


## Article

# Quantitative Study on the Law of Surface Subsidence Zoning in Steeply Inclined Extra-Thick Coal Seam Mining

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**Abstract:** The damage of overlying strata and ground surface caused by the one-time mining space is relatively severe in steeply inclined extra-thick coal seams. The unique law of surface subsidence at these conditions is still missing. Taking Huating Dongxia Coal Mine as the research background, this paper reveals the law-governing effects on rock strata and surface movement and deformation caused by steeply inclined extra-thick coal seam mining with different coal seam dip angles and coal thicknesses by using the methods of surface measurement, theoretical analysis, and numerical simulation. Based on the characteristics of the surface inclination deformation, the surface is divided into four areas along the tendency section line—namely, an outcrop discontinuous deformation area, an overall subsidence area, a gradual subsidence area, and a slight subsidence area. The results show that the influence of the coal seam dip angle on surface subsidence zoning in steeply inclined and thick coal seams is mainly reflected in the affected area range and the form of damage. Coal thickness has a weak effect on the form of rock strata damage and surface movement. Utilizing the influence of the coal seam dip angle and coal seam thickness on the change in the surface subsidence zoning, the calculation formulas for each area range and zoning angle in relation to the coal seam dip angle, coal thickness, mining depth, and vertical stage height are established. The research results can provide a reference to evaluate the influence of mining, especially in steeply inclined extra-thick coal seams.

**Keywords:** steeply inclined extra-thick coal seam; numerical simulation; discontinuous deformation; surface subsidence zoning; influence range; zoning angle



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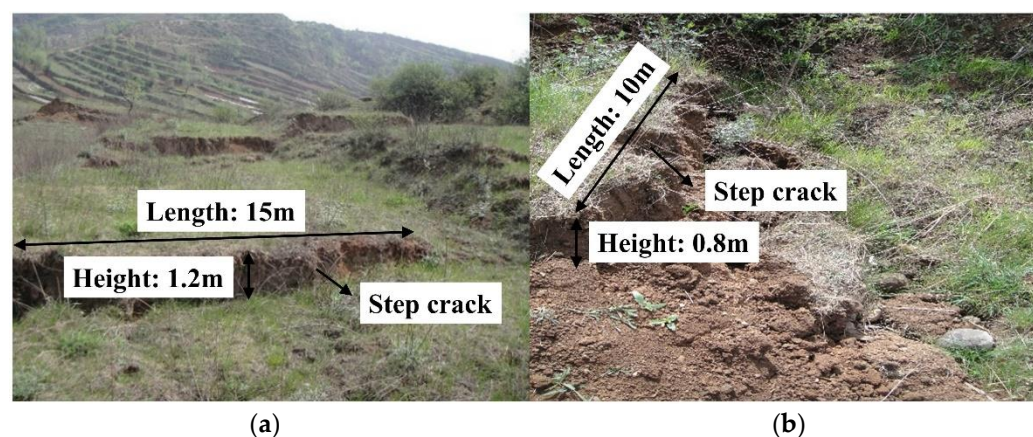


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## 1. Introduction

Generally speaking, a coal seam with a dip angle greater than  $45^\circ$  is a steeply inclined coal seam. The coal quality of steeply inclined coal seams is excellent, the degree of joint development and metamorphism is high, and the mining value is also high. Steep coal seams are widely distributed in China, covering many mining areas such as Huating, Beijing, Huainan, and Urumqi [1,2]. Compared with horizontal and gently inclined coal seams, steeply inclined coal seams have complex occurrence conditions and numerous influencing factors, and they undergo extensive changes. The outcrop area can become seriously damaged and it is easy for step cracks to form, as shown in Figure 1. There are thus many factors that lead to complex surface subsidence laws and rock strata control problems [3–5].

In recent years, a large number of scholars have produced a series of studies on rock damage, surface movement, and deformation laws in steep seam mining. The following two aspects can be noted: (1) the damage laws, mechanical mechanisms, rock strata control, and prediction methods for steep seam mining are studied based on field experience, mechanical theory, and numerical calculation methods; (2) the surface movement and deformation laws and surface subsidence zoning of steeply inclined coal seam mining are studied based on the analysis of measured data, similar material model tests, and numerical simulation.



**Figure 1.** Surface steps and cracks in a steeply inclined coal seam mine. (a) Surface steps; (b) Surface cracks.

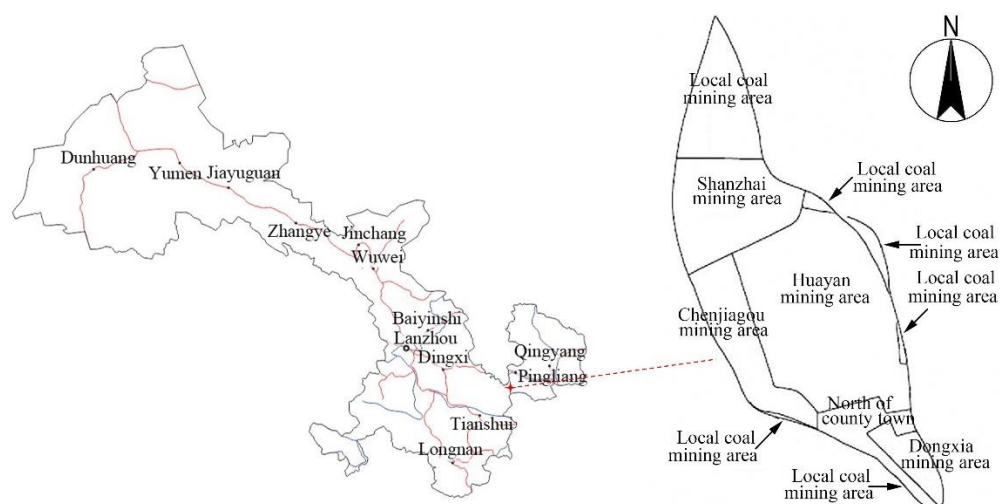
From the 1970s to 1985, the former Soviet Union carried out systematic research on steeply inclined coal seams and formulated the “Rules for the protection of natural objects and buildings in the mining area”, which summed up the typical predicted parameters for steeply inclined coal seam mining in the Dunbas mining area [6]. Afsari [7] used FLAC software to simulate the surface movement caused by the mining of steeply inclined coal seams and proposed a method to simulate the mining of inclined and steeply inclined coal seams, including a combination method utilizing both a macroscopic isotropic elastic model and a global node model. Alejano et al. [8] defined a rock behavior model and characteristics, used FLAC software to simulate the rock behavior characteristics, and proposed a prediction method for a surface subsidence trough basin in horizontal and inclined coal seam mining. Asadi [9] proposed a new section function method to predict the surface subsidence of inclined coal seam mining, and the results showed that the predicted value was in good agreement with the measured value. Ma et al. [10] used FLAC software to study the variation law for the stress and displacement of overlying strata caused by mining of steeply inclined coal seams under the influence of faults in Zhaozhuang. The results showed that due to the influence of a weak fault surface, the stress was concentrated around the roof and fault after mining. With an increase in the mining depth, the stress displacement around the fault changed obviously. Wang et al. [11] used numerical simulation to study the law determining overlying strata damage and coal pillar stability in a steeply inclined coal seam group, providing the technical basis for coal mining under buildings. Yang Fan [12] proposed a “factory”-type moving arch model of rock strata movement in steeply inclined coal seams utilizing the characteristics of rock strata movement and the force transmission mechanism and analyzed the stability of “factory”-type moving arch structures in steeply inclined coal seams, which provided a new theoretical basis for the prediction and control of mining subsidence in steeply inclined coal seams. Yi et al. [13] identified subsidence laws such as those that produce large surface movement ranges, severe deformations and easy formation of step cracks in the horizontal slicing mining of steeply inclined and extra-thick coal seams. They also proposed a calculation method for the surface movement angle parameter in horizontal slicing mining. Dai et al. [14,15] revealed the zoning characteristics of surface subsidence in space in steeply inclined coal seams based on the measured data accumulated over many years in Majiagou Mine, Tangshan. Utilizing the surface subsidence and its average change rate can divide the subsidence area into a slight subsidence area, a subsidence growth area, and an overall subsidence area. Yan et al. [16–18] used a similar material simulation to reveal the laws governing surface movement and deformation, surrounding rock collapse, and damage mechanisms. The surface subsidence basin can be divided into an outcrop subsidence area, an overall subsidence area, a gradual subsidence area, and a slight subsidence area.

The above research results combined with field practice, the characteristics of rock strata movement, and deformation under steeply inclined coal seam mining are studied. However, the stress condition and mechanical transmission mechanism of the rock strata caused by the mining of the steeply inclined coal seam are complex, and the research on the mining subsidence law of the steeply inclined coal seam in the relevant literature is not sufficient. At present, the research on the surface subsidence zoning is only qualitative research after mining the thin and medium-thickness coal seam, and the research on the surface subsidence zoning of the steeply inclined extra-thick coal seam is still in a relatively blank state. Because of this, in order to maintain the efficient and sustainable development of mining mines in steeply inclined extra-thick coal seams, it is necessary to study the subsidence law and surface subsidence zoning of steeply inclined extra-thick coal seams. This paper takes the steeply inclined extra-thick coal seam mining in Huating Dongxia Coal Mine as the research object, and the deformation and damage of rock strata, as well as the characteristics and laws of surface subsidence zoning in steeply inclined extra-thick coal seam mining, are analyzed and quantitatively studied. By changing the geometric conditions of coal seams, the formation, development, and deformation mode of surface subsidence zoning pattern is studied. The formation conditions and variation law of outcrop discontinuous deformation area are emphatically analyzed. The purpose is to provide guidance for the protection of buildings (structures) and land in the mining area and provide relevant theoretical guidance for preventing and controlling different subsidence areas in the mining area.

## 2. Materials and Methods

### 2.1. Overview of Study Area

The Huating mining area is located in Pingliang District of Gansu Province, which is jointly controlled by Huating County and Chongxin County. Figure 2 shows the geographical location and distribution of the Huating mining area, including Huayan, Shanzhai, Dongxia, and other mining areas. Dongxia Coal Mine is located in the southeast of Huating coalfield. The terrain in the mining area is complex, and the gully is vertical and horizontal. The surface is almost covered by loess, and the loess hilly landform is the main landscape. The highest altitude is +1701 m, and the lowest altitude is +1525 m. The general terrain is high in the southeast and low in the northwest.

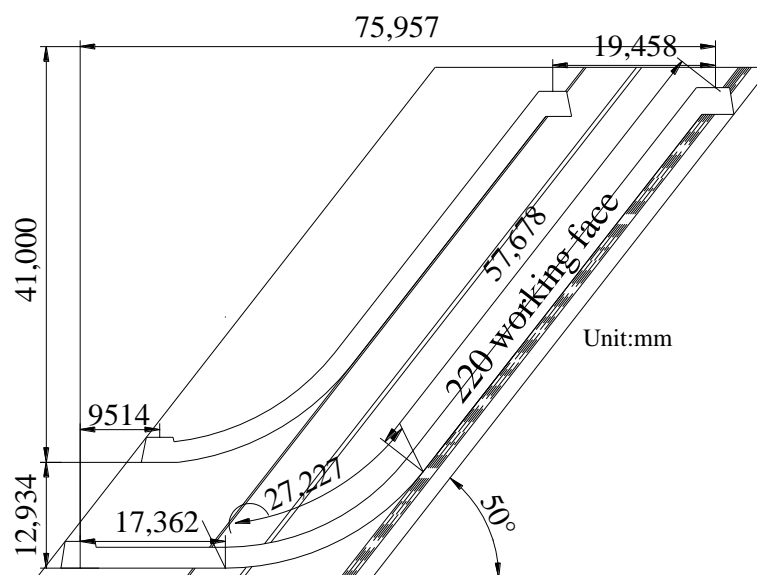


**Figure 2.** Geographical location and distribution of mining area.

The strata in the Dongxia mine are the Upper Triassic Yanchang Group, the Lower Jurassic Huating Group, the Middle Jurassic Zhiluo Group, the Lower Cretaceous Zhidan Group, the Upper Tertiary Gansu Group, and Quaternary. The direction of strata is generally  $20^{\circ}$  north to west (inclined to the southwest), the dip angle is  $28^{\circ}$ – $44^{\circ}$ , the shallow dip angle

is larger than the deep dip angle, and the northern dip angle is larger than the southern dip angle. The coal seam structure is simple in the north and complex in the south. The coal seam roof is sandy mudstone and mudstone, followed by carbonaceous mudstone; the north of the coal seam floor is mudstone and argillaceous sandstone, the middle is shale, and the south is carbonaceous shale.

The 220 working face is located in the west wing expansion area of the mine field. The average coal seam dip angle is  $50^\circ$ , the average coal thickness is 30 m, and the mining rate is 85%. The inclined length of the working face is 60 m, and the stage vertical height is 50 m. The mining depth of the lower trough is about 520 m, and the horizontal section is adopted. The working face adopts the longwall backward mining method. All caving methods manage the roof. The overlying strata can collapse automatically by gravity, and there are no additional measures to control surface subsidence. After the mining of the upper section is completed, and the next section of the working face is followed. The daily mining progress is 2.4 m, and the annual mining progress is 792 m. Figure 3 shows the layout of the working face.



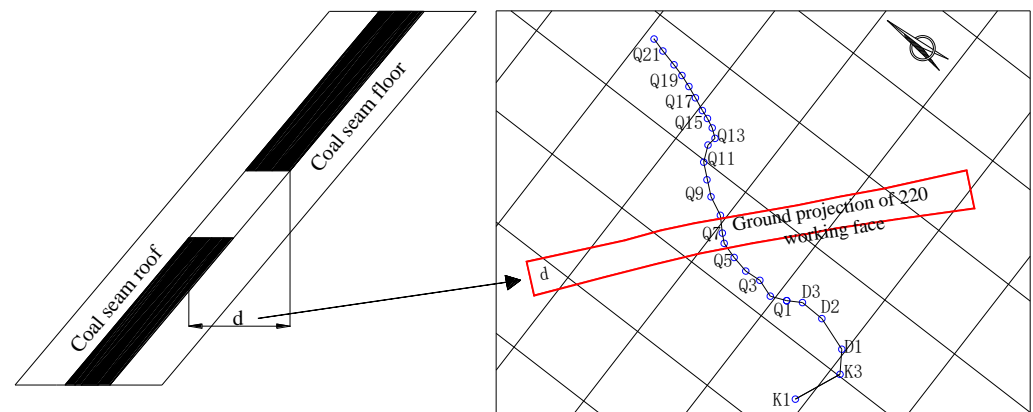
**Figure 3.** The layout of working face.

According to the terrain distribution of the 220 working face, an inclination observation line was set up. The inclination observation line is perpendicular to the strike of the working face. A measuring line is 820 m in length, including 28 monitoring points (3 control points and 25 monitoring points). The monitoring points numbered as D1, D2, D3, Q1, Q2...Q22, respectively, and the distance between each measuring points is 30 m. Three control points, K1, K2, and K3, respectively, with spaces of 50 m, are located outside the influence range of the working face (on the side of the floor). The layout of observation line is shown in Table 1, whereas the layout of measuring points and working face is shown in Figure 4.

**Table 1.** The layout of observation line.

Line Name	Time of Observation	Length (m)	Points Number	Observation Number	Remark
Q line	2012.7~2014.5	820	28	7	Vertical to the working face





**Figure 4.** The field layout of measuring points and working face.

## 2.2. Numerical Simulation

### 2.2.1. Introduction of 3DEC Numerical Simulation Software

In the field of geotechnical engineering, there are mainly numerical analysis methods, such as the finite element method (FEM), the finite difference method (FDM), the discrete element method (DEM), and the boundary element method (BEM). According to different principles, different numerical simulation software is generated, such as FLAC, PFC, and 3DEC [19].

FLAC is a finite difference software, mainly used through analyzing stress and plastic zone changes to express rock strata movement and deformation, and cannot directly see the surface discontinuous deformation. PFC is a particle flow software based on the discrete element. The numerical model is composed of many particles, which can intuitively see the development of cracks. However, it is difficult to model because of the large amounts of calculation involved. The analysis software 3DEC is based on the discrete element method. Because of the small amount of calculation required, simple modelling, and the ability to simulate discontinuous deformation, it is widely used in the engineering field. Based on the advantages and disadvantages of the above software, this paper selects the 3DEC software to carry out the related research on the law of surface subsidence zoning [20,21].

Furthermore, 3DEC software is a numerical analysis program used for discontinuous simulation developed by ITASCA based on two-dimensional discrete element software UDEC. This software has great application in rock engineering design and analysis, and is suitable for large deformation calculation, rotation calculation, and other problems. The application scope of 3DEC software covers the simulation analysis and calculation of rock slope instability, underground engineering excavation, rock joints, faults, and bedding structure effects. It can effectively solve the mechanical problems of potential instability caused by discontinuous characteristics [22].

### 2.2.2. Scheme Design and Parameter Determination

#### (1) Scheme design

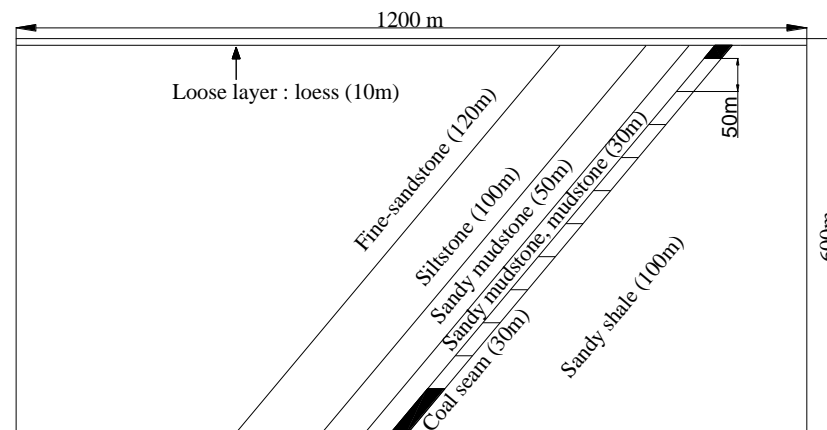
In order to study the surface subsidence zoning law, the surface movement, and the deformation law of steeply inclined thick coal seam mining, the 3DEC numerical simulation program was used to simulate coal seams with different geometric conditions under the same geological conditions. Taking the geological and mining conditions of Dongxia Mine as the prototype, a numerical model with a  $50^\circ$  dip angle and 30 m coal thickness was established. At the same time, the numerical models of different coal seam dip angles and coal thicknesses were established by changing the coal seam dip angle and coal thickness, namely the models of coal seam dip angles ( $45^\circ$ ,  $50^\circ$ ,  $55^\circ$ ,  $60^\circ$ ,  $70^\circ$ , and  $80^\circ$ ) (coal thickness of 30 m) and the models of coal thickness (20 m, 30 m, 40 m, and 50 m) (coal seam dip angle of  $50^\circ$ ). The specific simulation scheme is shown in Table 2.

**Table 2.** Numerical simulation scheme.

Number	Coal Seam Thickness (m)	Dip Angle (°)	Stage Mining Depth (m)	Stage Number	Mining Depth (m)
1	30	50	50	10	20~520
2	30	45	50	10	20~520
3	30	55	50	10	20~520
4	30	60	50	10	20~520
5	30	70	50	10	20~520
6	30	80	50	10	20~520
7	20	50	50	10	20~520
8	40	50	50	10	20~520
9	50	50	50	10	20~520

The numerical model is based on the steeply inclined extra-thick coal seam mining in the inclination direction of the Dongxia Coal Mine. The coal seam dip angle is  $50^\circ$ , the coal thickness is 30 m, the upper boundary of the goaf is 20 m, and the stage mining depth is 50 m. The model size is  $1200\text{ m} \times 600\text{ m} \times 1\text{ m}$ , and the thickness of the loose layer is 10 m. The Mohr–Coulomb model is selected as the constitutive model. According to different lithology, the mesh size of the model is divided into 10 m, 15 m, and 20 m, across a total of 3805 zones. The lateral displacement of the left and right boundaries of the model is constrained, and the bottom is clamped. The upper boundary is free and is loaded on the model by gravity (the gravity acceleration is  $9.8\text{ m/s}^2$ ).

There are seven layers of model rock strata. Except for the surface layer, the dip angle of the model rock strata is the same as that of the coal seam, and the names and thickness of each rock strata from left to right are as follows: (1) fine sandstone, with a thickness of 120 m; (2) siltstone, with a thickness of 100 m; (3) sandy mudstone, with a thickness of 50 m; (4) sandy mudstone and sandstone, with a thickness of 30 m; (5) coal seam, with a thickness of 30 m; and (6) sandy shale, with a thickness of 100 m. The surface layer is covered by loess, and the thickness is 10 m. The stratigraphic distribution is shown in Figure 5.

**Figure 5.** Numerical simulation design.

## (2) Parameter determination

The mechanical parameters are selected according to the geological conditions of the coal seam and the condition of the overlying strata, mainly including density, bulk modulus, shear modulus, friction angle, cohesion, and tensile strength. The relationship between bulk modulus  $K$ , shear modulus  $G$ , elastic modulus  $E$ , and Poisson's ratio  $\nu$  is as follows.

$$K = \frac{E}{3(1 - 2\nu)} \quad (1)$$

$$G = \frac{E}{2(1 + \nu)} \quad (2)$$

The block division of the discrete element should be based on the actual development and distribution of rock strata combined with the physical and mechanical properties of rock strata. The specific physical and mechanical parameters are shown in Tables 3 and 4. The selection of joint parameters is obtained by the empirical formula in [23,24].

**Table 3.** Physical and mechanical parameters of the 3DEC model.

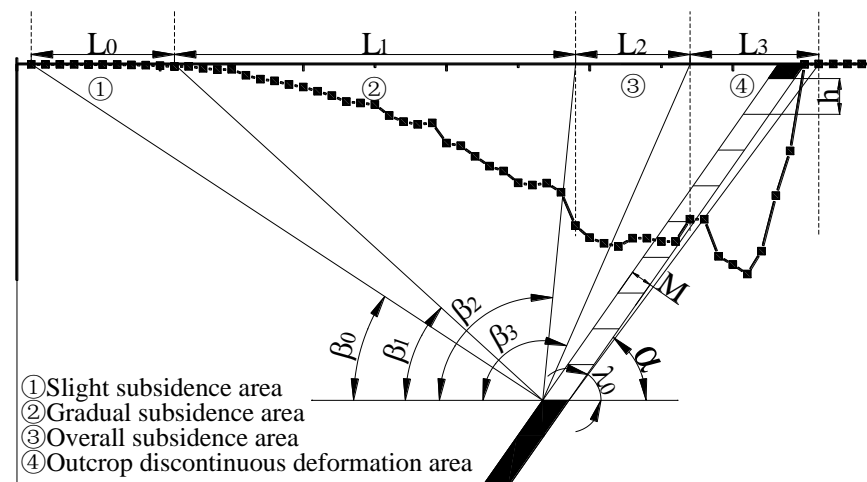
Lithology	Thickness (m)	Volume Weight (kg/m <sup>3</sup> )	Bulk Modulus (GPa)	Shear Modulus (GPa)	Cohesion (MPa)	Friction Angle (°)	Tension (MPa)
Sandy shale	100	2400	3.2	1.48	0.60	30	0.12
Coal	30	1350	1.62	0.62	0.28	28	0.10
Sandy mudstone and sandstone	30	2400	3.04	1.58	0.60	30	0.13
Sandy mudstone	50	2450	4.30	2.60	0.56	35	0.20
Siltstone	100	2300	2.80	1.28	0.48	34	0.24
Fine sandstone	120	2200	2.48	1.02	0.24	23	0.21
Loess	10	1600	0.16	0.06	0.20	17	0.10

**Table 4.** Physical and mechanical parameters of rock joints.

Lithology	Normal Stiffness (GPa)	Tangential Stiffness (GPa)	Friction Angle (°)	Cohesion (MPa)	Tension (MPa)
Sandy shale	3.2	1.48	22	0.21	0.12
Coal	1.62	0.62	20	0.13	0.10
Sandy mudstone and sandstone	3.01	1.58	22	0.21	0.13
Sandy mudstone	4.40	2.60	27	0.56	0.20
Siltstone	3.20	1.28	22	0.25	0.24
Fine sandstone	2.40	1.02	21	0.20	0.21
Loess	0.16	0.06	12	0.10	0.10

### 3. Quantitative Method of Surface Subsidence Zoning

According to the subsidence increase in the adjacent surface points in steeply inclined extra-thick coal seam mining, the surface movement basin can be divided into four areas from the coal seam floor to the roof: the outcrop discontinuous deformation area, the overall subsidence area, the gradual subsidence area, and the slight subsidence area. In order to further reveal the zoning law of surface subsidence in steeply inclined extra-thick coal seam mining, based on the results of field observation, it is determined that the surface subsidence of 10 mm is the outermost boundary in the slight subsidence area. The surface inclination deformation of 6 mm/m is the reference standard for other areas. At the same time, the subsidence curve is comprehensively determined as the division principle of each zoning boundary, as shown in Figure 6. In summary, we define the zoning angle and zoning range of each zone in steeply inclined extra-thick coal seam mining as follows.



**Figure 6.** Angle relation of each area.

(1) Floor boundary angle ( $\lambda_0$ )

The angle between the boundary point of the surface movement basin (subsidence of 10 mm) on the inclination main section and the boundary line on the floor side of the goaf and the horizontal line on the floor side.

(2) Roof boundary angle ( $\beta_0$ )

The roof boundary angle is also the zoning angle in the slight subsidence area, which tends to move the basin boundary point (subsidence of 10 mm) on the inclination main section to the angle between the boundary line on the roof side of the goaf and the horizontal line on the roof side.

(3) Zoning angle of the gradual subsidence area ( $\beta_1$ )

The angle between the boundary point on one side of the roof in the gradual subsidence area of the surface movement basin on the main section, the boundary line on the roof side of the goaf, and the horizontal line on the roof side.

(4) Zoning angle of the overall subsidence area ( $\beta_2$ )

The angle between the boundary point of the overall subsidence area of the surface movement basin on the inclination main section, the boundary line on the roof side of the goaf, and the horizontal line on the roof side.

(5) Zoning angle of the outcrop discontinuous deformation area ( $\beta_3$ )

The angle between the boundary point on the side of roof and the boundary line on the roof side of the goaf, and the horizontal line on the side of the roof in the outcrop discontinuous deformation area of the surface movement basin on the inclination main section.

(6)  $L_3$ : range of the outcrop discontinuous deformation area;  $L_2$ : range of the overall subsidence area;  $L_1$ : range of the gradual subsidence area;  $L_0$ : range of the slight subsidence area.

In [17,18,25], the authors believe that the main factors affecting the zoning law of surface subsidence are coal seam dip angle, coal thickness, mining depth, and stage vertical height. The change in surface subsidence zoning is mainly reflected in the surface subsidence, scope, and each zoning angle. Therefore, on this basis, this paper establishes the calculation model of zoning scope and zoning angle and various influencing factors, expressed by Formulas (3) and (4).

$$L = f(\alpha, H, M) \quad (3)$$

$$\beta = f(\alpha, h, M) \quad (4)$$



where  $L$  is the zoning range,  $\beta$  is the zoning angle,  $\alpha$  is the coal seam dip angle,  $h$  is the stage vertical height,  $M$  is the coal thickness, and  $H$  is the mining depth.

The influence range of surface subsidence in the outcrop discontinuous deformation area is:

$$L_3 = H(\cot \lambda_0 - \cot \beta_3) \quad (5)$$

The influence range of surface subsidence in the overall subsidence area is:

$$L_2 = H(\cot \beta_2 - \cot \beta_3) \quad (6)$$

The influence range of surface subsidence in the gradual subsidence area is:

$$L_1 = H(\cot \beta_1 - \cot \beta_2) \quad (7)$$

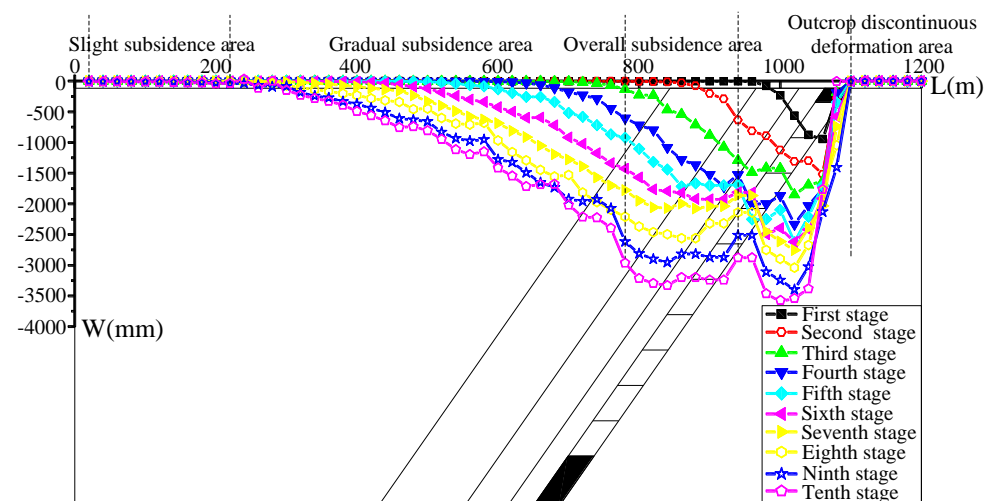
The influence range of surface subsidence in the slight subsidence area is:

$$L_0 = H(\cot \beta_0 - \cot \beta_1) \quad (8)$$

## 4. Results and Analysis

### 4.1. Division of Surface Subsidence Zoning

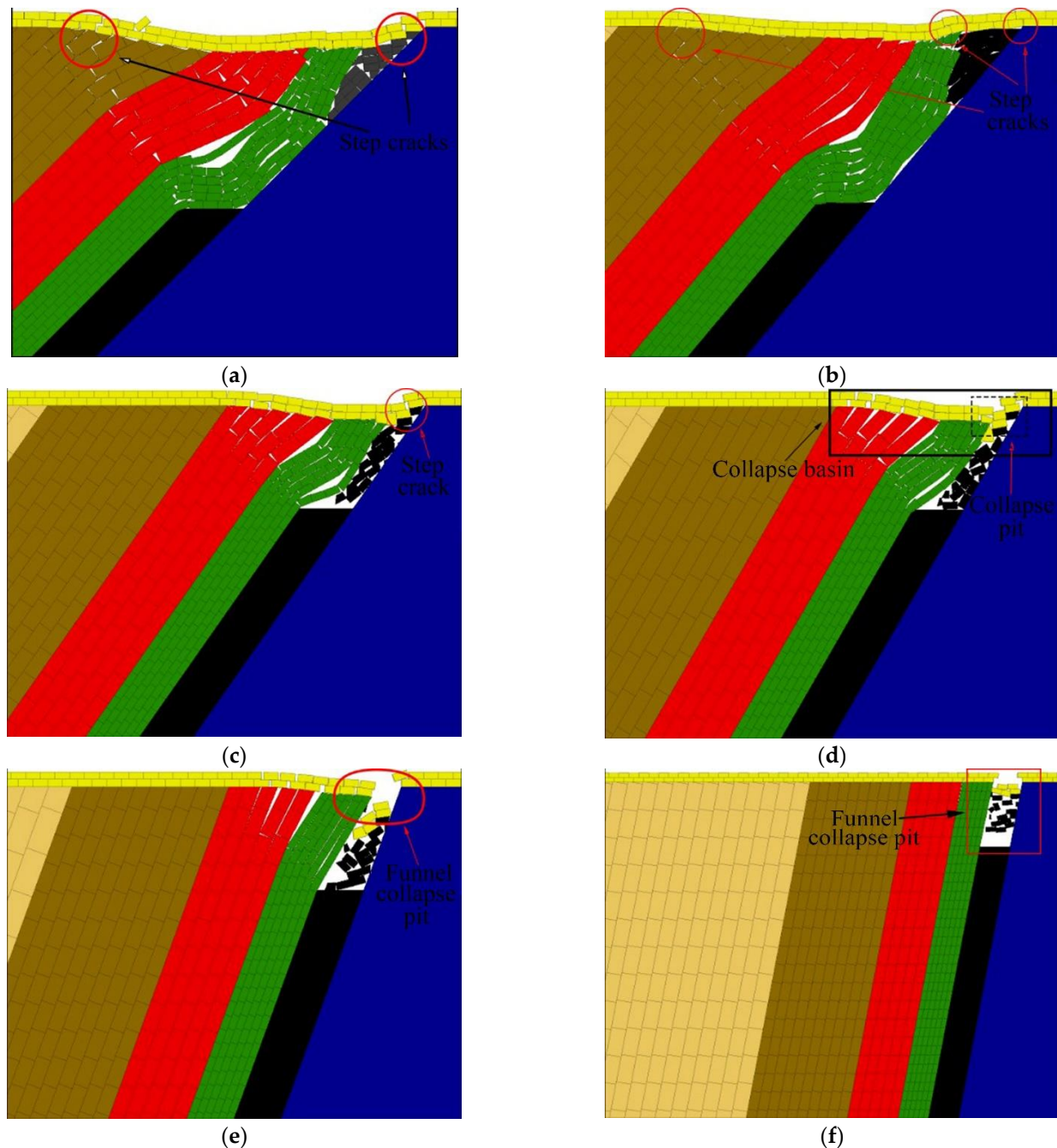
The subsidence curve is plotted by extracting the surface subsidence values calculated by the numerical model, as shown in Figure 7. In the early stage of working face mining, the subsidence curve is relatively gentle. With the deepening of mining, the influence range of surface movement and deformation is mainly extended to the roof side. The center of the surface subsidence curve shifts to the uphill side, showing obvious asymmetry. The surface influences the degree and range of the roof side, which are greater than those of the floor side. After the end of mining, the maximum surface subsidence is 3655 mm. According to the measured data of the surface, after the mining of the 220 working face, the maximum subsidence value of the surface is 3590 mm. By comparison, the numerical simulation results are evidently not much different from the actual results, indicating that the 3DEC numerical simulation software is reliable and correct for studying the zoning law of the surface subsidence.



**Figure 7.** Surface subsidence curve.

According to the representation method of the surface subsidence zoning in Section 3, the subsidence curve is divided, as shown in Figure 8. It can be seen from the figure that the difference of surface subsidence is large. However, the difference of subsidence in the same subsidence area is small, especially in the overall subsidence area and the slight subsidence area, and the amount of deformation is also small. The coal seam outcrop and its vicinity

are prone to serious discontinuous deformation, mainly reflected as cracks or collapse pits. In the overall subsidence area, the subsidence is large, but the surface inclination amount is small, and the surface subsidence is overall. The gradual subsidence area connects the slight subsidence area with the overall subsidence area or the outcrop discontinuous deformation area, and the subsidence varies greatly. The subsidence in the slight subsidence area is small, and the change in the surface damage range is stable. The subsidence increment in the subsidence area shows that the subsidence variation in the slight subsidence area is the smallest, followed by the overall subsidence area and the gradual subsidence area, and the subsidence variation in the outcrop discontinuous deformation area is the largest.



**Figure 8.** The outcrop discontinuous deformation of shallow mining. (a) Coal seam dip angle of  $45^\circ$ , (b) coal seam dip angle of  $50^\circ$ , (c) coal seam dip angle of  $55^\circ$ , (d) coal seam dip angle of  $60^\circ$ , (e) coal seam dip angle of  $70^\circ$ , and (f) coal seam dip angle of  $80^\circ$ .

According to Formulas (3)–(8), the zoning ranges of surface subsidence can be obtained as follows:  $L_0 = 120$  m;  $L_1 = 480$  m;  $L_2 = 200$  m; and  $L_3 = 180$  m. The total influence range of surface subsidence is 980 m.

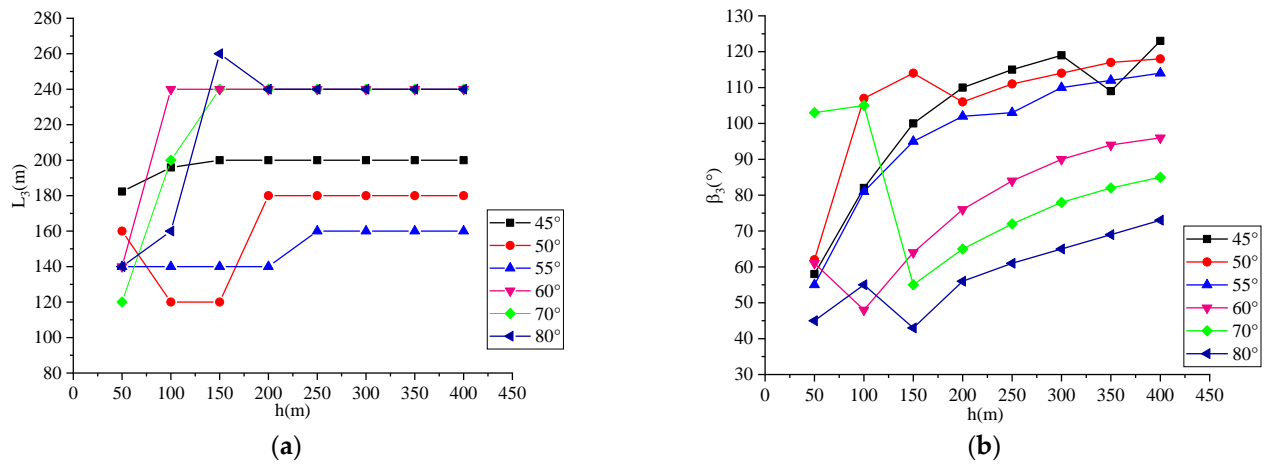
#### 4.2. Analysis of the Law of Surface Subsidence Zoning with the Change in the Coal Seam Dip Angle

With an increase in the coal seam dip angle, the degree of surface discontinuous deformation near the coal seam outcrop increases continuously, as shown in Figure 8. When the dip angle of the coal seam is less than  $55^\circ$ , in shallow mining, the coal above the goaf slides to the goaf under the action of its gravity parallel to the floor. At the same time, the roof rock above the goaf bends and collapses to the goaf, and a part of the rock mass squeezes and slides the coal. Under the combined action of the two, the surface near the coal seam outcrop is mainly characterized by the collapsed basin. The surface of the floor side and the roof side appear step cracks. The damage degree of the floor side is greater than that of the roof side. With an increase in the mining depth, the slope of the floor side increases.

When the dip angle of the coal seam is greater than  $55^\circ$ , in the shallow mining process, under the combined effect of the dip angle of the coal seam and the gravity of overlying strata, the coal above the goaf falls to the goaf and fills the goaf, which inhibits the caving of the boundary roof under the goaf. The boundary space above the goaf expands continuously, and the loose layer falls to the boundary space above the goaf, resulting in the formation of collapse pits on the surface. The size and offset distance of the collapse pit are related to the dip angle of the coal seam. The larger the dip angle of the coal seam, the larger the size of the collapse pit, and the smaller the deviation from the top of the coal seam outcrop. Because the coal above the goaf fills the goaf, which inhibits the collapse of the roof at the lower boundary of the goaf, a cantilever beam structure is formed at the upper boundary of the goaf. The larger the dip angle of the coal seam, the smaller the bending degree of the cantilever beam, the smaller the horizontal movement of the surface, and the deeper the funnel collapse pit formed on the surface. At the same time, the larger the coal seam dip angle, the longer the collapse pit exists. This is because the cantilever beam formed by the roof after coal seam mining is perpendicular to the side of the floor, and the cantilever beam needs a certain length to collapse to the goaf. When the coal seam with the dip angle of  $80^\circ$  is mined to the fourth stage (the mining depth is 200 m), the cantilever rock mass is filled in the goaf, and the funnel collapse pit gradually disappears.

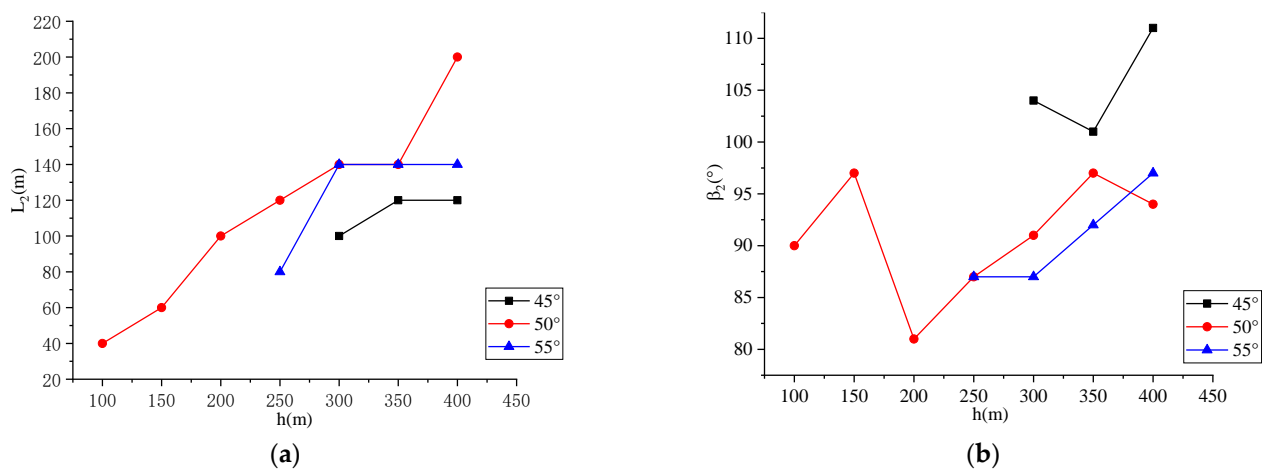
Figure 9 shows the variation curve of the range and zoning angle of the outcrop discontinuous deformation area with different coal seam dip angles. It can be seen from the figure that the range and zoning angle change more obviously during the shallow mining (50 m~200 m). When the coal seam dip angle is less than  $55^\circ$ , the range of the outcrop discontinuous deformation area decreases with an increase in the coal seam dip angle; when the coal seam dip angle is greater than  $55^\circ$ , the range of the outcrop discontinuous deformation area increases with an increase in the coal seam dip angle. During deep mining, the range of the outcrop discontinuous deformation area of each outcrop is no longer significantly changed, because the formation of the outcrop discontinuous deformation area is mainly caused by the collapse of coal above the goaf and the collapse of roof strata during shallow mining. When the coal seam dip angle is less than  $55^\circ$ , after the coal is mined out, the roof strata of the goaf bend to the goaf, which inhibits the surface movement above the goaf, and the surface subsidence tends to the downhill direction. With an increase in the coal seam dip angle, the coal caving in the upper part of the goaf increases, making it easier to form collapse pits above the goaf. The damage range of the outcrop discontinuous deformation area is more concentrated in the upper part of the goaf. When the coal seam dip angle is greater than  $55^\circ$ , after the coal is mined out, the upper coal of the goaf is filled in the goaf first, and the surface collapse pit appears. Due to the effect of the coal seam dip angle, the rock mass on the roof side will bend to the goaf in the form of a cantilever beam, thus filling the goaf. During the shallow mining, the collapse pits appear, while in deep mining, large cracks and steps appear on the surface, and the overall subsidence area no

longer appears on the surface, all of which are manifested as the outcrop discontinuous deformation area, increasing the range of the discontinuous deformation area. During deep mining, the area scope remains stable, and the change in the zoning angle is stable.



**Figure 9.** The variation curve of the range and zoning angle of the outcrop discontinuous deformation area with different coal seam dip angles. (a) The variation curve of the range, (b) the variation curve of the zoning angle.

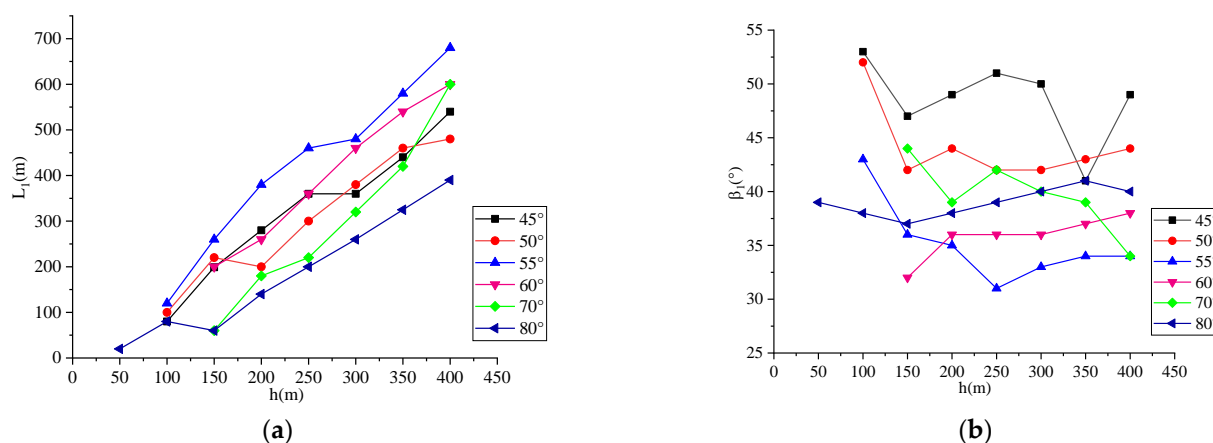
Figure 10 shows the variation curve of the range and zoning angle of the overall subsidence area with different coal seam dip angles. The overall subsidence area shows large subsidence, but the change in inclination is small. In the shallow mining of steeply inclined extra-thick coal seam, the surface mainly demonstrates discontinuous damage, and there is no overall subsidence area on the surface. When deep mining is carried out, due to a gradual increase in the range of internal rock movement, a part of the surface originally belonging to the gradual subsidence area forms an overall subsidence area. It can be seen from the figure that the overall subsidence area mainly occurs below the dip angle of the coal seam 55°, and it is easy to occur in deep mining. When the dip angle of the coal seam is greater than 55°, the “integrity” of the overall subsidence area no longer appears, but is presented in discontinuous deformation (large cracks and large steps). With the deepening of mining, the discontinuous deformation intensifies.



**Figure 10.** The variation curve of the range and zoning angle of the overall subsidence area with different coal seam dip angles. (a) The variation curve of the range, (b) the variation curve of the zoning angle.

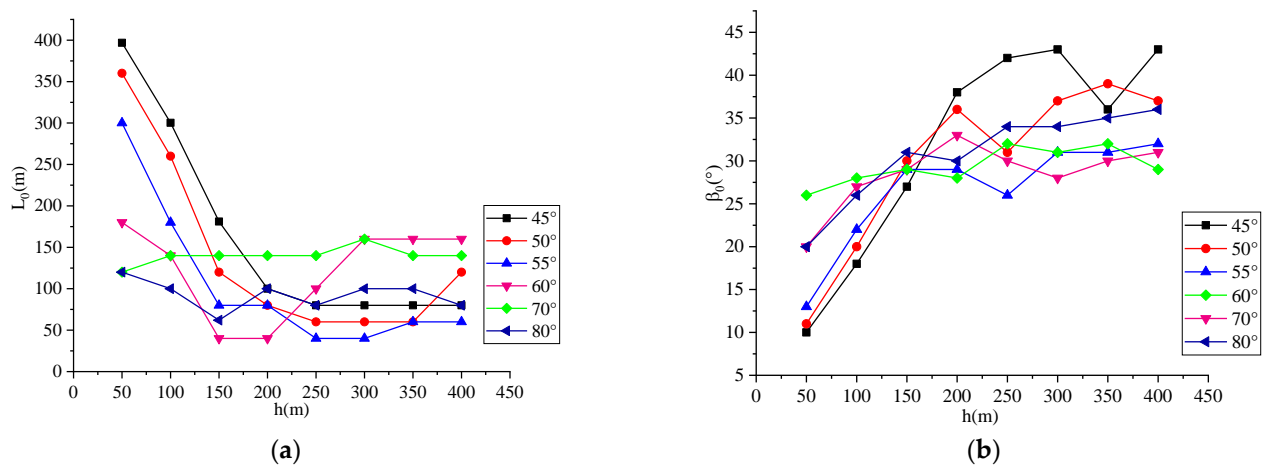


Figure 11 shows the variation curve of the range and zoning angle of the gradual subsidence area with different coal seam dip angles. It can be seen from the figure that with an increase in the mining depth, the range of gradual subsidence area increases continuously, and the growth rate remains stable. At the same time, with an increase in the coal seam dip angle, the range of gradual subsidence area is smaller. This is because with an increase in the coal seam dip angle, the influence range of the surface is more concentrated, and the surface deformation shifts more significantly to the side of the floor, and the horizontal movement is larger. When the dip angle of the coal seam is greater than  $55^\circ$ , the surface subsidence shows “mutation”, that is, from the discontinuous deformation area with large subsidence to the slight subsidence area with small subsidence, the range of intermediate gradual subsidence area is small, and the excessive area is not obvious. When the coal seam dip angle is less than  $55^\circ$ , the surface subsidence curve deviates significantly from the downhill side, and the surface subsidence changes more gently, and the range of gradual subsidence area is larger.



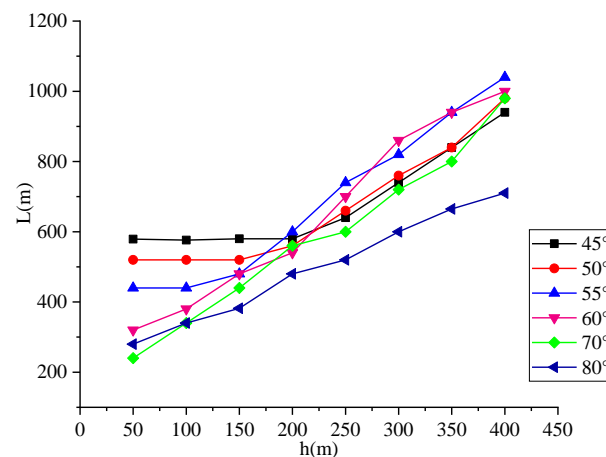
**Figure 11.** The variation curve of the range and zoning angle of the gradual subsidence area with different coal seam dip angles. (a) The variation curve of the range, (b) the variation curve of the zoning angle.

Figure 12 shows the variation curve of the range and zoning angle in the slight subsidence area with different coal seam dip angles. The slight subsidence area is the area with small surface subsidence and shows a certain integrity. The surface horizontal movement and inclination deformation are small. It can be seen from the figure that in shallow mining, a larger coal seam dip angle correlates with a smaller range in the slight subsidence area. This is because a smaller coal seam dip angle causes a larger influence range. The larger the coal seam dip angle, the more concentrated the damage is. With an increase in the mining depth, the range in the slight subsidence area decreases. At this time, the larger the dip angle of the coal seam, the larger the range in the slight subsidence area. This is because with a larger dip angle of the coal seam, the damage gradually concentrates in the outcrop area, and the surface subsidence shows a sudden change. From the outcrop discontinuous deformation area with very serious damage to the overall subsidence area, the excessive effect of the intermediate gradual subsidence area is no longer obvious, so the gradual subsidence area is small, and the slight subsidence area is large. When the dip angle of the coal seam is smaller, the surface area which belongs to the slight subsidence area is easier to change into the gradual subsidence area, and the change in the surface subsidence area is gentler, which makes the gradual subsidence area increase and the slight subsidence area decrease. Ultimately, the larger the dip angle of the coal seam, the larger the range in the slight subsidence area.



**Figure 12.** The variation curve of the range and zoning angle in the slight subsidence area with different coal seam dip angles. (a) The variation curve of the range, (b) the variation curve of the zoning angle.

Figure 13 presents the variation curve of the surface subsidence range with different coal seam dip angles. It can be seen from the figure that with the coal seam dip angle of 55° as the dividing line, the range of the surface subsidence basin shows different trends. The larger the coal seam dip during the shallow mining, the smaller the range of the surface subsidence basin. With the deepening of mining, when the coal seam dip angle is less than 55°, a larger coal seam dip angle correlates with a larger range in the subsidence basin. When the coal seam dip angle is greater than 55°, a larger coal seam dip angle correlates with a smaller influence range in the subsidence basin.



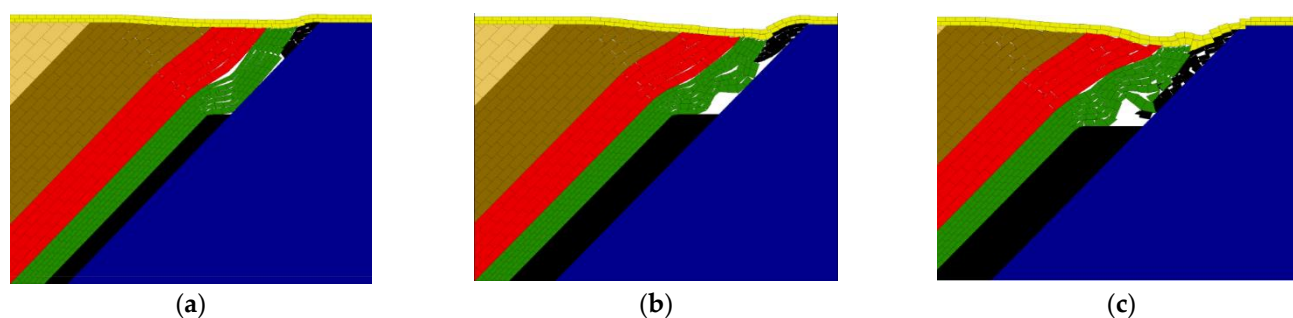
**Figure 13.** The variation curve of the surface subsidence range with different coal seam dip angles.

The above analysis shows that with the change in the coal seam dip angle, the surface subsidence zoning changes show different forms, and the influence of the coal seam dip angle on the mining zoning law is very obvious. When the outcrop discontinuous deformation area is shallow mining, a larger dip angle of the coal seam correlates with a smaller range of the outcrop discontinuous deformation area. However, in deep mining, a larger dip angle of the coal seam leads to a larger range, and the surface damage forms are mainly collapsed pits and step cracks. The overall subsidence area is characterized by large surface subsidence and small inclination deformation. With a change in the coal seam dip angle, the form is different: a larger coal seam dip angle increases the range, and the overall subsidence area is presented in the form of collapse basins. When the dip angle is greater than 55°, the overall subsidence area no longer appears. Most of it is integrated with the outcrop discontinuous deformation area. The surface demonstrates

serious discontinuous deformation. The gradual subsidence area shows that a larger coal seam dip angle reduces the range. When the slight subsidence area is shallow mining, a larger coal seam dip angle reduces the range. However, in deep mining, a larger coal seam dip angle increases the range. At the same time, for the mining of steeply inclined extra-thick coal seam with the same dip angle, with an increase in the mining depth, the range of the outcrop discontinuous deformation area and the overall subsidence area becomes larger, while the range in the slight subsidence area becomes smaller.

#### 4.3. Analysis of the Law of Surface Subsidence Zoning with the Change in the Coal Thickness

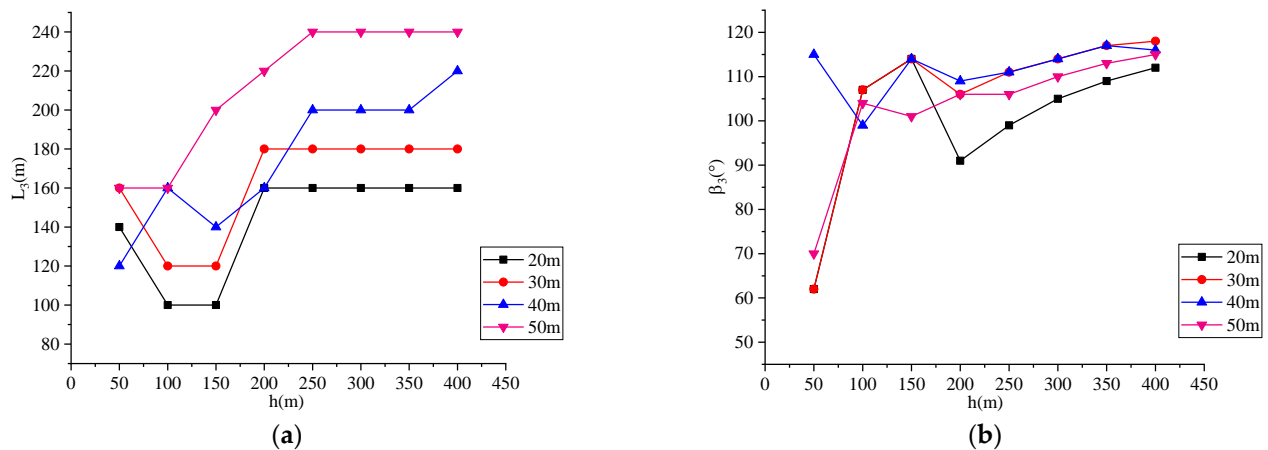
The influence of coal thickness on surface subsidence is mainly reflected in the degree of surface damage and subsidence. For coal seams with the same dip angle and different coal thicknesses, the damage mechanisms of the rock strata and the surface are basically the same, so the overall surface damage form and damage range have no obvious changes. However, a larger coal thickness leads to a greater outcrop discontinuous deformation in the surface, and increases the overall subsidence. Figure 14 shows the discontinuous deformation near the surface outcrop of shallow mining in a steeply inclined coal seam when the coal thickness is 20 m, 40 m, and 50 m (coal seam dip angle of  $50^\circ$ ). It can be seen from the figure that the change in coal thickness does not directly change the discontinuous deformation form near the surface outcrop, which is mainly presented as a collapse basin. The greater the coal thickness, the greater the degree of discontinuous deformation, making the damage near the surface outcrop more serious. With deep mining, the damage near the coal seam outcrop is more serious, and the slope of the floor is steeper.



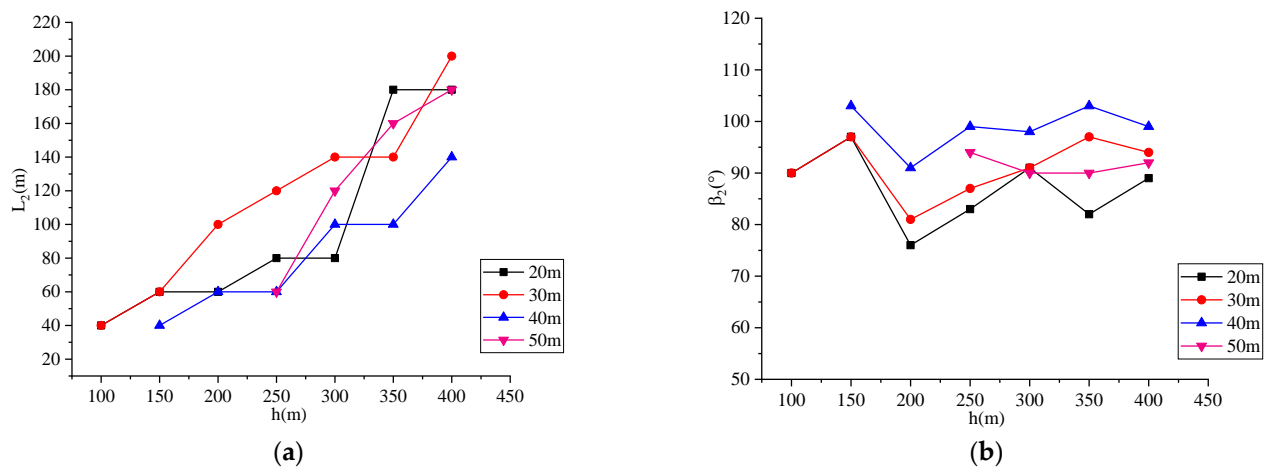
**Figure 14.** The discontinuous deformation near the surface outcrop of shallow mining in steeply inclined coal seam. (a) Coal thickness of 20 m, (b) coal thickness of 40 m, (c) coal thickness of 50 m.

Figure 15 shows the variation curve of the range and zoning angle of the outcrop discontinuous deformation area with different coal thicknesses. It can be seen from the figure that the coal thickness continuously increases the range of the outcrop discontinuous deformation area, and the surface is more likely to form discontinuous damage. With the same dip angle of the coal seam, when the steeply inclined coal seam with a different thickness is mined in the shallow mining, the discontinuous damage range of the outcrop area expands rapidly, while the range is basically unchanged when deep mining is carried out.

Figure 16 shows the variation curve of the range and zoning angle of the overall subsidence area with different coal thicknesses. With an increase in the mining depth, the range of the overall subsidence area continues to increase, and the expansion trend of the overall subsidence area with different coal thicknesses is basically consistent. For steeply inclined coal seams with the same dip angle and different coal thicknesses, a smaller coal thickness makes it easier for an overall subsidence area to form. A larger coal thickness makes the discontinuous deformation of the surface more serious, increases the influence range of the outcrop discontinuous deformation, and reduces the range of the overall subsidence. On the whole, there is little difference in the overall subsidence range corresponding to different coal thicknesses.



**Figure 15.** The variation curve of the range and zoning angle of the outcrop discontinuous deformation area with different coal thickness. (a) The variation curve of the range, (b) the variation curve of the zoning angle.

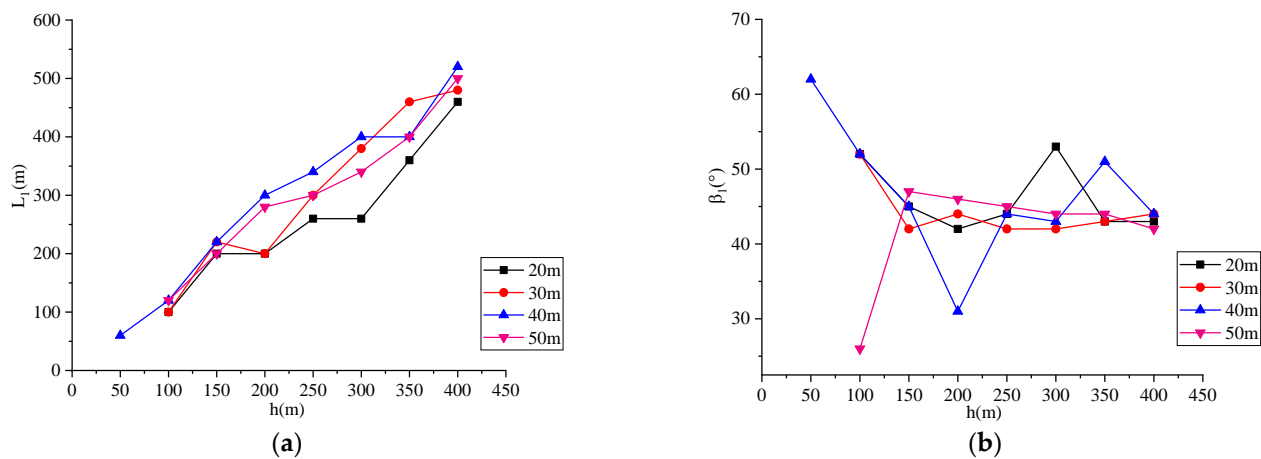


**Figure 16.** The variation curve of the range and zoning angle of the overall subsidence area with different coal thickness. (a) The variation curve of the range, (b) the variation curve of the zoning angle.

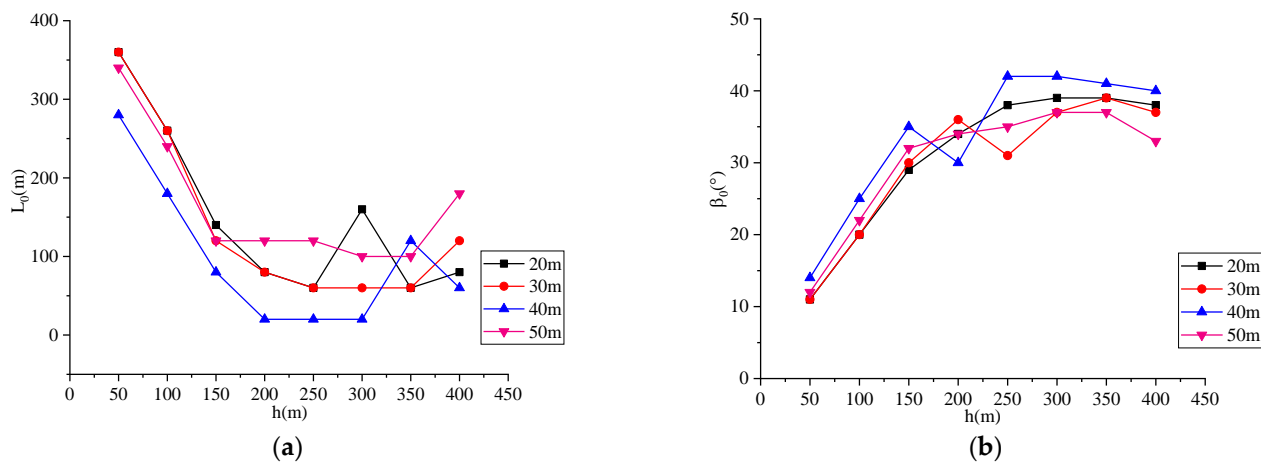
Figure 17 shows the variation curve of the range and zoning angle of the gradual subsidence area with different coal thicknesses. It can be seen from the figure that the change in the gradual subsidence area is basically the same in steeply inclined coal seam mining with the same coal seam dip angle and different coal thickness. From the overall trend, a larger coal thickness increases the gradual subsidence area, but the coal thickness has little effect on the change in the gradual subsidence area.

Figure 18 shows the variation curve of the range and zoning angle in the slight subsidence area with different coal thicknesses. It can be seen from the figure that an increase in the mining depth changes the range of slight subsidence area corresponding to different coal thicknesses from large to small. This is because in the process of deep mining, the range of the original slight subsidence area changes into the gradual subsidence area due to an increase in the subsidence, so the range in the slight subsidence area shrinks and the gradual subsidence area expands. At the same time, the variation trend in the slight subsidence area corresponding to different coal thicknesses is consistent. There is no significant difference in the range in the slight subsidence area between different coal thicknesses. On the whole, a larger coal thickness increases the range in the slight subsidence area.





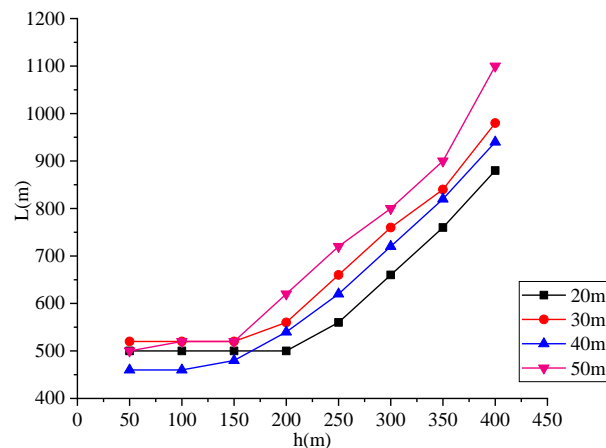
**Figure 17.** The variation curve of the range and zoning angle of the gradual subsidence area with different coal thickness. (a) The variation curve of the range, (b) the variation curve of the zoning angle.



**Figure 18.** The variation curve of the range and zoning angle in the slight subsidence area with a different coal thickness. (a) The variation curve of the range, (b) the variation curve of the zoning angle.

Figure 19 shows the variation curve of the surface subsidence range with different coal seam thicknesses. It can be seen from the figure that when in the shallow mining, the range of the surface subsidence basin is not significantly different. With the deepening of mining, the range of the surface subsidence basin grows steadily, and the range continues to expand. At the same time, a larger coal thickness increases the range of the surface subsidence basin, but the influence of different coal thicknesses on the range of the surface subsidence basin is not obvious.

The above analysis shows that the influence of coal thickness on the surface subsidence zoning is mainly reflected in the subsidence of each area and has no significant influence on the range of each area. The influence range of each area corresponding to different coal thicknesses is basically the same, but the damage degree is quite different. On the whole, the difference in the influence of coal thickness on the range of the surface subsidence basins is mainly reflected in the range of the outcrop discontinuous deformation area. A larger coal thickness increases the outcrop discontinuous deformation area, making the damage more serious, and making the surface more likely to form cracks and steps. The range of other areas keeps the same trend as the mining depth increases.

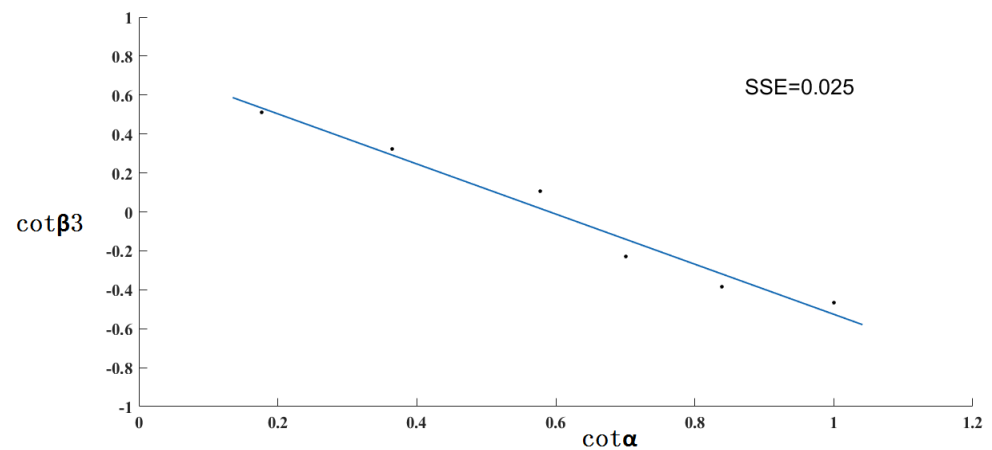


**Figure 19.** The variation curve of the surface subsidence range with different coal seam thickness.

## 5. Discussion

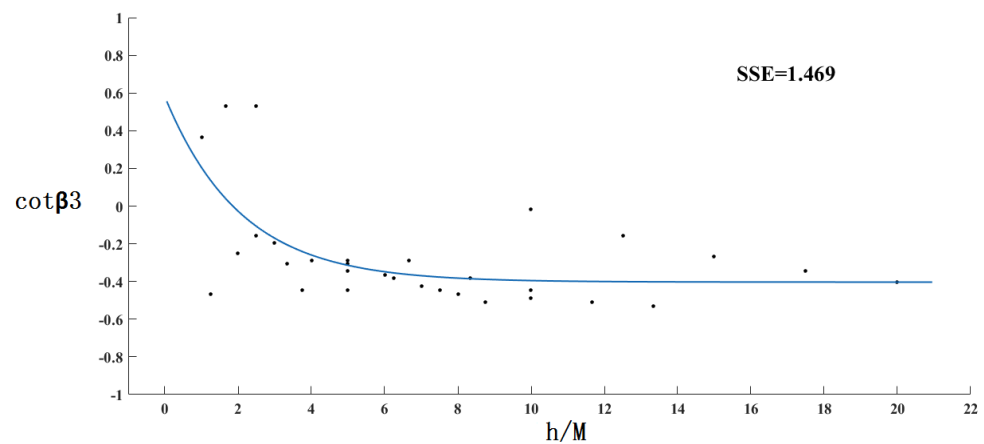
### 5.1. Variation Law of the Outcrop Discontinuous Deformation Area

Figure 20 shows the relationship between the coal seam dip angle and the zoning angle of the discontinuous deformation area, where SSE represents the sum of squares of the error term. A smaller SSE value correlates with a smaller error between the fitting curve and the sample value, thus improving the fitting degree. The figure shows a negative linear relationship between the cotangent value of the coal seam dip angle and the cotangent value of the zoning angle of the discontinuous deformation area. With an increase in the cotangent value of the coal seam dip angle, the cotangent value of the zoning angle of the outcrop discontinuous deformation area becomes smaller and smaller.



**Figure 20.** Relationship between the coal seam dip angle and the zoning angle of the discontinuous deformation area.

Figure 21 shows the relationship between the depth–thickness ratio (ratio of stage vertical height to coal seam thickness) and the zoning angle of the discontinuous deformation area. It can be seen from the figure that the cotangent value of the zoning angle of the outcrop discontinuous deformation area is negatively correlated with the depth–thickness ratio.



**Figure 21.** Relationship between the depth–thickness ratio and the zoning angle of the discontinuous deformation area.

Comprehensive analysis of the relationship between the zoning angle of the outcrop discontinuous deformation area and the coal seam dip angle and the depth–thickness ratio is shown in Formula (9):

$$\cot \beta_3 = ae^{-b\frac{h}{M}} + c \cot \alpha + d \quad (9)$$

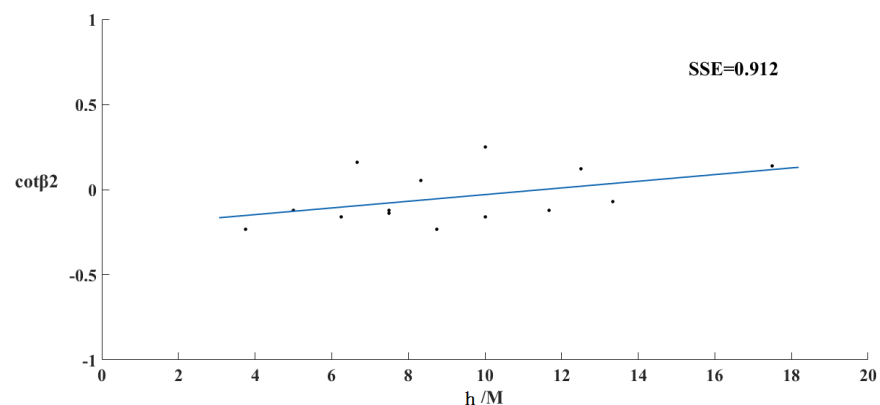
By using the indirect adjustment method to obtain the parameters of Formula (9), the fitting formula can be obtained as follows:

$$\beta_3 = \operatorname{arccot}(0.492e^{-0.482\frac{h}{M}} + 0.643 \cot \alpha + 0.179) \left( \begin{array}{l} 45^\circ < \alpha < 80^\circ \\ h > 0m \end{array} \right) \quad (10)$$

### 5.2. Variation Law of the Overall Subsidence Area

The coal seam dip angle greatly influences the overall subsidence area. When the coal seam dip angle is greater than  $55^\circ$ , the overall subsidence area of the surface no longer appears and becomes the outcrop discontinuous deformation area.

Figure 22 shows the relationship between the depth–thickness ratio and the zoning angle of the overall subsidence area. It can be seen from the figure that the cotangent value of the zoning angle of the overall subsidence area is linearly and positively correlated with the depth–thickness ratio. The overall trend of the curve shows that a greater depth–thickness ratio leads to a greater cotangent value of the zoning angle of the overall subsidence area. When the SSE is small, the fitting degree is good.



**Figure 22.** Relationship between the depth–thickness ratio and the zoning angle of the overall subsidence area.

Through comprehensive analysis of the relationship between the depth–thickness ratio and the zoning angle of the overall subsidence area, the relationship is shown in Formula (11):

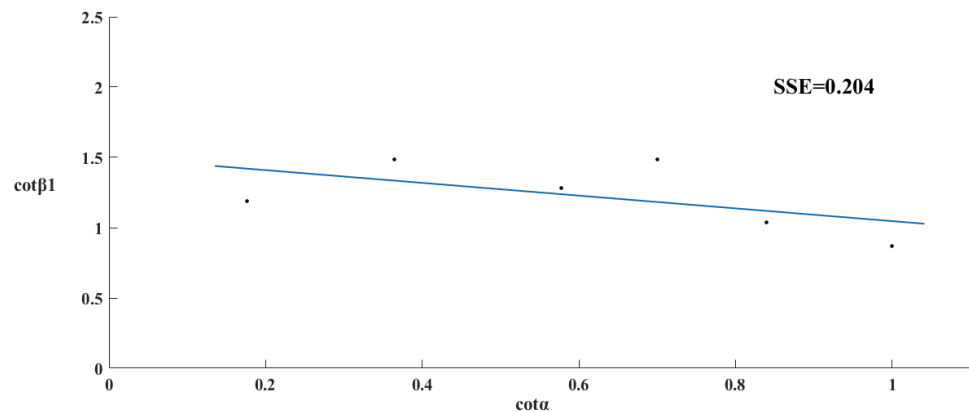
$$\cot \beta_2 = a \frac{h}{M} + b \quad (11)$$

By using the indirect adjustment method to obtain the parameters of Formula (11), the fitting formula can be obtained as follows:

$$\beta_2 = \operatorname{arccot}\left(0.012 \frac{h}{M} - 0.158\right) \left( \begin{array}{l} 45^\circ < \alpha < 55^\circ \\ h > 250m \end{array} \right) \quad (12)$$

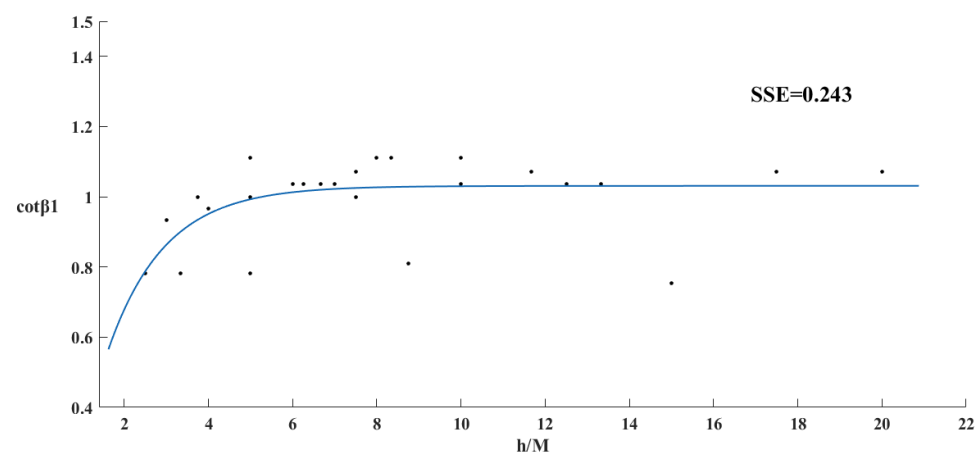
### 5.3. Variation Law of the Gradual Subsidence Area

Figure 23 shows the relationship between the coal seam dip angle and the zoning angle of the gradual subsidence area. It can be seen from the figure that the cotangent value of the coal seam dip angle and the cotangent value of the zoning angle of the gradual subsidence area have a negative linear relationship. The larger the cotangent value of the coal seam dip angle, the smaller the zoning angle of the gradual subsidence area.



**Figure 23.** Relationship between the coal seam dip angle and the zoning angle of the gradual subsidence area.

Figure 24 shows the relationship between the depth–thickness ratio and the zoning angle of the gradual subsidence area. It can be seen from the figure that the cotangent value of the zoning angle of the gradual subsidence area is positively correlated with the depth–thickness ratio. The curve fitting degree is good.



**Figure 24.** Relationship between the depth–thickness ratio and the zoning angle of the gradual subsidence area.



Comprehensive analysis of the relationship between the zoning angle of the gradual subsidence area and the coal seam dip angle and the depth–thickness ratio is shown in Formula (13):

$$\cot \beta_1 = ae^{-b\frac{h}{M}} + c \cot \alpha + d \quad (13)$$

By using the indirect adjustment method to obtain the parameters of Formula (13), the fitting formula can be obtained as follows:

$$\beta_1 = \operatorname{arccot}(-0.778e^{-0.742\frac{h}{M}} - 0.216 \cot \alpha + 0.765) \left( \begin{array}{l} 45^\circ < \alpha < 80^\circ \\ h > 100m \end{array} \right) \quad (14)$$

#### 5.4. Variation Law of the Slight Subsidence Area

Figure 25 shows the relationship between the coal seam dip angle and the zoning angle in the slight subsidence area. There is a negative linear relationship between the cotangent value of the coal seam dip angle and the cotangent value of the zoning angle in the slight subsidence area, and the curve fitting is good.

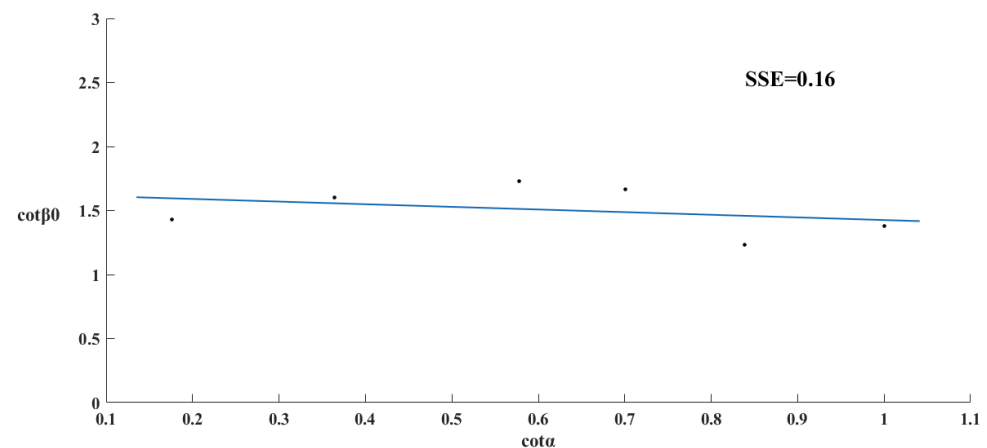


Figure 25. Relationship between the coal seam dip angle and the zoning angle in the slight subsidence area.

Figure 26 shows the relationship between the depth–thickness ratio and the zoning angle in the slight subsidence area. It can be seen from the figure that the depth–thickness ratio and the cotangent value of the zoning angle in the slight subsidence area have a negative exponential relationship, and the curve fitting is in good condition.

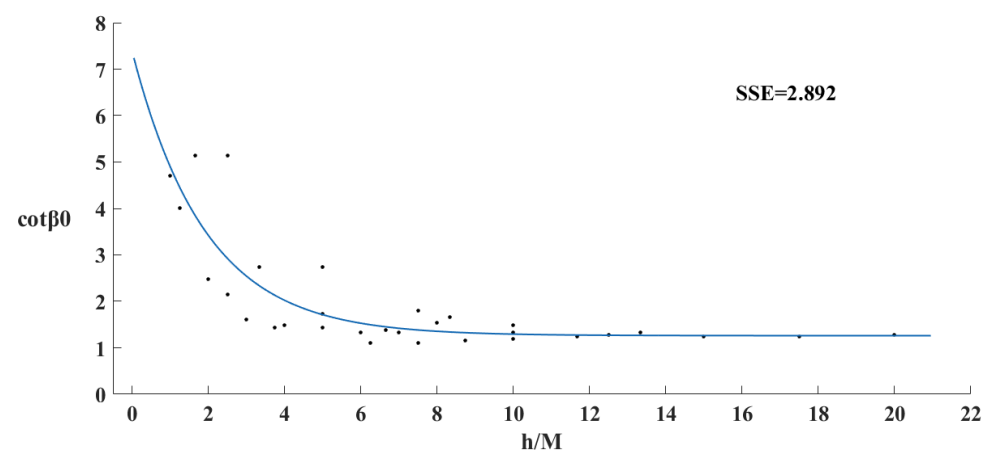


Figure 26. Relationship between the depth–thickness ratio and the zoning angle in the slight subsidence area.

The comprehensive analysis of the relationship between the zoning angle in the slight subsidence area and the coal seam dip angle and the depth–thickness ratio is shown in Formula (15):

$$\cot \beta_0 = ae^{-b\frac{h}{M}} + c \cot \alpha + d \quad (15)$$

By using the indirect adjustment method to obtain the parameters of Formula (15), the fitting formula can be obtained as follows:

$$\beta_0 = \operatorname{arccot}(3.067e^{-0.52\frac{h}{M}} - 0.103 \cot \alpha + 1.446) \quad \left( \begin{array}{l} 45^\circ < \alpha < 80^\circ \\ h > 0m \end{array} \right) \quad (16)$$

In summary, the zoning angle calculation model of each surface moving area is :

$$\left\{ \begin{array}{ll} \beta_3 = \operatorname{arc} \cot(0.492e^{-0.482\frac{h}{M}} + 0.643 \cot \alpha + 0.179) & (45^\circ < \alpha < 80^\circ, h > 0m) \\ \beta_2 = \operatorname{arc} \cot(0.012\frac{h}{M} - 0.158) & (45^\circ < \alpha < 55^\circ, h > 250m) \\ \beta_1 = \operatorname{arc} \cot(-0.778e^{-0.742\frac{h}{M}} - 0.216 \cot \alpha + 0.765) & (45^\circ < \alpha < 80^\circ, h > 100m) \\ \beta_0 = \operatorname{arc} \cot(3.067e^{-0.52\frac{h}{M}} - 0.103 \cot \alpha + 1.446) & (45^\circ < \alpha < 80^\circ, h > 0m) \end{array} \right. \quad (17)$$

Then, the range calculation model of each surface moving area is:

$$\left\{ \begin{array}{l} L_3 = H(\cot \lambda_0 - \cot \beta_3) \\ L_2 = H(\cot \beta_2 - \cot \beta_3) \\ L_1 = H(\cot \beta_1 - \cot \beta_2) \\ L_0 = H(\cot \beta_0 - \cot \beta_1) \end{array} \right. \quad (18)$$

Some scholars took the shallow-buried thick coal seam mining area as the research background and divided the different development areas of ground cracks through field measurement and similar material physical tests. The surface was divided into a crack-producing area, crack transfixion development area, and a stable crack area [26,27]. However, due to the severe surface movement and deformation caused by the mining of steeply inclined coal seam, the above research results are not applicable to this geological condition.

Some scholars' research on the law of surface subsidence zoning after mining in a thin and medium-thickness coal seam is only qualitative, lacking quantitative representation [16–18]. Moreover, with an increase in the coal thickness, the law of surface subsidence zoning becomes more complex, and the previous research results are no longer applicable.

For steeply inclined thick coal seam mining, the surface subsidence law of the trend main section is similar to that of the horizontal coal seam, and some scholars have carried out relevant research on this [28,29]. Therefore, this paper aims to study the surface subsidence zoning law of the inclination main section in the mining of steeply inclined extra-thick coal seams.

In this paper, a change in the surface tilt is used as the criterion to determine the area boundary. However, this criterion needs further research in the future to determine a more accurate criterion. At the same time, the zoning law of the whole subsidence basin has not been studied in detail in this paper. The next step is to extend the zoning law of the profile to the whole basin. The research results can be applied to the design and implementation of coal mining schemes under buildings (structures) in steeply inclined thick coal seams, which provides a basis for the safe mining of steeply inclined thick coal seams under buildings (structures).

## 6. Conclusions

In this paper, a calculation formula for the variation of each area range and zoning angle with a coal seam dip angle, coal thickness, mining depth, and stage vertical height area is established. The characteristics and deformation laws of rock strata and surface movement in the mining of steeply inclined extra-thick coal seam in Dongxia Coal Mine are

validated using the methods of field measurement, numerical simulation, and theoretical analysis. Based a systematic analysis, the following conclusions can be drawn:

- (1) Surface subsidence basins can be divided into four areas: the outcrop discontinuous deformation area, the overall subsidence area, the gradual subsidence area, and the slight subsidence area;
- (2) The influence of the coal seam dip angle on surface subsidence zoning of steeply inclined extra-thick coal seam mining is mainly reflected in the range of the affected area and the form of damage;
- (3) The influence of coal thickness on surface subsidence zoning of steeply inclined thick coal seam mining is mainly reflected in the surface subsidence and the degree of damage. On the whole, a larger coal thickness can increase the range of surface subsidence basins and subsidence zoning.

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**Conflicts of Interest:** The authors declare that they have no competing interests.

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