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Subsidence prediction of overburden strata and ground surface in shallow coal seam mining

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Shallow coal seam with thick soil layer is widely reserved in the Jurassic Coalfield, Western China, mining-induced subsidence represents complex characteristics. Combining with physical simulation, theoretical analysis and in-situ observation, the overburden strata structure in dip direction were revealed, and the subsidence prediction models were established, based on this, the subsidence equations of overburden strata and ground surface were proposed. The results show that after shallow coal seam mining, based on the subsidence and movement characteristics, the overburden strata structure can be divided into three zones, which are "boundary pillar F-shape zone" (BPZ), "trapezoid goaf zone" (TGZ) and "coal pillar inverted trapezoidal zone" (CPZ). The subsidence of overburden strata depends on the key stratum, while the subsidence of soil layer depends on the bedrock subsidence basin, which is between the bedrock and thick soil layer. The bedrock subsidence is mainly related to mining height and bulking coefficient in TGZ, while it is mainly affected by mining height and distribution load on the key stratum in BPZ and CPZ. According to physical simulation and theoretical model, the maximum surface subsidence of No.1-2 seam mining in Ningtiaota coal mine are 1.1 m and 1.07 m respectively, which is basically consistence with the result of in-situ observation (1.2 m).

The Jurassic Coalfield in Shaanxi Province, Western China, mainly reserves shallow coal seam with thick soil layer. Recently, due to high-strength underground mining, the subsidence of ground surface is serious, which easily causes the decline of groundwater level and desertization[1–3]. Taking Hongjiannao Scenic Area in northern of Shaanxi as example, from 1992 to 2000, the water level drops about 1.1 m, and the lake area decreases from 55 to 48 km^2, since 2000, the lake area decreases about 30%[4]. Besides, ground surface represents obvious uneven subsidence, subsidence of overburden strata and ground surface above goaf is larger, while it is smaller above pillar[5], and the uneven subsidence has obvious effect on the surface buildings[6]. Therefore, under mining conditions of shallow coal seam with thick soil layer, how to realize subsidence prediction of overburden strata and ground surface, it is a necessary and complicated scientific problem to be solved.

Overburden strata in the Jurassic Coalfield has its own characteristics, overall, the thick soil layer is widespread above the bedrock[7]. Due to soil layer and bedrock belong to two different media, the subsidence characteristics are also different[8–10]. In order to obtain quantitative subsidence prediction method, it is of great significance to study further.

To date, in-situ observation was widely applied to study the mining-induced ground surface subsidence. Xu et al.[11] obtained the surface dynamic movement parameters, and the subsidence velocity prediction equation of arbitrary point in advance profile was determined. Liu et al.[12] divided the mining process into the initial mining stage, the normal periodic stage and the final mining stage, the surface movement of different stages was studied. Xu et al.[13] analyzed the control effect of key strata on overburden and surface, and the effect of key block lumpiness on the subsidence curves was revealed. Zhu et al.[14] found that the main key strata is the control layer of overburden strata and surface. Wu et al.[15] revealed the control effect of thick and hard strata on the surface subsidence. Baek et al.[16] studied the mining-induced ground subsidence in Korea by SAR interferometry. Using TimeSAR in Springfield, USA, Grzovic et al.[17] evaluated the ground subsidence, and also measured the temporal pattern of deformation.

Furthermore, the other two methods, numerical simulation and physical simulation were also used to simulate the subsidence of overburden strata and surface. In order to observe the surface movement in thick loose layer high-intensity mining, Zhao et al.[18] analysed the failure characteristics of overburden strata and surface

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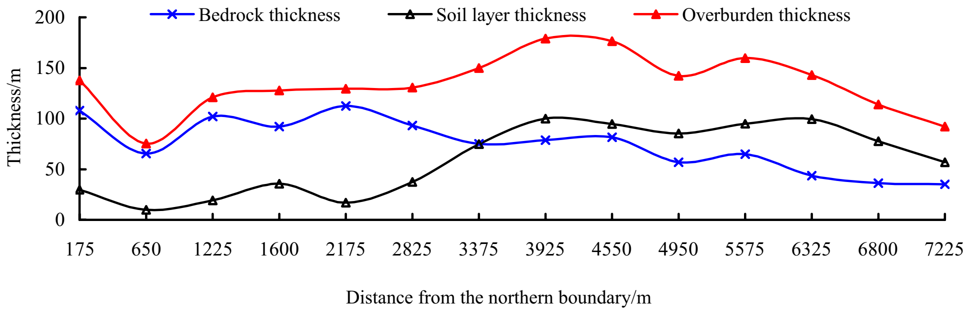

Figure 1. The thickness of bedrock and soil layer in Ningtiaota coal mine.

subsidence. Wang et al.[19] studied the subsidence and stress distribution of overburden strata, and it showed that there only exists caving zone and fracture zone in shallow coal seam mining. Xu et al.[20] revealed the effect of primary key stratum on the dynamic surface subsidence. Liu et al.[21] established the numerical model of strip-pillar mining, the surface subsidence and horizontal movement contours under different alluvium thickness were given. Wu et al.[22] found that the subsidence of soil layer was closely related to its own property. Based on deep mining and shallow mining, Xu et al.[23] studied the effect of key strata on ground surface subsidence. Taking three typical shallow coal seam conditions as the background, Fan et al.[24] analyzed the movement and fractures of overburden strata in the horizontal and vertical direction. Based on the geological information gathered from the GIS and MIS, Unlu et al.[25] established a number of two dimensional finite element model to analyse the ground subsidence occurring due to mining. Alejano et al.[26] studied the FDM predictive methodology for subsidence in inclined seam mining.

In addition, theoretical analysis related to the subsidence of overburden strata and surface was studied. Yang[27] put forward a prediction method of surface based on the boundary value method. Wang et al.[28,29] found the relationship between mining degree and subsidence pattern by rock mechanics. Under the mining conditions of thick alluvial soil, Zhang et al.[30] regarded the soil and bedrock as random medium and viscoelasticity beam respectively, and the calculation method of surface subsidence prediction was put forward. Wang et al.[31] divided the strata movement into four stages, and the movement models of overburden strata were established. Hou[32] analysed the effect of overburden property on the surface movement, it is found that the softer the overburden strata, the greater effect on the maximum surface subsidence values, and the greater the dip angle of the coal seam, the larger change of the maximum surface subsidence values. Based on pooling and meta-analysis of empirical data from a number of different countries and coalfields, McCay et al.[33] proposed an universal tool for the estimation of maximum subsidence. Karmis et al.[34] analysed the application of the influence function method for ground movement predictions, and demonstrated the applicability in U.S. coalfields. Singh et al.[35] established a visco-elastic model to predict the mining-induced surface subsidence in Indian coalfields.

Besides, other studies were carried out to reveal the subsidence characteristics of overburden strata under back-filling mining[36–40]. However, the previous studies were largely limited to the subsidence of overburden strata and surface above goaf, quantitative subsidence above pillar still remains unclear. In addition, subsidence prediction method in shallow coal seam with thick soil layer is less studied. Therefore, based on typical mining conditions in Ningtiaota coal mine, combining with physical simulation, theoretical analysis and in-situ observation, we studied subsidence characteristics of overburden strata and ground surface, the subsidence prediction models were established, and the prediction method were put up. This study is conducted to provide a new subsidence prediction method in shallow coal seam mining.

Subsidence law of overburden strata and ground surface

Engineering background. Ningtiaota coal mine is located in Shennan mining area, its mining conditions are mainly characterized by shallow depth (less than 200 m), nearly horizontal (1°–3°), and thick red soil is widespread over the bedrock. No. 1-2 and No. 2-2 seams are mainly mined, according to drillholes NBK8, NBK16, NBK22, NBK26 and NBK29, the thickness of bedrock and soil is shown in Fig. 1, overall, the average thickness of bedrock and soil are 74.65 m and 59.52 m respectively.

According to drillhole NBK26, the thickness of No. 1-2 seam is 1.9 m, and it mines 176.6 m deep, the bedrock thickness is 81.9 m, the soil thickness is 94.7 m, the width of coal pillar is 20 m, parameters of the coal, its roof and floor are listed in Table 1.

Physical simulation. In order to reveal the overburden strata and ground surface subsidence of No. 1-2 seam mining, the physical simulation model was built with the following dimensions: 5 m long × 0.2 m wide × 1.35 m high, the geometric ratio is 1:200 (Fig. 2). During model set up, the simulation materials of bedrock are composed of sand (aggregate), gypsum and calcium carbonate (cementitious materials), as for red soil, the simulation materials and its ratio can be determined by Reference[41].

The width of coal pillar between faces is 20 m, while the width of boundary pillar is 50 m. Three observation lines were established, and electronic total station was used to monitor the overburden strata subsidence, dial indicators were applied to monitor the ground surface subsidence, the detail position of observation lines is listed below:

Lithology	Thickness (m)	Depth (m)	Bulk density (kg/m^3)	Compressive strength (MPa)	Cohesion (MPa)	Poisson's ratio
Red soil	94.70	94.70	1860	0.29	0.77	0.35
Sandymudstone	14.80	109.50	2560	34.70	1.15	0.24
Siltstone	21.60	131.10	2420	31.90	0.65	0.32
Medium-grained sandstone	28.80	159.90	2160	35.30	0.80	0.29
Siltstone	6.70	166.60	2420	31.90	0.65	0.32
Medium-grained sandstone	10.00	176.60	2330	40.60	1.50	0.28
No. 1-2 seam	1.90	178.50	1290	15.70	1.10	0.28
Fine-grained sand-stone	9.40	187.90	2270	29.60	1.50	0.27
Siltstone	3.80	191.70	2440	36.00	0.90	0.30
Fine-grained sand-stone	5.90	197.60	2340	48.50	1.90	0.29
Siltstone	1.00	198.60	2400	45.30	1.20	0.30
Fine-grained sand-stone	13.20	211.80	2300	45.60	2.20	0.27
No. 2-2 seam	4.60	216.40	1340	13.80	1.20	0.27
Siltstone	3.50	219.90	2340	20.50	0.15	0.34
Fine-grained sand-stone	8.70	228.60	2280	39.10	2.20	0.27
Siltstone	2.40	231.00	2400	42.50	0.70	0.31
Fine-grained sand-stone	11.70	242.70	2350	47.50	2.40	0.27
Medium-grained sandstone	6.90	249.60	2260	41.90	2.50	0.26
Siltstone	3.50	253.10	2400	46.30	1.80	0.28
No. 3-1 seam	2.70	255.80	1270	10.90	1.10	0.29
Fine-grained sand-stone	2.00	257.80	2330	43.10	2.00	0.25

Table 1. The parameters of coal and its roof and floor.

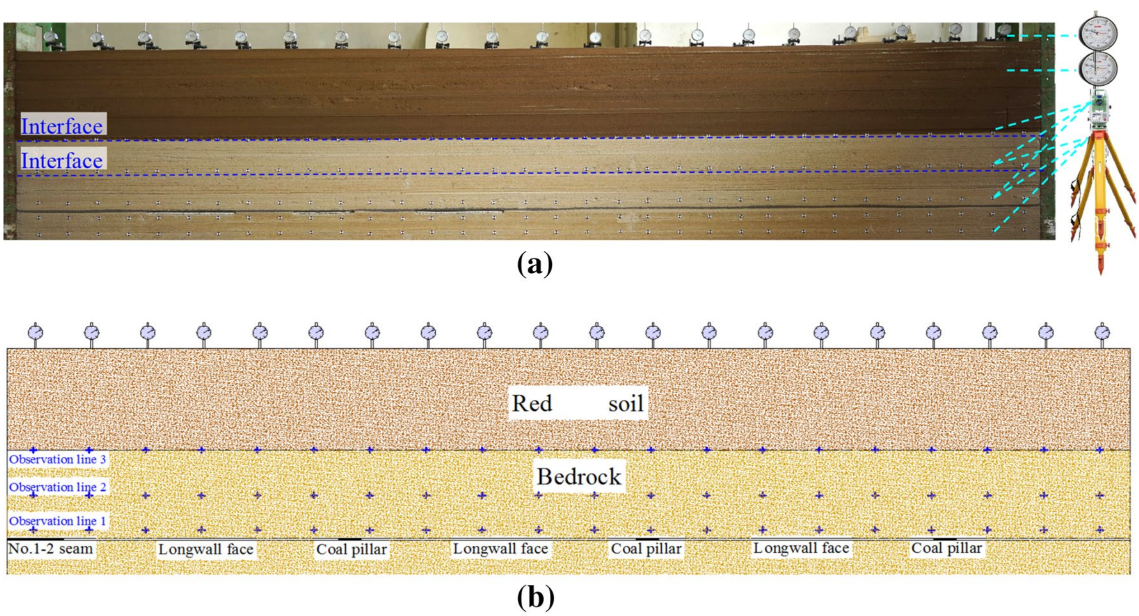

Figure 2. Physical simulation model: (**a**) Simulation model; (**b**) Position of observation lines.

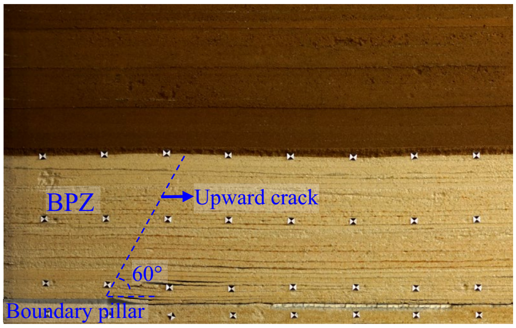

Figure 3. Strata subsidence in BPZ.

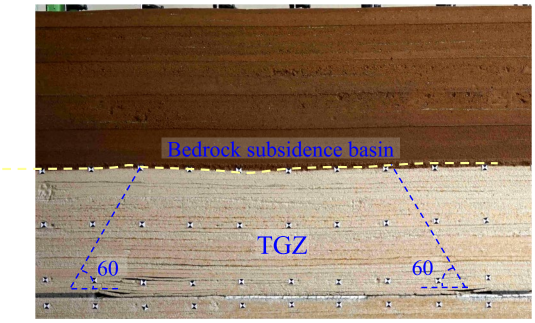

Figure 4. Strata subsidence in TGZ.

a. Line 1: 4 cm from the roof of No. 1-2 seam, monitoring the immediate roof subsidence.
b. Line 2: 20 cm from the roof of No. 1-2 seam, monitoring the key stratum subsidence.
c. Line 3: 40 cm from the roof of No. 1-2 seam, monitoring the interface subsidence.

After No. 1-2 seam mining, based on the subsidence and movement characteristics of the overburden strata, it can be divided into the following three zones in dip direction:

(1) Boundary pillar F-shape zone (BPZ)

The experiment shows that the upward crack is mainly located at the mining boundary, and the development angle is 60° (Fig. 3). Overall, the rock strata above BPZ are unbroken, but due to the rotation of rock strata on the mining side and the load of overburden, rock strata near the upward crack represent deflection.

(2) Trapezoid goaf zone (TGZ)

The upward cracks develop along the both sides boundaries of goaf, goaf represents trapezoid. The immediate roof caves and fills the goaf, the key stratum in bedrock can form articulated structure, which plays a skeleton role in the subsidence of overburden strata, the subsidence of ground surface depends on the subsidence basin of interface (bedrock subsidence basin). Overall, the subsidence in the middle of goaf is the largest, while it becomes smaller near the upward cracks (Fig. 4).

(3) Coal pillar inverted trapezoid zone (CPZ)

The overburden in CPZ represents "inverted trapezoid", Due to the "inverted trapezoid" structure by coal pillar, the subsidence of overburden strata and surface in CPZ is smaller. It can be known that the coal pillar causes the uneven subsidence of ground surface (Fig. 5).

According to physical similarity simulation, the movement and subsidence of overburden strata in dip direction is shown in Fig. 6. The subsidence in TGZ is the largest, while it is smaller in BPZ and CPZ, the movement of soil layer depends on the bedrock subsidence basin. In order to realize the quantitative analysis of the subsidence, it is necessary to establish the subsidence model based on the three zones above, and determine the subsidence of overburden strata and ground surface.

Subsidence prediction models and subsidence equations

Subsidence prediction model.

During mining, the overburden strata caves and moves from bottom to top, the subsidence of soil layer depends on the bedrock, consequently, the bedrock subsidence is analysed firstly. Based on the analysis above, the subsidence prediction model is established and shown in Fig. 7.

Where, h is the thickness of strata between the key stratum and coal seam, m; α is the caving angle, °; B_1 is width of the boundary pillar, m; L is the width of longwall face, m; B is width of coal pillar, m. The subsidence equation of the three zones should be solved respectively:

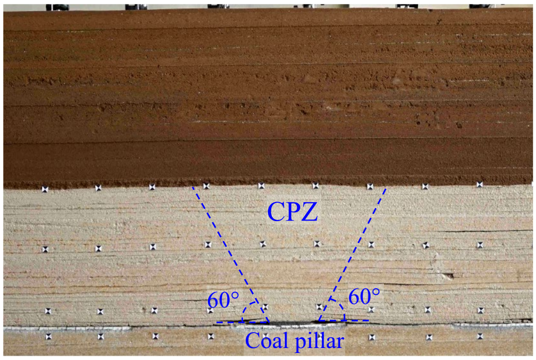

Figure 5. Strata subsidence in CPZ.

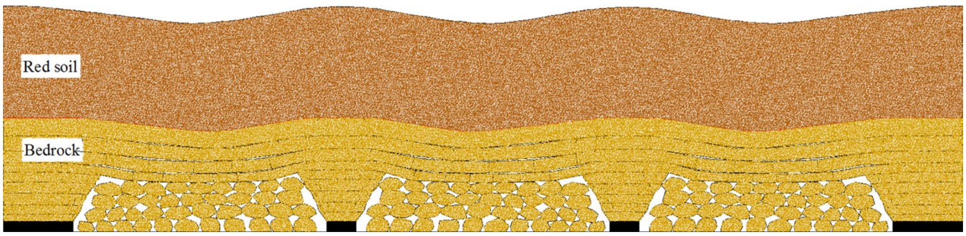

Figure 6. Movement and subsidence of overburden strata in dip direction.

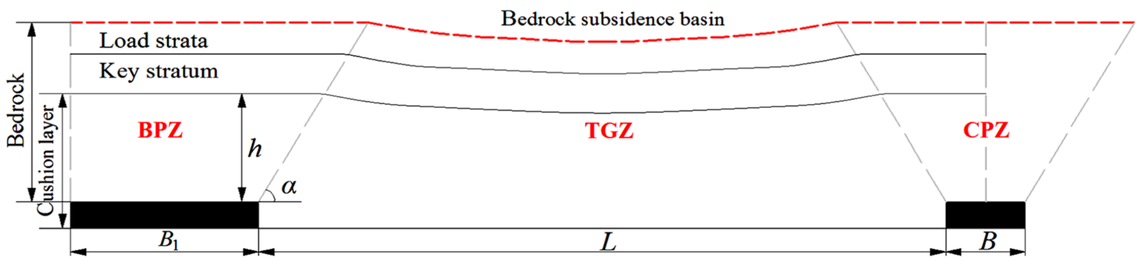

Figure 7. Subsidence prediction model in dip direction.

(1) TGZ: The key stratum plays a skeleton role in the bedrock subsidence, and its maximum subsidence value is related to the mining height, thickness of cushion layer and so on. The maximum subsidence is located in the middle of goaf, and it gradually decreases to the both sides, representing symmetrically distribution. The subsidence of load strata depends on the movement of the key stratum, finally it forms "bedrock subsidence basin" at the interface between the bedrock and soil layer.

(2) BPZ: The rock strata under the key stratum and coal seam can be regarded as "cushion layer", the subsidence equation of the key stratum in BPZ can be solved by Winkler elastic foundation beam model[42]. Caving angle had not considered in the in previous studies, in fact, it has an important influence on the subsidence of bedrock and soil layer, consequently it should be considered.

(3) CPZ: The elastic foundation in CPZ is the same as the BPZ, therefore, the improved Winkler elastic foundation beam model also can be used in CPITSZ. There are differences between CPZ and BPZ, one is the range of the zones, and another is that the subsidence curve in CPZ is symmetrical.

Bedrock subsidence equation. (1) Bedrock subsidence equation of TGZ

Due to the symmetry of TGZ, half of the zone is taken for study object, the coordinate system is established and shown in Fig. 8, according to subsidence and movement characteristics of the key stratum, the subsidence equation of key stratum in TGZ has been proposed by Reference[12]:

$$y_1(x) = y_{\max}\left[1 - \frac{1}{1 + \mathrm{e}^{(x-0.5l)/a}}\right] \quad \left(0 \le x \le \frac{L\tan\alpha - 2h}{2\tan\alpha}\right) \tag{1}$$

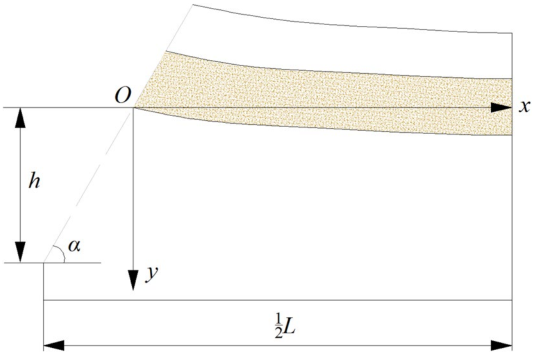

Figure 8. The mechanical model of key stratum in TGZ.

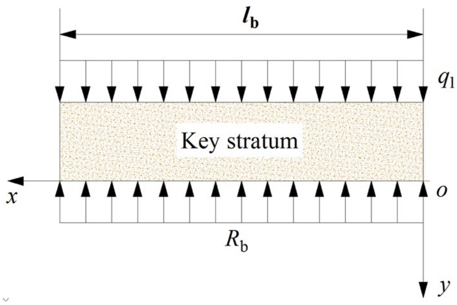

Figure 9. The mechanical model of key stratum in BPZ.

where, y_1 is subsidence value of the key stratum in TGZ, m; l is the block length of voussoir beam, m; a is coefficient related to lumpiness of voussoir beam and coal body stiffness, m, generally it is 0.25 l; y_{max} is the maximum subsidence value of the key stratum, m, it can be determined by the equation below:

$$y_{\max} = m - h\left(K_{\mathrm{p}} - 1\right) \tag{2}$$

where, m is the mining height, m; K_p the bulking coefficient of rock between the key stratum and coal seam.

Therefore, the subsidence equation of the key stratum in TGZ is:

$$y_1(x) = \left[m - h\left(K_{\mathrm{p}} - 1\right)\right]\left[1 - \frac{1}{1 + \mathrm{e}^{(x-0.5l)/a}}\right] \tag{3}$$

(2) Bedrock subsidence equation of BPZ

The improved Winkler elastic foundation beam model of the key stratum is established and shown in Fig. 9, l_b is the length of the key stratum, m; q_1 is the distribution load on the key stratum, MPa; R_b is the support stress of elastic foundation, MPa, it can be determined as:

$$R_{\mathrm{b}} = k_{\mathrm{b}} y_2 \tag{4}$$

$$l_{\mathrm{b}} = B_1 + \frac{h}{\tan\alpha} \tag{5}$$

where, y_2 is subsidence value of the key stratum in BPZ, m; k_b is the Winkler foundation coefficient, which is related to the thickness and mechanical properties of the elastic foundation, $k_b = E_0/h_0$, E_0 is the elastic modulus, MPa; h_0 is the foundation thickness, m.

The unit width of the key stratum is calculated with 1, consequently the subsidence differential equation of the key stratum is:

$$E_1 I_1 \frac{\mathrm{d}^4 y_2}{\mathrm{d}x^4} = q_1 - R_{\mathrm{b}} \quad (0 \le x \le l_b) \tag{6}$$

where E_1I_1 is bending rigidity of the key stratum, N·m^2.

According to Eqs. (4) and (6):

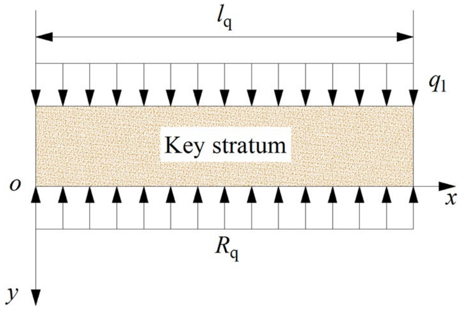

Figure 10. The mechanical model of key stratum in CPZ.

$$\frac{d^4y_2}{dx^4}+\left(\frac{k_b}{4E_1I_1}\right)4y_2=\frac{q_1}{E_1I_1}$$

Let $\beta_b=\sqrt[4]{k_b/4E_1I_1}$, where, β_b is characteristic coefficient of the foundation, therefore, the subsidence equation of the key stratum in BPZ is:

$$y_2(x)=e^{\beta_b x}(J\cos\beta_b x+K\sin\beta_b x)+e^{-\beta_b x}(U\cos\beta_b x+V\sin\beta_b x)+\frac{q_1}{k_b}$$

When it is far away from the mining boundary, the deflection of the key stratum tends to 0, consequently $J=K=0$, the equation above can be simplified as:

$$y_2(x)=e^{-\beta_b x}(U\cos\beta_b x+V\sin\beta_b x)+\frac{q_1}{k_b} \tag{7}$$

According to the relationship between TGZ and BPZ, the boundary conditions of the deflection curve equation are:

$$\begin{cases} y_1(x=0)=y_2(x=0) \\ y_1^{'}(x=0)=-y_2^{'}(x=0) \end{cases} \tag{8}$$

According to Eqs. (3), (7) and (8), it can be solved as:

$$\begin{cases} U=\dfrac{y_{\max}}{e^2+1}-\dfrac{q_1}{k_b} \\ V=\dfrac{y_{\max}}{e^2+1}-\dfrac{q_1}{k_b}+\dfrac{e^2y_{\max}}{a\beta_b\left(e^2+1\right)^2} \end{cases} \tag{9}$$

Therefore, the subsidence equation of the key stratum in BPZ is:

$$y_2(x)=e^{-\beta_b x}\left[\left(\frac{y_{\max}}{e^2+1}-\frac{q_1}{k_b}\right)\cos\beta_b x+\left(\frac{y_{\max}}{e^2+1}-\frac{q_1}{k_b}+\frac{e^2y_{\max}}{a\beta_b\left(e^2+1\right)^2}\right)\sin\beta_b x\right]+\frac{q_1}{k_b} \tag{10}$$

(3) Bedrock subsidence equation of CPZ

The subsidence curves in CPZ are symmetric, therefore, half of the zone is analysed, the elastic foundation beam model of CPZ is established and shown in Fig. 10. Where, l_q is the length of half of the key stratum in CPZ, m; R_q is the support stress of the elastic foundation, MPa, it can be determined as:

$$R_q=k_qy_3 \tag{11}$$

$$l_q=\frac{B}{2}+\frac{h}{\tan\alpha} \tag{12}$$

where, y_3 is subsidence value of the key stratum in CPZ, m; k_q is the Winkler foundation coefficient in CPZ, the same as the value in BPZ, $k_q=k_b=\frac{E_0}{h_0}$.

According to the analysis of BPZ, the subsidence curve equation of the key stratum is:

$$y_3(x)=e^{-\beta_b x}\left[\left(\frac{y_{\max}}{e^2+1}-\frac{q_1}{k_q}\right)\cos\beta_b x+\left(\frac{y_{\max}}{e^2+1}-\frac{q_1}{k_q}+\frac{e^2y_{\max}}{a\beta_b\left(e^2+1\right)^2}\right)\sin\beta_b x\right]+\frac{q_1}{k_q} \tag{13}$$

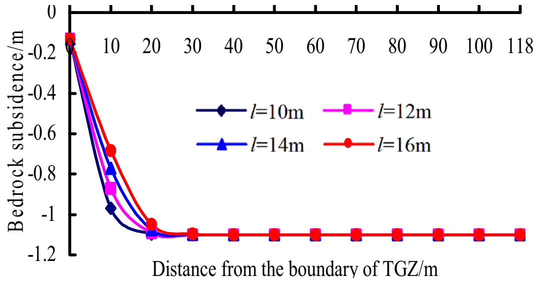

Figure 11. Bedrock subsidence vs. *l* in TGZ.

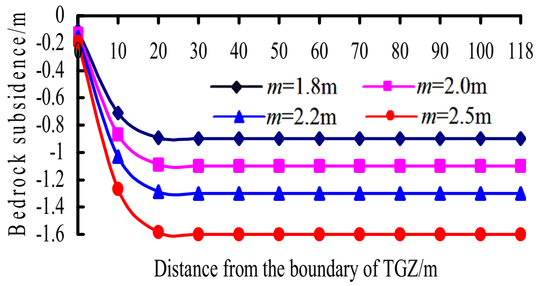

Figure 12. Bedrock subsidence vs. *m* in TGZ.

Soil layer subsidence equation. Due to the soil layer and the bedrock belong to two different medium, therefore, the subsidence characteristics are also different. The subsidence equation of soil layer should be established based on the subsidence equation of bedrock. At present, The stochastic medium theory is most widely used in the subsidence prediction of soil layer, which is recognized by most scholars[7,8,24,25], According to the probability integration method based on the stochastic medium theory, the subsidence equation of the surface soil layer is:

$$y_0(x) = \frac{y(x)}{2}\left[\operatorname{erf}\left(\frac{\sqrt{\pi}}{r}x\right) + 1\right] \tag{14}$$

where, $y_0(x)$ is the subsidence value of surface, m; r is the influence radius of soil layer, m; $y(x)$ is the subsidence value of the "bedrock subsidence basin", m, it is different in different zones:

$$\begin{cases} y(x) = y_1(x) & \text{TGZ} \\ y(x) = y_2(x) & \text{BPZ} \\ y(x) = y_3(x) & \text{CPZ} \end{cases} \tag{15}$$

$\operatorname{erf}\left(\frac{\sqrt{\pi}}{r}x\right)$ is Probability Integral Function, it can be determined by the Probability Integral Table.

According to the analysis above, subsidence of soil layer can be determined.

Subsidence effect factors of bedrock

Effect factors of bedrock in TGZ. According to the analysis above, subsidence of soil layer is based on the bedrock subsidence, therefore, the effect factors of bedrock subsidence are mainly analysed. According to the Eq. (3), the bedrock subsidence is mainly related to the mining height m, the thickness of rock between the key stratum and coal seam h, the bulking coefficient of rock K_p and the block length of voussoir beam l. According to the mining conditions of No. 1-2 seam in Ningtiaota coal mine, the calculation parameters are listed as follows: l = 10–16 m, m = 1.8–2.5 m, h = 6 m, K_p = 1.15, L = 245 m, α = 60°.

(1) When the mining height m = 2 m and l = 10–16 m, the change of bedrock subsidence curves with l is shown in Fig. 11. It can be known that:

a. The subsidence value of boundary point is invariable with l.

b. Within 30 m from the boundary of TGZ, As l increases, the bedrock subsidence acts as unobvious decrease.

c. When it is 30 m away from boundary, bedrock basically reaches fully subsidence, and the subsidence value does not change with l.

(2) When the block length of voussoir beam l = 12 m and m = 1.8–2.5 m, the change of bedrock subsidence curves with m is shown in Fig. 12. It can be known that:

a. As m increases, subsidence value of boundary point represents unobvious decrease.

b. As m increases, the maximum subsidence value decreases obviously, when it is 30 m away from boundary, the bedrock subsidence curves reach the peak value.

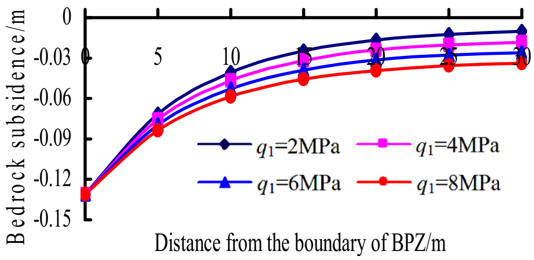

Figure 13. Bedrock subsidence vs. *q*igure in BPZ.

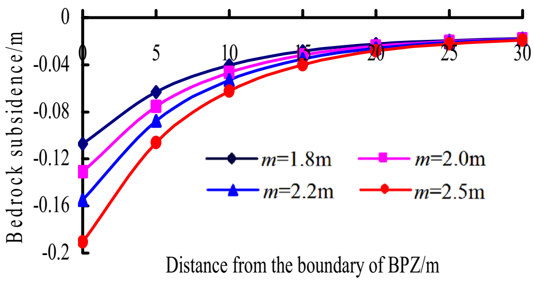

Figure 14. Bedrock subsidence vs. *m* in BPZ.

Overall, comparing with the block length of voussoir beam *l*, the mining height *m* has more obvious effect on the bedrock subsidence in TGZ.

Effect factors of bedrock in BPZ. Due to the subsidence equations of BPZ and CPZ are the same, only the range of the two zones is different, therefore, the effect factors of bedrock subsidence in BPZ are studied. According to Eq. (10), the bedrock subsidence in BPZ is mainly related to m, h, K_p, E_0, E_1I_1, and q_1, based on the mining conditions, the calculation parameters are listed as follows: $E_0 = 2500$ MPa, $h = 6$ m, $h_0 = 8$ m, $E_1I_1 = 164.6$ GN·m^2, $l = 12$ m, $K_p = 1.15$, $\alpha = 60°$, $B = 20$ m, the effect of m and q_1 on the bedrock subsidence is analysed.

(1) When the mining height $m = 2$ m and $q_1 = 2$–8 MPa, the change of bedrock subsidence curves with q_1 is shown in Fig. 13. It can be known that:

a. As the distance from the boundary of BPZ increases, the bedrock subsidence decreases at a decreasing speed.

b. With the value of q_1 increases, the bedrock subsidence increases, the subsidence curve is more gentle.

(2) When the distribution load on the key stratum $q_1 = 4$ MPa and $m = 1.8$–2.5 m, the change of bedrock subsidence curves with m is shown in Fig. 14. It can be known that:

a. Within 15 m from the boundary of BPZ, as the mining height increases, the bedrock subsidence increases obviously, and the closer to the boundary, the faster the bedrock subsidence increases.

b. When it is 15 m away from boundary, the effect of mining height on the bedrock subsidence is unobvious, and the bedrock subsidence value approaches 0.

Overall, the bedrock subsidence in BPZ is mainly related to the mining height and the distribution load on the key stratum. The mining height determines the subsidence value of boundary point, while the distribution load on the key stratum mainly affects the decreasing amplitude of the bedrock subsidence curves.

Verification of subsidence model

Theoretical model and physical simulation. Based on the mining conditions of No. 1-2 seam in Ningtiaota coal mine, $m = 2.0$ m, $l = 12$ m, $h = 6$ m, $K_p = 1.15$, $L = 245$ m, $\alpha = 60°$, $E_0 = 2500$ MPa, $h_0 = 8$ m, $E_1I_1 = 164.6$ GN·m^2, $B = 20$ m, $q_1 = 4$ MPa. According to Eqs. (3), (10) and (13), the bedrock subsidence curve can be obtained by theoretical model calculation.

In addition, according to observation data by physical simulation, the bedrock subsidence curve also can be obtained, the curves were shown in Fig. 15, it can be known that the result of theoretical calculation is basically consistent with physical simulation.

The buried depth of No 1-2 seam is 176.6 m ($H = 176.6$ m), and the tangent value of main influence angle $\tan\beta = 1.8$, consequently the influence radius of soil layer $r = H/\tan\beta = 98.1$ m, combining with Eq. (13), the soil subsidence curve is obtained. Combining with the observation data by physical simulation, the surface subsidence curves are shown in Fig. 16, it can be known that the result of theoretical calculation is basically consistent with physical simulation.

In-situ subsidence observation of surface. (1) Observation design

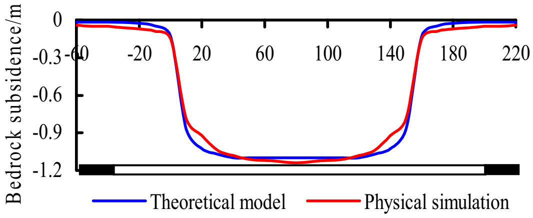

Figure 15. Bedrock subsidence curves.

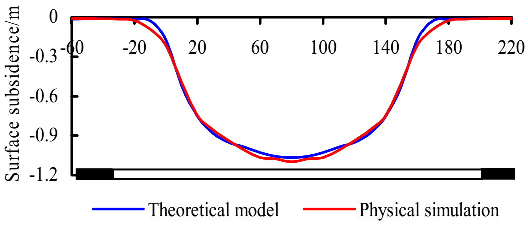

Figure 16. Surface subsidence curves.

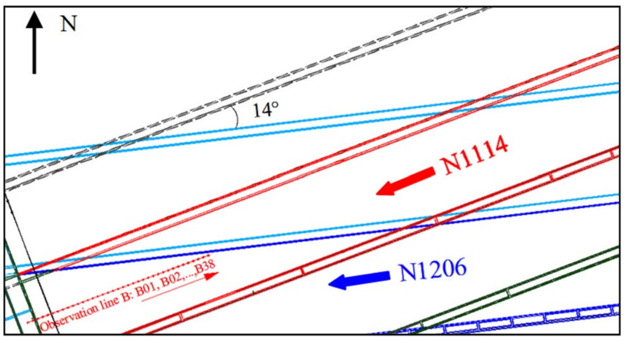

Figure 17. The arrangement of the observation line B.

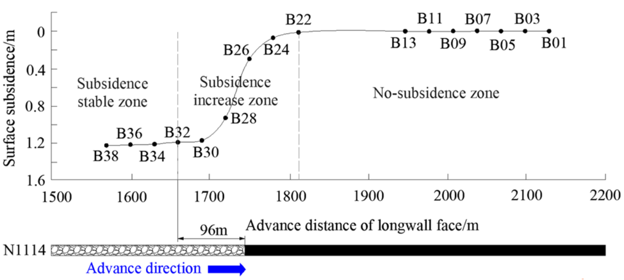

Figure 18. Surface subsidence by in-situ observation.

In-situ observation was carried out to obtain the surface subsidence of No. 1-2 seam mining in Ningtiaota coal mine[43], the depth of longwall face N1114 is 64–165 m, the thickness of bedrock is 54–66 m, the thickness of soil layer is 10–90 m, and its mining height is 1.9 m. The observation line B is arranged in the middle of the longwall face N1114 (Fig. 17), and it contains 38 observation points (B01, B02,…, B38).

(2) Observation results

When N1114 advances 1760 m, the surface subsidence is shown in Fig. 18. It can be divided into three zones, the first is no-subsidence zone which is in front of the longwall face. The second is subsidence increase zone, affected by mining, from Point B22 to B32, the surface subsidence increases. The third is subsidence stable zone, after longwall face advances, the caving roof becomes stable, and the subsidence tends to invariable.

Based on the observation data, the maximum subsidence value affected by N1114 mining is about 1.2 m. According to theoretical model calculation and physical simulation, the maximum subsidence is 1.07 m and 1.1 m respectively, consequently, the results obtained by the three methods are basically consistent.

Conclusions

During shallow coal seam mining, based on the subsidence characteristics of overburden strata, it can be divided into three structure zones in dip direction: boundary pillar F-shape zone (BPZ), trapezoid goaf zone (TGZ) and coal pillar inverted trapezoidal zone (CPZ). The subsidence in TGZ is the largest, while it is smaller in BPZ and CPZ.

The key stratum has control effect on the subsidence of overburden strata, and the subsidence of soil layer depends on the bedrock subsidence basin. The subsidence mechanical models of the three zones were established, and the subsidence equations of key stratum were given. According to the probability integration method based on the stochastic medium theory, the subsidence equation of the soil layer was obtained.

The effect factors of bedrock subsidence were analysed, the bedrock subsidence is mainly related to the mining height in TGZ, while they are mainly related to the mining height and the distribution load on the key stratum in BPZ and CPZ. the mining height determines the subsidence value of boundary point, while the distribution load on the key stratum mainly affects the decreasing amplitude of the bedrock subsidence curves.

The subsidence curves of bedrock and ground surface were obtained by theoretical model and physical simulation. The maximum subsidence of surface are 1.07 m and 1.1 m respectively by the two methods above, according to in-situ observation, it is about 1.2 m, they are basically consistent.

Data availability

The experimental data used to support the findings of this study are included within the article.

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References

1. Fan, L. M. *et al.* Groundwater response to intensive mining in ecologically fragile area. *J. China Coal Soc.* **41**, 2672–2678 (2016).
2. Song, S. J., Wang, S. M., Zhao, X. G. & Shen, T. Stratification transfer method of the mining subsidence based on the characteristics of layered structure in coal overburden. *J. China Coal Soc.* **43**, 87–95 (2018).
3. Lv, X., Wang, S. M., Yang, Z. Y., Bian, H. Y. & Liu, Y. Influence of coal mining on water resources: A case study in Kuye river basin. *Coal Geol. Explor.* **42**, 54–57 (2014).
4. Huang, Q. X. & Zhang, W. Z. *Roof Control of Water Conservation Strip-Filling Mining in Shallow Seam* (Science China Press, 2014).
5. Huang, Q. X. & Cao, J. Research on coal pillar malposition distance based on coupling control of three-field in shallow buried closely spaced multi-seam mining, China. *Energies* **12**, 462 (2019).
6. Bobrowsky, P. T. *Encyclopedia of Natural Hazards* (Springer, 2013).
7. Wang, S. M., Huang, Q. X., Fan, L. M. & Wang, W. K. *Coal Mining and Ecological Water Level Protection in Ecologically Fragile Areas* (Science China Press, 2010).
8. Gu, W., Tan, Z. X. & Deng, K. Z. Study on subsidence model based on double-medium mechanics coupling. *J. Min. Saf. Eng.* **30**, 589–594 (2013).
9. Zuo, J. P., Sun, Y. J. & Qian, M. G. Movement mechanism and analogous hyperbola model of overburden strata with thick alluvium. *J. China Coal Soc.* **42**, 1372–1379 (2017).
10. Yu, X. Y., Guo, W. B., Zhao, B. C. & Wang, F. L. Study on mining subsidence law of coal seam with thick overburden loess stratum. *Coal Sci. Technol.* **43**, 6–10 (2015).
11. Xu, G. S., Li, D. H., Hou, D. F. & Zhang, Y. B. Measurement and prediction of the transientsurface movement and deformation induced by mining under thick alluvium. *Rock Soil Mech.* **37**, 2056–2062 (2016).
12. Liu, W. G., Chen, T., Yao, J. K. & Zhao, X. D. Study on characteristics of overburden strata and surface subsidence under the shallow coal seam mining in Hanglaiwan coal mine. *J. Min. Saf. Eng.* **34**, 1141–1147 (2017).
13. Xu, J. L. & Qian, M. G. Study on the influence of key strata movement on subsidence. *J. China Coal Soc.* **25**, 122–126 (2000).
14. Zhu, W. B., Xu, J. L., Shi, X. S., Wang, X. Z. & Liu, W. T. Research on influence of overburden primary key stratum movement on surface subsidence with in-situ drilling test. *Chin. J. Rock Mech. Eng.* **28**, 403–409 (2009).
15. Wu, L. X., Wang, J. Z. & Zhao, S. S. Study of mining subsidence delay and concentration under the control of "holding-plate". *J. China Univ. Min. Technol.* **23**, 10–19 (1994).
16. Baek, J. *et al.* Analysis of ground subsidence in coal mining area using SAR interferometry. *Geosci. J.* **12**, 277–284 (2008).
17. Grzovic, M. & Ghulam, A. Evaluation of land subsidence from underground coal mining using TimeSAR (SBAS and PSI) in Springfield, Illinois, USA. *Nat. Hazards.* **79**, 1739–1751 (2015).
18. Zhao, G. B., Guo, W. B., Lou, G. Z. & Ma, Z. B. Numerical simulation of movement of both rock mass and surface under thick loose layer high-intensity mining condition. *China Saf. Sci. J.* **28**, 130–136 (2018).
19. Wang, Z. L. *et al.* Simulated and experimental study on the displacement tendency of the overburden strata in the mining of the shallow-buried coal seam. *J. Saf. Environ.* **17**, 2140–2145 (2017).
20. Xu, J. L., Qian, M. G. & Zhu, W. B. Study on influences of primary key stratum on surface dynamic subsidence. *Chin. J. Rock Mech. Eng.* **24**, 787–791 (2005).
21. Liu, Y. X., Dai, H. Y. & Guo, W. B. Surface movement laws of deep wide strip-pillar mining under thick alluvium. *J. Min. Saf. Eng.* **26**, 336–339 (2009).
22. Wu, K., Jin, J. M., Dai, Z. Q. & Jiang, J. B. The experimental study on the transmit of the mining subsidence in soil. *China Saf. Sci. J.* **27**, 601–603 (2002).
23. Xu, J. L., Lian, G. M., Zhu, W. B. & Qian, M. G. Influence of the key strata in deep mining to mining subsidence. *China Saf. Sci. J.* **32**, 686–690 (2007).
24. Fan, G. W., Zhang, D. S. & Ma, L. Q. Overburden movement and fracture distribution induced by longwall mining of the shallow coal seam in the Shendong coalfield. *J. China Univ. Min. Technol.* **40**, 196–201 (2011).
25. Unlu, T., Akcin, H. & Yilmaz, O. An integrated approach for the prediction of subsidence for coal mining basins. *Eng. Geol.* **166**, 186–203 (2013).

26. Alejano, L. R., Ramırez-Oyanguren, P. & Taboada, J. FDM predictive methodology for subsidence due to flat and inclined coal seam mining. *Int. J. Rock Mech. Min. Sci.* **36**, 475–491 (1999).
27. Yang, Z. L. Prediction of surface subsidence in underground mining seam based on the boundary value method. *Rock Soil Mech.* **31**, 232–236 (2010).
28. Wang, J. Z., Chang, Z. Q. & Chen, Y. Study on mining degree and patterns of ground subsidence in condition of mining under thick unconsolidated layers. *J. China Coal Soc.* **28**, 230–234 (2003).
29. Wang, J. Z., Li, Y. S., Zhou, X. & Wu, L. X. Ground movement caused by mining under thick alluvium. *J. China Coal Soc.* **22**, 18–22 (1997).
30. Zhang, X. D., Zhao, Y. H. & Liu, S. J. A new method of calculating surface subsidence and deformations under thick alluvial soil. *Chin. J. Nonferrous Met.* **9**, 435–440 (1999).
31. Wang, Y. H., Deng, K. Z., Wu, K. & Guo, G. L. On the dynamic mechanics of mining subsidence. *Chin. J. Rock Mech. Eng.* **22**, 352–357 (2003).
32. Hou, C. X. A study on relationship between overburden property and direction of influence propagation. *J. Xiangtan Min. Inst.* **14**, 20–24 (1999).
33. McCay, A. T., Valyrakis, M. & Younger, P. L. A meta-analysis of coal mining induced subsidence data and implications for their use in the carbon industry. *Int. J. Coal Geol.* **192**, 91–101 (2018).
34. Karmis, M., Agioutantis, Z. & Jarosz, A. Recent developments in the application of the influence function method for ground movement predictions in the US. *Min. Sci. Technol.* **10**, 233–245 (1990).
35. Singh, R. P. & Yadav, R. N. Prediction of subsidence due to coal mining in Raniganj coalfield, West Bengal, India. *Eng. Geol.* **39**, 103–111 (1995).
36. Huang, Q. X. & Zhang, W. Z. Mechanical model of water resisting strata group in shallow seam strip-filling mining. *J. China Coal Soc.* **40**, 973–978 (2015).
37. Chen, J., Du, J. P., Zhang, W. S. & Zhang, J. S. An elastic beam model of overburden strata movement during coal mining with gangue back-filling. *J. China Univ. Min. Technol.* **41**, 14–19 (2012).
38. Zhang, J. X., Li, J., An, T. L. & Huang, Y. L. Deformation characteristic of key stratum overburden by raw waste backfilling with fully-mechanized coal mining technology. *J. China Coal Soc.* **35**, 357–362 (2010).
39. Yao, Q., Feng, T. & Liao, Z. Damage characteristics and movement of inclined strata with sublevel filling along the strike in the steep seam. *J. China Coal Soc.* **42**, 3096–3105 (2017).
40. Zuo, J. P., Zhou, Y. B., Liu, G. W., Shao, G. Y. & Shi, Y. Continuous deformation law and curvature model of rock strata in coal backfill mining. *Rock Soil Mech.* **40**, 1097–1104 (2019).
41. Huang, Q. X., Zhang, W. Z. & Hou, Z. C. Study of simulation materials of aquifuge for solid-liquid coupling. *J. China Univ. Min. Technol.* **29**, 2813–2818 (2010).
42. Qian, M. G., Miao, X. X. & Xu, J. L. *Key stratum theory of roof control* (China University of Mining and Technology Press, 2000).
43. Zhao, B. C. *et al.* Analysis of surface rock movement parameters in ningtiaota coal mine superimposed mining. *Saf. Coal Mines.* **47**, 213–216 (2016).

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Jian Cao and Qingxiang Huang wrote the main manuscript text, and established the physical simulation experiment and theoretical model, Lingfei Guo analyzed the in-situ observation data. All authors reviewed the manuscript.

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