Variation in shallow sandy loam porosity under the influence of shallow coal seam mining in north-west China

Fan Cui, Yunfei Du, Baiping Chen, Yuxuan Zhao and Yingqing Zhou

Abstract
To study the influence of coal mining on the porosity of shallow sandy loam under conditions of shallow seam mining in thick, loose layers in north-west China, a typical surface sandy loam stratum in Shaanxi Province was taken as the study area, and experiments were performed to test the variation of soil porosity at different depths of 0–10 m in strata before, during and after mining therein. The experimental results demonstrate that the overall average porosities in the disc-shaped edge area, the disc-shaped edge area to the disc-shaped basin bottom area and the disc-shaped subsidence centre area of shallow sandy loam in mining increased by (23.51, 18.07 and 22.61%) respectively compared with that before mining. Mining meant that the soil porosity in the period of stable subsidence after mining changed significantly in the disc-shaped edge area and the disc-shaped edge to the disc-shaped basin bottom area. The disc-shaped edge area shows a trend of slowly rising porosity with the increase of depth, and the disc-shaped edge area to the disc-shaped basin bottom area shows a trend of gradually increasing first and then gradually becoming stable. Although the porosity in the central area of disc-shaped subsidence increased before mining, its trend was similar to that before mining. Although the change in soil porosity in the period of post-mining settlement stability is greater than that before mining, it is best fitted by a quintic polynomial. In general, the rate of change of soil porosity in the study area shows similar trends with depth. It showed a U-shaped variation that first decreased, stabilised for a distance and then gradually increased. This study provides theoretical support for surface soil remediation and ecological environment restoration in coal mining areas.
Keywords
North-west China, mining area, sandy loam stratum, soil porosity, mining-induced influences

Introduction
After decades of development, China has become both the largest producer and the consumer of coal in the world. As of the end of 2018, the proven reserves of China's coal resources are 138,819 million tons, of which more than 60% are distributed in the northwest (Dudley, 2019; Jinhua et al., 2018; Wang and Zhang, 2018); however, most of these areas have extremely fragile ecosystems, especially with regard to the shortage of water resources, soil erosion and desertification. Long-term coal mining has intensified damage to the ecosystems in mining areas, and land degradation is particularly severe. In coal mining areas, large amounts of land have been occupied and degraded through mining subsidence, excavation damage and pollution. These impacts have resulted in severe social, ecological and environmental problems (Bian and Lu, 2013; Ma et al., 2015). It is important to conduct land reclamation and ecological restoration in the north-west mining area for a country such as China with few land resources per capita.

Soil structure plays an important role in regulating soil fertility and ecological functions. Among them, soil pore structure and pore distribution are important factors affecting soil properties such as soil texture, fertility and water content. It counts much for the circulation and storage of soil water, air and heat, as well as whether the supply for plants is sufficient and coordinated (Bateman et al., 2019; Martin et al., 2017; Pagliai and Vignozzi, 2002).

Soil porosity is an essential characteristic of the soil skeleton: it refers to the percentage of pore volume per unit volume of soil (Abrahå et al., 2019; Lipiec et al., 2006), which can be measured indirectly by calculation of soil bulk density and soil specific gravity. As one of the main physical characteristics of soil, its value is related to soil types, texture and organic matter content, which exerts a significant influence on soil water and fertiliser conservation, root extension, microbial activity, nutrient transformation, etc., and plays an important role in soil structure. Soil porosity affects many natural physical processes, such as erosion, runoff, infiltration capacity, soil water retention, soil evaporation and root penetration resistance (Blavet et al., 2009; Bottinelli et al., 2010; Lamande et al., 2003; Lipiec et al., 2006; Sillon et al., 2003). There is a certain relationship between soil quality decline and soil porosity reduction (Arshad and Coen, 1992). Soil porosity is an important parameter in soil physics research, agriculture and environmental protection. The traditional method of measuring soil porosity relies on calculation of soil bulk density and specific gravity (Schjønning et al., 2013; Tang et al., 2016). In addition, the commonly used methods also use the water characteristic curve (Burger and Shackelford, 2001), the mercury intrusion curve (Liu et al., 2015; Zhang et al., 2010) and the mark penetration curve (Allaire et al., 2002) to obtain the distribution of soil pores. Among them, the soil pore size calculated by the water characteristic curve is an equivalent pore diameter, not the real aperture size. Although determination by mercury intrusion method is fast, it is often affected by external factors. The penetration curve method can specifically research the influence of the existence of soil macropores on the migration of water and solute in the soil, but usually it can only partially reflect the migration and changes in water and solute contents at depth. With the development of soil micromorphology, soil slice (Guimarães et al., 2011) has become a common
method for studying soil pore characteristics; however, the soil slicing process is cumbersome, requires particular, onerous experimental conditions, and may destroy the soil pore structure during preparation by slicing. In recent years, computerised tomography imaging techniques (Pires et al., 2014) have been applied to the visualisation and quantification of soil pore structure with their advantages of rapidity, accuracy and convenience. The method can provide a three-dimensional image of the micro pore structure without destroying the original pore structure of the porous medium; however, it is expensive in terms of equipment and test consumables, and entails a heavy workload due to the large amount of field and laboratory test data that need to be collected.

Many scholars have investigated soil porosity to good effect but most of the existing research focuses on the influence of rainfall (Armenise et al., 2018; Lin et al., 2012; Wang et al., 2018), soil improvement measures (Ahmad et al., 2009; Josef et al., 2017), cultivation methods (Celik et al., 2012; Xue et al., 2018) and planting patterns (Iqbal et al., 2014; Park et al., 2011; Xia et al., 2019) on soil pores, and little attention has been paid to the influence of coal mining on soil structure. However, coal mining has led to the degradation of vegetation cover and soil quality and to the dumping of overburden materials in mining areas in north-west China (Bi et al., 2018; Li et al., 2015). Therefore, it is necessary to study the influence of coal mining on soil porosity, which is of significance when aiming to control surface damage and soil erosion, and to protect, restore and reconstruct the mining area ecological environment.

The remainder of this paper is organised as follows: the next section introduces the geographical location, geomorphological characteristics, annual rainfall and vegetation growth of the study area; Section ‘Materials and methods’ outlines the research methods, including the test design scheme, sampling time, sample preparation and testing; Sections ‘Results’ and ‘Discussion’ cover the changes in soil porosity before and after mining and the relationship between porosity and depth; and the final section concludes.

Study area

The study area is located at a surface sandy loam stratum directly above the 52,305 working face of Daliuta Coal Mine, Shenmu County, Shaanxi Province, China. The geographical location is shown in Figure 1. It is an approximately east-west rectangular area with a length of 900 m and a width of 280 m (consistent with the width of the working face), which is approximately 600 m from the 52,305 open-off cut. The layout plan is shown in Figure 2. The study area is a typical aeolian sand accumulation landform, the upper part of which is covered with a sandy loam stratum with a thickness of 7–13 m and an average thickness of about 10 m. The maximum elevation difference in the area is 15.2 m. The effect of groundwater on the recharge of the soil moisture content within 10 m is negligible because there is no surface water in the area and the average depth of water table is 37.6 m. The solar radiation in the study area is strong, annual evaporation is 2000–2900 mm and annual precipitation is only 131–571 mm. Precipitation (mainly as rainfall) is concentrated from June to September every year, which typifies such an arid climate. The surface sandy loam in the area can be restored to the moisture content before rainfall within 3–5 days after the rain, because of the low and discontinuous rainfall and the poor water storage capacity of sandy loam. In addition, there is no surface water, no shallow groundwater impact and no crops or irrigation water sources in the area. Vegetation cover is mainly tree and shrub, such as poplar, salix, sea buckthorn, amorpha, etc.; some areas contain herbosa.
Materials and methods

Experiment design and soil sampling

Three lines, each 900-m long and 140-m apart, parallel to the mining direction of the working face, were laid in the study area to cover the entire 52,305 working face. The layout location is shown in Figure 2, in which Lines 1 and 3 were arranged at the edge of both sides of the working face, and Line 2 was arranged in the middle of the working face.
Furthermore, the water content of the unconsolidated layers in the aeration zone of the shallow surface was mainly supplied by the meteorological water, the capillary action of the underground water table and the crystal water formed by the water vapour condensation at night: some of the water was lost through evaporation and water demand for plant growth, so it is very difficult to eliminate the comprehensive influence of the above factors on the soil porosity in any direct manner. Line 4 was laid in the area near the north of working face 52,305 where the shallow stratum was undisturbed by coal mining, to reveal the influence of coal mining on the soil porosity of shallow unconsolidated layers under many complicated external influence factors. The area undisturbed by coal mining was taken as a reference value to explore its change with time, and then it was compared with the change of soil porosity in the area affected by mining to study the variational characteristics of shallow surface soil porosity during different periods of coal mining. One sampling point was set every 50 m along each survey line, and the distribution of sampling points is shown in Figure 2. There is a minable coal seam in the 52,305 working face where the research area was located. The burial depth of the coal-bed was 142–275 m, the average burial depth was 190 m, the thickness of the coal seam was 1.35–7.75 m (with a mean average thickness of 5.60 m) and the thickness of the overlying unconsolidated layers was 0–55 m. The period of influence of mining on surface settlement was shorter than that under slice-mining conditions, which was mainly due to the use of full-seam mining and the rapid rate of advance.

From 1 September 2013, the 52,305 working face started mining at an average mining footage rate of about 10 m/day from the open-off cut side of the working face in the study area. Three sampling operations were designed according to the mining schedule. The first sampling was carried out on 27 August 2013. At this time, the working face in the study area has not been mined. The second sampling operation was conducted on 15 October 2013, at which point the working surface had just advanced to the centre of the study area. The third sampling operation was carried out on 5 March 2014. At this time, the advancing position of the working face has left the study area for more than 90 days, and the surface had undergone the settlement development period (0–30 days), active period (30–60 days) and attenuation period (60–90 days), and had entered its stable stage. Each sampling operation was completed within four days, during which the weather was fair.

**Laboratory assay**

**Sample preparation.** A Luoyang shovel was taken as a tool to drill and sample the measuring points on each survey line: the drill was lifted every 0.5 m with a sampling depth of 10 m used. The soil samples were removed from the drill using a cutting ring. Then they were immediately put into aluminium boxes for sealing and preservation to ensure that the physical properties of the soil were not damaged. The actual sampling site is shown in Figure 3.

**Porosity determination.** The aluminium box containing the soil sample was weighed on an electronic balance to obtain a mass $m_1$. Thereafter, it was baked in an oven at 105°C for about 12 h until of constant mass, and its mass $m_2$ was recorded. After removal of the dried soil sample for porosity testing, we weighed the aluminium box (mass $m_3$). The cutting ring measured $\Phi$ 50.46 mm x 50 mm and had a volume $V_0$ of 100 cm$^3$. The total volume of the soil sample in the aluminium box (the cutting ring volume $V_0$) and the total moisture loss ($m_2 - m_3$) were known, and the bulk density $m_1V$ of the soil sample could be directly obtained.
A certain amount of dried soil was taken and its specific gravity was calculated as \( m_p \) using the pycnometer method. Figure 4 shows the schematic diagram of partial test processes, in which (a) shows the sample drying process, (b) illustrates the sample weighing process after drying and (c) shows the use of the pycnometer method to calculate the specific gravity of soil sample.

The soil porosity is given by

\[
P = \left( 1 - \frac{D}{d} \right) \times 100\% = \left( 1 - \frac{m_2 - m_3}{\rho_w V_0 d} \right) \times 100\% \tag{1}
\]

where \( P \) is the total porosity of the soil (%), \( D \) is the bulk density of soil sample (g/cm\(^3\)), \( d \) is the specific gravity of soil sample (g/cm\(^3\)), \( m_2 \) represents the mass of the dry soil plus box (g), \( m_3 \) is the mass of the aluminium box (g), \( \rho_w \) is the density of water (g/cm\(^3\)) and \( V_0 \) is the volume of cutting ring (cm\(^3\)).

**Results**

*Changes in soil porosity before and after mining*

The soil porosity is not only related to soil properties, but also depends on the size of soil particles, the uniformity of medium, the shape of soil particles, the arrangement mode, relative density and degree of cementation. The variation of the surface stress distribution
and the surface deformation area will change the soil porosity of the shallow stratum above the working face during underground coal mining. In the study area, the shallow stratum medium is mainly sandy loam, and the average porosity of common sandy loam is about 35–45%. To investigate the variation of shallow sandy loam porosity under the influence of mining, the soil porosity data in the study area before mining, when mining to the centre of the study area and during the settlement stability period after mining were measured to a depth of 10 m and along a length of 900 m parallel to the advancing direction of the working face.

The distribution of soil porosity in the depth direction before mining, when mining to the centre of the study area and during the settlement stability period after mining was averaged and compared with the data from Line 4 (unaffected by mining), to analyse the variation in soil porosity before and after mining.

The mean average value of measured soil porosities at the same depth of each measuring point on each measuring line was taken as the value of soil porosity at a certain depth in this period and compared with other periods to analyse the variation thereof before and after mining. The variations of soil porosities with depth obtained from three sampling of four survey lines are plotted in Figure 5. The overall average porosities of soil obtained by sampling at different times along four lines were compared and plotted in Figure 6.

Figures 5 and 6 show that the overall average porosities along Lines 1, 2 and 3 were (61.56, 56.41 and 57.24%), respectively, when mining to the centre of the study area. Compared with those before mining, the porosity increased by (23.51, 18.07 and 22.61%), respectively. This was due to the large-scale movement of the overlying strata in the stope and the continuous adjustment of the stress caused by coal seam mining at the working face. As the working face and the support advance, the rear rock formation gradually lost support. The gangue cut from the goaf roof gradually collapsed under the overburden and its self-weight. Then the subsidence of unconsolidated layers and surface ensued. Surface subsidence will lead to surface movement and deformation. At the onset of surface subsidence, the movement and deformation of the surface are not large. In the active stage, the surface movement and deformation increase rapidly, which often leads to the surface soil cracking and deformation, and even produces widely-developed, difficult-to-close fractures, thus increasing the soil porosity in the shallow stratum. The fracture development process is illustrated in Figure 7. In Figure 7, the fracture is parallel to the mining direction of the working face.

Line 1 had the largest increase in porosity under the influence of mining, followed by Line 3, then Line 2 with the smallest increase. The reasons for this may be as follows: the surface will sink to form a disc-shaped basin when it is affected by the full amount of subsidence. According to the principle of mining subsidence and the results of field monitoring (Chen et al., 2019), along the strike direction of the 52,305 working face, the flat bottom began to appear in the subsidence basin 60 m from the open-off cut. The surface began to sink and the shape of subsidence basin was more symmetrical when advancing 415 m along the trend direction of working face. The maximum settlement point on the inclination observation line was found at 25 m from the centreline between Lines 1 and 2. Line 1 lay within the disc-shaped edge area, Line 2 lay within the disc-shaped subsidence centre area and Line 3 was located between the disc-shaped edge area and the disc-shaped basin bottom area.

The overall mean average porosities along Lines 1, 2 and 3 were (58.54, 52.29 and 55.00%), respectively, during the settlement stability period after mining. Compared with mining to the centre of the study area, the porosity decreased by (4.90, 7.31 and 3.91%),
Figure 5. Soil porosities obtained with the four lines at different times varied with depth. The soil porosity is taken as the mean average value of measured porosity of all sampling points at a certain depth. (a) Variation of soil porosity with depth obtained from three sampling operations along Line 1. (b) Variation of soil porosity with depth obtained from three sampling operations along Line 2. (c) Variation of soil porosity with depth obtained from three sampling operations along Line 3. (d) Variation of soil porosity with depth obtained from three sampling operations along Line 4.

Figure 6. Overall mean average porosities along four lines at different times. The overall mean average porosity is the mean average of the porosities at all depths at each sampling point and time.
respectively, but remained larger than the overall average porosity before mining. The reason is that the goaf collapsed and was gradually compacted by the process of rotary subsidence of the main roof over time after the study area entered its settlement stability period. The roof pressure does not change, the surrounding rock forms a stable structure and the surface subsidence decreases (Ghabraie et al., 2015; Woo et al., 2013; Yin et al., 2019). Some of the surface fractures formed during the coal mining process gradually close or stop developing. Among them, the overall average porosity along Line 2 underwent the largest reduction compared with that found when mining to the centre of the study area (mainly because Line 2 lay in the middle of mining subsidence area, which was subject to the most subsidence). In the process of advancing, the surface in front of the working face will produce many fractures (manifest as crazing and with fractures running parallel to the working face), but the width and depth of the fractures are relatively small. The fracture development is shown in Figure 8. This kind of fracture first opens, then close gradually with the advance of the working face.

The overall average porosities along Line 4 were 43.27, 43.83 and 43.62% before mining, when mining to the centre of the study area, and during the settlement stability period after mining, respectively. Compared with those before mining, when mining to the centre of the study area and during the settlement stability period after mining, the porosity increased by 1.30% and 0.80% respectively, with increases of less than 2%. This indicated that the shallow soil porosity of the unaffected area had not changed substantially before and
after the three sampling operations. It also showed that, under similar conditions of rainfall, temperature and other factors, it can reflect the variation in shallow sandy loam porosity under the influence of mining by comparing the changes in porosity in the study area before and after the three sampling operations along Lines 1–3.

**Relationship between porosity and depth before and after mining**

The soil porosities at different depths before and after mining were regressed to compare the relationship between porosity and depth along each survey line in different areas before and after mining. It can be seen from Figure 5 that, when mining to the centre of the study area, the shallow soil porosity was unstable under the influence of mining, so only the data before and after mining were regressed (Figure 9).

It can be seen from Figure 9 that soil porosity increased with depth before coal mining. After 3–4 m, it fluctuated slightly, until at 6.5–8 m, it gradually decreased and stabilised. The possible reasons for this were as follows: the shallow stratum in this area was covered by medium sand above 3–4 m. Beyond 3–4 m, it was affected by complex strata such as coarse sand, loess layers and gravel. Therefore, the soil porosity showed a tendency to increase gradually and fluctuate. Beyond 6.5–8 m, the relative density of the soil gradually increased, and the clay layer thickness increased, so the soil porosity gradually decreased and tended to be stable.
Figure 9. Regression curve of soil porosity in different depths before and after mining. (a) The relationship between porosity and depth before and after the influence of mining around Line 1. (b) The relationship between porosity and depth before and after the influence of mining around Line 2. (c) The relationship between porosity and depth before and after the influence of mining around Line 3.
Although the change in soil porosity in the settlement stability period after mining is larger than that before mining, the regression analysis shows that the change of soil porosity with depth in the range of 0–10 m before and after mining is best fitted with a quintic polynomial

\[ \bar{P} = A_0 + ax + bx^2 + cx^3 + dx^4 + ex^5 \]  

(2)

where \( \bar{P} \) is the overall average porosity (%), \( A_0, a, b, c, d \) and \( e \) are correction factors (these are constants, which can be calibrated according to measured data). \( A_0 \) can be taken as the soil porosity at zero depth. The model provides a reference for the prediction of porosity at different depths in the shallow sandy loam stratum of coal mine; however, since the test data are all taken from 0–10 m in the stratum, the error in the prediction of soil porosity below 10 m may be large.

**Influence of mining on the change in soil porosity at different locations and depths below the surface**

To analyse the changes in soil porosity with depth from 0–10 m before and after mining, the soil porosity changes at different depths before and after mining along Lines 1–3 were studied. The rate of change of soil porosity is the ratio of the difference of soil porosity at a certain depth before and after mining to that before mining (Figure 10).

It can be seen from Figure 10 that, before and after mining, the trend in rate of change of soil porosity with depth along different survey lines was similar. That is, it shows a U-shaped trend, decreasing, stabilising for a distance and then increasing. The average rates of change of porosity along Lines 1, 2 and 3 were 0.1804, 0.0980 and 0.1952, respectively.

To obtain the variation in rate of change of soil porosity at different depths, the data from different depths before and after mining were also regressed (Figure 11).

![Figure 10. Rate of change of soil porosity at different depths before and after mining.](image-url)
Figure 11. Regression curve of soil porosity change rate with depth before and after mining. (a) Regression curve of soil porosity changes along Line 1 with depth before and after mining. (b) Regression curve of soil porosity changes along Line 2 with depth before and after mining. (c) Regression curve of soil porosity changes along Line 3 with depth before and after mining.
It was found that the data from Lines 1 and 3 were best fitted by quartic polynomial, but this was not possible for the data from Line 2. It was possible to predict the rate of change of soil porosity at different depths in the marginal area of mining subsidence from such regression results; however, after many attempts, no ideal prediction model of the changes in porosity could be found for the central area of mining subsidence.

**Discussion**

Line 1 lay within the disc-shaped edge area. The surface ground soil in this area was always under tension throughout the mining process and was influenced by mining of the previous working face. Therefore, the area around Line 1 was that most affected by the disturbance, and there will be permanent and step-like fractures on the surface. Usually these fractures are deeper and wider, resulting in a larger increase in soil porosity. Line 3 lay between the disc-shaped edge area and the disc-shaped basin bottom area. The surface ground soil in this area was mainly affected by the tensile forces imposed in the initial stages of coal mining. Compared with area around Line 1, this was less influenced previous mining work, resulting in the larger fractures with a shallower depth and smaller width. After formation of the subsidence basin, the surface ground soil gradually changed from a state of tension state to one of compression; therefore, the fractures in this area were produced in the preliminary stage of coal mining, and some fractures gradually became smaller or even closed under pressure in the later stages of mining, so the increase of porosity was slightly smaller than that along Line 1: because Line 2 lay within the disc-shaped subsidence central area, many fractures in the form of crazing, and with some fractures running parallel to the working face, will be produced in this area under the action of tension in the preliminary stages of coal mining (Strzałkowski and Ściegala, 2020; Wang et al., 2020). However, with the advance of mining face, the force on the surface points gradually changes from tension to compression. Hence, there is a process from generation to gradual reduction and then to closure of fractures, so the increase in soil porosity is small.

The soil porosities along Lines 1 and 3 changed by significant amounts in the period of stable subsidence after mining. Among them, the soil porosity along Line 1 tended to increase with depth, while that along Line 3 tended to gradually increase, then stabilise. Although the porosity along Line 2 was larger than that before mining, the trend therein was similar because Line 2 lay within the middle of the mining subsidence area. The stress on surface points was mainly compressive, and the surface subsidence was uniform within this range. Line 1 lay between the goaf boundary and the subsidence basin boundary. The surface subsidence there was non-uniform, and the surface movement inclined to the basin centre (Peng et al., 1992). This results in many tensile fractures that are difficult to close at a later stage. It is difficult for the surface point to reach stable state in the settlement stability period after mining. The area around Line 3 is located between the disc-shaped edge area and the disc-shaped basin bottom area. In the preliminary stage of coal mining, the surface soil is mainly affected by tensile stresses, thus suffering larger fractures, however, compared with the area around Line 1, the fracture depth is shallow and the width is small due to the lower influence exerted by the previous working face. The stress on the surface stabilises more readily in the settlement stability period after mining.

The average rate of change of porosity along Line 2 is the smallest, that along Line 1 ranked second and that along Line 3 was the largest. The reason may be that Line 2 lay within the disc-shaped subsidence central area, wherein the surface subsidence was uniform.
Although there were many fractures on the ground surface in front of the working face during the advancing process, the width and depth of the fractures were relatively small, and the fractures could open and gradually close as the working face advanced. Line 1 lay between the goaf boundary and the subsidence basin boundary. Due to the vicinity of the 52,304 goaf, some fractures had already occurred during mining of the previous 52,304 working face. Line 3 lay near the unmined 52,306 working face. Compared with the area around Line 1, it was less affected by the mining of the 52,304 working face. Therefore, the rate of change of porosity along Line 3 was lower than that along Line 1.

**Conclusion**

When the coal seam was mined to the centre of the study area, the overall average porosity increased compared with that before mining. Among them, the increase of porosity was greatest in the disc-shaped edge area, followed by that from the disc-shaped edge area to the disc-shaped basin bottom area, and the smallest increase occurred in the disc-shaped subsidence central area.

During the settlement stability period after mining, the soil porosity in the disc-shaped edge area and the disc-shaped edge to the disc-shaped basin bottom area changed by a significant amount due to the influence of mining. Among them, the soil porosity in the disc-shaped edge area increased slowly with increasing depth, and the area between the disc-shaped edge and the disc-shaped basin bottom area tended to gradually increase, then stabilise. Although the porosity in the central area of the disc-shaped subsidence zone increased after mining, its trend was similar to that before mining.

A mathematical model revealing how soil porosity varied with depth in the range of 0–10 m before and after mining was established. The model provided a reference for soil porosity prediction at different depths in the shallow sandy loam stratum of this coal mine. Before and after the influence of mining, the variation in rate of change of soil porosity with depth along different survey lines showed a U-shaped pattern, first decreasing, stabilising for a certain distance and then gradually increasing. However, after many attempts, no ideal predictive model of the change in porosity could be found for the central area of mining subsidence. In the future, more consideration should be given to research into such changes in porosity.

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