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 desertization1-3. Taking Hongjiamao 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 km², 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 pillar5, and the uneven subsidence has obvious effect on the surface buildings6. 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 bedrock7. Due to soil layer and bedrock belong to two different media, the subsidence characteristics are also different8-10. 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...
Subsidence. Wang et al.\textsuperscript{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.\textsuperscript{20} revealed the effect of primary key stratum on the dynamic surface subsidence. Liu et al.\textsuperscript{21} established the numerical model of strip-piller mining, the surface subsidence and horizontal movement contours under different alluvium thickness were given. Wu et al.\textsuperscript{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.\textsuperscript{23} studied the effect of key strata on ground surface subsidence. Taking three typical shallow coal seam conditions as the background, Fan et al.\textsuperscript{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.\textsuperscript{25} established a number of two dimensional finite element model to analyse the ground subsidence occurring due to mining. Alejano et al.\textsuperscript{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\textsuperscript{27} put forward a prediction method of surface based on the boundary value method. Wang et al.\textsuperscript{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.\textsuperscript{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.\textsuperscript{31} divided the strata movement into four stages, and the movement models of overburden strata were established. Hou\textsuperscript{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.\textsuperscript{33} proposed an universal tool for the estimation of maximum subsidence. Karmis et al.\textsuperscript{34} analysed the application of the influence function method for ground movement predictions, and demonstrated the applicability in U.S. coalfields. Singh et al.\textsuperscript{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.\textsuperscript{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 observations, 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\textsuperscript{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:

![Figure 1. The thickness of bedrock and soil layer in Ningtiaota coal mine.](https://doi.org/10.1038/s41598-021-98520-9)
| Lithology          | Thickness (m) | Depth (m) | Bulk density (kg/m³) | 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 sandstone | 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 sandstone | 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 sandstone | 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 sandstone | 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 sandstone | 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 sandstone | 2.00         | 257.80    | 2330                 | 45.10                     | 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.
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, \( m; \) \( \alpha \) 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:
(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\(^\text{42}\). 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\(^\text{12}\):

\[
y_1(x) = y_{\text{max}} \left[ 1 - \frac{1}{1 + e^{(x-0.5)/\alpha}} \right] \quad \left( 0 \leq x \leq \frac{L \tan \alpha - 2h}{2 \tan \alpha} \right) \quad (1)
\]
where, \( y_1 \) is subsidence value of the key stratum in TGZ, \( l \) 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:

\[
y_{max} = m - h(K_p - 1)
\]  

(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:

\[
y_1(x) = \left[ m - h(K_p - 1) \right] \left[ 1 - \frac{1}{1 + e^{(x - 0.5l)/a}} \right]
\]  

(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:

\[
R_b = k_b y_2
\]  

(4)

\[
l_b = B_1 + \frac{h}{\tan \alpha}
\]  

(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:

\[
E_1 I_1 \frac{d^4 y_2}{dx^4} = q_1 - R_b \quad (0 \leq x \leq l_b)
\]  

(6)

where \( E_1 I_1 \) is bending rigidity of the key stratum, N·m².

According to Eqs. (4) and (6):
Let $\beta_b = \sqrt{k_b/4E_1I_1}$, where, $\beta_b$ 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:

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

(7)

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

$$\begin{align*}
&y_1(x = 0) = y_2(x = 0) \\
y_1'(x = 0) = -y_2'(x = 0)
\end{align*}$$

(8)

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

$$\begin{align*}
U &= \frac{\gamma_{\text{max}}}{e^2+1} - \frac{q_1}{k_b} \\
V &= \frac{\gamma_{\text{max}}}{e^2+1} - \frac{q_1}{k_b} + \frac{e^2\gamma_{\text{max}}}{a\beta_b(e^2+1)^2}
\end{align*}$$

(9)

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

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

(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:

$$R_q = k_q y_3$$

(11)

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

(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, $k_q = k_b = \frac{E_0 h_0}{B}$.

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

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

(13)
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:

\[
y_0(x) = \frac{y(x)}{2} \left[ \text{erf} \left( \frac{\sqrt{\pi}}{r} x \right) + 1 \right]
\]  \hspace{1cm} (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:

\[
\begin{align*}
y(x) &= y_1(x) \quad \text{TGZ} \\
y(x) &= y_2(x) \quad \text{BPZ} \\
y(x) &= y_3(x) \quad \text{CPZ}
\end{align*}
\]  \hspace{1cm} (15)

\(\text{erf} \left( \frac{\sqrt{\pi}}{r} x \right)\) 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 mining conditions of No. 1-2 seam in Ningtiaota coal mine, the calculation parameters are listed as follows: \(l = 10–16\ m, m = 1.8–2.5\ m, h = 6\ m, K_p = 1.15, L = 245\ m, \alpha = 60^\circ\).

(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.
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 \( m, h, \) and \( K_p \), \( E_0, E_1, I_1, \) and \( q_1 \), based on the mining conditions, the calculation parameters are listed as follows: \( E_0 = 2500 \text{ MPa}, h = 6 \text{ m}, \) \( h_0 = 8 \text{ m}, E_1 I_1 = 164.6 \text{ GN-m}^2, l = 12 \text{ m}, K_p = 1.15, \) \( \alpha = 60^\circ, B = 20 \text{ m}, \) the effect of \( m \) and \( q_1 \) on the bedrock subsidence is analysed.

1. When the mining height \( m = 2 \text{ m} \) and \( q_1 = 2–8 \text{ MPa} \), 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 \( q_1 = 4 \text{ MPa} \) and \( m = 1.8–2.5 \text{ m} \), 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, \( m = 2.0 \text{ m}, l = 12 \text{ m}, h = 6 \text{ m}, K_p = 1.15, L = 245 \text{ m}, \alpha = 60^\circ, E_0 = 2500 \text{ MPa}, h_0 = 8 \text{ m}, E_1 I_1 = 164.6 \text{ GN-m}^2, B = 20 \text{ m}, q_1 = 4 \text{ MPa}. \) 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 \( (H = 176.6 \text{ m}) \), and the tangent value of main influence angle \( tan\beta = 1.8, \) consequently the influence radius of soil layer \( r = H/tan\beta = 98.1 \text{ m}, \) 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
In-situ observation was carried out to obtain the surface subsidence of No. 1-2 seam mining in Ningtiaota coal mine\(^4\), 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.

Received: 4 April 2021; Accepted: 8 September 2021
Published online: 23 September 2021

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Acknowledgements
We thank the National Natural Science Foundation of China (grant number No.51674190.) for its support of this study. We thank the academic editors and anonymous reviewers for their kind suggestions and valuable comments.

Author contributions
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.

Funding
This research was funded by the National Natural Science Foundation of China, grant number No.51674190.

Competing interests
The authors declare no competing interests.

Additional information
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