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Impact of soil erosion voids on reinforced concrete pipe responses to surface loads

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ABSTRACT

This paper discusses the results of controlled, full-scale laboratory experiments on 0.9 m (36 in.) internal diameter reinforced concrete pipes (RC pipes) in the presence of simulated erosion voids. This study introduces a novel, yet practical, experimental method to simulate erosion voids near buried pipes. Using this method, the paper focuses on capturing the circumferential moment changes experienced by a 0.9 m (36 in.) internal diameter RC pipe buried at 0.9 m depth as voids of different sizes (approximate cross-sectional areas of 0.16 m^2 and 0.31 m^2) develop beside it, which have not been investigated before in such tests. The tests were also repeated after the erosion voids were repaired using a low strength grout (~2 MPa) to characterize it as a potential rehabilitation solution, and the moment changes were recorded. The presence of erosion voids resulted in an overall increase in bending moment with the invert moments being affected the most (e.g., 70% increase in the invert moment between the intact soil result and the small void result and a 26% increase in the invert moment between the intact soil result and the extrapolated large void results). While, grouting the erosion voids resulted in an overall improvement in the pipe responses, there was still a 50% increase in the invert moment between the intact soil result and the grouted small void result and a 22% change between the grouted large void and the intact soil tests. The large void tests showed that soil collapse is the dominant failure mechanism at high loads. Comparing the modified bedding factor values for pipes with different void sizes and void condition (pre- and post-grouting), the intact soil always featured the highest bedding factor, followed by grouted large void (approximately 22% reduction in bedding factor), grouted small void (approximately 36% reduction), and small void before grouting (approximately 39% reduction).

1. Introduction

According to McGrath et al. (1999), the longevity of a pipe relies heavily on the pipe-soil interaction. However, over time, reinforced concrete pipes (RC pipes) develop issues such as cracks, leaking joints, or experience misalignment from rotation and movements (Moore, 2008a,b). These issues contribute to groundwater infiltration that causes smaller soil particles in the backfill to be washed away causing erosion voids to develop.

The presence of erosion voids next to pipes removes soil support at that location, which can result in uneven load spreading in the ground surrounding the pipe (Tan and Moore, 2007; Balkaya et al., 2013). A rigid pipe, such as an RC pipe, resists surface loads in bending and shows negative arching, where surface load is attracted to the pipe by virtue of its higher stiffness compared to the soil it replaced (Young and Trott, 1984). The loss of soil support during the formation of erosion voids affects the soil-pipe interaction and has the potential to increase the bending moments in the pipe, which could lead to failure of the system if the erosion voids are large enough. Hence, it is necessary to address questions such as how do voids influence soil-pipe interaction, do voids increase the live load bending moments in the pipes, what is the effect of void size on bending moments, and can grouting of the void restore the 'intact soil' strength?

Previous finite element studies have investigated surface load transfer to buried pipes when there were erosion voids in the backfill. For example, Tan and Moore (2007) calculated an increase in the bending moments in rigid pipes with erosion voids located beside the pipe springlines (see also Tan, 2007). For the assumptions associated with their elastic-plastic finite element modelling and voids with circular boundaries, they show that void location beside the springline

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causes earth load bending moment in the pipe to increase, and for voids under the invert or over the crown moments decrease. The deterioration of the soil support can in fact result in the pipe reaching its performance limits before the end of its design life. In addition, groundwater infiltration can have other undesirable effects if left unattended including negative hydraulic impacts, spills, sinkhole formation, and therefore disruption to traffic or loss of life. One potential method of mitigating these issues is to grout the erosion voids, however no experimental work has been undertaken to investigate the performance of a rigid pipe with grouted erosion voids.

Pipe design equations consider intact soil support surrounding a buried pipe, and recently MacDougall et al. (2016) reported on an experimental study to quantify concrete pipe response and evaluate the performance of reinforced concrete pipe design for 'intact ground' (where no erosion void has developed). Peter (2018) reports on full-scale experiments to quantify the effect of an erosion void on the response of a corrugated steel pipe under surface live load, and no full-scale experiments have examined the effect of erosion voids on rigid pipes.

One final challenge associated with erosion voids and rehabilitated erosion voids is how to quantify their impact on the capacity of the pipe. Currently, bedding factors are used in the Indirect Design method to relate the behaviour of a concrete pipe when buried to the results of a D-load or three edge bearing test (ASTM C497-16a). Thus, a potential method of accounting for the presence of erosion voids would be to develop modified bedding factors that would account for the effects of the reduced soil support.

In light of this background, this paper reports the outcomes of a full-scale experimental study conducted on 0.9 m (36 in.) diameter reinforced concrete pipes with simulated erosion voids. The objectives of the paper are to (i) measure the difference in pipe bending moments for pipes with and without erosion voids, (ii) measure the difference in bending moments for pipes with and without grouted voids, and (iii) use these experimentally measured bending moments to develop modified surface load bedding factors for pipes with erosion voids and grouted erosion voids.

2. Background

2.1. Void geometry

El-Taher and Moore (2008) looked at the influence of erosion voids on the yielding and buckling failure of corroded metal culverts using finite element analysis. They found that in the presence of an erosion void, the moments were more affected than the thrust in the pipe. Additionally, moment (the controlling factor for rigid pipes), was affected by both changes in the position of the erosion void with respect to the pipe and the volume of the void.

The void location on the circumference of the pipe considered in the current study is based on the work of two previous investigations. Firstly, the numerical study presented by Tan and Moore (2007) considered erosion voids at the invert of a rigid pipe that resulted in a decrease in the magnitude of the overall bending moments experienced by the pipe. However, the presence of an erosion void at the springline was the most critical as it resulted in an increase in the magnitude of bending moments at all critical locations (i.e. crown, invert, and springlines). As a result, the void in the present study was simulated at the springlines to capture the critical changes in bending moments around the pipe circumference. Secondly, the first study by Spasojevic et al. (2007) found that although a common location for voids is under the invert due to fluids leaking from drainage and sewer pipes, these voids are unstable since the soil around the springlines tends to collapse and fill the void at the invert.

Obtaining images of erosion voids is challenging and hence replicating their true geometry is difficult. However, drawing on the geometry considered in Tan and Moore (2007), El-Taher and Moore (2008), and Balkaya et al. (2012), the erosion void was represented as a prismatic arc shape running along the length of the pipe on one side, thus making it a 2-D problem. Furthermore, Balkaya et al. (2012) studied the stresses and deformations in a PVC water pipe with different void geometries at the invert and haunches located at the joints using finite element analysis and found that joint rotation was magnified when voids were present at the joints. This study was validated by Becerril García and Moore (2014a,b) using full-scale experiments. Hence, in order to avoid this complexity and to focus on the impact of erosion voids on pipe strength, the voids in the present study were represented only along the length of the pipe barrel.

In addition, Tan and Moore (2007) showed that the contact angle of erosion voids plays a dominant role in stress changes. Hence, in the present study different sizes of voids were also considered.

2.2. Soil cover

Lay and Brachman (2013) looked at the response of a RC pipe to surface live loads in an intact soil condition using full-scale experiments. RC pipes showed only 50–60% of cracking strain at nominal loads. As a result, no cracking developed in the pipe when it was subjected to CL-625 single-axle truck loading at nominal loads. It was also found that increasing the soil cover caused a reduction in the crown bending moment due to load spreading and arching. Hence, a minimum cover depth to diameter ratio of one was selected for the present study.

2.3. Accuracy of bedding factors

Indirect design of buried concrete pipes uses a quantity called the Bedding Factor. Bedding factors were originally defined as the load per unit length along the pipe crown that induced the limiting crack (width of 0.25 mm) in a D-load test divided by the load that induced the limiting crack when the pipe was buried. This will subsequently be referred to as the 'moment resistance' Bedding factor, since it relates to load that induces the design limit state in the pipe. However, until the recent work of MacDougall et al. (2016), there were no experiments performed where crack width was measured for tests on buried pipes. Therefore, the Bedding factor has been quantified considering the ratio of moment induced under vertical loads in a three edge bearing test on the pipe in a laboratory, to the moment that develops in the same pipe under the same level of vertical load in the field when it is buried. This will be subsequently be referred to as the 'moment demand' bedding factor, since it is calculated using the moment demands in the pipe at loads below any design limit state.

The Bedding factor is greater than 1 (and the bending moments in the buried pipe decrease relative to those in the three edge bearing test) since the soil around the pipe spreads load across the top and bottom of the pipe, and lateral earth pressures develop that counteract the moments from the vertical loading. MacDougall et al. (2016) used tests on 0.6 m and 1.2 m diameter pipes at shallow cover to show that for those structures, the Indirect Design method gives conservative solutions when designing RC pipes and this could mean that reinforced concrete pipes already have the necessary reserve capacity to negate the effects of an erosion void beside a pipe. Since the Indirect Design method represents the most common approach used in pipe design across North America, the effect of erosion voids on Bedding Factors will be used to quantify the resulting changes in pipe capacity.

3. Methods

3.1. Introduction

In order to achieve the objectives of the study, seven full-scale buried experiments using 0.9 m (36 in) internal diameter RC pipes were conducted with and without simulated erosion voids. This section initially describes the testing arrangement and setup, followed by details