Installation loads on new pipelines during pipe bursting

V. Fernando
Graduate Student, The University of Western Ontario, Canada

I.D. Moore
Professor, The University of Western Ontario, Canada

ABSTRACT: In urban areas, the zone near the ground surface is often congested with existing services. These complicate the replacement of a defective service with a new line. The existing hole in the ground thus becomes valuable as a route. Pipe bursting and pipe splitting have been developed to exploit this resource. The new pipeline is installed by splitting the defective pipe and displacing the fragments outwards. This enables a new pipeline of the same or larger diameter to be pulled into place. Pipelines installed by pipe bursting are subjected to external pressure due to soil-pipe interaction and axial forces generated by the surface friction mobilized on the exterior of the pipe as it is pulled into position. The installation load may be more severe than the operational load and may govern the pulling length. This paper presents a method for estimating the external pressures on pipes pulled into place during pipe bursting. A parametric study is presented which covers a range of soil parameters and pipe geometries.

1 INTRODUCTION

One of the biggest problems facing municipal governments together with public and private utilities is the rehabilitation of decaying infrastructure. Underground infrastructure includes water distribution and wastewater collection systems, gas, petroleum and chemical pipelines. Since many of these systems are located in congested urban areas, installation or rehabilitation using conventional open trench construction may be very disruptive. These problems can be minimized through the use of trenchless technology, and in many cases, the work may be performed at similar cost to conventional open-trench operations.

Pipe bursting is a trenchless technology used to install the new pipe by fragmenting the existing pipe prior to drawing a new pipe into the cavity. There are three systems commonly used by the pipe bursting industry, those involving static pulls, pneumatic bursting heads, and hydraulic expansion systems. The major difference between these alternatives is the manner in which the bursting force is generated and transmitted to the existing pipe. For bursting under a static pull, static forces are generated as a cone shaped bursting head is winched forward, while dynamic forces are generated used the other bursting systems.

The bursting head is usually larger then the inside diameter of the existing pipe and slightly larger than the outside diameter of the new pipe, since this reduces the friction between the new pipe and its surroundings, and provides space to manoeuvre the new pipeline. The oversized cavity contracts back onto the new HDPE pipe pulled into place behind the bursting head. The mechanism of expansion and contraction during pipe bursting is of fundamental importance, as it influences the radial stresses that develop between the soil, the original pipe, the bursting head and the pulled-in-place pipe. The axial friction that develops on the external boundary of the HDPE pipe during winching is influenced by the final radial stresses acting on its external boundary (from the surrounding soil). The radial stress is also expected to influence the local contact forces that develop between the original pipe fragments and the new HDPE pipe.

This paper presents a simple analysis of static pipe bursting. This is being used to develop a correlation between the pulling length and pipe upsizing. The analysis is based on the semi-analytic solutions of Yu and Houlsby (1991, 1995). A parametric study has been carried out to determine the effect of the soil parameters on the radial earth pressures. The study is viewed as a first approximation, and consideration of factors such as the curvature of the pipe, local stress concentrations due to fragments of existing pipe, and other potentially significant factors will be left to future investigations.

2 PROBLEM DEFINITION

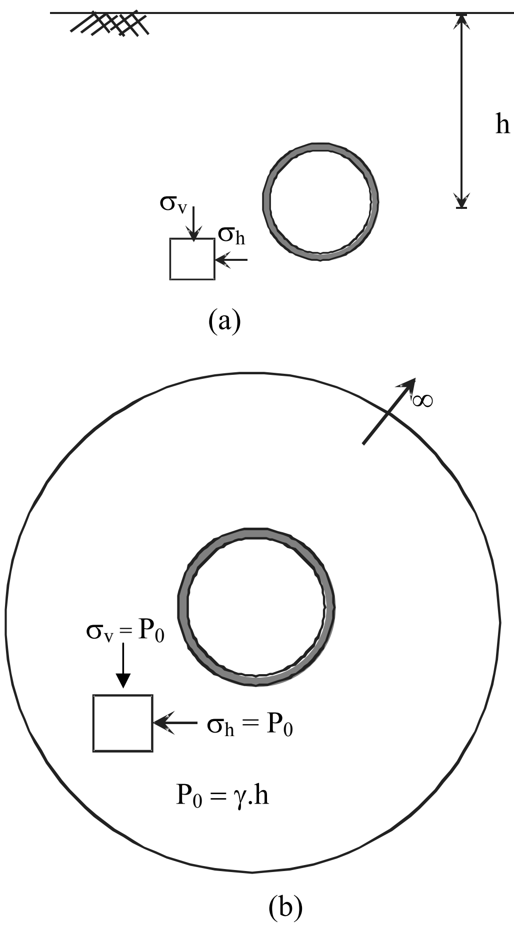

Figure 1: a. Buried Pipe and earth stress conditions
b. Approximation of soil support and earth stresses

As can be seen from Figure 1a, the pipe-bursting problem involves a pipe installed below the ground surface that needs to be expanded and replaced. The initial conditions will be simplified as shown in Figure 1b, assuming that,

a) The pipe is buried within an unbounded homogeneous continuum.
b) Soil properties will be uniform
c) Pre-existing earth stress will be assumed to be uniform and isotropic (homogeneous) (i.e. $\sigma_h = \sigma_v = P_0$)

In addition to that

d) All local stress concentrations between the fragments of existing pipe and the new HDPE pipe will be neglected.
e) Longitudinal effects will be ignored.

Based on these assumptions, the response of the soil during pipe bursting can be viewed as satisfying axi-symmetric and plane strain conditions. The effect on the final radial stresses of the longitudinal shear stresses (often controlled through the use of lubricant placed on the external surface of the new HDPE pipe) will not be considered.

Important features of the pipe bursting problem as seen in Figure 2 are:

(a) The large change in geometry where the internal cavity diameter changes more than 10% during the pipe bursting operation; the soil response is expected to be geometrically non-linear.
(b) Pipe bursting involves both loading (expansion) and unloading (contraction) phases.
(c) Shear failure is expected in the soil surrounding the cavity. The radial pressure from the bursting head creates a plastic zone around the expanded cavity. In addition to the plastic zone that develops during expansion, the contraction of the soil can create a plastic zone around the cavity. Use of plasticity theory to model the constitutive behaviour of the soil after shear failure is therefore required.

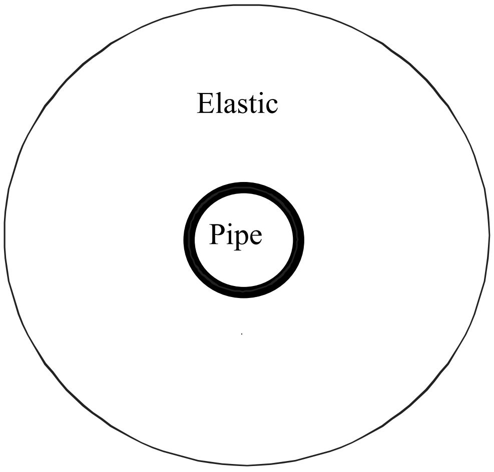

Figure 2: a. Ground condition before bursting

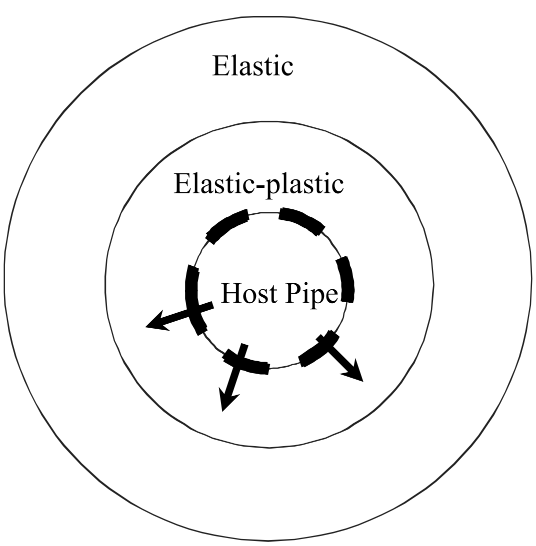

Figure 2: b. Ground condition during bursting

The cavity expansion and contraction theory of Yu and Houlsby (1991, 1995) incorporates all three of these important features and the availability of this solution represents an important opportunity to apply cavity theory to this application (Yu, 2000, presents a number of other applications of cavity expansion theory, as well as details of the theory formulation).

3 PARAMETRIC STUDY

3.1 *Purely frictional materials*

In this section, some results are presented for a purely frictional soil (i.e. sand) with angles of friction 30^o, and 40^o, a Poisson's ratio of 0.25 and elastic moduli of 10MPa and 20MPa. The angle of dilation for granular soils has a significant effect on loading and unloading as it controls the volume changes in sand during loading and unloading. An angle of dilation of 13^o is chosen for the sand, which is reasonable if it is chiefly composed of quartz particles (Skempton, 1984). The unloading is assumed to start after cavity expansion by 10%, 30% or 50% (corresponding to a maximum ratio of the radius of the internal surface of the soil a to the initial radius a_o equal to a/a_o of 1.1, 1.3, and 1.5).

The effect of soil modulus on loading and unloading path is shown in Figure 3 with normalised pressure P/P_o plotted as a function of normalised cavity radius, a/a_o. The cavity expansion and contraction curves for angles of friction of 30^o and 40^o are plotted in Figures 4 and 5.

As can be seen from Figure 3, the variation of soil modulus makes a large difference to the loading path, but the unloading path almost coincides after elastic unloading is completed and the unloading response becomes elastic-plastic. Furthermore, from 80% to 90 % of the peak pressure at the end of the loading phase is released once contraction reduces the peak diameter by from 5 to 10%.

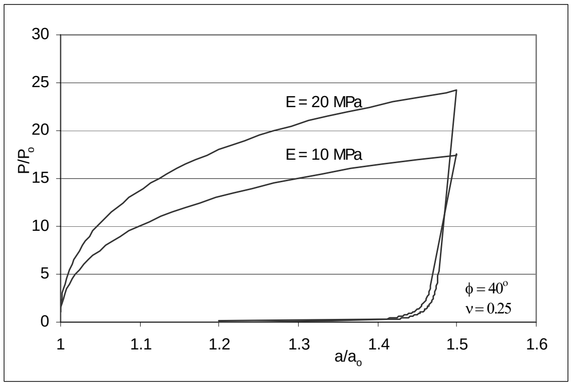

Figure 3: The effect of soil modulus on the loading and unloading paths (friction angle 40^0).

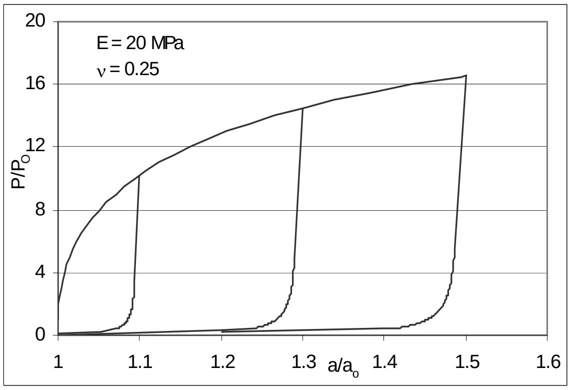

Figure 4: Loading and unloading paths for the soil with angle of friction 30^o

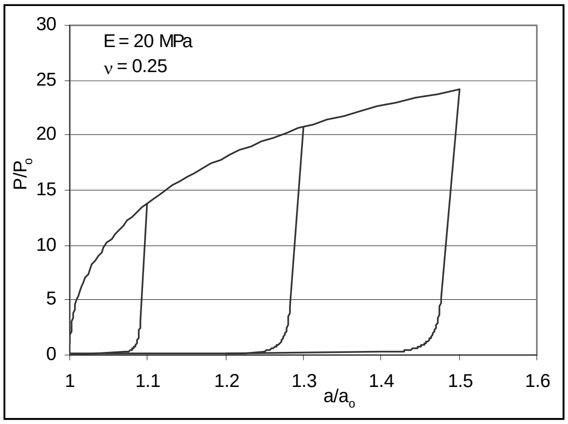

Figure 5: Loading and unloading paths for the soil with angle of friction 40^o

Figures 3, 4 and 5 indicate that the initial stresses P_0 and the shear strength of the soil (friction angle ϕ) are the dominant factors influencing the radial pressures after the soil contracts back onto the new pipe.

3.2 *Purely cohesive and Frictional-cohesive materials*

In this section, some results are presented for a purely cohesive soil with cohesion of 40 kPa and a frictional-cohesive soil with cohesion of 40 kPa and angle of friction of 5^o, soil modulus of 10 MPa and a Poisson's ratio of 0.49 (an appropriate value for the rapid or "undrained" response of a fine grained soil expected during a pipe bursting operation). An associate flow rule is assumed where dilation angle equals friction angle, also reasonable for cohesive soils. Once again, three unloading conditions are examined (where unloading commences after cavity expansion ratios a/a_o reach 1.1, 1.3, or 1.5).

The cavity expansion and contraction curves for different cohesion and angles of friction are graphed in Figure 6.

As can be seen from Figure 6, the addition of a small amount of frictional shear strength has a significant effect on the radial stresses. At larger cavity contractions (10% or more), the radial pressure on the cavity drops to zero during the unloading phase of the load history for these cohesive soils.

4 ESTIMATION OF PULLING LENGTH AND AXIAL TENSIONS

In this section, a potential method of calculating the maximum pulling length is presented. Pipe length is evaluated to control the maximum axial load in the HDPE pipe, which is taken as corresponding to a maximum allowable stress for the HDPE material, σ_{max}.

The following assumptions have been used in order to simplify the problem.

a) The curvature of the pipe is ignored
b) The local stress concentrations due to fragments of the existing pipe are ignored
c) A uniform friction coefficient **tan**δ is specified between the pipe and the soil and old pipe fragments surrounding it.

Consideration of horizontal force equilibrium gives,

$$\begin{aligned} W_{\max} &= \sigma_{\max} D\pi t \geq P \tan\delta\pi DL \\ i.e.\, L_{\max} &= \sigma_{\max} t / \tan\delta P \end{aligned} \tag{1}$$

where σ_{max} = the maximum allowable axial stress in the HDPE pipe, D = the internal pipe diameter, t = the thickness of the pipe, P = the radial pressure on the cavity wall, L_{max} = the maximum pulling Length, **tan**δ = the friction coefficient between the pipe and the soil, and W_{max} = the maximum winch force.

Equation (1) could be used to calculate the maximum pulling length, based on the maximum axial force allowed on the pipe generated from friction associated with the radial pressures acting on the external boundary of the pipe. Work is currently underway to compare estimates of pulling length obtained from Equation (1) with experience in the field.

This analysis is expected to yield conservative results since most of the approximations used in formulating the analysis (e.g. the isotropic initial stress condition and constant soil parameters) are conservative. The contribution to the pulling force associated with resistance to longitudinal movement of the bursting head has been neglected. While this will not influence the peak force acting on the HDPE pipe being pulled into place, it will increase the winching force that is required and further work is needed if limits are to be developed for winching loads during pipe installation.

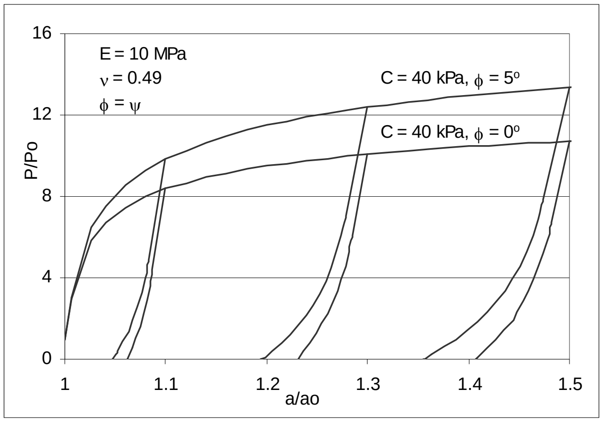

Figure 6: Loading and unloading paths for soils

5 CONCLUSIONS AND RECOMMENDATIONS

Installation of new pipe or replacement of existing pipe using pipe bursting has been developed over the past 10 years and is now often a feasible option for replacement of damaged pipes. It is important to limit the axial installation loads on new pipes during pipe bursting, to improve the process of selecting pipe wall thickness and to ensure adequate trenchless construction practices.

A semi-empirical solution has been developed to estimate the radial pressures at the boundary of the soil cavity during the pipe bursting process. These pressures are related to those that act on the external boundary of the new pulled-in-place pipe, and they are expected to influence the shear stresses that are mobilized to resist the pulling operation. A parametric study has been undertaken to examine the influence of soil parameters and pipe and bursting geometry. This study indicates that the effect of the elastic soil modulus on the final radial stresses is negligible, that the initial ground stresses and shear strength of the soil are the most important soil properties, and that residual pressures on pipes inserted into cohesive ground may be negligible.

The analysis may prove useful to the pipe bursting industry, indicating what soil loads can be expected on the newly installed pipe and providing approximate values of maximum pulling length. Further work is needed to more fully investigate its effectiveness, and to examine the influence of factors such as the ground surface, gradients of initial stress with depth and stress conditions that are not initially isotropic

6 ACKNOWLEDGEMENTS

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