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Research Article

Mechanism of Reinforcement on Inwall of Coal Mine Shaft Wall

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Abstract: Based on the theory of elasticity, the analytic solution of temperature stress on shaft wall of coal mine with reinforcement on inwall is deduced. It is shown that with the increment of reinforcement stress P_a, the radial compressive stress σ_r become larger, the vertical compressive stress σ_z become less, while the circumferential stress σ_θ changed from compressive stress to tensile stress. The stability of shaft wall enhanced with vertical stress reduced by reinforcement on inwall of shaft wall. Compressive steel plate could be used to reinforce the inwall, characterized with low-cost, short time and construction easy. While the intelligent equipment should be developed further to provide everlasting and greater reinforcement on in wall of coal mine shaft wall.

Keywords: Inwall, reinforcement, shaft wall, temperature stress

INTRODUCTION

Recent 20 years, lots of shaft wall of coal mine sequentially broken at mining area of Huaibei, Datun, Xuzhou, Yanzhou of China, which make great influence on the regular production of coal mine (Bi, 1996; Cui *et al*., 1998; Yang and Jiang, 2003). Popularly, the failure surface of shaft wall located at the interface of topsoil and bedrock, characterized with vertical bar inflected, concrete appeared annular transverse cracks, water dripped, sometimes sand ejected, even cage beam bended which make the drain pipe and pressure ventilation pipe longitudinal warping and cage jammed. It is obviously that broken of shaft wall bring severe influence on safety of coal mine (Zhang *et al*., 2008; Liang *et al*., 2010a, b). Currently, there are some methods to repair and prevent broken of shaft wall, such as:

- Digging pressure relief slot. At the key position of shaft wall, steel concrete punched and water stopped firstly, pressure relief slot molded by controlled blasting secondly, compressible Polymer of Vinyl Chloride (PVC) sheets installed in pressure relief slot thirdly, which adapting to the consolidation deformation of stratum. This method has been used in main shaft wall of Haizi coal mine, air shaft wall of Henghe and Baodian coal mine, which obtained good reinforcement effect. The shortcoming of this method is, when the compression deformation of pressure relief slot reached its maximal value, another digging pressure relief slot should be done again. And the passage of cage and lots of pipeline should adapt and bear the compression deformation of shaft wall (Cui, 1998).
- Reinforcement of stratum by injection concrete from hole of shaft wall. In a certain degree, shaft wall is broken by negative friction of stratum, induced by consolidation settlement of topsoil and drainage of mining engineering. Settlement of topsoil could be reduced and stability of shaft wall could be enhanced by reinforcement of stratum by injection concrete around shaft wall from hole of shaft wall. In Datun coal mine of China, the scope of 2. 5 m~ 3. 0 m topsoil around shaft wall had been reinforced by injecting concrete, which keep the stability of shaft wall 2~6 years. The shortcoming of this method is, much of working time of shaft wall of should be used or occupied to do the work of reinforcement (Cui, 1998).
- Reinforcement of stratum by injection concrete from ground. Distinguished with method (2), concrete is injected from ground to reinforce the topsoil around shaft wall. In main shaft wall and auxiliary shaft wall of Baodian coal mine, stability of shaft wall have been reinforced successfully with this method (Liu and Cheng, 2000; Huang *et al*., 2005). The shortcoming of this method is, high cost and long time should be spent.

Sometimes, when the potential failure surface of shaft wall fixed or founded, shaft wall could be

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reinforced inside, which maybe an easy and cheap method. Therefore, the mechanism reinforcement on inwall of coal mine shaft wall has been discussed in this article, which aims to providing a method of reinforcement of shaft wall.

FAILURE CRITERION OF SHAFT WALL

In a certain degree, the concrete of shaft wall is in the state of three-dimensional or two-dimensional compression. The value of compression stress of concrete varied little than 5% when the effect of bar included (Jing and Wang, 2000), so the influence of bar could be ignored, and shaft wall could be treated as pure concrete. Due to concrete is a fragile material and destructed by shear, the Coulomb-Navier failure criterion could be used to simulate the behavior of concrete (Zhou, 1989), described as:

$$\sigma_1\left[\left(1+f^2\right)^{\frac{1}{2}}-f\right]-\sigma_3\left[\left(1+f^2\right)^{\frac{1}{2}}+f\right]=2c \tag{1}$$

where, σ_1, σ_3 is the maximal and minimal principal stress at failure surface respectively, c is the cohesive strength of concrete, $c = (\sqrt{\sigma_c - \sigma_t})/2$, f is the coefficient of internal friction of shaft wall, $f = (\sigma_c - \sigma_t)/(2\sqrt{\sigma_c . \sigma_t})/2$, σ_c and σ_t is the compressive strength and tensile strength of concrete respectively.

A function $F(\sigma_1, \sigma_3)$ could be used to represent the left side of formula (1):

$$F(\sigma_1,\sigma_3)=\sigma_1\left[\left(1+f^2\right)^{\frac{1}{2}}-f\right]-\sigma_3\left[\left(1+f^2\right)^{\frac{1}{2}}+f\right] \tag{2}$$

According to formula (1), when the value of $F(\sigma_1, \sigma_3)$ reached the value of 2c, shaft wall would be failure. So trying to reduce the value of $F(\sigma_1, \sigma_3)$ could enhance the stability of shaft wall. The inwall of shaft wall would be cracked first according to statistic failure phenomena of shaft wall (Jing, 2000a; Wu, 2003). While at inwall of shaft wall, the minimal principal stress $\sigma_3 = 0$, $F(\sigma_1, \sigma_3)$ get its maximal value by formula (2).

Therefore, trying to increase the value of the minimal principal stress ($\sigma_3 > 0$) at inwall of shaft wall by engineering method, would educe the value of $F(\sigma_1, \sigma_3)$ and enhance the stability of shaft wall.

The total vertical stress of shaft wall could be decomposed as vertical stress generated by negative friction of stratum, gravity of shaft wall, earth pressure of shaft wall and temperature stress, as showed in Fig. 1. Where a, b is the inside radius and outer radius of shaft wall respectively, T_a, T_b is the temperature of inside and outside of shaft wall respectively, P_z is the lateral earth pressure on shaft wall, P_a is the stress reinforced on inwall of shaft wall. It can be found that negative friction and gravity of shaft wall are generated vertical stress directly, while lateral earth pressure and temperature stress are distributed at horizontal direction, which generated vertical stress indirectly. Therefore, the vertical stress generated by lateral earth pressure and temperature stress should be got by theoretical analysis.

THEORETICAL ANALYSIS OF TEMPERATURE STRESS

Now the theoretical vertical stress solution generated by horizontal earth pressure and temperature stress, as showed in Fig. 1d, is to be studied. Based on the theory of elasticity, the control formulas of axisymmetrical heat stress problem at plane strain are showed as following (Xu and Liu, 1995):

$$\begin{cases}\sigma_r=-\dfrac{\alpha_f E}{(1-u)r^2}\displaystyle\int_a^r T\cdot rdr+D_1+\dfrac{D_2}{r^2}\\ \sigma_\theta=\dfrac{\alpha_f E}{(1-u)r^2}\left[\displaystyle\int_a^r T\cdot rdr-T\cdot r^2\right]+D_1-\dfrac{D_2}{r^2}\\ \sigma_z=u(\sigma_r+\sigma_\theta)-\alpha_f\cdot E\cdot T\\ \tau_{r\theta}=0\end{cases} \tag{3}$$

where,

E = Young's modulus of shaft wall
u = Poisson's ratio of shaft wall
αf = Expansion coefficient of shaft wall
T = Temperature along thickness of shaft wall, and could be calculated as following (Xu and Liu, 1995):

$$T=T_a+\left(T_b-T_a\right)\frac{\ln\frac{r}{a}}{\ln\frac{b}{a}} \tag{4}$$

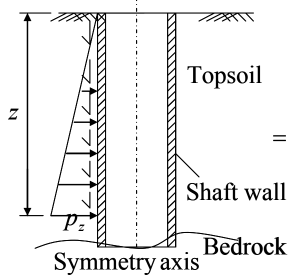
The boundary condition of formula (1) is showed as following:

$$\left(\sigma_r\right)_{r=a}=-P_a\,,\ \left(\sigma_r\right)_{r=b}=-P_z \tag{5}$$

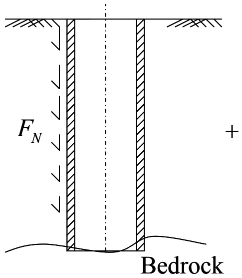
Combined formula (3) and formula (5), the following formula could be got:

$$\begin{cases}D_1=\dfrac{\alpha_f\cdot E}{(1-u)\left(b^2-a^2\right)}\displaystyle\int_a^b T\cdot rdr+\dfrac{a^2P_a-b^2P_z}{b^2-a^2}\\ D_2=\dfrac{a^2\cdot\alpha_f\cdot E}{(1-u)\left(a^2-b^2\right)}\displaystyle\int_a^b T\cdot rdr+\dfrac{P_z-P_a}{b^2-a^2}a^2b^2\end{cases} \tag{6}$$

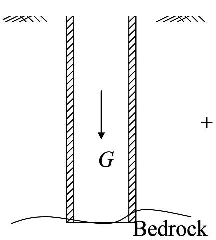
According to formula (4), there is:



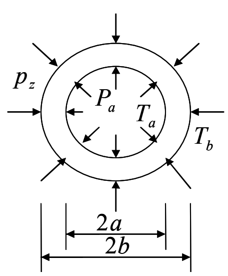
(a)Total stress of shaft wall



(b) Negative friction of shaft wall



(c) Gravity of shaft wall



(d) Earth pressure and temperature stress of shaft wall

Fig. 1: Mechanical analysis of shaft wall

$$\int_a^r T\cdot rdr = \frac{T_a}{2}\left(r^2-a^2\right)+ \frac{T_b-T_a}{\ln\frac{b}{a}}\left(\frac{r^2}{2}\ln\frac{r}{a}-\frac{r^2-a^2}{4}\right) \tag{7}$$

Combined formula (1)~formula (7), the theoretical solution of temperature stress could be got as following:

$$\sigma_r = \frac{\alpha_f E\left(T_b-T_a\right)}{2(1-u)\ln\frac{b}{a}}\left[-\ln\frac{r}{a}+\frac{b^2\ln\frac{b}{a}}{b^2-a^2}\left(1-\frac{a^2}{r^2}\right)\right] + \frac{b^2\left(a^2-r^2\right)}{r^2\left(b^2-a^2\right)}P_z+\frac{a^2\left(r^2-b^2\right)}{r^2\left(b^2-a^2\right)}P_a \tag{6a}$$

$$\sigma_\theta = \frac{\alpha_f E\left(T_b-T_a\right)}{2(1-u)\ln\frac{b}{a}}\left[-1-\ln\frac{r}{a}+\frac{b^2\ln\frac{b}{a}}{b^2-a^2}\left(1+\frac{a^2}{r^2}\right)\right] + \frac{b^2\left(a^2+r^2\right)}{r^2\left(a^2-b^2\right)}P_z+\frac{a^2\left(b^2+r^2\right)}{r^2\left(b^2-a^2\right)}P_a \tag{6b}$$

$$\sigma_z = \frac{\alpha_f E\left(T_b-T_a\right)}{2(1-u)\ln\frac{b}{a}}\left[-u-2\ln\frac{r}{a}+\frac{2b^2u\ln\frac{b}{a}}{b^2-a^2}\right] -\alpha_f ET_a+\frac{2ub^2}{a^2-b^2}P_z+\frac{2ua^2}{b^2-a^2}P_a \tag{6c}$$

At inwall of shaft wall r = a, the corresponding stress component is showed as following:

$$\left(\sigma_r\right)_{r=a} = -P_a \tag{7a}$$

$$\left(\sigma_\theta\right)_{r=a} = \frac{\alpha_f E\left(T_b-T_a\right)}{2(1-u)\ln\frac{b}{a}}\left[-1+\frac{2b^2\ln\frac{b}{a}}{b^2-a^2}\right] +\frac{2b^2}{a^2-b^2}P_z+\frac{b^2+a^2}{b^2-a^2}P_a \tag{7b}$$

$$\left(\sigma_z\right)_{r=a} = \frac{\alpha_f E\left(T_b-T_a\right)}{2(1-u)\ln\frac{b}{a}}\left[-u+\frac{2b^2u\ln\frac{b}{a}}{b^2-a^2}\right] -\alpha_f ET_a+\frac{2ub^2}{a^2-b^2}P_z+\frac{2ua^2}{b^2-a^2}P_a \tag{7c}$$

At external wall of shaft wall $r = b$, the corresponding stress component is showed as following:

$$\left(\sigma_r\right)_{r=b} = -P_z \tag{8a}$$

$$\left(\sigma_\theta\right)_{r=b} = \frac{\alpha_f E\left(T_b-T_a\right)}{2(1-u)\ln\frac{b}{a}}\left[-1+\frac{2a^2\ln\frac{b}{a}}{b^2-a^2}\right] +\frac{a^2+b^2}{a^2-b^2}P_z+\frac{2a^2}{b^2-a^2}P_a \tag{8b}$$

$$\left(\sigma_z\right)_{r=b} = \frac{\alpha_f E\left(T_b-T_a\right)}{2(1-u)\ln\frac{b}{a}}\left[-u-2\ln\frac{b}{a}+\frac{2b^2u\ln\frac{b}{a}}{b^2-a^2}\right] -\alpha_f ET_a+\frac{2ub^2}{a^2-b^2}P_z+\frac{2ua^2}{b^2-a^2}P_a \tag{8c}$$

EFFECT OF REINFORCEMENT AT INWALL OF SHAFT WALL

As described before, the most dangerous surface located at $r = a$, where stress component is showed at in formula (7). Now the main shaft wall of Baodian coal mine, broken at depth of 136 m~144 m, is to be studied with following parameters:a = 6.5m, b = 7.5m,T_a = 22°C, T_b =10°C, u=0.18, α_f = 10×10^{-6}(°C)$^{-1}$, σ_t = 2.8MPa, σ_c= 28MPa, E=25.48×10^6kPa.

According to formula (7), if there is no reinforcement at inwall of shaft wall (P_a = 0), the corresponding stress components are: $(\sigma_r)_{r=a}$ = 0, $(\sigma_r)_{r=a}$ = -9.07MPa, $(\sigma_z)_{r=a}$ = -7.24MPa, and $F(\sigma_1, \sigma_3)$ =2.87MPa

Now the shaft wall is to be reinforced at inwall, which would enhance the value of P_a. Table 1 showed the value of temperature stresses with different reinforce stresses P_a at inwall of shaft wall, the curves of corresponding stress component are showed in Fig. 2. The negative value means compressive stress. It can be found when P_a <1.29MP_a, the stress component σ_r σ_r, σ_θ and$\sigma_z$are all negative value at r = a, which indicated the concrete is in three-dimensional compressive state. When P_a ≥1.29MPa, the value of σ_Θ become positive value, which means circumference stress σ_Θ in the tensile state, while σ_r and σ_z still at compressive state. With the increasing of reinforcement stress P_a, radial compressive stress σ_r increased, vertical compressive stress σ_z decreased, and circumference stress σ_θ changed from compressive stress to tensile stress. When Pa <2.0MPa, the biggest absolute value among three stress components is σ_z, so σ_z act as the maximum principal stress. But when P_a ≥2.0MPa, the biggest absolute value among three stress components is σ_θ, so σ_θ act as the maximum principal stress now. It can be found that the stress of shaft wall complicatedly varied with different reinforcement stress

The effect of reinforcement at inwall of shaft wall could be studied by the value of vertical stress σ_z and function $F(\sigma_1, \sigma_3)$. The failure of shaft wall essentially is the vertical stress greater than compression strength of concrete. The vertical stress σ_z generated by temperature is also participated in the failure of shaft wall. Therefore, the stability of shaft wall could be enhanced by reducing the vertical stress σ_z generated by temperature. On the other hand, according to Coulomb-Navier failure criterion, it is good for the stability of shaft wall when the value of function $F(\sigma_1, \sigma_3)$ decreased, which less than the value of 2c.

The tendency of σ_z and $F(\sigma_1, \sigma_3)$ with different reinforce stresses P_a at inwall of shaft wall are showed in Fig. 3. It can be found vertical stress σ_z generated by temperature increased and function $F(\sigma_1, \sigma_3)$ decreased when reinforcement stresses P_a increased. Therefore, the value of function $F(\sigma_1, \sigma_3)$ is much less than the value of $2c$ when reinforcement stress P_a increased, and the stability of shaft wall increased correspondingly.

The degree of stability of shaft wall enhanced by reinforcement stress could also be quantitatively analyzed. Such as when reinforcement stress P_a = 2.0MPa, the corresponding vertical stress generated by temperature is $(\sigma_z)_{r=a}$= -5.07MPa. When without reinforcement stress (P_a = 0), the corresponding vertical stress generated by temperature is $(\sigma_z)_{r=a}$= -7.24MPa. Thus the vertical stress reduced 7.24-5.07 = 2.17MPa when reinforcement stress P_a = 2.0MPa. At the failure position (136~144m) the gravity of shaft wall is

Table 1: Value of temperature stresses with different reinforce stresses at inwall of shaft wall

P_a/MPa	σ_r/MPa	σ_θ/MPa	σ_z/MPa	$F(\sigma_1,\sigma_3)$/MPa
0.5	-0.5	-5.55	-6.70	0.54
1.0	-1.0	-2.03	-6.15	-1.22
1.5	-1.5	1.48	-5.61	-2.91
2.0	-2.0	5.0	-5.07	-4.72
2.5	-2.5	8.52	-4.53	-5.21
3.0	-3.0	12.04	-3.98	-5.68
3.5	-3.5	15.56	-3.44	-5.95

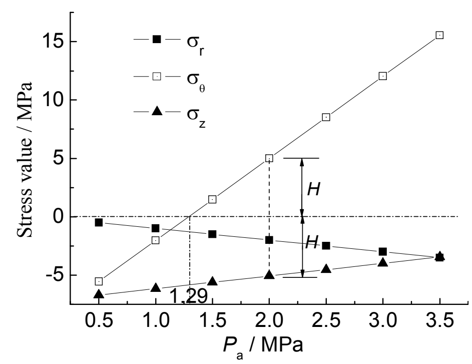


Fig. 2: Tendency of temperature stresses with different reinforce stresses at inwall of shaft wall

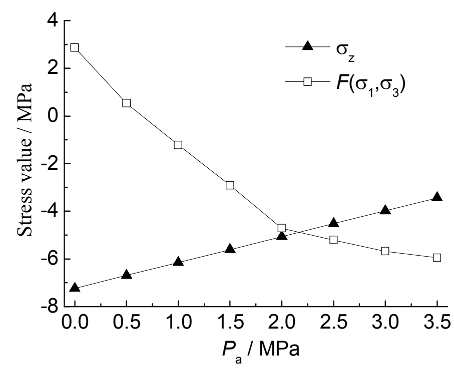


Fig. 3: Tendency of σ_z and $F(\sigma_1, \sigma_3)$ with different reinforce stresses at inwall of shaft wall

about $\sigma_z^{'} = \gamma_c$. H = 25×140 = 3500kPa = 3.5MPa. The ratio of effect of reinforcement stress could be approximately calculated as 2.17/3.5 = 62%, that is, the effect of reinforcement stress Pa = 2.0MPa likely reduced the gravity of 62%. The axis compression strength of concrete at Baodian coal mine is σ_a23.48MPa, which means that the shaft wall would be cracked when the vertical stress generated gravity, negative friction and temperature together arrived 23.48MPa. 2.17/23.48 = 9.3%, which means 9.3% of compression strength of concrete has been "liberated" by reinforcement stress P_a = 2.0MPa.

METHOD OF REINFORCEMENT AT INWALL OF SHAFT WALL

As mentioned above, stability of shaft wall could be effectively enhanced by reinforcement at inwall of shaft wall. How to execute and achieve the reinforcement at inwall of shaft wall in engineering? Some author (Jing, 2000b) introduced the whole process of design and construction:

- The position of reinforcement, that is, the most dangerous position which to be cracked or failure firstly in shaft wall, should be found by calculation and experiences.
- Steel plate device as showed in Fig. 4 should be designed and produced. The thickness of steel plate is about 5~10 mm, the breadth of steel plate could be defined by needing. Every steel plate should be bended with the same curvature of in wall of shaft wall. Rubber bedding cushion with thickness of 10~15 mm should be affixed at outer flank of steel plate, which enhanced the friction of interface between steel plate and in wall of shaft wall.
- A tailor-made jacking apparatus is used to fix and install the steel plates, which make the steel plates arrive its designed reinforcement stress. The steel plates should be riveted or welded into a whole body.

Auxiliary shaft wall of Hongyang coal mine has been reinforced with the method described above, which ability of resistance to rupture has been enhanced 24.89% (Jing and Wang, 2000). It can be seen the effect of reinforcement at in wall of shaft wall.

The method of reinforcement at in wall of shaft wall characterized with easy construction, low cost and short time for installation. The main problems of this method maybe are:

- When jacking apparatus removed after steel plates installation, the reinforcement stress generated by steel plates could arrive and remain the designed value or not.

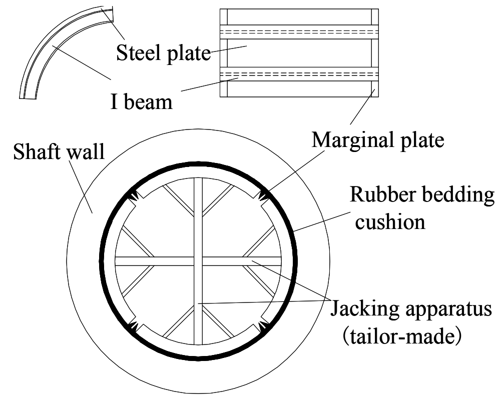


Fig. 4: Design and installation of pressure steel plate

- In the environment of fluctuation of temperature, earth pressure and mining pressure, the interface between steel plates and inwall of shaft wall could loose and released or not.
- More intelligent and robust equipments for reinforcement at inwall of shaft wall need to be developed, and the stress and strain of shaft wall should be real-time exported by need.

In a word, the technique of reinforcement at in wall of shaft wall should be updated combined with the knowledge of material science, information science, industrial design and so on.

CONCLUSION

- Based on the theory of elasticity, the analytic solution of vertical stress generated by temperature has been deduced, and the character of which has been studied with parameters of real shaft wall of coal mine.
- With the increasing of reinforcement stress P_a, radial compressive stress σ_r increased, vertical compressive stress σ_z decreased, and circumference stress σ_θ changed from compressive stress to tensile stress. The stability of shaft wall increased with reinforcement stresses P_a increased.
- The method of reinforcement at inwall of shaft wall could be accomplished with combined steel plates, characterized with easy construction, low cost and short time for installation. More intelligent and robust equipments for reinforcement at inwall of shaft wall need to be developed.

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