Research Article

Investigation of the Load-Sharing Theory of the RC Pipes Rehabilitated with Slip Liners

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Slip-lining is a preferred rehabilitation approach in the departments of transportation in China. Although the method is the most common rehabilitation technique, few research studies have been conducted on the mechanical behavior of a rehabilitated reinforced concrete pipe (RCP). A series of experiments were conducted on RCPs rehabilitated with a corrugated steel pipe (CSP), a steel pipe, a high-density polyethylene (HDPE) pipe, and a shape steel bracket. The RCP rehabilitated with the CSP showed an increase in both the load-carrying capacity (3.46 times greater than the RCP) and the stiffness (5.35 times greater than the RCP). The RCP rehabilitated with the steel pipe, HDPE pipe, and steel bracket exhibited an increase in the load-carrying capacity (1.23, 1.50, and 1.31 times greater than the RCP, respectively), and the stiffness of these three pipes was not markedly changed. The slip-lined pipe acts as a “pipe within a pipe” system. A “load-sharing” theory was proposed in this study and provides estimates of the load-carrying capacity of the slip-lined pipes.

1. Introduction

Slip-lining, which involves inserting a liner into an existing culvert and grouting the space between them [1], is a preferred technique by the engineers [2], not only does it reduce reconstruction costs but also will not cause traffic disruption. A variety of pipe materials can be used as the liners such as high-density polyethylene (HDPE) pipes and corrugated steel pipes (CSPs) [3, 4].

This rehabilitation technique is commonly used in China, but few researches have been performed when an reinforced concrete (RC) culvert is used. Zhao and Daigle [5] used a cast-iron pipe rehabilitated with a liner to conduct a two-point loading experiment and found that the existing pipe, grout, and liner acted independently; an approach was proposed to estimate the service life of a slip-lined pipe. McAlpine [6] used a rehabilitated concrete sewer to investigate a slip-lined pipe and found that a composite model could be used to estimate the effect of the enhancement. Other researches are devoted to explore the mechanical properties of the rehabilitated pipes. SnapTite [7] considered that the compressive strength of the grout was not important, but Smith et al. [8] considered that a higher compressive strength of the grout resulted in a higher load-carrying capacity of the rehabilitated pipe. Garcia and Moore [9] found that the steel culverts rehabilitated with spray-on liners responded like semirigid structures after rehabilitation. Moore and Garcia [10] found that full interaction and partial interaction both occurred between the corrugated steel pipelines and spray on cementitious. Simpson et al. [11] found that the stiffness of the corrugated steel culverts rehabilitated with grouted HDPE pipe was larger than the pre-rehabilitated pipe and the negative arching of the soil had increased. Simpson et al. [12] found that the existing pipe carried most of the load, the grout and RC pipe (RCP) were bonded, and the ultimate load-carrying capacity of the pipes depended on the bearing capacity of the unpaved ground surface. Tetreault et al. [13] concluded that the level of corrosion had no impact on the structural behavior and that paving the invert improved the structural performance. However, there are no guidelines for designing a slip-lined RC culvert and the load-sharing theory of these culverts, so there is an urgent need to investigate the performance and load-sharing theory of the rehabilitated RC culvert.
In the current research, an RCP was used as a culvert and four liners were used to investigate the performance of the culvert before and after rehabilitation. A series of experiments was conducted on RCPs rehabilitated with a grouted steel pipe, CSP, HDPE, and shape steel bracket liners. The objectives of this research were to determine (1) the load-carrying capacity of the five specimens (including an RCP, an RCP rehabilitated with grouted steel pipe, an RCP rehabilitated with grouted CSP, an RCP rehabilitated with grouted HDPE pipe, and an RCP rehabilitated with shape steel bracket, respectively), (2) the load-deformation curves of five specimens, (3) failure characters and the cracks distribution of the specimens, and (4) the load-sharing theory of the slip-lined pipes.

2. Laboratory Tests

Five specimens were used in this experiment to investigate the load-sharing mechanism of the slip-lined RCPs, including (1) an RCP, (2) an RCP rehabilitated with a CSP (RGChereafter), (3) an RCP rehabilitated with a steel pipe (RGS hereafter), (4) an RCP rehabilitated with a HDPE pipe (RGH hereafter), and (5) an RCP rehabilitated with a shape steel bracket (RGB hereafter). The RCPs had an internal diameter of 1200 mm and a wall thickness of 120 mm. Double-layer cold-stretched steel bars (Ø6, HRB400) were arranged in the RCPs at a spacing of 50 mm. The strength grade of the RCPs is C60 with a compressive strength of 59.73 ± 2.77 MPa and an elastic modulus of 36 GPa, the strength grade of the steel bars is HRB400 Cold-stretched steel bar with a tensile strength of 575 ± 9 MPa and an elastic modulus of 210 GPa. The pitch of the CSP was 200 mm with a depth of 50 mm with an intact wall thickness of 3 mm. The steel pipe had an internal diameter of 1100 mm and a wall thickness of 10 mm. The specification of the shape steel bracket is 70 × 5 with a leg length of 70 mm and thickness of 5 mm. The designations of the steel pipe, CSP, and shape steel bracket are Q235, which has a minimum yield strength of 235 MPa and a minimum tensile strength of 370 MPa and an elastic modulus of 210 GPa. The HDPE pipe (DN/ID 1000, SN 8) had an internal diameter of 1000 mm, a ring stiffness of 8.2 kN/m², a tensile strength of 16 MPa, and a modulus of 800 MPa. All pipes were 1000 mm long. The spacing of the shape steel bracket is 200 mm, and short shape steel was used to connect the shape steel bracket longitudinally.

Two types of grout were used, including (1) C40 concrete for RGC and RGS and (2) high-performance grouting material for the RGH. The C40 concrete has a compressive strength of 49.93 ± 4 MPa and an elastic modulus of 32.5 GPa, and the high-performance grouting material has a compressive strength of 87.7 ± 3 MPa and an elastic modulus of 38 GPa. No grout was used for the RGB, and the shape steel bracket is directly contacted with the RCP. The grout rings of RGC has a minimum thickness of 50 mm (from the crest of the CSP to the inner of the RCP), that of RGS has a thickness of 50 mm, and that of the RGH had a thickness of 20 mm. The RGB has no grout.

A two-point loading experiment was used in this study, and the load was applied to the specimens using a 2500 kN hydraulic actuator, which was attached to a reaction frame over the pipes. A distributing girder and two base plates were used to ensure that the concentrated load could not cause a deterioration of the specimens or a stress concentration. The specimens were loaded to the ultimate state with a loading rate of 15 kN/min, and the loading was paused at various stages to observe the experimental phenomena. The schematic of loading frame is shown in Figure 1, and the specimens are shown in Figure 2.

Four string potentiometers with an accuracy of 0.1 mm were used to measure the vertical and horizontal diameter changes. Two string potentiometers were installed inside the rehabilitated pipe at the crown and invert, and the other two were installed outside of the rehabilitated pipe at the springlines. Because the RCP, grout, and liners are in close contact with each other at the crown and invert, the diameter changes of the three pipe materials should be equal; in addition, the base plates were installed outside the pipe, making it impossible to install the string potentiometers outside of the pipe. Therefore, the string potentiometers were installed inside the rehabilitated pipe. However, if the RCP, grout, and liners were to separate from each other at the springlines, the diameter change of the RCP would be larger than that of the other components; considering the most unfavorable situation; the string potentiometers were, therefore, installed outside of the rehabilitated pipe to monitor the diameter change of the RCPs.

3. Experimental Results

3.1. Loads versus Diameter Changes. Figure 3 shows the results of the applied loads versus the diameter changes for the unrehabilitated pipe (RCP) and the rehabilitated pipe (RGC, RGS, RGH, and RGB). The vertical and horizontal diameter changes for each pipe are of similar magnitude but have opposite directions. It can be seen from Figure 3 that the liners increased the load-carrying capacity of the RCP.

The load-carrying capacities and stiffness of the specimens were used to compare the results. When the specimens were cracking, the RGC had approximately 3.70 times the load-carrying capacity of the RCP (370 kN versus 100 kN) and 1.86 times the vertical diameter change of the RCP (1.7 mm versus 0.915 mm); the RGS had approximately 1.5 times the load-carrying capacity of the RCP (150.3 kN versus 100 kN) and 1.0 times the vertical diameter change of the RCP (0.9 mm versus 0.915 mm); the RGH had approximately 1.16 times the load-carrying capacity of the RCP (116.1 kN versus 100 kN) and 1.0 times the vertical diameter change of the RCP (0.9 mm versus 0.915 mm); the RGB had approximately 1.6 times the load-carrying capacity of the RCP (901 kN versus 249 kN), 1.68 times the vertical diameter change of the RCP (16.5 mm versus 9.835 mm), and 1.70 times the horizontal diameter change of the RCP (13.3 mm versus 7.84 mm); the RGS had approximately 1.07 times the load-carrying capacity of the RCP (266.74 kN versus...
249 kN), 0.34 times the vertical diameter change of the RCP (3.34 mm versus 9.835 mm), and 0.26 times the horizontal diameter change of the RCP (2.04 mm versus 7.84 mm); the RGH had approximately 1.2 times the load-carrying capacity of the RCP (298.1 kN versus 249 kN), 0.62 times the vertical diameter change of the RCP (6.1 mm versus 9.835 mm), and 0.42 times the horizontal diameter change of the RCP (3.3 mm versus 7.84 mm); the RGB had approximately 0.91 times the load-carrying capacity of the RCP (225.9 kN versus 249 kN), 0.99 times the vertical diameter change of the RCP (7.8 mm versus 7.84 mm). When the specimens reached their ultimate state, the RGC had approximately 3.46 times the load-carrying capacity of the RCP (968 kN versus 280 kN), 0.65 times the vertical diameter change of the RCP (22.9 mm versus 35.425 mm), and 0.52 times the horizontal diameter change of the RCP (19.6 mm versus 37.61 mm); the RGS had approximately 1.23 times the load-carrying capacity of the RCP (344 kN versus 280 kN), 1.0 times the vertical diameter change of the RCP (35.35 mm versus 35.425 mm), and 1.16 times the horizontal diameter change of the RCP (43.75 mm versus 37.61 mm); the RGH had approximately 1.51 times the load-carrying capacity of the RCP (422 kN versus 280 kN), 1.46 times the vertical diameter change of the RCP (51.7 mm versus 35.425 mm), and 1.28 times the horizontal
diameter change of the RCP (48.1 mm versus 37.61 mm); the RGB had approximately 1.31 times the load-carrying capacity of the RCP (366 kN versus 280 kN), 1.27 times the vertical diameter change of the RCP (45.1 mm versus 35.425 mm), and 1.02 times the horizontal diameter change of the RCP (38.3 mm versus 37.61 mm).

The stiffness was also different for these specimens as shown in Figure 3. The RCP had an initial stiffness of 109.3 kN/mm and a secant stiffness of 7.9 kN/mm at the ultimate state; the RGC had a much higher initial stiffness than the RCP (217.6 kN/mm versus 109.3 kN/mm) and a much higher secant stiffness (42.3 kN/mm versus 7.9 kN/mm); The RGS had an initial stiffness of 167 kN/mm and a secant stiffness of 9.73 kN/mm; The RGB had an initial stiffness of 129 kN/mm and a secant stiffness of 8.16 kN/mm; The RGB had an initial stiffness of 48 kN/mm and a secant stiffness of 8.12 kN/mm. From the load-carrying capacity, diameter change, and stiffness enhancement in the two-point loading tests, it can be inferred that the CSP improved the load-carrying capacity of the RCP because of a significant increase in its stiffness and capacity but reduced the ductility of the rehabilitated pipe (reduction in the ultimate diameter change); the steel pipe, HDPE pipe, and shape steel bracket improved the load-carrying capacity of the RCP slightly, but the stiffness of the RCP has not been changed much by these liners.

3.2. Cracks Distribution. The crack distribution at ultimate state is shown in Figure 4. The crack distribution of the RCP reflects the ductility of the specimens, i.e., if the cracks are distributed over a wide range with equal spacing and the maximum width of the crack is small, it indicates that the specimens have good ductility. The cracks of RCP distributed over a wide range and the maximum width is 18 mm; the steel bar is broken; the cracks of RGS distributed a small range and the maximum width is 17 mm, the steel bar is broken; the cracks of RGB distributed over a wide range with equal spacing and the maximum width is 3 mm. The distribution of the cracks illustrated that the RCP, RGH, and RGB have better ductility than that of RGC and RGS.

The cracks at the ends of the specimens can be used to illustrate the combination of RCP, grout, and liners (Figure 5). Circumferential cracks appeared on the interface between grout and RCP, it showed that there is a circumferential slip between them, and they were not completely bonded together (Figures 5(b)–5(d)). The RGB, on the other hand, only contains RCP and liner, no bonding existed between them at all, slip occurred on the contact surface, and the shape steel bracket was buckling (Figures 5(e) and 5(f)). This phenomenon is particularly clear in liners and grouts, liners, and grouts separated with each other especially at the springlines. Figure 5 shows that RCP, grout, and liners are likely to act independently, rather than a composite system.

4. Load-Sharing Mechanism

If RCP, grout, and liner act as a pipe within a pipe system, the vertical deflections of RCP, grout, and liner should be equal. Deflection of the pipe subjected to the concentrated load at the ends of the specimens can be used to illustrate the combination of RCP, grout, and liners (Figures 5(b)–5(d)). The RGB, on the other hand, only contains RCP and liner, no bonding existed between them at all, slip occurred on the contact surface, and the shape steel bracket was buckling (Figures 5(e) and 5(f)). This phenomenon is particularly clear in liners and grouts, liners, and grouts separated with each other especially at the springlines. Figure 5 shows that RCP, grout, and liners are likely to act independently, rather than a composite system.

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where $\varphi_1$ is the stiffness factor of the liner, $\varphi_2$ is the stiffness factor of the grout, and $\varphi_3$ is the stiffness factor of the RCP.

Equation (4) indicates that the concentrated load $F$ is shared among the pipe materials and that the distribution of the load depends on the stiffness factor $\varphi$. It should be noted that concrete has different short-term and long-term stiffness and the long-term stiffness decreases over time [5], and the term $E_3I_3$ is not applicable. In assessing the load sharing and stresses, the value of the long-term stiffness taken at the expected design life should be used for the expected loads and the value of the short-term stiffness should be used for loading conditions of a transient nature. The stiffness of a concrete component can be calculated using the Code for Design of Concrete Structures [15]. For this experiment, a short-term stiffness was used to calculate the load-carrying capacity and the expression is as follows:

$$B_s = \frac{E_s A_s h_0 \psi}{1.15\psi + 0.2 + (6a\rho/\rho_t (1 + 3.5\rho_t))},$$  \hspace{1cm} (5)

$$\psi = 1.1 - \frac{0.65f_{tk}}{\rho_t \sigma_{eq}},$$ \hspace{1cm} (6)

where $B_s$ is the short-term stiffness of the RCP, $E_s$ is the elastic modulus of the steel bar, $A_s$ is the area of the tensile steel bar, $h_0$ is the effective thickness of the RC pipe, $\psi$ is the nonuniform coefficient of the strains, $\sigma_{eq}$ is the ratio of the elastic modulus of the steel bar to the elastic modulus of the
The calculation results are shown in Table 2. The percent error for RGC and RGS (8% and 13.4%) is considerably higher than that for RGH and RGB (0.6% and 0.5%), and this may due to the thickness of the slip-lined pipe wall and the buckling of the steel pipe. The RGC has a thickest wall than the other pipes, this will cause the load to diffuse in the pipe wall tremendously, so that the range of the loads act on the liners will be larger than that act on the RCP, and this indirectly improves the load-carrying capacity of the liners. Since the theoretical analysis did not consider the diffusion of the loads and assumed the ranges of the loads act on the RCP, grout, and liner are same, this will make the calculated value is lower than the tested value. The RGS, on the other hand, takes the steel pipe as the liner; the steel pipe is easy to buckle under pressure, and this will make the actual load-carrying capacity lower than that when it yields, while the theoretical analysis assumed the steel pipe could yield which make the calculated value higher than the tested value. Overall, it can be seen from Table 2, the maximum difference between the theoretical and experimental results is less than 13.4%, the minimum difference between them is 0.5%; the calculated results are so close to the experimental results. This proves that the above theory is very reasonable.

In the theoretical derivation, the short-term stiffness is used to consider the nonlinear effects of the RCP, and elastic stiffness is used for the grout and liners. The liners, on the other hand, have formed plastic hinge at the crown, invert, and springlines, when the slip-lined pipes reached the ultimate state. Once the plastic hinge formed, the liners should be regarded as destructive [16]; the maximum stiffness that the liners can provide is the elastic stiffness, which should be used in load-sharing calculation. Foamed cement banking, cement mortar, and fine aggregate concrete are always used as grout; once these materials cracked, they cannot carry any loads, but only when they work alone. In a slip-lined system, the radial pressures applied by the RCP and liners will constrain the radial deformation of the grout. Moreover, friction exists on the contact surface of RCP, grout, and liners, though it will not prevent slipping, it will reduce the tensile stress of grout. The friction is always opposite to the tensile stresses caused by the bending moments, and this is similar to an imaginary force that resists the tensile stress of grout at the crack, which allows the grout to act like an elastic body and to exert an imaginary pull. If the elasticity hypothesis is wrong, the calculated results in Table 2 cannot be as good as the experimental results, which indirectly shows that the elasticity hypothesis is correct.

The results also indicate that the plasticity approach and composite behavior method used by Smith et al. [8] are likely not appropriate for rehabilitating RCPs given the behavior demonstrated by these specimens.

5. Conclusions

This paper presented a load-sharing theory to estimate the load-carrying capacity of the slip-lined pipes. The CSP, steel pipe, HDPE pipe, and shape steel bracket were used as liners to rehabilitated RCPs. Including an RCP, there are 5 pipes were tested in two-point loading experiments. The current...
Table 1: Stiffness factors of the tested pipes.

| Type of pipe ring | Mean radii (mm) | Elastic modulus (MPa) | Pipe stiffness factor, \( \varphi \) (MPa) |
|-------------------|----------------|----------------------|----------------------------------|
| RCP               | 660            | 36000                | 4.786                            |
| For CSP           | 550            | 32500                | 8.54                             |
| Grout             | 580            | 32500                | 1.78                             |
| For steel pipe    | 550            | 38000                | 2.32                             |
| CSP               | 527.5          | 2.1 \times 10^5      | 1.90                             |
| Steel pipe        | 555            | 2.1 \times 10^5      | 0.1                              |
| HDPE              | 539.75         | 800                  | 0.066                            |
| Shape steel bracket | 562.5       | 2.1 \times 10^5      | 1.5                              |
| RGB               | 367.22         | 344                  | 15.23                            |
| RGS               | 419.47         | 422                  | 6.67                             |
| RRC               | 419.47         | 422                  | 6.67                             |
| RGH               | 539.75         | 800                  | 7.17                             |
| RGB               | 367.99         | 366                  | 6.29                             |

Table 2: Calculation results of the load-carrying capacity.

| Type of pipe ring | \( F_c \) (calculated) (kN) | \( F_t \) (tested) (kN) | \(|(F_c - F_t)/F_t|\) (%) |
|-------------------|-----------------------------|-------------------------|---------------------------|
| RCP               | —                           | 280                     | —                         |
| RGC               | 891.02                      | 968                     | 8                         |
| RGB               | 390.22                      | 344                     | 13.4                      |
| RGH               | 419.47                      | 422                     | 0.6                       |
| RGB               | 367.99                      | 366                     | 0.5                       |

Note: \( F_c \) is the calculated load-carrying capacity, as \( F_c = \sum \varphi_i \); \( F_t \) is the tested load-carrying capacity.

While the experiments were undertaken under two-point loading, the RCPs were buried in the soil in practical engineering. The surrounding soil would influence the vehicle loads distribution and make an interaction between the soil and RCP, and the stress state of the RCP will be very different from these experiments. Therefore, the surrounding soil should be considered in the future research.

**Abbreviations**

- RCP: Reinforced concrete pipe
- RGC: Reinforced concrete pipe rehabilitated with a corrugated steel pipe
- RGS: Reinforced concrete pipe rehabilitated with a steel pipe
- RGH: Reinforced concrete pipe rehabilitated with a high-density polyethylene pipe
- RGB: Reinforced concrete pipe rehabilitated with a shape steel bracket
- \( \Delta_r \): Vertical decrease in the diameter of each pipe
- \( \Delta_i \): Vertical decrease in the diameter of the liner
- \( \Delta_r \): Vertical decrease in the diameter of the grout
- \( \Delta_i \): Vertical decrease in the diameter of the RCP
- \( F_c \): Concentrated load carried by the slip-lined pipe
- \( \varphi \): Stiffness factor, as \( EI/r^3 \)
- \( \varphi_i \): Stiffness factor of the liner, as \( E_i I_i/r_i^3 \)
- \( \varphi_2 \): Stiffness factor of the grout, as \( E_2 I_2/r_2^3 \)
- \( \varphi_3 \): Stiffness factor of the RCP, as \( B_3/r_3^3 \)
- \( B_3 \): Short-term stiffness of the reinforced concrete, N-mm²
- \( E_i \): Elastic modulus of the steel bar, MPa
- \( A_i \): Area of the tensile steel bar, mm²
- \( h_{0i} \): Effective thickness of the RCP, mm
- \( \psi \): Nonuniform coefficient of the strains
α\varepsilon: Ratio of the elastic modulus of the steel bar to the elastic modulus of the concrete
ρ: Reinforcement percentage of the tensile steel bar
f\varepsilon_c: Characteristic value of the concrete tensile strength, MPa
\rho_{te}: Effective reinforcement percentage
\sigma_{te}: Tensile stress of the steel bar at the crack section, MPa
\rho_2: Density of the grout, kg/m³
f_2: Compressive strength of the grout, MPa
F_c: Calculated load-carrying capacity of the slip-lined pipe
F_t: Tested load-carrying capacity of the pipe
1: Liner
2: Grout
3: RCP.

Data Availability

The (experimental results) data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] ASTM, Standard Guide for Insertion of Flexible Polyethylene Pipe into Existing Sewers, ASTM F585, West Conshohocken, PA, USA, 2013.
[2] S. Syachrani, H. S. Jeong, V. Rai, M. J. Chae, and T. Iseley, “A risk management approach to safety assessment of trenchless technologies for culvert rehabilitation,” Tunnelling and Underground Space Technology, vol. 25, no. 6, pp. 681–688, 2010.
[3] C. A. Ballinger and P. G. Drake, Culvert Repair Practises Manual, FHWA-RD-95-089, US Department of Transportation, Federal Highway Administration (FHWA), McLean, VA, USA, 1995.
[4] J. Vaslestad, A. Madaj, L. Janusz et al., “Field measurements of old brick culvert slip lined with corrugated steel culvert,” in Proceedings of 83rd Annual Meeting of the Transportation-Research-Board, pp. 227–234, Washington, DC, USA, January 2004.
[5] J. Q. Zhao and L. Daigle, “Structural performance of slip-lined watermain,” Canadian Journal of Civil Engineering, vol. 28, no. 6, pp. 969–978, 2001.
[6] G. McAlpine, “Structural rehabilitation of semi elliptical concrete sewers,” in Proceedings of Pipelines, pp. 1–7, ASCE, Reston, VA, USA, 2006.
[7] SnapTite, Design Guide, SnapTite, Erie, PA, USA, 2013, http://www.culvert-rehab.com/pdfs/2013_manual.pdf.
[8] T. Smith, N. A. Hoult, and I. D. Moore, “Role of grout strength and liners on the performance of slip-lined pipes,” Journal of Pipeline Systems Engineering and Practice, vol. 6, no. 4, article 04015007, 2015.
[9] D. B. Garcia and I. D. Moore, “Performance of deteriorated corrugated steel culverts rehabilitated with sprayed-on cementitious liners subjected to surface loads,” Tunnelling and Underground Space Technology, vol. 47, pp. 222–232, 2015.
[10] I. D. Moore and D. B. Garcia, “Ultimate strength testing of two deteriorated metal culverts repaired with spray-on cementitious liners,” Transportation Research Record: Journal of the Transportation Research Board, vol. 2522, pp. 139–147, 2015.
[11] B. Simpson, I. D. Moore, and N. A. Hoult, “Experimental investigation of rehabilitated steel culvert performance under static surface loading,” Journal of Geotechnical and Geoenvironmental Engineering, vol. 142, no. 2, article 04015076, 2016.
[12] B. Simpson, N. A. Hoult, and I. D. Moore, “Rehabilitated reinforced concrete culvert performance under surface loading,” Tunnelling and Underground Space Technology, vol. 69, pp. 52–63, 2017.
[13] J. Tetreault, N. A. Hoult, and I. D. Moore, “Pre- and post-rehabilitation behaviour of a deteriorated horizontal ellipse culvert,” Canadian Geotechnical Journal, vol. 55, no. 3, pp. 329–342, 2018.
[14] R. K. Watkins and L. R. Anderson, Structural Mechanics of Buried Pipes, CRC Press, Boca Raton, FL, USA, 1999.
[15] MOHURD (Ministry of Housing and Urban-Rural Development), Code for Design of Concrete Structures, GB 50010-2010, National Standards of People’s Republic of China, Beijing, China, 2011.
[16] CSA International (Canadian Standards Association International), Canadian Highway Bridge Design Code, CAN/CSA-S6-06, Canadian Standards Association, Mississauga, Canada, 2006.
