USE OF CAVITY EXPANSION THEORY TO PREDICT GROUND DISPLACEMENT DURING PIPE BURSTING

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Abstract

A parametric study is undertaken using axisymmetric cavity expansion theory to investigate the effect of soil parameters on ground movements in the vicinity of the static pipe bursting operations. Comparisons are made with experimental results reported by other workers, and these indicate that cavity expansion theory has the potential to be a valuable design tool. The parametric study shows that ground movements are controlled by soil strength and dilation angle, rather than the elastic soil properties.

Introduction

Trenchless technology is increasingly used as a pipe rehabilitation technique, since it can significantly reduce the disruption caused by construction in busy urban areas. However, municipal governments and pipe utility companies may be reluctant to use this technique, due to concerns regarding subsurface ground movement associated with trenchless pipe replacement. Knowledge of ground disturbance becomes very important in the case of pipe bursting where the bursting head breaks the original pipe fragments and forces them out into the soil surrounding the pipe being replaced. Adjacent underground services and neighbouring structures may be subjected to excessive ground displacements caused by the replacement operation.

This paper investigates the use of the cavity expansion theory developed by Yu and Houlsby (1991) to predict the ground displacements during static bursting operations. A parametric study is used to investigate the effect of soil parameters on the ground movement. Finally, comparisons between theoretical and experimental results are made to assess the feasibility of using the cavity expansion solution to estimate ground disturbance during pipe bursting. The study is viewed as a first approximation, and factors such as the influence of the pipe fragments on ground movement at the proximity of the cavity, longitudinal progression of the bursting head, and other potentially significant factors are neglected. Comparison with experimental results, however, gives some indication of performance relative to real field conditions.

Cavity Expansion During Pipe Bursting

Replacement of pipe using pipe bursting involves outward displacement of the soil surrounding the pipe. Soil movement has components both longitudinal and perpendicular to the pipe-axis during the bursting operation. The axial movement of soil is associated with the progressive movement of the bursting head down the existing pipe, which is accompanied by lateral soil movement to accommodate the bursting head which is larger in size than the existing pipe.

Any upsizing (increase in diameter) relative to the existing pipe causes permanent outward displacement of the soil around the bursting head. The zone of permanent displacement is called the plastic zone, and its outer dimensions depend on the existing soil condition, the initial cavity radius, and the expansion ratio (the ratio of bursting head and existing pipe diameters). Soil within the plastic zone reaches its yield stress, while soil outside the plastic zone remains in the elastic state.

The greatest potential for damaging underground utilities is expected in the plastic zone due to the large deformations. The displacement profile and the distance the plastic zone extends away from the new pipe are both important to the safety of other utilities.

A number of researchers have proposed theoretical solutions to predict the plastic zone. O'Rourke (1985) proposed a solution to predict the radius of the plastic zone, dependent on the amount of cavity expansion and the stiffness of the soil. There has been little research undertaken to investigate the stresses and displacements within the plastic zone during the pipe bursting process. Atalah et al. (1997) used the cavity expansion theory developed by Vesic (1972) to predict the radius of soil plasticity, and attempted to compare the experimental data recorded just one foot away from the bursting unit with predicted strain at the edge of the plastic zone (the Vesic solution does not allow calculations of plastic deformation within the plastic zone). Chapman and Rogers (1992) used a flow model to predict soil displacements and compared these with their experimental results. In this model, the extent of the plastic zone is not calculated, and the soil medium is assumed to be incompressible. This assumption cannot be true for granular materials as significant dilation develops when changes in geometry are large. A geometrical analysis has been proposed to predict the ground disturbance during bursting by Heinz et al. (1992). The geometrical analysis was also developed independently by Palmer (1972) and Ladanyi (1972) for the interpretation of pressuremeter tests in clay. This theory was further developed for the interpretation of expansion tests in sand by Wroth and Windle (1975). The important shortcoming of this model is the assumption of small deformations and strains around the cavity during expansion, which is usually not true for bursting operations.

Theoretical Prediction Using Semi-Analytical Solution

The cavity expansion theory developed by Yu and Houlsby (1991) is proposed for use in prediction of soil displacements around the old pipe during static bursting operations. The authors reported earlier the use of both the cavity expansion and contraction solutions of Yu and Houlsby (1991, 1995) to evaluate the earth pressures that develop during static pipe bursting. The comparison between the reported field experience and the results calculated using this theory lead to estimates of pulling length that followed trends reported in the literature, such as reductions in pulling length with increases in upsize (Fernando and Moore, 2002).

In the case of ground disturbance, the potential for damage to underground utilities is related to the maximum ground displacement that occurs during the expansion phase of the bursting process. Therefore, use of just the cavity expansion theory of (Yu and Houlsby, 1991) is proposed to predict the maximum ground movements.

The pipe bursting operation in the field is complex, and use of cavity expansion theory involves simplifying assumptions neglecting the inhomogeneous soil properties, the initial geostatic stress gradient, local stress concentrations, and longitudinal effects during the pipe bursting process. Specifically, this "first approximation" approach based on cavity expansion theory assumes that:

a) The pipe is buried within an infinite elasto-plastic continuum;
b) Soil properties are uniform;
c) Pre-existing earth stresses are uniform and isotropic;
d) The effect of local stress concentrations between the fragments of existing pipe is negligible;
e) Longitudinal effects can be ignored, and the cavity response can be modelled using plane strain theory.

Based on these assumptions, the soil response will be evaluated for axisymmetric and plane strain conditions. Furthermore, these conditions impose restrictions on the geometry of displacements and limit the prediction of the displacements to the radial movement away from the axis of the pipe.

Important features of this cavity problem include:

(a) Large change in geometry where internal cavity diameter generally changes more than 10% during the pipe bursting operation; the soil response is expected to be geometrically non-linear.
(b) Shear failure is expected in the soil surrounding the cavity, so that use of plasticity theory is required.
(c) It is valuable to predict the distribution of displacement in the plastic zone.

The cavity expansion theory of Yu and Houlsby (1991) incorporates all these features and the availability of this solution represents an important opportunity to predict the ground displacement during pipe bursting.

Semi-analytical solution of Yu and Houlsby

For completeness, the main equations, which are used to calculate the ground displacement in plastic and elastic zone are presented here. Full details are reported by Yu and Houlsby (1991).

Geometry

Figure 1 defines important dimensions that apply to the soil surrounding the pipe being replaced, with dimensions pertinent to the system during the expansion. The cavity has initial radius of a_o. It is expanded to a radius of a. The external radius of the plastic zone that develops during the expansion is b.

Displacement within elastic zone

Ground displacement within the elastic zone can be calculated as

$$u=\frac{\delta b^2}{r_o} \tag{1}$$

Displacement within plastic zone

Ground displacement within the plastic zone can be calculated as the difference between the radius r at any given internal pressure σ, corresponding to a point with the initial radius r_o,

$$u=r-r_o \tag{2}$$

Now,

$$\left((1-\delta)^{\frac{(\beta+1)}{\beta}}-\left(\frac{r_o}{b}\right)^{\frac{(\beta+1)}{\beta}}\right)\frac{\eta}{\gamma}-\int_1^{\rho}\exp(\rho\xi)\rho^{(-\gamma-1)}d\rho=0 \tag{3}$$

where

$$\rho=\left(\frac{b}{r}\right)^{\frac{(\alpha-1)}{\alpha}} \tag{4a}$$

$$\delta=\left(\frac{\left(Y+(\alpha-1)\sigma_o\right)}{2(\alpha+1)G}\right) \tag{4b}$$

$$G=\left(\frac{E}{2(1+\nu)}\right) \tag{4c}$$

$$b=\left(\frac{(\alpha+1)\left[Y+(\alpha-1)\sigma\right]}{2\alpha\left[Y+(\alpha-1)\sigma_o\right]}\right)^{\frac{\alpha}{(\alpha-1)}}a \tag{4d}$$

$$\eta=\exp\left[(\beta+1)(1-2\nu)\left(Y+(\alpha-1)\sigma_o\right)\frac{(1+\nu)}{E(\alpha-1)\beta}\right] \tag{4e}$$

$$\xi=\frac{2(1-\nu^2)\delta}{(1+\nu)(\alpha-1)\beta}\left[\alpha\beta+1-\frac{(\alpha+\beta)\nu}{(1-\nu)}\right] \tag{4f}$$

$$\alpha=\frac{(1+\sin\phi)}{(1-\sin\phi)} \tag{4g}$$

$$\beta=\frac{(1+\sin\varphi)}{(1-\sin\varphi)} \tag{4h}$$

$$\gamma = \frac{\alpha(1+\beta)}{(\alpha-1)\beta} \tag{4i}$$

$$Y = \frac{2C\cos\phi}{(1-\sin\phi)} \tag{4j}$$

where C = soil cohesion, ϕ = angle of internal friction of the soil, φ = dilation angle, E = Young Modulus, ν = Poisson's ratio, σ = radial cavity pressure at the internal radius a, σ_o = the initial soil pressure (equal to the initial radial and circumferential pressure at the cavity position)and δ, α, β, γ, η, ξ, and Y are constants.

The method of calculating σ during expansion of the cavity has been reported elsewhere by Fernando and Moore (2002).

Parametric Study

Purely frictional material

In this section, some results are presented for purely frictional soil with an angle of friction 35°, a Poisson's ratio of 0.25, unit weight of 18.5 kN/m^3, and elastic moduli of 10 MPa and 20 MPa. Angles of dilation of 13°, 26°, and 35° have been used in the analysis to investigate the effect of dilation on ground displacement. The soil parameters have been selected to represent a typical granular soil seen in the field.

The effect of soil modulus on ground disturbance is shown in Figure 2. The ground displacement above the crown of the cavity is plotted as a function of height from the axis of the existing pipe. The calculation of radius of plastic zone reveals that the soil is in a plastic state within the heights shown here. It can be seen in Figure 2 that the variation of soil modulus does not influence the ground displacement in proximity to the cavity. The difference between solutions for the two modulus values is less than 5% within a distance of 3 times the final radius of the cavity, while the difference no more than 10 % for radial distances more than 3 times the final cavity radius. The semi-analytical solution models displacement in the plastic zone as having elastic and plastic components Yu and Houlsby (1991). The insensitivity to elastic modulus is likely due to the small contribution of elastic deformation to the total displacement within the plastic zone. Elastic modulus will control deformations beyond the plastic zone, though deformations are not expected to be significant in that region.

Figure 3 shows the correlation between the displacement above the crown of the cavity and height from the axis of the existing pipe. As can be seen in Figure 3, the displacement of soil is increased with increasing dilatancy. This is logical, because the dilation angle controls the volumetric strain, and the increase of dilation angle increases the volumetric strain.

Cohesive frictional material

In this section, results are presented for cohesive frictional soil with cohesion of 40 kPa, angle of friction 0.1°, a Poisson's ratio of 0.49, and elastic moduli of either 20 MPa or 10

MPa. Pipe bursting is performed rapidly, and fine-grained soils are expected to respond under undrained conditions. An angle of friction of 0^o should be used to undertake total stress analysis of the undrained response. However, an angle of friction of 0.1^o is employed since the semi-analytical solution cannot be solved for purely cohesive material (finite element analysis indicates there is no noticeable difference between solutions obtained using angles of friction of 0 and 0.1^o, Fernando and Moore, 2002).

The effect of soil modulus on ground disturbance is shown in Figure 4. The calculation of radius of plastic zone reveals that the soil is in plastic state within the plotted values of height above crown. Figure 4 indicates that the effect of soil modulus on ground disturbance can also be neglected for cohesive soils. Again, this trend is likely because the contribution of elastic strain to the total ground deformations is negligible in the plastic zone.

Discussion

Comparison between theoretical and experimental results

Chapman and Rogers (1992) simulated the static bursting process in the laboratory. A clear-sided tank with 1.5 m length, 1.5 m height and 1 m width was used in the laboratory to observe the soil displacement while the bursting head progressed through the soil. The steel frame supporting the sides of the tank was intended to maintain plane strain conditions at the viewing faces throughout the test, and while friction on the viewing face and the test box analyses of Brachman et al (2000) imply that plane strain conditions are unlikely, the observed ground movements will nevertheless be assumed to represent useful measures of ground deformation.

Chapman and Rogers (1992) examined an existing pipe with external diameter of 182 mm and thickness of 7mm, oversized to 210mm. They report that the burster ran along the invert of the existing pipe, due to the shallow nature of the bursting operation. With the exception of the unit weight, the properties of the test soil are not reported. An angle of friction for the dense soil is assumed to be 40^o. Elastic modulus of the soil is estimated as 20 MPa using the database of Selig (1990).

Figure 5 shows the comparison between the experimental results (Chapman and Rogers, 1992) and the author's theoretical predictions for this purely frictional material. Distance above the pipe is shown on the vertical axis, and ground deformations are presented on the horizontal axis. Since the bursting head ran along the invert of the pipe, movements at the invert are close to zero and those at the crown will be almost doubled. The cavity expansion theory models the ground response as axisymmetric, so deformation values above the crown have been estimated by doubling those obtained from that theory.

Figure 5 indicates that the difference between the measured and estimated ground displacements are less than 12% within the heights examined here.

Atalah et al. (1997) conducted trenchless pipe replacement experiments in a controlled soil environment. One static bursting experiment was reported, involving expansion of a vitrified clay pipe of 8inch diameter buried at a depth of 6 feet within silty clay. A bursting head with diameter of 15.5inch was used to replace the clay pipe with a new HDPE pipe of 12.75inch diameter. Subsurface displacement at 12 inches above the pipe centerline was measured by heave plate. The properties of the soil and the measured ground movement are reported in Table1. Table 1 also shows the theoretical estimate of ground movement for this case. The difference between the semi-analytical deformation and the experimental measurement is small.

Summary And Conclusions

The installation of new pipe using pipe bursting causes disturbance to the surrounding soil. Ground displacement due to the pipe bursting operation and the effects on adjacent utilities and neighbouring structures should be managed to avoid the risk of failure of other utilities in the proximity of the replacement pipe.

This paper presents a theoretical approach to predict the subsurface disturbance during static bursting operations. Earlier investigations of ground disturbance during static pipe bursting have also been reviewed.

While only limited measurements of ground movement have been available, comparisons between the ground displacements calculated using the semi-analytical solution of Yu and Houlsby (1991) and with the measurements of Chapman and Rogers (1992) and Atalah et al (1997) are promising. The theoretical estimates are based on axisymmetric cavity expansion theory, so were doubled for the case where the pipe burster ran along the invert of the existing pipe. More extensive test results are needed to further investigate the effectiveness of the semi-analytical procedure, prior to use of this approach to obtain initial assessments of expected ground movement.

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TABLE 1: Data taken from Atalah et al. (1997)

Soil Properties	Displacement 1 foot above the cavity/(mm)		
$E = 28$MPa $\nu = 0.4$ $c = 95.8$ kPa $\phi = 10^o$ $\gamma = 15.71$ kN/m^3	Experimental	Theoretical	Numerical
		$\varphi = 10^o$	$\varphi = 10^o$
	39	37	64

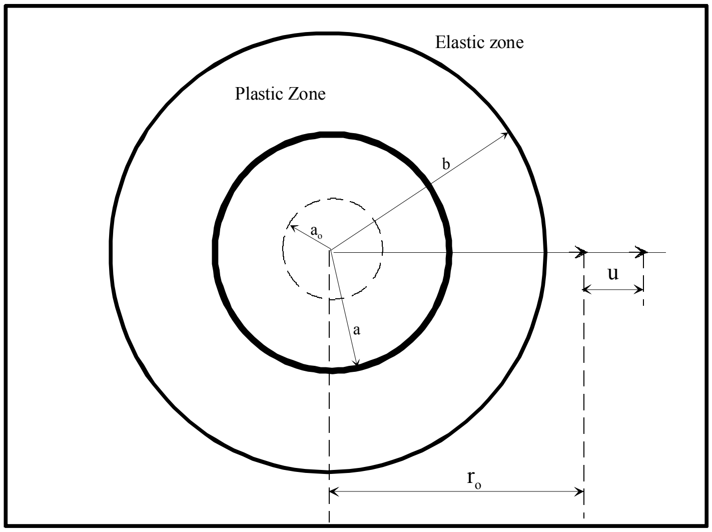

FIGURE 1: Geometry of the different soil zones during bursting operations

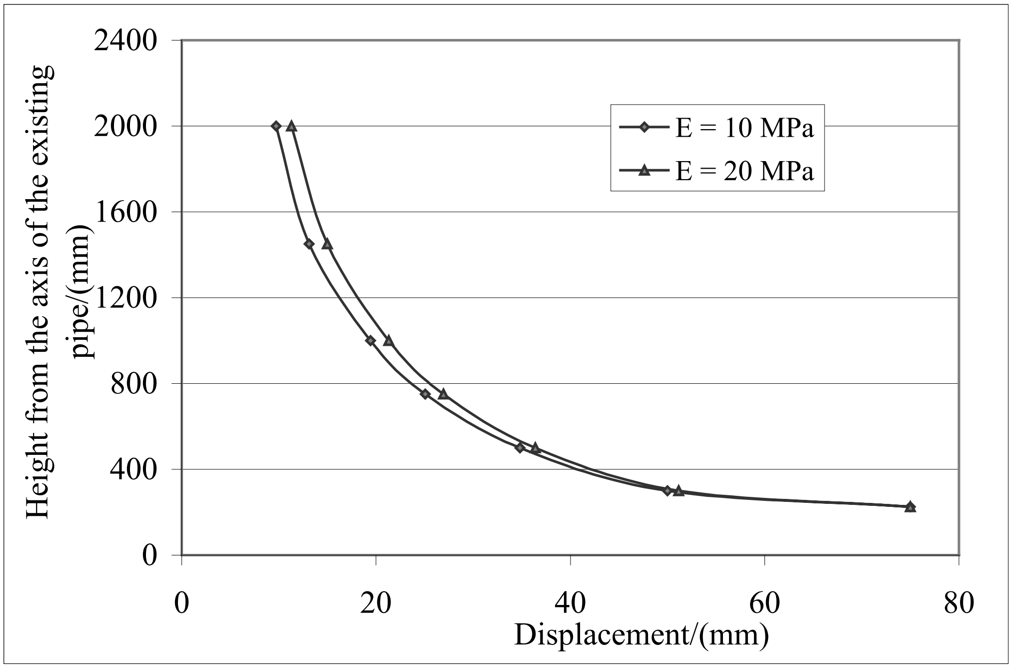

FIGURE 2: The effect of soil modulus on ground displacement

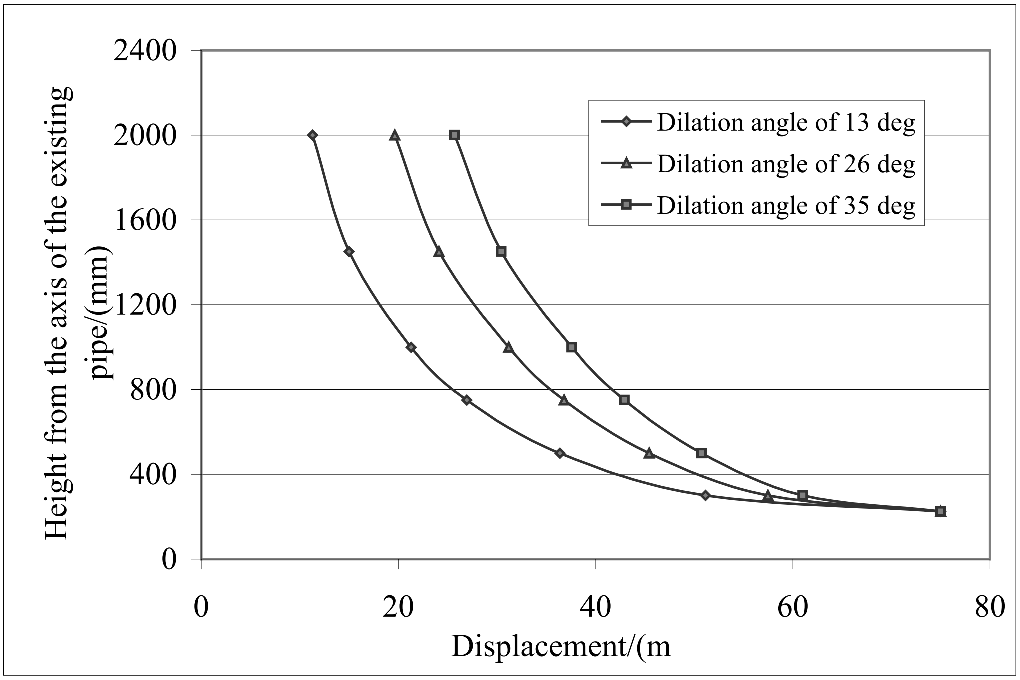

FIGURE 3: The effect of angle of dilation on ground displacement

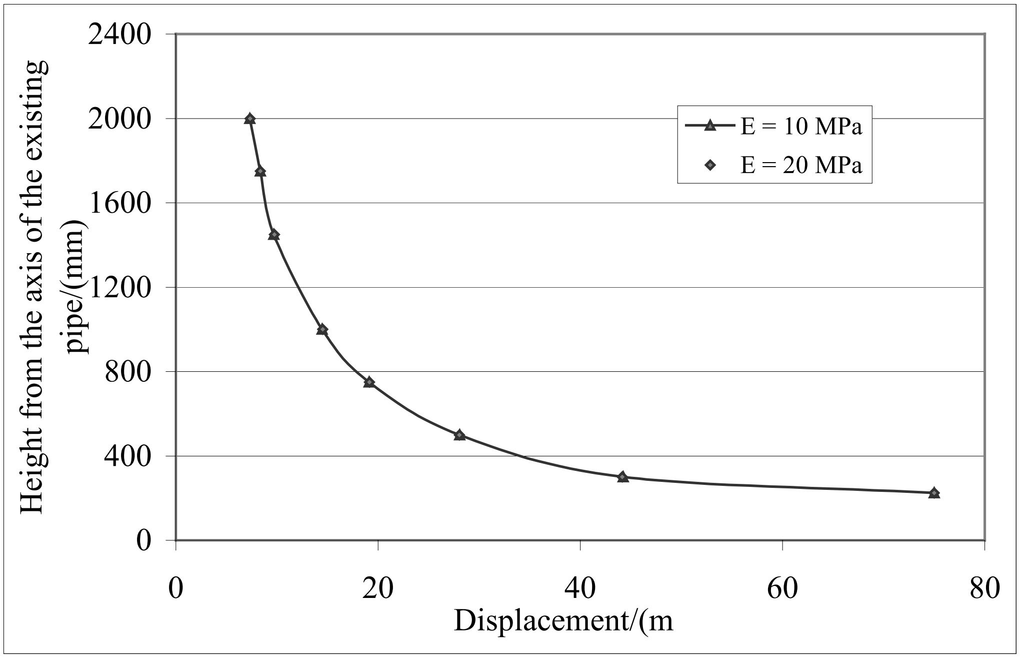

FIGURE 4: The effect of modulus on ground displacement

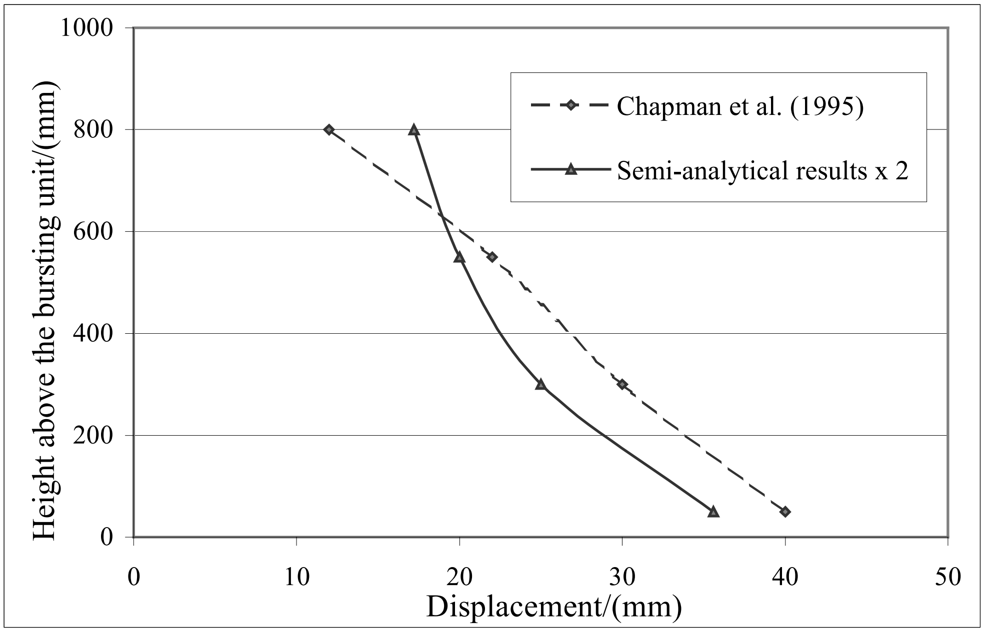

FIGURE 5: Comparison between experimental and theoretical and numerical results