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RATIONAL GUIDELINES FOR EXPECTED GROUND DISTURBANCE DURING STATIC PIPE BURSTING THROUGH SAND

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ABSTRACT: Empirical guidelines are often used to prevent disturbance to adjacent infrastructure during pipe bursting operations. Finite element techniques have recently been developed to calculate levels of ground disturbance. Comparisons with test measurements confirm that the analysis produces good estimates of ground movement in sands. The procedure has therefore been used to undertake a parametric study. Numerical solutions for maximum uplift at the ground surface are reported for cohesionless soils, considering different burial depths, trench widths, and various levels of cavity expansion (degree of upsizing).

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. Excavation can damage buried electricity and gas lines which halt the replacement or construction process. Under extreme circumstances, it can result in explosions and breakdown in communication networks. Underground congestion is ever increasing, with growing urbanization and new communication technologies. In Hong Kong, for example, the use of non disruptive methods is enforced by means of road excavation permits and charges. Breaches of conditions of those permits can lead to fines and even jail time (ISTT Roundup, Trenchless Asia, 2002). In some urban environments, pipes can be extremely deep and/or are below highly congested areas with buildings, roads and other underground infrastructure. In these situations, open cut methods are not feasible. The best solution often involves use of a trenchless technology that minimizes excavation, traffic and business disruption.

Pipe bursting is particularly attractive since it permits on-line pipe replacement, the substitution of the existing pipe by a pipe of equal or larger diameter, Atalah et al. (1997). The pipe bursting process involves inserting a cable or rod within an existing pipeline composed of brittle material, using this to pull through a conically shaped bursting head which breaks the original pipe into fragments, and pulling into place a replacement pipe that is attached at the rear of the bursting head. The bursting process is illustrated in Figure 1.

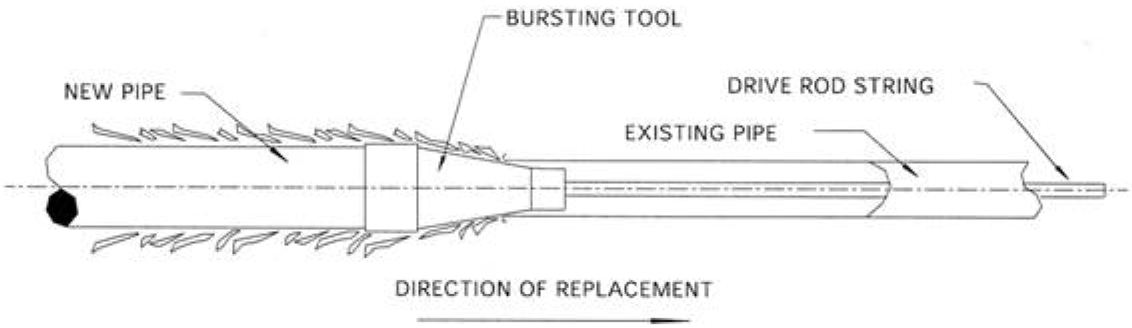

Figure 1. STATIC BURSTING MECHANISM (AFTER ATALAH ET AL., 1997)

Ground movements are a major concern when replacing underground pipes in close proximity to other utilities. For safe and successful pipe bursting projects, the magnitude of ground movements needs to be estimated to manage the risk of damage to other infrastructure. This issue has traditionally been treated using empirical ground disturbance data. The costs of field-work are high, however, so field data is limited (just one test appears to have been used by Advantica to produce proximity charts for their new pipe-splitting technology, Chapman et al. 2003).

The authors have recently used finite element analysis to examine a series of pipe bursting tests reported by Lapos et al. (2004), and this has confirmed that the computational procedures of Fernando and Moore (2002) are effective in estimating ground deformations in granular soils, Nkemitag et al. (2005). The present paper presents finite element results from a parametric study to establish numerically based levels of ground disturbance associated with pipe bursting in cohesionless soils (sands). The study examines the effect of burial depth, various levels of cavity expansion (pipe replacement and upsizing), and the width of the trench in which the existing pipe was buried.

2. LITERATURE REVIEW

Leach and Reed (1989) described various contexts where site conditions can influence ground movements, Figure 2.

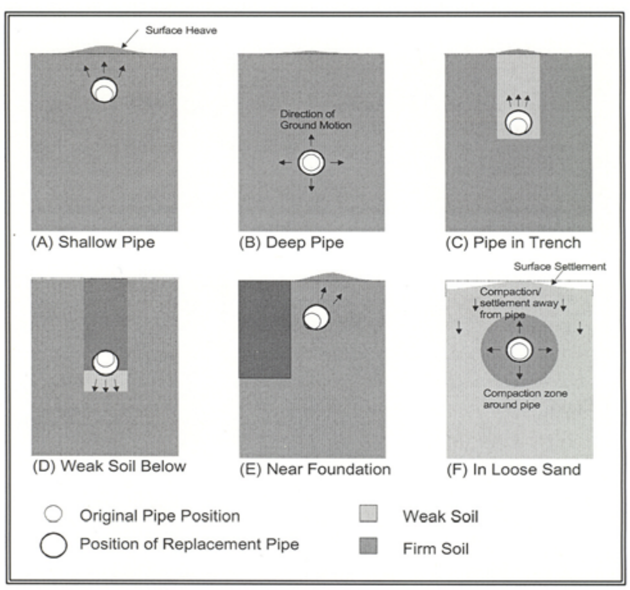

Figure 2. CONCEPTUAL EFFECT OF SITE CONDITIONS ON GROUND MOVEMENTS

While no procedure was proposed to estimate the magnitude of those movements, they explained the expected response of shallow and deeply buried bursting operations, the influence of trench sidewalls, the impact of a zone of soft soil under the pipe invert, how the cavity expansion process can be skewed in the vicinity of a rigid foundation, and the possible nature of ground response when bursting in loose sand.

Simicevic and Sterling (2001) produced bursting guidelines where the primary design considerations are ground and ground water conditions, degree of upsizing required, construction and depth of the existing pipeline, the nature of the replacement pipe, and the length of burst. While they did not propose any specific method for the estimating the magnitude of ground movements, they stressed the importance of ensuring that distances to other services are adequate to prevent damage.

Earlier studies of pipe bursting are also described in the literature. Swee and Milligan (1990) used clear-sided tanks to observe the soil displacements during pipe bursting tests in the laboratory, and thereby contributed to understanding of the soil displacements and the potential risk of damage to adjacent utilities. Rogers and Chapman (1995) conducted laboratory pipe bursting tests in a 1.0 m wide, 1.5 m long, and 1.5 m deep glass-fronted tank, driving a semi-circular bursting head of 210 mm diameter into semi-circular plaster pipes of 175 mm and 124 mm internal diameters buried 450 mm from the surface of the sand. Observations at a long glass face at the end of the bursting operation were used to characterize ground disturbance in the vicinity of the pipe bursting project. They constrained the bursting head to run along the invert of the buried pipe, and this may have affected the surface heave magnitude. Photographs taken for tests in both dense and loose sand were interpreted using stereographic projection, to provide the patterns of ground movements in both horizontal and vertical directions.

Atalah et al. (1997) conducted full scale pipe bursting experiments in a controlled soil environment and undertook numerical modeling of pipe bursting operations. Using a general three-dimensional finite difference program (FLAC3D), the bursting process was modeled by imposing a sinusoidal velocity profile on the boundary of the soil cavity in the outward direction until the required upsizing was approximately achieved. Once the required level of upsize was reached, the soil cavity was then restrained to simulate the introduction of a new pipe. Upsizing was then repeated at the next station, located approximately 30 cm along the longitudinal axis inside the soil cavity. Their comparisons of finite difference and experimental results indicated that the numerical solution overestimated ground velocities and underestimated ground displacements.

Fernando and Moore (2002) used the cavity expansion theory of Yu and Houlsby (1995) to examine the load path in soil surrounding the existing pipe as it is expanded and a new pipe is installed. They also used two dimensional finite elements analysis to examine the influence of the ground surface above the pipe being replaced, developing two dimensional finite element techniques to evaluate ground movements and vertical movement of the axis of the bursting head.

3. METHODOLOGY

Plane strain finite elements calculations were 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. For these analyses, the soil used was modeled as linear, isotropic elastic until yielding. The plastic flow was governed by a non-associated flow rule, where dilation angle for the soil can be set as lower than the angle of internal friction. The geometrically non-linear formulation of Carter et al. (1977) is used to account for the substantial increases in cavity geometry surrounding the old damaged pipe that occur during pipe bursting. Changes in cavity size influence the incremental stiffness of the system (change in size relative to the original cavity dimensions influences geometrical non-linearity rather than change in size with respect to the overall problem dimensions).

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 by introducing an artificial ring with 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 3. The applied pressure is given by

$$p = \frac{u_r EA}{r^2} \qquad [1]$$

where EA = axial ring stiffness, u_r = radial displacement, r = radius, p = radial pressure. This approach is used to define specific values of ring expansion (diameter increase) while allowing vertical movement of the cavity axis to bring the radial pressures on the outside diameter of the ring into vertical equilibrium.

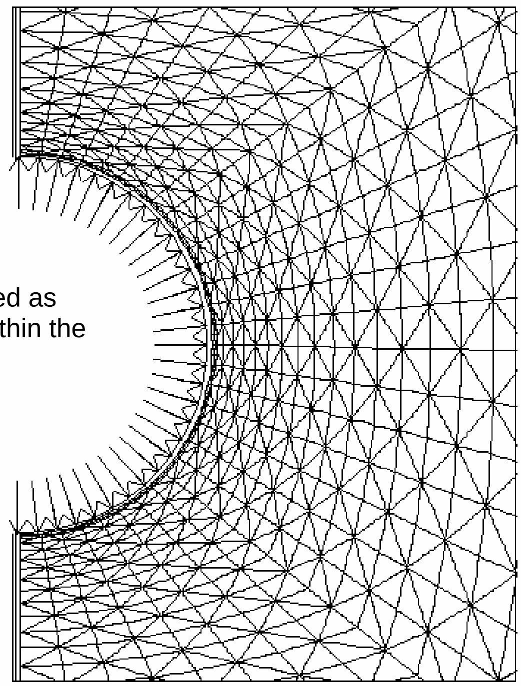

Figure 3. APPLICATION OF PRESSURE AS NODAL FORCES ON THE CIRCUMFERENCE OF THE RING

By using this technique for modeling expansion, the uplift of the axis of the bursting head in dense sand observed during experiments is captured and the maximum surface movements are well predicted. Comparisons have been made between the results of this form of analysis and the measured ground displacements, Nkemitag et al. (2005), and these demonstrate that the numerical procedures work effectively. Data from the tests of Lapos et al. (2004) will be reviewed again in a later section to provide further comparisons between the computational results and these measurements.

4. PARAMETRIC STUDY

A set of numerical calculations was carried out using the plane strain finite element procedures described above, to investigate the effect of various parameters on the maximum surface heave caused by pipe bursting below. A purely frictional soil with a Poisson's ratio of 0.254 and an elastic modulus that increases with depth was studied. The Gibson (linear distribution) constants, namely surface modulus Eo of 300kPa and modulus gradient with depth E_g of 2100kPa/m were determined using Janbu constants K = 340 and n = 0.81 reported for the test soil by Lapos and Moore (2002). These represent conditions in the stiff granular backfill with significant modulus increases with depth.

Analyses using both non-associated and associated plastic flow rules were obtained to investigate the effect of dilation angles that are lower than and equal to the friction angle respectively. This reveals how dilation angle influences the maximum surface heave. The angles of friction, dilation and unit weight used for the study were respectively 44°, 30° and 15kN/m³. The sand condition in the laboratory tests and the analyses reported here was very dense, a condition that is expected to produce the greatest amounts of surface heave given the high amounts of volume increase from a high dilation angle. One specific depth and a number of common pipe diameters were used. Table 1 gives both the geometric and material parameters that were employed. A normalization procedure described in the next section was developed to allow these specific results to have more general applicability.

Table 1. GEOMETRIC PARAMETERS AND SOIL PROPERTIES

D_0 (mm)	Depth (mm)	Depth/D_0 h/D_0	ϕ(°)	ψ(°)	ν	k	n	E_0 (kPa)	E_g (kPa/m)
100		12							
150	1200	8	44	30	0.254	340	0.81	300	2200
200		6							

5. EFFECT OF BURIAL DEPTH

Three different h/D_0 values were studied to investigate how they affect the maximum surface heave when replacing a pipe of a specific diameter buried at a specific depth. The values of 12, 8 and 6 were used to cover a range of common pipe bursting configurations. Figure 4 shows results for the maximum surface heave normalized by ΔD, the amount of cavity expansion imposed by the burst head (the difference between the maximum diameter D and the initial diameter D_0 of the soil cavity around the old pipe). Solutions are presented as a function of the cavity expansion ΔD normalized by D_0.

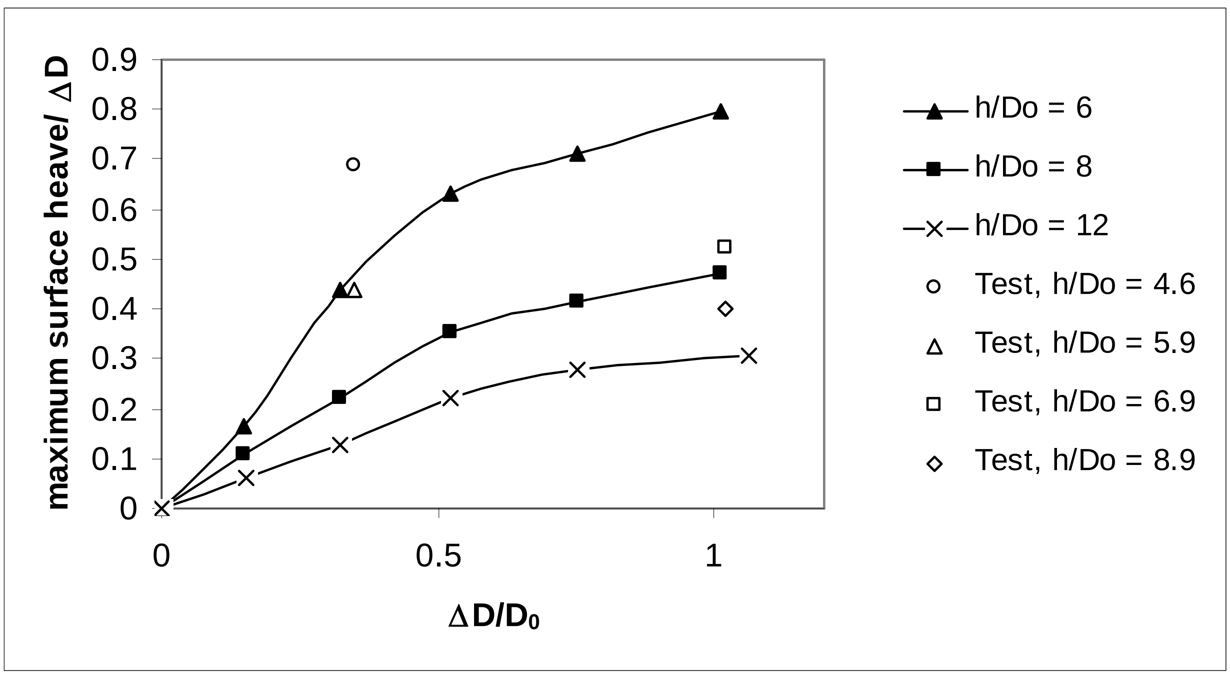

Figure 4. NORMALIZED MAXIMUM SURFACE HEAVE VERSUS NORMALIZED DIAMETER CHANGE; BURIAL IN DENSE SAND (ϕ OF 44°, ψ OF 30°).

The laboratory data reported by Lapos et al. (2004) are also shown on Figure 4. Four tests results are available, representing two burial depths at two different expansion ratios. These four tests featured h/D_0

values of 4.6, 5.9, 6.9 and 8.9. The normalized surface heave results for those tests appear to be near the expected locations relative to positions interpolated from the theoretical results for h/D_0 of 6, 8 and 12, or from 5 % to 15% lower than the theory would suggest. Since the normalized surface heave measurements from the tests are lower, the theoretical results are somewhat conservative.

For each ratio of h/D_0, computer analyses were also obtained with diameters and depths scaled in proportion to those presented in Table 1, to ensure the results for each specific h/D_0 applies to all installations in that soil with similar dimensionless geometry (confirming, for example, that results for a borehole of twice the size at twice the depth plot at the same location). The comparisons with the measurements of Lapos et al. (2004) also support the conclusion that the normalization used in Figure 4 is effective, since the experiments were conducted using different initial cavity dimensions and burial depths.

For each depth ratio, the amount of surface heave normalized by ΔD increases in an almost bilinear manner with respect to $\Delta D/D_0$. Normalized heave grows rapidly until a cavity expansion ratio of about 50% is reached. Beyond that value, normalized surface heave grows more slowly. Not surprisingly, the results for shallowest burial (h/D_0 of 6) give the highest surface heave as a proportion of cavity diameter increase. Solutions for h/D_0 of 8 are about 40% smaller, and results for h/D_0 of 12 are about 60% smaller.

It is concluded from this discussion that the theoretical results in Figure 4 represent reasonable and conservative estimates of uplift expected at the ground surface.

6. EFFECT OF EXTENT OF VOLUME EXPANSION OF THE SOIL

Uplift was also calculated for a higher dilation angle, to see the impact of the enhanced shear-related volume increases. A condition of associated plastic flow (where angles of friction and dilation are equal) was employed in preparing Figure 5, where the results from Figure 4 are included for comparison. This clearly shows how use of dilation angle equal to friction angle increases the surface movements. These movements are more than 50% greater than those for ψ of 30^o, and those observed in the tests (Figure 4).

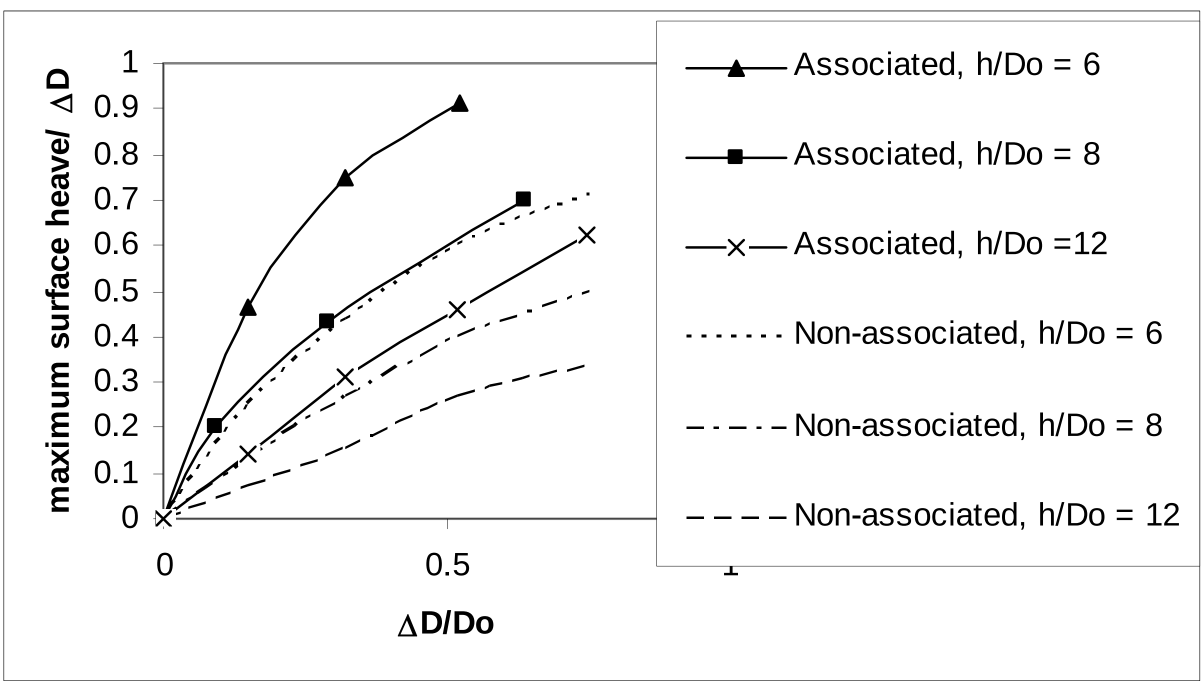

Figure 5. COMPARISON BETWEEN SURFACE HEAVE RESULTS FOR HIGH DILATION ANGLE ($\phi = \psi = 44^O$) AND LOWER DILATION ANGLE ($\psi = 30^O$, $\phi = 44^O$).

Dilation angle for both dense and loose granular materials is always likely to be less than friction angle, and dilatancy in loose sands is often negligible. Furthermore, the analyses reported here feature dilation that increases indefinitely as shear strains are accumulated, whereas real materials have volume increases that eventually cease as they approach a critical density (corresponding to critical void ratio). The results provided in Figure 4 are therefore conservative relative to those for looser materials, though additional analyses could always be undertaken to obtain results for specific materials with lower density.

7. EFFECT OF TRENCH WIDTH *W*

Underground pipes in urban settings are usually installed in narrow trenches excavated into the native soil material. Following excavation and pipe placement, the trench is generally backfilled with material that is more compressible than the undisturbed native soil. The influence of the stiff native material beyond the sides of the trench has therefore been examined using the finite element analysis. A conservative approach was adopted, where the lateral boundaries of the trench were modeled by completely preventing horizontal movement (corresponding to a condition where the native soil has huge stiffness compared to the backfill).

Figures 6 and 7 present solutions for normalized uplift for two different values of cavity expansion (50% and 100% respectively). Results are presented for a range of trench widths *W* normalized using initial pipe diameter D_o. The three different values of normalized burial depth h/D_o were again considered, and the soil was again assigned a dilation angle $\psi = 30^o$. Both Figures 6 and 7 show how the maximum surface heave is substantially enhanced as trench width W/D_0 is decreased. Maximum surface heave approaches the cavity diameter decrease ΔD at the narrowest trench width of W/D_o=3. Results for very wide trench (very large values of W/D_0) approach those reported in Figure 4 for pipe in an embankment condition.

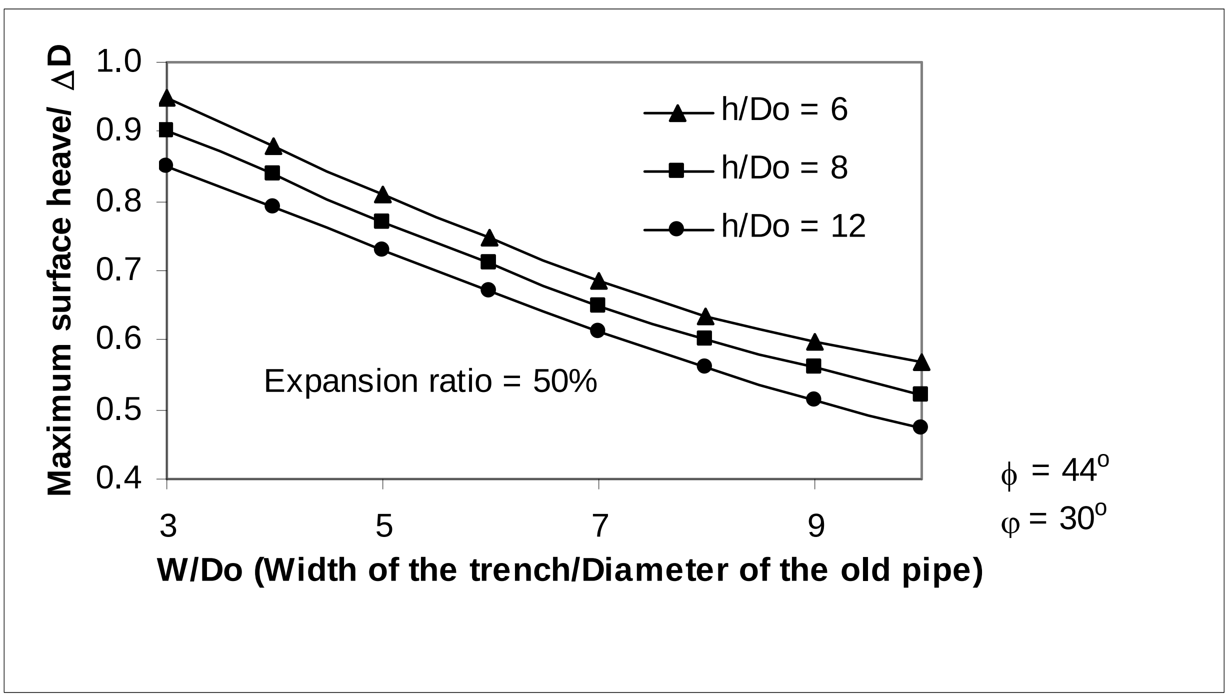

Figure 6. NORMALIZED MAXIMUM SURFACE HEAVE VERSUS W/D_O FOR EXPANSION RATIO $\Delta D/D_O$ OF 50%

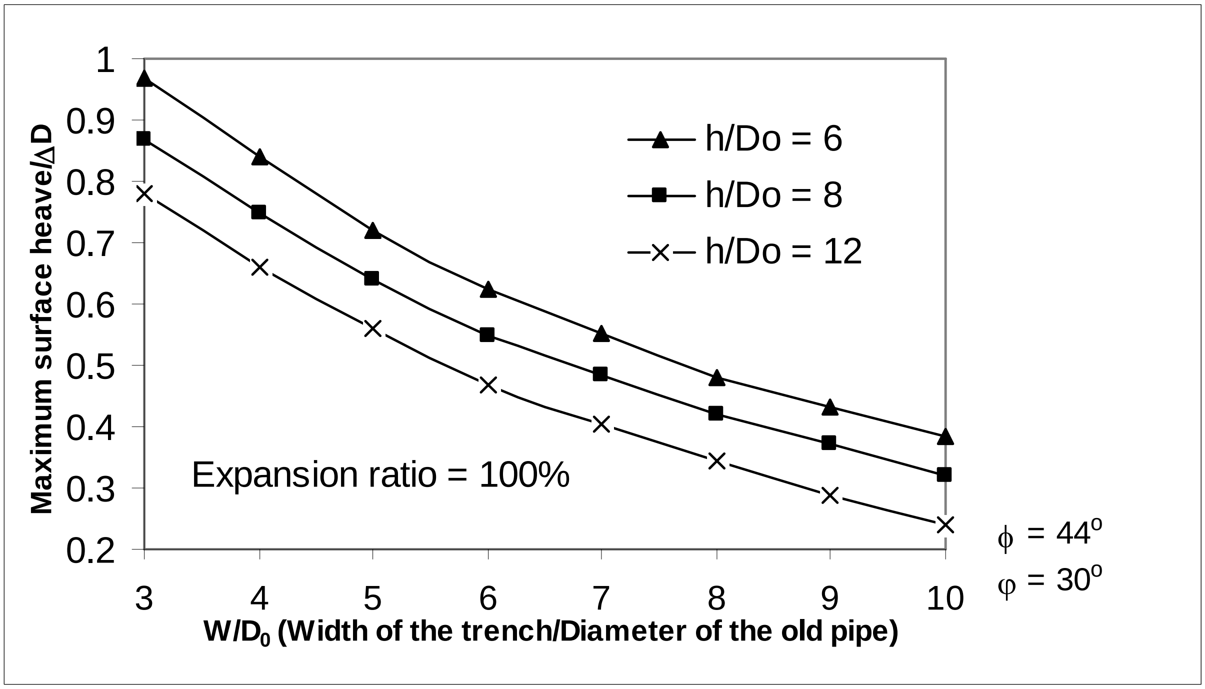

Figure 7. NORMALIZED MAXIMUM SURFACE HEAVE VERSUS W/D_O FOR EXPANSION RATIO $\Delta D/D_O$ OF 100%

8. CONCLUSIONS

Comparisons of laboratory data with finite element solutions indicate that two dimensional finite element analysis can be used to provide useful estimates of maximum ground heave. Results are presented for one cohesionless soil (dense sand), considering different burial depths and various levels of cavity expansion. The effect of trench width was examined by conservatively simulating trench sidewalls of very high stiffness.

For each different depth ratio considered, the change in normalized surface heave with cavity increase exhibits almost bilinear behavior. Heave as a proportion of diameter increase grows rapidly until a cavity expansion ratio of about 50% is reached. Beyond that value, the ratio of surface heave to cavity increase grows more slowly. Not surprisingly, the results for shallowest burial (h/D_0 of 6) give the highest surface heave as a proportion of cavity diameter increase. Solutions for h/D_0 of 8 are about 40% smaller, and results for h/D_0 of 12 are about 60% smaller.

Calculations using a high dilation angle for the sand (equal to the friction angle) produced peak surface movements that were more than 50% higher that those for more typical angle of dilation. Use of a high value for the dilation angle produces conservative estimates of surface uplift. The effect of trench width on surface movements was also quantified. Bursting operations in narrow trenches with very stiff sidewalls produce much higher ground surface movements than for pipes in wide trenches or embankments.

9. ACKNOWLEDGMENTS

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