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Stress Analysis of Surrounding Rock of Rectangular Pipe Gallery in Mountain City

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Abstract. In this paper, the basic methods and principles of complex variable function to solve the excavation problem of caverns in single connected domain are studied. Based on the basic principle of conformal transformation and the engineering practicability, the problem of excavating rectangular section single warehouse pipe gallery in a single rock stratum is simplified as a semi-infinite plane rectangular hole problem. The rectangular hole problem is transformed into an equivalent circular hole by conformal transformation. A simplified calculation model of the extruding rectangle comprehensive pipe gallery is proposed and its surrounding rock stress calculation formula is deduced. Combined with the example of mountainous city comprehensive pipe gallery project, Theoretical calculation and numerical simulation show that the surrounding rock stress of the comprehensive pipe gallery is close, which verifies the applicability of the simplified formula. The structural design and construction design of rectangular integrated pipe gallery provide theoretical support. Comparing the stress of surrounding rock of different width pipe gallery, it is found that the stress concentration degree at the top corner of the rectangular pipe gallery increases with the increase of the width of the pipe gallery. The width of the excavation of the rectangular pipe gallery must be strictly controlled during construction.

1. Introduction

At present, the most comprehensive section form of the pipe gallery is rectangular section. Most of the construction methods are open-cut method. In some special sections, the excavation construction method is used to assist. In the mountainous city, combining the open-cut method with the under-cut method are used more in the construction of the rectangular integrated pipe gallery [1]. Wang [2] studied the feasibility and advantages of the integrated design of large tunnels and comprehensive pipe galleries; Yang and Feng [3] conducted a theoretical study on the safety distances of various pipelines in the integrated pipe gallery. Combined with the spatial interaction model, the negative power law distance attenuation curve is used to establish the safety distance model between the pipelines in the pipe gallery. The model is applied to the examples of pipe gallery engineering to verify the practicability of the model. Due to the special section form, the surrounding rock force and displacement of the rectangular integrated pipe gallery have unique characteristics, which have an important influence on the supporting form and structural arrangement [4]. Many domestic and foreign scholars have carried out in-depth research on the design and construction of the integrated pipe gallery with circular section, and given reasonable calculation methods and research methods for the stress distribution of the surrounding rock of the pipe galleries [5]. Yang, Wang et al. [6-9] used the mathematical method of complex variable function to derive the surrounding rock pressure of shallow tunnels. Huang, Wang, Wang et al. [10-12] used numerical simulation to reveal the variation of surrounding rock pressure caused by tunnel construction and give methods and parameters for numerical simulation of surrounding rock pressure. Lu[13] used the optimization method of the hybrid penalty function to transform the surrounding rock pressure into a double-pass domain by mapping the closed integral support of non-circular roadway conformally into a circular domain; Zhu and Qian[14] took the calculation and analysis of the arbitrarily shaped cavity mapping function as the starting point, combined with the elastic mechanics analysis method, the solution was solved by means of the computer program, which expands the scope and prospect of solving the underground cavern, and makes full use of the complex mapping function to solve surrounding rock pressure of underground caverns of any complex shape. Chen, Tang et al. [4] used the complex variable function to get the elastic analytical results of surrounding rock in rectangular roadways to find the influencing laws of the roadway aspect ratio and side pressure on the surrounding rock stress of rectangular-section roadways. Although these research calculation methods are relatively mature, most of them need to be calculated by computer programming, and no intuitive simplified calculation formula is given. Due to the limited computer level of on-site construction management personnel, the existing research results are not directly applicable to the project. In this paper, the solution of the surrounding rock stress of the rectangular pipe gallery is simplified and the simplified calculation formula is derived, which is convenient for the on-site construction personnel to judge the safety state of the surrounding rock during the construction process.

2. Simplified calculation model for rock pressure around pipe gallery

2.1. Simplified model

According to the characteristics of mountainous cities, the underground tunnels have strong self-supporting ability when they traverse the rock stratum with good surrounding rock. Using the conformal transformation and the elastic mechanics complex function to solve the solution principle, the surrounding rock stress can be solved by the following formula.

$$\sigma_V=\gamma H \qquad \sigma_H=\gamma\left(H+\frac{1}{2H_t}\right)\tan^2\left(45^\circ-\frac{\varphi_c}{2}\right) \tag{1}$$

The side pressure coefficient can be taken as:

$$\lambda=\frac{\sigma_H}{\sigma_V}=\left(1+\frac{1}{2H*H_t}\right)\tan^2\left(45^\circ-\frac{\varphi_c}{2}\right) \tag{2}$$

Among them:

σ_H -horizontal pressure

σ_v -plumb pressure

$2b$ - the width of the outer contour of the rectangular integrated pipe gallery

2h - the height of the outer contour of the integrated pipe gallery

γ -the average gravity of the rock and soil

H -the buried depth of the integrated pipe gallery

H_t -the height of the section of the integrated pipe gallery

λ-the side pressure coefficient of the rock and soil body

φ_c -the calculated friction angle of the rock mass

2.2. Conformal transformation

According to the basic idea of solving the stress problem of the plane hole of elastic mechanics according to the complex variable function, the rectangular domain problem can be transformed into a circular domain by conformal transformation, which is convenient for calculation and calculation, as shown in figure 1.

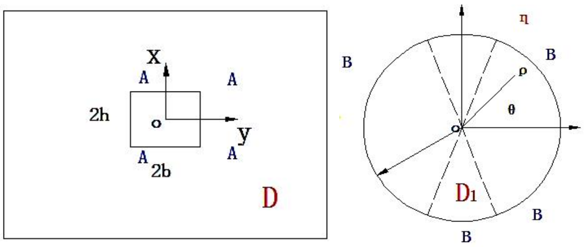


Figure 1. The conformal transformation of rectangle integrated pipeline.

Firstly, at the centroid of the rectangular integrated pipe gallery, the Cartesian coordinate system o-xy with this point as the origin is established; and the plane where the plane is located is the Z plane, and the area where the surrounding rock of the rectangular integrated pipe gallery is located is the area D. By the conformal transformation, the region D is mapped to the unit circle field with the ζ =0 as the center on the ζ plane, and as D_1 .

According to the basic knowledge of the conformal transformation of the single hole problem of the elastomer, we use $\zeta=\rho e^{i\theta}$ at any point in the ζ plane. According to Schwarz-Kritofel's research method of mapping, the following general form of conformal transformation can be used:

$$\omega = K\int\left[\left(z-x_1\right)^{\frac{\alpha_1}{\pi}-1}\left(z-x_2\right)^{\frac{\alpha_2}{\pi}-1}\cdots\left(z-x_k\right)^{\frac{\alpha_k}{\pi}-1}\cdots\left(z-x_n\right)^{\frac{\alpha_n}{\pi}-1}\right]dz + C \tag{3}$$

Where α_1,x_1 、 α_2,x_2 … α_n,x_n represent the mapping angle of the polygon and the position of the mapping point respectively. From the theory of complex variable function, the rectangular outer boundary on Z-plane is mapped into the unit circle area on ζ -plane , then the following mapping relation of C=0 can be found through finding the appropriate α and x ,then through sorting and deriving.

$$z = \omega(\zeta) = \mathrm{R}\left(\frac{1}{\zeta} + c_1\zeta + c_3\zeta^3 + c_5\zeta^5 + \ldots\right) \tag{4}$$

Substituted into the complex function expression, the following formula can be obtained according to the mapping correspondence:

$$c_1 = \frac{b-h}{2R}\ ;\quad c_3 = \frac{b+h}{2R} - 1$$

$$R = \frac{\frac{b-h}{2}\cos\theta + \frac{b+h}{2}\cos 3\theta - b}{\cos 3\theta - \cos\theta} \tag{5}$$

$$\left(\frac{b-h}{2}\cos\theta + \frac{b+h}{2}\cos 3\theta - b\right)\left(\sin 3\theta + \sin\theta\right) - \left(\frac{b-h}{2}\sin\theta + \frac{b+h}{2}\sin 3\theta - h\right)\left(\cos 3\theta - \cos\theta\right) = 0 \tag{6}$$

Where b is 1/2 the width of the pipe; h is 1/2 the height of the pipe.

Substituting the values of b and h, θ, c_1, c_3 and R can be respectively obtained, and the relevant parameters of the conformal mapping are obtained.

3. Analytical solution to the pressure of surrounding rock of pipe gallery

3.1. Complex function expression of the pressure of surrounding rock around pipe galleries

It is known from the fundamental principle of the complex variable function to solve the elastic mechanics problem that the planar problem can be represented by the complex potential functions $\varphi(z)$、$\psi(z)$ parsed everywhere in the region. Therefore, it is the main task of solving the complex analytic function that satisfies the given boundary condition that is, solving $\varphi_0(\zeta)$、$\psi_0(\zeta)$、$\varphi(\zeta)$、$\psi(\zeta)$.

First, from the Cauchy integral, if $F(\zeta)$ is continuous and resolved within the unit circle and circumference, then at any point in the circle there is:

$$F(\zeta)=\frac{1}{2\pi i}\int_{\sigma}\frac{F(\sigma)}{\sigma-\zeta}d\sigma \tag{7}$$

At the same time, if it is continuous and parsed outside the unit circle, then at any point outside the unit circle there is:

$$F(\infty)=\frac{1}{2\pi i}\int_{\sigma}\frac{F(\sigma)}{\sigma-\zeta}d\sigma \tag{8}$$

It is known by the boundary conditions:

$$\frac{1}{2\pi i}\int_{\sigma}\left[\varphi_0(\sigma)+\frac{\omega(\sigma)}{\omega'(\sigma)}\overline{\varphi'(\sigma)}+\overline{\psi(\sigma)}\right]\frac{d\sigma}{\sigma-\zeta}=\frac{1}{2\pi i}\int_{\sigma}f_0\frac{d\sigma}{\sigma-\zeta} \tag{9}$$

According to A, B which are continuous and parsed, the following expression can be got:

$$\begin{aligned}&\frac{1}{2\pi i}\int_{\sigma}\varphi_0\frac{F(\sigma)}{\sigma-\zeta}d\sigma=\varphi_0(\zeta)\\&\frac{1}{2\pi i}\int_{\sigma}\overline{\psi_0(\sigma)}\frac{d\sigma}{\sigma-\zeta}=\overline{\psi_0(\infty)}=0\end{aligned} \tag{10}$$

Substituting equation (7) into equation (8) yields:

$$\varphi_0(\zeta)+\frac{1}{2\pi i}\int_{\sigma}\frac{\omega(\sigma)}{\omega'(\sigma)}\frac{\overline{\varphi'(\sigma)}}{\sigma-\zeta}d\sigma=\frac{1}{2\pi i}\int_{\sigma}f_0\frac{d\sigma}{\sigma-\zeta} \tag{11}$$

The same can be obtained:

$$\psi_0(\zeta)+\frac{1}{2\pi i}\int_{\sigma}\frac{\overline{\omega(\sigma)}}{\omega'(\sigma)}\frac{\varphi'(\sigma)}{\sigma-\zeta}d\sigma=\frac{1}{2\pi i}\int_{\sigma}\overline{f}_0\frac{d\sigma}{\sigma-\zeta} \tag{12}$$

Where $\psi_0(\zeta)=\int_{\sigma}\frac{\psi_0(\zeta)}{\sigma-\zeta}d\sigma$

From $\varphi_0(\zeta)=\sum_{k=1}^{+\infty}a_k\zeta^k$, it can be obtained:

$$\varphi_0'(\zeta)=\sum_{k=1}^{+\infty}ka_k\zeta^{k-1} \qquad \overline{\varphi_0'(\zeta)}=\sum_{k=1}^{+\infty}k\overline{a_k}\frac{\rho^{2k-2}}{\zeta^{k-1}} \tag{13}$$

After derivation, we can get:

$$\varphi(\zeta)=\alpha\omega(\zeta)+\varphi_0(\zeta)=\alpha\mathrm{R}\left(\frac{1}{\zeta}+c_1\zeta+c_3\zeta^3\right)+a_1\zeta-2\alpha c_3R\zeta^3 \tag{14}$$

$$\psi(\zeta)=(\alpha_1+i\beta)\omega(\zeta)+\psi_0(\zeta)=\frac{\alpha_1R-c_3a_1}{\zeta}-2\alpha R\zeta-\alpha_1Rc_3\zeta^3-\frac{\zeta^4+c_1\zeta^2+c_3}{3c_3\zeta^4+c_1\zeta^2-1}\left(\frac{a_1}{\zeta}-6\alpha c_3R\zeta\right) \tag{15}$$

Therefore:

$$\varphi'(\zeta)=\alpha\mathrm{R}\left(-\frac{1}{\zeta^2}+c_1+3c_3\zeta^2\right)+a_1-6\alpha c_3R\zeta^2 \tag{16}$$

$$\begin{aligned}\psi'(\zeta)=&-\frac{\alpha_1R-c_3a_1}{\zeta^2}-2\alpha R-3\alpha_1Rc_3\zeta^2-\frac{2\left(a_1c_1-6\alpha c_3^2R\right)+4\left(a_1-6\alpha c_3Rc_1\right)\zeta-36\alpha c_3R\zeta^4}{3c_3\zeta^4+c_1\zeta^2-1}\\&+\frac{\left[a_1c_3+(a_1c_1-6\alpha c_3^2R)\zeta^2+(a_1-6\alpha c_1c_3\,\mathrm{R})\zeta^4-6\alpha c_3R\zeta^6\right](15c_3\zeta^4+3c_1\zeta^2-1)}{\zeta^2(3c_3\zeta^4+c_1\zeta^2-1)^2}\end{aligned} \tag{17}$$

$$\Phi(\zeta)=\frac{\varphi'(\zeta)}{\omega'(\zeta)}=\alpha+\frac{\frac{a_1}{R}-6\alpha c_3\zeta}{-\frac{1}{\zeta^2}+c_1+3c_3\zeta^2} \tag{18}$$

$$\Phi'(\zeta)=\frac{\frac{2a_1}{R}\zeta-24\alpha c_3\zeta^3}{-1+c_1\zeta^2+3c_3\zeta^4}-\frac{\left(\frac{a_1}{R}\zeta^2-6\alpha c_3\zeta^4\right)(2c_1\zeta+12c_3\zeta^3)}{(-1+c_1\zeta^2+3c_3\zeta^4)^2} \tag{19}$$

$$\begin{aligned}\psi(\zeta)=\frac{\psi'(\zeta)}{\omega'(\zeta)}=&\frac{1}{R\left(-\frac{1}{\zeta^2}+c_1+3c_3\zeta^2\right)}\\&\bullet\left\{\begin{aligned}&-\frac{\alpha_1R-c_3a_1}{\zeta^2}-2\alpha R-\frac{2(a_1-6\alpha c_3^2R)+(4a_1-6\alpha c_1c_3\,\mathrm{R})\zeta^2-36\alpha c_3R\zeta^4}{3c_3\zeta^4+c_1\zeta^2-1}\\&+\frac{\left[a_1c_1+(a_1c_1-6\alpha c_3^2R)\zeta^2+(a_1-6\alpha c_1c_3R)\zeta^4-6\alpha c_3R\zeta^6\right]\left(15c_3\zeta^4+3c_1\zeta^2-1\right)}{\zeta^2(3c_3\zeta^4+c_1\zeta^2-1)^2}\end{aligned}\right\}\end{aligned} \tag{20}$$

According to the method of curve coordinate expression for the stress components, there is the following formula:

$$\begin{aligned}&\sigma_\varphi+\sigma_\rho=4\mathrm{Re}\left[\Phi(\zeta)\right]\\&\sigma_\varphi-\sigma_\rho+2i\tau_{\rho\varphi}=\frac{2\zeta^2}{\rho^2\overline{\omega'(\zeta)}}\left[\overline{\omega(\zeta)}\Phi'(\zeta)+\omega'(\zeta)\psi(\zeta)\right]\end{aligned} \tag{21}$$

Then, the deduced $\Phi(\zeta)$ 、 $\Phi'(\zeta)$ 、 $\psi(\zeta)$ can be substituted into the above formula to obtain the surrounding rock stress of the integrated pipe gallery in polar coordinates.

3.2. Simplified calculation formula

According to the simplified calculation model of 2.1 and related derivation, combined with the actual and unsupported boundary conditions, it can be seen that at the boundary of the rectangular integrated pipe gallery chambers:

$$\rho=1,\ \zeta=e^{i\varphi},\ \sigma_\rho=\sigma_{\rho\varphi}=0 \tag{22}$$

It can be obtained from the previous derivation:

$$\begin{aligned}\sigma_\varphi&=4\mathrm{Re}[\Phi(\zeta)]=4\mathrm{Re}\left[\alpha+\frac{s_2\alpha-6\alpha c_3e^{2i\varphi}}{-e^{-2i\varphi}+c_1+3c_3e^{2i\varphi}}\right]\\&=4\mathrm{Re}\left[\alpha+\frac{s_2\alpha-6\alpha c_3\cos2\varphi-i6\alpha c_3\sin2\varphi}{c_1+(3c_1-1)\cos2\varphi+i(1+3c_3)\sin2\varphi}\right]\\&=4\alpha+4\frac{(s_2\alpha-6\alpha c_3\cos2\varphi)}{\left[c_1+(3c_3-1)\cos2\varphi\right]^2+(1+3c_3)^2\sin^2 2\varphi}\end{aligned} \tag{23}$$

In the formula, $s_1=c_1+(3c_3-1)\cos2\varphi$, $s_2=2\dfrac{c_1+1+(c_1-1)\lambda}{(c_3-1)(1-\lambda)}$ 。

According to the definition in the previous formula derivation process, c_1、c_3、R are respectively obtained, and substituted into the above formula, the surrounding rock pressure of the rectangular integrated pipe gallery under polar coordinates can be obtained.

4. Calculation and comparison of examples

4.1. Theoretical calculation

Combined with the relevant pipe network specification and actual engineering, the common section size of the single-layer and single-warehouse rectangular integrated pipe gallery is around 3.5m high, with width between 3.5-6m.

For the safety of the geotechnical environment on the surface, the minimum recommended depth of the undercutting integrated pipe galleries refers to the recommended minimum value of adjacent underground pipelines and underground structures (table 1).

Table 1. Rectangular integrated pipeline and minimum spacing table of construction.

Construction method / Adjacent situation	Open-cut construction	Under-cut construction
Integrated pipe galleries and buildings	1.0 m	outer diameter of integrated pipe galleries
Clear distance between integrated pipe galleries and underground pipelines	1.0 m	outer diameter of integrated pipe galleries
Cross vertical distance between integrated pipe galleries and underground pipelines	0.5 m	1.0 m

According to table 1, the minimum distance between the integrated pipe gallery and the building is the outer diameter of the integrated pipe gallery (generally 3~4 m). Therefore, the buried depth of the pipe gallery for theoretical analysis is 3.5m. At the same time, the commonly used section height of 3.5m was taken as the analysis section height, and the four sections with the section width of 3.5m, 4m, 5m and 6m were respectively analyzed.

The example is based on the analysis of the underground comprehensive pipe gallery project of Xincheng District, Nanchuan, Chongqing. The total length of the integrated pipe gallery is 10060 m, and it is crossed at the intersection of several main roads. The traffic flow is large. According to the design and geological survey data, the grade of the surrounding rock of the integrated pipe gallery is

IV. The geometric parameters of the pipe gallery and the mechanical parameters of the surrounding rock are listed in table 2.

Table 2. Calculation parameter table.

parameters	Parameters of pipe galleries			Parameters of rock mass		
	Width 2b /m	Height 2h /m	Buried depth H /m	$\gamma/(kn/m^2)$	φ_c /°	λ
values	3.5/4/5/6	3.5	3.5	23	40	0.22

Because the collapse of the rectangular integrated pipe gallery is mostly located at the side wall and the roof, and because the rectangular integrated pipe gallery and the model have symmetry, only the stress distribution of the surrounding rock in the range of 0° to 90° is analyzed. According to the above parameters, the theoretical values of the stresses in polar coordinates of the four rectangular sections with a height of 3.5 m and a width of 3.5 m, 4.0 m, 5 m and 6 m under unsupported conditions can be obtained, as shown in table 3.

Table 3. Analytical solution of stress of pipe gallery surrounding rock.

Width（m）	Surrounding rock pressure of the pipe galleries（kN/m^2）						
	0	15	30	θ	45	60	90
3.5	-102.31	-127.71	-204.49	-306.11	-306.11	11.89	39.3
4	-108.59	-127.71	-222.12	-339.38	-277.55	20.41	40.37
5	-120.2	-142.77	-255.11	-357.31	-215.15	30.8	41.94
6	-130.08	-155.83	-284.25	-397.97	-162.17	37.64	43.13

In order to facilitate the understanding of the trend of stress change, a coordinate system is established with φ as the angle between the horizontal plane and the centroid of the pipe in the rectangular pipe gallery. The theoretical calculation results are plotted on a graph, and the stress curve can be obtained, which is shown in figure 2.

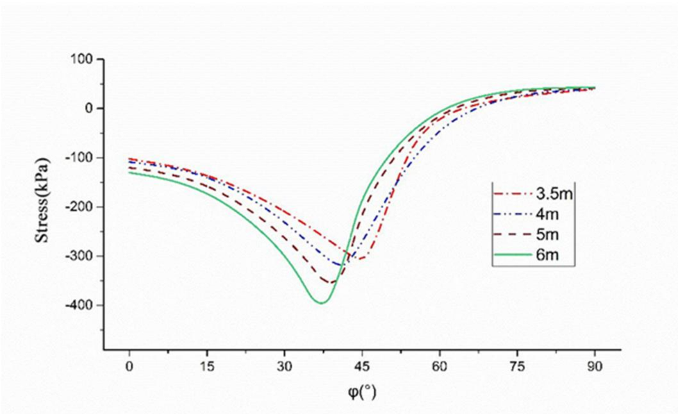


Figure 2. The stress curve of corridor chamber.

According to the curve above, most of the surrounding rock of the rectangular integrated pipe gallery is under pressure, and local tensile stress occurs at the middle of the top plate. In polar coordinates, the surrounding rock pressure of the rectangular pipe gallery is compressive stress at $\varphi=0$ (the middle of the side wall of the pipe gallery) and is the minimum pressure at the side wall. By comparing the four curves, it can be seen that as the width of the rectangular integrated pipe gallery increases, the aspect ratio of the pipe gallery decreases, and the surrounding rock stress of the pipe gallery gradually increases. Especially in the top corner of the figure, not only the stress is getting larger and larger, but also the stress curve is getting steeper. This shows that as the width of the pipe gallery increases, the compressive stress at the top corner of the pipe gallery increases and the stress concentration becomes more obvious. It can be concluded that the width of the integrated pipe gallery is an important determinant of the degree of stress concentration at the apex angle and the maximum stress.

4.2. Comparative analysis for the numerical simulation

In order to verify the rationality of the above assumptions and derivation, the surrounding rock stress of the rectangular cross-section integrated pipe gallery is taken as the research object, and the numerical simulation of the above examples is carried out by using the finite element numerical simulation software according to the theoretical calculation of the example parameters and dimensions.

Take 3B (here take the rectangular integrated pipe gallery excavation width B) to the left and the right from the excavation boundary of the cave, take 3 H_t down (here take the rectangular pipe gallery height) as the size of the model; at the same time, for the convenience of analysis and Observe, the horizontal level is in the X-X direction and the vertical direction is in the Y-Y direction. The calculation model is shown in figure 3.

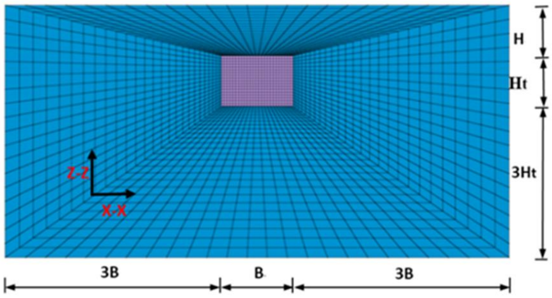


Figure 3. The computational model.

Through numerical simulation, the stress in the X-X and Y-Y directions around the pipe gallery can be obtained. According to the case where the tangential stress around the pipe gallery is zero, the numerical solution of the stress around the pipe gallery can be obtained from the two-dimensional numerical simulation of the rectangular integrated pipe gallery.

$$\sigma = \sqrt{\sigma_x^{\ 2} + \sigma_y^{\ 2} + 2\sigma_x\sigma_y \cos\langle X-X,\ Y-Y \rangle} \tag{24}$$

And $\langle X-X,\ Y-Y \rangle = \pi/2$, yields

$$\langle X-X,\ Y-Y \rangle = \pi/2 \tag{25}$$

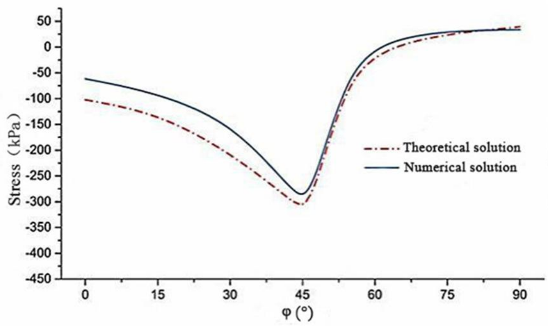
The stress values of the two-dimensional numerical simulation of the rectangular integrated pipe porch with the section form with widths of 3.5m, 5m and 6m can be obtained from the extracted values and the above formula, as is listed in table 4.

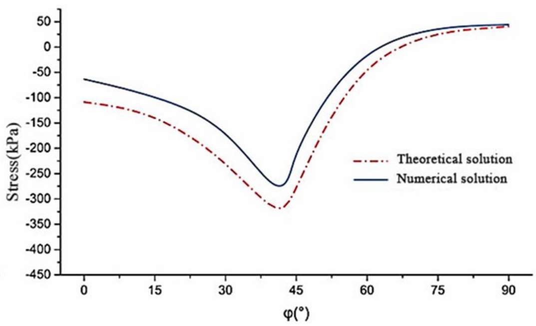
Table 4. Analytical solution of stress of pipe gallery surrounding rock.

Angle (°)	Stress category	Stress (kN/m^2)			
		Width 3.5 m	Width 4 m	Width 5 m	Width 6 m
0.00	σ_{x-x}	-0.27	-0.43	-0.79	-0.99
	σ_{y-y}	-61.70	-63.35	-66.53	-69.54
	σ	-61.70	-63.35	-66.53	-69.55
15.00	σ_{x-x}	-12.91	-14.32	-20.92	-25.97

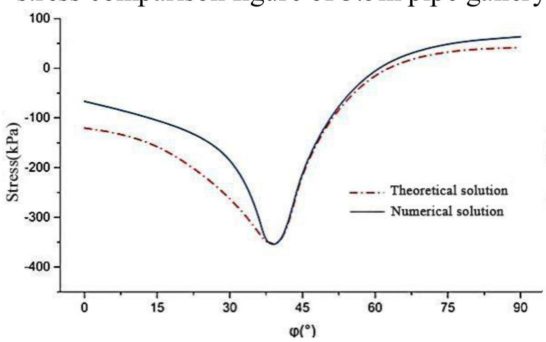
	σ_{y-y}	-87.61	-94.26	-99.29	-107.21
	σ	-88.56	-95.34	-101.47	-110.31
30.00	σ_{x-x}	-24.95	-25.92	-26.78	-30.29
	σ_{y-y}	-143.26	-148.97	-155.32	-158.67
	σ	-145.42	-151.21	-157.61	-161.54
θ	σ_{x-x}	-231.02	-239.42	-269.80	-330.64
	σ_{y-y}	-168.62	-182.05	-238.07	-232.74
	σ	-286.01	-300.80	-359.82	-404.34
45.00	σ_{x-x}	-231.02	-177.35	-149.57	-140.96
	σ_{y-y}	-168.62	-79.51	-68.79	-69.74
	σ	-286.01	-194.36	-164.63	-157.27
60.00	σ_{x-x}	27.61	33.21	39.72	40.95
	σ_{y-y}	7.41	10.75	9.69	14.51
	σ	28.59	34.91	40.88	43.44
90.00	σ_{x-x}	32.37	42.33	60.56	87.69
	σ_{y-y}	10.01	12.80	19.25	26.98
	σ	33.88	44.22	63.55	91.75

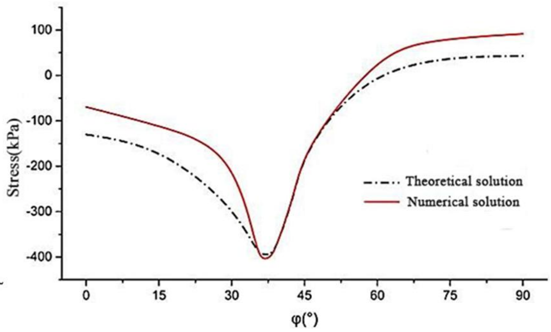
Comparing the numerical solution of the above table with the theoretical solution, the contrast curves of the four sections with widths of 3.5m, 4m, 5m and 6m can be obtained (figure 4).





（**a**）stress comparison figure of 3.5m pipe gallery.（**b**）stress comparison figure of 4m pipe gallery.





（**c**）stress comparison figure of 5m pipe gallery.（**d**）stress comparison figure of 6m pipe gallery.

Figure 4. Stress contrast diagram at the periphery of a tube Gallery.

From the comparison results of the theoretical analysis and numerical simulation of the surrounding rock stress of the rectangular integrated pipe gallery, it can be seen that the stress distribution of the theoretical calculation formula and the numerical simulation of the stress distribution of the rectangular integrated pipe gallery are generally the same. Stress concentration occurs both at the top corner of the gallery's rectangular sections. And the stress value of the same part is also close, the overall performance of the numerical calculation of the stress results is larger than the theoretical calculation results, and the main reasons for this result may have the following factors:

(1) In the theoretical calculation, the load is equivalent to the outer boundary of the model, especially the gravity load directly acts on the top of the model, which is a possible factor that causes the theoretical calculation result to be larger than the numerical calculation result;

(2)There is a certain deviation between the equivalent side pressure coefficient and the actual side pressure coefficient obtained by the formula $\lambda=\frac{\sigma_H}{\sigma_V}=\left(1+\frac{1}{2H*H_t}\right)\tan^2\left(45^\circ-\frac{\varphi_c}{2}\right)$.

Although there are some errors in the analytical solution of the pipe gallery between the theoretical formula and the numerical simulation, the formula can accurately reflect the surrounding rock stress distribution law of the rectangular integrated pipe gallery, and the error with the numerical solution is also within a certain range. And the calculated value is slightly larger than the numerical solution, which can meet the safety requirements of the project. It can be seen that the theoretical calculation formula has relatively strong engineering applicability, which can correctly calculate the stress distribution of the surrounding rock of the rectangular integrated pipe gallery, and has a reliable advantage in terms of safety and simplified calculation.

5. Conclusion

(1) From the view of the engineering application, the single-cylinder integrated pipe gallery with a rectangular section in a single rock layer is simplified into a semi-infinite planar rectangular square hole problem, and it is converted into a circular hole problem by using the conformal change, and then the basic knowledge of the complex variable function is used to derive the simplified calculation formula of the surrounding rock stress of the integrated pipe gallery and analyze the engineering examples.

(2) According to the theoretical calculation example and the selected rock mechanics parameters, a two-dimensional numerical model is established. The surrounding rock stress of the pipe gallery is compared with the theoretical calculation results to verify the applicability of the simplified calculation formula. Although the simplified calculation formula and numerical simulation results of surrounding rock stress have certain errors, the distribution trend and the overall results agree well. It is considered that the simplified calculation formula has certain engineering applicability.

(3) Based on the results of numerical simulation and theoretical calculation, comparing the surrounding rock stresses of four different widths with the width of 3.5m, 4m, 5m, 6m, it is found that the stress concentration at the top corner of the pipe gallery increases with the increase of the width. It is recommended that the width of one excavation of the rectangular pipe section must be strictly controlled during construction.

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