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Performance of two-dimensional analysis: Deteriorated metal culverts under surface live load

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A B S T R A C T

As buried infrastructure assets reach the end of their service lives, better methods to assess these assets are required in order to optimize infrastructure budgets and management programs. As a first step towards developing these more accurate methods, the results of four currently available culvert modelling approaches were compared with the results of experiments on a deteriorated culvert as well as two buried culverts (one with significant deterioration and poor backfill, and one with limited deterioration and well compacted backfill) subjected to simulated vehicle loading. Two finite element analysis programs were used: CANDE, a commonly used software package specifically for culverts, and ABAQUS, a more robust general use package. Three different live load spreading factors were used with these programs to determine which one most accurately modelled the three dimensional live loading effects in two dimensions. The capacity of the culverts was also estimated using the design equations given in the Canadian and American bridge design codes. All the finite element models were unable to capture the non-linear behaviour of the deteriorated culvert with poor backfill as well as both culverts at high surface loading due to the use of linear elastic models. CANDE was found to provide very poor estimates of culvert diameter change but good estimates of culvert performance for the culvert with limited deterioration and well compacted backfill. ABAQUS could be used to predict culvert diameter change and thrust force with good accuracy in the linear elastic region or provide an upper bound estimate depending on the surface load spreading model that was employed. Both the Canadian and American design code equations underestimated the thrust forces in the culverts, suggesting that these approaches could be unconservative.

1. Introduction

Many parts of the world find themselves on the threshold of an infrastructure crisis as buried structures, such as steel culverts, sewers, and tunnel linings, reach the end of their design lives and are clearly deteriorated but replacing all of these buried structures is not financially or practically viable. In order to address these ever worsening issues surrounding infrastructure deterioration, many government agencies have conducted investigations over the years to study culvert stability and produced guidelines on culvert assessment. Most of these methods for culvert assessment are based on qualitative approaches primarily based on visual inspection (Arnoult, 1986). The outcomes of a visual inspection have significant variability associated with them (Graybeal et al., 2003) and do not typically contain the quantitative data that is required to develop numerical models of a buried structure and its interaction with the surrounding soil. Some transportation authorities (e.g. the Departments of Transportation in the states of California and Utah) attempt to predict the culvert's service life using both pH and minimum resistivity values (Wyant, 2002); however these methods only provide general guidelines and do not address the stability of individual culverts. As such, an assessment method based on quantitative data needs to be developed to provide accurate estimates of the capacity of the deteriorated metal culvert, so that more effective management strategies can be developed.

In order to do this, engineers require methods for measuring the remaining wall thickness of corroded culverts and numerical models to estimate the culvert's stability with clear guidance on where to take measurements and how often. Methods that avoid coring

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the structure will clearly be preferable. However, validation work is also required to ensure that these models provide conservative and accurate predictions of culvert behaviour. Previous research (Mai et al., 2012b) has demonstrated the effectiveness of using an ultrasonic thickness gauge to estimate the reduction in wall thickness due to corrosion. Work in the area of numerical modelling has focused on developing models to estimate the behaviour of new metal culverts under the effect of earth load and surface live load using finite element analysis (e.g. Taleb and Moore, 1999; Moore and Taleb, 1999). El-Taher and Moore (2008) conducted a numerical analysis using the finite element analysis program ABAQUS to study the stability of deteriorated metal culverts. Mai et al. (2012a) performed a numerical analysis using both ABAQUS and CANDE (a program developed specifically for culvert analysis and design) to calculate the remaining structural capacity of deteriorated metal culverts under earth load at different burial depths. However, to evaluate these models, they must be compared against full-scale experiments conducted on deteriorated culverts.

In this paper, a numerical study will be conducted using the results from an ultrasonic wall thickness survey of two deteriorated culverts combined with the results from a series of full-scale experiments conducted using these culverts that will be introduced here but are described in greater detail elsewhere (Mai et al., 2014). To predict the remaining structural capacity of the two deteriorated metal culverts prior to testing, a numerical analysis was performed using two finite element packages: (i) CANDE-2007 (Mlynarski et al., 2008) and (ii) ABAQUS version 6.9 (Dassault Systèmes Simulia Corp., 2009). The results from CANDE and ABAQUS will be compared to the experimental results to determine the accuracy of both packages in terms of estimating the remaining structural capacity of deteriorated metal culverts. The experimental results will also be compared to different design approaches including: (i) the current American Association of States Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications (AASHTO, 2012) and (ii) the current Canadian Highway Bridge Design Code (CSA, 2006). The comparison will be used to indicate whether or not the current culvert design methods can be used to estimate the stability of deteriorated metal culverts.

The next section introduces the full-scale experiments, the finite element models and the design guidelines. The results from the finite element analysis and design approaches will then be presented and compared to the experimental results in terms of both predicted deflections (serviceability) and thrust forces (strength). Finally, conclusions will be drawn regarding the effectiveness of using 2-D finite element models and design codes to predict deteriorated culvert behaviour.

2. Test description

2.1. Introduction

Two-full scale deteriorated corrugated metal culvert specimens were tested under laboratory control. Two types of tests were performed: (i) a preliminary culvert-only loading test was conducted on the most deteriorated specimen (denoted as CSP1) and (ii) surface live load testing was undertaken on both specimens (CSP1 and the less deteriorated culvert specimen, denoted as CSP2).

2.2. Specimens

Both specimens had an approximate diameter of 1.8 m and were 3 m long. CSP1, the more deteriorated specimen, was slightly deformed. At the south end of the specimen, the distance between the crown and the invert was 1.87 m, while the distance between the two springlines was 1.82 m. At the north end of the specimen the crown to invert distance was 1.85 m while the distance between springlines was 1.87 m. In the numerical models the culvert diameter was taken as 1.86 m. The corrugation profile had amplitude of 12.7 mm and period of 67.7 mm. The intact wall thickness for both specimens was 4.5 mm. CSP1 had extensive corrosion along both sides of the invert while CSP2 had only light corrosion on either side of the invert. The average wall thicknesses along either side of the invert as a percent of intact wall thickness were 70% (West haunch) and 48% (East haunch) for CSP1, and 83% (West haunch) and 90% (East haunch) for CSP2. The wall remained intact in the top section of both culverts (from haunch to haunch).

2.3. Culvert-only load test

CSP1 was placed on soil compacted to 95% of standard Proctor, and a parallel plate loading test was conducted prior to burial. A wooden joist (150 mm by 150 mm) was placed on small bags of plaster of Paris that were placed between the crown of the culvert

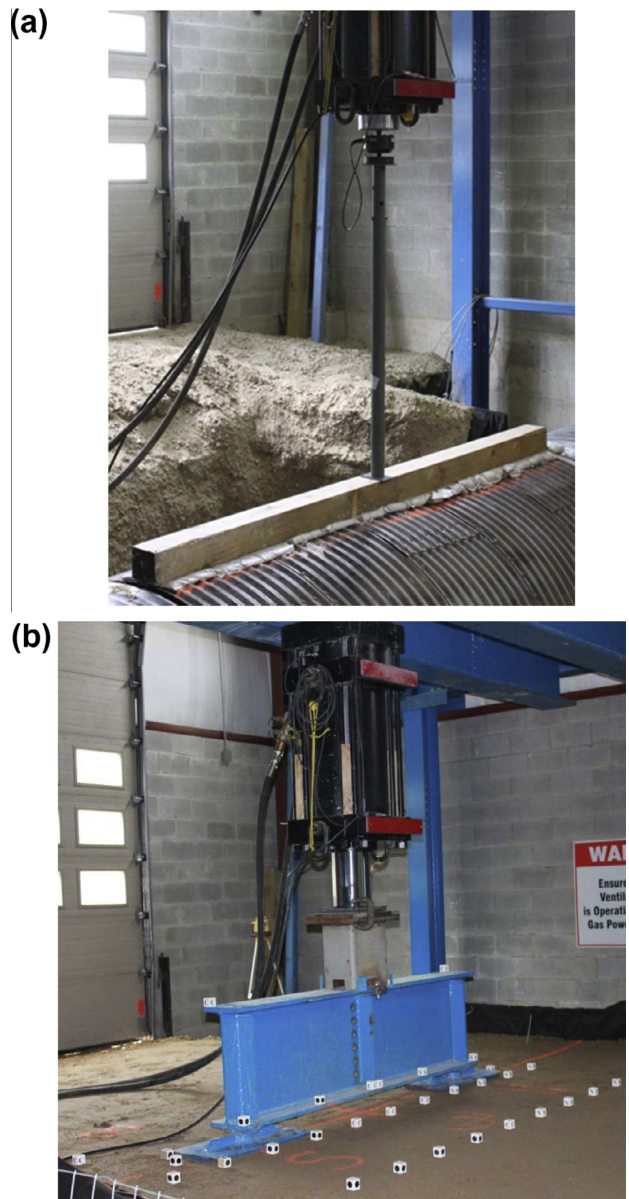

Fig. 1. Pipe loading arrangement. (a) Culvert-only test with spreader beam and (b) live load tests with single axle and 0.6 m cover.