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Construction and Application of an Intelligent Roof Stability Evaluation System for the Roof-Cutting Non-Pillar Mining Method

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Abstract: In order to sustainably use coal resources and reduce coal mine accidents, the stability evaluation of roadway roofs is particularly important. The existing methods of roof stability evaluation and control application are greatly disjointed, the relationship between roof stability evaluation and early warning control is ignored, and an intelligent evaluation and calculation control system is lacking. Based on the successful application of the roof-cutting non-pillar mining method in various engineering geology and mining conditions, the roof stability evaluation system, mobile intelligent computing system, and engineering application research are carried out. An evaluation index system for roof stability in the roof-cutting non-pillar mining method is established, including the roof rock integrity and the roof-surrounding rock displacement. A comprehensive evaluation method for roof stability grades is proposed based on the coupling of evaluation index grading criteria and improved analytic hierarchy process (AHP) weight assignment. A handheld mobile intelligent platform for roof stability evaluation, roof hazard zone, and control suggestion is developed. The research results have been applied in the coal mine of Hecaogou with good outcomes. This intelligent stability evaluation system will provide an economical and effective approach to achieving sustainable use of coal resources.

Keywords: coal resources; roof cutting and pressure release; roof stability; non-pillar mining; evaluation system; intelligent computing; roof control

Citation: Chen, Q.; Zou, B.; Tao, Z.; He, M.; Hu, B. Construction and Application of an Intelligent Roof Stability Evaluation System for the Roof-Cutting Non-Pillar Mining Method. *Sustainability* **2023**, *15*, 2670. https://doi.org/10.3390/su15032670

Academic Editors: Fangtian Wang, Cun Zhang, Shiqi Liu and Erhu Bai

Received: 11 January 2023
Revised: 25 January 2023
Accepted: 26 January 2023
Published: 2 February 2023

1. Introduction

The roof-cutting and pressure-releasing non-pillar mining method is a new type of gob-side entry retaining based on roof-cutting short-arm beam theory [1–6]. Through the roof directional pre-splitting cutting seam and constant-resistance large deformation anchor cable support, the stress transfer path between the roof of the roadway and the roof strata of the goaf is cut off, and the mining roadway and coal pillar are not required to be excavated in advance in the mining area, so as to avoid the occurrence of disaster accidents. At present, the technology has been successfully tested in different geological conditions such as the thick coal seams of the Ningtiaota coal mine, the high-gas Baijiao coal mine, and the composite roof of the Halagou coal mine [7–16]. However, in the process of its implementation, because the roof of the roadway is not only the working platform of directional pre-splitting cutting but also the support platform of the constant-resistance large deformation anchor cable, the stability of the roof is the necessary condition for the safe and efficient mining of the technology of cutting roof and relieving pressure without a coal pillar.

According to statistics [17], from 2013 to 2017, China's coal mine roof accidents a total of 760, accounting for 39.07% of the total number of accidents, while the roof accident deaths were 1000, accounting for 26.52% of the total number of deaths in accidents. The number of accidents in coal mine accidents ranked first and the death ranked second. The roof-cutting non-pillar mining method can effectively solve the problem of frequent disasters of cross-heading roofs by changing the structure of the entry roof and goaf roof through roof cutting and pressure release [1–10]. Therefore, roof stability evaluation is the core technology of roof strata control and disaster prevention. The existing evaluation of roof stability is mainly based on classical methods, machine learning methods, deep learning methods, and computational theories. Wang et al. [15] analyzed the roof deformation and its influencing factors by using energy theory and displacement variational method. He et al. [18] analyzed the evolution law of the roof weighting in mining under the inclined coal pillar. Zhu et al. [19] studied the mechanism of roof pressure release through the structural mechanics model. Gao et al. [20] built a finite difference model to investigate the stabilities under different mining conditions. Yang et al. [21] adopted the discrete element simulation method to study the large deformation mechanism of roadways. Xiong et al. [22] analyzed roof stability based on the composite roof structure model. Winn et al. [23] analyzed the stability of roofs by analytical and numerical methods. Das et al. [24] analyzed the effect of fault on the stability of coal mine roofs based on the DEM model. Wang et al. [25] proposed a cavern safety evaluation system composed of cavern volume shrinkage, expansion safety factor, and equivalent strain. Das et al. [26] analyzed the influence of strata dip angle and coal seam dip angle on the stability of surrounding rock by numerical simulation. The existing research and development of roof stability calculation systems is mainly based on Visual Basic and Java. Feng et al. [27] developed software for judging the stability of roadway composite roofs based on Java. Qin [28] developed the direct roof disaster warning system software. Liu et al. [29] developed Matlab and Surfer based on Visual Basic to automatically draw the partition map of the roof stability type. However, there is a big gap between the existing roof stability evaluation methods and control application research. The existing roof stability evaluation methods ignore the relationship between the relevant factors of roof stability evaluation and early warning control and lack intelligent evaluation and control systems, which makes it difficult to provide decision support for roof stability evaluation and control application. There is a lack of a dynamic intelligent calculation system for the roof stability evaluation of the roof-cutting non-pillar mining method, which integrates evaluation, control suggestions, and risk partition.

Therefore, this paper adopts the methods of field investigation, expert consultation, theoretical analysis, and field test to study the roof stability evaluation system and mobile intelligent computing application of the roof-cutting non-pillar mining method. An evaluation index system for roof stability of the roof-cutting non-pillar mining method was established, which included the integrity of roof strata and the displacement characteristics of the roof's surrounding rock. The intelligent evaluation, risk partition, and control suggestion portable mobile application for the stability evaluation of the roof-cutting non-pillar mining method is developed based on Android. This provides a theoretical basis for improving the early warning level of the roof stability of non-pillar entry retaining and promoting its development toward standardization, digitization, and intelligence.

2. Key Problems in Roof Stability Evaluation

The core of the roof-cutting non-pillar mining method is to cut off the connection between part of the mined-out roof area and the roadway roof by a bilateral cumulative explosion and to form a short-arm beam structure on the roof within a certain range above the mining roadway. At the same time, an NPR (negative Poisson's ratio) anchor cable is used to support the roof surrounding the rock of the mining roadway. After the working face is mined, the roof is cut off along the cutting line under the action of mine pressure, and the supporting structure of the overlying rock beam is formed by using the self-expansion characteristics of the roof rock, as shown in Figure 1 [3–10].

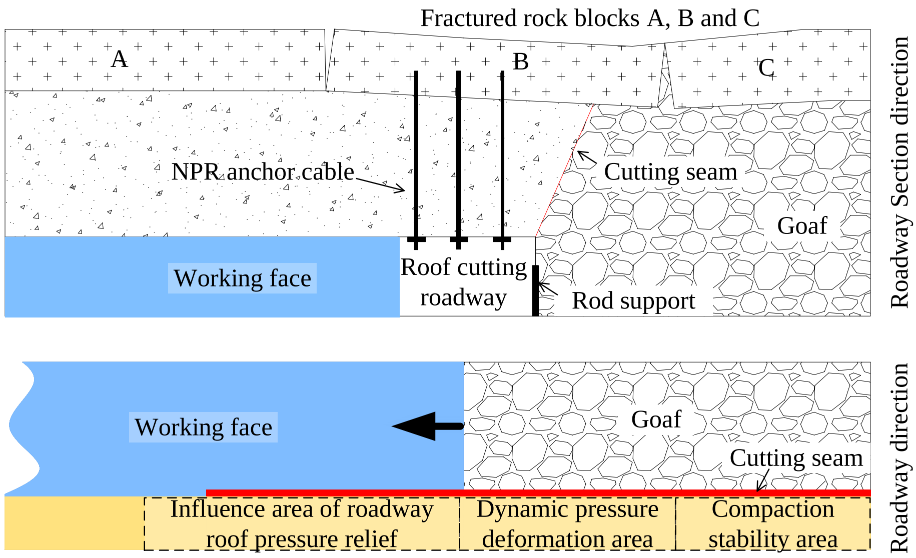


Figure 1. Structure of the roof-cutting non-pillar mining method.

During the period of gob-side entry retaining, the roof of the mined-out area collapses, deforms, and compacts from top to bottom, forming fractured rock blocks A, B, and C, so the surrounding rock of the roadway roof presents different deformation characteristics from traditional gob-side entry retaining [3–16]. Therefore, in this paper, the roof of roadway in the roof-cutting non-pillar mining method is divided into the influence area of roadway roof pressure relief, the dynamic pressure deformation area of the roadway roof, and the compaction stability area of the roadway roof (Figures 1 and 2). In the influence area of pressure relief of the roadway roof shown in Figure 2a, the roof within the scope of the directional cutting seam gradually collapses, while the roof in the area without the cutting seam does not move obviously. Roof cutting by the cutting seam causes the roof surrounding the rock to be in a pressure-relief state, which affects the stability of the roof. In the dynamic pressure deformation area of the roadway roof shown in Figure 2b, the rock beam above the cutting seam produces fracture, sinking, and rotating motion under the action of mine pressure, resulting in the deformation of the roadway roof by the extrusion of the fractured rock block. In the compaction stability area of the roadway roof shown in Figure 2c, the roof above the cutting seam basically stops moving, and the surrounding rock of the roof will no longer be significantly deformed by severe dynamic pressure before the mining of adjacent working faces. Therefore, the stability of the roof of the roadway in the roof-cutting non-pillar mining method has obvious stage deformation characteristics. In different sections of roof deformation, it is not scientific to evaluate the stability of the roof by using a single unsystematic evaluation index, as it is not conducive to the partition support of the roof. Therefore, the establishment of a unified standardized roof stability evaluation index system is the key to objectively and comprehensively reflecting the classification and grading of the roof stability of the roof-cutting non-pillar mining method.

According to the application of the roof-cutting non-pillar mining method [5], the main types of roof cutting are composite roofs containing coal, broken roofs, and hard roofs. The rock pressure of these three different types of roofs after the directional cutting seam has different effects on the stability of the roadway roof below. It is unsafe and uneconomical to use the same support method and support parameters to quantitatively evaluate the roof stability of different types and areas. Therefore, the establishment of a coupled unified evaluation system, dynamic control recommendations, and real-time three-color risk partition integration of a dynamic intelligent computing system is an effective solution to the roof-cutting non-pillar mining method stability evaluation theory and control application.

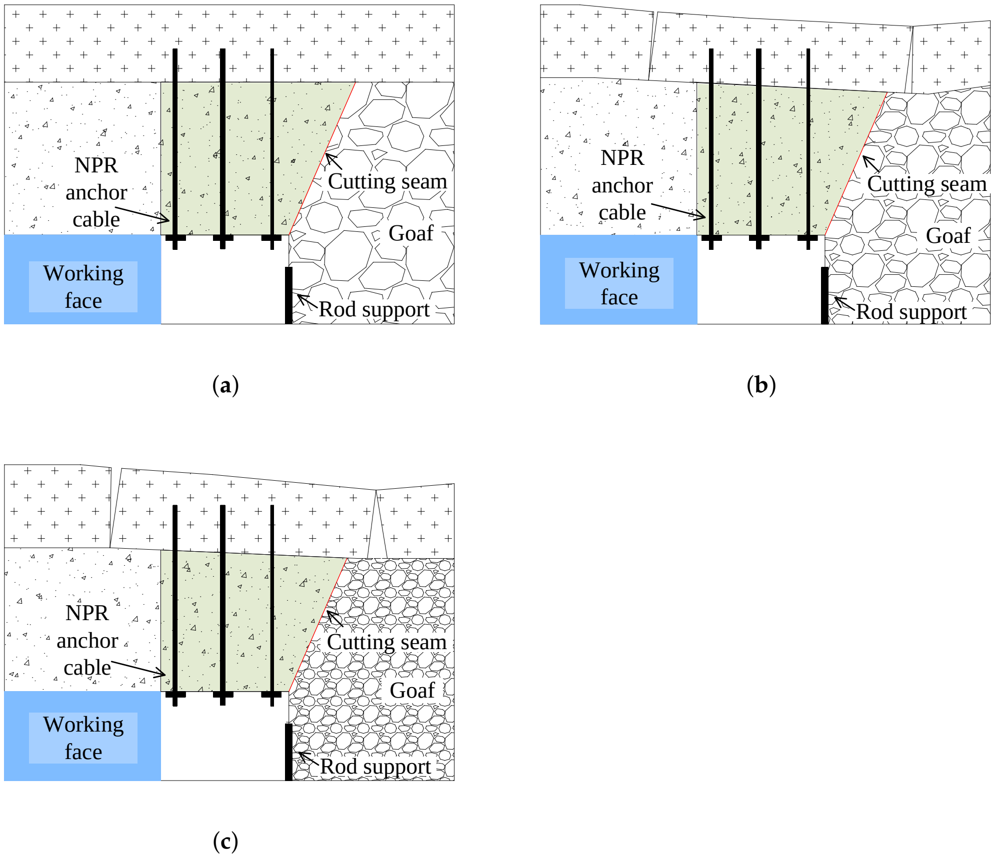


Figure 2. Roadway roof subdivision deformation section. (**a**) The influence area of roadway roof pressure relief. (**b**) The dynamic pressure deformation area. (**c**) The compaction stability area.

3. Evaluation of Roof Stability in the Roof-Cutting Non-Pillar Mining Method

3.1. Roof Stability Evaluation Index Data Acquisition

There are many factors that influence roof stability [15,16,29]. In order to avoid all the influencing factors in the potential evaluation analysis, the construction of the evaluation index mainly follows the principles of operability, representativeness, and qualitative and quantitative combination. Data collection methods mainly include field investigation, expert consultation, literature research, and experimental research [1–16]. Index collection is divided into five grades [30]. Statistics on very important (grade 1, 5 points) and relatively important (grade 2, 4 points) evaluation indicators with an adoption rate ≥50% are shown in Figures 3 and 4, respectively.

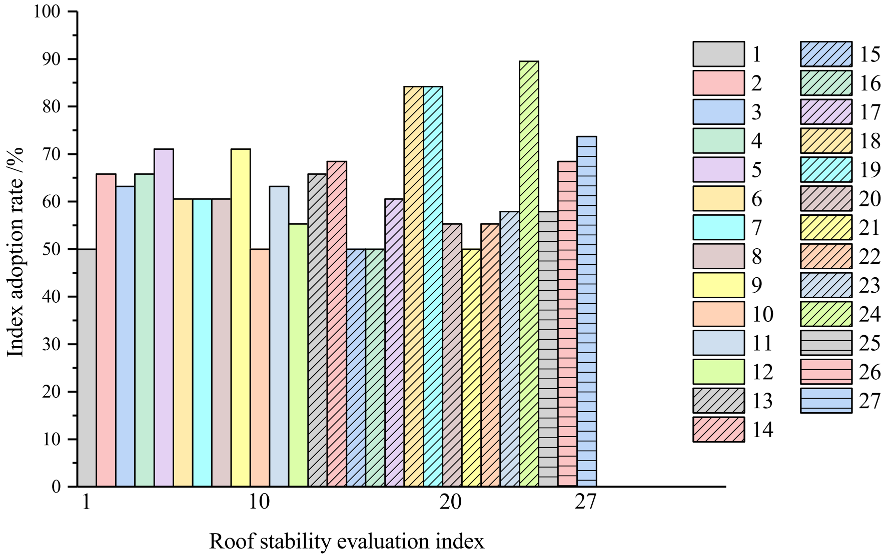


Figure 3. Statistics of roof stability index (grade 1, 5 points). Note: The evaluation indexes of roof stability represented by each number are: 1: rock mass block degree; 2: roof crushing degree; 3: roof deformation speed; 4: roof deformation amount; 5: roof strength; 6: direct roof rock strength; 7: direct roof thickness; 8: roof fracture development degree; 9: construction quality; 10: section area; 11: roof control method; 12: roadway use time; 13: support measures; 14: surrounding disturbance influence; 15: roof lithology; 16: mining process selection; 17: organization and management measures; 18: bolt support effect; 19: anchor cable support effect; 20: span; 21: area; 22: height; 23: burial depth; 24: support quality; 25: mining effect; 26: roadway overall stability; 27: surrounding rock local stability.

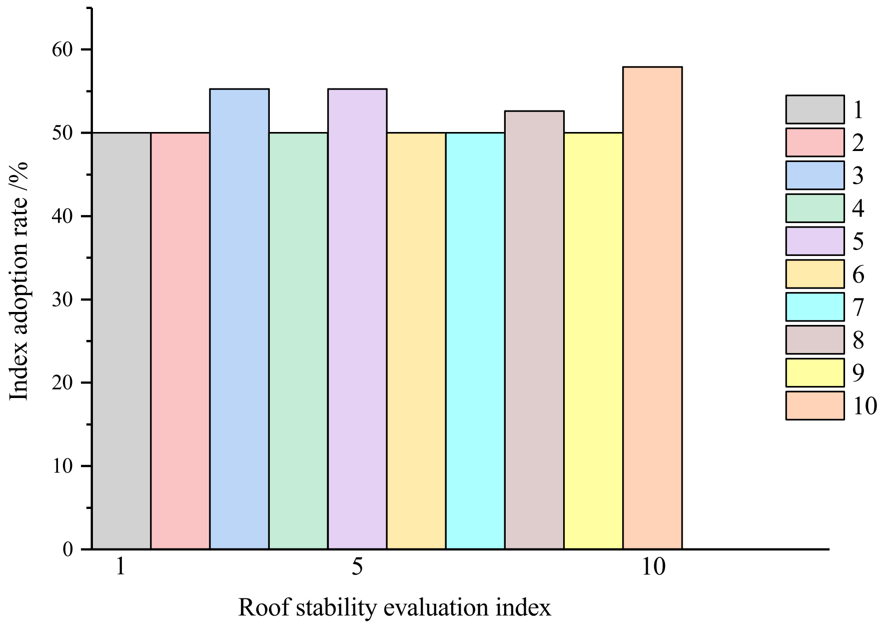


Figure 4. Statistics of roof stability index (grade 2, 4 points). Note: The evaluation indexes of roof stability represented by each number are: 1: roof thickness; 2: thickness and roof combination strength; 3: roof main lithology and sand mud ratio distribution characteristics; 4: Poisson's ratio; 5: rock mass integrity; 6: roof strata comprehensive characteristics; 7: section shape; 8: rock combination effect coefficient; 9: rock mass acoustic velocity; 10: simply supported beam safety factor.

3.2. Establishment of Roof Stability Evaluation Index System

At present, there is no uniform standard for evaluating the stability of a roof in the roof-cutting non-pillar mining method. However, the existing roof stability evaluation criteria have limitations when used in this method. For example, the rock mechanical properties (rock quality designation (RQD) index, softening coefficient, rock mass quality index, etc.) of roadway roofs in different types and different intervals cannot be obtained quickly at the construction site. Accurate parameters can only be obtained afterward for roof stability evaluation, which is not conducive to the accurate and efficient evaluation and control of roof stability. In order to evaluate the stability of the roof in a standardized, comprehensive, and objective way and avoid the intersection of indexes, based on the results of field investigation, expert investigation, current specification, engineering cases, and field test research in the literature [1–16], the improved analytic hierarchy process (AHP) method [31] is used to construct the roof stability evaluation index system in the roof-cutting non-pillar mining method, which includes 25 indexes, from the aspects of the integrity of the roof strata and the displacement characteristics of the roof-surrounding rock, as shown in Figure 5. It can be seen from Figure 5 that according to the contribution of the weight coefficient of the roof stability index, the roof stability evaluation index is ranked from large to small: maximum subsidence, deformation speed, fragmentation rate, roof lithology, development degree of roof fracture, and the number of layers. Based on the short-arm beam roof deformation and its influencing factors under the condition of the roof-cutting non-pillar mining method [15,16], the current roof stability evaluation indexes and evaluation methods domestically and internationally are comprehensively compared [7,22–29], and six indexes with the largest contribution of weight coefficient of roof stability index are selected to evaluate the roof stability of the roof-cutting non-pillar mining method, as shown in Table 1. In Table 1, the integrity of the roof strata mainly characterizes the amount of instability caused by the failure of the roof strata due to excessive force. The displacement characteristics of the roof's surrounding rock mainly characterize the value of the minimum space required by the roof strata to ensure the production space of the roof-cutting roadway, which is difficult to guarantee due to a large amount of subsidence. Roof lithology refers to the characteristics reflecting the hardness grade of roof strata, mainly including hard rock, soft rock, and extremely soft rock. Fragmentation rate refers to the characteristics reflecting the integrity of the roof strata, expressed as a percentage, the unit is %. The development degree of roof fracture refers to the extent to which the roof strata are staggered or cracked, mainly including developed, relatively developed, and undeveloped. The number of layers refers to the number of layers of roof strata. The maximum subsidence refers to the maximum roof subsidence in the roof control area of the roof-cutting roadway, the unit is mm. Deformation speed refers to the deformation degree of roof strata in unit time, the unit is mm/d.

Table 1. Index system for roof stability evaluation of non-pillar mining.

Target Layer	Criterion Layer	Index Layer (Unit)
Index system for roof stability evaluation of non-pillar mining A	Roof rock integrity B_1	Roof lithology C_{11}
		Fragmentation rate C_{12} (%)
		Development degree of roof fracture C_{13}
		Number of layers C_{14}
	Displacement characteristics of roof surrounding rock B_2	Maximum subsidence C_{21} (mm)
		Deformation speed C_{22} (mm/d)

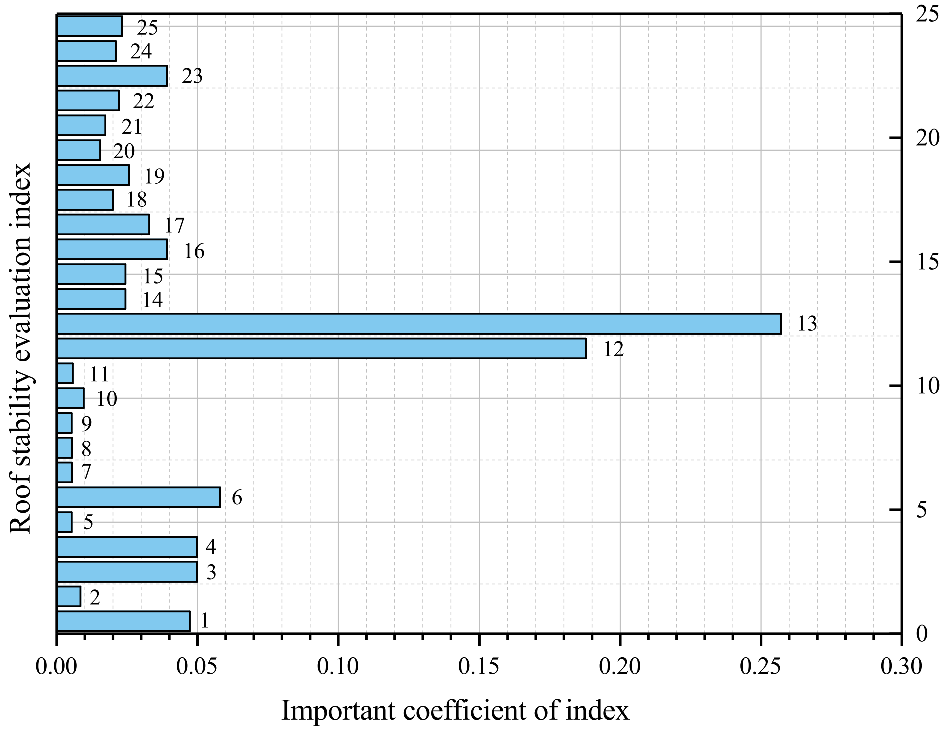


Figure 5. Important coefficient of roof stability evaluation index of the primary election. Note: The evaluation indexes of roof stability represented by each number are: 1: number of layers; 2: overall stability of roadway; 3: roof lithology; 4: development degree of roof fracture; 5: rock mass block degree; 6: fragmentation rate; 7: local stability of surrounding rock; 8: main lithology of roof and distribution characteristics of sand-mud ratio; 9: comprehensive characteristics of roof strata; 10: rock combination effect coefficient; 11: acoustic velocity of rock mass; 12: deformation speed; 13: maximum subsidence; 14: roof thickness; 15: roof rock strength; 16: disturbance effect; 17: support quality; 18: area; 19: roof control method; 20: roadway use inches; 21: mining process selection; 22: height; 23: burial depth; 24: span; 25: section shape.

3.3. Weight Calculation of Roof Stability Evaluation Index

The weight calculation of the roof stability evaluation index based on the improved AHP method [31] is shown in Tables 2–4, and the weight of the established roof stability evaluation index is shown in Figure 6.

Table 2. Weight relationship between target layer and criterion layer.

Index System for Roof Stability Evaluation of None-Pillar Mining	Roof Rock Integrity	Displacement Characteristics of Roof Surrounding Rock	W_i
Roof rock integrity	1	3	0.75
Displacement characteristics of roof-surrounding rock	0.3333	1	0.25

W_i denotes weight. The judgment matrix consistency ratio is 0.0000 and the weight of the total target is 1.

Table 3. Weight relation between criterion layer (roof rock integrity) and index layer.

Roof Rock Integrity	Roof Lithology	Fragmentation Rate	Development Degree of Roof Fracture	Number of Layers	W_i
Roof lithology	1	0.1667	0.5	1	0.1
Fragmentation rate	6	1	3	6	0.6
Development degree of roof fracture	2	0.3333	1	2	0.2
Number of layers	1	0.1667	0.5	1	0.1

W_i denotes weight. The judgment matrix consistency ratio is 0.0000 and the weight of the total target is 0.75.

Table 4. Weight relation between criterion layer (displacement characteristics of roof-surrounding rock) and weight of index layer.

Displacement Characteristics of Roof Surrounding Rock	Maximum Subsidence	Deformation Speed	W_i
Maximum subsidence	1	3	0.75
Deformation speed	0.3333	1	0.25

W_i denotes weight. The judgment matrix consistency ratio is 0.0000 and the weight of the total target is 0.25.

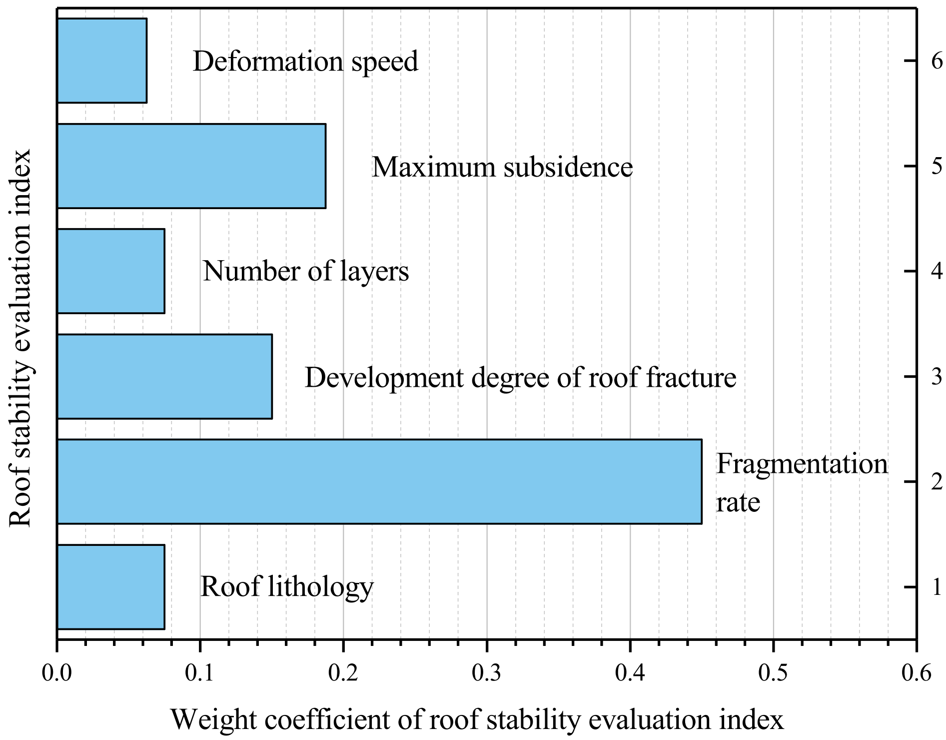


Figure 6. Weight coefficient of roof stability evaluation index for non-pillar mining.

3.4. Comprehensive Evaluation Model of Roof Stability Grade

The ratio vector of the quantitative evaluation index value of the roof-cutting non-pillar mining method and the corresponding index value limit is $l_i = (l_{i1}, l_{i2}, \cdots, l_{in})$ and satisfies $0 \le l_{ij} \le 1$ and $\sum_{j=1}^{n} l_{ij} = 1$. The normalized quantitative value vector of the quantitative evaluation index value of the roof-cutting non-pillar mining method is $m_i = (m_{i1}, m_{i2}, \cdots, m_{in})$ and satisfies $0 \leq m_{ij} \leq 1$ and $\sum_{j=1}^{n} m_{ij} = 1$. F_i is the ratio coefficient of the ith quantitative evaluation index value to the corresponding index value limit, and F_y is the quantitative value coefficient of the yth qualitative evaluation index value. The comprehensive evaluation model of the roof stability evaluation index is:

$$RSI = \sum_{i=1,y=1}^{n} (F_i \cdot \omega_i + F_y \cdot \omega_y) \tag{1}$$

where RSI refers to the roof stability evaluation index for the roof-cutting non-pillar mining method. ω_i refers to the weight of ith index value and ω_y refers yth index value.

3.5. Roof Stability Evaluation Index Classification Standard

Domestic and international scholars have carried out a lot of research work on roof lithology, rock strata stratification, roof fragmentation degree, and roof fracture development degree [15,16,22–29]. With reference to various Chinese national classification standards of rock mass engineering stability [32–34], as well as the statistical classification results of evaluation indexes of roadway roof stability at different levels in China and abroad [22–29], and combined with the existing mining level of the roof-cutting non-pillar mining method [1–16], the evaluation index classification standard and evaluation grade classification standard are formulated, as shown in Tables 5 and 6.

Table 5. Index system for roof stability evaluation for non-pillar mining.

Roof Stability Classification	Roof Rock Integrity				Displacement Characteristics of Roof Surrounding Rock	
	Roof Lithology	Fragmentation Rate (%)	Development Degree of Roof Fracture	Number of Layers	Maximum Subsidence (mm)	Deformation Speed (mm/d)
III	Extremely soft rock	>30%	Developed	>3	>150	>30
II	Soft rock	20–30%	Relatively developed	2	100–150	20–30
I	Hard rock	<20%	Not developed	1	<100	<20

Table 6. Grading table for the roof stability evaluation index for non-pillar mining.

Roof Stability Evaluation Index (RSI)	Roof Stability Partition (Grade)
$0.3 < RSI \leq 1$	Dangerous area (Grade III)
$0.2 \leq RSI \leq 0.3$	Relatively dangerous area (Grade II)
$0 \leq RSI < 0.2$	Relatively stabilized area (Grade I)

4. Mobile Intelligent Computing System Development

4.1. System Function Design

The design of the system includes seven items, namely roof stability data input (including photos), roof stability data modification, roof stability data delete, roof stability evaluation index weight setting, roof stability evaluation, roof stability control, and roof stability partition diagram output, as shown in Figure 7.

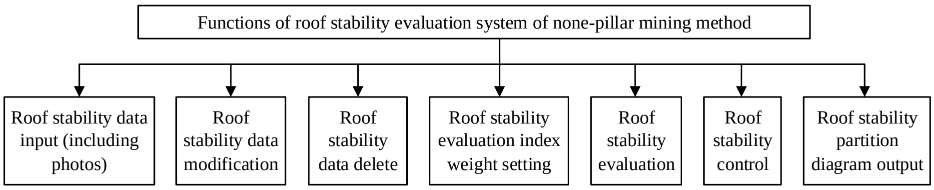


Figure 7. Functions of the non-pillar mining roof stability evaluation mobile application.

4.2. System Module Design

The roof stability evaluation system for the roof-cutting non-pillar mining method includes 11 modules. That is, the welcome module (Welcome Activity), the main system module (Main Activity), the evaluation module (Evaluate List Activity), the control suggestion module (Suggestion Activity), the stability zoning map module (Map Activity), the data interface module (Data List Activity), the weight setting module (Evaluate Weights Activity), the data add module (Data Add Activity), the data modify module (Data List Activity), the data storage service module, and the roof stability evaluation database module for the roof-cutting non-pillar mining method, as shown in Figure 8.

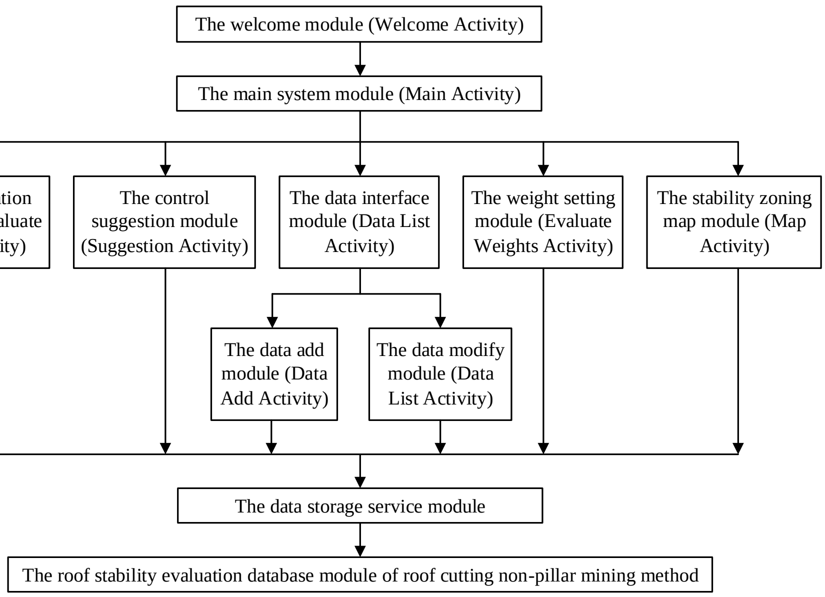


Figure 8. Function modules of non-pillar mining roof stability evaluation mobile application.

4.3. System User Interface Design

The roof stability evaluation system for the roof-cutting non-pillar mining method includes 11 user interaction interfaces, namely, the welcome interface, the main interface, the monitoring number list interface, the adding roof data interface, the modifying roof data interface, the setting interface, the weight setting interface, the stability evaluation interface, the control suggestion interface, the stability partition diagram interface, and the help interface, as shown in Figure 9.

The welcome interface includes the name of the system and research and development institutions. When the user clicks on the "roof stability evaluation", the system shows the welcome interface, and then automatically enters the main interface, as shown in Figure 9a. The main interface includes data management, stability evaluation, stability partition diagram, settings, and help. The monitoring number list interface shown in Figure 9b displays the recorded monitoring number in a list. When the user clicks the "adding data" button below the interface, the system will automatically enter the adding roof data interface, as shown in Figure 9c. The main function of this interface is to input the initial data of the roof stability evaluation index value and add real-time photos of the roadway roof taken on the spot. In order to standardize the roof stability evaluation index, the naming format of the monitoring number is explained as Code_Start position_End position, e.g., DB_0_10. Users can take real-time photos of the roof deformation of each monitoring number on the spot or import the photos that have been taken. The modifying roof data interface as shown in Figure 9d is mainly to update the evaluation index values corresponding to the stored monitoring numbers.

The setting interface shown in Figure 9e includes weight setting, stability partition diagram output setting, and other settings. When the user clicks the "'weight setting" button, it enters the weight setting interface. When the user clicks the tick boxes under "Stability partition diagram output setting", the output of the partition diagram of dangerous area, relatively dangerous area, and relatively stabilized area can be realized. The evaluation weight setting interface shown in Figure 9f is used to assign the weight to the roof stability evaluation index.

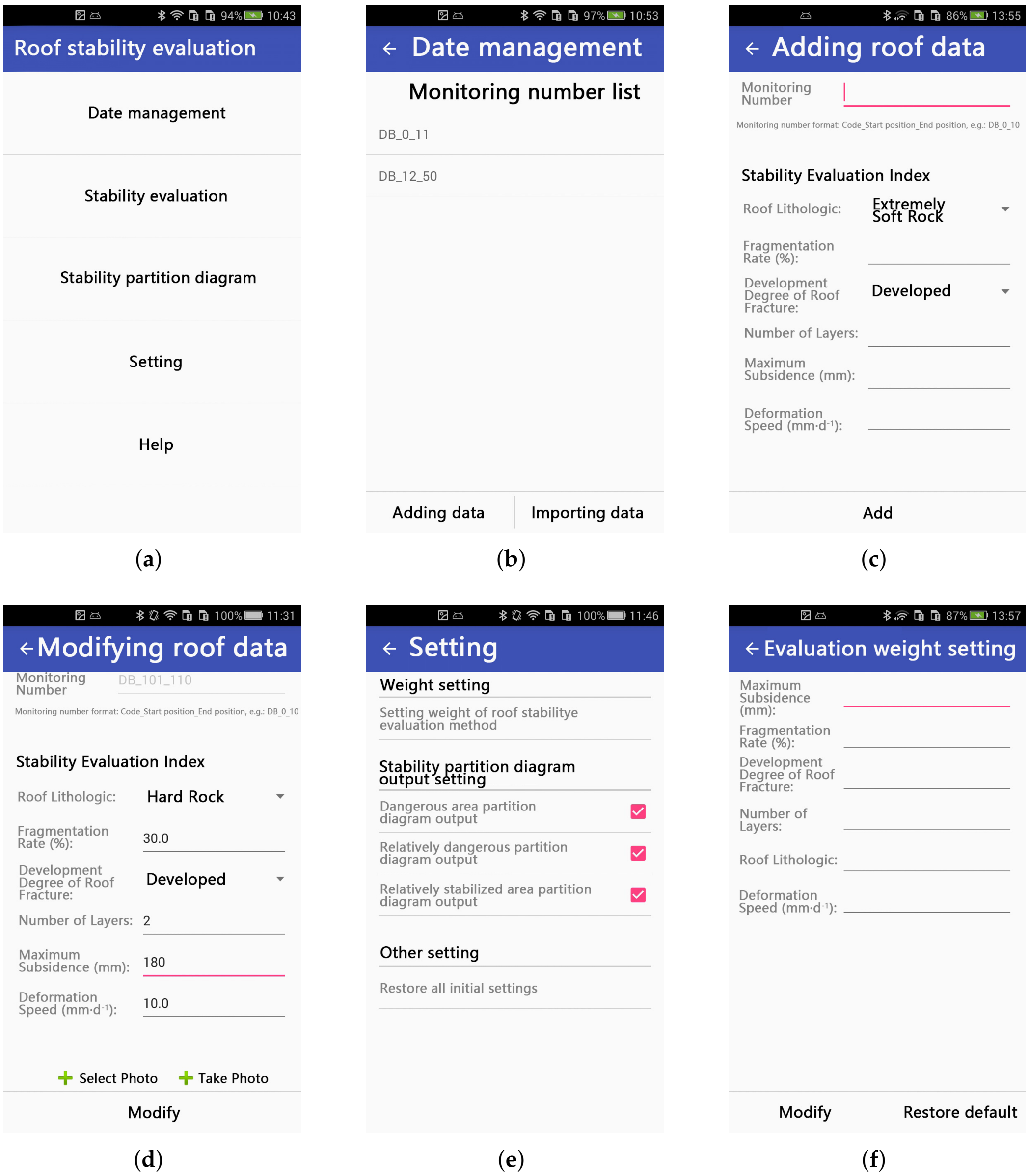
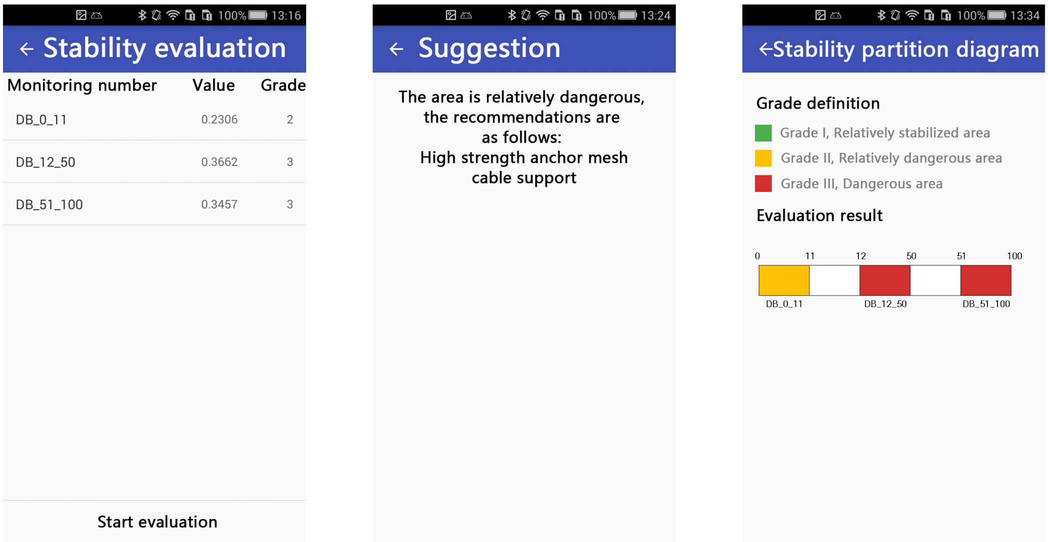


Figure 9. *Cont.*



(**g**) (**h**) (**i**)

Figure 9. System user interface. (**a**) The main interface. (**b**) The monitoring number list interface. (**c**) The adding roof data interface. (**d**) The modifying roof data interface. (**e**) The setting interface. (**f**) The weight setting interface. (**g**) The stability evaluation interface. (**h**) The control suggestion interface. (**i**) The stability partition diagram interface.

The stability evaluation interface shown in Figure 9g is mainly to evaluate the roof stability of each monitoring number after assignment, and a total of four categories of columns are designed: monitoring number, value, grade, and start evaluation. The control suggestion interface as shown in Figure 9h mainly shows the support control suggestions corresponding to the roof stability evaluation grade. The stability partition diagram interface shown in Figure 9i is mainly for the plotting and output of the risk partition diagrams of the roof stability evaluation area, including the grade definition and evaluation results (including evaluation mileage, monitoring number, evaluation grade, and three-color risk partition diagram). The help interface mainly shows the basic principle of system implementation, application operation guide, etc.

5. Engineering Application

Based on the 1107 working face of Hecaogou No. 2 coal mine in Yan'an City, the stability of the roof at intervals of 6–51 m, 431–442 m, 562–580 m, and 590–600 m between the 1107 transport crossheading and the cutting hole position is evaluated. The mining elevation of the 1107 working face is +1054 to +1061 m. The roof of the coal seam is mainly argillaceous siltstone and siltstone. The direct roof of the coal seam is silty mudstone with a thickness of 1.9–2.54 m. The upper part of the direct roof is fine-grained sandstone with a thickness of 5.62–10.02 m. The upper part of fine-grained sandstone is argillaceous siltstone with a thickness of 19.34–31.30 m. According to the investigation of the roof stability of the roadway, it was found that the combined deterioration characteristics between the roof strata are obvious, and the large deformation of the roof and the loose and broken phenomenon of the roof appear (see Figure 10), which makes it easy to break the roof. It is necessary to evaluate the stability of the 1107 working face and put forward support countermeasures.

(**a**) (**b**)

Figure 10. Roof stability status. (**a**) Large deformation of the roof. (**b**) Loose and broken phenomenon of the roof.

Roof stability evaluation index collection involves using a combination of qualitative and quantitative methods, the index data are shown in Table 7. In the roof stability evaluation site, the user clicks the "Roof stability evaluation" to enter the main interface, then clicks the "Data management" button to enter the monitoring number list interface, and then clicks the "Adding data" button below the interface to enter the adding roof data interface.

Table 7. Roof stability evaluation index data collected.

Roof Stability Evaluation Index	Measurement Value of Evaluation Index			
	6–51 m Interval	431–442 m Interval	562–580 m Interval	580–590 m Interval
Roof lithology	Soft rock	Soft rock	Soft rock	Soft rock
Fragmentation rate (%)	60	45	38	44
Development degree of roof fracture	Relatively developed	Not developed	Relatively developed	Not developed
Number of layers	2	2	2	2
Maximum subsidence (mm)	160	110	180	82
Deformation speed (mm/d)	40	23	45	10

In this interface, the monitoring numbers (DB_6_51, DB_431_442, DB_562_80, and DB_580_590), each evaluation index value, and the photograph of roof stability can be input, as shown in Figure 11a,b. For qualitative indicators such as roof lithology and development degree of roof fracture, users can click on the inverted triangle symbol on the right side of the indicator to select the system design options.

After the index data are successfully added, it returns to the main interface and then enters the setting interface. The weight setting adopts the default index weight of the system, as shown in Figure 11c. In the stability partition diagram output setting, click all the tick boxes to output the partition diagram of dangerous area, relatively dangerous area, and relatively stabilized area. Then enter the stability evaluation interface through the main interface, click on the "Start evaluation" button, and then the top of the interface shows the monitoring number, evaluation value, and grade, as shown in Figure 11d. Then enter the stability partition diagram interface through the main interface to view the evaluation results, as shown in Figure 11e, including roof stability grade, three-color risk partition diagram, evaluation mileage, and monitoring number. Finally, the corresponding control suggestion is proposed for the roof stability grade, which can be viewed by clicking the monitoring number in the stability evaluation interface into the control suggestion interface, as shown in Figure 11f,g.

From Figure 11d–g it can be seen that the evaluation values of the 6–51 m interval, 431–442 m interval, 562–580 m interval, and 590–600 m interval are 0.43, 0.3181, and 0.34166, respectively. The roof stability is classified as grade III, and the roof stability partition is a dangerous area. The support control countermeasure is anchor net cable with shed composite support. The evaluation value of the 580–890 m interval is 0.295, the roof stability is classified as grade II, and the roof stability partition is a relatively dangerous area. The support control countermeasure is anchor net cable with shed composite support.

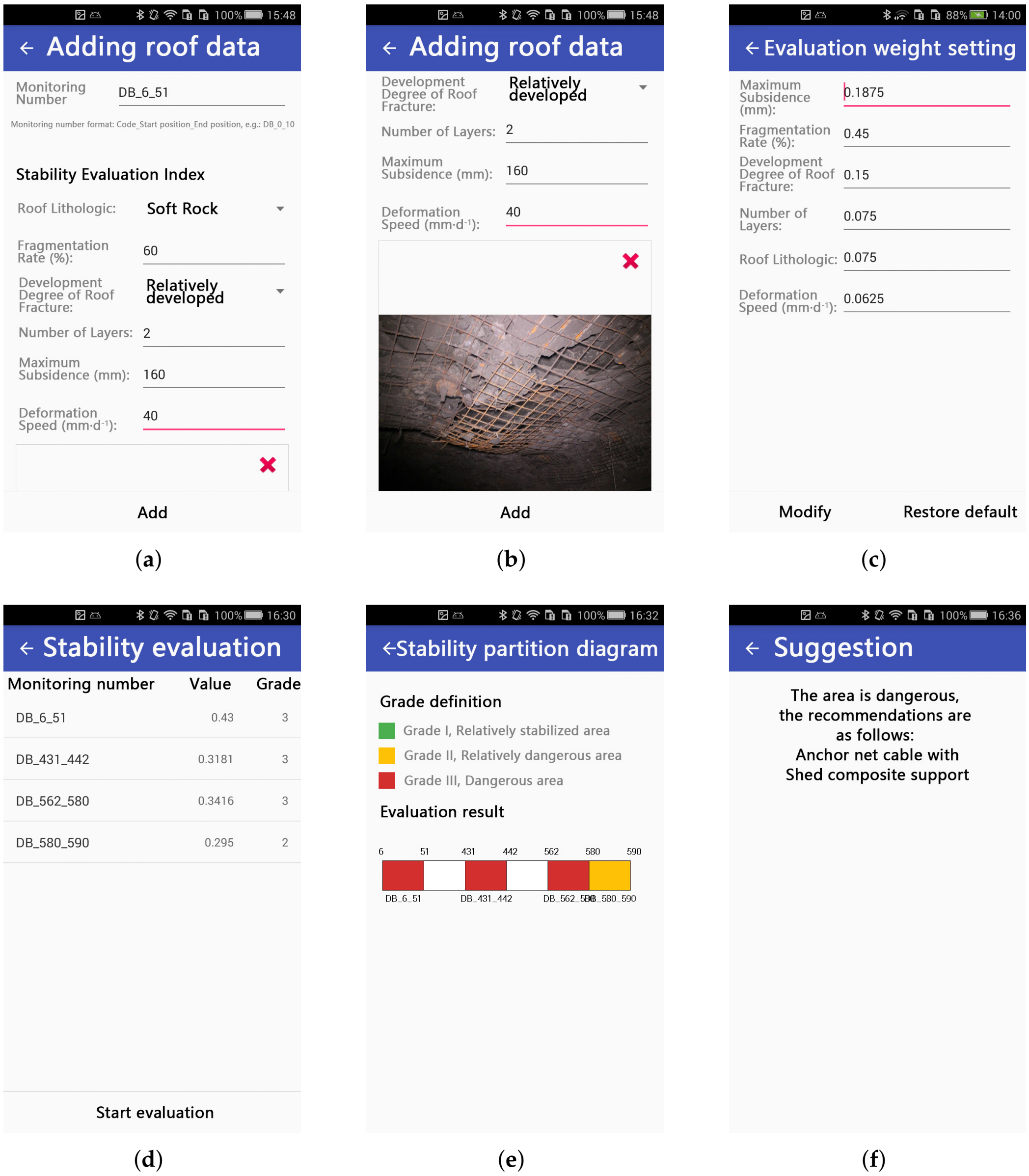


Figure 11. *Cont.*

(**g**)

Figure 11. System user interface in the engineering application. (**a**) Addition of roof data (the 6–51 m interval). (**b**) Addition of roof data (the 6–51 m interval). (**c**) Evaluation weight setting. (**d**) Evaluation value and grade. (**e**) Roof stability partition. (**f**) Corresponding control suggestions for dangerous areas. (**g**) Corresponding control suggestions for relatively dangerous areas.

6. Conclusions

In order to achieve sustainable and safe utilization of coal resources, the roof stability evaluation index system for the roof-cutting non-pillar mining method is established and an intelligent evaluation, risk partition, and control suggestion portable mobile application for the stability evaluation of the roof-cutting non-pillar mining method is developed. Then an engineering application is presented. Several conclusions can be drawn, as follows:

1. In view of the deformation characteristics of the roof of the roadway behind the working face of the self-formed roadway without a coal pillar, this paper proposed that different roof deformation sections should be distinguished in the evaluation of roof stability, and the roof of the mining roadway should be divided into the influence area of roadway roof pressure relief, the dynamic pressure deformation area of the roadway roof, and the compaction stability area of the roadway roof.
2. The roof stability evaluation index system for the roof-cutting non-pillar mining method is established, which includes the integrity of the roof strata and the displacement characteristics of the roof-surrounding rock. A comprehensive evaluation method of the roof stability grade of the roof-cutting non-pillar mining method is proposed, which integrates the classification standard of the roof stability evaluation index and the index weight assignment of the improved AHP method.
3. The intelligent evaluation, risk partition, and control suggestion portable mobile application for the stability evaluation of the roof-cutting non-pillar mining method is developed based on Android. In the application, functions of data input including photos, data modification, data deletion, evaluation index weight setting, roof stability evaluation, roof stability control, roof stability partition diagram output, and other integrated functions of roof stability for the roof-cutting non-pillar mining method are realized.
4. Taking the No. 1107 working face of Hecaogou No. 2 Coal Mine in Yan'an City as an example, the stability evaluation and intelligent calculation control of the roof-cutting non-pillar mining method were carried out. The evaluation results include roof stability grade, stability partition diagram, and control suggestions corresponding to different stability grades, which provide a theoretical basis for the partition support

of roadway roofs. This successful engineering application can provide a basis for the sustainable utilization of coal resources in the future.

Author Contributions: Conceptualization, Q.C. and M.H.; software, Z.T. and M.H.; validation, B.Z., M.H. and B.H.; data curation, B.H.; writing—original draft preparation, Q.C.; writing—review and editing, B.Z. and M.H.; supervision, Q.C.; funding acquisition, Q.C. All authors have read and agreed to the published version of the manuscript.

Funding: The financial support from the National Natural Science Foundation of China (NSFC Grant No. 52008373) is greatly acknowledged.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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