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Effect of Residual Deformation and Reinforcement on Double Column Bridge in Mined-out Area

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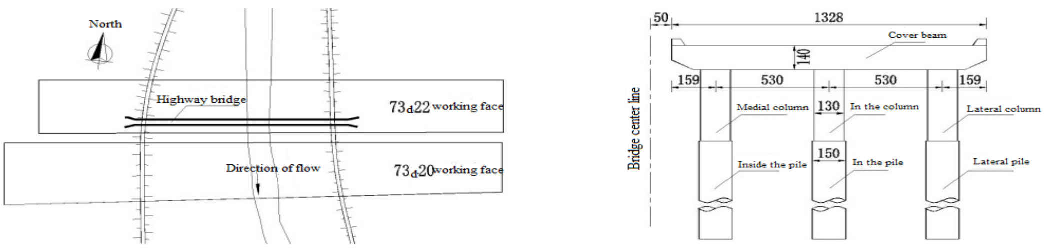
The residual deformation poses tremendous challenges to the safety of the newly built buildings and bridges in coal mined-out areas. In this paper, the residual deformation is predicted at the very beginning, followed by the investigation of the damages on the bridge piles due to the deformation. Multiple retrofitting and strengthening schemes are then proposed, including linking the piles with straining beams and increasing the cross sectional area of the cap beam. After that the optimized scheme is determined through FEM simulation.

1. Introduction

After the mining of underground coal seam, the mined-out area is formed in the rock mass, and the stress balance state of the surrounding rock mass is destroyed. The rock mass above the mined-out area is caving, fracture and bending (Guo et al., 2004). The mining rock mass will be naturally compacted by its own weight and ground stress to achieve a new balance. The residual voids, segregation and cracks in the rock mass cannot be fully compacted (Zhu et al., 2012). Under the influence of external factors, the surface will continue to deform. The deformation at this stage is small, namely, residual deformation. The amount has been far beyond the piers and abutments settlement value the bridge code allows. The residual deformation of the mined-out area not only lasts for a long time (maybe even 50 years after mining), but also has more crypticity and abruptness (Xu, 2015), which brings great potential safety hazard to the surface structure. Zhu (2012) and (Guo et al., 2004; Guo et al., 2002) studied the mechanism of surface residual deformation, the stability of mined-out area ground and the deformation and damage law of buildings, but the researches on bridge are little. Based on the prediction of residual deformation, through theoretical analysis and numerical simulation, this paper studies the adverse effect of surface residual deformation on the bridge and the damage of the bridge substructure. The reinforcement and reconstruction scheme for substructure is proposed and the optimal scheme is obtained through the numerical simulation method to ensure the safety of the new bridge in the process of residual deformation (Yin and Yu, 2016).

2. Prediction of residual deformation at bridge site

2.1 Bridge overview



(a) (b)

Figure 1: (a) The contrast graph between highway bridge and mining areas and (b) Arrangement for bridge substructure

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The relationship between highway bridge and mining areas is shown in Figure 1(a), and the arrangement for bridge substructure is shown in Figure 1(b).

2.2 Analysis of residual deformation at bridge site

73_d22 working face is not fully exploited mining, and the subsidence coefficient is only 0.406. After longwall face mining, the overburden would form collapse zone, fracture zone and bending zone. At the end of a certain period of time, the fractured rock layer reaches a new relative equilibrium, and the surface movement tends to stop. However, the overburden will have residual voids, cracks, segregation and broken rock mass in the mined-out area. Over time, the strength of the fractured rock mass will gradually decrease. Under the action of natural forces and external forces or disturbances (such as earthquakes, mining activities, loads, etc.), the relatively balanced mined-out area will cause structural deformation and compaction, leading to the occurrence of residual settlement, that is, to produce activation subsidence. The results of physical simulation, numerical simulation and field measurement (Guo et al., 2002; Guo et al., 2008) show that when the depth ratio exceeds a certain value (> 30), the active surface subsidence of the mined-out area appears as a continuous gradient, and does not appear abrupt and non-continuous subsidence. According to the residual settlement and deformation of the surface, we can take some structural anti-deformation measures to buildings, which is to ensure the safety of the buildings. The mining deep ratio of 73_d22 working face surface is 89>30. The subsidence distribution in the mined-out area is big in the middle and small at the edge like a basin. After that the residual settlement is stable, there will be large residual deformation at the bridge site. It will inevitably have a negative impact on the bridge built on it, and even affect the safety of the bridge.

2.3 Prediction of surface residual deformation

The residual deformation and subsidence law at the bridge site is the key to the research. The probability integral method (Liu et al., 2016) derived from the theory of granular media mechanics is the most widely used mining subsidence prediction method. It is assumed that under all kinds of factors, all the possible residual settlement in the mined-out area occurs. After the end of the rock movement, the internal gap are fully filled and compacted, and the formed surface movement basin is the ideal limit subsidence distribution, namely, the ideal subsidence curve can be expressed by Eq. (1):

$$W'(x) = \frac{q'm}{2}\left[erf\left(\frac{\sqrt{\pi}}{r}\right)x + 1\right] \tag{1}$$

where, $W'(x)$ means ideal subsidence curve, x denotes the distance from the boundary of mined-out area, m is mining thickness, r is main effect radius, q' is limit subsidence coefficient.

Under actual conditions, after the new stress balance that the overburden rocks in the mined-out area reached through broken structures, moving and deforming, the broken-down masonry beams are still present in the overburden. Therefore, the actual subsidence curve can be expressed by Eq. (2):

$$W(x) = \frac{qm}{2}\left[erf\left(\frac{\sqrt{\pi}}{r}(x-S)\right) + 1\right] \tag{2}$$

where, W(x) means actual subsidence curve, q is the subsidence coefficient of current subsidence basin ($q<q'<1$), S is the inflection point offset.

The maximum residual subsidence curve that may occur above the mined-out area can be expressed bt EQ. (3):

$$W_e(x) = W'(x) - W(x) = \frac{W_0'}{2}\left[erf\left(\frac{\sqrt{\pi}}{r}x\right) + 1\right] - \frac{W_0}{2}\left[erf\left(\frac{\sqrt{\pi}}{r}(x-S)\right) + 1\right] \tag{3}$$

where, $W_0' = q'mcos\,\alpha$ is the maximum surface residual subsidence value after coal seam mining of α,$W_o = q'mcos\,\alpha$ the maximum subsidence value after relative stabilization of coal seam mining of α.

According to the first derivative of Eq. (4), the surface residual tilt above the mined-out area is:

$$i_e(x) == \frac{W_0'}{r}e^{-\pi\frac{x^2}{r^2}} - \frac{W_0}{r}e^{-\pi\frac{(x-S)^2}{r^2}} \tag{4}$$

The level movement of surface residual is:

$$U_e(x) == bW_0^{'} e^{-\pi\frac{x^2}{r^2}} - bW_0 e^{-\pi\frac{(x-S)^2}{r^2}} \tag{5}$$

The calculation formula of residual level deformation and residual curvature can be obtained (Liu et al., 2016). $W_\varepsilon(x)$ can be used as the maximum estimate of the residual settlement in the mined-out area. The bridge construction in the mined-out area should ensure the long-term safety of the bridge structure. Therefore, the maximum predictive value should be taken as the basis to study the anti-deformation structure of the bridge.

3. Influence of residual deformation at bridge site on bridge

3.1 Relationship between surface deformation and deformation of bridge foundation

According to the measured data of bridge deformation and surface deformation (Tan et al., 2007), the bridge deformation is linear with the surface deformation. The bridge subsidence is slightly larger than the surface subsidence, and the bridge slope is slightly larger than the surface tilt, the difference is not big, and the tilt of the bridge caused by uneven subsidence is the main reason for the destruction (Zhu and Jiang, 2014).

3.2 Prediction result and analysis of surface residual deformation at bridge site

According to the spatial position relationship between the bridge pier and the working face, the predicted cross-section is set at the bridge pier and platform position, that is, on both sides of the abutment north and south (denoted by N and B), center line (denoted by Z), a total of 7 expected cross-section. The expected point arrangement is shown in Figure 2.

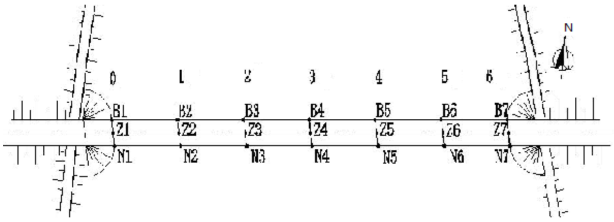
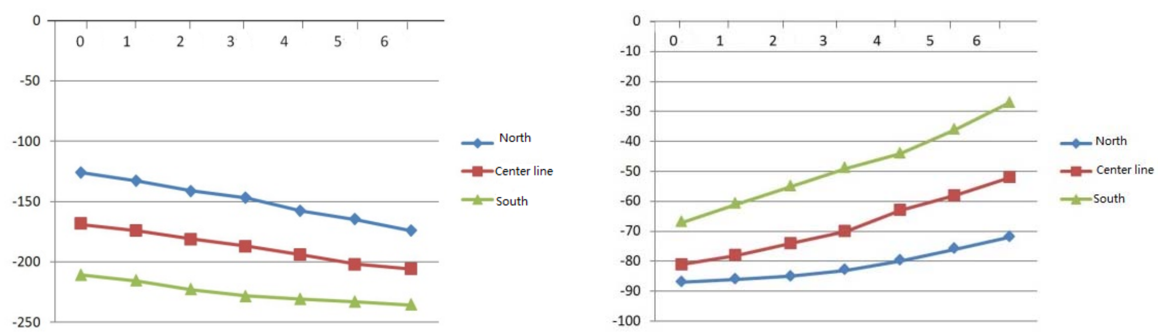


Figure 2: Sketch map of residual deformation in bridge substructure

From Figure 3 (a), it is shown that the bridge has a great sinking from west to east. The maximum sinking value of 235mm is far beyond the requirements of the specification. The North Bridge is smaller than the South Bridge. The residual deformation causes the bridge uneven settlement in the east-west direction. The uneven settlement difference of North Bridge is 6~10mm, while that of South Bridge is 3~7mm, which allows the bridge to produce additional longitudinal, and the value is less than the standard value of 0.2% (Liu et al., 2014). Figure 3 (b) shows that both the north and south bridges produce large horizontal displacements ("-" sign indicates southward movement). The maximum value is at the No. 0 platform of North Bridge and its value is 87mm. Because of the simple structure of the bridge system, the uneven subsidence and horizontal movement does not produce additional internal forces within the structure (including substructure and superstructure).



(a) (b)

Figure 3: (a) Residual subsidence curve of the piers and abutments (mm) and (b) Residual horizontal movement curve of the piers-abutments in north-south direction(mm)

4. Influence of residual deformation on bridge substructure

4.1 Numerical model

Use ANSYS finite element analysis software to establish the real bridge model to study the impact of residual deformation, model size 50×14×57(m). Concrete used C30. According to the measured elastic modulus E=2.4×10^4MPa, Poisson's ratio $\mu = 0.2$; The shear transfer coefficient of concrete crack is 0.5, the shear transfer coefficient of closed crack is 1.0, the uniaxial tensile strength of concrete is 1.43MPa and the uniaxial compressive strength is 14.3MPa. Calculation model and mesh division is shown in Figure 4, the concrete unit used solid65 unit, reinforced role used dispersion model.

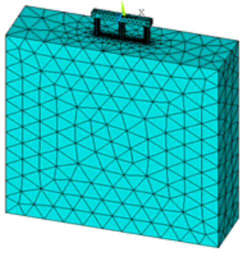


Figure 4: The model and FEM mesh

4.2 Analysis of calculation results

The calculation results of four kinds of working conditions are analyzed (1) The substructure of the bridge is in good condition and normal work under condition 1 and condition 2 (2) Under condition 3, the concrete structure of the bridge is slightly damaged (3) Under condition 4, 80% of the pile body concrete is severely damaged, the upper and the outer pile body of the middle pile is slightly damaged, but it can no longer work.
Table 1 lists the maximum compressive stress and maximum tensile stress of the structure situation under conditions 1 and 4.

Table 1: Comparison of the initial stress due to residual deformation

Maximum stress		Cap beam		Piers		Pile foundation	
(MPa)		1	4	1	4	1	4
Maximum compressive stress	Value	0.86	0.865	1.11	1.99	1.08	1.63
	Increasing amount	0.58%		79.28%		50.93%	
Maximum tensile stress	Value	1.14	1.30	0.11	0.70	0.952	2.54
	Increasing amount	14.04%		536.36%		166.81%	

5. Reinforcement scheme analysis for substructure of bridge

5.1 Structural reinforcement scheme

Setting up cross-beam between the two columns can effectively improve the overall structure and reduce the impact of uneven settlement (Liu et al., 2014). According to the force condition of substructure under the impact of residual deformation, we proposed the reinforcement measures of adding cross-beam between the piers and increasing the cross-section including four programs (see Table 2). Scheme A adds a transverse beam at the position 0.6H (H is the height of the pier) at the bottom of the pier column, and scheme B adds the cross-beam at the position 0.3H and 0.8H from the bottom of the pier column respectively. The beam cross-section of the scheme C and D is the same as the scheme A and B, but the cross-sectional dimension of the cap beam and the cross-beam is appropriately increased in consideration of the non-uniform subsidence requirements.

Table 2: Reinforcement plans for Substructure

Scheme	Cross-beam		Cap beam
	Number	Cross-section b×h(m)	b×h(m)
A	1	1.2×1.2	1.7×1.5
B	2	1.2×1.2	1.7×1.5
C	1	1.2×2.0	2.0×2.0
D	2	1.2×2.0	2.0×2.0

5.2 Calculation result and analysis of reinforcement

5.2.1 Influence of cross - beam installation on internal force of substructure

Comparing the reinforcement schemes, A and B in Table 3, it can be seen that a transverse beam is added between the piles, which greatly improves the stress state of the structure and reduces the additional internal forces under the influence of the residual inclination of the pile foundation and piers, especially moment and additional shear force, in which the reduction range of pile foundation is 20~30%, and the reduction range of piers is 15~20%. The additional bending moment and the additional shear force of the upper and lower crossbeams are greatly improved, and the bending moment is the most obvious. And the number of the additional beam has little effect on the maximum bending moment and the maximum shear force of the cap beam. Similarly, the similar results can be obtained by comparing the internal forces of the structures under C and D with residual tilting deformation. It can be seen that the strengthening scheme of the double-tie beam makes the force of the substructure reasonable. Correspondingly, after the addition of a cross-beam, the pillar of the axial force has increased with the change rate of about 10%.

Table 3: Comparison of the internal forces between scheme A and scheme B

Structure name		Torque (kN˙m)			Force (kN)		
		Scheme A	Scheme B	Variation (%)	Scheme A	Scheme B	Variation (%)
Pile foundation	Inside the pile	-992.1	-764.9	22.90	428.4	320.7	25.14
		991.1	678.8	31.51			
	In the pile	-678.1	-520.7	23.21	407.1	323.7	20.49
		999.6	707.6	29.21			
	Lateral pile	-997.7	-802.1	19.61	388.0	283.1	27.04
		1061.4	744.0	29.90			
Piers	Medial column	-665.2	-548.3	17.57	312.3	257.6	17.52
	In the column	-1311.5	-1097.6	16.31	49.8	39.2	21.29
	Lateral column	-747.3	-636.9	14.77	435.3	347.5	20.17
Straining beam	Up beam	-612.3	-345.1	43.64	267.2	197.9	25.94
		474.4	262.2	44.73	79.6	66.1	16.96
	Down beam		-329.4	46.20		212.0	20.66
			387.1	18.40		51.2	35.68
Cap beam		-1324.0	-1253.2	5.35	1824.6	1824.6	0
		1291.8	1286.7	0.39	-1824.6	-1824.6	0

5.2.2 Influence of increasing cross section on internal force of substructure

Table 4: Comparison of the internal forces about the sectional dimension of cap beam and straining beam

Structure name		Torque (kN˙m)			Force (kN)		
		Scheme D	Scheme B	Variation (%)	Scheme D	Scheme B	Variation (%)
Pile foundation	Inside the pile	-786.0	-764.9	2.68	320.7	320.7	0
		679.0	678.7	0.04			
	In the pile	-533.6	-520.7	2.42	324.0	323.7	0.09
		707.6	707.6	0			
	Lateral pile	-825.2	-802.1	2.79	283.0	283.1	-0.04
		744.1	744.0	0.01			
Piers	Medial column	-574.0	-548.3	4.48	282.0	257.6	8.65
	In the column	-1200.0	-1097.6	8.53	-659.0	-623.1	5.45
	Lateral column	-671.0	-636.9	5.08	377.0	365.5	3.05
Straining beam	Up beam	-402.3	-345.1	14.23	186.3	126.1	32.31
	Down beam	-395.1	-329.4	16.63	323.1	242	25.10
Cap beam		1480.0	1286.7	13.06	1879.3	1824.6	2.91

Table 4 shows that the internal forces of the substructure will change after the enlarged cross and beam: (1) the internal force extremum increment of the pile is less than 3%, which is not affected; (2) Column internal force value increased obviously with bending moment of 6% and shear force of 5.7%; (3) The bending moment of transverse beam increased by 15.4% and the shear force increased by 28.7% on average; (4) The bending moment of the cap beam increased by 13.1%, and the shear force increased 2.9%. Similarly, a comparison of the internal forces of schemes C and A yields similar results. It can be seen that the reinforcement scheme with the enlarged section will increase the internal force of the substructure with varying degrees.

6. Conclusions

(1) Under the action or perturbation of natural force and external force, the mined-out area in the relatively balance will produce structural deformation and compaction, resulting in the surface residual deformation. The bridge deformation is similar to surface deformation, appearing residual settlement, residual inclination, and residual horizontal movement and so on, and the bridge structure will be destroyed.
(2) Residual tilting deformation will cause great additional internal forces on the substructure of the bridge, resulting in the destruction of the substructure (especially the pile foundation and pier columns). The reinforcement measures should be taken to the influence of the residual deformation on the substructure of the bridge.
(3) The addition of transverse beams between piles can greatly reduce the internal force extremes of pile foundation, pier column and transverse beam, and it can also reduce the additional stress the adverse influence of residual tilting deformation on the substructure. Section reinforcement schemes C and D, and reinforcement schemes A and B can all meet the requirements of residual deformation of the ground surface, but the internal force of the substructure will increase to some extent when the section is enlarged. Therefore, reinforcement scheme B is a preferable scheme.
(4) The length of the pile body should be reinforced according to the internal force of the pile to strengthen the bending reinforcement at the bottom and the top of the pile body. At the same time, it is suggested to strengthen the reinforcement check of the pier column, the cross beam and the cap beam according to the increment of internal force value of the residual tilting deformation, so as to ensure that the subpart of the bridge has sufficient resistance to deformation.

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