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A three-dimensional analysis of the effects of erosion voids on rigid pipes

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ABSTRACT

In this study, elasto-plastic finite element analyses are performed to investigate the three-dimensional effects of erosion voids developing behind the walls of an existing sewer pipe on the earth pressure distribution around the pipe and the stresses in the pipe wall. Initial earth pressures are first calculated and compared with field measurements. Erosion voids of different sizes are then introduced at the springline and invert of the pipe and the changes in pressure are evaluated and compared with the initial values. The effects of increasing the void length, depth and angle are examined. Results clearly reveal that the presence of erosion voids can have a significant impact on the earth pressure distribution around an existing pipe as well as on the pipe wall stresses. Increase in pressure is found to be mainly influenced by the void length and location with respect to the pipe circumference. Voids introduced at the springline resulted in earth pressure increase of more than 100% near the void boundaries whereas the pressure change was less significant when the void is introduced at the pipe invert. The findings of this study highlight the importance of locating voids behind pipe walls to prevent further deterioration and possibly sewer failure.

1. Introduction

Concrete pipes are used extensively for sanitary sewer, industrial discharge lines, culverts, and storm drains. These pipes are generally designed using either standard trench or embankment installation. The earth pressure acting on the pipe wall is usually calculated using various empirical (e.g. Marston and Anderson, 1913; Spangler and Handy, 1973), analytical (e.g. Burns and Richard, 1964; Hoeg, 1968), and numerical methods (e.g. Katona and Smith, 1976; Tohda et al., 1990) assuming full contact between the pipe and the surrounding soil. With time deterioration of the pipe-soil system and water leakage can result in local support loss due to loosening of the supporting material and, eventually, the development of erosion voids behind the pipe wall. In addition, improper construction procedure can accelerate the deterioration process, shortening the service life of the pipe and in some cases can lead to sudden failure. Talesnick and Baker (1999) reported the failure of a 1.2 m diameter concrete-lined steel sewage pipe buried in clayey soils. Field investigations revealed the formation of a physical gap of approximately 20 mm between the invert and the bedding layer. Severe cracking developed at the crown and springline along a 300 m segment of the pipeline. Although the loss of soil support in the above example may not have been due to soil erosion, it illustrates the possible consequences of support loss around or under buried pipes.

Tan and Moore (2007) investigated numerically the effect of erosion voids on the wall stresses of rigid pipes using two-dimensional (2D) analysis. The influence of both the void size and location (e.g. springline and invert) on the stresses and bending moments developed in the pipe wall was investigated. Results of an elastic model showed that the presence of a void at springline leads to an increase in the extreme fiber stresses and the bending moments at all critical locations: crown, springlines and invert. The rate of increase was found to be controlled by the growth of the void in contact with the rigid pipe. Extending the model to include the shear failure effect of the soil resulted in stresses and moments higher than those reported in the elastic analysis. Changing the location of the void from springline to invert resulted in reduction in bending moment values followed by a reverse of the moment sign at crown, springlines and invert.

Meguid and Dang (2009) studied numerically the effect of void formation around an existing tunnel on the circumferential stresses in the lining. A series of elastic–plastic finite element analyses were carried out to investigate the effect of different parameters (e.g., flexibility ratio, coefficient of earth pressure at rest and void size) on thrust forces and bending moments in the lining. When

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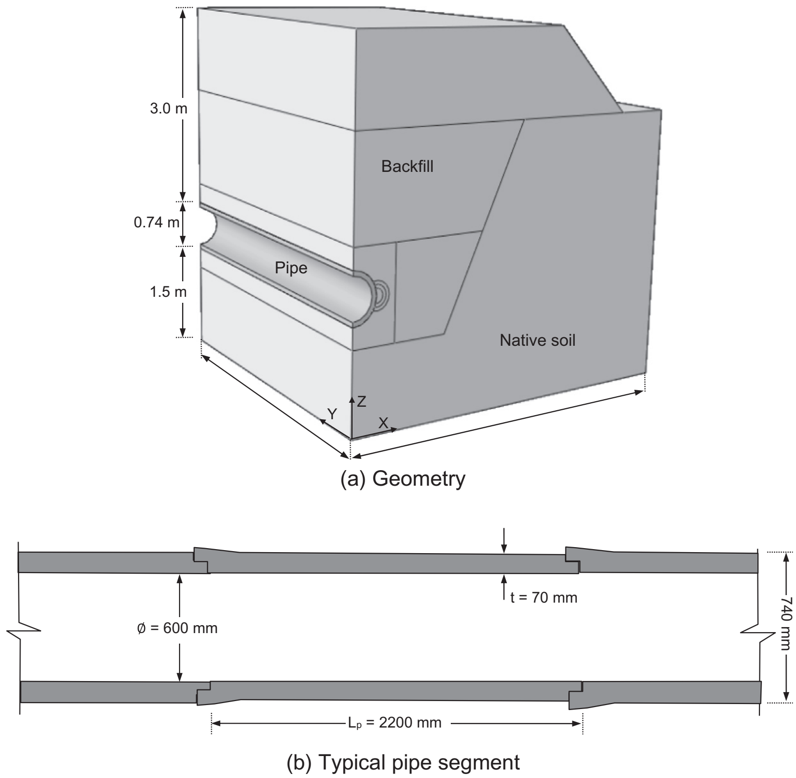

Fig. 1. Problem statement (a) geometry; (b) typical pipe segment (adapted from Liedberg, 1991).

the void was located at the springline, bending moment significantly increased. Similar results were reported for the thrust forces under the same conditions regardless of the flexibility ratio. The presence of erosion void at the lining invert was found to reduce the bending moments causing reversal in the sign of the moment as the void size increased.

Leung and Meguid (2011) conducted an experimental investigation to measure the changes in earth pressure around a tunnel lining due to the introduction of a local contact loss at different locations around the lining. The results showed that earth pressure increased locally around the separated section with a maximum increase of 25% at the springline.

The above studies illustrate the significant changes in earth pressure and internal forces in the walls of buried structures when the soil separates locally from the structure. However, these studies were limited to 2D models assuming that erosion void extends significantly along the wall of the buried structure.

The objective of this paper is to investigate the three-dimensional (3D) effects of erosion voids induced in the vicinity of the wall of a buried concrete pipe on the earth pressure distribution around the pipe and on the pipe wall stresses. Series of 3D nonlinear finite element analyses have been performed to investigate how a progressive increase in the void size affects the initial earth pressure acting on the pipe and the stresses in the pipe wall. The size and location of the induced voids have been varied and the corresponding pipe response has been calculated.

2. Problem statement

The investigated problem involves a concrete pipe 600 mm in inner diameter and 70 mm in wall thickness installed using the embankment installation method with 3 m soil cover above the crown. The pipe is first placed in a large trapezoidal shaped trench on a layer of bedding material and backfilled in layers and covered by an embankment. The problem geometry and material properties used in this investigation were based on the full scale field tests carried out in an abandoned sand pit (Liedberg, 1991). The geological formation of site was reported to consist of a glaciofluvial delta built up of uniformly graded medium sand. This particular case study was chosen due to the availability of a complete set of soil and earth pressure data. The problem geometry showing the pipe location is shown in Fig. 1a. The dimensions of a typical pipe segment as reported by Liedberg (1991) are presented in Fig. 1b.

To simulate the presence of erosion voids around the existing pipe in 3D space, semi-cylindrical zones were predefined at specific locations next to the pipe wall assuming that voids will have a simplified circular geometry. The void sizes have been varied spatially in the x, y and z directions to reflect the effect of increasing the void depth, length, and angle, respectively. The voids were introduced at two locations around the pipe circumference, namely, springline and invert. The three parameters controlling the size of voids have been normalized. The void depth (V_D), length (V_L), and angle (V_A) have been normalized with respect to the mean pipe radius (R), segment length (L_p), and pipe circumference (2π), respectively, throughout the analysis. The above controlling parameters have been varies incrementally as summarized in Table 1.

Table 1
Parameters investigated.

Void angle (V_A) (°)	Void depth (V_D) (cm)	Void length (V_L) (cm)
31	2.5	20, 40, 60
	5	
	10	
47	5	
	10	
	15	
63	7.5	
	15	
	20	