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Performance of deteriorated corrugated steel culverts rehabilitated with sprayed-on cementitious liners subjected to surface loads

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ABSTRACT

A variety of alternatives to rehabilitate culverts have been developed over the past decades given their advantages over conventional open-cut culvert replacement. However, the performance of many of these systems has not yet been examined through laboratory testing. The objective of the present paper is to examine the performance of deteriorated steel culverts rehabilitated with spray-on liners when subjected to surface loads. Two 1200 mm diameter corrugated steel pipelines with similar levels of deterioration in the invert-haunch area were buried to a depth of 1200 mm and tested under service load employing a load frame simulating a single axle of a Canadian design truck. The pipelines were then rehabilitated with spray on-cementitious liners (each with a different target thickness). Once rehabilitated, the pipelines were examined again under the service load employing the single axle load frame at 1200 mm of soil cover, and then tested employing a tandem axle load frame at 2100 and 1200 mm of soil cover. During all tests, changes in diameter, curvature and liner strains were monitored. The data obtained indicates that the flexible pipelines responded like semi-rigid structures after rehabilitation. It was also observed that the difference in liner thickness of 30% did influence the response of the pipelines, and that extreme fiber tensions during service loading were 7% and 13% of the tensile strength of the liner materials for the 76 mm and 51 mm liner thicknesses that were specified.

1. Introduction

Culverts need to withstand loads generated by the fill cover and by the road traffic. This type of buried infrastructure comes in a variety of shapes, sizes and materials. It was estimated that in the 90s over hundreds of thousands of culvert served under highways of the United States of America, many of them 50 years or older (Ballinger and Drake, 1995). In a survey performed by Bhattachar (2007) seeking information from departments of transportation in the USA and in Canada, 13% of the participants indicate that their culverts were at the limit of their service life. When culverts approach or reach their design service life, transportation agencies have three options: repair, rehabilitate or replace (NCHRP synthesis 303, 2002). Amongst the most common trenchless techniques currently employed to rehabilitate deteriorated culverts and pipes are: segmental lining, spiral wound lining, cured in place lining, fold and reform lining, and spray-on lining (Hollingshead and Tullis, 2009). The selection of the technique for any given project depends on considerations such as the type of pipe/culvert, size and the level of deterioration. Matthews et al. (2012) developed a flowchart to help in the selection of the most suitable rehabilitation technique of corrugated metal pipes based on the condition of the pipeline.

Corrugated steel pipes, fabricated from sheets of galvanized steel, are amongst the most common structures employed to construct culverts in North America. Because of their wall profile, these culverts possess large ring compression strength but relatively low circumferential bending stiffness, thus are considered flexible. Abrasion and corrosion damage is the most common cause of replacement for these type of culverts (Arnoult, 1986; Ballinger and Drake, 1995), and this deterioration usually concentrates in the invert region of the culvert. Corrosion leads to reduction of the wall and eventually creates perforations which reduce the structural capacity of the culvert. In addition, perforation of the wall may generate erosion of the soil which will further reduce the capacity of the soil-pipe structure. Several research studies have demonstrated that culverts with substantial amounts of wall loss may still possess the required capacity (El-Taher and Moore, 2008; Mai et al., 2012, 2014). However corrosion is a process that

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will continue with time thus collapse of the culvert may eventually occur. One of the rehabilitation methods employed to provide protection against corrosion in steel culverts is the spray-on liner technique. In addition to the corrosion protection, the liner also provides hydraulic repair and structural strength to the culvert, with this last feature influenced by the liner thickness. Quick installation and low cost are advantages of the spray-on liner technique.

The structural capacity and response of rehabilitated culverts is clearly influenced by the method employed and research is needed to develop adequate design guidelines and standards for the rehabilitation techniques currently employed. Work has been performed on the behavior of cured in place pipes (CIPP) (e.g. El-Sawy and Moore, 1997, and Allouche et al., 2005), and on the behavior of slip liners (e.g. Simpson et al., 2013) for example. In addition, design guidelines are mentioned by standards for some rehabilitation methods. ASTM F1216-09 defines design considerations for the thickness of liners in CIPP based on the condition of the existing (host) pipe. If the existing pipe can sustain soil and surcharge loads during the design life of the rehabilitated structure (partially deteriorated pipe), the liner should only be design to sustain hydrostatic loads due to groundwater. If the existing pipe is unable to sustain soil and live loads (fully deteriorated pipe), the liner should be design to sustain hydraulic, soil and live loads (also mentioned in ASTM F1606-05 and ASTM F1741-08). However none of the current North American standards define design guidelines for spray-on liners and no research studies have been performed to examine the performance and behavior of this type of rehabilitation method.

The objective of the present paper is to examine the performance of steel culverts rehabilitated with spray-on liners (two thicknesses are examined) when subjected to surface loads and compare their response at two burial depths when subjected to single and axle loading configurations. To achieve these objectives, two deteriorated 1200 mm diameter corrugated steel pipelines donated by the 407 Express Toll Route (ETR) were examined. These pipelines were buried until 1200 mm of soil cover and then loaded with a frame that simulates a single axle of a design truck. The pipes are subsequently repaired with a spray-on liner employing a fiber reinforced cement (geopolymer nano-ceramic according to the manufacturer) mortar, each one with a different thickness (51 and 76 mm nominal thicknesses). The rehabilitated pipelines are then tested again under the same burial and loading configuration to assess the influence of the liner on the performance of the pipelines. Additional testing is then performed in which the burial depth is increased (up to 2100 mm of soil cover) and the loading configuration is modified (tandem axle). Finally the added soil cover is removed and the pipelines are retested at 1200 mm of cover with a tandem axle load configuration. All the loading configurations examined correspond to a standard Canadian design truck (almost the same as those for the AASHTO design truck, 2007). During all tests the rehabilitated pipelines were monitored with electric foil strain gauges, optical fiber and with string potentiometer. The paper also presents a survey of the wall thickness across the deteriorated pipelines employing an ultrasonic thickness gauge that was performed before the pipelines were instrumented and buried.

2. Experimental setup

2.1. Specimens

The two pipelines examined for this research study were assembled employing three 1200 mm diameter deteriorated corrugated steel pipes that were exhumed and donated by the 407 ETR, which is a privately operated tolled highway that crosses the Great Toronto Area in Ontario, Canada. Two of these pipe were employed as the main elements of the examined pipelines, while segments of the third pipe were used to extend the culverts to a total length of 7000 mm. All pipes featured helically wound corrugations (approximate angle of 79.5°, see Fig. 1b) with a pitch of 68 mm, depth of 13 mm, and a nominal thickness of 2 mm. The main component of Pipeline 1 (PL1) had a length of 6020 mm and exhibited corrosion that extended approximately from haunch to haunch (i.e. from 4 to 8 o'clock position with the invert located at the 6 o'clock mark), and perforated strips at both sides of the invert with a void (i.e. perforation) percentage between 10% and 20%, see Fig. 1a. The main component of Pipeline 2 (PL2) had a length of 4565 mm and also exhibited corrosion extending from haunch to haunch, although the void percentage in the perforated strips was between 20% and 40%. The corroded region in the third pipeline (employed to extend the length of the pipelines) was essentially the same as those in the main elements of the pipelines and had a void percentage in the perforated strips between 40% and 60%.

2.2. Thickness survey

Measurements of the steel thickness of the main elements of the pipelines were obtained employing an ultrasonic thickness gauge (Olympus 38DL Plus) with a dual element transducer. Mai et al. (2012) employed this equipment and measuring procedure described below to monitor the thickness of a deteriorated metal culvert and reported that measurements with this equipment were on average within 3% and 23% of measurements taken with a micrometer for lightly and heavily corroded regions respectively. For each of the main elements of the pipelines, thickness measurements were taken in the region subsequently located under one of the loading pads (representing a pair of wheels) and in the region subsequently located between the loading pads (denoted the "East offset" and the "Center" region respectively in the remainder of this paper). Thicknesses between 1.81 and 1.86 mm were measured in non-corroded regions of the main pipe of PL1, while the thickness in non-corroded regions in the main pipe of PL2 ranged between 1.83 and 1.87 mm. In corroded regions of the main pipe of PL1 the thickness ranged from 1.46 to 1.65 mm, and between 1.33 and 1.48 mm in main pipe of PL2. The points where measurements were taken were sanded down to remove the galvanizing coat and/or corrosion products to improve the quality of the measurements. Such measurements were taken in areas where the steel was unaltered (taken from inside the pipe) as well as in corroded areas (taken from outside the pipe). In all cases the measurements were taken in the flat regions of the corrugation (i.e. between the corrugation crest and valley). Fig. 2 shows the prepared surfaces where the measurements were obtained in the main element of PL1 (the same pattern was employed for the main element of PL2), and the perforations.

2.3. Burial configuration

As noted before, each of the two examined pipelines was formed with a main pipe and with segments cut from a third pipe to achieve a total length of 7000 mm. Both pipelines were assembled and placed in the West pit of the GeoEngineering Laboratory at Queen's University; the pipes were separated by two diameters (i.e. 2400 mm) to limit interactions between the structures. The locations of the pipelines within the testing pit and their configurations are shown in Fig. 3a. Before placing the pipelines, the soil foundation was compacted employing a vibrating plate packer (Wacker WP1550AW). A GP-SP soil (poorly-graded sandy gravel) or A-1 as defined by AASHTO was employed as the test soil throughout. Characteristics of the soil gradation can be found in