NUMERICAL SIMULATION OF GROUND MOVEMENTS CAUSED BY PIPE BURSTING

Michael Nkemitag, Research assistant, GeoEngineering Centre at Queen's – RMC, Queen's University Kingston, ON, Canada
Ian D. Moore, Professor and Canada Research Chair in Infrastructure Engineering, GeoEngineering Centre at Queen's – RMC, Queen's University Kingston, ON, Canada

ABSTRACT
Results of ground movements obtained from numerical and physical simulations of pipe bursting are compared. Physical simulation involves the specific case where an existing intact clay pipe with an external diameter of 184 mm backfilled with poorly-graded dense sand was replaced with a polyethylene pipe with an outside diameter of 165 mm. A commercially available burst head was used featuring a diameter of 202 mm. Numerical simulation is performed using two dimensional finite element analysis. The dense, poorly graded sand is modeled as a Gibson soil. The maximum surface heave recorded in the experiment was 27 mm, while the maximum surface heave obtained from the numerical simulation was 29.2 mm. Ground movements at some points were difficult to quantify experimentally and the numerical method was used. Strengths and weaknesses of plane strain finite element modeling to investigate the pipe bursting process are discussed.

RÉSUMÉ
Des résultats des mouvements du sol obtenus à partir de simulations numérique et physique d'éclatement de conduite sont comparés. La simulation physique concerne un tuyau en argile de diamètre extérieur de 184 mm, remblayé avec du sable dense et remplacé par un tuyau de polyéthylène de diamètre extérieur de 165 mm, à l'aide d'un éclateur de diamètre de 202 mm. La simulation numérique est effectuée en utilisant l'analyse bidimensionnelle d'éléments finis. Le sable dense est modélisé comme sol de Gibson. Le soulèvement maximal de surface obtenu de l'expérience était de 27 mm tandis que le soulèvement maximal donné par la simulation numérique était de 29.2 mm. Il était difficile de mesurer expérimentalement des mouvements du sol à certains points où la méthode numérique était employée. Les points forts et les lacunes de modélisation d'éclatement de conduite comme déformation plane par des éléments finis sont mis en exergue.

1. INTRODUCTION

Replacement of existing defective or damaged underground pipes by direct excavation can be expensive particularly in urban areas where the potential for disruption of economic and social activity associated with such replacement is acute. Pipe bursting can be used not only to mitigate but also to remedy this situation.

Pipe bursting is a process in which a cable or rod placed within an existing pipeline of brittle material (clay, concrete, iron) is used to pull through a bursting head which breaks the original pipe. A replacement pipe is then pulled into place behind the bursting head. The new pipe may be of the same size or may be larger than the original, since the bursting operation pushes the fragments of the original pipe radially outwards to make room. There are four systems commonly used in the pipe bursting industry namely static pull, pneumatic, implosion and hydraulic expansion. The static pull system also called static bursting is the predominant process used in Canada and was used for the laboratory testing. The static bursting mechanism is illustrated in figure 1

Although, the use of trenchless technology in general and pipe bursting in particular is growing worldwide, some municipalities and engineers are still reluctant to use the bursting technique. This reluctance of engineers and municipalities is enhanced by the fact that some degree of damage is inflicted on the surrounding environment by pipe bursting. Ground displacements are of primary concern when replacing underground pipes in close proximity to other existing buried utilities or structures.

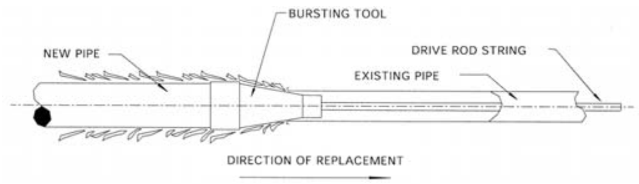

Figure 1: Static bursting mechanism
(from Atalah et al. 1997)

Understanding, and hence predicting, the ground displacements generated by pipe bursting is of vital importance when considering safe distances to other services and controlling possible damage to the road surface and other infrastructure.

To encourage the general acceptance and widespread use of pipe bursting for municipal water mains, sanitary and storm sewers, techniques and tools to quantify and predict ground disturbances are needed.

Preliminary studies conducted to examine the disturbance of the soil in the vicinity of a pipe bursting operation have consisted mostly of field measurements, laboratory model tests, and to a lesser extent numerical analyses. Reed (1987) provides displacement and strain data for an instrumented ductile iron pipe above the clay pipe replaced by pipe bursting. Leach and Reed (1989) using the Reed (1987) data developed a methodology by which the mechanism of ground movement generation and the extent of movement and its effect on nearby utilities can be observed and measured. They proposed a typical pattern of ground displacements according to site conditions shown on figure 2. Swee and Milligan (1990) using clear-sided tanks to observe the soil displacements during pipe bursting tests in the laboratory, provided an understanding of the soil displacements and the potential risk of damage to adjacent utilities. Rogers and Chapman (1995) have conducted laboratory tests for shallow buried pipelines in sand. Atalah et al. (1997) conducted full scale pipe bursting experiments in a controlled soil environment and numerical modeling of pipe bursting operations, during which ground movements in terms of vibration and vertical displacement at different depth and offsets from the pipe were measured. They found that, although ground vibrations may be quite noticeable to a person standing on the surface close to a bursting operation, the levels of vibrations are very unlikely to be damaging except at very close distances to the bursting operation.

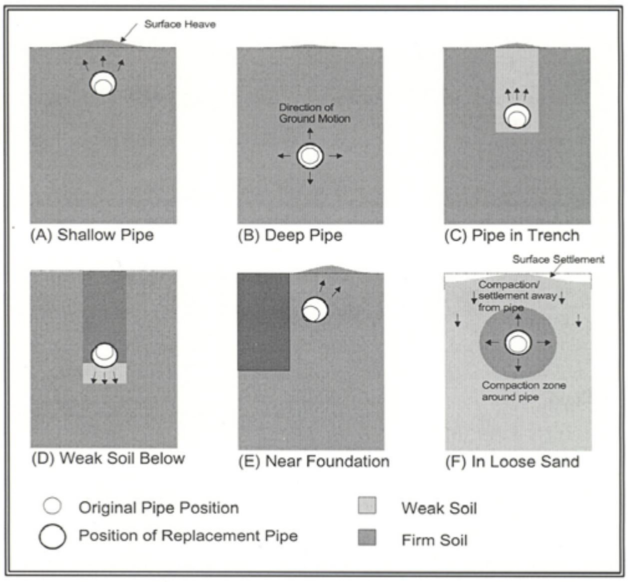

Figure 2: Ground displacements pattern according to site conditions (from Leach and Reed 1989)

Guice et al. (1997) have reported fieldwork and first-approximation finite element analysis. Researchers have conducted simple surveys of pipe-bursting contractors to learn what they are currently doing. For example, Lueke et al. (1999) have reported on typical static bursting operations, listing details such as the sizes of existing and replacement pipes and the length of pipe pulled into place.

Yu and Houlsby (1995) developed a useful theoretical solution that models cavity expansion follow by contraction in elastic-plastic ground, and Fernando and Moore (2002) have used that cavity expansion theory to examine the load path in soil surrounding the existing pipe as it is expanded and a new pipe is installed. That work demonstrated that it is the strength characteristics (cohesion and angle of friction) rather than the elastic stiffness (modulus) of the soil that controls the radial stresses that press onto the fragments of the existing pipe as the new pipe is dragged into position. Fernando and Moore (2002) used two dimensional finite element analysis to examine the influence of the ground surface above the pipe being replaced, and pre-existing ground stresses that are non-uniform and anisotropic. These analyses by Fernando and Moore (2002) have the potential to provide calculations of ground displacements in the vicinity of the bursting head, and estimates of earth pressures applied to the pulled-in-place pipe, so that axial force and axial stress can be estimated. The effectiveness of these analyses needs to be assessed using a careful comparison with actual measurements reported either in the laboratory or in the field.

The objective of this paper is to evaluate a plane strain numerical model for pipe bursting operations with data from pipe bursting experiments. The evaluation of the model is focused on ground disturbance in the vicinity of bursting head. In order to compare ground movements obtained from the model and experiments, the surface heave and points where heave plates were installed are considered. This comparison then makes it possible to discuss strengths and weaknesses of plane strain finite element modeling of the pipe bursting process.

2. 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). He started by bursting a new clay pipe with an outside diameter of 184 mm and wall thickness of 19 mm. The new pipe to be installed within was a high density polyethylene (HDPE) pipe with an outside diameter of 165 mm. The backfilled clay pipe was placed in such a way that the enlarged bell ends of the pipe were against the walls of the steel tank. The effect of friction mobilized along the walls of the steel tank was minimized using multiple layers of plastic film with grease (Tognon et al. 1999). Lapos used poorly-graded sand (synthetic olivine with a mean grain size of 0.5 mm) as a backfill material. He placed the sand in 200 mm thick lifts and each lift was compacted by dropping a 250 mm square plate with mass of 6.8 kg from a distance of 0.3-0.4 m. A photograph showing the steel tank, burst head and HDPE pipe prior to the experiment is shown in figure 3. Lapos then used a commercially available burst head with a maximum outside diameter of 202 mm to break the clay pipe while pulling into place the HDPE pipe. A profile view showing the bursting process is given on figure 4.

Lapos measured ground movements at selected points. Surface heaves were measured using 19 reflective prisms placed on the ground surface together with a total station.

Ground movements at distances of 0 mm, 250 mm and 500 mm directly above the pipe crown were measured using linear potentiometers attached to three heave plates located at these points.

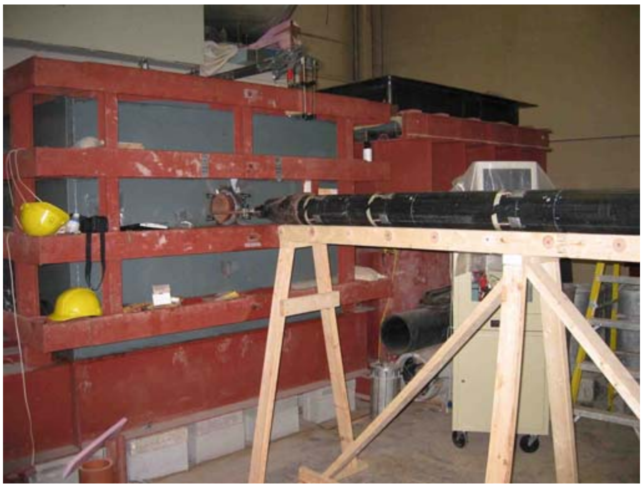

Figure 3: Steel tank, burst head and HDPE pipe prior to the experiment (from Lapos et al.2004)

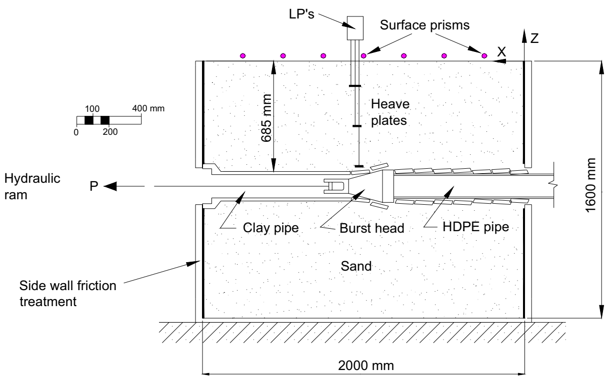

Figure 4: A profile view showing the bursting process (from Lapos et al. 2004)

3. STATEMENT OF THE PROBLEM AND FINITE ELEMENT MODELING

Pipe bursting is a complex three dimensional process. By making certain approximations a two-dimensional finite element analysis can be used to model this process as seen on figure 5. In order to use a plane strain finite element model, it is assumed that longitudinal ground movements are very small compared to radial ground movements. The validity of this assumption is investigated here. An important approximation used in the testing is the fact that the tests were carried out in a finite sized soil box with restrained boundaries rather than the actual field operations with distant boundaries. The friction mobilized along the walls of the steel tank minimized using multiple layers of plastic film with grease (Tognon et al. 1999) was accommodated in the analysis by modeling these boundaries as smooth and rigid.

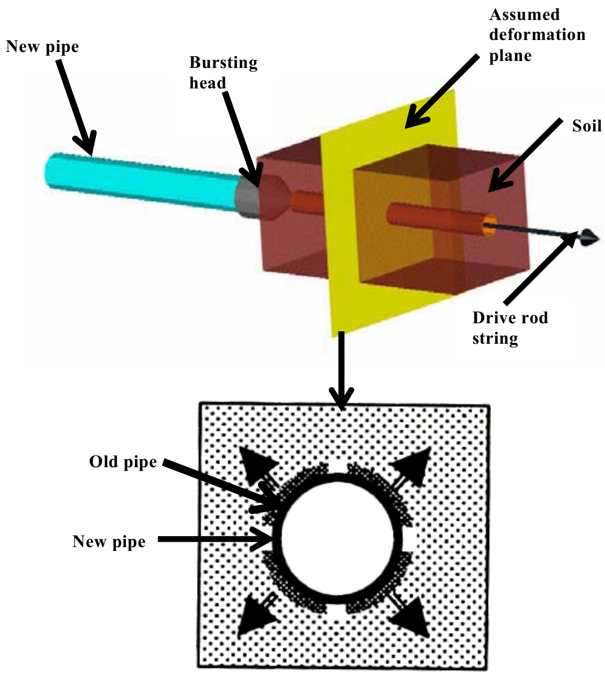

Figure 5: Plane strain analysis idealization

Figure 6 shows the finite element mesh and boundary conditions used in the plane strain pipe bursting modeling. There is a line of symmetry, so only half of the geometry needs to be included in the finite element mesh.

Fernando and Moore (2002) developed an effective technique to model expansion of the soil boundary surrounding the existing pipe. The external boundary of the bursting head is modeled using a ring that has a high axial and very high flexural stiffness. The ring is expanded by applying pressure as nodal forces on the circumference of the ring as show on figure 7. The applied pressure is given by

$$p = \frac{u_r EA}{r^2}$$

where EA = axial ring stiffness, u_r = radial displacement, r = radius, p = radial pressure

This approach is used to obtain specific values of ring expansion without knowing the magnitude of the upward movement of the center of the ring (unknown, since it depends on equilibrium of radial pressures on the outside of the ring).

It is important to evaluate any model used to investigate physical processes in the field. Measurements taken during either laboratory or field tests can be employed for this purpose.

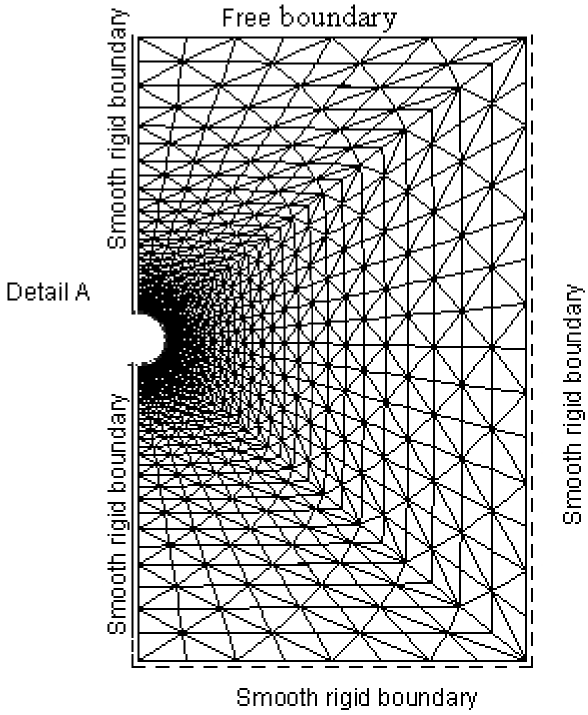

Figure 6: Finite element mesh and boundary conditions

Case histories can also be used. The task considered here is the assessment of plane strain finite element modeling of pipe bursting operations using experimental data obtained in the laboratory. Plane strain finite element models are often employed for calculating ground movements and stresses in the soil. Only ground movements were measured during the experiment; so the model is assessed with respect to that aspect in particular.

The plane strain numerical simulation was carried out using AFENA, Carter and Balaam (1980), geotechnical software capable of analyzing large strain non-linear behavior of soils. The finite element formulation incorporates conventional elastic-plastic constitutive relations based on Mohr-Coulomb shear strength modeling. The fact that the geometrically non-linear formulation of Carter et al. (1977) is included is very important since increases in the cavity surrounding the old damaged pipe can be large during pipe bursting operations (it is the change in cavity size relative to the original cavity size that most influences geometrical non-linearity, not change in size with respect to the overall dimensions of the soil zone).

As explained earlier the sand was compacted to a density of 1490 kg/m^3. Lapos and Moore (2002) showed that at this density the sand has an internal angle of friction of 44^o. For numerical analysis, the dense poorly-graded sand is modeled as a Gibson soil. Gibson constants E_0 and E_g were determined using Janbu constants K = 340 and n = 0.81 determined by Lapos and Moore (2002) as seen in figure 8.

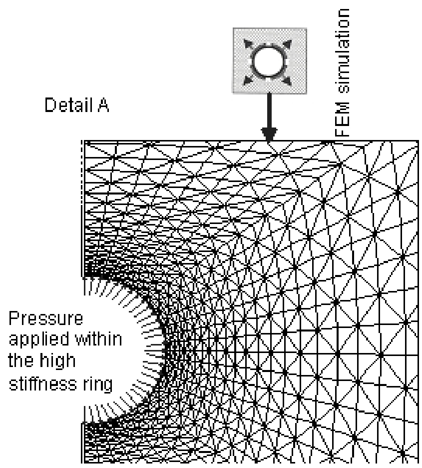

Figure 7: Expansion simulated by nodal forces on the ring

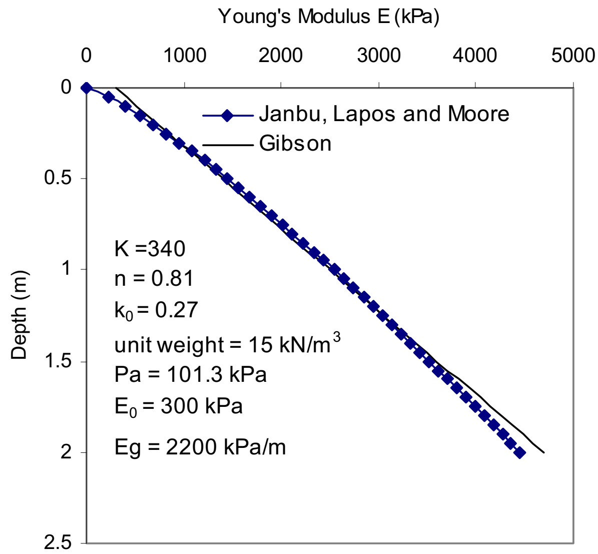

Figure 8: Determination of Gibson constants from Jambu constants

4. CALCULATIONS OF SURFACE MOVEMENT

Surface heave is of primary concern when replacing shallow buried pipes by pipe bursting in close proximity to existing surface utilities and structures. When planning to use pipe bursting as a replacement method for pipes buried at shallow depths in urban areas, surface heave is an important concern. Lapos et al. (2004) studied surface movements during laboratory pipe bursting tests. He measured surface heaves using 19 reflective prisms placed on the ground surface and a total station. Surface movements obtained from plain strain finite element analysis and the pipe-bursting tests are shown in figure 9. The difference between the maximum heave calculated by the numerical model and the experimental results is less than 8%. The differences in surface heave values grow at locations more distant from the centerline of the pipe, becoming very significant at the walls of the test cell. The surface heave calculated by the numerical model is higher than that measured during the experiment. This is attributed to the three-dimensional nature of ground movements as the soil expands in the vicinity of the pipe bursting head. Plane strain numerical modeling features cavity expansion that is two-dimensional, essentially modeling the bursting head as having infinite length. Naturally, the bursting head is of finite length, so that ground movements attenuate at locations in front and behind the bursting head. A much greater volume of soil is therefore available to accommodate the volume reductions imposed by the external boundary of the bursting head. An alternative way of viewing the difference involves consideration of cavity expansion that is more spherical in nature, rather than as purely cylindrical.

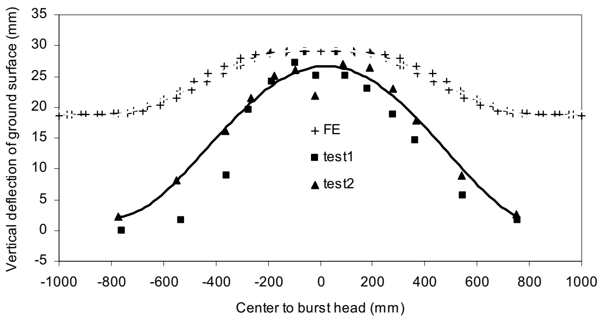

Figure 9: Comparison between finite element and tests' surface heaves

5. VERTICAL MOVEMENT ABOVE PIPE CROWN

Figure 4 shows how the three heave plates used to measure the ground movement at distances of 0 mm, 250 mm and 500 mm above the pipe crown were placed. Comparison between the plane strain finite element and experimental results obtained at these points is shown in figure 10. It can be seen from this figure that the ground heave calculated at these points using plane strain finite element analysis and the experimental heaves are similar. The largest difference between numerical and experimental ground heaves appears at the surface.

6. ANALYSIS REDUCING THE EFFECT OF CELL WALLS

The proximity of the stiff walls of the test cell influences the numerical ground heave values, given that the finite element calculations of surface uplift exceed 15 mm at the sides of the test cell, Figure 9. The influence of those boundaries on the physical test results is considered much smaller, since the experimental ground heaves drop below 5 mm within 300 mm of the cell boundaries. Given this difference, finite element calculations are included in Figures 11 and 12 using a mesh that extends well beyond the sides of the test cell. Meshes of two times and three times the test cell's width were used to study the influence of side walls on numerical results. Figure 11 indicates that the numerical results more closely match the test measurements of surface uplift using these wider meshes. The width of the finite element mesh has a more limited effect on the vertical soil movements directly above the pipe crown, Figure 12.

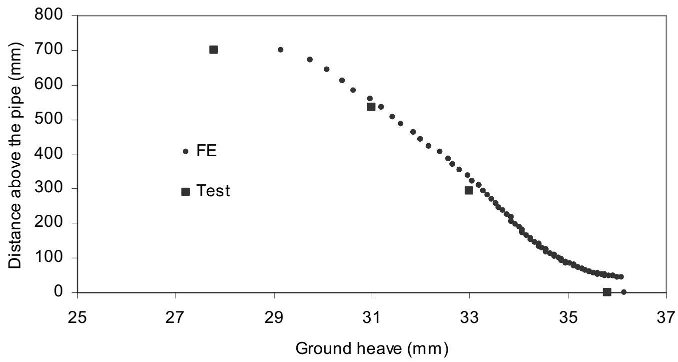

Figure 10: Comparison between finite element and tests' ground heaves versus distance above the pipe crown

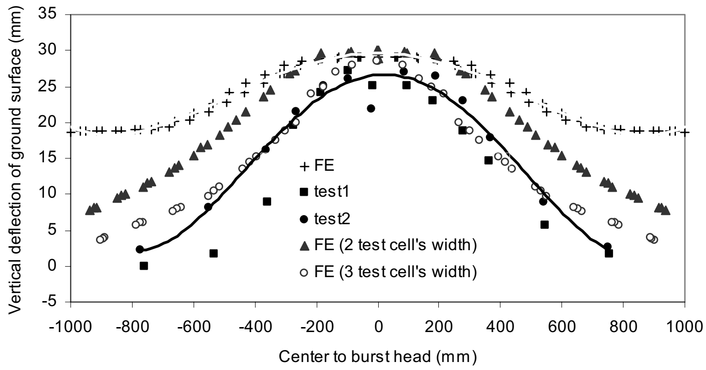

Figure 11 Influence of the width of the finite element mesh on numerical ground heave values

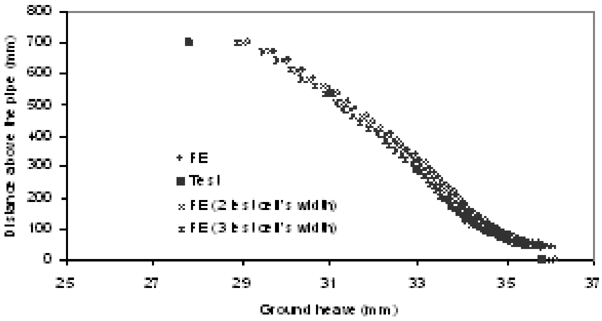

Figure 12. Influence of the finite element mesh width on numerical ground heaves above the pipe crown

7. CONCLUSION

It is important to evaluate numerical models being used to solve practical problems, to ensure they provide credible results compared to laboratory or field test data. A plane strain numerical model for pipe bursting operations has been assessed using data from pipe bursting experiments. The comparison of the results calculated using the finite element procedure with experimental results proves the feasibility of modeling a three-dimensional pipe bursting operation by two dimensional plane strain finite element analysis. The primary difference between the numerical and experimental results relates to the finite length of the bursting head, and the three dimensional nature of ground movement attenuation away from the burst head position. Ground movement attenuation in the plane strain analysis is two dimensional and corresponds to cylindrical cavity expansion, whereas the actual pipe bursting process is three dimensional and it exhibits somewhat spherical cavity expansion characteristics.

Although the plane strain finite element analysis over-calculates the surface heave, it has many advantages over laboratory testing. First, the plane strain finite element analysis permits ground movements to be estimated at points where experimental results are difficult to obtain. Second, it permits parametric evaluations to study ground response for a range of soil and geometrical conditions. Once calibrated, the plane strain finite element model can be used to design pipe bursting operations in various site conditions. The two-dimensional plane strain calculation is much simpler than full three-dimensional analysis and it requires much less computational time. Further studies are in progress to provide more specific guidance for consulting, municipal and construction engineers undertaking pipe bursting operations.

8. ACKNOWLEDGMENTS

This research was funded by Strategic Project Grant No. 257858 from the Natural Sciences and Engineering Research Council of Canada (NSERC). The experimental apparatus and associated instrumentation were developed with funding from NSERC, the Canadian Foundation for Innovation and the Ontario Innovation Trust. The polyethylene pipe samples were provided by KWH Pipe the USA and Canada

9. REFERENCES

Atalah, A., Lei, Y. and Du, X.C. 1997. The effect of pipe bursting on nearby utilities, pavement, and structures. Technical Report, Trenchless Technology Center, Louisiana Tech. University.

Brachman, R.W.I, Moore, I.D. and Rowe, R.K. 2001. The performance of a laboratory facility for evaluating the structural response of small-diameter buried pipes. Canadian Geotechnical Journal, Vol. 38, pp. 260-275.

Carter, J.P. and Balaam, N.P. 1980. AFENA-A general Finite Element Algorithm: user manual. School of Civil and Mining Engineering, University of Sydney, N.S.W. 2006, Australia.

Carter, J.P., Booker, J.R., and Davis, E.H. 1977. Finite deformation of an elasto-plastic soil. Int. J. for numerical and analytical methods in Geomechanics, Vol. 1, 25-43.

Chapman, D.N. and Rogers, C.D.F. 1991. Ground movements associated with trenchless pipelaying operations, Proceedings of the Fourth International Conference on Ground Movement and Structures, Cardiff, Edited by J.D. Geddes, Published by Pentech press, pp. 91-107.

Fernando, V. and Moore, I.D. 2002. Use of cavity expansion theory to predict ground movements during pipe bursting, Proc. Of pipelines, American Society of Civil Engineers, Cleveland, OH.

Fernando, V. 2002. Simulating ground response during pipe bursting, M.E.Sc. thesis, Faculty of Engineering Science, The University of Western Ontario.

Guice, L.K, Straughan, T., Norris, C.R. and Bennett, R.D. 1997. The Effect of Pipe Bursting on Nearby Utilities Pavement, Trenchless Technology Center Newsletter in the USA and Canada.

Lapos, B. and. Moore, I.D. 2002. Evaluation of the strength and deformations properties of Olimag Synthetic Olivine. Proceedings of 55th Canadian Geotechnical Conference, Niagara Falls, ON, pp. 729-734.

Lapos, B., Brachman, R.W.I. and. Moore, I.D. 2004 Laboratory measurements of pulling force and ground movement during a pipe bursting test. North American Society for Trenchless Technology (NASTT) NO-DIG 2004, New Orleans, Louisiana.

Leach, G. and Reed, K. 1989. Observations and assessment of the disturbance caused by displacement methods of trenchless construction, Proceedings of the Fourth International Conference on Trenchless construction utilities, NO-DIG, London, Paper 2.4.

Lueke, J.S., Ariaratnam, S.T. and Strychowskj, P. 1999. A modeling approach for designing and planning of static pipe bursting operations. No-Dig 1999 conference, North American Society for Trenchless Technology, Orlando, Florida, 39-46.

Reed, Y. 1987. The Application of Moling Techniques in the Water Industry Proceedings of NO-DIG International, London, UK, pp. 2.2.2-2.2.10.

Swee, J. and Milligan, G. 1990. Pipe Bursting Model Tests, Proceedings of NO-DIG International, Osaka, Japan, pp. H3.1-H3.8.
Tognon, A.R.M., Rowe, R.K., and Brachman, R.W.I. 1999. Evaluation of Sidewall Treatment for a Buried Pipe Testing Facility. *Geotextiles and Geomembranes*, Vol. 17, pp. 193-212.
Yu, H.S and Houlsby, G.T. 1995. A large strain analytical solution for cavity contraction in dilatants soils. Int. J. for numerical and analytical methods in Geomechanics, Vol. 19, 793-811.