OPTIMIZATION OF CONCURRENT MINING AND RECLAMATION PLANS FOR SINGLE COAL SEAM – A CASE STUDY IN NORTHERN ANHUI, CHINA

Zhenqi Hu[2], Wu Xiao

Abstract: The extraction of underground ore body inevitably causes a large amount of land subsidence. Current reclamation technologies in China mainly focus on stable subsided land. Therefore, a new technology for reclaiming unstable subsiding land is being studied for restoring farmland as much as possible based on a case study in Northern Anhui, China. In consideration of the mining plan, subsidence processes in various stages were analyzed and some related factors such as vertical subsidence, post-mining slope, water area, and land use condition were also generated. Due to mining activities, useful farmland gradually decreases to merely 14.4% of the pre-mining area. In this study the following stages were modeled from pre-mining to post-mining: (1) rate of farmland was 100% in stage (a) (pre-mining), (2) 72.5% in stage (b), (3) 67.3% in stage (c), and (4) 14.4% in stage (d) (post-mining). The results show that 86.6% of cultivated land was submerged into water and lost its capacity for cultivation. Reclamation plans for stages (b), (c), and (d) were made by a traditional reclamation method called "Digging Deep to Fill Shallow". Based on scenario simulation, the farmland reclamation rates were improved to 78.3%, 73.3%, and 40.70% respectively. Taking the rate of reclaimed farmland as preferred standard, concurrent mining and reclamation for stage (b) and(c) could increase farmland reclamation rates to 37.6% and 32.6% respectively, compared with the farmland reclamation rate of post-mining. The results reveal that optimum reclamation time should be at stage (b). Therefore, under current technical conditions, concurrent mining and reclamation could enhance the quantity of cultivated land, and provide better land-protection and food security in high water table mined areas.

Additional Key words: Mining Subsidence; Concurrent Mining and Reclamation; Land Protection; Subsidence Prediction; Planning Scheme

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Introduction

China is the number one coal production and consumption country. The coal outputs exceeded 3 billion tons in 2010, accounting for 42% of global production (Wang, 2009). However, mining and utilization of coal may cause serious environmental impacts such as coal waste disposal, poisonous gases emissions, land subsidence, landscape change, etc. Comparatively, land subsidence seems to be one of the most prominent problems in China because 92% of the coal output comes from underground mining, with thousands of underground longwall panels. Underground mining activities disturb the surface severely, and this situation is even more prominent in east and northeast China (Xiao et al., 2009), which are both a main coal and agricultural production region (called “Overlap Region”）. The Overlap Region covers 40% of the total farmland in China, and contains 58% of national coal production and 45% of food production (Hu and Luo, 2006). High intensity extraction of coal underground results in large scale ground settlement, barren farmland, and a decrease in cultivated land. It is estimated that the subsidence area extends from a high of 0.533 ha, to a low of 0.033 ha, with an average between 0.2 and 0. 33 ha for each 10 thousand tons of coal is extracted underground. Subsidence is expected to expand to 2×10^4ha annually (Hu, 1996). Thousands of hectares of affected land will lose it’s the capacity to be under cultivation following the extraction of a thick coal seam where a high groundwater table is present. The depth of water in subsided areas could reach as much as 13 m (Wang et al., 2009). Thus, farmland degradation caused by underground mining activities is serious in China. In fact, coal mine production has increased over the past 10 years, and has reached a peak of 18.35% growth rate in 2003 (Fig. 1). It is predictable that mining production will continue to expand in the foreseeable future, because of rapid economic growth. Thus, the quantity of subsided agricultural land will continue to rise.

According to Annual Bulletin issued by Ministry of Land and Resource (MLR) in 2008, cultivated land was decreased to 1.22×10^8 ha at the end of December 2008, with merely 0.09ha per capita farmland (Fig. 2). Consequently, the Chinese government also retains the amount of 1.2×10^8 ha farmland as a base red line to ensure food security in 2020. How to protect the limited cultivated land resources is particularly important at this stage of rapid economic growth. Nevertheless, it is expected that coal mining will continue to increase at a high speed rate to comply with economic growth in China, resulting in increased severity of land subsidence. Thus, applying timely and efficient measures to restore the damaged land could be an effective way to ameliorate the current situation.

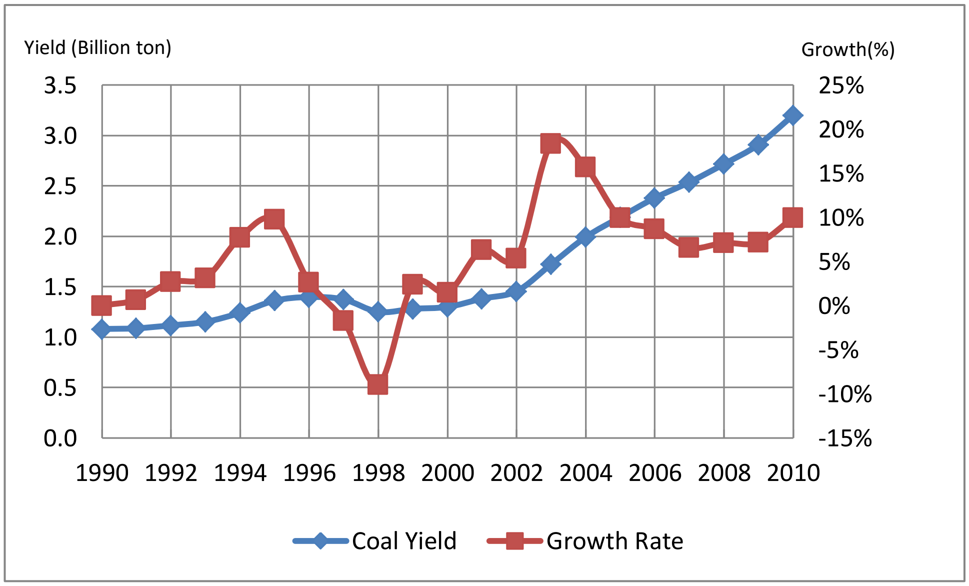


Figure 1.Coal yield and growth rate from 1990 to 2010 in China.

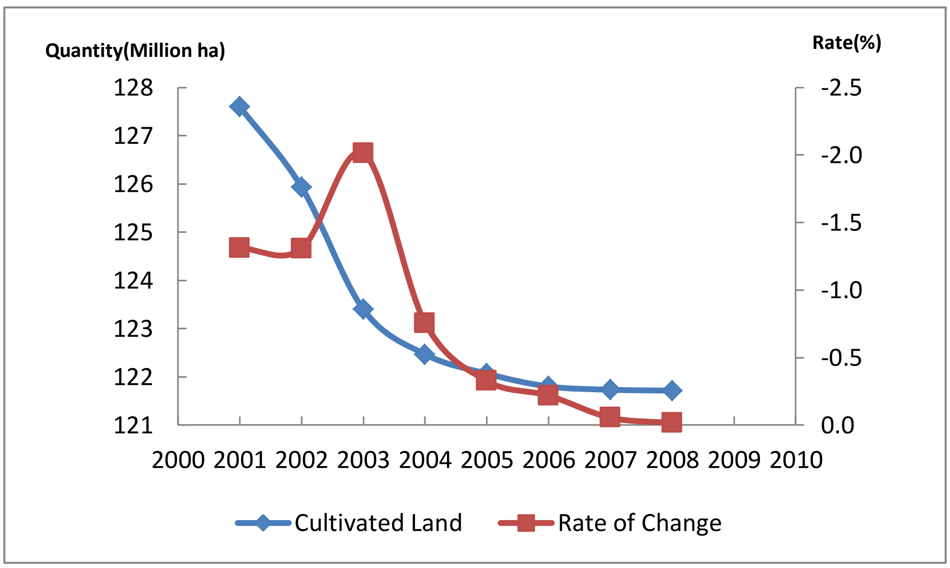


Figure 2.Cultivated land quantity variation from 2001 to 2008 in China.

Actually, mine land and abandoned mine site hazards assessment (Kim et al., 2006, 2009), and reclamation has been extensively studied by many scholars (Bascetin, 2007; Wu et al., 2009; Xiao et al., 2011). Approximately 60% of the world's coal production comes from underground mines, and China accounts for much of the world-wide underground operations (Table 1). Comparatively, the other 4 major coal production countries; USA, India, Australia, and Germany, employ less underground mining methods for coal extraction, therefore, farmland subsidence and related reclamation are relatively less of a concern (Bell, 2005). The impact of subsidence may vary from site to site due to differences in geology and soil conditions. For example, in Illinois, USA, also with coal and agricultural production overlapping regions, has maximum subsidence of about 3m (Darmody 1992, 1995), thus, making reclamation work easier as compared to China. In addition, reclamation strategies are much more diverse outside of China where agricultural land resources and population pressures are not as pressing.

Table 1 Percentage of coal production by mining method in 2006*.

Country	Underground (%)	Surface (%)	Total (Mt)
China	95	5	2,380
USA	31	69	1,054
India	19	81	447
Australia	22	78	405
Russia			309
South Africa			257
Germany			197
Indonesia			195
Poland			156
Total world	60	40	6,195

Note: *Data source: http://www.bp.com.

Since the 1980's, China's land reclamation has made considerable progress in restoring subsided land using different technologies (Hu, 1994a, 1994b), and include the following:

(a) "Digging Deep to Fill Shallow" , the technology divide the subsidence prone area into two parts: deep and shallow, where soil is removed from the deeper areas by a excavator creating a fish pond, and this soil is placed in the shallow parts thus creating land capable of being cultivated.

(b) Directly reconditioning, where there is not a high water table and where there is minimally subsided areas, the method of directly reconditioning the subsided land can be used. Usually, leveling of the subsided land by bulldozers or manual work is often used. If the slope of the subsided land is large, the terraces are used.

(c) Filling, a type of landfill method, filling subsidence land with some filling materials such as coal wastes and fly ash;

(d) Drainage, establishment of a system of drainage ditches to allow the impounded water drain away and lower the subsurface water level so that the subsidence land is able to be cultivated.

Both filling methods and non-filling methods are well applied in China. However, all aforementioned technologies are focused on stable land, which means half, or even more than half of land already submerged in water, including the fertilized topsoil is untouched. This method of reclamation is considered a post-mining retreatment, and results in a low rate of farmland reclamation with an associated high cost of reclamation. Therefore, it is desirable to develop a new technology that could take advantage of advanced planning, conservation, and management before land subsidence falls below the water table. The improved plan and technology could raise the amount farmland created at a lower reclamation cost. This research takes a colliery located on the eastern plain in China as an example of this technology, in an attempt to analyze and predict the subsidence processes according to the existing geological conditions and mining system being used, and thus optimizing concurrent mining and reclamation planning.

Basic information in study area and research methods

Basic information in study area

The study area is located in the northern part of Anhui Province in eastern China, covering about 24.1 ha. It is a typical plain mining area in eastern China, with subsidence flooded lands and densely populated villages. Natural elevation is +30 m to+32 m above mean sea level, with an average +31.0 m. The water table is about 2 m below the soil surface, and the ground is nearly level with slope between 0 to 2°. The climate is humid continental, typical of that of eastern China, with great inter-annual variability of precipitation. Most precipitation falls between June and September. Because of its mild climate, abundant sunshine, and four distinct seasons, it is one of the most important grain production areas in China.

The main coal seams in this area are named No.4 and No.6, with average thickness of about 2.2 m and 2.8 m, respectively. Depth is to these seams is about 50 to 300 meters and 380 to 440 meters, respectively. Dip angle of coal seams ranges from 3° to 15°. The overburden has a thick alluvial strata reaching to 120 to 160 m, compaction of soil for the loss of water introduced by mining subsidence makes subsidence factor reaches 1.0 (Table 2). Typical geological section schematic is shown in Fig. 3; the No.6 coal seam is about 92 m below No.4 coal seam.

Table 2. Basic parameters for surface movement and deformation prediction

Parameters	**Value**
Coefficient of the initial mining	0.96
Coefficient of the repeated mining	1.20
Horizontal movement coefficient	0.3
Influence propagation angle tangent	1.80
The displacement distance	$0.03H_0$
Influence angle	89°

The 8 panels referred to No.6 coal seam have been extracted from March 1997 to the end of 2004, leading to a total of 2.5 m of subsidence. The coal mine arranged rehabilitation in 2005, and the impacted land was then restored to original elevation. Exploitation of No.4 coal seam commenced in January 2007, 4 panels are included, and will last to September 2012, the layout of panels and mining schedule are illustrated as Fig. 4 and Table 3. Thus, the influence of the mining activity in study area could be treated as a single coal seam (No.4) extraction. This paper will analyze the dynamic evolution of ground condition and land use to optimize the concurrent mining and reclamation.

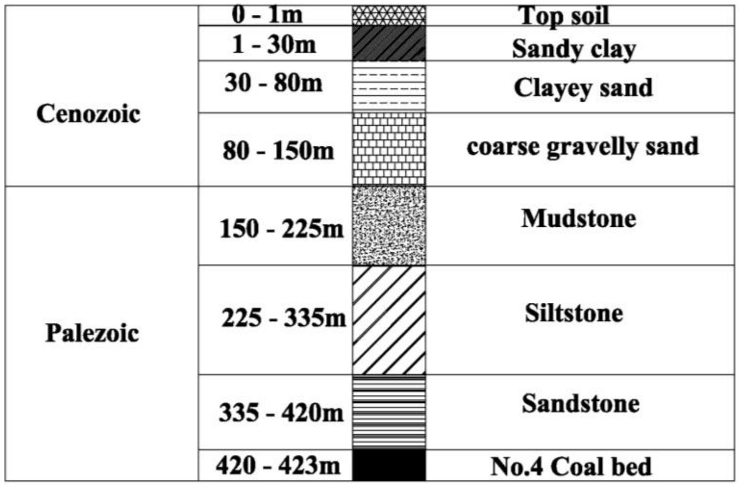


Figure 3. Typical geological section schematic in study area

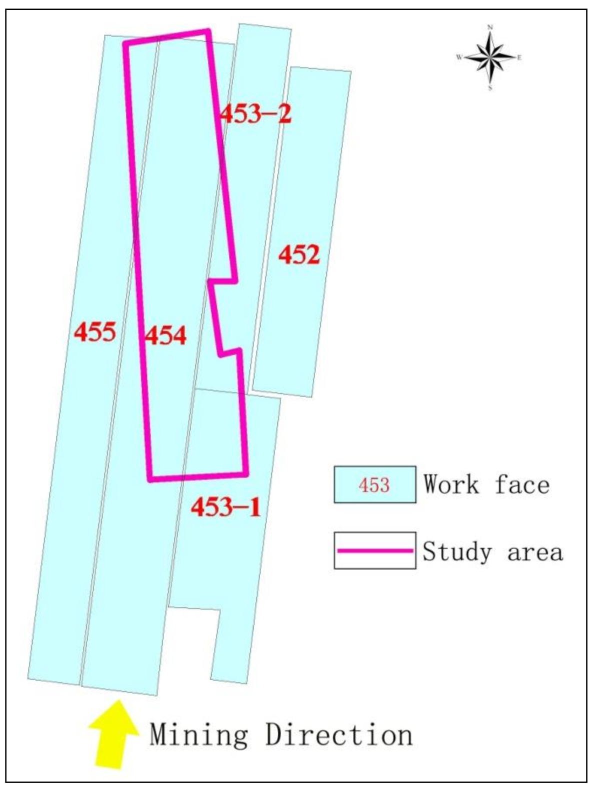


Figure 4. Layout of No.4 coal seam workface.

Table 3.Mining schedule of No.4 coal seam.

Number of panel	Mining Time	Average depth(meter)	Average seam thickness（meter）
452	2007.1-2007.12	280	2.2
453-1	2009.12-2010.6	280	2.3
453-2	2010.11-2011.3	280	2.3
454	2011.9-2012.9	300	2.0
455	2008.4-2009.7	250	2.1

RESEARCH METHODS

Dynamic mining subsidence prediction and Geological Information System (GIS) are employed in this paper, the process of dynamic scenarios simulation is derived according to the specific geological condition and mining schedule in different stages. Mining subsidence prediction system (MSPS) which is developed by China University of Mining and Technology is chosen to analyze the mining impact, and ArcInfo released by Environmental Systems Research Institute (ESRI) is chosen for ground analysis and simulation. Procedures are as follow:

(1) Acquisition of original terrain data

According to the information provided by Hengyuan colliery, the topographic map surveyed in 2005 by [the] total station is adopted; elevation information will be illustrated as elevation points and isograms.

(2) Acquisition of subsidence information in various stages

After decades of development, mining subsidence prediction has formed a mature geometrical theory (Konthe, 1959; Peng and Luo, 1991) which includes profile function, influence function, and probability integration method etc., while in the recent thirty years, deterministic (mechanistic) theory including finite element, boundary element based on rock mechanics are involved in (Kratzsch, 1983). In deterministic modeling, the in-situ mechanical properties of rocks are of a particular importance. Probability integration method, developed from random medium theory, is the most mature and applied prediction model in China, the software (MSPS) employed in this paper is programmed based on this theory.

(3) Construction of dynamic ground subsidence model

Interpolate the elevation information generated from step (2) and step (3) separately using ArcInfo, which includes inverse distance weighted interpolation, spline interpolation, and kriging interpolation, and the dynamic subsidence model will generated after superposition of the two layers in various stages.

(4) Analyze and monitoring

Combined with the exploitation of mining schedules, the dynamic ground subsidence model for each panel and various stages could be determined and analyzed, and dynamic changes of the ground in temporal and spatial domain could be monitored, including vertical subsidence, extent of water area, land use change, slopes, and aspects. The virtual reclamation plan will be compared between different stages. Finally, rate of restored farmland will be considered as preferred standard to optimize the plans.

RESULTS AND ANALYSIS

Scenario simulation

(1) Original terrain data

Our study area is 24.1 ha, with north-south length of about 1,100 m and east-west width of about 220 m (Fig. 5). The surface is roughly flat before extraction of No.4, with elevation between 30 m to 32 m and slope between 0° to 2°. Study area is all fertilized, cultivated land with aquaculture ponds on both sides.

(2) Mining subsidence prediction in various stages

Prediction of ground subsidence associated with underground mining based on the shape of final settlement trough of ground surface could be insufficient. Surface subsidence due to mining is a dynamic process which obeys mechanical principles (Saids, 1995). Particularly, dynamic processes of land use change and water ponds distribution in temporal and spatial domain could provide a more intuitive and rational vision for manager and engineer in coal and grain overlap region. Characteristic and timing of mining subsidence could be mined through dynamic prediction. The prediction parameters are indicated in Table 2.

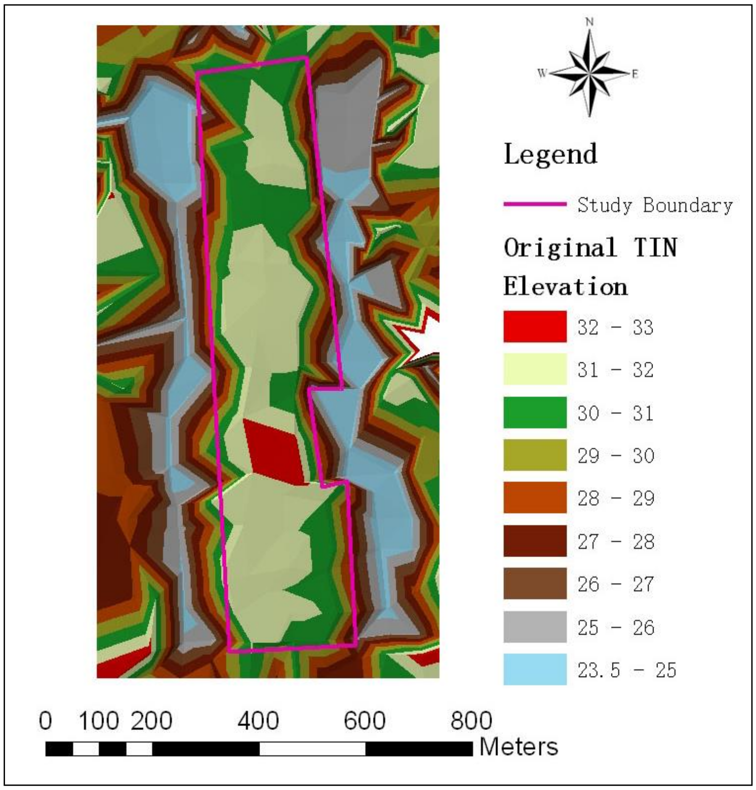


Figure5. Pre-mining Triangulated Irregular Network (TIN) in study area.

In consideration of mining schedule and layout, study area is divided into four stages, which is shown below:

A. After panel 452 and 455 finished (July, 2009)

B. After panel 452, 455 and 453-1finished (September, 2010)

C. After panel 452, 455, 453-1 and 453-2 finished (March, 2011)

D. After panel 452, 455, 453 and 454 finished (September, 2012)

Movement and deformation in various stages are represented as subsidence isograms, deformation isograms, and also profiles. The study area is located in eastern China, a region where thick alluvium on the near surface and a high underground water table, according to the studies previously, combine with cracks which are derived from deformation. These have a large influence on the utility of cultivated land surface. The most significant impacts of cultivated land are submergence by water caused by vertical subsidence, and soil erosion and deterioration caused by additional slope in the edges of subsidence basin (Hu et al., 1997). Therefore, dynamic vertical subsidence based on temporal and spatial distributions will be treated as a major consideration for scenario simulation.

(3) Scenario simulation in various stages

Local government set the vertical subsidence of 2.0 m as permanent water area and 1.5 m as seasonal water area. The reasonability and rationality were validated through field measurement in this research, and ground elevation of +29.0 m and +29.5 m were defined as permanent and seasonal water criteria. These validated criteria could benefit us when quantitative analyses are conducted in temporal and spatial domain. Ground water trend in the mining stages is shown in Fig. 6, and is subdivided into four stages:

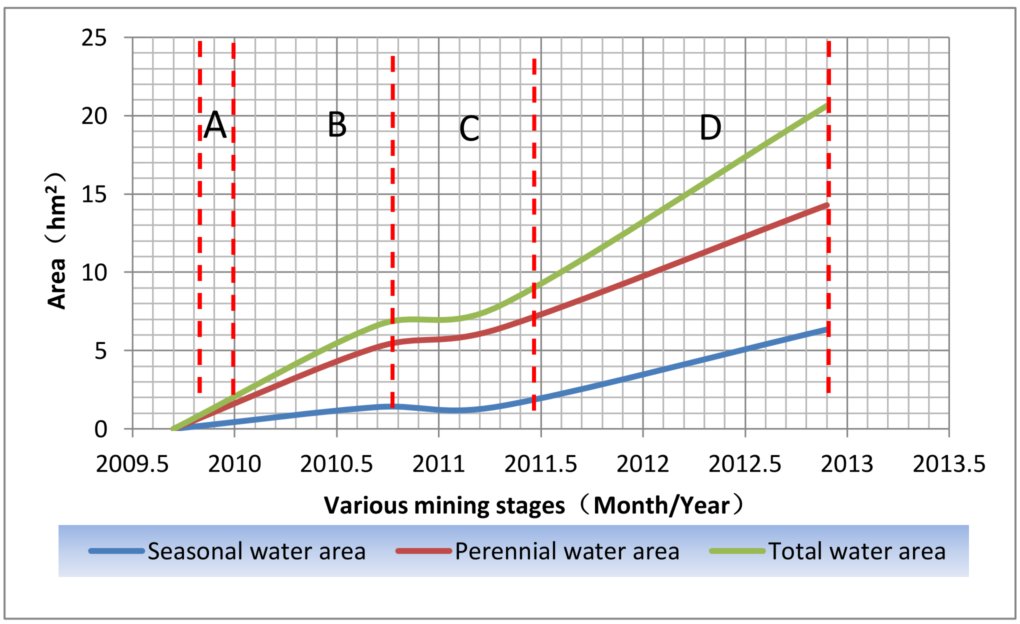


Figure 6. Changes of water area in various stages.

Stage A (2007.1-2009.7): Commencement of extraction in this area to panel 452 and panel 455 was finished. In this stage, the two panels were separated by panel 453 and panel 454. Mining activities only reached super-critical in strike orientation, and were sub-critical in inclination orientation. Thus, vertical subsidence on the ground was not serious, and ponding conditions did not occur.

Stage B (2009.8-2010.9): Begins at the end of mining panel 455 and beginning of panel 453-1. In this stage, water arises in the ground and expands gradually until September 2010.

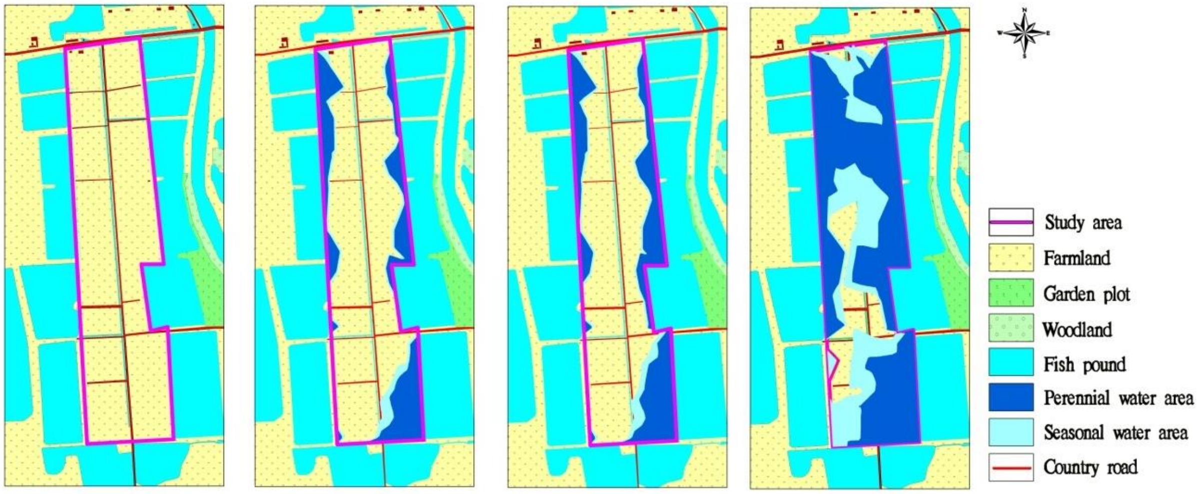
Stage C (2010.9-2011.3): After a slight break, the extraction of panel 453-2 made the situation even worse. However, water area, including both the perennial and seasonal, changed slowly.

Stage D (2011.4-2012.10): Mining of panel 454 formed the isolated subsidence basin as a whole, thus, the mining reached super-critical both in inclination and strike orientation. This led to a severe water expansion in the ground.

According to dynamic ground subsidence simulation, land use change is analyzed (Fig. 7). The (a), (b), (c), and (d) correspond to the four mining stages of (A), (B), (C), and (D). Although the exploitation of panel 452 and 455 impacted the ground severely, it did not change the land use (Fig.8 a). From the commencement of panel 453-1, water gradually rose in the ground and finally reached to 20.6ha, accounting for 85.6% of the study area; the area of cultivated land reduced to 3.5ha, only accounting for 14.4% of study area. Proportions of cultivated land were 100%, 72.5%, 67.3%, 14.4%, respectively, corresponding to the four mining stages. This shows that the exploitation of No.4 led to most of the study area becoming water area, and changed the landscape severely in this region (Table 4).

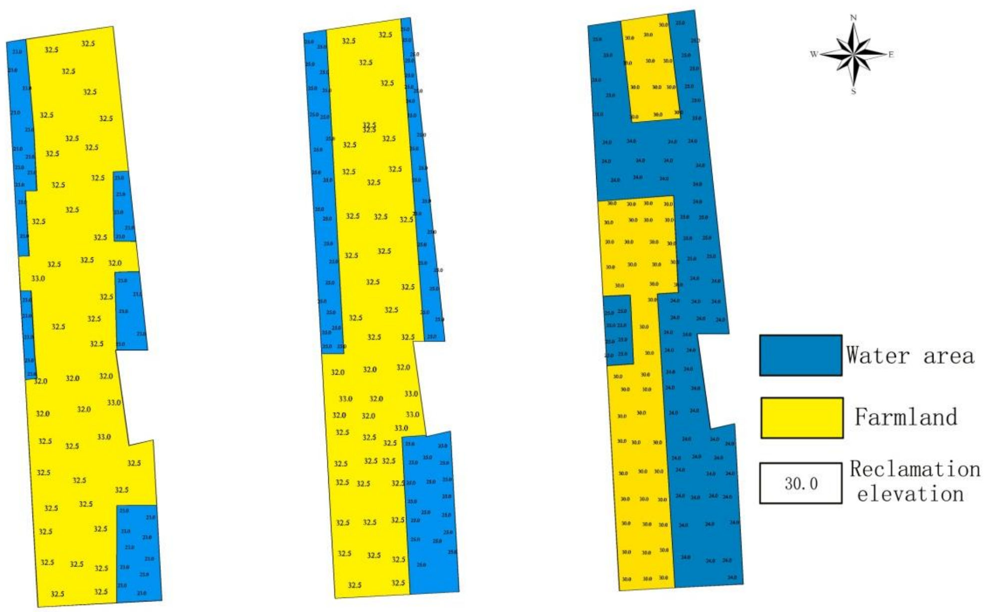
Table 4. Cultivate land in different mining stages.

Mining Stages	Cultivate Land（ha）	Percentage（%）
Stage (A)	24.1	100
Stage (B)	17.5	72.5
Stage (C)	16.2	67.3
Stage (D)	3.5	14.4



(a) (b) (c) (d)

Figure 7. Land use changes in various stages on the ground.



（b） （c） （d）

Figure 8. Reclamation layout and elevation in various stages.

<u>Optimization of reclamation plans and analysis</u>

Dynamic ground scenario simulation provides a vision to understand the development of subsidence in the ground. Through analysis, if reclamation work is launched after all the mining activities are ended, on the one hand, inadequate filling and important topsoil loss becoming submerged into water may cause a lower rate of farm land reclamation; on the other hand, existence of large areas of water may make the construction more difficult and increase reclamation costs. Therefore, reasonable reclamation time and the best reclamation plan seem to be particularly important in a high underground water table area.

(1) Optimization of reclamation plan

Many scholars have been studying reclamation measures in stable subsided land and they have concluded that many technologies such as Digging Deep to Fill Shallow, Directly Reconditioning, Filling, and Drainage. This paper discussed these mature technologies and concluded:

(a) Reclamation is primarily based on “Digging Deep to Fill Shallow” technology;

(b) There should not be filling outside of the study area but use earthwork balance within this area.

(c) Residual subsidence of various stages is taken into account. Additional elevation is reserved in every reclamation stage to ensure the project could withstand the impact of follow-up settlements.

According to the considerations above, different stages of mining reclamation measures were taken into account. Extraction level of panel 452 and 454 had less impact on agriculture in stage (a), therefore, only reclamation in stage (b), (c), and (d) was relevant. The layout and designed elevation is shown in Fig.8.

(2) Result analysis

It is a continuous, slow, and gradual process when extracting a horizontal layered ore body. The manner and extent are different in various stages. Table 5 shows the advantages, disadvantages, and also the reclamation efficacy in various stages.

Table 5. Optimization and comparison of reclamation plans in various stages.

Stages	Mining condition	Condition before reclamation	Advantages	Disadvantages	Percentage of reclaimed farm land
（a）	452 and 455	Start subsidence, no water area	Most of the topsoil resources, high rate of reclaimed farmland	High reclamation costs, occupying the land for so long[a] period, influent[ces] normal agricultural work, more residual subsidence	--
（b）	452,455, and 453-1	Water area arise, with less area	More topsoil could be protected, high rate of reclaimed farmland	High reclamation costs, partial residual subsidence influence	78.3%
（c）	452,455,and 453	Subsidence increases, water area expand[s], but still with low proportion	More topsoil could be protected, high rate of reclaimed farmland	High reclamation costs, partial residual subsidence influence	73.3%
（d）	452,455,453 ,and 454	Most of the area submerged into water, little farm land exist	Stable on the ground, less residual settlement exist	No topsoil resource endurance, low rate of reclaimed land and difficult to construct	40.7%

If reclamation measures were taken too early (stage a), the influence of extraction underground has not transmitted to the ground completely or the effect is insufficient to interrupt normal agricultural activities. This means increased costs and more interruption of agricultural activities. The reclamation project needs to accommodate subsequent settlement, including vertical subsidence, tilts, horizontal deformation, and curvatures. Conversely, if reclamation measures are taken too late (stage d), most of the topsoil will sink below the water table, and soil resources can't be guaranteed for reclamation. This increases both reclamation costs and construction difficulties, and may lead to a very low rate of farmland reclamation. Therefore, the most appropriate stages would be stage (b) and stage (d), when panel 453 is under mining. In this stage, ground water is beginning to emerge, restoring the land in this stage will facilitate to protect topsoil and the rate of farmland reclamation could be guaranteed.

Conclusions

(1) Based on mining schedule and geological condition, dynamic scenario influence of cultivated land could be simulated by using dynamic subsidence prediction and spatial analysis for a single horizontal layered coal seam. This paper simulated three stages of impacts caused by

underground exploitation; quantitative analysis involving the failure mode, damage area, and the degree of damage. Our conclusion is that that: rate of cultivated land was decreased gradually from 100% to mere 14.4% (four stages correspond to 100%, 72.5%, 67.3%, 14.4%, respectively). If reclamation measures are adopted after the ground is stabilized, 86.6% of cultivated land would submerge into water and lead to a low rate of reclaimed farmland.

(2) Based on the scenario simulation, virtual reclamation plan is under consideration for three mining stages. Farmland reclamation rates are 78.3%, 73.3%, and 40.7% corresponding to stage (b), stage (c), and (d).

(3) Taking rates of reclaimed farmland as the preferred standard, the farmland reclamation rates at stage (b) and (c) could be increased to37.6% and 32.6%, respectively, compared against delaying reclamation until the land stabilizes (stage (d)). Consequently, restoring subsided land in stage (b) or stage (c) could decrease construction difficulty, maximally protect the topsoil, and enhance farmland reclamation rate. The optimum reclamation time is at stage (b).

In a word, the research shows that: using dynamic subsidence prediction with reclamation scenario simulation, and taking the rate of reclaimed farmland as preferred standard, the best concurrent mining and reclamation time and plan could be obtained.

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