Modeling burst head advance during static pipe bursting

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Abstract

Two dimensional finite element analyses can successfully estimate ground movements and stresses associated with static pipe bursting in the plane perpendicular to the pipe axis. However, they provide no information about the ground movements parallel to the pipe axis or the magnitude of pulling force needed to advance the burst head. Axisymmetric finite element analysis has therefore been developed to explore the axial progression of the burst head, the ground resistance to that advance, the magnitude of axial ground movements, and the effect of soil characteristics on the response of the burst head and the surrounding ground. Calculated response is compared to laboratory measurements of ground movement and pulling force to evaluate the effectiveness of the finite element modeling.

Introduction

Pipe bursting involves using a cable or rod placed within an existing pipeline of brittle material, pulling through a bursting head which breaks the original pipe apart and radially expands the pipe fragments and the surrounding soil, and then pulling into place a new pipe attached behind the bursting tool. There are a number of methods by which pipe bursting can be carried out: pneumatic, implosion, hydraulic and static. In the static method of pipe bursting, the original pipe is usually broken by concentrated forces from a blade or blades attached to the conical section of the bursting head.

Field measurements, laboratory tests, and to a lesser extent numerical analyses of the pipe bursting operation have primarily focused on the ground movements in the soil in the vicinity of the bursting head. While most pipe bursting research has made no attempt to study forces involved in the process, two investigations have examined forces during static pipe bursting. First, Hahn and Ariaratnam (2003) outlined the general form of an equation for estimating pulling force, though they did not quantify various terms (leaving these for field evaluation).

Lapos et al. (2004) conducted laboratory pipe bursting tests. A load cell measured the forces needed to move the bursting head. A continuous record was obtained for total load (force to break the old pipe, expand the soil cavity, and pull in the new).
One important question for pipe replacement contractors is the total pulling force to be encountered in any specific pipe replacement project; the contractor needs to assess whether the equipment being used has sufficient capacity to be able to complete the pull or installation (Lueke and Ariaratnam, 2001; Saccogna, 1997). Although machine capacities may be obtained from the manufacturer's user book, the required loads can be underestimated, causing delay in the schedule; alternatively, if they are overestimated, more costly equipment may be deployed. Currently the pipe bursting industry mostly relies on past experience and empirical rules thumb.

This paper describes axisymmetric numerical modeling of the longitudinal progression of the bursting head through the soil cavity, to calculate the ground resistance to that progression, the magnitude of the longitudinal ground movements, and the effect of soil characteristics on the response of the bursting head and the surrounding ground during static pipe bursting. Calculated response is compared to laboratory measurements of ground movement and pulling force to evaluate the significance of the processes that are modeled in the analysis, and those that are neglected. The objectives of this work are to better understand the geomechanics of the pipe bursting process and to develop practical guidance on pulling forces for the pipe bursting industry.

Summary of laboratory tests

Lapos et al. (2004) conducted pipe bursting tests in a 2 m wide by 2 m long by 1.6 m deep steel tank developed by Brachman et al. (2001). The tests included the bursting of clay pipes with inside diameters of 146 mm and 100 mm and wall thicknesses of 19 mm and 14 mm. The clay pipes were burial at depths of 685 mm and 885 mm within a dense, poorly graded sand (synthetic olivine with a mean grain size of 0.5 mm). Lapos and Moore (2002) reported that this backfill at maximum density has an internal angle of friction of 44^{o}. The high density polyethylene (HDPE) replacement pipe had an inside diameter of 145 mm and wall thickness of 10 mm. The bursting head featured a maximum outside diameter of 202 mm. Further details are provided by Lapos (2004).

Statement of the problem

The pipe bursting problem involves complex three dimensional conditions and processes. First, different zones of soil may lie in the vicinity of the existing pipe (e.g. the native soil around a trench, the bedding and backfill). Initial earth pressures may be nonuniform and anisotropic (with coefficient of lateral earth pressure not equal to unity). A free ground surface will lie at distance h above the existing pipe, and there may be a pavement structure at the surface. Next, the pipe replacement process involves the bursting head imposing complex ground deformations and shear stresses to the fragments of existing pipe and the surrounding soil. At the same time, further ground movements and friction are associated with interactions between the new pipe and the surrounding soil (including contraction of the soil annulus left by burst head onto the new pipe). Bentonite may be used to stabilize this annulus, or other lubricants may be used to reduce friction on the interface between the new pipe and the surrounding soil. Pipe bursting generates outward and upward ground displacements adjacent to and over the pipe alignment, respectively. Soil movements occur in three directions. This first study of the longitudinal progression of the pipe bursting process will be approximated as an axisymmetric process, Figures 1a, b, c.

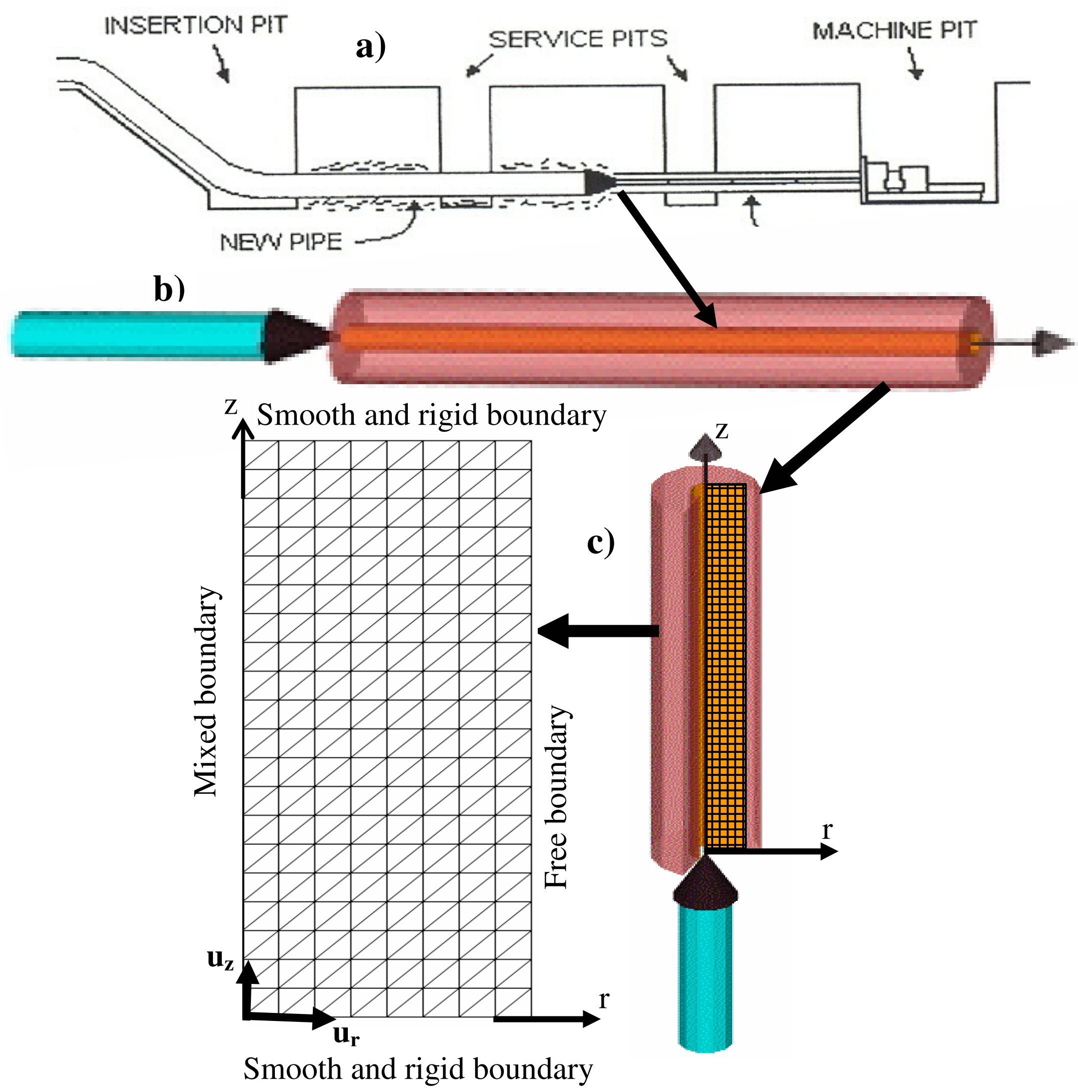

Figure 1 Static pipe bursting process: (a) Field configuration (Ariaratnam et al. 1999), (b) Axisymmetric idealization (c) Mesh and boundary conditions

Specific assumptions are as follows:

- the existing pipe is buried in an extensive zone of single phase elasto-plastic continuum
- the influence of the free ground surface above the pipeline is neglected
- soil properties are uniform (the case of a pipe buried in an embankment or where a trench has been backfilled with native soil)
- pre-existing earth pressures are uniform and isotropic (K_0 = 1)
- fragments of the existing pipe are neglected – all interactions are assumed to occur directly between the soil and the bursting head or new pipe.
- ground vibration caused by the bursting head advance is neglected.
- the presence of Bentonite or other lubricants is neglected.

The influence of many of these approximations is investigated later in this paper using comparisons to laboratory measurements.

Figure 1c shows the finite element mesh. A total length of 1m has been used for calculations of longitudinal progression of a bursting head of length 40cm. The inner boundary has a mixed condition which is described in more detail in the following two subsections. The outer boundary is placed at a distance equal to the burial depth of the pipe (dimensions of 685 mm or 885 mm for the two test conditions examined by Lapos et al. 2004). This outer boundary is left unrestrained (with zero normal and shear stresses). The upper and lower boundaries (z=1m and z=0 respectively) are set as smooth and rigid (axial displacements are restrained). The dense granular soil used in the laboratory tests has modulus of 10 MPa, Poisson's ratio of 0.25, friction angle of 44^o, and dilation angle of 30^o (Lapos and Moore, 2002).

Radial deformations imposed by the bursting head

The internal boundary of the soil around the existing pipe displaces radially from 0 to u_r, where u_r is half the difference between the maximum diameter of the bursting head (d_b) and the initial diameter of the existing pipe (d_c). Six noded triangular elements are used to discretize the soil surrounding the old pipe. To simulate the longitudinal progression of the bursting head, the nodal points located along the conical part of the bursting head are displaced in a systematic process that starts from the first node and can continue to any desired point in the mesh

Consider mesh geometry where the length l_e is the axial distance between successive nodes on the inner boundary. Furthermore, consider a bursting head with a cone length of l_c and an apex angle of α, Figure 2. The progression of the bursting head can be subdivided into small incremental axial advances. First, node 1 will be displaced radially. Once it reaches a radial movement of l_e tan,(α/2), node 2 can contact the cone. Node 3 can contact the bursting head once node 2 reaches l_e tan(α/2), and so on. All nodes located at the inner boundary of the cavity will be displaced radially in this manner, in succession. This radial movement reaches a limit of $l_c tan(\alpha/2)$ once the bursting head progresses forward by l_c so the barrel reaches the node. Geometrically and materially nonlinear soil response is accommodated in the analysis by implementing all nodal displacements in small increments.

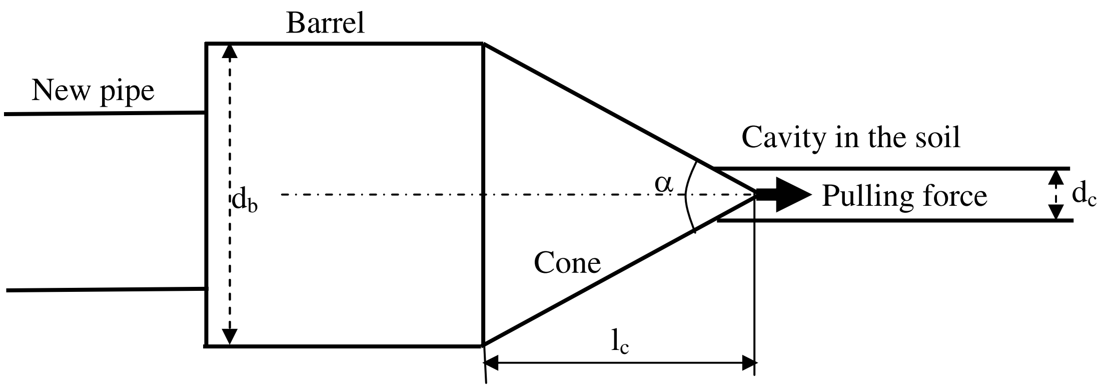

Figure 2 Definition of variables

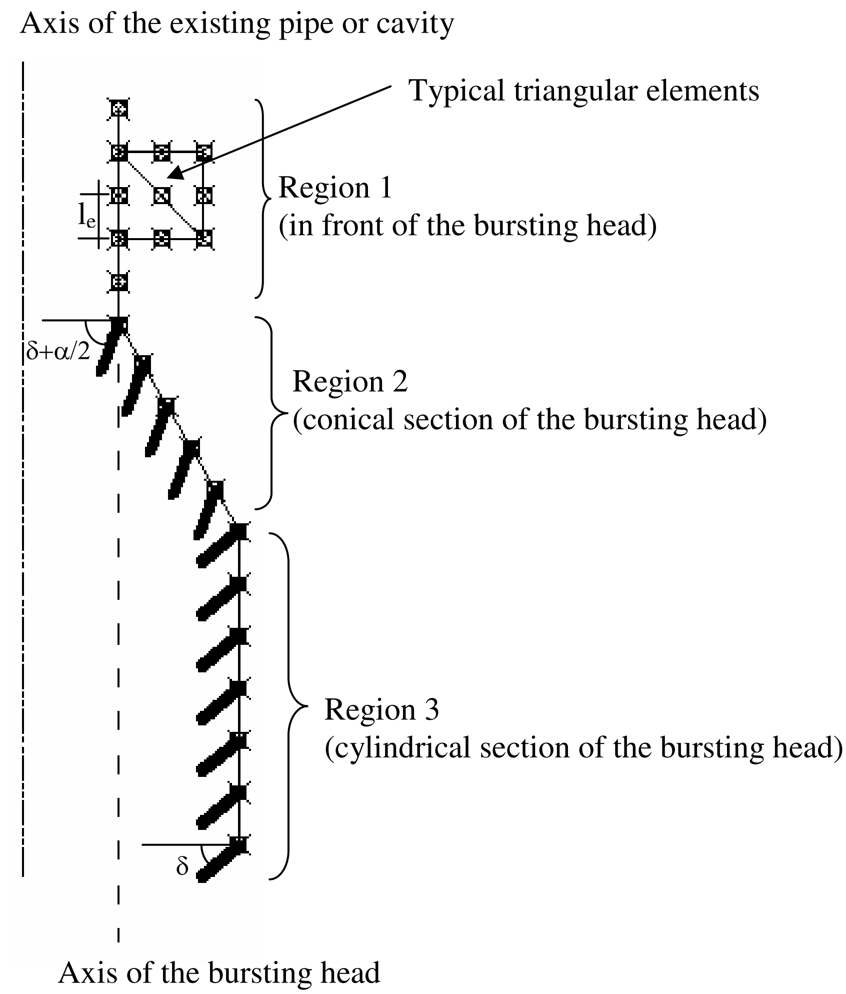

Figure 3 Modeling details

Friction modeling

In addition to the radial movements, the burst head applies friction loads to the inner surface of the soil. If the angle of friction between burst head and ground is denoted as δ, then the resultant nodal force from the cone of the burst head is oriented at an angle of $\delta + \alpha/2$ to the radial axis. When nodes are in contact with the barrel, the force resultants are at an angle of δ to the radial direction. This mixed boundary condition (where the radial displacement is prescribed and resultant force has known direction) is handled by introducing spring elements in contact with each boundary node. Those spring elements are given high axial stiffness, and low shear stiffness, and they are set with orientations that are $\delta + \alpha/2$ or δ relative to the radial axis depending on whether the node is passing along the cone or the barrel of the bursting head. This ensures that the resultant forces and radial displacements have the required characteristics.

Material modeling

The numerical simulation was carried out using AFENA, Carter and Balaam (1980), geotechnical software that features Mohr-Coulomb shear strength modeling and geometrically nonlinear analysis based on the formulation of Carter et al. (1977). Inclusion of both kinds of nonlinearity is important, since the large increases in the size of the soil cavity surrounding the old damaged pipe induce changes in material and geometrical characteristics that substantially affect cavity stiffness.

Comparison of longitudinal ground movements with measured values

Lapos et al. (2004) report on measurements of axial ground movements during laboratory pipe bursting tests. Using 19 reflective prisms placed on the ground surface and a total station, ground movements were measured in lateral, vertical and axial directions. Nkemitag and Moore (2004) used plane strain finite element analysis to simulate these tests, and obtained excellent correlations between calculations and measurements of both lateral and vertical ground displacements. One fundamental approximation used in plane strain analysis is the assumption that the axial movements and axial strains within the soil are negligible. The new axisymmetric analysis of bursting head advance does not rely on that assumption, so axial movements are calculated. Axial displacement calculations at the external boundary of this new analysis are included on Table 1, where they are compared to average measurements of axial movements measured by Lapos (2004) on the ground surface.
There is a very good correlation between calculated and measured values of u_z, with differences varying from 0.5 mm to 1.5 mm.

Comparison of pulling forces with measured values

Lapos (2004) reports on pulling force measurements for four laboratory pipe bursting simulations. During each experiment, the pulling force was continuously recorded using a load cell.

Table 1 Comparison of maximum experimental and FEA axial displacements

	Cavity expansion ratio (%)	Depth of Cover (mm)	Maximum experimental axial displacement (mm)	Maximum calculated axial displacement (mm)
Test 1	33.33	685	14.1	15.2
Test 2	100.00	685	20.5	21.1
Test 3	33.33	885	9.0	10.5
Test 4	100.00	885	13.7	14.2

The axisymmetric finite element model discussed above provides calculations of pulling force associated with advance of the bursting head. This includes the force associated with expansion of the soil in the vicinity of the conical section of the bursting head, as well as friction between the soil, and the conical and cylindrical sections of the bursting head. The component of the pulling force needed to break apart the old pipe is not included in the finite element calculation.

Table 2 shows calculated and measured values of pulling force for the tests of Lapos (2004). The original values of measured pulling forces are shown in column (4) of Table 2, and a second set is included in column (6) which has been reduced by the forces needed to break the clay pipe (column 5, measured by pushing the burst head into a clay pipe placed on an MTS universal test machine).

Table 2 Comparison of experimental and FEA pulling forces

	Cavity expansion ratio (%) (2)	Depth of cover (mm) (3)	Total pulling force (kN) (4)	Breaking force (kN) (5)	Adjusted test force (kN) (6) = (4) – (5)	FEA.pulling force (kN) (7)
Test 1	33.33	685	24.20	5.90	18.3	21.5
Test 2	100.00	685	34.25	6.15	28.1	30.5
Test 3	33.33	885	31.40	5.90	25.5	28.0
Test 4	100.00	885	36.75	6.15	30.6	34.5

The calculated pulling forces were found to lie between 109% and 117% of the total pulling force measurements, and 89% to 94% of the total forces reduced by breaking force. It appears that the axisymmetric finite element model effectively captures the soil resistance to forward movement of the burst head. The analysis also provides reasonable estimates of the impact of burial depth and burst head geometry on pulling force. For example, the analysis suggests that pulling force increases by 9kN and 6.5kN when initial pipe diameter is decreased (for the 685mm and 885mm burial depths, respectively). Measured changes were 10kN and 5.4kN. The analysis indicates that pulling force rises by 6.5kN and 4.5kN as depth is increased (for the larger and smaller initial pipe diameters respectively). The measured increases were 7.2kN and 2.5kN.

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