Numerical simulation and mechanical analysis of square corrugated steel pipe gallery with different top angle

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Abstract: To investigate the load and stress characteristics of the underground square arch gallery, a numerical model was proposed. Equivalent stress, lateral displacement and vertical displacement of the structure of different angles were discussed, with the increase of filling height, and the appropriate section angle was selected according to the variation rules of the stress. The results show that the maximum Mises equivalent stress is lower when the top Angle is 50° than that of the other two top angles. The maximum transverse displacement is the smallest when the pipe top Angle is 50°, and the structure has a better ability to resist the transverse displacement.

1. Introduction
With the rapid development of the city, the traditional buried pipelines no longer meet its needs, and it is an inevitable trend to promote the development of underground structures. Since 2013, the Ministry of Housing and Urban-Rural Development, Development and Reform Commission and other relevant departments have successively issued documents to propose support for underground structures. As a good material, corrugated pipe has the advantages of simple construction, short construction period and wide application range. And due to the existence of the axial corrugation, the stress concentration of the upper load can be better dispersed. Therefore, the application prospect of corrugated steel pipe corridor in our country is very broad[1-3,12].

At present, there are many research results on corrugated steel pipes with circular and tubular arch sections. Peng Li[4] relied on actual engineering to influence the parameters of circular corrugated pipe culverts with high fill and large span, and proposed to use AASHTO to design pipe soil pressure; T Elshimi, Kyong Y.Y., Demian Beben[5-7] Other scholars established two-dimensional and three-dimensional models of corrugated steel structures, applied shock waves to intervene in radar detection of built culverts, and analyzed the mechanical performance. However, there is little research on the square arch section in China. The square arch corrugated steel pipe corridor has a larger effective use of space, compared with the round section, the arch height is lower, and the clearance is smaller. In order to enrich the section types of corrugated steel pipe corridors in my country, it is necessary to perform finite element simulation calculation analysis on the section. Through the finite element calculation of...
the corrugated steel pipe corridor with square arched cross-section, the stress distribution law and the transverse and longitudinal strain law of the corrugated steel pipe of the cross-section are obtained; effective protective measures for this cross-section form are obtained. And give reasonable suggestions in the actual project.

2. Section type
The pipe gallery mainly bears the pressure of the upper soil column on the structure. For the whole structure, the arch crown radian is very important. Therefore, the arch crown angle (θ) is a key parameter for the stress of the whole structure. Through the change of the vault angle, corrugated steel pipes with different vault angles are designed, as shown in figure 1.

3. Establishment of numerical model
In order to establish a more close to the actual situation of the square arch corrugated pipe gallery finite element model, some cases that can not be simulated in the finite element method are simplified. The interaction between corrugated steel structure and soil adopts node coupling mode. The element type of corrugated steel pipe is shell element[11], and the element type of soil body is hexahedron 8-node solid element. The order of mesh generation for the whole model is as follows: Firstly, the corrugated steel pipe is divided into quadrilateral elements, and the aspect ratio of each element should be approximately 1, as shown in figure 2. Then the soil body around the pipe is divided and the quality of the grid is checked. Finally, the pipe gallery model is assembled.

3.1. Material and physical parameters
The whole structure is divided into two parts: pipe gallery and soil. The soil body is divided into fill stratum, sand cushion and foundation layer. The thickness of sand cushion and foundation layer is 1m respectively, and the process of soil backfill is realized with the help of finite element software. The material parameters are shown in Table 1.

| Material          | Elasticity Modulus | Density (kg·m$^{-3}$) | Poisson's |
3.2. Boundary conditions

The wave shape of square arch corrugated pipe is 190mm × 70mm, the wall thickness of bellows is 7mm, and the center angle of arch ring is 50°, 60°, and 70° respectively. The boundary conditions of the model are simulated according to compaction[8], as shown in figure 3, that is, the bottom surface of the soil is fully fixed (all DOF), and the two sides of the soil body are fixed, \( U_Y = U_X = 0 \). In this paper, only the dead load is considered, and the vertical pressure of the soil is applied by layered backfill. Referring to Saint Venant's principle, the local pipe body with six wavelengths is selected for modeling[9], and Mohr-Coulomb criterion is used for calculation of backfill, cushion and foundation layer in finite element software[10].

![Figure 3. Boundary conditions for complete compaction of soil layers.](image)

3.3. Load cases

The backfill is filled in 8 times, and the filling process is realized by the life and death element method in the finite element software. As shown in Table 2, the first four times are backfilled to 4m at the top of the pipe, and then every 2m interval is backfilled until the filling height reaches 12m. The overall working condition is shown in figure 4.

| Load case | Fill height (m) | Load case | Fill height (m) |
|-----------|-----------------|-----------|-----------------|
| ①         | 1.5             | ⑤         | 6               |
| ②         | 1.9             | ⑥         | 8               |
| ③         | 3               | ⑦         | 10              |
| ④         | 4               | ⑧         | 12              |
4. Results and analysis

For square arch corrugated steel, take symmetry axis point 1-point 7, as shown in figure 5.

Figure 5. Arrangement of measuring points for corrugated steel tubes.

The square arch is an axisymmetric model, so half of the cross section is taken as the research object. Each measuring point rotates anticlockwise from the top of the pipe to the official bottom, and the angle between points 1-7 is 30° when the measuring point position is selected. By analyzing the Mises equivalent stress and transverse and longitudinal deformation of each measuring point, the optimal section is found.

4.1. Tube Mises stress of different top angle

Based on the finite element calculation, the variation of Mises stress around the square arch corrugated pipe with three angles of 50°, 60° and 70° pipe top angle with the filling height and the pipe vault angle is analyzed, as shown in figure 6.
It can be seen from figure 6 that with the change of the number at the wave crest, the Mises stress around the pipe decreases first and then increases when the filling height is 1.5m, 1.9m, 3m and 4m. The Mises stress around the corrugated pipe with 6m, 8m, 10m and 12m filling height decreases first, then increases, then decreases and finally increases. It shows that the effect of the square arch corrugated steel pipe in the early stage is small, but as the filling load continues to increase, there is a "Hump" at point 3, which indicates that the filling has a greater impact on the shoulder of the corrugated pipe. It is also found that the growth is weakened at point 6-7, which indicates that the soil extrusion around the bottom of the pipe gallery is gradually weakened. Compared with the three angles, when the pipe top angle is 50°, the maximum Mises stress is lower than the other two sections, which indicates that the soil load does not increase with the increase of pipe top angle. The greater the component force in the x-axis direction, the more obvious the effect on the shoulder of pipe gallery.

4.2. Vertical displacement of different top angle
With the increase of filling height, the maximum vertical displacement of bellows decreases at first and then increases, as shown in figure 7. When the filling height is 3m, the maximum vertical displacement of the three sections is the minimum, and the minimum value is 2.28mm when the pipe top angle is 70°. Comparing the three sections, it is found that the vertical displacement is the largest when the pipe top angle is 50° and the minimum when the pipe top angle is 70°. It shows that the square arch corrugated steel pipe with 70° pipe top angle has the most advantages in resisting vertical displacement.

When the filling height is fixed, the maximum vertical displacement is almost the same when the filling height is 1.5m-4m; when the filling height is more than 4m, the maximum vertical displacement
presents a downward trend. It shows that the effect of filling load on the square arch bellows is small at the beginning of filling. However, if it exceeds its specific height, it will have a great impact on the structure itself.

Figure 7. Variation of vertical displacement with different filling height.

Figure 8. Variation of vertical displacement with different pipe tip angle.

4.3. lateral displacement of different top angle

As the fill height increases, it can be seen from figure 9 that when the pipe top Angle is 60°, the maximum lateral displacement reaches 58mm, and the maximum lateral displacement is in an increasing trend. Compared with the maximum vertical displacement of the bellows, the "V" type change did not occur at the stage of filling height not exceeding 4m. It shows that the horizontal component of soil load has a great influence on the structure at the initial stage of filling, and the structure is mainly squeezed by the soil. From the Angle of pipe tip analysis, it is found that its regularity is not obvious, and the influencing factors are not unique.

Figure 9. Variation of lateral displacement with different filling height.

Through comparative analysis of figure 8 and figure 10, when the fill height is greater than 4m, the maximum lateral displacement of the structure first increases and then decreases. When the fill height is no more than 4m, the transverse displacement tends to be consistent.
5. Conclusion

(1) Low fill soil has little influence on the structure itself. When the soil is filled high, the equivalent stress is mainly between points 3 and 6-7, that is, the pipe shoulder and the bottom of the waist. Specific soil mass should be used for buckfilling and compaction should be noted.

(2) When the filling height is no more than 4m, the equivalent stress around the pipe first decreases and then increases. When the fill height exceeds 4m, the equivalent stress around the pipe decreases first, then increases, then decreases, and finally increases. The maximum Mises equivalent stress was significantly lower when the top angle was 50° than that of the other two angles.

(3) With the increase of filling height, the maximum vertical displacement decreases first and then increases. When the top Angle is 50°, the vertical displacement is the maximum. When the pipe top Angle is 70°, the vertical displacement is minimum. Bellows with a top Angle of 70° have more advantages when resisting vertical deformation.

(4) When the filling height is greater than 4m, the maximum lateral displacement of the structure first increases and then decreases. The maximum transverse displacement is the smallest when the pipe top Angle is 50°, and the structure has a better ability to resist the transverse displacement.

(5) The square arch bellows has the advantages of various cross section forms, but in practical engineering applications, it is very important to select the appropriate pipe Angle.

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