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MODELLING PIPE BURSTING-INDUCED DEFORMATION PROPAGATION

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Abstract

Trenchless pipe replacement technologies have been developed during the past decades in order to cope with the space limitations of urban settings and work more conveniently within such areas. Two trenches are placed along an existing pipe which will host the pipe bursting tool. The tool is placed into the host pipe at the entry pit or manhole. The tool is guided by a cable under a constant tension which is attached to the head of the tool and is based at the exit area pit. The tool is either hammered or pulled through the host pipe. Continuous percussion or passage of the tool fractures the host pipe and creates a cavity large enough for placing a new pipe. The number of the pits and the required distance between them depends on the tool size, subsurface soil type, and the pipeline depth. Pipe bursting is the only trenchless method of replacement that allows for upsizing the original pipe.

The subject of this paper is the upsizing of a vitrified clayey sewer pipe line from an existing 0.61-m- to a final 0.91-m-diameter pipe. To achieve the proposed final pipe diameter, a 1-m pipe bursting tool is proposed for this project. Several other utility lines are in the vicinity of the host pipeline, including a 2-m water line and another 1-m sewer line. The subsurface material consists of low to high plasticity silty clayey soils. Fast Lagrangian Analysis of Continua (FLAC), a finite difference numerical model by Itasca (2002), is utilized to model the void expansion induced by the pipe bursting method. The existing pipelines are modeled as structural elements in the numerical model. This study is performed to evaluate the propogation/attenuation of deformations in the vicinity of the host pipe and their effects on the neighboring pipelines.

Introduction

As an alternative to the traditional excavation and pipe replacement, trenchless pipe replacement technologies have been developed during the past decades in urban settings. Pipe bursting is one such technology and is the only one that also makes it possible to upsize an existing pipeline. Pipe bursting involves insertion of a conically shaped tool (bursting head) into the old pipe by pneumatic, static pull, or hydraulic action. In a direct bursting operation, the head shatters the old pipe and forces its fragments into the surrounding soil. At the same time, a new pipe is pulled or pushed in (depending on the type of the new pipe) behind the bursting head. Pipe bursting offers significant potential savings to public and private utility owners in replacing and upsizing utility conduits. However, many potential applications are constrained due to lack of understanding of the allowable proximity of the process to various structures in different soils.

In addition to the direct cost advantage of pipe bursting over open cut, pipe bursting, as a trenchless technology, provides indirect cost savings by lessening traffic disturbance, road or lane

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closure, time for replacement, business interruption, and environmental disturbance. Another disadvantage to traditional excavation is that compaction under the surface in the trench may be poor due to lack of adequate space for compaction, which will affect the pipe and create surface subsidence. The patching in road pavement structures associated with open cut work combined with the backfill settlement reduces the life of the pavement structure (Rodgers, 1995).

This paper presents an analytical approach which makes it possible to evaluate the deformations induced by pipe bursting both vertically at the ground surface and laterally on adjacent pipelines. Due to the clalyey nature of the subsurface material, deformations were evaluated only for the cavity expansion and the vibration induced deformations were ignored. The following section will present a brief literature review and then continued with the numerical modelling and conclusions.

Review of Existing Experimental and Analytical Procedures

The majority of the existing studies and procedures are based on laboratory tests using clear-sided tanks (Swee and Milligan, 1990) and instrumented field measurements (Reed, 1987 and Atalah, et al. 1998). Swee and Milligan (1990) presented the surface heave for different cover-to-pipe diameter ratios and different depth-to-pipe-diameter ratios. They also concluded that the range of surface heave is limited to a wedge that is offset from the vertical by the soil's dilation angle. Leach and Reed (1989) developed a simplified surface damage chart based on the maximum surface heave and the spread of the heave triangle, separating zones of slight heave with little damage, noticeable heave with minor new cracks and the opening of existing cracks, and pronounced heave with severe cracking and joint separation. Cavity expansion theory was utilized to evaluate the extent of the plastic zone around the burst pipe by O'Rourke (1985) and Falk and Stein (1994). O'Rourke (1985) indicated that the radius of the plastic zone increases as the amount of cavity expansion and the stiffness of the soil increase.

Recent comprehensive field testing by Atalah et al. (1998) resulted in the following conclusions:

Ground Vibrations: Adopting the 95 percent prediction interval, upper limit for the data collected from the pneumatic system, as a conservative line for the attenuation of velocity with distance from the head leads to the following results: i) The damping level for buried structures (for velocities higher than 13 cm/second) occurs at a distance of less than 0.76 m. Pipes closer than 0.76 m from the line to be replaced should be exposed to provide stress relief; ii) The damaging levels for sensitive surface structures (velocity of 5 cm/sec with frequency in the range from 30 to 100 Hz) are reached within distances of 2.4 m from the bursting head. This will rarely be an issue when replacing pipes in a public right-of-way, due to the requirement that buildings be set back 9.75 m from any sewer or water line in the right of way, iii) Overall, it can be summarized that while ground vibrations may be quite noticeable to a person standing on the surface close to a trenchless pipe replacement operation, the levels of vibrations are very unlikely to be damaging except at very close distances to the trenchless pipe replacement operation.

Ground Movements: Pipe bursting's ground displacement tends to be localized and to dissipate rapidly away from the bursting operation. The greatest displacement occurs as the expansion head passes. If the soil has a tendency to move preferentially to one side due to variations in soil stiffness or the presence of other structures, it is possible that settlement could occur on the opposite side. If a poorly compacted zone were present, then it is possible that the trenchless pipe replacement could cause consolidation in one area while causing heaving in another area.

Pipe Profile: Generally the replacement pipe follows the same slope as that of the old pipe. Most of the differences between the centerline elevation of the two pipes are upward, but downward differences are possible. The amount and the direction of the difference depend on the upsizing percentage, soil conditions, construction details, profile of the old pipe, etc.

Damage to Nearby Pipes: It had been expected that all the pipes at 0.3 m from the top of the burst pipe would be unlikely to survive the replacement. In practice, pipes within two diameters of a pipe to be burst and especially to be upsized would be locally excavated to provide stress relief to the existing pipe.

The previous studies have the following limitations: i) The laboratory and field tests had size limitations that were much smaller than the expansion diameter presented in this paper; ii) Heaving/settlement in the sand layers was not predictable and is potentially dependent on the dynamic and/or poor compaction of those layers; and iii) the utilized bursting tools in the earlier researches were smaller than the bursting head proposed for this study.

Numerical Model

As a part of this study, a numerical model was prepared to evaluate a sewer line upsizing. A seismic cone penetration test was performed in the vicinity of the modeled cross section. The location of the cross-section was selected based on the relatively shallow depth of the sewer line and its proximity to the other utilities in the area. The modeled cross-section is shown in Figure 1. The proposed sewer line upsizing in this area is from an existing 0.6-m- to a final 0.9-m-diameter pipe. To achieve the proposed final pipe diameter, a 1-m-diameter pipe-bursting tool was proposed for this project. Several other utility lines were in the vicinity of the host pipeline, including a 1-m sewer line and a 2-m water line at approximate center to center distances of 4.9 m and 8.8 m, respectively. The subsurface material consisted of low to high plasticity silty clayey soils.

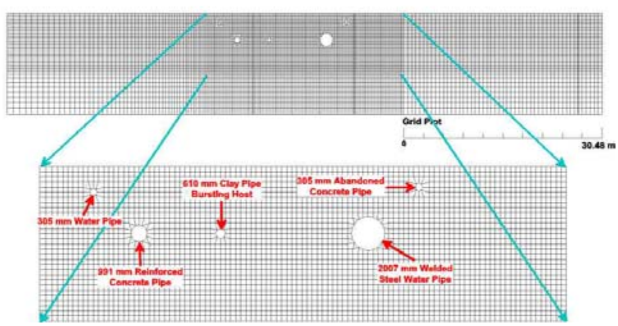

Figure 1. Existing utilities relative to the pipeline to be burst.

Fast Lagrangian Analysis of Continua (FLAC), a finite difference numerical model, was utilized to model the void expansion induced by the pipe bursting procedure. The dimensions of the grid were 91.5 meters long and 15.2 meters deep, which was extended enough to minimize the boundary conditions. The grid was fixed horizontally at its vertical boundaries and in both directions at the grid bottom. The existing pipelines were modeled as structural elements in the numerical model; however, due to the lack of as-built information and age of the pipelines, accurate estimation of their properties was not possible. This study was performed to evaluate the approximate propagation/attenuation of deformations in the vicinity of the host pipe and their effects on the neighboring pipelines. The proposed void expansion was modeled by two approaches. The first method induced the void expansion by applying equal radial forces at the grid nodes of the expanding pipeline. This procedure is close to the reality of forces applied by the pneumatic and hydraulic pipe burstings tools; however, it may not result into a perfect circular shape. The grid nodes were moved by application of equal radial velocities in the second numerical model to satisfy a final circular shape. However, this method may not accurately predict the induced-stresses. A conventional Mohr-Coulomb constitutive model was utilized for modeling the soil behavior.
Based on the shear wave velocities obtained from the seismic CPT results and our laboratory test results in the vicinity of this cross-section, the following layering and parameters were utilized in our analyses as shown in Table 1.

Table 1 – Soil properties

Depth (m)	V_s (m/s)	ν	G (kPa)	ϕ' (deg)	C' (kPa)
0-3.66	238	0.35	108647	24	44
3.66-8.53	169	0.35	55006	22	13.9
8.53-11.13	219	0.35	92575	24	44
11.13-15.24	245	0.35	115723	24	44

Note: V_s: Shear Wave Velocity, ν: Poisson's ratio, G: Shear Modulus, ϕ': Effective Friction Angel, and C': Effective Cohesion. Unit weight: 1922 kg/m^3.

In both cases a maximum surface heaving on the order of 8 cm above the burst pipe was calculated (see Figure 2). The shape of surface deformations followed the expected theoretical bell shape. The resulting deformations in both models were relatively similar; however, in both cases the dynamic impact of the pneumatic pipe-bursting tool was not modeled. The maximum calculated deformations of the adjacent 1-m sewer line and 2-m water line are estimated to be on the order of 1 and 0.5 cm, respectively. Both models indicated that the expansion is favored towards the ground surface at the pipe level as shown in the comparison of the grids in Figure 2.

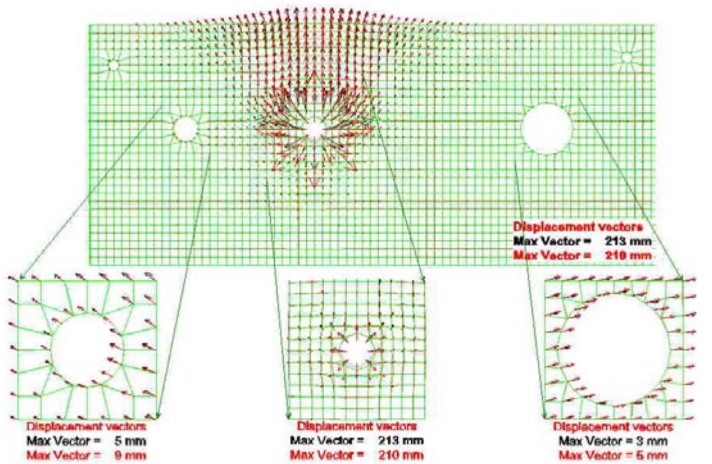

Figure 2. Deformation pattern in the vicinity of the burst pipe. The black (upper) and the red (lower) values indicate the results of the first and second models, respectively.

Figure 3 shows the horizontal stresses for the first set of analyses, in which the void expansion was induced by equal-radial grid loads and the second set of analyses, in which the void expansion was induced by equal-radial grid velocities. The induced stresses were symmetrically increased in the horizontal direction around the bursting face with their maximum values at the lower parts of the pipeline.

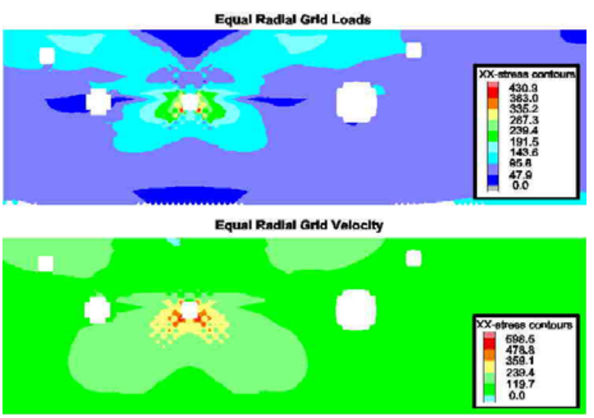

Figure 3. Horizontal Stresses (kPa) due to pipe bursting.

The vertical stresses were symmetrically increased around the bursting face in the first numerical model, as expected, due to the uniform grid load application and asymmetrical in the second model due to the larger confinement below the pipe as presented in Figure 4.

The induced stresses by application of equal radial grid velocity were determined to be on the order of 1.5 to 2 times higher than the equal radial grid pressure.

In general, these analyses were performed to observe the general behavior of the soil in the vicinity of the proposed bursting area, the surface heave pattern and magnitude, and deformation of the adjacent utilities. The analyses show an increase of stresses in the vicinity of the bursting head. The deformations rapidly attenuated with distance from the bursting area as indicated by Atalah et al. (1998) and as shown in Figure 2. However, the magnitude of deformations may be different in the field in comparison to those observed in these analyses since the dynamic impact of the bursting tool was not modeled. The dynamic impact of bursting tool will be more pronounced in the areas with granular/sandy soils, causing less predictable deformations and potentially inducing surface subsidence.

In both cases the induced surface deformations resembled a normal distribution shape with its peak over the center of the bursted pipeline. The deformation shape is presented in Figures 1 and 5 and matches the deformation patterns by Swee and Milligan (1990).

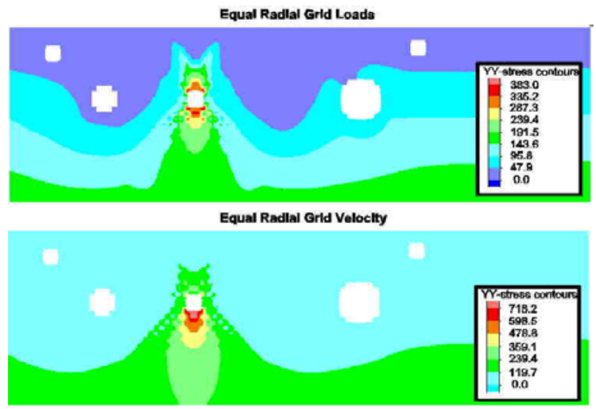

Figure 4. Vertical Stresses (kPa) due to pipe bursting.

Figure 5 indicates that the surface deformations greater than 10 percents of the peak are located within a 1.23:1 (Horizontal:Vertical) wedge from the center of the pipeline. This angle is slightly smaller than the expected soil's passive wedge angle. The area of the surface heave is approximately 85 percents of the expansion area, which in general conforms with the clayey soil behavior observed by Swee and Milligan (1990).

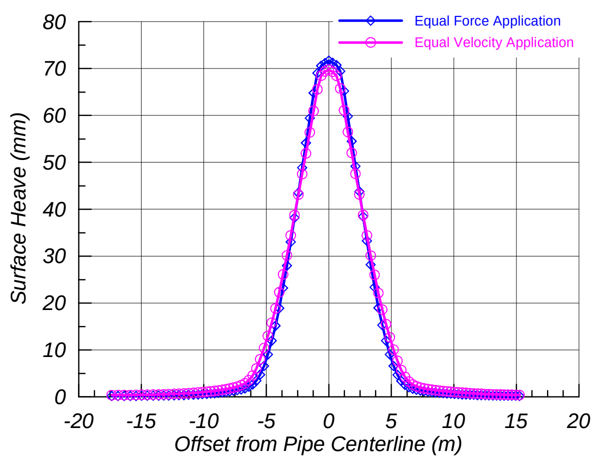

Figure 5. Surface Heave Pattern.

Conclusion

This paper presents a numerical procedure for evaluating deformations from static pipe bursting procedures or the static portion of the pneumatic pipe bursting. The predicted ground surface deformation pattern matched the theoretical bell shape and the observed values in previous experiments and field observations.

The procedure uses available numerical models and a conventional constitutive model available to many geotechnical engineers. Additional verification should be performed during the field application by monitoring the surface and the utilities in the vicinity.

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