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Estimating the Required Jacking Force

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Session D

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ABSTRACT

The process of estimating the required jacking force to jack a pipe through the ground was, and still is, an art requiring much experience and good judgement. Many factors and risks affect the determination of the jacking force. This paper is an attempt to use civil engineering techniques to rationalize and compare methods for estimating the required jacking force. Four of these methods are summarized and used to estimate the jacking loads on a job completed in Staten Island, New York. The actual and predicted results are compared.

The frictional resistance values estimated based on Terzaghi's silo theory with the parameter values selected based on guidance given in the German AWPC manual "ATVA 161" and in the Kubota are five to seven times higher than the average actual jacking forces. On the other hand, the frictional resistance force calculated by Marston's formula and Terzaghi's coefficient are about twice the average actual jacking force. Therefore, based on this comparison only, multiplying the force calculated by these latter two formulas by an adequate factor of safety would be more appropriate. Terzaghi's theory with the parameter set of the ATVA 161 and Kubota method are conservative but not the most economical solution. The penetration or tip resistance values estimated using the shear strength resistance method are much lower than those calculated using the passive earth pressure method, which represents the most conservative method.

INTRODUCTION

In pipe jacking and microtunneling, the jacking pipe carries axial (horizontal) loads during the construction (jacking) phase and vertical loads from soil, surcharge, and live loads both during and after jacking. It is important to calculate these loads as accurately as possible to

- design the jacking pipe safely and economically.
- Select the jacking system capacity
- determine the jacking distance and spacing between intermediate jacking stations,
- design the jacking pit and thrust block,
- choose the jacking method and equipment.
- Stabilize the face of excavation to prevent soil failure

In pipe jacking and microtunneling, the jacking force must overcome the frictional resistance of the pipe in the ground (skin friction), as well as the penetration resistance of the jacking shield or boring machine and steering head into the ground. If the soil is excavated at the face under compressed air or fluid support, then the fluid or air pressure applied is to be taken into account in the determination of the penetration resistance. As shown in Figure 1, the required jacking force P is calculated as follows:

$$P = P_p + P_f + P_w \quad [F] \tag{1}$$

Where

P = Total jacking force [F]
P_p = Penetration resistance [F]
P_f = Friction between soil and pipe due to soil pressure [F]
P_w = Friction between soil and pipe due to pipe weight [F]

$$P_w = \mu \times W_p \qquad [F] \tag{2}$$

where

μ = Coefficient of friction between soil and pipe
W_p = weight of the pipe. [2]

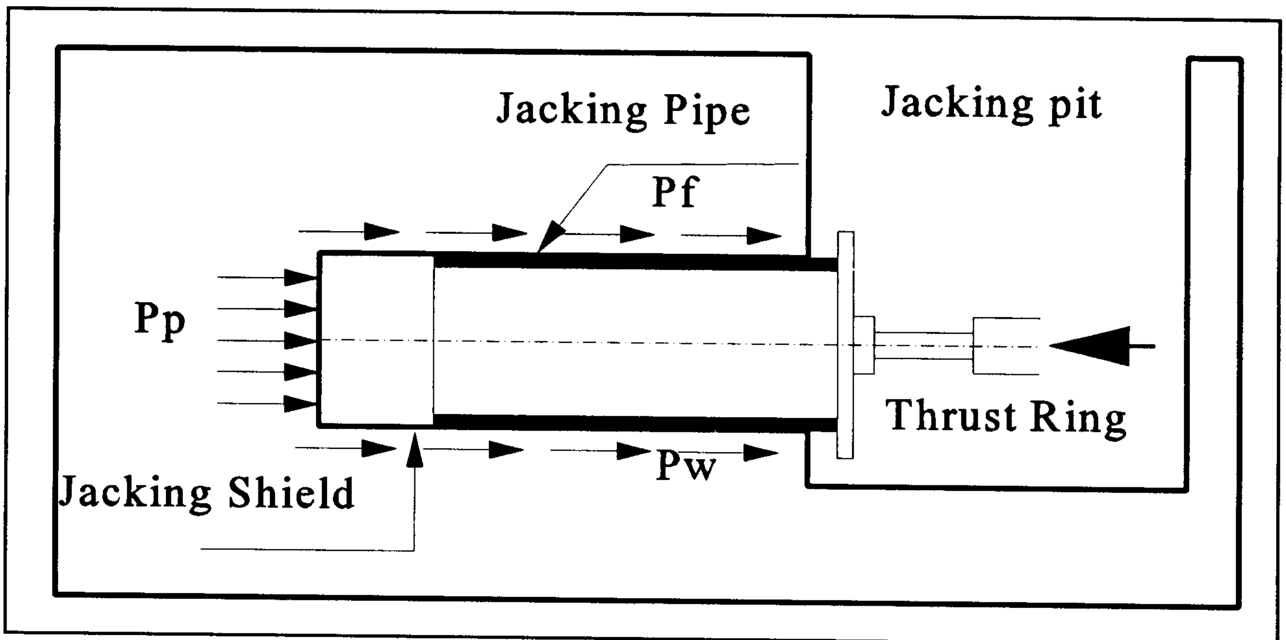

Figure 1 Components of the Jacking Force during the Construction Phase.

Penetration Resistance

The penetration resistance opposes the advance of the jacking shield or the boring head throughout the jacking operation. The penetration resistance varies depending on the shape and the action of the shield/head, and on the position of the face of excavation relative to the tips of the shield. It is called cutting edge resistance when an open jacking shield or auger microtunneling machine is used and face resistance when a closed boring machine such as a slurry microtunneling machine is used. [8]

Cutting Edge Resistance

There are various methods to calculate the cutting edge resistance. The differences among these methods depend on how the soil reacts to the cutting edge to generate the tip resistance. In the first method, the determination of the cutting edge resistance is based on statistical review of previous jacking jobs to get empirical values for the tip resistance. In the second method, the tip resistance is built up and calculated from the shear strength of the soil; and in the third method, the tip resistance is built up and determined from the passive earth pressure of the soil. In the three methods, the cutting edge resistance is the product of the cutting edge area by the tip resistance in the soil as follows:

$$P_p = \pi \times D_o \times t \times P_s \qquad [F] \tag{3}$$

where

D_o = cutting edge diameter [L],
t = cutting edge thickness [L],
p_s = tip resistance [F/L^2]. [8]

<u>**Empirical methods**</u>. Empirical values of the tip resistance are calculated through statistical studies of previous jacking jobs. The tip resistance p_s is dependent on the soil type as shown in Table 1. The values in Table 1 are based on an analogy with calculations of the load-bearing capacity of cast-in-place piles. Moreover, these values have been confirmed by recalculating previous pipe jacking jobs. [8]

TABLE 1
TIP RESISTANCE DEPENDING ON SOIL TYPE [8]

Soil Type	P_s [psi]
Rock-like soil	17,400
Gravel	10,150
Sand, dense bedding	8,700
Sand, medium dense bedding	5,800
Sand, loose bedding	2,900
Marl	4,350
Tertiary clay	1,450
Silt, Quaternary clay	580

On the other hand research conducted in Germany, utilizing theoretical and experimental examinations involving the use of mathematical models of microtunneling, indicated that the tip resistance ranges from 435 to 870 psi. The purpose of the research was to establish the relation between tip resistance and specific marginal conditions regarding type of soil, height of cover, and cutting edge design. [8] These values, which are far lower than the values shown in Table 1, may be more appropriate because they are based on simulations with microtunneling methods.

<u>**Shear strength resistance method**</u>. In this method, the tip resistance is equal to the shearing strength of the soil. The edge of the shield is resisted by the shear strength of the soil, cohesion and friction, reduced by the bearing coefficient λ dependent on the angle of internal friction ϕ as shown in Figure 2. The following equation is based on statistical evaluation of construction site records (Table 2) and tests made in the laboratory. [8]

$$P_p = (w \times H \times \tan\phi + c)\lambda \times \pi \times D_o \times t \qquad [F] \qquad (4)$$

where

w = soil density $[F/L^3]$,
H = depth of cover [L],
ϕ = angle of internal friction [°],
c = soil cohesion $[F/L^2]$,
λ = coefficient of load bearing capacity (equivalent to N_c in Meyerhoff equation to calculate the bearing capacity) [-]
D_o = cutting edge diameter [L],
t = cutting edge thickness [L].

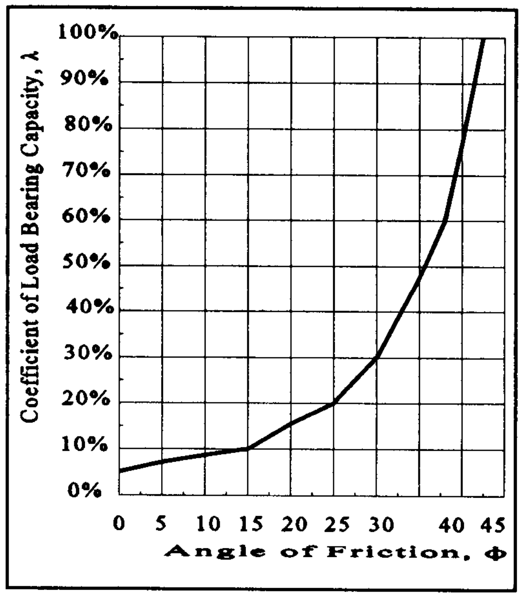

Figure 2 Coefficient of Load Bearing Capacity, λ, vs Angle of Friction, ϕ. Note that λ is equivalent to the bearing capacity factor, N_c, in Meyerhoff equation.

TABLE 2
STATISTICALLY DETERMINED CUTTING EDGE FORCE BASED ON SITE RECORDS [8]

Soil Type	Cutting Edge Force, [lb/ft]
Gravel, sand	3900 ± 1367
Loamy sand	4580 ± 1367
Loam	6700 ± 1367
Loam stones	6835 ± 1367

Passive earth pressure method. The tip resistance is assumed to be equal to the passive earth pressure of the soil. The cutting edge has to overcome the passive earth pressure in order to penetrate forward. The tip resistance values calculated from the passive earth pressure method are much higher than those calculated from the shearing strength method. The passive earth pressure method does not consider the effect of soil cohesion in the earth pressure calculation in spite of the fact that the cohesion increases the penetration resistance of the soil. Yet it still represents the upper limit (the most conservative method) for calculating the tip resistance. The following equation determines the penetration resistance:

$$P_p = [\pi \times D_o \times t] \times [w \times (H + D_o/2) \times \tan^2(45 + \phi/2)] \qquad [F] \qquad (5)$$

Because the cross sectional area of cutting edge is small, the tip resistance in most soft soils is small, compared to the frictional resistance. However, the tip resistance can be a significant component of the jacking loads in rock and similar stable soils where large over cut and adequate lubrication are used to reduce friction.

Face Resistance

The penetration resistance of the closed shield/boring head is called face resistance, P_f, to distinguish it from the edge resistance of the open shield. The face resistance is composed of the following two components:

- boring head contact force on the face, P_1.
- hydraulic force in the suspension chamber to support the face and remove the soil, P_2.

Boring head contact force. The contact force has to be higher than the force resulting from active earth pressure acting on the area of the face and lower than the force resulting from passive earth pressure acting on the area of the face in order to avoid slumping the face and settlement of the soil, or heaving the ground surface. The boring head contact force is calculated as follows:

$$P_1 = \frac{\pi}{4} \times d_1^2 \times p_b \qquad [F] \tag{6}$$

where

d_1 = boring head diameter [L],

p_b = boring head contact pressure [F/L²]. [2]

To satisfy the above mentioned conditions, $w(H+d_1/2)k_A > P_1 > w(H+d_1/2)k_P$ where k_A is the coefficient of active earth pressure = $\tan^2(45-\phi/2)$, k_P is the coefficient of passive earth pressure = $\tan^2(45+\phi/2)$, and H is the depth of soil cover.

The hydraulic supporting force in the suspension chamber. The pressure in the suspension chamber serves to create the equilibrium of forces between the face and the existing hydrostatic pressure whose value depends on the ground water level. The hydraulic supporting force "P_2" should be greater than the force generated by water pressure at the face by 10% to 20% to ensure adequate support, and it is calculated as follows:

$$P_2 = (1.1 \rightarrow 1.2)\ \frac{\pi}{4} \times d_{sh}^2 \times p_w \qquad [F] \tag{7}$$

where

d_{sh} = inside diameter of the shield tunneling machine [L],

p_w = water pressure [F/L²]. [8]

$$P_w = w_w \times h \qquad [F/L^2] \tag{8}$$

where

w_w = density of water [F/L³],

h = depth of water column at the bottom of the pipe [L].

Empirical method. Based on the evaluation of data gathered on numerous pipe jacking jobs, the face resistance can be determined by taking into account the standard penetration resistance (N) value as follows:

$$P_f = 13.2 \times \pi \times d_o \times N \qquad [kN\text{-}F] \tag{9}$$

where

13.2 = empirical value based on linear regression analysis

d_o = pipe outside diameter [m-L],

N = number of impacts/standard penetration test [-]. [8]

Frictional Resistance

The second component of the jacking force is the force required to overcome the frictional resistance between the outside surface of the pipe and the surrounding soil. There are many methods to calculate the frictional resistance, but there is a great variance between the results of these methods. The variance results from the different assumptions and concepts that each method is based upon.

The concept behind these methods is presented in the following paragraphs. Evaluation of and comparison among these methods is presented in the sensitivity analysis part of this chapter. Moreover, comparison between these methods and the actual data of a project constructed in Staten Island, New York, is also presented in this chapter.

The Basic Theory

The idea of frictional resistance is based on the theory of simple friction. As shown in Figure 3, to move an object resting on a fixed plane, the driving force ,P, must overcome the frictional force ,R, which is developed against the direction of movement. The friction is a function of the perpendicular force to the surface ,V, and the roughness of the contact surfaces of the object and the plane. Therefore, the frictional resistance ,R, is calculated as follows:

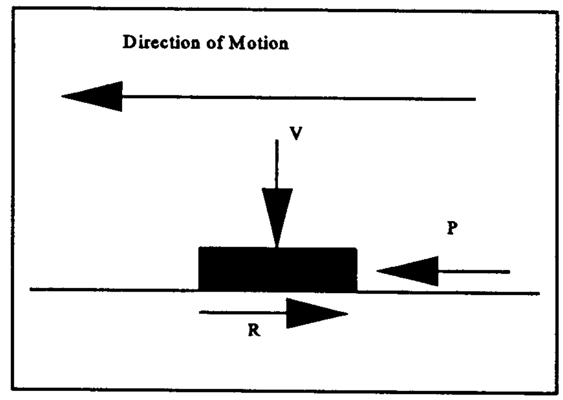

Figure 3 The Simple Theory of Friction.

$$R = \mu \times V \quad [F] \qquad (10)$$

where

μ = coefficient of friction [-].
V = the force perpendicular to the contact surface [F],

The friction between the pipe and the soil is calculated similarly. The perpendicular force is the total of vertical effective loads from the soil and the superimposed loads acting on the top of the pipe. The coefficient of friction between the soil and the pipe depends primarily on the type of soil and the roughness of the outside surface of the pipe, in addition to many other operational factors such as misalignment and steering corrections. The frictional resistance is calculated as follows:

$$R = \mu \times V \times \pi \times D_o \times L \quad [F] \qquad (11)$$

where

V = the average normal force along the outside surface of the pipe [F],
μ = the average coefficient of friction [-],
D_o = the outside diameter of the pipe [L];
L = the jacking length [L].

Iseki Poly-Tech method. In respect to cohesive soil, the frictional resistance consists of two components, friction and adhesion. Therefore, the Iseki method differentiates between actual share of friction and adhesion C_a existing between the soil and pipe. The frictional resistance (R) is calculated as follow:

$$R = \pi \times D_o \times L \times (V \times \mu + C_a) \qquad [F] \qquad (12)$$

where C_a is the adhesion between soil and pipe. Table 3 contains the empirical data on adhesion of cohesive soil with reinforced concrete pipe (RCP) and steel and fiberglass pipes (FRP). This data has been used in the design of piles in cohesive soil. [12] These values would be expected to decrease with overcut and use of lubricant.

TABLE 3
TYPICAL VALUES FOR SOIL PIPE ADHESION [12]

Pipe Material	Soil	Cohesion, psf	Adhesion, psf
Concrete	Soft	0-750	0-700
	Firm	750-1500	100-900
	Stiff	1500-3000	900-1300
Steel/FRP	Soft	0-750	0-600
	Firm	750-1500	600-1500
	Stiff	1500-3000	-

The Coefficient of Friction

As mention, the coefficient of friction between the soil and the pipe depends on the type of soil and the type of pipe. Table 4 presents standard values for the coefficient of friction for different combinations of pipes and soil types. [8] The table indicates that, in case of lubrication, the coefficient does not depend on the soil type but rather on the liquid limit of the lubricant.

TABLE 4
STANDARD VALUES FOR COEFFICIENT OF FRICTION μ [8]

For static friction	
concrete on gravel or sand	$\mu = 0.5$ to 0.6
concrete on clay	$\mu = 0.3$ to 0.4
asbestos cement on gravel or sand	$\mu = 0.3$ to 0.4
asbestos cement on clay	$\mu = 0.2$ to 0.3
For sliding friction	
concrete on gravel or sand	$\mu = 0.3$ to 0.4
concrete on clay	$\mu = 0.2$ to 0.3
asbestos cement on gravel or sand	$\mu = 0.2$ to 0.3
asbestos cement on clay	$\mu = 0.1$ to 0.2
For fluid friction	
when using bentonite suspension as supporting and lubricating fluid, the coefficient μ will depend on the liquid limit of the suspension	$0.1 < \mu < .3$

The coefficient of friction is determined based on the angle of friction between the soil and the wall, δ. [8]

$$\mu = \tan\delta \qquad [-] \tag{13}$$

Table 5 presents the values of δ and μ as a function of the soil and pipe types. This table is used for calculating the frictional resistance between soils and piles. [12] The coefficient of friction between the FRP and soil is less than the values shown in the table because the FRP is smoother than the RCP and the steel pipes. It can be considered, however as an approximation, equal to the coefficient between steel and soil. [3, 10]

TABLE 5
SURFACE FRICTION ANGLES AND COEFFICIENTS [12]

Soil Type	RCP		Steel/FRP	
	δ°	μ=tan δ [-]	δ°	μ=tan δ [-]
Sandy gravel, clean	30	0.58	28	0.55
Sandy gravel, silty	22	0.40	23	0.42
Dry medium sand	30	0.58	28	0.55
Damp sand	31	0.60	28	0.55
Saturated sand	30	0.58	26	0.49
Dry silt	30	0.58	28	0.53
Wet silt	22	0.40	20	0.36

The Normal Force Acting on the Pipe Surface

Accurate estimation of the normal stress and shear stress acting on the pipe are critical ingredients for making reliable estimates of pipe jacking forces. Yet normal stresses and shear stress acting along the pipe can be difficult to estimate accurately. Some of the methods used for estimating normal stresses are discussed in the following paragraphs.

The normal force acting on the outside surface of the pipe is considered the total of vertical loads from the dead load of the soil and the superimposed load acting on the top of the pipe. It can be calculated by the following techniques: (1) Marston's formula, (2) Terzaghi's silo theory, (3) the Kubota method which is an adaption to Terzaghi's theory, and (4) Japan Sewerage Association's modified formula.

Marston's formula. Marston's formula to calculate the dead load, W_t, above the pipe is

$$W_t = C_t\, B\, (wB - 2c) \qquad [F/L] \tag{14}$$

where

W_t = Normal load on the pipe [F/L],
w = Unit weight of soil above the pipe [F/L^3],
B = Maximum width of trenchless excavation [L],
c = Cohesion coefficient [F/L^2],

C_t = Load coefficient [-],

$$C_t = \frac{1 - e^{-2k \times \mu \times H/B}}{2k \times \mu} \qquad [-] \qquad (15)$$

where

e = Base of natural logarithms [-],
k = Rankine's ratio of lateral to vertical pressure,
= (1-sin φ)/(1+sin φ) [-]
φ = Angle of internal friction [°],
μ ≈ tan φ = Coefficient of internal friction [-],
H = Depth of cover above the pipe [L]

Figure 5-2 presents the load coefficient, C_t, for pipe in undisturbed soil for $k \times \mu = 0.165, 0.15, 0.13$, and 0.11. [2]

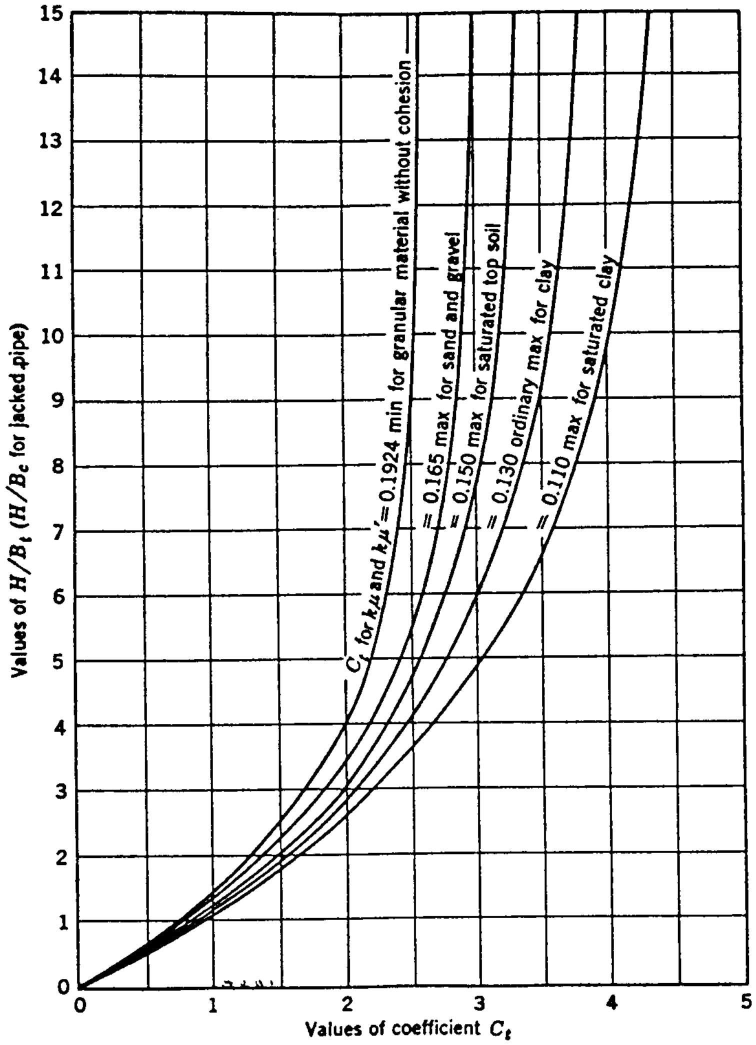

Figure 4 Load Coefficient, C_t, for Pipes Jacked in Undisturbed Soil.

The proper selection of the coefficient of cohesion is extremely important. It varies widely even for similar types of soil. It is strongly recommended that the c value be determined by appropriate tests. However, if large overcut is used between pipe and soil and the annular space is not properly filled; the soil cohesion may be reduced or destroyed and dead loads higher than that calculated by equation (14) are encountered. Therefore, the reduction of earth load due to cohesion must be carefully consedered. In case there is swelling soil around the pipe, additional swelling pressure must be considered. [8]

For shallow cover; the calculated values of W_t could be zero or negative due to the effect of cohesion, but the actual force acting on the pipe cannot be less than zero due to a variety of factors including the weight of the pipe and ground disturbance during the tunneling operations. For shallow cover, judgement is required to select a reasonable value of W_t.

Terzaghi's method. Terzaghi established a calculation model featuring the forces acting on a horizontal soil slab as shown in Figure 5. The forces acting on the soil slab are (1) downward, the weight of the soil column on the top of the slab; (2) downward, the weight of the soil slab; (3) upward, the shear resistance; and (4) upward, the reaction to the vertical load. Equilibrium in the vertical direction ($\Sigma V = 0$) results in the following:

$$w \times b \times dH + P \times b - (P + dP) \times 2 \times (c + P \times K \times \tan\delta) dH = 0 \qquad (16)$$

where

c	= cohesion [F/L^2],
δ	= angle of wall friction [O],
T	= the shear resistance [F/L^2],
	= c + P x K tan δ,
K	= soil pressure coefficient [-],
P	= weight of soil above the slab [F],
dP	= weight of soil slab [F],
w	= soil density [F/L^3],
H	= depth of soil above the slab [L],
dH	= thickness of the slab [L]
b	= width of the slab [L].

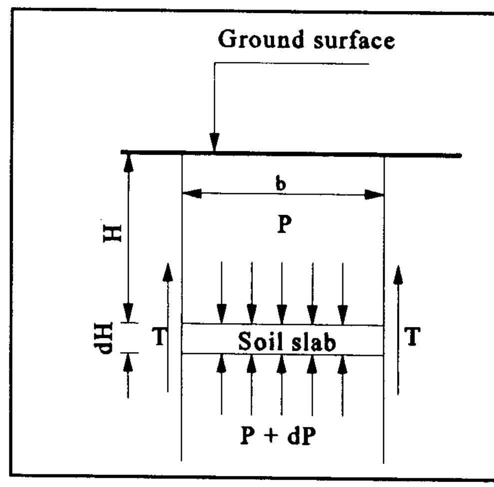

Figure 5 Terzaghi's Calculation Model.

$$\frac{dP}{dH} = w - \frac{2c}{b} - 2K \times P \times \frac{\tan\delta}{b} \qquad (17)$$

$$P_{EV} = \frac{b(w - 2\frac{c}{b})}{2K \times \tan\delta} \times (1 - e^{-2k \times \tan\delta \times H/b}) \qquad [F/L2] \qquad (18)$$

If cohesion is neglected, the vertical soil load, P_{EV}, would be

$$P_{Ev} = w \times H \times k \quad [F/L^2] \tag{19}$$

which lead to the inclusion of the coefficient of soil load k which, as a reducing factor, takes into consideration the supporting effect of the soil. The coefficient of soil load becomes

$$k = \frac{1 - e^{-2k \times \tan\delta \times H/b}}{2K \times \tan\delta \times H/b} \quad [-] \tag{20}$$

The functional parameters H and w are values which can be clearly determined but K, B and δ are values which must be assumed based on the geotechnical parameters of the soil. In accordance with the German Association for Water Pollution Control (ATVA 161); K = 0.5, δ = 1/2 φ and B = √3 D_o. Figure 6 is a graphic representation of the value of k as a function of φ and the ratio H/D_o for K = 0.5 where D_o is the outside diameter of the pipe. On the other hand, in Japan, K = 1 which is the mean value of the values developed by Terzaghi, δ = φ and B = D_o (0.5 + tan (45 - φ/2); where φ = angle of internal friction of soil Table 6 summarizes the soil parameters which are assumed by ATVA 161 and by Terzaghi (which is used in Japan). [8] It is believed that these parameters have been selected because most of the data in Japan were for clay soils while in Germany, especially Berlin, they were for sands.

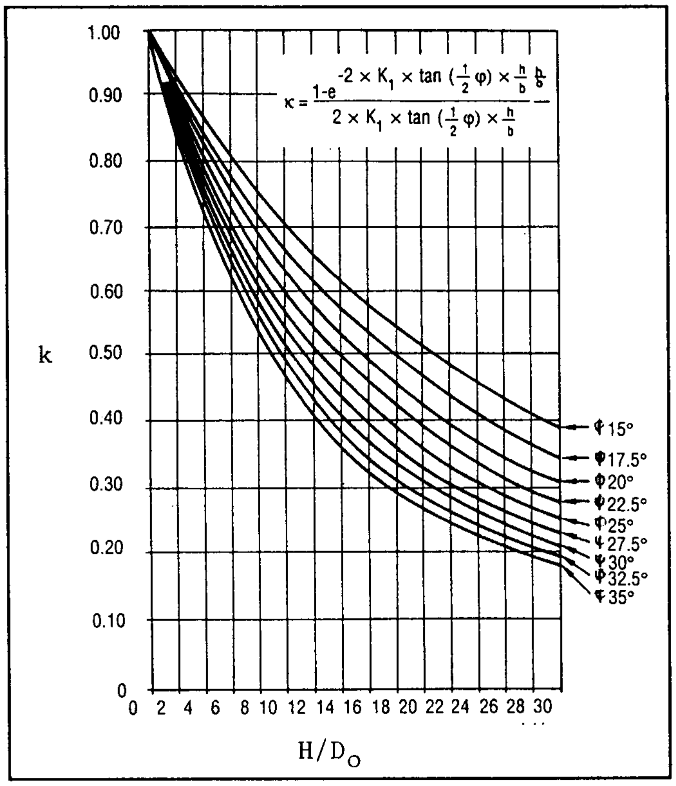

Figure 6 Reduction Factor k for K_1 = 0.5 in accordance with ATVA 161.

Although ground water does not significantly influence the soil friction, the ATVA 161 specifies, for safety reasons, that the full soil load should be applied in case of jacking below the ground water table. [8]

TABLE 6
ASSUMED SOIL PARAMETERS IN GERMANY AND JAPAN [8]

	K	δ	B
Germany, ATVA Manual	0.5	0.5 φ	$\sqrt{3}\,D_o$
Japan	1	φ	0.5 D_o tan (45 - φ/2)

Kubota manual method. The Kubota manual method assumes a soil slacking height by arching efficiency, that is the soil deforms and creates an arch acting on top of the pipe. The weight of soil arch, not the weight of the whole depth of cover, is carried by the pipe. This method takes the normal force on the outside surface of the pipe as the average of the vertical earth pressure and the active horizontal earth pressure at the top and at the bottom of the pipe resulting from the slacking height of soil. Therefore, the frictional resistance R is calculated as follows:

$$R = 0.5 \times \pi \times D_o \times \mu \times L \times [W + 0.5(W_1 + W_2)] \qquad [F] \tag{21}$$

where

W = Vertical earth pressure [F/L^2],

$$W = k \times w \times h_o \qquad [F/L^2] \tag{22}$$

h_o = soil slacking height by arching efficiency

$$h_o = \frac{B_1(1 - e^{-k \times \tan\phi \times H/B_1})}{k \times \tan\phi} \qquad [L] \tag{23}$$

k = Terzaghi's coefficient = 1

$$B_1 = B_o + h_1 \times \tan(45-\phi/2) \qquad [F/L^3] \tag{24}$$

$$h_1 = w \times [1 + \sin(45 - \phi/2)] \qquad [F/L^3] \tag{25}$$

$$B_o = w \times \cos(45-\phi/2) \qquad [F/L^3] \tag{26}$$

W_1 and W_2 are the horizontal earth pressure at the top and the bottom of the pipe [F/L^2].

$$W_1 = K_a \times w \times h_o \qquad [F/L^2] \tag{27}$$

$$W_2 = K_a \times w \times (h_o + D_o) \qquad [F/L^2] \tag{28}$$

$$K_a = \tan^2(45-\phi/2) \qquad [-] \tag{29}$$

K_a= coefficient of active earth pressure. [2]

Japan Sewerage Association Modified Formula. The basic theory behind this method is that the frictional resistance is equal to the shear resistance between soil and pipe. Similar to the Iseki Poly-Tech method, it considers both adhesion and angle of wall friction between soil and pipe surface. Thus, the friction resistance R is calculated by the following equations:

$$R = D_o \times \tau \times L \qquad [F] \tag{30}$$

where

D_o = outside diameter of the pipe,
L = jacking length,
τ = shear resistance between soil and pipe; it is calculated by the following equation:

$$\tau = C_a + V \times \mu \qquad [F/L^2] \tag{31}$$

where

C = adhesion between soil and pipe [F/L²],

μ = coefficient of friction between soil and pipe [-],

V = normal stress on the pipe circumference [F/L²],

$$V = \alpha \times W + \frac{2 \times w}{\pi^2 \times (D_o - t)} \qquad [F/L^2] \tag{32}$$

where

α = factor for pressure perpendicular to pipe circumference excluding self weight. Table 7 presents values of α for various types of soil,

W = uniform load on pipe [F/L²],

w = unit weight of pipe [F/L],

t = thickness of pipe wall [L].

TABLE 7
VALUES OF THE PRESSURE FACTOR (α) [12]

Type of Soil	Pressure Factor (α)
Sand	0.75-1.1
Compacted Sand	1.5-2.7
Gravel	0.75
Compacted Gravel	1.5-2.7
Clay	0.5-0.8
Compacted clay	0.8-1.5

Research in Germany on skin friction (M) by Scherle and Weber indicated that the relation between skin friction and depth of cover is not linear as shown in Figure 7[8]. Rather relative skin friction increases but at a decreasing rate, as the ratio of cover to pipe diameter increases. For H/D > 10, the relative skin friction is almost constant.

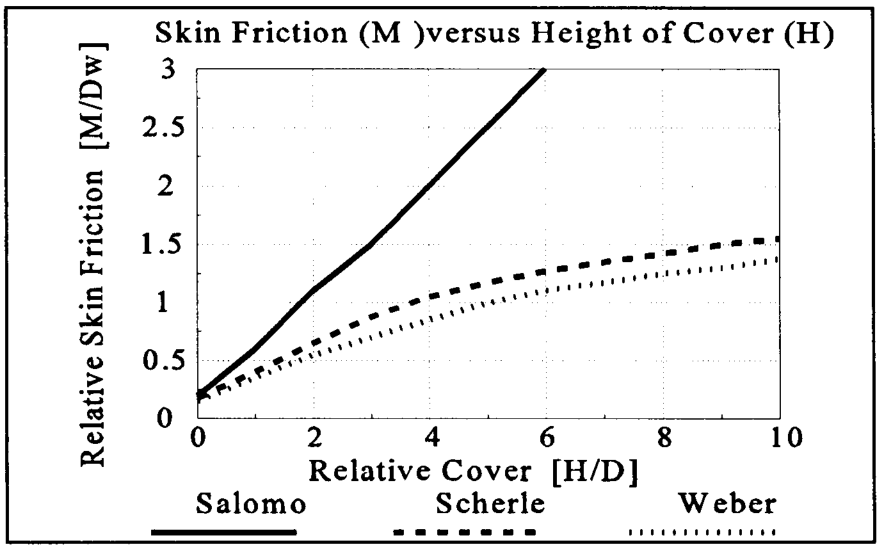

Figure 7 Skin Friction M Versus The Height of Cover. [7]

On the other hand, the relation between skin friction and surface area of the pipe is linear as shown in Figure 8.

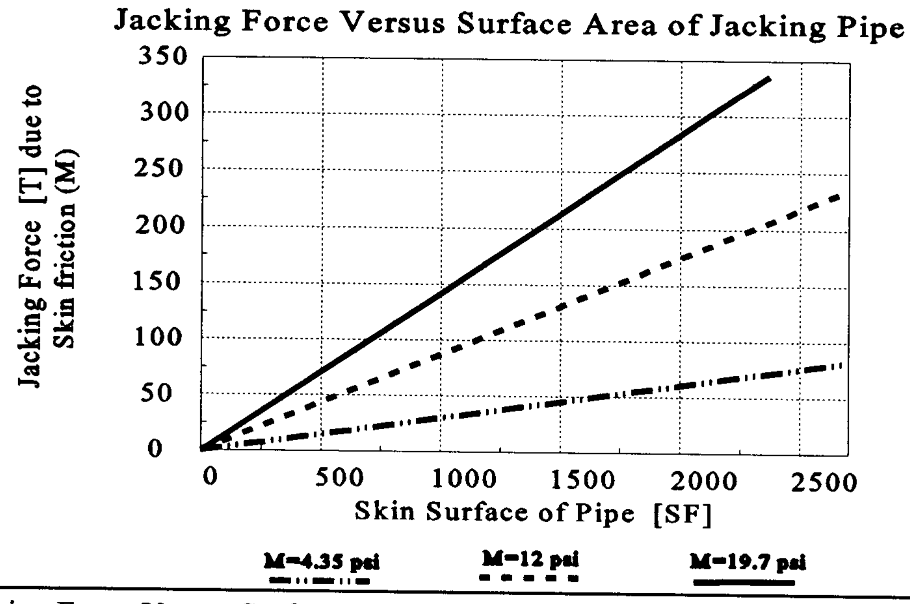

Figure 8 Jacking Force Versus Surface Area of Jacking Pipe under Different Values of Skin Friction (M).

Methods for Reducing Skin Friction and Increasing jacking Distances

Oversize cut of the face and lubrication of the outside surface of the pipe are two methods to reduce the frictional resistance. The intermediate jacking stations are employed as techniques to jack long drives within the maximum capacity of the pipe and the main jacking station.

Oversize cut. In stable soil types, an oversize cut can be maintained throughout the jacking distance with the result that frictional force occurs only on the bottom of the pipe run. However, the oversize cut will not serve the purpose of reducing the skin friction in unstable soil such as soft clay, wet silt; and loose sand. An oversize cut should be made nevertheless to facilitate steering operations of the jacking shield or the boring machine. [8]

Lubrication of the outside surface of the pipe. It is a common practice to use bentonite slurry as a lubricant and support for the jacking pipe. Bentonite injection reduces the coefficient of friction to the range from 0.1 to 0.3 which results in significant reduction of the frictional resistance. [4] In dry soils, it is possible to reduce frictional resistance to 200 to 300 psf. In wet soils, a frictional resistance of 200 psf can be achieved and a resistance of 100 psf is possible. [9]

Intermediate jacking stations. Even though the friction between pipe and soil can be reduced considerably by injecting bentonite slurry, the jacking force increases linearly with the length of the jacking distance, as long as friction processes in uniform ground conditions are being discussed. The jacking force reaches the capacity of the main jacking station or of the jacking pipe after a certain distance. The length of this distance varies with the pipe diameter, type of pipe and kind of soil etc. [8] Intermediate jacking stations open another horizon for long pipe jacking projects. In Germany, 16.4 ft external diameter pipe have been jacked for more than 4600 ft. In the US., 3415 ft long drives have been successfully jacked in very unstable soil. [1]

Comparison Between Actual Project and Four Different Calculation Methods

Scope of the Project

The actual pipe jacking project was Oakwood Beach Interceptor, Staten Island, NY. The project is the installation of 6900 ft, 60 in. nominal diameter FRP at depths of cover varying from 60 ft to 92 ft. The sewer alignment was through soils of glacial and cretaceous origin. The ground water table was 40 to 50 ft above the top of the sewer. The FRP was jacked through coarse, medium, to fine sand with N value (Standard Penetration Resistance) averaged 30. [7]

Drive description. The available jacking data was collected during the construction phase of the drive connecting manhole two to manhole four. The length of the drive was 1203 ft, but the available data was for only 1110 ft. The inside diameter was 57.5 in. and the outside diameter of the pipe was 62.5 in. Each jacked pipe section was 10 ft long and 385 lb/ft weight. The average depth of cover was 84 ft so that the live load pressure on the top of the pipe can be safely neglected. The ground water table in that drive was 50 ft to 55 ft above the pipe crown. The pipes were jacked through and below medium to fine sand, 1% to 10% silt/clay with N ranging from six to more than 100 and average of more than 40. [7]

The pipe jacking machine. The pipe jacking machine was a pressurized slurry closed shield machine, Unclemole, manufactured by Iseki Poly-Tech, Inc. of Tokyo, Japan. The machine automatically counter-balanced the earth pressure at the tunnel face by mechanically coordinating excavation speed, cutting face pressure and jacking thrust. The ground water pressure was balanced by adjusting the slurry pressure, flow and density.

The capacity of the main jacking station was 880 tons from four jacks, the capacity of each is 220 tons. According to the original design, an intermediate jacking station was required after 250 ft to complete jacking the 1203 ft-drive because the required force was more than the capacity of the main jacking station. [7]

In the actual practice, the intermediate jacking station was installed after jacking 350 ft, but it was not activated until after 500 ft when the required jacking force reached the maximum capacity of the main jacking station. The combination of main jacking station and the intermediate jacking station was enough to jack the remaining length of the drive.

The Different Methods of Calculation

The actual jacking data was compared with four different methods of calculations. The difference between the four methods of calculation is in calculating the load normal to the outside surface of the pipe. They are Kubota manual method; Terzaghi's silo theory using the parameters of ATVA 161 for δ, k, B; Terzaghi's silo theory using Terzaghi's parameters for δ, k, B; and Marston's formula.

The coefficient of friction between pipe and soil is considered equal to 0.3 because the surrounding soil is submerged fine sand, and the outside surface of the FRP is smoother than that of the concrete pipe. In case of lubrication, the friction coefficient is considered equal to 0.15 which is half the friction coefficient, if no lubrication is used; and it is within the range of 0.1 to 0.3, the range for the coefficient, with lubrication as discussed previously.

The outside diameter of the boring machine was 63 in. and the jacking pressure for the cutter head area was 3075 psf and the slurry pressure was 175 psf. The penetration resistance = $(3075 + 175)(63/24)^2 \pi = 72134$ lbs. = 36 tons. Since this calculated values of tip resistance is only a small fraction of the total jacking resistances, it was not included in the following comparisons. Instead, actual jacking loads were compared with calculated frictional resistance values.

Results

Figure 9 depicts the actual jacking force in the main jacking station, the intermediate jacking station and the sum of them. As shown in the chart, the jacking force is not directly proportional to the jacked length. Some of the reasons that participate in the difference are correcting steering errors, work interruption for any reason, for example, end of working day, week end, or equipment breakdown.

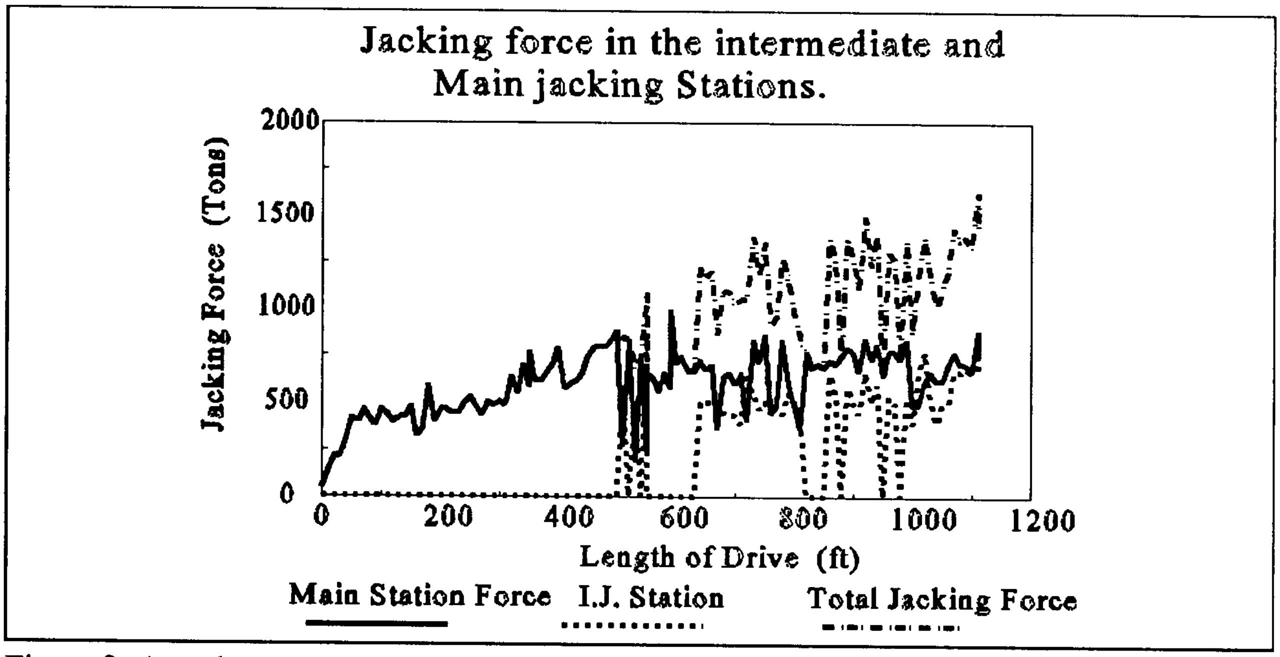

Figure 9 Actual Force Exerted from Main and Intermediate Jacking Stations.

One of the major problems that was repeatedly reported in the data was the movement of the laser transit unit in the jacking pit because of the movement of the jacks and their high pressure on the thrust block. The alignment deviation was not discovered until the next direction check which meant that the pipes installed since the deviation were not placed accurately, and the accumulation of errors could have been significant. Figure 10 shows the actual jacking force after regression, and in general, it is directly proportional to the jacked length.

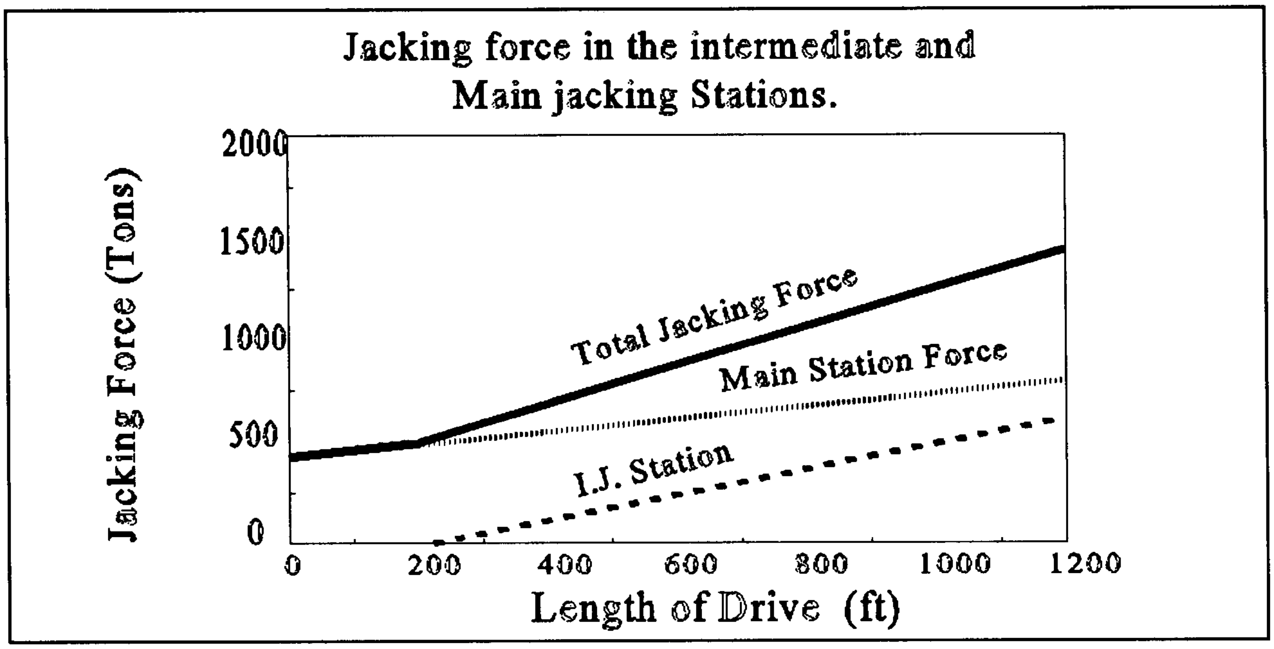

Figure 10 Actual Forces Exerted from Main and Intermediate Jacking Station after Regression.

Figure 11 depicts the percentage of the calculated skin friction to the actual jacking force for the four methods of calculation. Figure 12 presents the actual total jacking force versus the jacking force calculated by the four different methods. The methods are (1) Kubota manual, (2) Terzaghi's silo theory using the parameters of ATVA 161, (3) Terzaghi's silo theory using Terzaghi's parameters, and (4) Marston's formula

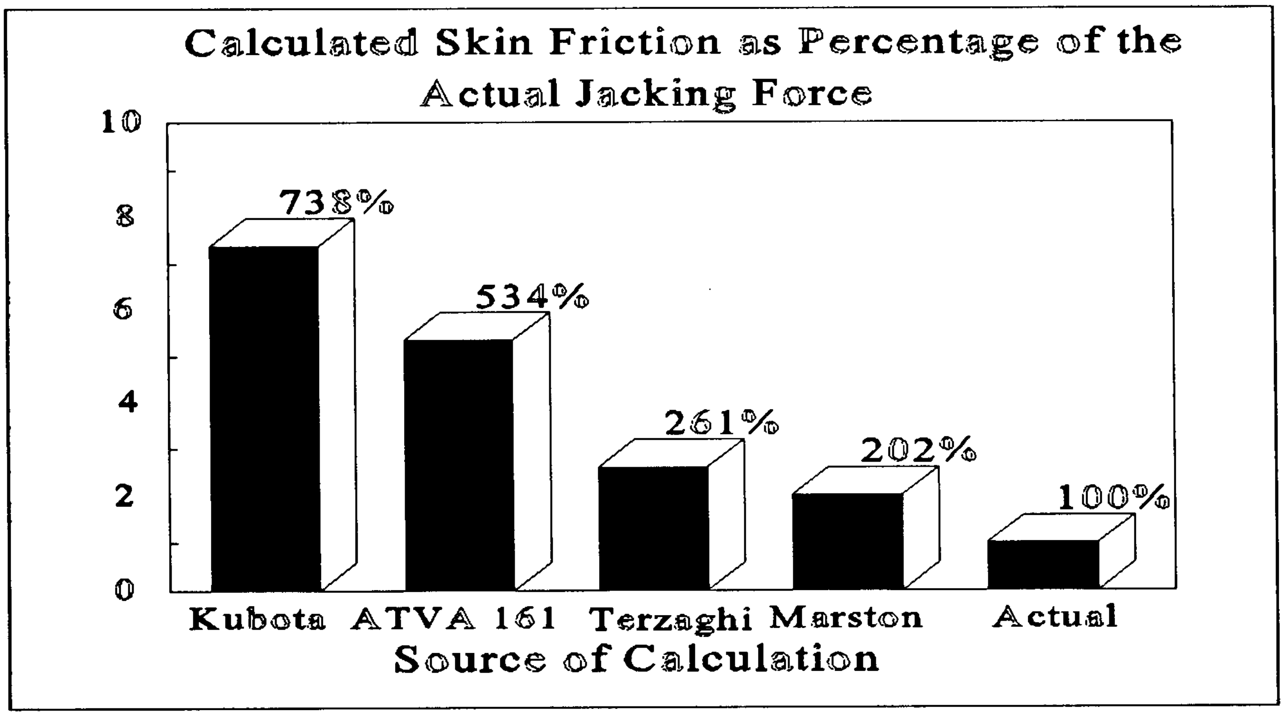

Figure11 Percentage of the Calculated Skin Friction Relative to the Actual Jacking Force.

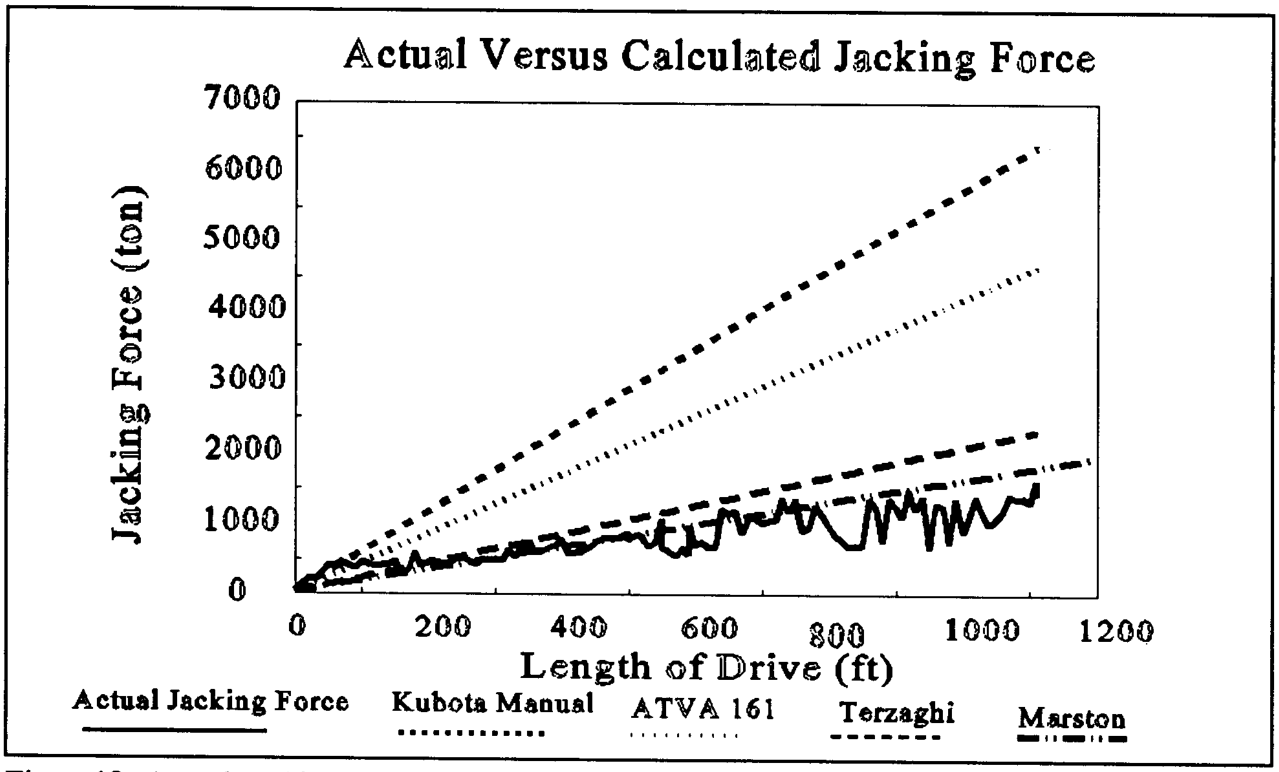

Figure12 Actual Jacking Force Versus Calculated Jacking Force due to Frictional Resistance.

Comparison Between the Calculation Methods

The factors influencing the jacking force include type of soil, type of pipe, depth of cover, live load, outside surface area of the pipe and its smoothness, and oversize cut. Lubrication significantly reduces the jacking force. [8,9] The required jacking force could be higher or lower if the string of pipes is jacked below the ground water table depending on soil conditions. Moreover, the construction detail such as rate of jacking, interruption, steering, etc. have a great influence on the jacking force.

The objectives of the comparison are to evaluate the effects of the different factors that impact the jacking force and, to develop a sense of how to manage the complicated parameters and their combinations. In the comparison between the actual jacking force for the Oakwood Beach Project, the effects of the length of the drive and lubrication have been analyzed. In the next paragraphs, the effects of the depth of cover and the type of soil on the penetration resistance and the frictional resistance are analyzed for the same four methods used in the comparison with the actual force.

OSHA Soil Classification

The OSHA soil classification system developed for open trenching has been used, as an example, in this paper due to its familiarity in the American utility construction industry. It is very simple to use for estimating, planning, and executing pipe jacking jobs. On the other hand, because this classification does not cover all types of soil or even all soil parameters, the developed charts may not be reliable unless the actual soil matches the classified type. The following paragraphs describe the characteristics of each soil type in the OSHA system. [5]

<u>Type "A" soil</u>. Soil is classified as Type "A" if it meets one of the following:

- cohesive soil with an unconfined compressive strength of 1.5 tsf or greater, or
- cemented granular soil such as hardpan, till, cliche.

The soil is not classified as type "A" if it meets one of the following:

- it is fissured, subject to vibration, or previously disturbed,
- it is part of a sloped layered system where the layers dip into the excavation on a slope of 4:1 or greater, or
- it is subject to any other factors that would require it to be classified as less stable material.

<u>Type "B" soil</u>. Soil is classified as type "B," if it meets one of the following:

- cohesive soil with unconfined strength greater than 0.5 tsf. but less than 1.5 tsf.,
- granular soil that can stand on slope of 3:1 or greater without slumping,
- soil that meets the requirements of type "A" soil, but is fissured, subject to vibration or has been disturbed,
- dry rock that is not stable, or
- material that is part of a sloped, layered system where layers dip into excavation on a slope less steep than 4:1. [5]

<u>Type "C" soil</u>. Soil is classified as type "C," if it meets one of the following:

- cohesive soil with an unconfined compressive strength of 0.5 tsf or less;
- granular soil that can not stand on a slope of 3:1 without slumping;
- unstable saturated or submerged soil or rock; or
- soil in a sloped, layered system where layers dip into the excavation on slope of 4:1 or greater. [5]

<u>Penetration Resistance</u>

The penetration resistance at the various depths of cover for the three types of soil classified by OSHA is calculated by the shearing strength method and the passive earth pressure method as explained earlier. The depth range compared is from 5 ft to 63 ft. Figure 13 depicts the results of the analysis which indicate

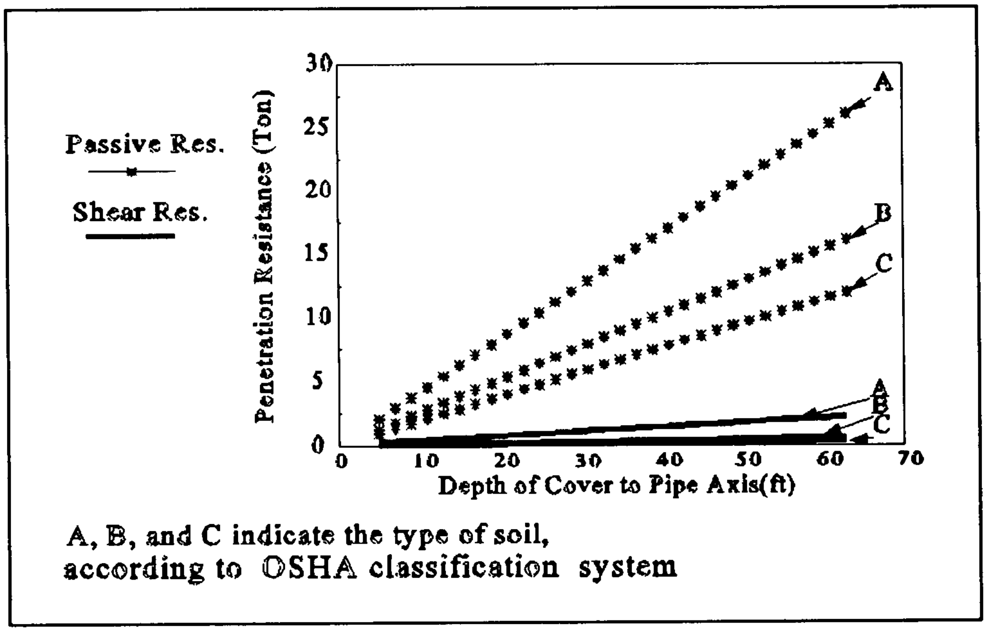

Figure 13 The Penetration Resistance Calculated by the Shear Strength and the Passive Earth Pressure Methods for the Three Types of Soil.

- the passive earth pressure method is more conservative than the shearing strength method, as expected;
- a linear relationship exists, as expected, between the penetration resistance and the depth of cover because the passive earth pressure and the shearing strength have a linear relationship with the weight of the soil column on top of the pipe;
- penetration resistance is highest for soil type A and lowest for soil type C, as would be expected, based on the relative strength of these soils.

Frictional Resistance

The frictional resistance has a linear relationship with the outside surface area of the pipe. Consequently, the frictional resistance per unit area of the outside surface of the pipe is a more useful term than the total force for comparison purposes, and is used in this analysis of frictional resistance. The frictional resistance is calculated by the same four methods employed previously for the three OSHA soil classes versus range of depth from 4 ft to 88 ft. Figures 14 and 15 present the analysis for the 60 in diameter RCP. The figures show the following:

- all the methods indicate nonlinear relationships between the skin friction and depth of cover except the Kubota manual method which is very conservative,
- for the same conditions, the skin friction results of the Kubota manual method are the highest, followed by those of the ATVA 161 method, then of Terzaghi method, then of Marston method. All the methods yield results higher than actual loads,
- the results of the Kubota and ATVA 161 methods are close to each other until the depth of 30 to 40 ft. but diverge as depth increases. On the other hand, the results from the Terzaghi method differ greatly from those of the Marston method.

The comparison between the actual job and the four methods reveals that the results from Marston and Terzaghi's formulas are more accurate than those from the Kubota and ATVA 161 method which are too conservative as shown in Figure 12. Figure 14 presents the skin friction results calculated by Terzaghi and Marston's method for the three types of soil and reveals the following contradiction:

- In Marston's formula, the skin friction of soil type C is higher than that of soil type B which is higher than that of soil type A,
- on the other hand, in Terzaghi's method, the skin friction of soil A is higher than that of soil B until certain depth then the relationship opposite, and both of them are higher than that of soil C for all depths.

Terzaghi and Marston's methods indicate that the frictional resistance is not dependent on the depth of cover after a certain depth as a result of the soil arching theory. Where the height of the arch is less than the depth of cover, the height of the arch is the effective weight on the pipe. The depth of cover is not a decisive factor when it is more than the height of the arch.

Figure 15 depicts the results from the Kubota and the ATVA 161 methods for the three types of soil. Both of them indicate that soil type A offers higher frictional resistance than that of soil B which in return is higher than that of soil C.

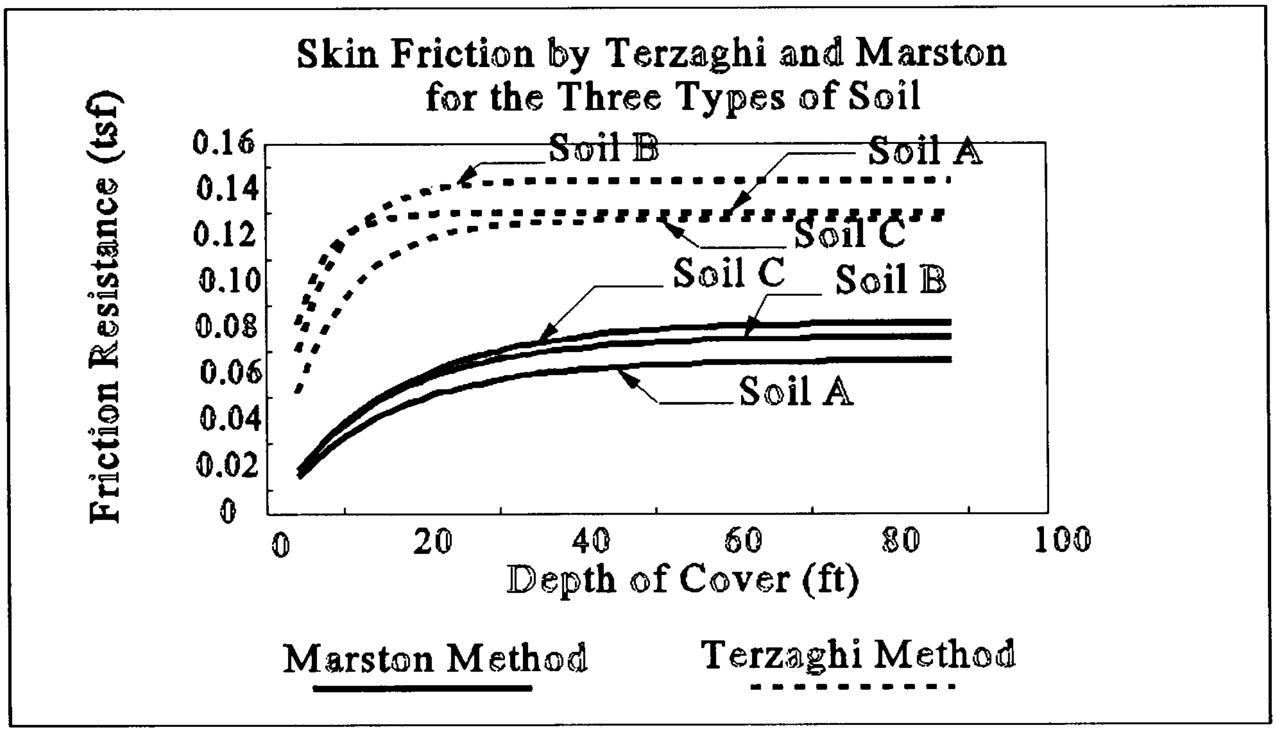

Figure 14 Skin Friction per Unit Area for the Three Types of Soil by Terzaghi and Marston Methods for 60 inch Diameter RCP.

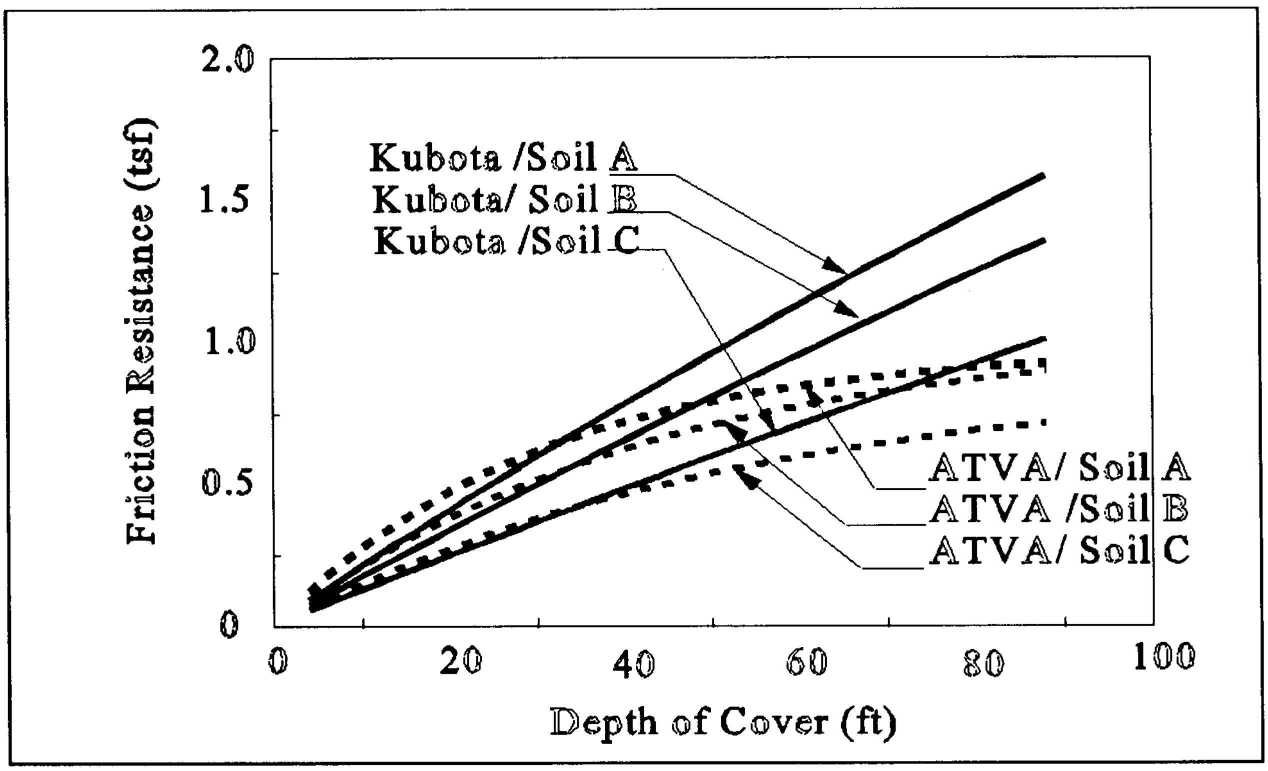

Figure 15 Skin Friction per Unit Area for the Three Types of Soil by Kubota and ATVA 161 Methods for 60 inch Diameter RCP.

Conclusions and Recommendations

There are many techniques to calculate the jacking force; all of them assume that the jacking force is the sum of the penetration resistance and the frictional resistance due to soil and pipe weights. Penetration resistance is calculated by three basic methods: (i) shear resistance, (ii) passive earth pressure resistance, and (iii) empirical methods using case history data. All the methods for calculating the frictional resistance component of jacking force consists of multiplying the normal force on the outside surface of the pipe by a frictional coefficient depending on the type of soil, pipe, and lubrication.

Five methods of calculating the frictional resistance have been presented. They are based on the following: (a) the force normal to the pipe surface is the weight of the slacking arch of soil above the pipe (Kubota, Japan); (b) the vertical load calculated by Terzaghi's silo theory with the parameters set in Germany for $K = 0.5$, $\delta = 0.5\ \phi$, $B = \sqrt{3}D_o$, (c) the normal pressure calculated by the same theory but with the parameters set by Terzaghi for $K = 1$, $\delta = \phi$, $B = 0.5D_o \tan(45-\phi/2)$, (d) the vertical load calculated by Marston's formula, and (e) empirical frictional values between pipe and soil developed from case history data.

The variation between these methods is significant. More study supported by field measurements is required. The required studies should include studying the records of previous jacking jobs in various soil conditions, and the soil behavior around the pipe. The calculated jacking force should be multiplied by an adequate safety factor, which depends on the risk of change in soil conditions, steering errors, equipment breakdown, and degree of reliability in the approximation of the soil parameters.

There are two techniques to reduce the frictional resistance, and consequently the jacking force. They are primarily the oversize cut and lubrication of the outside surface of the pipe. Oversize cut is more effective in reducing the jacking force if the soil is highly stable. In unstable soil, oversize cut must be made nevertheless to allow performing the required steering operations of the jacking shield or the boring machine. Oversize cut should be reduced as possible in very unstable soil when there is a risk from settlement. The use of lubrication significantly reduces the jacking force. Lubrication is generally recommended around the whole perimeter of the pipe and along the whole length of the drive.

Intermediate jacking stations can be used to increase the drive lengths achievable. Lengths up to 4600 ft have been reported with up to 17 intermediate jacking stations in the US and Europe, [1] but usually a fewer number of intermediate jacking stations is used.

Comparison was made between the actual jacking force for the Oakwood Beach project in Staten Island, NY, and four methods of calculating the vertical loads and jacking loads on the pipe to try to find the most reliable method of calculating the jacking force.

The results based on Terzaghi's theory with the parameter values based on the ATVA 161 and results from the Kubota manual method are five to seven times the average actual jacking force. On the other hand, the force calculated by Marston's formula and Terzaghi's coefficient are about twice the average actual jacking force. Therefore, based on this comparison only, multiplying the force calculated by these formulas by an adequate factor of safety would be appropriate. The other two methods are conservative and on the safe side, but not the most economical solution.

The jacking force per unit of surface area of the pipe is a more useful parameter than total jacking force and should be adopted in job records and reports. Jacking loads dramatically increase after interruptions for any reason such as equipment breakdown, beginning of the day or the week, or other shutdowns.

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