Test-loading Capacity Estimation of Slip-lined RCPs using a plastic approach

Yuting He¹, Xinsha Fu¹ and Baijian Li¹,2*

¹School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong 510640, China
²School of Architectural Engineering, Tianhe College of Guangdong Polytechnic Normal University, Guangzhou, Guangdong 510540, China
*Corresponding author’s e-mail: BJian_Li@163.com

Abstract. As many reinforced concrete pipes (RCPs) need to be rehabilitated due to the reconstruction, expansion of highways and structural damage. Inserting a corrugated steel pipe (CSP) into the existing RCP is an economical rehabilitation technique in China, the current research seeks to better understand the performance of the RCP rehabilitated with grouted CSP by using the reinforced concrete pipes (RCPs) as the host pipes. Experiments were conducted to (1) determine the test-loading capacity of five specimens; (2) understand the role of the liner (CSP); (3) understand the influence of eccentric rehabilitation on the test-loading capacity of the slip-lined pipe; (4) explore an approach to estimate the load-carrying capacity of the rehabilitated pipes. The test-loading capacity of an RCP rehabilitated with grouted CSP mainly depends on the RCP and the grout before the first peak value of the applied versus diameter change curve, CSP improved the maximum test-loading capacity and ductility of rehabilitated pipe. The test-loading capacity of an eccentric rehabilitated pipe was lower than that of a concentric rehabilitated pipe. The comparison of the calculated results showed that the plastic approach was reasonable for an RCP rehabilitated grout CSP. Meanwhile, an approach for analyzing a vertical eccentric rehabilitated pipe was proposed based on the plastic approach. The errors between the theoretical results and experimental results were basically less than 30%.

1. Introduction

Currently, most of reinforced concrete pipes (RCPs) exist in China need to be reinforced due to the reconstruction and expansion or structural deterioration. To reinforce these pipes, inserting a new corrugated steel pipe (CSP) into the RCP and grouting the space is a new rising technology in China, this technology is called slip-lining[1-4], which has been used in Europe, America and other countries for many years.

Previous research has been conducted to investigate the performance of a water main or a corrugated steel culvert rehabilitated by a high-density polyethylene (HDPE) pipe. Zhao and Daigle [5] used a cast-iron pipe rehabilitated with a liner to carry out a two-point loading experiment and found that the cast-iron pipe, grout, and liner acted independently. McAlpine [6] used a rehabilitated concrete sewer to investigate a sliplined pipe and found that a composite model could be used to estimate the effect of the enhancement. WRC [7] give the designer an option of considering the sliplined system as "fully bonded" or "completely unbonded", these two models are still not very reasonable. SnapTite [8] was developed for use with an HDPE liner, it was considered 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. [9] investigated the compressive strength of the grout and found that a higher compressive strength of the grout resulted in a higher load-carrying capacity of the rehabilitated pipe. Moore and Garcia [10] investigated two deteriorated corrugated steel pipelines repaired with spray-on cementitious liners and found that full interaction and partial interaction both occurred between the pipes, it was determined that a liner design should not rely on the assumption of a bond between the two components [11]. Simpson et al. [12] investigated corrugated steel culverts rehabilitated with grouted HDPE pipe and found that the rehabilitated culvert was stiffer, the negative arching of the soil had increased, and a higher strength of the grout resulted in a higher load-carrying capacity of the pipe. Simpson et al. [13] investigated rehabilitated reinforced concrete (RC) pipes and found that the existing pipe carried most of the load, the grout and RC pipe were bonded, and the ultimate load-carrying capacity of the pipes depended on the bearing capacity of the unpaved ground surface. Tetreault et al. [14] 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.

Although scholars have done some researches on slip-lined pipes, there are no guidelines for designing such structures [e.g., an ASTM [1], a Canadian Standards Association [15] standard, or a Chinese design code[16]], and in order to make this design more conservative, Chinese engineers always treat a CSP as a new culvert. This conservative design method does not consider the contribution of the existing RCP, resulting in a waste of resources and money.

Against this background, a series of experiments were conducted on RCPs rehabilitated with grouted CSPs in this study to investigate the mechanical performance and test-loading capacity estimation method. The objectives of this research were to determine: (1) the test-loading capacity of the specimens, (2) the roles of the grout and CSP, (3) influence of eccentric CSP on the test-loading capacity of the slip-lined pipe, and (4) an approach to estimate test-loading capacity of the slip-lined pipe. The results of the experiment are presented and discussed. Additionally, the calculation formula of the test loading capacity under the ultimate limit state is presented. Finally, salient conclusions from the experiments are presented.

2. Experimental Background

2.1. RCPs
In order to investigate the mechanical performance of the slip-lined pipes, four RCPs were used in this experiment. 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 (Φ 6, HRB400) were arranged in the RCP at a spacing of 100 mm. The strength grade of the RCPs was C45, which represents a compressive strength of 43.97±4.00 MPa and an elastic modulus of 33.5 GPa. The strength grade of the steel bars was HRB400 cold-stretched steel bar with a minimum yield strength of 400 MPa and a tensile strength of 575±9 MPa, the elastic modulus of the steel bar is 210 GPa.

2.2. CSPs
The corrugation amplitude of the double-side zinc coating CSPs was 25 mm with a period of 125 mm with an intact wall thickness of 3 mm. The designation of the CSPs 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.
2.3. Grout

Many materials can be used as grout, such as mortar, high-performance grout material, fine aggregate concrete and so on. Concrete is the most commonly used as grout in China, because the constructors will probably not mix grout on site for a rehabilitated project alone, they usually share the same batch of commercial concrete with other concrete structures, this will shorten the construction period. So, in this experiment, C30 concrete was used as the grout, it had a compressive strength of $30.35 \pm 2.00$ MPa and an elastic modulus of 30 GPa.

2.4. Experimental specimens

A total five specimens were used in this experiment, including (1) an RCP, (2) an RCP rehabilitated with a grouted CSP (RGC hereafter), (3) an RCP rehabilitated only with grout (RG hereafter), (4) an RCP rehabilitated with a vertical eccentric grouted CSP (ERGC hereafter), and (5) a CSP. 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.

The grout rings of the RGC and RG had a minimum thickness of 75 mm (from the crest of the CSP to the inner surface of the RCP). The grout rings of the ERGC, however, had a minimum thickness of 150 mm (from the crest of the CSP to the inner surface of the RCP), whereas that of 0mm at the invert (Figure 1).
2.5. 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.

![Figure 2](image)

Figure 2. Specimens used in the two-point loading setup: (a) RCP; (b) RGC; (c) RG; (d) ERGC; (e) CSP

Strain gauges were used to monitor the strains of the CSP used in RGC (strain gauge type: BE120-3AA-P300). All strain gauges were attached circumferentially at eight equally spaced points of the pipe and on the interior extreme faces of the CSP (each section was affixed with 1 strain gauge on the crest and 1 on the trough and 16 strain gauges were used). Additionally, temperature compensated steel strain gauges were used to prevent the effects of the temperature changes. The strain gauges used to monitor the CSPs had a gauge length of 3 mm. The gauge resistance was $120 \pm 0.3\%$ with a gauge factor of $2.11 \pm 1\%$. Figure 1 illustrates the relative location of the strain gauges attached to the specimens.

2.6. Loading
This study enables a better understanding of the mechanical performance of the slip-lined pipes. 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 experimental results; this represents an advantage of the two-point loading approach.

The load was applied to the specimens using a 1500 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 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.

3. Experimental results

3.1. RCP
The reinforcement percentage of the RCPs used in this experiment is 0.2826%, the area of tensile and compressive steel bars is $310.86 \text{ mm}^2$ respectively. The minimum steel ratio is 0.2%, which means that the RCPs are very close to Rare-reinforced Concrete. The failure characteristics of this kind of RCPs
are that, once the concrete cracks, the tensile stress of the steel bar at the crack quickly reaches its yield strength and enters the strengthen stage. The RCPs show good elastic performance before cracking. The load-carrying capacity of the RCPs continues to increase after cracking until the RCPs damaged. At this time, the steel bar is broken and the concrete cracks in the tension zone are very wide. The experimental phenomena were in good agreement with the above situation, the applied load versus the diameter change curves were shown in Figure 3. The vertical and horizontal diameter changes for each pipe are of similar magnitude but have opposite directions. It can be seen that the curve contained only two stages, one was elastic stage, the other was elastic-plastic stage, no obvious yield point was shown in this curve. The cracking load of the RCPs $F_{cr}$ is 41.7 kN, and the ultimate test-loading capacity is $F_{RCP}=93.7$ kN.

3.2. CSP

Steel is a good elastic-plastic material, the CSP made of steel also shows good elastic-plastic performance. As can be seen from the applied load versus the diameter change curve of CSP shown in Figure 3, CSP still exhibits good elastic performance in the case of large deformation. Due to the length of the coordinate axis, the plastic stage of the curve was not drawn, the ultimate test-loading capacity is $F_{CSP}=80$ kN.

![Figure 3. Applied load versus diameter change for the CSP, RCP and RGC](image)

3.3. RGC

The RGC reflects the rehabilitated effect of the grouted CSP on the RCPs, the applied load versus the diameter change curve of RGC also was shown in Figure 3. The curve contained three peaks and two valleys before reaching its ultimate test-loading capacity. The RGC exhibited good elastic performance before reaching the first peak. At this time, the test-loading capacity and stiffness of RGC are much higher than that of RCP, this illustrated that the grout and CSP play an important role in strengthening RCP (Figure 3). The curve from the first peak to the second valley represented the further cracking of the grout and RCP, the diameter changes of the RGC increased and the test-loading capacity decreases slightly. The curve between the second valley and the third peak indicated that the CSP played a more important role than before, which further improved the test-loading capacity. The first peak value of the curve was 230.81 kN and the maximum test-loading capacity of RGC was $F_{RGC}=255.94$ kN, the corresponding diameter change was 20.97 mm.
3.4. ERGC
ERGC represented an RCP rehabilitated with a vertical eccentric grouted CSP, the applied load versus the diameter change curves of RGC and ERGC were shown in Figure 4 together. As can be seen from Figure 4, the curves of these two specimens are similar, but the peak and valley values were different. Because the RCP and CSP were in close contact at the invert of ERGC and lack of grout, the first peak value of ERGC (164.6 kN) was much less than that of RGC (230.81 kN), and the maximum test-loading capacity of ERGC (220.7 kN) was much less than that of RGC (255.94 kN) either. Meanwhile, the diameter changes corresponding to the maximum test-loading capacity of ERGC was 10 mm, also less than that of RGC (20.97 mm). This illustrated that the test-loading capacity of eccentric rehabilitated pipe was lower than that of concentric rehabilitated pipe.

![Figure 4](image4.png)

Figure 4. Applied load versus diameter change for the RGC and ERGC

![Figure 5](image5.png)

Figure 5. Applied load versus diameter change for the RGC and RG
3.5. RG
RG represented an RCP rehabilitated only with grout, the applied load versus the diameter change curves of RGC and RG were both shown in Figure 5. The curve of RC only contained one peak and one valley, and the shape of this curve was similar to that of RGC before the second valley. This indirectly reflected that, before the first peak of the curve, the test-loading capacity of the specimens depends on the RCP and grout. the applied load versus the diameter change curve of RG did not have the second and third peaks due to the lack of CSP. So far, it is very clear that the test-loading capacity of the rehabilitated pipe before the first peak value was mainly provided by RCP and grout, and the third peak value was provided by the RCP, grout and CSP together.

Oddly, the test-loading capacity of RG was higher than that of RGC, this was impossible. The most likely reason was the dispersion of material strength, the material strength of RG is higher than that of RGC resulting a higher test-loading capacity. Nevertheless, the applied load versus the diameter change curves of RG and RGC reflected that test-loading capacity of rehabilitated pipes was provided by grout and RCP in the early stage, and by grout, RCP and CSP together in the later stage. Especially when RCP and grout cracked, CSP played a significant role.

The maximum test-loading capacity of RG was $F_{RG}=280$ kN, the corresponding diameter change was 8.2mm.

Steel is a good elastic-plastic material, the CSP made of steel also shows good elastic-plastic performance. As can be seen from the applied load versus the diameter change curve of CSP shown in Figure 3, CSP still exhibits good elastic performance in the case of large deformation. Due to the length of the coordinate axis, the plastic stage of the curve was not drawn, the ultimate test-loading capacity is $F_{CSP}=80$ kN.

3.6. Bonding condition
Figure 6 showed the crack distribution on the end face of the specimen, it can be seen that the cracks breakthrough the grout. In addition, concrete was a cohesive material, resulting in grout and RCP usually bonded together. The specimen was carefully cut off from the crack, it can be seen that the RCP and grout bonded together very well (Figure 7). Whether the RCP and grout were bonded or not can be judged intuitively through experimental phenomena, whereas the bonding condition of CSP and grout needed further judgement.

It can be seen from Figure 6c and Figure 7, the contact surface of the CSP and grout detached from each other obviously. This indicated that the CSP and grout were not bonded together and probably slipped.
Figure 7. The RCP and grout bonded together

Figure 6 and Figure 7 were taken after the test and may not be persuasive, so the strains of CSP were used to judge the bond condition as a supplementary criterion, e.g., if the CSP, grout, and RCP are fully bonded, the strains should be distributed along the height of the section as a straight line, which should satisfy the fully bonded condition as shown in Figure 8. Neglecting the axial force for the time being, the moment at the crown and invert was different from that at the springlines, the moments caused the RCP to go into compression and the grout nearest the CSP experienced tension at the crown and invert; at the springlines, the grout closest to the CSP was compressed, whereas the RCP experienced tension; the CSP should experience tension at the crown and invert, and compression at the springlines.

However, 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 (Figure 9), which mean that the CSP and grout were not bonded.

Figure 8. strains distribution under different bonding conditions

The actual bonding conditions of the RCP, grout and CSP may be more similar to the “actual condition” shown in Figure 8, the RCP and grout were fully bonded, whereas the CSP acted
independently. The next theoretical analysis of the test-loading capacity of the specimens will be based on this bonding condition.

4. Pipe Test-loading Capacity Estimates

4.1. Test-loading capacity estimation of concentric rehabilitated pipe

When the specimens reached their maximum test-loading capacity, plastic hinges formed at the crown, invert, and springlines of the rehabilitated pipes under the two-point loading. The premise of using plastic method is that plastic hinges can be developed, which based on the applied load versus diameter change curves shown in Figure 3, Figure 4 and Figure 5, would seem to be the case because ductile plateaus were seen in each curve (RGC and ERGC).

As mentioned before, RCP and grout formed a composite system, the moments caused RCP to go into compression and the grout nearest the CSP experienced tension at the crown and invert; once the grout cracks, only the RCP remains to take the bending moment. At the springlines, the grout closest to the CSP was compressed, whereas the RCP experienced tension; therefore, the cross-section at the springlines acted like an RC section. As such, an RC approach was used to calculate the plastic moment capacity as described in the research by Smith et al.[9]. This approach conservatively neglects the beneficial effects of the thrust on the moment capacity. The CSP, however, acted independently, when plastic hinges were formed in the RCP and grout, plastic hinges were also formed at the same position in the CSP. So, the maximum test-loading capacity of rehabilitated pipe was equal to the sum of the load-carrying capacity of composite system and that of CSP, whereby the load-carrying capacity was calculated as the load required to form a plastic collapse mechanism.

The maximum applied load, \( F \), can be applied to the pipe can be calculated by

\[
F = F_1 + F_2
\]

\[
F_1 = \frac{M_{pcrown}}{R_{RCP}} + \frac{M_{pinvert}}{R_{RCP}} + \frac{2M_{pspringline}}{R_{RG}}
\]

\[
F_2 = \frac{4M_{pCSP}}{R_{CSP}}
\]

Where \( F \) is the load-carrying capacity of the rehabilitated pipe; \( F_1 \) is the load-carrying capacity of the composite system formed by RCP and grout; \( F_2 \) is the load-carrying capacity of the CSP; \( M_{pcrown} \), \( M_{pinvert} \), and \( M_{pspringline} \) represent the plastic moment capacities of the composite system at the crown, invert, and springlines, respectively; \( M_{pCSP} \) represent the plastic moment capacities of the CSP; \( R_{RCP} \) is the radius of the RCP taken to the centroid of the pipe wall = 660 mm; \( R_{RG} \) is the radius of the composite system taken to the centroid of the pipe wall = 610 mm; \( R_{CSP} \) is the radius of the CSP taken to the centroid of the pipe wall = 512.5 mm;

Since the test-loading capacity of RCP has been tested, the plastic moment capacities of the RCP can be obtained by \( M_{pRCP} = FR/4 = 93.7 \times 0.66/4 = 15.5 \text{ kN} \cdot \text{m} \). According to the above-mentioned plasticity theory, the plastic moment capacities of the rehabilitated pipe at the crown and invert of the pipe is equal to that of the RCP. So,

\[
M_{pcrown} = M_{pinvert} = M_{pRCP} = 15.5 \text{ kN} \cdot \text{m}
\]

At the springlines, RCP and grout formed a composite section, grout experienced compression and RCP experienced tension. The plastic moment capacity can be calculated using a reinforced concrete approach such as the one in the Code for design of concrete structures [16] as given by Eq. (4).

\[
M_{pspringline} = f_y A_s \left( h_0 - \frac{f_y A_s}{2 \alpha_s f_y b} \right)
\]
where \( f_y \) is the yield strength of the steel bar in MPa = 400 MPa; \( A_s \) is area of tensile steel bar in mm\(^2\) = 621.72 mm\(^2\); \( h_0 \) is the effective depth of the composite section in mm = 135 mm; \( b \) is section width of the RCP wall in mm = 1000 mm; \( \alpha_1 = 1.0 \); and \( f_c' \) is the grout compressive strength in MPa = 20.1 MPa.

The plastic moment capacity of the corrugated steel section, \( M_{pCSP} \), can be calculated by

\[
M_{pCSP} = f_{yCSP} Z
\]

(5)

where \( Z \) is plastic section modulus of CSP; and \( f_{yCSP} \) is yield strength of the CSP MPa = 235 MPa. For the CSP used in this experiment, \( Z \) is approximately 26.493 mm\(^3\)/mm.

Using a yield strength of 400 MPa, the \( M_{pCSP} \) is calculated as 32.03 kN \( \cdot \) m. The calculated \( M_{pCSP} \) using the tensile strength of 575 MPa is 45 kN \( \cdot \) m. So, if the yield strength of 400 MPa is used in Eq. (4), then the calculated applied load \( F_1 \) is 152 kN, whereas if the tensile strength of 575 MPa is used, then the applied load \( F_1 \) is 194.5 kN. The calculated \( M_{pCSP} \) using the yield strength of CSP of 235 MPa is 6.23 kN \( \cdot \) m, then the calculated applied load \( F_2 \) is 48.7 kN. The maximum applied load, \( F_1 \), is equal to the sum of \( F_1 \) and \( F_2 \), and the calculated value using the yield strength of steel bars of 400 MPa is 200.7 kN, whereas the calculated value using the tensile strength of steel bars of 575 MPa is 243.2 kN. This calculation result is close to the experimental value 255.94 kN, which shows that this plasticity approach is reasonable for an RCP rehabilitated with grouted CSP.

4.2. Test-loading capacity estimation of vertical eccentric rehabilitated pipe

For a pipe with an identical cross section around its circumference, the positions where plastic hinges were formed are all cross-sections subjected to the largest bending moment. So, these sections are usually simplified into fixed connections, which can bear bending moments. As it is shown in Figure 11a, plastic hinges will be formed at crown, invert and springlines of the concentric rehabilitated pipe under two-point loading, and the calculation model can be simplified to a semi-circular fixed arch.

However, the failure mechanism of a vertical eccentric rehabilitated pipe is different from that of concentric rehabilitated pipe. As it is seen from Figure 10c, two plastic hinges formed still at the crown and invert, but the other two formed at the shoulders of the eccentric rehabilitated pipe, not at the springlines. This is mainly because the thickness varies around its circumference resulting in the different stiffness, the sections with smaller stiffness are easier to form plastic hinges.
Figure 10. Failure mechanism of an eccentric and a concentric rehabilitated pipe: (a) computing model; (b) failure picture of the concentric rehabilitated pipe; (c) failure picture of the eccentric rehabilitated pipe.

The plastic hinges at the shoulders located between the springlines and crown. To simplify the analysis, it is assumed that the central angles between these two plastic hinges are exactly $\pi/2$. Therefore, the arch between these shoulders was taken for theoretical analysis, since the pipe wall in this section was very thin and the bending capacity of the pipe mainly depended on it (see computing model for an eccentric rehabilitated pipe shown in Figure 10a).

The RCP and CSP were in close contact at the thinnest section, and nearly no grout between them. Moreover, the CSP acted independently, so the test-loading capacity of the thinnest section was the sum of the maximum load-carrying capacity of RCP and that of CSP, but the computational model was a quarter circle.

$$F' = F'_1 + F'_2$$

$$F'_1 = 2\sqrt{2} \left( \frac{M_{\text{pCSP}}}{R_{\text{pCP}}} + \frac{M_{\text{pshoulder}}}{R_{\text{pCP}}} \right)$$

$$F'_2 = 4\sqrt{2} \frac{M_{\text{pCSP}}}{R_{\text{CSP}}}$$

Figure 11. Computational model for plastic load-carrying capacity.

Half of a quarter circle was taken and the plastic hinge has been formed, the equilibrium equation was established under this situation (Figure 11) [17]. The following formula can be obtained:
Where $F'$ is the load‐carrying capacity of the vertical eccentric rehabilitated pipe; $F_1'$ is the load‐carrying capacity of the RCP a; $F_2'$ is the load‐carrying capacity of the CSP; $M_{pcrown}$ and $M_{pspringline}$ represent the plastic moment capacities of the RCP at the crown and shoulder respectively; $M_{pCSP}$ represent the plastic moment capacities of the CSP; $M_{pRCP}$ represent the plastic moment capacities of the RCP; $R_{RCP}$ is the radius of the RCP taken to the centroid of the pipe wall = 660 mm; $R_{CSP}$ is the radius of the CSP taken to the centroid of the pipe wall = 512 mm;

Since the test‐loading capacity of RCP has been tested, the plastic moment capacities of the RCP can be obtained by $M_{pRCP}=FR/4=93.7×0.66/4=15.5$ kN·m. The calculated $M_{pCSP}$ using the yield strength of CSP of 235 MPa is 6.23 kN·m (Eq. 5), then the calculated applied load $F'$ is 201.68 kN.

5. Discussion
A plastic approach was used in this research to investigate the calculation method of load‐carrying Capacity of the RCPs rehabilitated with grouted CSPs, the calculation results were shown in Table 1. It can be seen from Table 1, the errors between the calculation results and experimental results were 5.0% for RGC, 8.6% for ERGC and 30.5% for RG. This showed that the plastic approach might be suitable for calculating the load‐carrying capacity of the RCP rehabilitated with grouted CSP. Moreover, the calculated results were lower than the experimental results, which was beneficial to engineering design.

| Type of pipe ring | $F_c$ † (kN) | $F_t$ (kN) | $|F_c-F_t|/F_t$ % |
|------------------|-------------|------------|-----------------|
| RGC              | 243.2       | 255.94     | 5.0             |
| ERGC             | 201.68      | 220.7      | 8.6             |
| RG               | 194.5       | 280        | 30.5            |

† represents the load‐carrying capacity calculated by using the tensile strength of the steel bars. $F_c$ represents the calculated values. $F_t$ represents the experimental values.

It was surprising that the maximum test‐loading capacity of RG was even higher than that of RGC, it was not clear why RG had the highest test‐loading capacity. It may be due to the dispersion of material strength or improper loading, which made its test‐loading capacity higher than other specimens. Nevertheless, the applied load versus diameter change curves of the two specimens basically coincide before the first peak value of RGC. This indirectly reflected that the test‐loading capacity of the rehabilitated system mainly depended on the RCP and grout before the first peak value of the curve. The applied load versus diameter change curve of RG had no second and third peaks, which was due to the lack of CSP. Obviously, the test‐loading capacity between the second and the third peak values was provided by RCP, grout and CSP together. The CSP began to play an important role after the second peak value. In addition, the applied load versus diameter change curve of RGC had obvious strengthen stage (second valley to third peak value) and better ductility than RG.

The CSP indeed act independently based on its section strains, and it was not difficult to imagine that the CSP did not bond with grout because of the CSP was galvanized on both sides.

6. Conclusions
The current investigation was undertaken to examine the performance of the RCPs rehabilitated with grouted CSPs and an approach to estimate the load‐carrying capacity of a rehabilitated pipe. The five specimens were tested in a two‐point loading experiment across the vertical diameter of the pipes. The following key conclusions are drawn from this work:

- The test‐loading capacity of an RCP rehabilitated with grouted CSP mainly depends on the RCP and the grout before the first peak value of the curve, CSP began to play an important role after the
second peak value. The main function of CSP was to improve the maximum test-loading capacity and ductility of the rehabilitated pipe.

- The test-loading capacity of an eccentric rehabilitated pipe was lower than that of a concentric rehabilitated pipe, since the RCP and CSP were in close contact at the invert and lack of grout, which would change the failure mode of the rehabilitated pipe.

- The comparison of the calculated results showed that the plastic approach was reasonable for an RCP rehabilitated grout CSP. Meanwhile, an approach for analyzing a vertical eccentric rehabilitated pipe was proposed based on the plastic approach. The errors between the theoretical results and experimental results were basically less than 30%.

Although the performance of RCPs rehabilitated with grouted CSPs was presented and a method to estimate of the load-carrying capacity of the slip-lined pipes was proposed, there were still some problems that need to be solved further. The experiments were conducted under two-point loading, but the actual working condition is the RCP is buried in the soil. This will cause axial forces in the rehabilitated pipe, how the axial forces affect the load-carrying capacity of the rehabilitated pipes needs to be investigated further. Different thickness of grout rings and types of the host pipes should be also investigated to discuss which approach is more reasonable.

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 (number2015039). 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.(2013) Standard guide for insertion of flexible polyethylene pipe into existing sewers. ASTM F585, West Conshohocken.

[2] Syachrani S., Jeong H. S. D., Rai V., et al. (2010) A risk management approach to safety assessment of trenchless technologies for culvert rehabilitation. Tunnelling Underground Space Technol,25(6): 681-688.

[3] Vaslestad J., Madaj A., Janusz L. et al. (2004) Field Measurements of Old Brick Culvert Slip Lined with Corrugated Steel Culvert. In: 83rd Annual Meeting of the Transportation-Research-Board. Washington.pp. 227-234.

[4] Ballinger C. A., Drake P. G. (1995) Culvert repair practises manual. U.S. Dept. of Transportation, Federal Highway Administration (FHWA), McLean.

[5] Jack Q Zhao, Lyne Daigle.(2001)Structural performance of sliplined watermain. Canadian Journal of Civil Engineering, 28(6): 969-978.

[6] McAlpine G. (2006) Structural rehabilitation of semi elliptical concrete sewers. In: Pipelines: Service to the Owner, Reston, 2006:1-7.

[7] Ed.Swindon.(2001) Sewerage rehabilitation manual .WRC (Water Research Centre) , U.K.

[8] SnapTite. (2013) Design guide.http://www.culvert-rehab.com/pdfs/2013_manual.pdf.

[9] Smith T., Hoult N. A., Moore I. D. (2015) Role of grout strength and liners on the performance of sliplined pipes. J. Pipeline Syst. Eng. Pract., 6(4): 04015007.

[10] Moore I. D., Garcia D. B. (2015) Ultimate Strength Testing of Two Deteriorated Metal Culverts Repaired with Spray-On Cementitious Liners. Transportation Research Record, 2522(1):139-147.

[11] Garcia D. B., Moore I. D. (2015) Performance of deteriorated corrugated steel culverts rehabilitated with sprayed-on cementitious liners subjected to surface loads. Tunnelling and Underground Space Technology, 47: 222-232.
[12] Simpson B., Moore I. D., Hoult N. A. (2016) Experimental Investigation of Rehabilitated Steel Culvert Performance under Static Surface Loading. J. Geotech. Geoenviron. Eng., 142(2): 04015076.
[13] Simpson B., Hoult N. A., Moore I. D. (2017) Rehabilitated reinforced concrete culvert performance under surface loading. Tunnelling and Underground Space Technology, 69: 52-63.
[14] Tetreault J., Hoult N. A., Moore I. D. (2018) Pre- and post-rehabilitation behaviour of a deteriorated horizontal ellipse culvert. Canadian Geotechnical Journal, 55(3): 329-342.
[15] CSA.(2004). Design of concrete structures. Standard CAN A23.3-04, Canadian Standards Association, Rexdale.
[16] Tetreault J., Hoult N.A., Moore I. D. (2018) Pre- and post-rehabilitation behaviour of a deteriorated horizontal ellipse culvert. Canadian Geotechnical Journal, 55(3): 329-342.
[17] Liu H. W.(2004) Mechanics of materials (I), 4th ed. Higher Education Press, Bei Jing.