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Study on Surface Subsidence Characteristics Based on Three-Dimensional Test Device for Simulating Rock Strata and Surface Movement

Xingyin Ma [1,2], Zhiyong Fu [3,*], Yurong Li [1,2,*], Pengfei Zhang [1,2], Yongqiang Zhao [4] and Guoping Ma [5]

1 College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China; ma.xingyin@sdust.edu.cn (X.M.); pfzhang@sdust.edu.cn (P.Z.)
2 State Key Laboratory of Mining Disaster Prevention and Control Co-Founded by Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology, Qingdao 266590, China
3 College of Mining, Liaoning Technical University, Fuxin 123000, China
4 State Key Laboratory of Water Resource Protection and Utilization in Coal Mining, Beijing 102209, China; 20039429@chnenergy.com.cn
5 Qianjiaying Mining Branch, Kailuan (Group) Co., Ltd., Tangshan 063000, China; maguoping@kailuan.com.cn
* Correspondence: fuzhiyonghappy@163.com (Z.F.); li.yurong@sdust.edu.cn (Y.L.)

Abstract: The main functions of a three-dimensional test device for simulating rock formations and surface movement affected by underground coal mining were described in detail, and a series of similar related tests were carried out. The device consisted of an outer frame, a pressurization unit, a pulling unit, and a coal seam simulation portion. Using this test device, supported by monitoring methods such as the three-dimensional laser scanner method, a model test study on the surface subsidence characteristics caused by coal seam mining was carried out. Combined with the field measurements, the transfer law of surface subsidence caused by coal seam mining was revealed, and the whole surface subsidence response process was analyzed. The experimental results show that the subsidence caused by mining disturbances below the coal seam accounts for 79.3% of the total subsidence, which is the dominant factor of the total surface subsidence. After long-term surface observations, surface subsidence can be divided into four stages after coal mining, and the settlement value of the obvious settlement stage accounts for more than 60% of the total settlement value. The above test results fully reflect the feasibility and practicality of the three-dimensional test device to simulate rock strata and surface movement and provide a new experimental research tool that can be used to further study the surface subsidence characteristics and control caused by coal mining.

Keywords: rock formations; surface subsidence law; surface subsidence process; 3D test device; 3D laser scanning

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1. Introduction

With the transformation and upgrade of coal development and people's increased awareness of environmental protection issues, the vast majority of coal mines in China will encounter problems related to coal pressing to protect buildings, structures, water bodies and other protected bodies during the construction and production process, as well as mining problems that are influenced by protective bodies, that is, problems related to subsidence control and coal mining activities under special conditions, seriously restricting the production of coal mining enterprises [1–3]. Fundamentally, technical measures that reduce subsidence and control loss mainly include filling mining, partial mining, coordinated mining, etc. [4–7]. Filling mining is a method that has been proven to solve pressed coal problems. The use of this method supports the rock mass over the mined-out area, thereby alleviating surface subsidence, reducing damage to surface buildings, achieving the goals of efficiently mining coal mine resources and of controlling surface damage [8–13]. Controlling the deformation and destruction of structures, such as villages, railways and other structures is one of the problems that the mining industry urgently needs to solve. After mining, stress in the overlying rock mass is redistributed, causing local stress concentration in the surrounding rock, causing the top of the mined-out area to sink, become crushed, or fall [14–16]. As the stress in the support body changes, surface deformation will be induced within a certain range [17–20]. Therefore, studying the influence of strata movement and surface subsidence on the villages and buildings on the surface during and after coal mining is of great significance [21–23].

There are many theoretical methods and monitoring methods related to surface subsidence, and many achievements have been made [24,25]. For example, Sun proposed a theoretical method to predict surface subsidence caused by inclined coal seam mining [26]. Dong studied the influence of different factors on tomography [27]. Existing test devices for similar coal mining material simulations are mostly two-dimensional test benches that simulate the roof and rock formation movement in coal mines and represent mature technology, but there are certain surface movement limitations that must be accounted for during simulation [28–30]. The control process of the coal seam simulation components in three-dimensional test equipment is complex, and successful trial production is difficult or is limited by the bearing capacity, function and size, making it difficult to effectively combine these simulations with engineering practices to carry out model test research [31–33]. Therefore, in order to better study the strata and surface movement characteristics caused by coal mining, this paper adopts a method combining field measurements and the development of a test device to conduct simulation tests. Through the "three-dimensional test device to simulate the influence of underground coal mining on strata and surface movement", developed by the authors of this paper, combined with three-dimensional laser scanning technology, simulation tests determining surface subsidence after coal mining are carried out. Combined with long-term surface observations, the laws of strata and surface movement caused by coal mining are revealed.

2. Testing Device

2.1. The Overall Structure of the Test Device

This paper introduces a three-dimensional test device that simulates the impact of underground coal mining on rock formations and surface movement, as shown in Figure 1. This device belongs to independent research and development, and has obtained the Chinese utility model patent authorization. And entrust Qingdao local testing machine manufacturers to cooperate in manufacturing. It includes an outer frame, pressurization unit, pulling unit, and coal seam simulation portion. The coal seam simulation portion is located inside the outer frame, the upper surface of which is filled with similar m coal seam materials, and the coal seam simulation portion consists of multiple mining blocks and multiple reserved coal pillar assemblies. The pressurization unit is located on the top of the outer frame, and the pressurization unit is connected to the outer frame by the pressurizing position adjustment unit. The pulling unit is located at the bottom of the outer frame, and the pulling unit is connected to the outer frame by the pulling position adjustment unit. This device can be combined with the coal mining site to simulate the mining process and can simulate the variable mining height, controlled mining speed and ease of pressurization, and laying of similar materials.

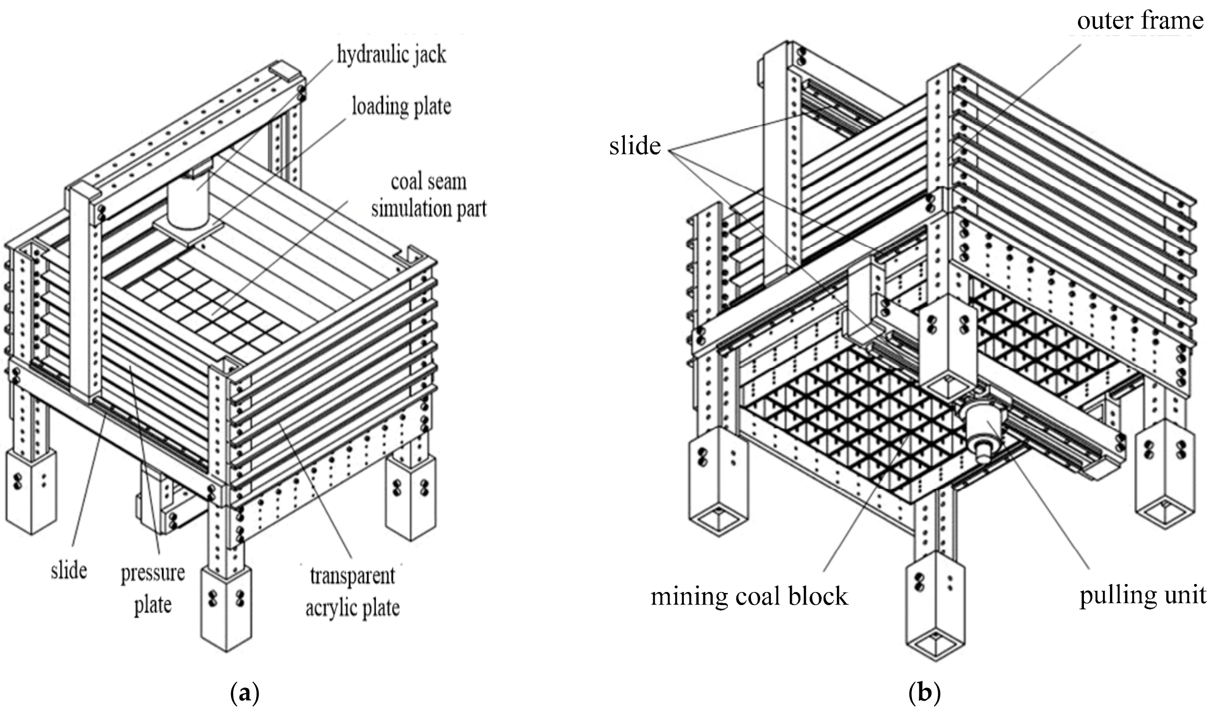

Figure 1. Schematic diagram of the device structure: (**a**) the top structure and components of the device; (**b**) bottom structure and components of the device.

2.2. Introduction of Function and Test Method

Using a "three-dimensional test device for simulating surface movement in underground coal mining" that was developed by the authors independently to carry out the test, a certain degree of model simplification was carried out during the physical processing process of the test device. The specific size of the model is as follows: x × y × z = 0.60 m × 0.60 m × 0.80 m. A detailed image of the model and its size parameters is shown in Figure 2.

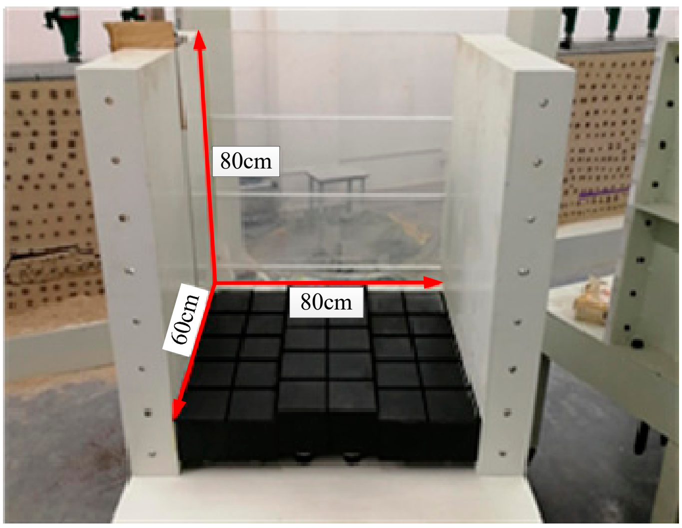

Figure 2. The three-dimensional test device for simulating surface movement in underground coal mining.

This device mainly addresses the technical problems that are present in the existing technology, thus providing a three-dimensional simulation test device and test method that can simulate different coal seam mining schemes and that can facilitate the observation of surface deformation characteristics, as shown in Figure 3. In order to achieve the design purpose of the device, it was determined that the overall structure of the device should mainly consist of the outer frame, pressurization unit, pulling unit, and coal seam simulation portion:

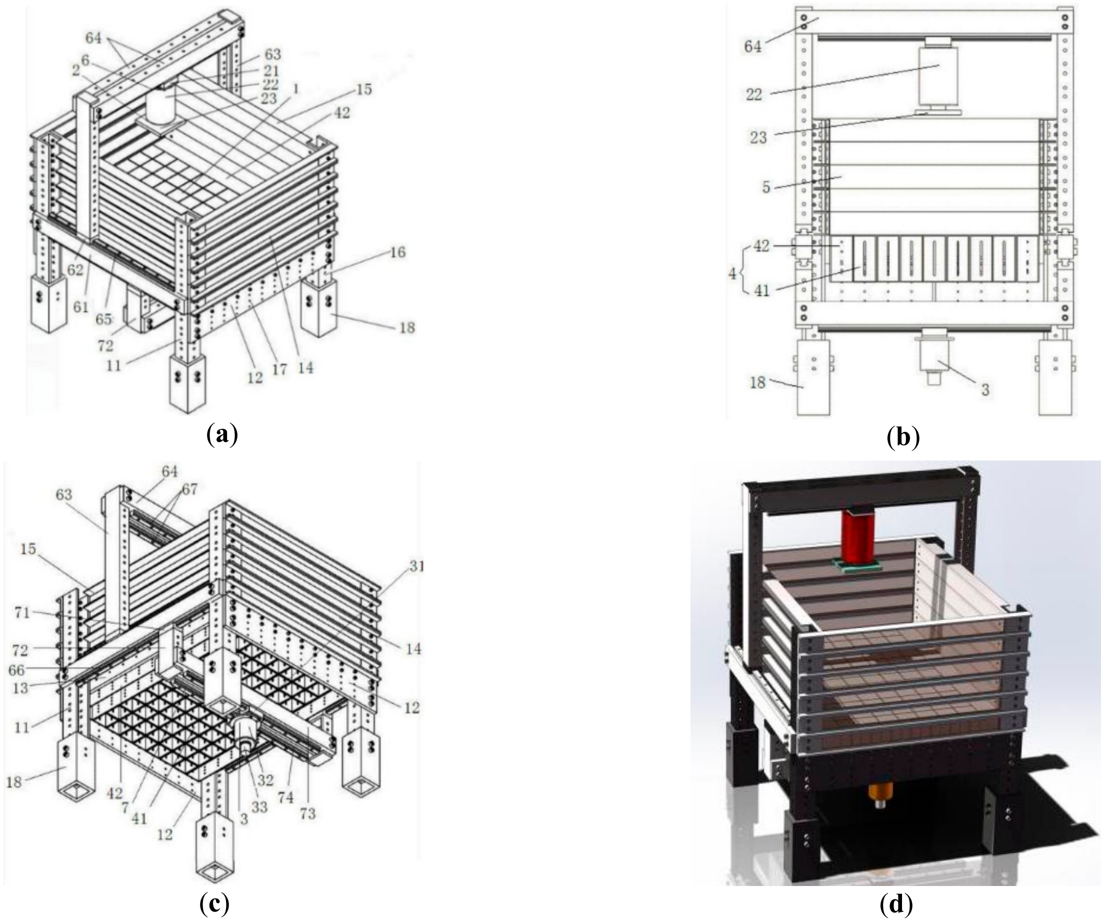

Figure 3. Structure diagram of the test device. The numbers in the diagrams can be described as follows: 1—outer frame, 11—column, 12—the first pressure plate, 13—the second pressure plate, 14—the first baffle, 15—second baffle, 16—threaded hole, 17—the first threaded hole, 18—bearing, 19—transparent acrylic plate, 2—pressurization unit, 21—the first ball slide, 22—hydraulic jack, 23—loading plate, 3—pulling unit, 31—third ball slide, 32—drawing instrument, 33—pull rod, 4—coal seam simulation part, 41—mining coal block, 42—reserved coal pillar assembly, 5—similar materials for coal rock formations, 6—pressurizing position adjustment unit, 61—central rail beam, 62—second ball slide, 63—upper track column, 64—upper rail beam, 65—upper slide, 66—lower slide, 67—first slide, 7—pulling position adjustment unit, 71—fourth ball slide, 72—lower track post, 73—lower track beam, 74—second slide. (**a**) direction view 1 (**b**) left view (**c**) direction view 2 (**d**) 3D schematic.

(1) The outer frame includes columns located in the four corners. Multiple threaded holes are spaced throughout the column. Four pressure plates are installed in four columns on all sides with bolts.

(2) The coal seam simulation portion is composed of mining coal blocks and reserved coal column components that are staggered and connected on the horizontal plane. The coal seam simulation portion is connected with four pressure plates, which are all around this part of the model.

(3) The pressurization unit is set at the top of the outer frame and is connected to the outer frame by the pressurizing position adjustment unit. The pressurization unit is used to pressurize the surface of coal rock formations that are composed of similar material; if surface deformation observations are required, then the test geometric similarity ratio can

be adjusted to make the whole range of the model correspond to the whole stratum. Then, there is no need to apply the surface pressure to the model.

(4) The pulling unit is located at the bottom of the outer frame and is connected by the pulling position adjustment unit to the outer frame. The pulling unit is used to pull down the mining coal block in order to simulate coal mining.

In order to coordinate the operation of the unit and to work closely with the various parts of the system, the detailed features of each component were designed so that the functions could be achieved without affecting the overall structure of the equipment: The reserved coal pillar assembly and the mining block comprise a rectangular steel body with a bottom opening, a waist through-hole is located on the inner four walls of the rectangular steel body, and the top also has a welded nut that extends inward and that is connected to the pulling unit. The coal seam simulation portion is bolted through the threaded hole to connect it to the four pressure plates; the surface is also filled with a similar coal seam material surrounded by baffles that are set on all sides, and the front baffle is fitted with a transparent acrylic plate to observe the overall deformation of the specimen during the experimental process. The pressurization unit consists of the first ball slide, hydraulic jack and load plate; the first ball slide is connected to the pressurizing position adjustment unit, the position of the loading plate corresponds to the surface position of the similar coal rock formation material, and the pressurization unit is connected to the outer frame by the pressurizing position adjustment unit. The pressurizing position adjustment unit consists of a central rail beam, a second ball slide, an upper rail column, and an upper rail beam.

By combining the overall structure and the other components, the device can effectively simulate the surface subsidence characteristics of coal seam mining. During the test, the HandyScan700 three-dimensional laser scanner was used to scan the surface of the model multiple times in order to obtain the deformation characteristics of the model. The HandyScan700 three-dimensional laser scanner includes a handheld scanner as well as the control host and control software VXelements, as shown in Figure 4. During operation, the scanner is able to calculate the shape of the object accurately based on the triangulation principle combined with the positioning spots on the object by projecting the laser mesh onto the object being tested, and the camera is used to capture the laser mesh shape. The following are the positive characteristics of this method: fast, non-contacting, high-density, high-precision, digital, automatic, etc.

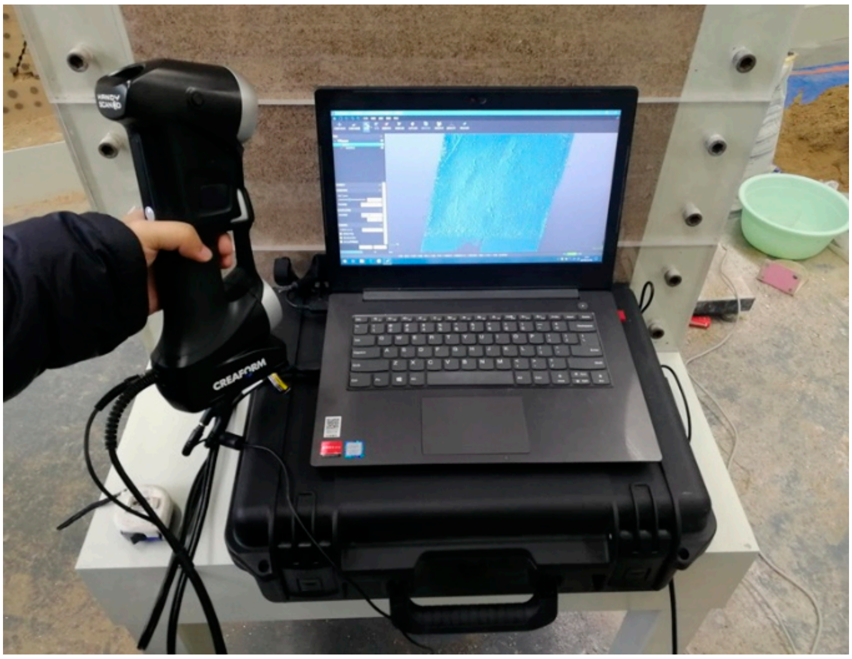

Figure 4. HandyScan700 three-dimensional scanner and support equipment.

2.3. Test Steps

When using this device to simulate underground coal mining processes and to observe its surface movement features, the following steps should be followed:

(1) According to the actual situation of the project site, develop pre-simulation mining conditions (mining area, number of working faces, mining methods, etc.), assemble the test device;

(2) Obtain the on-site coal seam and rock formations parameters, and formulated similar materials indoors;

(3) Test to determine the parameters of the formulated similar materials;

(4) Place similar materials in the test device, arrange the sensors, and compact the layers;

(5) Place the three-dimensional scanners in the surface deformation observation positions of the test device and scan and store the surface and building deformation and movement in real-time;

(6) Conduct similar simulation tests according to the established mining simulation scheme: the non-slip fastening screws between the mining coal blocks will be loosened, and the pulling mechanism will be pulled down one by one to simulate coal mining. After the test is completed, according to the corresponding data and the processing steps, conduct the analysis.

3. Characteristics Analysis of Surface Subsidence in Coal Seam Mining

3.1. Test Scheme

During the field engineering measurement process, due to the influence of building surfaces and other factors, irregular monitoring points will be laid down according to the actual situation on the surface to obtain the subsidence law of the monitoring polyline on the surface. Two-dimensional planar or the three-dimensional spatial features of surface subsidence can only be studied by means of indoor experiments. In order to better analyze the dynamic spatial characteristics of surface subsidence caused by coal seam mining, a test device for simulating rock formations and surface movement can be used, and supplementary research and analysis of the temporal and spatial surface subsidence characteristics are conducted through the test results.

3.1.1. Formulation Ratio of Similar Materials

The test scheme is designed based on a similar material test design principle, combined with the characteristics of the overlying strata of Tangshan ore. To highlight the geological features of the thick, loose layers on the surface, the thickness of the loose layer on the surface is set to 300 m, and the parameters of the remaining rock formations are listed in Table 1.

Table 1. Formulation ratio of the test.

Layer No.	Lithology	Thickness/m	Model Thickness/cm	Unit Weight g/cm^3	Formulation Ratio	Amount of Material/kg				
						Total Weight	Sand	Calcium Carbonate	Gypsum	Water
R4	Loose Layer	300	33	0.95	673	182.40	156.34	18.24	7.82	20.27
R3	Bedrock Layer	300	33	1.60	537	230.40	192.00	11.52	26.88	25.60
R2	Basic Roof	100	11	1.70	755	73.44	64.26	4.59	4.59	8.16
R1	Immediate Roof	30	3	1.80	773	34.56	30.24	1.30	3.02	3.84
	Total	730	80			520.80	442.84	35.65	42.31	57.87

3.1.2. Test Steps

(1) Design the similarity ratio of the test according to the purpose, calculate the material formulation ratio based on the similarity ratio and rock formations, and determine the formulation scheme;

(2) Adjust the mining block according to the test scheme and raise the expected mined coal seam range, as shown in Figure 5a;

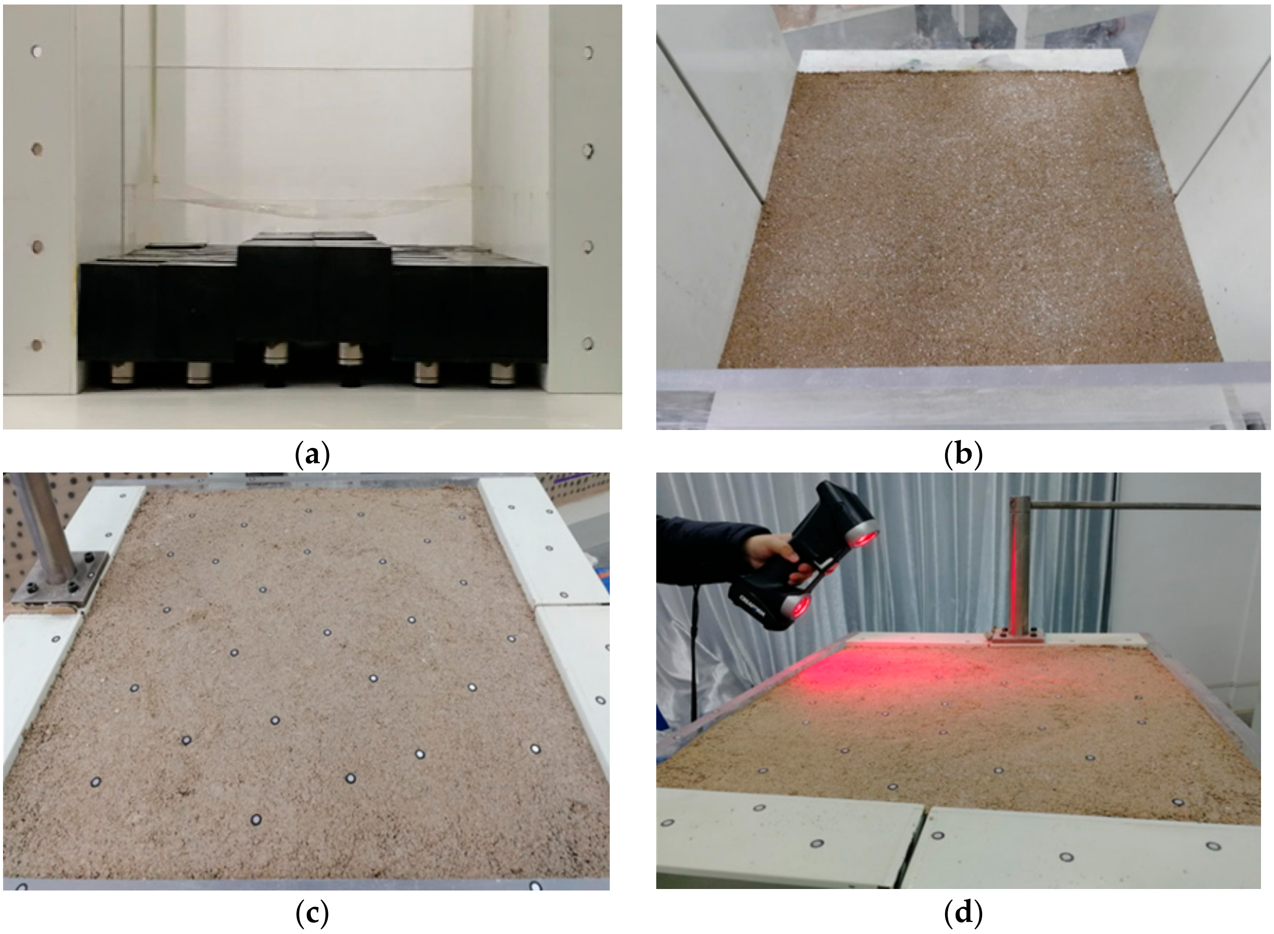

Figure 5. Operating steps of the test process: (a) adjusted mining blocks; (b) layered laying model; (c) placement location punctuation; (d) three-dimensional scanning monitoring.

(3) Formulate the similar material of each rock formation according to the test scheme, lay the model out, and compact each layer, as shown in Figure 5b;

(4) Lay out the three-dimensional scanning positions of the surface on the model, as shown in Figure 5c;

(5) Mine the model step-by-step and lower the pre-raised mining blocks to their original position while using a three-dimensional laser scanner to monitor the vertical deformation of the surface on the model, as shown in Figure 5d.

3.2. Analysis of Test Results

3.2.1. Surface Subsidence Characteristics of Coal Seam Mining

In order to compare the surface subsidence morphology after coal seam mining, a cloud map of the vertical displacement on the surface of the model and a schematic of the measuring line of the model are calculated by Geomagic Control X, as shown in Figures 6 and 7, respectively. After coal seam mining, the surface subsidence pattern is symmetrically distributed along the working surface. The sediment volume gradually decreases from the center to the edges of the mined-out area: With coal seam mining, the surface subsidence gradually radiates in the direction of the work surface, and the peak settlement position gradually shifts from the center to the back of the mined-out area. The early stage of mining has a greater impact on surface subsidence. During coal seam mining, partial positive vertical displacement occurs. At the beginning of coal seam mining, positive vertical displacement is concentrated at the edges of the mining area and at the edges of the model. In the mid to late stages of mining, positive vertical displacement is more distributed at the edges of the surface subsidence, which is because the stress is redistributed during the surface subsidence, resulting in the formation particles being squeezed and the upward vertical displacement occurring.

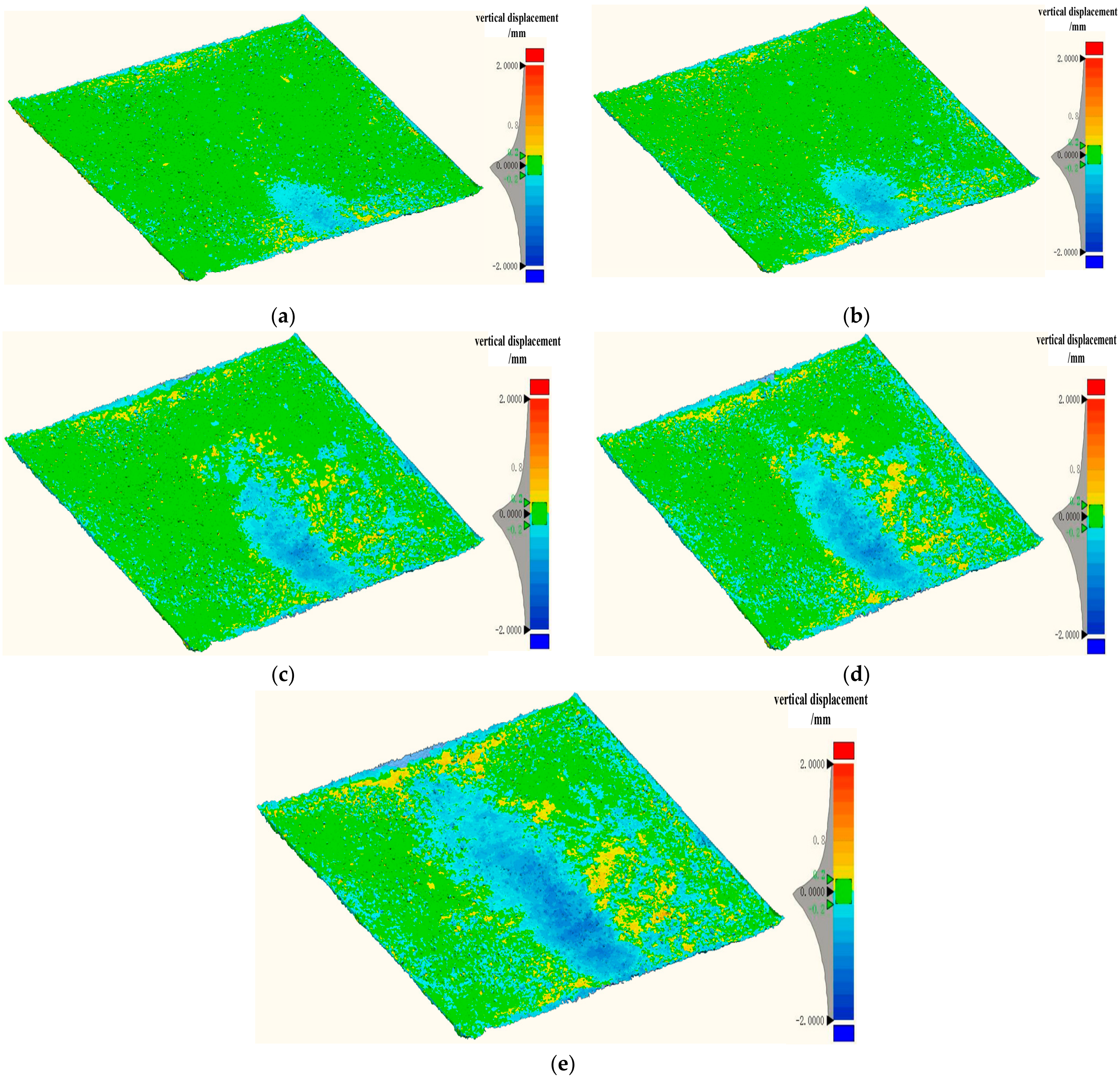

Figure 6. Cloud map of cumulative settlement of the model: (**a**) first mining; (**b**) second mining; (**c**) third mining; (**d**) fourth mining; (**e**) fifth mining.

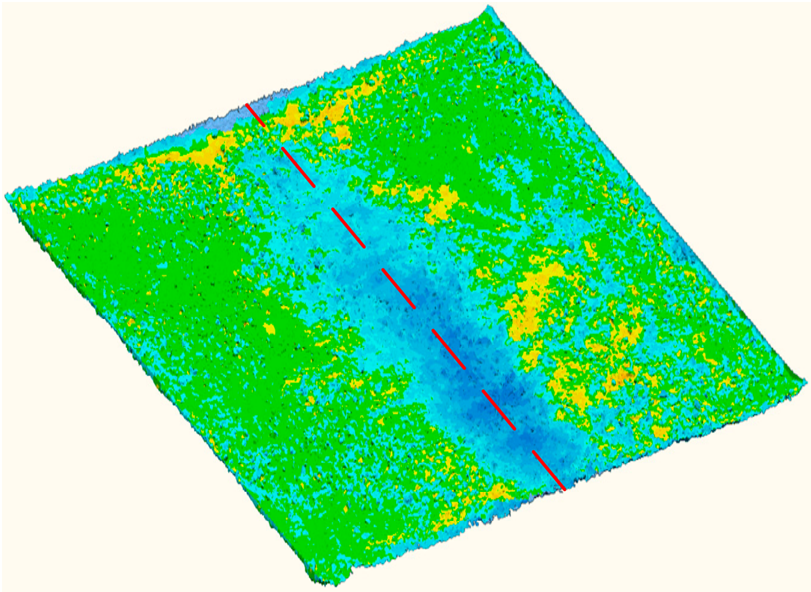

Figure 7. Schematic diagram of the model measuring line.

The statistical average and maximum sedimentation curves of the surface after coal seam mining are shown in Figure 8. As seen from the figure, the average and maximum surface settlement volume gradually increase with the work surface, and after the coal seam is mined out, the average surface settlement volume is about 0.837 mm, and the maximum settlement volume is about 1.841 mm.

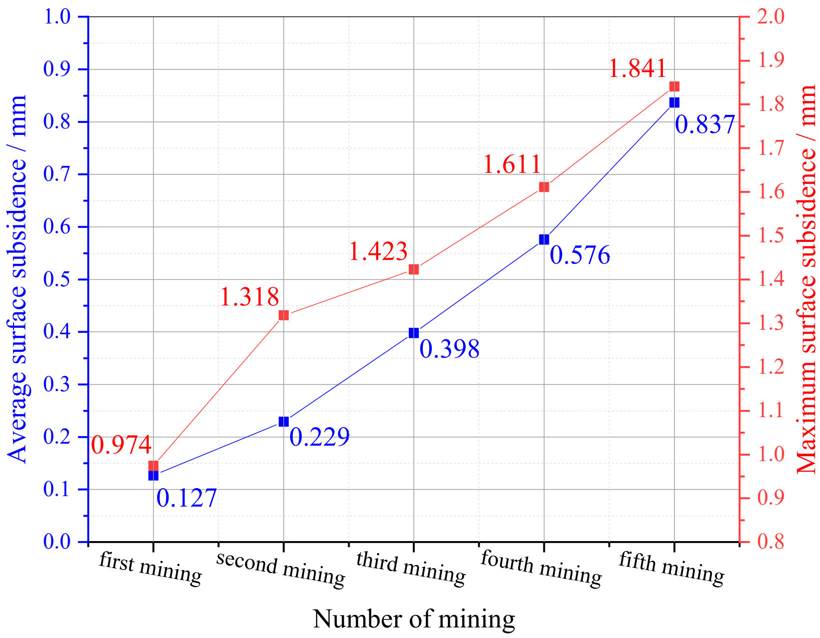

Figure 8. Statistical curve of surface settlement.

The sediment characteristics of the surface measuring line are shown in Figure 9, and the corresponding settlement monitoring curve is shown in Figure 10. According to Figure 9, after coal seam mining, the surface subsidence parallel to the mined-out area is presented as asymmetrical distribution, the settling pattern is similar to the spoon type, the central settlement of the mined-out area is larger, the edge settlement is smaller, the sedimentation slope is larger, the slope is steeper on the open-off cut side, the sedimentation slope is smaller, and the slope is relatively slower on the working face side.

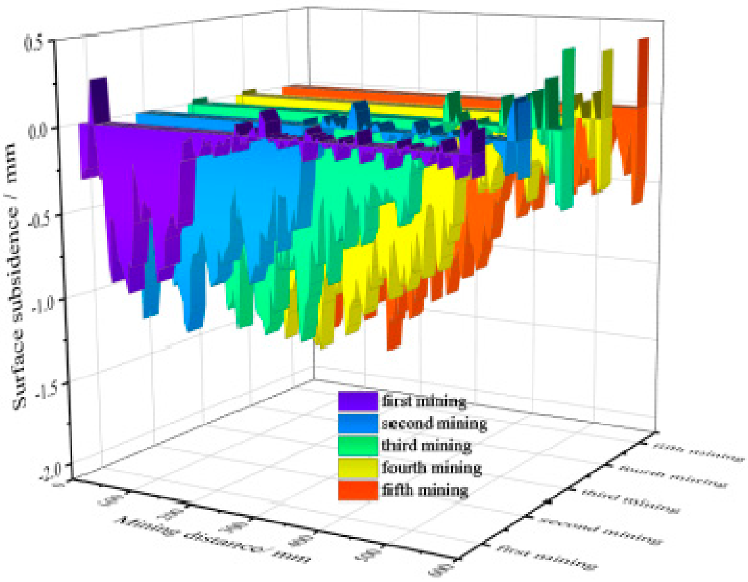

Figure 9. Three-dimensional strip diagram of surface measuring line settlement.

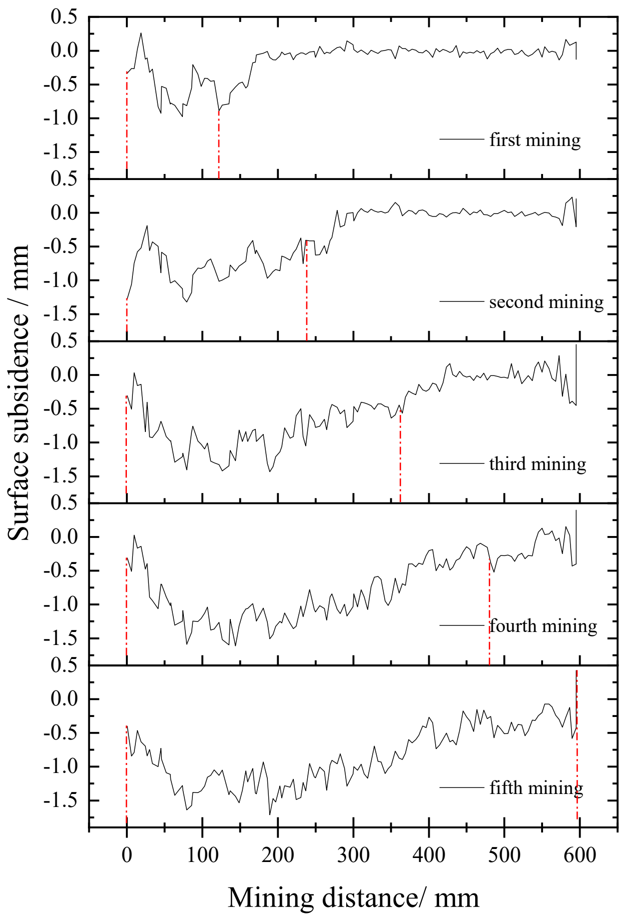

Figure 10. Monitoring curves of surface measuring line settlement.

3.2.2. Transfer Law of Surface Subsidence in Coal Seam Mining

In order to compare the impact of coal seam mining on the sediment at different areas of the surface, the surface range right above the five mining stages is divided into five areas to analyze the changes in the measuring line sediment in the five regions, as shown in Figure 11. The analysis shows that:

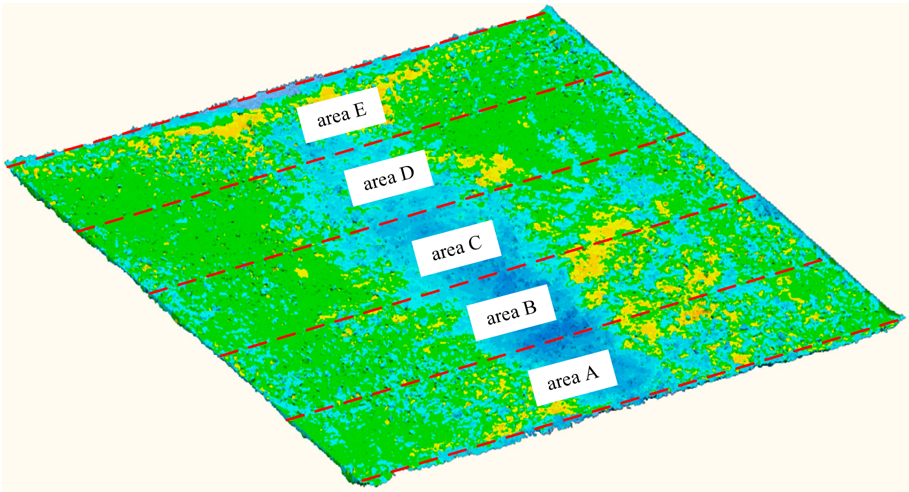

Figure 11. Region division for surface analysis.

(1) The changes in average sedimentation in different surface regions are shown in Figure 12. As seen from the figure, all the surface regions saw an increase in the amount of sedimentation, and the increase gradually decreased. After the stability of the strata, the total settlement is the largest in area II, with an average of 1.323 mm, and the smallest overall settlement is observed in area V, with an average of 0.334 mm. Therefore, the early middle stage of the surface in the mined-out area is the area with the largest amount of settlement, and measures need to be taken to focus on prevention and control.

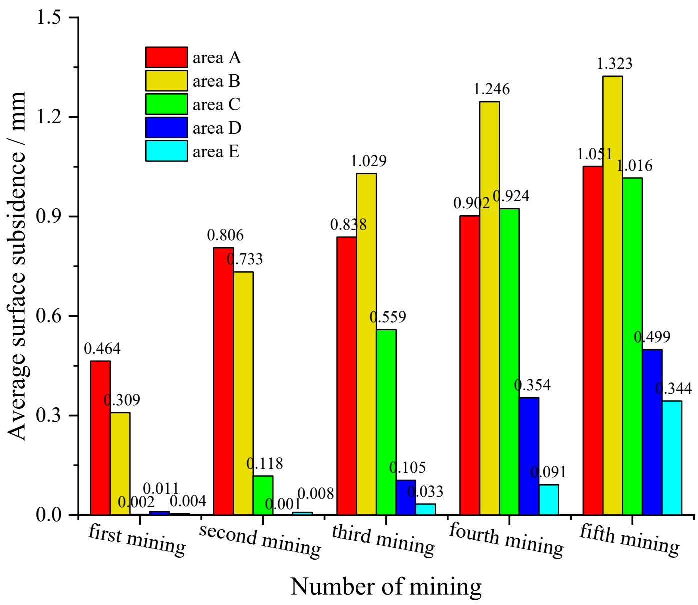

Figure 12. Histogram of average sediment volume change in different regions of the surface.

(2) The radar map of the average sedimentation for the different surface regions is shown in Figure 13. With the exception of area I, each area settles when the coal seam corresponds to the previously mined area, and the amount of advanced settlement caused by coal seam mining in areas II to V is 0.309 mm, 0.118 mm, 0.105 mm, 0.091 mm, respectively, with an overall decreasing trend being observed. At the same time, during the third mining operation, area V shows a mild response, indicating that as the range of the mined-out area increases, the degree of surface subsidence advance that is caused by the continuously advancing working surface is gradually reduced, but the advance impact range gradually increases.

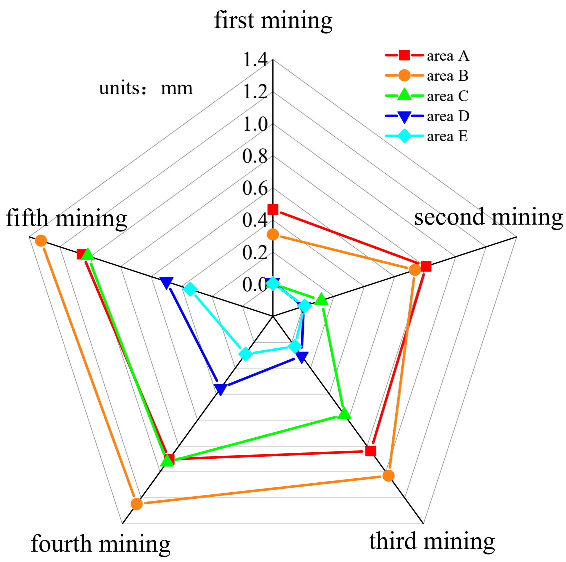

Figure 13. Radar map of average sediment volume change in different regions of the surface.

(3) Different coal seam mining stages have different degrees of influence on the corresponding surface. The settlement increments caused by coal seam mining right under the five areas are 0.464 mm, 0.424 mm, 0.441 mm, 0.249 mm, and 0.253 mm, and exceed the settlement increments caused by coal seam mining in other areas. Taking area III as an example for analysis, the surface subsidence caused by the first two, the third and fourth, and the fifth mining simulations accounted for 11.6%, 79.3%, 9.1% of the total subsidence, respectively. The analysis shows that the surface subsidence is the superposition of advanced settlement caused by coal seam mining, disturbance settlement caused by subsurface coal seam mining, and prolonged post-mining subsidence. The settlement caused by the disturbance of subsurface coal seam mining is the dominant factor in total surface subsidence.

4. Field Engineering Validation

In order to analyze the surface subsidence characteristics of coal seam filling mining in the Tangshan mine, a regional surface subsidence observatory was established in the corresponding surface area. The station layout is shown in Figure 14 and has a total of 87 observation points, the average observation point spacing is 30 m, the total length of the measuring line is 2700 m, and both ends of the measuring point distance from the T3292 working surface boundary are located about 750 m or so away [34].

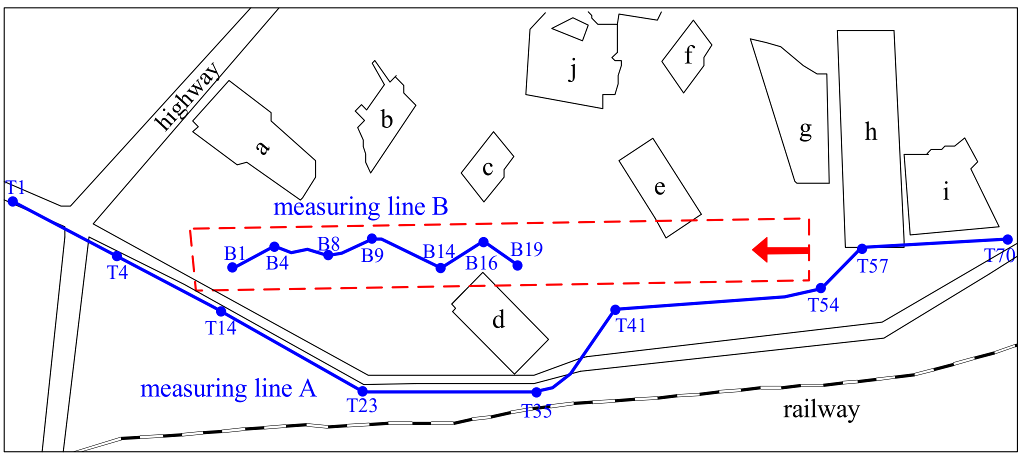

Figure 14. Measuring line layout.

Surface subsidence observation line B was established in the main section and was located on both sides of the main section of the working surface and had a total length of 470 m as well as a total of 19 observation stations from B1 to B19. The average distance between the observation positions was 26 m, and the surface subsidence caused by mining on the T3292 working surface was observed.

By studying the influence range of the surface subsidence of the working surface and analyzing the long-term observation results of each measuring point of measuring line B, the settlement vs. time curve of some observation positions could be obtained, as shown in Figure 15.

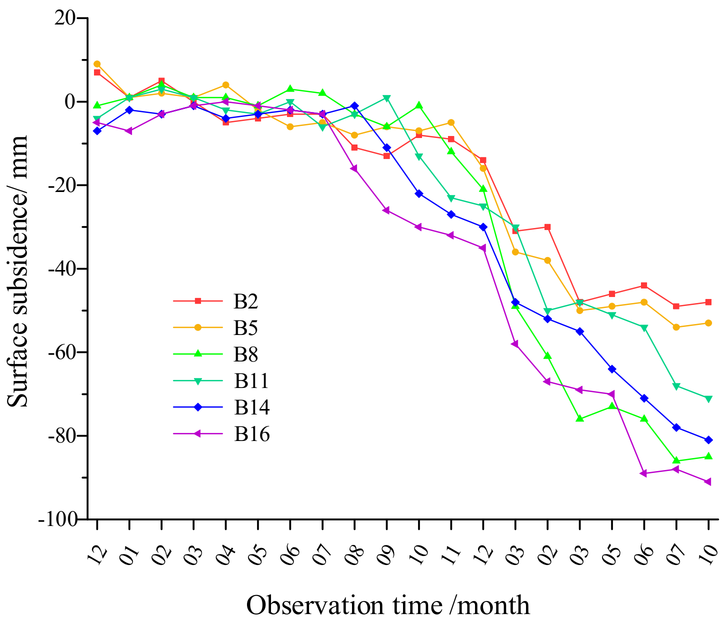

Figure 15. Settlement vs. time curve of measuring line B.

In order to study the surface subsidence response process, we take observation positions B11, B14s, and B16 as examples. The advanced influence surface subsidence process can be divided into four stages, as shown in Figure 16.

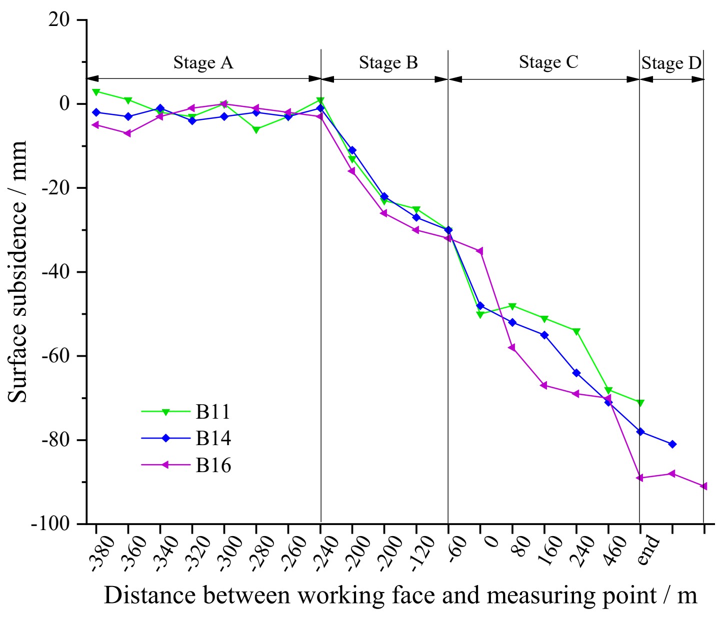

Figure 16. Advanced impact stage division.

Combined with field engineering tests, the field engineering situation and the analysis of the device test results are consistent. The study reveals the following:

(1) Stage A—No settlement stage. Before the working surface advances to 240 m, each measuring point settlement value is small, fluctuating around the threshold value, and the average value is lower than the surface subsidence threshold value (10 mm). Multiple observations on the surface lasting more than a dozen months showed small changes in the settlement, indicating that the observation area is far away from the mining area and that it is only slightly affected by the advance.

(2) Stage B—Slight settlement stage. When the working surface advances to the position of 240-60 m ahead of the measuring point, the curve slope increases, the settlement increased to 30 mm, exceeding the threshold of surface subsidence (10 mm), the surface of the observation area begins to be affected by the advance, and displacement settlement occurs.

(3) Stage C—Significant settlement stage. After the working surface advances to the position of 60 m ahead of the measuring point, the settlement exhibits a major increase as the working surface advances. After mining, the settlement continues to increase over time, with the final settlement of each measuring point increasing to more than 70 mm.

(4) Stage D—Residual settlement stage. After experiencing significant growth, the settlement of each observation point and the ground surface gradually reach a stable state; the stabilized subsidence value is affected by the location of the measuring point and the surface situation, which has a larger stabilized subsidence value near the strike of the working surface inclination and is close to the middle position.

5. Conclusions

(1) A "three-dimensional test device for simulating surface movement in underground coal mining" was self-designed and developed. The overall structure of the device consisted of an outer frame, pressurization unit, pulling unit, and coal seam simulation portion that can effectively simulate the law of surface subsidence caused by underground coal seam mining.

(2) The final surface subsidence state is the superposition of advance settlement caused by coal seam mining, disturbance settlement caused by subsurface coal seam mining, and prolonged post-mining subsidence. The surface subsidence caused by the three mining stages accounted for 11.6%, 79.3%, and 9.1% of the total surface subsidence, respectively. The settlement caused by the disturbance of subsurface coal seam mining is the dominant factor in the total surface subsidence.

(3) The device model test was effectively combined with actual engineering practices. The field engineering tests and model test results analysis are consistent, and a conclusion can be drawn: after coal seam mining, the surface subsidence comprised four stages, including a no settlement stage (ahead of 240 m), a slight settlement stage (ahead of 240~60 m), a significant settlement stage (ahead of 60 m ~ the end of mining), and a residual settlement stage (after the end of mining), with the settlement from the significant settlement stage accounting for more than 60% of the total settlement.

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