Study on calculation method of new corrugated steel reinforcement structure of highway tunnel

Chengshuo Yu1,2, Wenqi Ding1,2, Tianxiang Wu1,2 and Qingzhao Zhang1,2,*

1Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China
2Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China
*Corresponding author’s e-mail: zqz0726@163.com

Abstract. Corrugated steel, a new structure, shows great advantages in many fields, however, it is rarely used in the reinforcement of highway tunnels. Besides, corresponding design method and mechanical properties are still not clear yet. In this study, a full-scale test is carried out to explore the calculation method of corrugated steel as a new reinforcement structure. Combining with numerical simulation and theoretical calculation, the load-deflection law of corrugated steel is revealed, which has a two-stage stiffness characteristic (anti-backlash stage and elastic stage). Equivalent stiffness coefficient is proposed to establish a simplified calculation method of the equivalent stiffness of corrugated steel. And RDP (Ratio of Depth to Pitch) is the main factor affecting the equivalent stiffness coefficient.

1. Introduction

In recent years, with the continuous development of highway transportation infrastructure, highway tunnels have been approved by more and more road designers [1]. By the end of 2018, there were 17738 highway tunnels in China, totaling 17236.1 kilometers. Highway tunnels play an important role in transportation infrastructure. However, due to the complexity of operation and maintenance of highway tunnels, and natural or man-made disasters that may occur, the safety of public traffic of highway tunnels is seriously affected and service life is reduced[2]. Therefore, it has become a research hotspot on how to find a fast and effective reinforcement structure to reinforce the damaged highway tunnels and prolonging their service life.

Corrugated steel, as a new type of reinforced structure, shows great advantages, such as convenient construction, good adaptability, excellent durability, easy maintenance and replacement. At present, corrugated steel structure has been widely used in bridge, shed and culvert, comprehensive pipe gallery and other fields. Many studies have been conducted to explore the application and mechanical mechanism of corrugated steel. Han C.G. and Luo X. explored the influence of the upper fill material of steel corrugated structure in reinforcement of bridge structure [3]. Xu J.S. et al verified the technical feasibility and safety reliability of the fabricated corrugated steel in the engineering of shed structure construction[4]. Peng L. and Zhang Y. et al investigated the effects of corrugated steel corrugation parameters, soil elastic mode, asymmetric filling, and uneven foundation settlement on the stress and deformation of pipe culvert, based on the actual pipe culvert engineering [5]. Chan C.L carried out a test to explore the bearing capacity of corrugated steel sheets under different working conditions, such as widths, thicknesses and radius. And influence on the overall performance of corrugated steel was...
obtained [6]. However, corrugated steel is rarely used in the reinforcement of highway tunnels, and the corresponding design method and mechanical properties are still not clear yet. This study provides a technical support for the stress process, deformation law and calculation methods of the corrugated steel used as a new reinforcement structure of highway tunnel through full-scale test (FST) and numerical simulation.

2. Full-scale test

2.1. Specimen design

The corrugated steel used as reinforcement structure is Q235 steel plate, whose cross-section parameters are $D_{ep} \times \text{Pitch} \times \text{Thickness} = 380 \text{mm} \times 140 \text{mm} \times 5 \text{mm}$, Figure 1(a). The size of the corrugated steel plate is designed as $l \times b \times h = 1630 \text{mm} \times 830 \text{mm} \times 150 \text{mm}$, Figure 1(b) and Figure 1(c).

Because of the complexity of the shape of corrugated steel plate, channel steel installed at both ends of the corrugated steel plate is designed to ensure that it can be subjected by uniform force under horizontal loading. Cylindrical steel bars are placed under the channel to provide constraints, simplifying the constraints of the corrugated steel plate as simply supported beams, Figure 2.

![Corrugated steel specimen cross-section parameters (mm)](image1)

![Corrugated steel plate](image2)

![Corrugated steel plate size (mm)](image3)

Figure 1. Details of corrugated steel specimen selection and plate size

2.2. Loading equipment and mode

TJ-GPJ1300 three-dimensional structural mechanical property test system of Tongji University is used, which consists of a reaction frame, a horizontal loading system, a vertical loading system, a distribution beam and a rolling support (Figure 2). The horizontal axial load $N_4$ is $5kN$ applied by the horizontal jack. One-way loading mode is adopted in vertical loading process, which means that there is no unloading process during the FST until the specimen is destroyed.
2.3. Measuring system

Measurement contents of key geometric and mechanical information such as load and deflection are arranged to capture mechanical response process of corrugated steel plate in test conditions. Deflection measuring points are set at the bottom center span of the corrugated steel plate, including 5 vertical displacement measuring points in the corrugated steel wave crest and trough. There is a spacing of 190 mm between two adjacent YHD-100 slide bar displacement meters (Figure 3).

![Figure 2](image1.jpg)

**Figure 2.** Details of loading system in corrugated steel FST

![Figure 3](image2.jpg)

**Figure 3.** Layout of measurement system in corrugated steel test

3. Test results and numerical simulation

3.1. Data processing

Grading loading method is adopted in the test. Servo jack system and vertical displacement meters are used to measure the force of the two jacks (F1 and F2) and cross-center deflections of corrugated steel after each stage of loading. According to the FST, vertical load-deflection relationship is obtained as shown in Figure 4. Data of vertical displacement meters D2, D3 and D4 are reserved, discarding that of D1 and D5, in the subsequent analysis for accurately reflecting mechanical response of corrugated steel.
3.2. Numerical simulation and analysis

Numerical simulation is carried out to mutual verify FST based on ABAQUS 6.14. Corrugated steel, which is the same model and size as FST, is simulated by shell element. Channel steel is simulated by solid element. The channel and corrugated steel are connected by bonded contact (Tie). Vertical load that is consistent with the actual jack data is achieved by loading the reference point. Joint deflections of the D2, D3, and D4 measuring points in the finite element model is extracted (Figure 5). Combined with the mechanical test data above, the comparison between the numerical simulation and mechanical test is represented in Figure 6.

Figure 6 shows that the vertical load-deflection curve of full-scale mechanical test has a two-stage stiffness characteristic, which are anti-backlash stage and elastic stage, according to different slopes of the curve. Anti-backlash stage is because of the existence of gap between corrugated steel specimen and the loading system. The initial loading force is mainly used to eliminate the inelastic deformation, which
means that applying less force will result in a larger deflection. When the gap in the anti-backlash stage is compacted, the specimen comes to the elastic stage. At this stage, the corrugated structure actually starts to show overall performance.

Vertical load-deflection curve of numerical simulation is substantially parallel to the vertical load-deflection line of the elastic stage of the mechanical test (Figure 7). When the vertical force is $\Delta F=20kN$, the mid-span deflection is $\Delta w_e=0.799\text{mm}$ (calculation of numerical simulation); $\Delta w_e=0.802\text{mm}$ (calculation of mechanical test). The difference between the two deflections is small, and the error is only 0.38%, which means that it is reliable to calculate the stiffness of the corrugated steel specimen by numerical simulation.

4. Equivalent stiffness coefficient of corrugated steel

4.1. Proposal of equivalent stiffness coefficient

Refer to the "Corrugated Steel Embedded Structure Design and Construction Manual" [7], theoretical moment of inertia of corrugated steel can be obtained. For instance, the theoretical moment of inertia of corrugated steel $380\times140\times5\text{mm}$ is $15117.8\text{mm}^4/\text{m}$, and the theoretical stiffness is $3023.6\text{kN} \cdot \text{m}^2/\text{m}$. According to the Equation (1), increment of midspan deflection of corrugated steel can be calculated as $\Delta w_{\text{theory}}=1.05\text{mm}$.

$$w_{\text{theory}} = \sum \int \frac{MM_p}{EI} ds$$

(1)

Real deflection can be calculated by numerical simulation as a reference value. Under the vertical force load increment $\Delta F=30kN$, the actual mid-span deflection of the corrugated steel can be calculated as $\Delta w_{\text{true}}=1.20\text{mm}$. The error between $\Delta w_{\text{true}}$ and $\Delta w_{\text{theory}}$ of the corrugated steel is up to 14%, so the theoretical stiffness cannot be simply regarded as the actual corrugated steel. Therefore, the concept of "equivalent stiffness coefficient" of corrugated steel is presented to revise theoretical calculation formula. Corresponding amendments are made to the theoretical calculation formula as Equation (2).

$$w_{\text{true}} = \sum \int \frac{MM_p}{\eta EI} ds$$

(2)

In summary, by jointly solving Equation (1) and Equation (2), the formula for calculating the "equivalent stiffness coefficient" of corrugated steel is

$$\eta = \frac{w_{\text{theory}}}{w_{\text{true}}} = \frac{\Delta w_{\text{theory}}}{\Delta w_{\text{true}}}$$

(3)

4.2. Establishment of the equivalent stiffness coefficient table

Different types of corrugated steel has different equivalent stiffness coefficients. Through numerical calculation, equivalent stiffness coefficients of various types of corrugated steel are obtained (Table 1). A simplified calculation method of the actual corrugated steel stiffness can be obtained by the way of multiplying by its theoretical stiffness.
Table 1. General equivalent stiffness coefficient of corrugated steel sheet

| Thickness (mm) | Pitch-Depth (mm) | 150-50 | 200-55 | 300-110 | 380-140 | 400-150 |
|---------------|-----------------|--------|--------|---------|---------|---------|
| 3             | 1.008           | 1.008  | 0.897  | 0.826   | 0.780   |
| 4             | 1.001           | 1.005  | 0.924  | 0.849   | 0.811   |
| 5             | 0.994           | 1.000  | 0.928  | 0.879   | 0.850   |
| 6             | —               | 0.996  | 0.929  | 0.883   | 0.856   |
| 7             | —               | 0.991  | 0.934  | 0.885   | 0.864   |
| 8             | —               | 0.986  | 0.932  | 0.893   | 0.875   |
| 9             | —               | 0.980  | 0.929  | 0.892   | 0.879   |
| 10            | —               | 0.975  | 0.927  | 0.890   | 0.881   |

4.3. Influencing factors and changing rules

Equivalent stiffness coefficient of corrugated steel is mainly affected by two factors, which are thickness and depth-pitch as shown in Table 1. They mean wave fluctuation of the corrugated steel. To obtain the variation law of the equivalent stiffness coefficient of corrugated steel conveniently, the concept of "RDP" (Ratio of Depth to Pitch) of corrugated steel is proposed as Equation (4).

\[ RDP = \left( \frac{\text{Depth}}{\text{Pitch}} \right) \times 100\% \]  

Larger wave pitch and higher wave depth don’t necessarily mean more undulation of the corrugated steel, however, RDP can characterize the undulating shape better. Hence, the fact that wave thickness and RDP are two main factors influencing the general equivalent stiffness can be obviously obtained.

Figure 7 shows that when wave thickness is constant, the higher RDP is, the smaller equivalent stiffness coefficient is, which means that the undulation of the corrugated steel has a negative effect on the stiffness. Besides, RDP is the main factor affecting the equivalent stiffness coefficient. When RDP is larger than 0.333, there is a positive correlation between equivalent stiffness coefficient and wave thickness; When RDP is less than or equal to 0.333, there is a negative correlation between equivalent stiffness coefficient and wave thickness.

5. Conclusion

1) Vertical load-deflection curve of the corrugated steel plate specimen has a two-stage stiffness characteristic (the anti-backlash stage and elastic stage) in FST. And the reliability of numerical simulation of the corrugated steel sheet is verified in elastic stage.

2) A simplified calculation method for equivalent stiffness of corrugated steel is proposed. The actual stiffness of the corrugated steel plate can be calculated by multiplying the equivalent stiffness coefficient by theoretical stiffness. Equivalent stiffness coefficient of corrugated steel can be consulted in Table 1.
3) Law of variation of equivalent stiffness coefficient is obtained. It shows that RDP is the main factor affecting the equivalent stiffness coefficient. The higher RDP is, the smaller the equivalent stiffness coefficient is.

Acknowledgments
This project is financially supported by National Key R&D Plan Project (No.2017YFC0806004, China) and Research on Key Technology of Quick Initial Support Structure for Corrugated Steel Assembly of Highway Tunnel (Tongji University Scientific Project, China).

References
[1] Liu, Y.C. (2018) Numerical Simulation Study on Reinforcement Countermeasures of Expressway Tunnel Lining. Xi'an University of Technology, Xi'an.
[2] Yu, C.S., Ding, W.Q., Zhang, Q.Z. (2018) Research on Calculation Method of Damage Evaluation of Existing Urban Tunnel Lining Structure. Modern Tunnel Technology, 55(05):11-18.
[3] Han, C.G., Luo, X. (2016) The Research of Corrugated Sheet Steel Bridge Structure Reinforced Based on the Change of the Soil Characteristics. Journal of Jiaying University, 34(11):46-52.
[4] Xu, J.S., Li, G.Z., Li, L., Jiang, H., Li, W.H. (2018) Preliminary Research on the Arch Shed-Tunnel Structure with Assembly Corrugated Steel. Modern Tunnel Technology, 55(S2):1091-1098.
[5] Peng, L., Zhang, Y., Mu, C., Gong, J.F. (2016) Analysis and Test of Mechanical Properties of High Filled Large Span Steel Bellows. Chinese and Foreign Roads, 36(06):103-108.
[6] Chan, C.L. (2002) Finite element analysis of corrugated web beams under bending. Journal of Constructional Steel Research, 58:1391-1406.
[7] Yu, S.X. (2014) Corrugated Steel Embedded Structure Design and Construction Manual. People's Communications Publishing Co., Ltd., Beijing.