Research Article

Experimental Investigation of an Existing RCP Rehabilitated with a Grouted Corrugated Steel Pipe

Bai-jian Li ^{1,2}, Liang-sheng Zhu,¹ Yong Li,¹ and Xin-sha Fu ¹

¹School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong 510640, China

²Tianhe College of Guangdong Polytechnic Normal University, Guangzhou, Guangdong 510540, China

Correspondence should be addressed to Xin-sha Fu; fuxinsha@163.com

Received 31 January 2019; Revised 17 April 2019; Accepted 13 May 2019; Published 16 June 2019

Academic Editor: Piero Colajanni

Copyright © 2019 Bai-jian Li et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Although slip-lining is the most common rehabilitation technique, few research studies have been conducted on the behavior of rehabilitated reinforced concrete pipes (RCPs). Experiments were conducted on a RCP rehabilitated with a grouted corrugated steel pipe (CSP). The RCP rehabilitated by the CSP showed an increase in both load-carrying capacity and stiffness. The grout played an important role in distributing the loads when the RCP was deteriorated, whereas the load shared by the CSP represented only a small part. When the CSP was closely fitted to the RCP at the invert, the load was shared between the PCP and CSP and the CSP carried most of the load when the RCP was fully deteriorated. The slip-lined pipe acted 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

Currently, a culvert crisis exists in China because structures built many years ago are reaching the end of their intended service lives; many culverts cannot be removed and reconstructed because of economic constraints. Not only is the reconstruction cost prohibitive but the resulting social impacts and traffic disruption are also unacceptable. To overcome this problem, a new technique has been developed, i.e., slip-lining, which involves inserting a liner into an existing reinforced concrete (RC) culvert and grouting the space between the pipes [1]. This technique has been increasingly applied in engineering [2]; a variety of pipe materials can be used for the liner, such as corrugated steel pipes (CSPs) and high-density polyethylene (HDPE) pipes [3, 4].

The most popular technology in China consists of inserting a CSP into an existing RC culvert because the CSP has a higher load-carrying capacity and stiffness than the HDPE pipes. However, few research studies have investigated reinforced concrete pipes (RCPs) rehabilitated with grouted CSPs. Previous research has been conducted to investigate the performance of a water main or a corrugated steel culvert rehabilitated by an HDPE pipe. 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. SnapTite [7] was developed for use with an HDPE liner; it was determined that the compressive strength of the grout was not important, whereas the density and viscosity of the grout were two primary design considerations. Smith et al. [8] investigated the compressive strength of the grout and found that a higher compressive strength resulted in a higher load-carrying capacity of the rehabilitated pipe. Moore and Garcia [9] investigated two deteriorated corrugated steel pipelines repaired with spray-on cementitious liners and found that both full interaction and partial interaction occurred between the pipes; it was determined that a liner design should not rely on the assumption of a bond between the two components [10]. Simpson et al. [11] investigated a corrugated steel culvert rehabilitated with a grouted HDPE pipe and found that the rehabilitated culvert was stiffer, the negative arching of the soil had increased, and the higher strength of the

grout resulted in a higher load-carrying capacity of the pipe. Simpson et al. [12] investigated rehabilitated RCPs and found that the existing pipe carried most of the load, the grout and 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] investigated a corrugated steel horizontal ellipse rehabilitated using the paved invert technique and concluded that the level of corrosion had no impact on the structural behavior and that paving the invert improved the structural performance. Li et al. [14] investigated the RCPs rehabilitated with four different liners and concluded that all the liners improved the load-carrying capacity of the RCPs, and a load-sharing theory was proposed to estimate the load-carrying capacity of the rehabilitated pipes.

However, there are no guidelines for designing an RC culvert rehabilitated with a grouted CSP and, in order to ensure that this design is conservative, engineers have always treated the CSP as a new culvert. This inappropriate design method does not consider the contribution of the existing RC culvert, resulting in a waste of resources and money. Generally, when an existing RC culvert has many longitudinal cracks, it has to be reinforced or repaired. In this condition, the existing RC culvert still has a residual capacity and the conditions of “fully” and “partially” deteriorated are based on two completely different evaluation criteria for existing RC culverts [15]; a partially deteriorated culvert can still endure external loads depending on the confining pressure of the surrounding soil [16]. In addition, culverts that are not deteriorated may also have to be reinforced to meet the requirements of upgrading the load-carrying capacity. In China, highways are divided into five grades: expressways, grade I, grade II, grade III, and grade IV. Expressways and grade I highways are usually regarded as high-grade highways, whereas grade II, grade III, and grade IV highways are regarded as low-grade highways. The differences between high-grade and low-grade highways are the traffic volume and design loads; if a low-grade highway is converted to a high-grade highway, the load-carrying capacity of the culvert also needs to be increased to the corresponding grade. In this case, the reinforced structural system becomes a composite system of an “un-deteriorated culvert” and a slip-liner. Therefore, it is inappropriate to design a slip-liner as a new culvert and there is an urgent need to investigate the performance of the rehabilitated RC culvert.

Against this background, a series of experiments were conducted on RC pipes rehabilitated with a grouted CSP in this study. The objectives of this research were to determine: (1) the load-carrying capacity of the RCP, (2) the load-carrying capacity of the RCP reinforced with the grouted CSP, (3) the strain state of the cross-section, and (4) the load-sharing mechanism of the slip-lined pipe. The results of the experiment are presented and discussed. Additionally, the calculation formula of the load-carrying capacity under the ultimate limit state is presented. Finally, salient conclusions from the experiments are presented.

2. Laboratory Tests

2.1. Pipe Specimens. In order to investigate the load-sharing mechanism of the slip-lined RCPs, two specimens were used in this experiment, including (1) an RCP and (2) a RCP rehabilitated with a grouted CSP (RGC hereafter). The RCPs were purchased from a pipe manufacturer and had an internal diameter of 1200 mm and a wall thickness of 120 mm. Double-layer cold-stretched steel bars ($\phi 6$, HRB400) were arranged in the RCP at a spacing of 50 mm. The strength grade of the RCPs was C60, which represents a compressive strength of 59.73 ± 2.77 MPa and an elastic modulus of 36 GPa. The strength grade of the steel bars was HRB400 cold-stretched steel bar with a tensile strength of 575 ± 9 MPa and an elastic modulus of 210 GPa. The corrugation amplitude of the CSP was 55 mm with a period of 200 mm with an intact wall thickness of 3 mm. The designation of the CSP is Q235 and it had a minimum yield strength of 235 MPa, a minimum tensile strength of 370 MPa, and an elastic modulus of 210 GPa. All pipes were 1000 mm long. The schematic of the loading frame is shown in Figure 1 and the specimens used in this experiment are shown in Figure 2.

2.2. Grouts. Many materials can be used for the grout, such as foamed cement banking, cement mortar, fine aggregate concrete, and ordinary concrete. Considering that China usually uses concrete and many engineering practices have confirmed this point [17–19], C40 concrete was used for the grout; it had a compressive strength of 49.93 ± 4 MPa and an elastic modulus of 32.5 GPa. The grout rings of the RGC had a minimum thickness of 50 mm (from the crest of the CSP to the inner surface of the RCP) and a maximum thickness of 105 mm (from the trough of the CSP to the inner surface of the RCP) (see Figure 1).

2.3. Instrumentation. 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 CSP 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 CSP 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 RCP.

Strain gauges were used to monitor the strains of the RCPs (strain gauge type: BQ120-60AA-P300) and the CSP (strain gauge type: BE120-3AA-P300). All strain gauges were attached circumferentially at the crown, invert, springlines, and shoulders (at eight equally spaced points of the pipe) and

FIGURE 1: The schematic of the loading frame: (a) longitudinal section; (b) cross-section; (c) section A-A; (d) details for distributing girder and base plate.

FIGURE 2: Specimens used in the two-point loading setup: (a) RCP; (b) RGC.

the RCP was attached circumferentially to both the interior and exterior extreme faces of the RCP wall (each section was affixed with 3 strain gauges and a total of 48 strain gauges were used). The RGC consisted of three pipe materials (RCP, grout, and CSP) and the strain gauges were attached to the RCP and CSP; the installation method of the strain gauges on the RCP was the same as before, whereas the strain gauges were attached circumferentially on the interior extreme faces of the CSP (each section was affixed with 3 strain gauges on the crest and 3 on the trough and a total of 48 strain gauges were used). The 1/4 bridge connection method was used for the strain gauges and temperature compensation gauges, including a concrete strain gauge and a steel strain gauge, were used to prevent the effects of the temperature changes.

The strain gauges used to monitor the RCP had a gauge length of 60 mm and the strain gauges used to monitor the steel pipe and the CSP had a gauge length of 3 mm. The gauge resistance was $120 \Omega \pm 0.3\%$ with a gauge factor of $2.11 \pm 1\%$.

2.4. Loading. A slip-lined RCP is a buried structure that is surrounded by soil and soil arching greatly influences the distribution of the surface load of a buried RCP. Additionally, because of the confining pressure of the soil, it is difficult to calculate the internal force, which complicates the analysis of a slip-lined RCP. This study, however, enables a better understanding of the load-sharing mechanism of the slip-lined RCP. A two-point loading experiment was used in this study because the internal force of the pipe under a two-point load can be calculated using a theoretical method and it is convenient to compare the theoretical results with the measured results; this represents an advantage of the two-point loading approach.

The load was applied to the specimens using a 2500 kN hydraulic actuator, which was attached to a reaction frame over the pipe. 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 tests were performed under load control with a rate of 15 kN/min before the specimens reached its ultimate state, and slow displacement controlled should be required after the specimens were in the softening stage. However, the objectives of the test were to investigate the rehabilitated effect, load-carrying capacity, and failure characteristics of the rehabilitated pipe. The mechanical performance during the softening stage was not important to this study. Therefore, the load control scheme was adopted during the whole loading stage.

2.5. Steps of the Experiment. This experiment consisted of three steps:

(i) Determine the mechanical behavior of the pre-rehabilitated pipe, represented by the ultimate load-carrying capacity, crack distribution, load-diameter change curve, and strains of the RCP. The objectives of testing an RCP without slip-lining were to evaluate the reinforcement effect and to obtain the load-carrying capacity of the prerehabilitated pipe in order to calculate the load-carrying capacity of the post-rehabilitated pipes.

(ii) Determine the mechanical behavior of the post-rehabilitated pipe, i.e., the RCP rehabilitated with the grouted CSP, using the same parameters as for the pre-rehabilitated pipe.

(iii) Compare the experimental results of the prerehabilitated and postrehabilitated pipes and investigate the effect of the slip-liner on the load-carrying capacity and stiffness.

(iv) Determine the bonding condition of the CSP, grout, and the RCP based on the strains and the load-sharing mechanism of the slip-lined culvert.

3. Experimental Results

Figure 3 shows the results of the applied load versus the diameter change for the unrehabilitated pipe (RCP) and the rehabilitated pipe with the CSP (RGC). 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 CSP increases the load-carrying capacity of the RCP significantly.

This experiment was used to evaluate the load-carrying capacity and stiffness of the specimens; the load-carrying capacities of the pipes at different stage 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]. When the specimens were yielding, the RGC had approximately 3.62 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]. 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 stiffness was also different for these two specimens as shown in Figure 3. The RCP had initial stiffness of 109.3 kN/mm and secant stiffness of 7.9 kN/mm at the ultimate state. The RGC, on the other hand, had much higher initial stiffness than the RCP [217.6 kN/mm versus 109.3 kN/mm] and much higher secant stiffness [42.3 kN/mm versus 7.9 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 crack distribution of the two specimens in the ultimate state is shown in Figure 4. The crack distribution reflects the ductility of the specimens from another angle; e.g., 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; otherwise, the specimens have poor ductility. It can be seen from the experimental results that the cracks of the RCP are distributed

FIGURE 3: Applied load versus diameter change for the RCP and RGC.

FIGURE 4: Crack distribution of the specimens: (a) RCP; (b) the largest crack of the RCP; (c) RGC; (d) the largest crack of the RGC.

over a wide range and the maximum width of the crack is 5 mm; the steel bar is not broken, which indicates that the RCP has good ductility. However, the crack distribution of the RGC has a smaller range than the RCP and the maximum crack width is 18 mm; the steel bar is broken, which indicates that the RGC has lower ductility than the RCP.

The crack distribution in the transverse section (shown in Figure 5) directly reflects the bond condition of the RCP, grout, and CSP. At the crown and invert of the slip-lined pipe, there are two shear cracks extending from the edge of the base plate to the CSP; this result is attributed to the shear force at the concentrated loading point. Aside from the shear cracks, short circumferential cracks appeared at the interface between RCP and grout at the crown and extended to the shoulder of the pipe. At the springlines, the CSP was significantly detached from the grout and circumferential cracks appeared at the interface between the RCP and grout and extended to the invert of the pipe. In addition, the radial cracks at the springlines did not extend through the RCPs and grout but occurred only in the RCP and grout, which means that both tensile and compressive regions appeared in the RCP and grout. The distribution of the cracks is an indication that the RCP, grout, and CSP were not fully bonded.

In order to determine the bond condition of the RCP, grout, and CSP, the strains were used to determine the bond condition as a supplementary criterion; i.e., if the RCP, grout, and CSP are fully bonded, the strains should be distributed along the height of the section in a straight line. Three strain gauges were installed in each section at the crown, invert, and springlines. The average strain values are shown in Figure 6; it is evident that the actual distribution of the strains does not really correspond to this situation because the compressive strains and tensile strains occur alternately along the height of the section, which means that a slip occurred among the RCP, grout, and CSP. This conclusion is in agreement with the conclusion derived from the distribution of the cracks. These results imply that the three pipes most likely acted independently.

4. Load-Sharing Mechanism

Smith et al. [8] used a plasticity approach to estimate the load-carrying capacity of a slip-lined pipe; it was demonstrated that the moment capacity at the crown and invert was different from the moment capacity at the springlines and different methods were used to calculate the moment capacity at these sections; i.e., the moments caused compression in the CSP and the grout nearest the liner experienced tension at the crown and invert. In addition, the grout closest to the liner (inside of the pipe) was compressed, whereas the CSP experienced tension; therefore, the cross-section at these locations acted like an RC section where the pipe represented the tension reinforcement at the springlines. As such, an RC approach was used to calculate the plastic moment capacity as described in the research by Smith et al. [8]. This approach conservatively neglects the presence of the liner and the beneficial effects of the thrust on the moment capacity.

Based on the experimental results, it can be concluded that the slip-lined system acted as a “pipe within a pipe

system”; thus, the load-sharing mechanism under a two-point loading condition can be determined. Figure 7 shows a sketch of the pipe ring under a two-point loading condition. The vertical deflection of the existing pipe, grout, and liner should be equal. The subscripts 1, 2, and 3 represent the liner, grout, and existing pipe respectively and the vertical deflections of each pipe are expressed as [20]

$$\Delta_i = \frac{F_i r_i^3 (\pi/4 - 2/\pi)}{E_i I_i} \quad i = 1, 2, 3 \quad (1)$$

where Δ_i is the vertical decrease in the diameter of each pipe; F_i is the concentrated load shared by each pipe; r_i is the mean radius of each pipe; E_i is the modulus of elasticity; and I_i is the moment of inertia of the wall's cross-section per unit length of the pipe.

Therefore, the vertical deflections are equal to ($\Delta_1 = \Delta_2 = \Delta_3 = \Delta$) and the following is obtained:

$$\frac{F_1}{E_1 I_1 / r_1^3} = \frac{F_2}{E_2 I_2 / r_2^3} = \frac{F_3}{E_3 I_3 / r_3^3} \quad (2)$$

The concentrated load shared by each pipe F_i should satisfy

$$\sum_{i=1}^3 F_i = F \text{ or } F_1 + F_2 + F_3 = F \quad (3)$$

where F is the concentrated load carried by the slip-lined pipe.

If a stiffness factor φ , as EI/r^3 , is defined, (2) can be changed into

$$\frac{F_1}{\varphi_1} = \frac{F_2}{\varphi_2} = \frac{F_3}{\varphi_3} \quad (4)$$

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 φ . This information is very useful for a structural analysis. It should be noted that concrete is a nonelastic material and when it is cracked or crushed, the term $E_3 I_3$ is not applicable; therefore, the short-term or long-term stiffness should be used to consider this nonlinear behavior. In assessing the load sharing and stresses, the value of the long-term stiffness for 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 [21]. For this experiment, a short-term stiffness was used to calculate the load-carrying capacity and the expression is as follows:

$$B_s = \frac{E_s A_s h_0^2}{1.15\psi + 0.2 + 6\alpha_E \rho / (1 + 3.5\gamma'_f)} \quad (5)$$

$$\psi = 1.1 - \frac{0.65 f_{tk}}{\rho_{te} \sigma_{sq}} \quad (6)$$

FIGURE 5: Crack distribution in the transverse section of the specimens.

FIGURE 6: Strain distribution along the height of the section (unit: 10^{-6}).

FIGURE 7: Deflection of the pipe subjected to the concentrated load F .

where B_s is the short-term stiffness of the reinforced concrete, N-mm²; E_s is the elastic modulus of the steel bar, MPa; A_s is the area of the tensile steel bar, mm²; h_0 is the effective thickness of the RCP, mm; ψ is the non-uniform coefficient of the strains; α_E is the ratio of the elastic modulus of the steel bar to the elastic modulus of the concrete; ρ is the reinforcement percentage of the tensile steel bar; f_{tk} is the standard value of the concrete tensile strength, MPa; ρ_{te} is the effective reinforcement percentage; σ_{sq} is the tensile stress of the steel bar at the crack section, MPa.

At this point, φ_3 is changed into the following expression:

$$\varphi_3 = \frac{B_s}{r_3^3} \quad (7)$$

At the ultimate state, the RCP reaches its ultimate load-carrying capacity and its stiffness factor declines rapidly; therefore, the loads shared by the grout and CSP will increase. Plastic hinges will appear at the crown, invert, and springlines and the specimen will experience failure. It should be noted that once the plastic hinges form, the stiffness of the pipe is very low and it can hardly carry a load anymore. According to the Canadian Highway Bridge Design Code [22], when the plastic hinges form in a CSP structure, the CSP has been already damaged and elastic methods should be used for the analysis of these structures. Therefore, the elastic stiffness of CSP was used in the experiments.

If we substitute (7) and (4) into (3), the load-carrying capacity of the slip-lined pipe can be calculated using the following formula:

$$F = \left[1 + \frac{E_1 I_1}{B_s} \frac{r_3^3}{r_1^2} + \frac{E_2 I_2}{B_s} \frac{r_3^3}{r_2^2} \right] F_3 \quad (8)$$

where F_3 is the load carried by the RCP; E_1 and E_2 are the moduli of elasticity of the CSP and grout respectively; I_1 and I_2 are the moments of inertia of the CSP and grout respectively; and r_1 , r_2 , and r_3 are the mean radii of the CSP, grout, and RCP, respectively; the moments of inertia and neutral axis of the grout can be determined by drawing software (such as auto CAD), and the position of the neutral axis is the position of the centroid.

When the load-carrying capacity of the RCP is known, (8) can be used to calculate the rupture load of the rehabilitated pipe.

The modulus of the concrete or the cement used for the grout depends on their compressive strength and density [23]:

$$E_2 = 0.043 \rho_2^{1.5} \sqrt{f_2} \quad (9)$$

where E_2 is the modulus of elasticity of the grout, MPa; ρ_2 is the density of the grout, kg/m³; f_2 is the compressive strength of the grout, MPa.

Therefore, the load-carrying capacity of the rehabilitated pipe depends on the thickness, density, and compressive strength of the three pipe rings.

Although the short-term stiffness of the concrete pipes has been taken into account in the nonlinear behavior of the RCP and the elastic modulus of the CSP have been

taken into account with regard to the elastic behavior, the mechanical behavior of the grout has yet to be considered. It is well known that the grout located between the RCP and CSP is constrained by the two pipes. The RCP and CSP result in radial pressure applied to the grout and the pressure at the crown and invert are higher than that at the springlines because the three pipes are mutually extruded at the crown and invert and are separated at the springlines in this experiment, which is shown in Figure 8(a). The radial pressure resulting from the RCP and CSP constrain the radial deformation of the grout.

In addition, the grout nearest the RCP experienced compression at the crown and invert, whereas it experienced tension at the springlines; this is contrary to the situation of the grout nearest the CSP, which experienced tension at the crown and invert and compression at the springlines. This stress state divides the grout into two parts along the neutral axis of the grout. In each part, tension and compression occur alternately; i.e., if the grout experiences tension at the springlines, it would experience compression at the crown and invert. Moreover, the RCP and CSP not only constrain the radial deformation of the grout but also constrain the circumferential deformation; these constraints will make the grout carry more loads than that without constraints.

As mentioned earlier, a slip occurred among the RCP, grout, and CSP and this caused frictions at the contact surface and the direction of the friction was opposite to the tensile and compressive stress of the grout. This friction reduced the compressive stress of the grout and prevented further expansion of the cracks (see Figure 8(b)), thereby reducing the stress on the grout. In this case, even though the grout cracked, the friction prevented the cracks from further development. This is similar to an imaginary force that resists the tensile stress at the crack.

The friction appeared to affect the load distribution among the RCP, grout, and CSP but it is known that it has little effect on the load-carrying capacity of the RCP and CSP after careful consideration. At the ultimate state of the slip-lined pipe, the load-carrying capacity of the slip-lined pipe is determined by the crown, invert, and springlines; these positions have the largest internal forces. Once the concrete at these positions is cracked or the RCP, grout, and CSP separate from each other, a slip will occur at the contact surface and the friction at these positions will disappear. The "pipe within a pipe system" theory is applicable to these positions. The frictions play a role only near these positions to prevent further expansion of the cracks.

The RCP and CSP constrain the deformation of the grout and the friction reduces the stress of the grout, which allows the grout to act like an elastic body and to exert an imaginary pull.

Regardless whether the RCP was damaged or not, the external load (concentrated load F in this experiment) was borne by the RCP directly, which means that the RCP took the full external load before and after rehabilitation. Once the RCP was damaged after rehabilitation, the load shared by the grout and CSP suddenly increased, resulting in damage. As a result, the load-carrying capacity of the slip-lined pipe indirectly depends on the RCP. Therefore, the load-carrying

FIGURE 8: Stress graphic of the grout: (a) radial pressure; (b) circumferential friction force.

capacity of the slip-lined pipe should be calculated based on the RCP (see (8)).

When the load-carrying capacity of the prerehabilitated pipe is known based on experimental or theoretical methods, the load-carrying capacity of the slip-lined pipe can be calculated using (8). As an example, the load-carrying capacity of the RCP (280 kN) was used as the load-carrying capacity of the pre-rehabilitated pipe (F_3) and (8) was used to calculate the load-carrying capacity of the RGC: $F_c = F_3 \times \Sigma \varphi_i / \varphi_3 = 280 \times 14.624 / 4.184 = 978.6$ kN.

Table 1 shows the rigidity factors of the tested pipe and the calculation results are shown in Table 2. The maximum difference between the theoretical and the experimental results is 1.1%. The results also indicate that the plasticity approach and composite behavior method used by Smith et al. [8] are likely not appropriate for rehabilitating an RCP given the behavior demonstrated by these specimens.

5. Load-Sharing among the Three Pipe Materials

The RGC was used to illustrate the load-sharing among the three pipe materials. Figures 9–11 actually show the proportion of the ring stiffness of each pipe to the total ring stiffness; this proportion is also the proportion of load sharing. Figure 9 demonstrates the effects of a reduction in the pipe stiffness of the RCP; the results were obtained by varying the pipe stiffness of the RCP and keeping all other parameters constant.

When the pipe stiffness of the RCP was reduced from 0% to 100% (undeteriorated to fully deteriorated), the load carried by the grout increased rapidly (the portion of the load carried by the grout ranged from 30% to 80%), whereas the load carried by the CSP increased only slightly (the portion of the load carried by the CSP ranged from 7% to 18%).

TABLE 1: Stiffness and rigidity factors of the tested pipe.

Type of pipe ring	Outside diameter, OD (mm)	Inner diameter, ID (mm)	Thickness, t (mm)	Modulus (MPa)	Pipe stiffness factor, ϕ (MPa)
RCP	1440	1200	120	36000	4.184
Grout	1200	1000	50 for CSP*	32500	8.54
CSP	1110	1000	—	2.06×10^5	1.90
RGC	1440	1000	220	—	14.624

*The distance from the outer edge of the CSP (crest of the CSP) to the inner edge of the RCP.

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	978.6	968	1.1

This illustrates that the grout plays an important role in distributing the load and the CSP only carries a small part of the load. When the RCP reached its ultimate state, the stiffness of the RCP decreased drastically and the load shared by the RCP was smaller than that of the grout. As mentioned before, the grout was constrained by the RCP and CSP and even though the RCP fully deteriorated, the constraint did not disappear but only weakened. Due to this constraint, the grout carried most of the load in the pipe within a pipe system without steel bars.

This conclusion is correct only when the existing pipe, grout, and liner are concentric. Otherwise, the results are very different.

In practical engineering, it is difficult to achieve a true concentric configuration of the three pipe materials in slip-lining construction and sometimes the pipes are eccentric; e.g., the CSP is always placed directly inside the RCP and the invert of the CSP is connected to the inner wall of the RCP. In this condition, the CSP is closely fitted to the RCP at the invert and the load is shared among the RCP and CSP, whereas the load is shared among the three pipe materials at the springlines and crown of the slip-lined pipe because the grout has a certain thickness at these positions. Overall, the load-carrying capacity of an eccentric slip-lined pipe depends on the load-carrying capacity of the thinnest section, which should be located where the CSP is closely fitted to the RCP (mostly at the invert). Figure 10 demonstrates the load-sharing between the RCP and the CSP at the invert (the grout should be ignored).

It can be seen that the RCP carried most of the load until it reached the ultimate state (the portion of the load carried by the existing pipe ranged from 90% to 70%); the CSP only carried a small portion of the load (the portion of the load carried by the liner ranged from 10% to 30%). When the RCP reached its ultimate state, the stiffness of the pipe decreased drastically and the portion of the load carried by the RCP ranged from 70% to 0%, whereas the CSP carried most of the load (the portion of the load carried by the CSP ranged from 30% to 100%).

Equation (9) shows that the modulus of the grout depends on the compressive strength and density, which influences the stiffness of the grout ring. The effect of the strength of the grout on the load sharing is shown in Figure 11; the results are obtained by varying the strength of the grout while holding all other parameters constant. The RCP reached its ultimate state. The load-sharing proportion of the grout increased from 0% to 58% with an increase in the grout strength from 0 MPa to 35000 MPa, and the load-sharing proportion of the RCP decreased from 69% to 29%, and the load-sharing proportion of the CSP decreased from 31% to 13%. In summary, the grout strength has an important influence on the load-carrying capacity of the slip-lined pipe.

It should be noted that, once the RCP is fully deteriorated and cannot continue to carry a load, the load shared by the grout and CSP will increase so that the grout and CSP will probably fail to withstand such a large load and damage; as a result, the slip-lined pipe will also be damaged.

6. Limitation of Current Research and Suggestions for Future Research

In this paper, the performance of an RCP rehabilitated with a CSP was presented and a method to estimate of the load-carrying capacity of the slip-lined pipe was proposed. The experiments were conducted under two-point loading, which does not reflect the actual working conditions of the pipe. Under actual working conditions, the RCPs are buried in the soil and an interaction occurs between the surrounding soil and the RCPs; this changes the stress state of the RCPs. Moreover, the soil will diffuse the vehicle loads, which will change the loads acting on the RCP to uniform loads. As such, the surrounding soil should be considered in future research.

Due to the limitation of the laboratory space, the specimens were short, and the aspect ratio of the specimens was not representative of pipelines, in which the possible eccentricity between the top and the reaction bottom force can produce a different stress configuration in the pipe, as

FIGURE 9: Effect of the stiffness reduction of the RCP on the load sharing.

FIGURE 10: Load sharing between existing pipe and liner at the invert.

FIGURE 11: Effect of the strength of the grout on the load sharing.

well as the interaction with the soil. This should be overcome in future researches, and the specimens which can represent real pipelines should be used to investigate the mechanical performance of the slip-lined pipes.

The influence of the compressive strength of the grout on the load-carrying capacity and stiffness should be also investigated because, in this study, we used a theoretical analysis to deduce that the compressive strength of the grout will affect the load-carrying capacity and stiffness of the slip-lined pipes; this requires verification. Additionally, the influence of the different deterioration levels of a buried RC

culvert on the load-carrying capacity and stiffness also needs to be investigated because engineers will only rehabilitate an existing RC culvert after a deterioration occurred in an actual engineering situation and an existing RC culvert has a different residual capacity, which will influence the load-carrying capacity and stiffness of the slip-lined pipes.

The friction and constraints provided by RCP and CSP make the grout can carry more loads. As it was known, if the grout ring is not located between the RCP and the CSP, it will lose its load-carry capacity once it cracks due to lack of friction and constraints. In theoretical analysis,

friction and constraints were considered to be the reasons why grout can carry loads, but their values and distributions were not determined, which should also be investigated in future researches.

The number of specimens was very small; only an RCP and an RGC were used in this experiment, totally inadequate to state general conclusions. The conclusions of this paper were only based on the results of this experiment, and more specimens should be used to verify the generality of the conclusions in the future.

7. Conclusions

The current investigation was undertaken to examine the performance of an RCP rehabilitated with grouted CSP. Two specimens of RCP and RGC were tested in a two-point loading experiment across the vertical diameter of the pipes. The following key conclusions are drawn from this work:

(1) The load-carrying capacity and stiffness of RGC were 3.46 times and 5.35 times greater than the RCP respectively. The CSP significantly increased the load-carrying capacity and stiffness of the RCP but reduced its ductility.

(2) When the CSPs is used to rehabilitate the RCPs, the CSP should not be treated as a new pipe for the structural analysis but the load-carrying capacity of the RCP and grout should also be considered. The load-carrying capacity of the rehabilitated pipe depends on the total stiffness factors (φ) and the load-carrying capacity of the RCP. Once the RCP is damaged after rehabilitation, the loads distributed by the grout and CSP will suddenly increase so that they cannot withstand a large load and damage will occur.

(3) Based on both the experimental observations and the strain distribution, the slip-lined pipe acted as “a pipe within a pipe system”. A “load-sharing” theory was proposed in this study and (8) provides estimates of the load-carrying capacity of the slip-lined pipes to within 1.1%. At this time, the short-term or long-term stiffness should be used to calculate the stiffness factor of the RCP.

(4) The radial pressures and circumferential frictions exerted by the RCP and CSP constrained the deformations of the grout, which resulted in an acceptable stress state of the grout, allowing it to carry a larger load.

(5) The grout played an important role in distributing the load when the RCP was deteriorated and the liner shared only a small part of the load. However, when the three pipe materials were eccentric, the CSP was closely fitted to the RCP at the invert. In this condition, the load was shared between the RCP and the CSP. When the RCP was fully deteriorated, the CSP carried most of the load and, in this condition, it should be treated as a new culvert.

Notations

RCP: Reinforced concrete pipe
 RGC: Reinforced concrete pipe rehabilitated with a corrugated steel pipe
 Δ_i : Vertical decrease in the diameter of each pipe

Δ_1 : Vertical decrease in the diameter of the CSP
 Δ_2 : Vertical decrease in the diameter of the grout
 Δ_3 : Vertical decrease in the diameter of the RCP
 F_i : Concentrated load shared by each pipe
 F_1 : Concentrated load shared by the CSP
 F_2 : Concentrated load shared by the grout
 F_3 : Concentrated load shared by the RCP
 r_i : Mean radius of each pipe
 r_1 : Mean radii of the CSP
 r_2 : Mean radii of the grout
 r_3 : Mean radii of the RCP
 E_i : Modulus of elasticity of each pipe
 E_1 : Modulus of elasticity of the CSP
 E_2 : Modulus of elasticity of the grout
 E_3 : Modulus of elasticity of the RCP
 I_i : Moment of inertia of the wall's cross-section per unit length of the pipe
 I_1 : Moment of inertia of the CSP
 I_2 : Moment of inertia of the grout
 I_3 : Moment of inertia of the grout RCP
 F : Concentrated load carried by the slip-lined pipe
 φ : Stiffness factor, as EI/r^3
 φ_1 : Stiffness factor of the CSP, as $E_1 I_1 / r_1^3$
 φ_2 : Stiffness factor of the grout, as $E_2 I_2 / r_2^3$
 φ_3 : Stiffness factor of the RCP, as $E_3 I_3 / r_3^3$
 B_s : Short-term stiffness of the reinforced concrete, N·mm²
 E_s : Elastic modulus of the steel bar, MPa
 A_s : Area of the tensile steel bar, mm²
 h_0 : Effective thickness of the RCP, mm
 ψ : Non-uniform coefficient of the strains
 α_E : 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_{tk} : Standard value of the concrete tensile strength, MPa
 ρ_{te} : Effective reinforcement percentage
 σ_{sq} : Tensile stress of the steel bar at the crack section, Mpa
 ρ_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: CSP
 2: Grout
 3: RCP.

Data Availability

The data [experimental results] used to support the findings of this study are included within the article.

Conflicts of Interest

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

Acknowledgments

This work was supported by the National Natural Science Fund under Grant (number 51278202) and the Science and Technology Support Program of Hunan Province under Grant (number 2015039). The authors are grateful to the Guangzhou Communication Investment Group co., Ltd and Hunan Jindi Corrugated Pipe Co., Ltd, for providing funds and experimental specimens. The authors would also like to thank Xiao-li ZHANG for supporting this research.

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] J. Vaslestad, A. Madaj, L. Janusz, and B. Bednarek, "Field measurements of old brick culvert slip lined with corrugated steel culvert," *Transportation Research Record*, no. 1892, pp. 227–234, 2004.
- [4] C. A. Ballinger and P. G. Drake, "Culvert repair practises manual," FHWA-RD-95-089, U.S. Dept. of Transportation, Federal Highway Administration (FHWA), McLean, VA, 321-330, 1995.
- [5] J. Q. Zhao and L. Daigle, "Structural performance of sliplined 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 the Pipeline Division Specialty Conference 2006*, pp. 1–7, Chicago, Illinois, United States, 2006.
- [7] SnapTite, "Design guide," 2013, <http://159.203.158.151/wp-content/uploads/delightful-downloads/2015/12/Snap-Tite-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 ID 04015007, 2015.
- [9] I. D. Moore and D. B. García, "Ultimate strength testing of two deteriorated metal culverts repaired with spray-on cementitious liners," *Transportation Research Record*, vol. 2522, no. 1, pp. 139–147, 2019.
- [10] D. B. García 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.
- [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 ID 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] B. Li, L. Zhu, and X. Fu, "Investigation of the load-sharing theory of the RC pipes rehabilitated with slip liners," *Advances in Civil Engineering*, vol. 2019, Article ID 9594379, pp. 1–8, 2019.
- [15] RIHMT (Research Institute of Highway Ministry of Transport), "Standards for technical condition evaluation of highway bridges," JTG/T H21-2011, National Standards of People's Republic of China, 2011.
- [16] CCCC Highway Consultants CO, "Code for design of highway reinforced concrete and prestressed concrete bridges and culverts," JTG D62-2012, National Standards of People's Republic of China, 2012.
- [17] P. P. Shang, "Defect culvert reinforcement technology using corrugated plate on existing heavy haul railway," *Railway Engineering*, vol. 57, no. 8, pp. 50–53, 2017.
- [18] Z. H. Wang, "On application of corrugated steel pipe culvert in road construction," *Shanxi Architecture*, vol. 38, no. 25, pp. 186–188, 2012.
- [19] C. Chen, "On consolidation of steel corrugated pipe culvert on expressways," *Shanxi Architecture*, vol. 42, no. 17, pp. 142–143, 2016.
- [20] R. K. Watkins and L. R. Anderson, *Structural Mechanics of Buried Pipes*, CRC Press, London, UK, 1999.
- [21] 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, 2011.
- [22] CSA International (Canadian Standards Association International), "Canadian highway bridge design code," CAN/CSA-S6-06, Canadian Standards Association, Mississauga, Ontario, Canada, 2006.
- [23] CSA, "Design of concrete structures," Standard CAN A23.3-04, Canadian Standards Association, Rexdale, Ont, Canada, 2004.