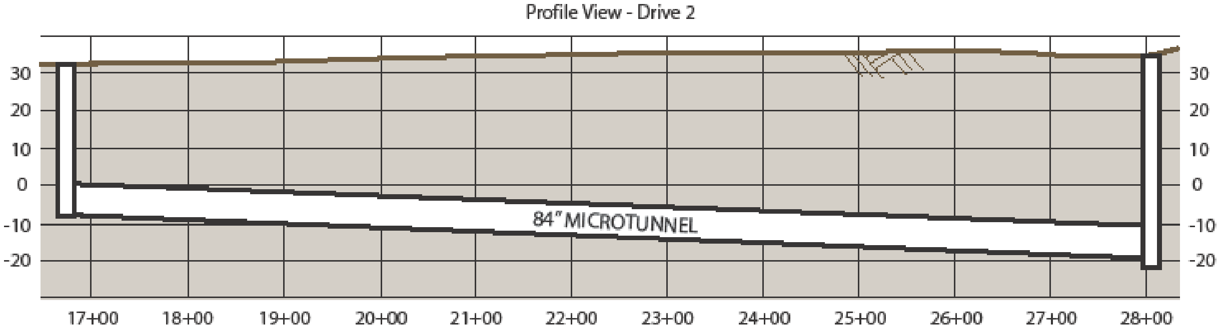

Figure 4. Profile View of Drive 2.

6. CHANGES TO THE LUBRICATION SCHEME

Based on the analysis of the first drive, it was determined that on longer drives (i.e. drives longer than 350 feet), it was necessary to change the lubrication scheme and pump lubrication at the head of the microtunneling machine on a more frequent basis. Initially it was decided to pump at the head on every third injection sequence, i.e. at the head, the first port, the second port, the head, the third port, the fourth port, the head, etc. However, during the drive when they were approximately 160 feet into the tunnel, the operator decided to have a dedicated lubrication line to the tail end of the microtunneling machine and to use the automated system to supplement the lubrication on the pipe string in a sequential matter, very much like the first drive.

Figure 5 shows the actual jacking forces observed during the drive and the estimated jacking forces with a 90% reduction on the interface friction coefficient due to lubrication.

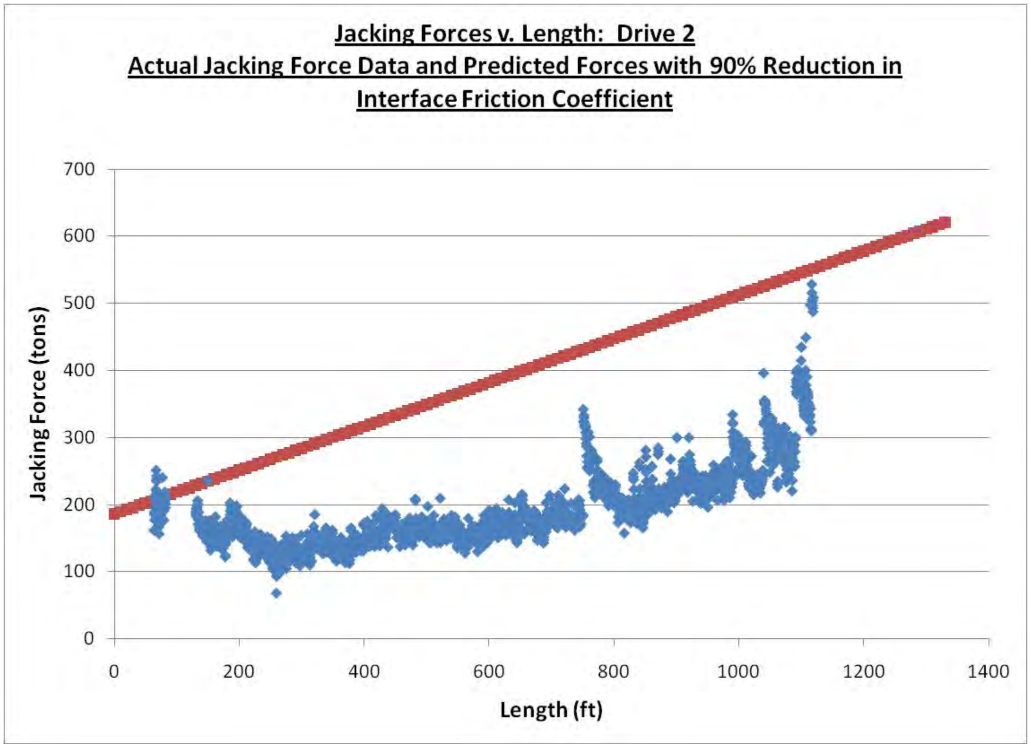

Figure 5. Jacking Force v. Length for Drive 2—Actual Jacking Forces and Predicted Forces using a 90% Reduction of Interface Friction Coefficient for Lubrication.

Figure 5 shows a clear drop in the jacking forces at approximately 160 feet, when the dedicated lubrication line was connected at the first port located at the tail end of the machine. Once the forces decreased in the zone between 250 and 700 feet, bentonite was pumped at a rate that markedly exceeded the amount necessary to completely fill the annular space. As a result, jacking forces remained extremely low. Figure 5 shows the jacking forces between 250 and 700 feet and back-calculates the decrease in interface friction coefficient due to the lubrication in this zone. Throughout this zone, the jacking forces realized a 96.6% decrease in the interface friction coefficient due to lubrication.

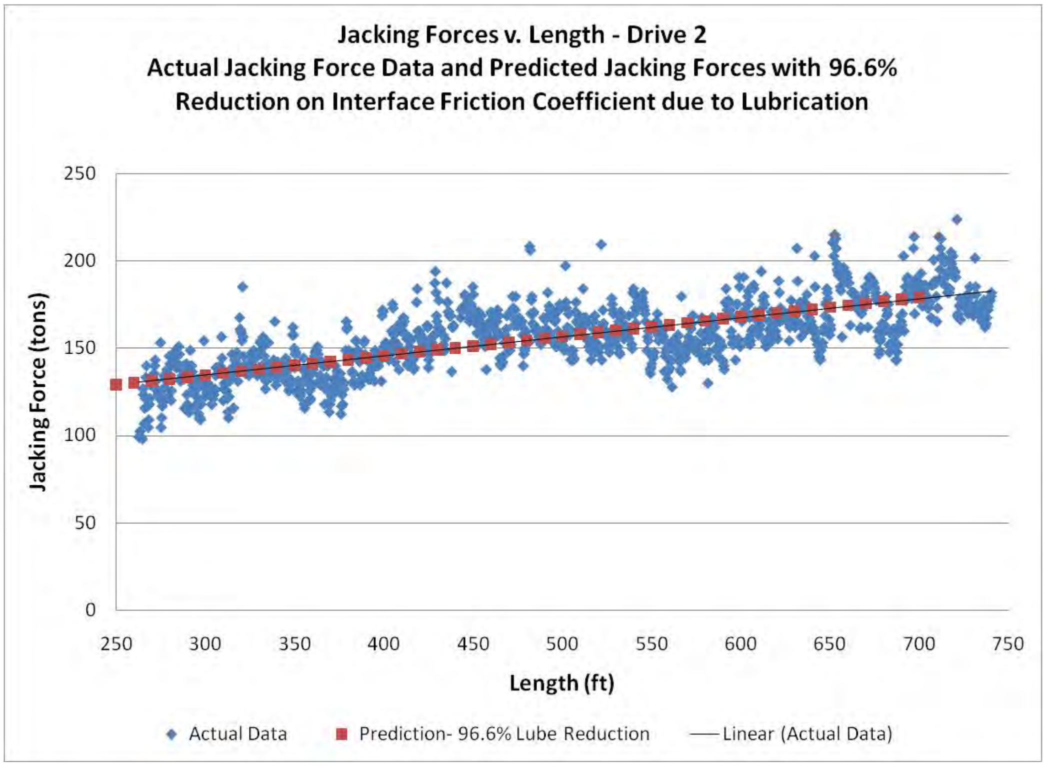

Figure 6. Jacking Force v. Length for Drive 2—Actual Jacking Forces and Predicted Forces from 250 to 750 feet using a 96.6% Reduction of Interface Friction Coefficient for Lubrication.

Although there was a spike in the jacking forces at approximately 780 feet (due to a long period of shut-down without movement or lubrication), one can see from Figure 5 that once jacking and lubrication resumed, the jacking forces continued along the same trend as during the zone depicted in Figure 6, with a marked decrease in the interface friction coefficient due to lubrication—evidence that the change in lubrication scheme from the first drive was very successful in managing jacking forces.

7. CONCLUSIONS

The use of bentonite lubrication has been shown to have a marked impact on jacking forces. Serious consideration should be given not only to the amount of lubrication pumped but also to the location of the pumping ports. When using an automated bentonite system, it is important to consider the length of the drive, the rate of tunnel advance, and the amount of time between injection intervals at the microtunneling head to ensure that excavation does not occur without sufficient lubrication. If the automated bentonite system is set to lubricate sequentially down the pipeline and the drive is longer than approximately 350 feet, the advance rate of the machine could result in tunnel excavation without lubrication, seriously impacting the overall jacking force on a project. In these cases, serious consideration should be given to having a dedicated bentonite line to the microtunneling machine to reduce the amount of tunnel excavation that will occur without any lubrication.

8. REFERENCES

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