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Technological innovation and engineering practice of damage reduction mining and ecosystem restoration in open-pit coal mine

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Abstract

Non-technical summary. To address the issues of declining groundwater levels and the degradation of soil ecological functions caused by open-pit coal mining in China. Based on theoretical analysis, laboratory experiments, on-site monitoring, mathematical modeling, and other means, the concept of coal ecological protection mining of 'damage reduction mining, three-dimensional protection, systematic restoration' is proposed. The mining concept has achieved remarkable ecological restoration effects, leading the scientific and technological progress of safe, efficient and green mining in open-pit coal mines.

Technical summary. The mechanism of damage propagation among 'rock-soil-water' ecological elements in open-pit coal mining was revealed. Adopting comprehensive damage-reducing mining technology throughout the entire stripping process, mining and drainage, shengli open-pit coal mine has doubled its production capacity, and reduced the land excavation and damage by 60 mu/year, reduced the mining area by 1,128 mu, and raised the groundwater level by 2.6–6 m, and the ecological restoration of the drainage field was advanced by more than 1 year. Adopting the three-dimensional water storage technology involves underground reservoirs, aquifer reconstruction, and near-surface distributed water storage units, baorixile open-pit mine has built the world's first open-pit underground water reservoir, with a water storage capacity of 1.22 million m^3, and the speed of groundwater level restoration has been increased by more than 70%. By adopting the systematic restoration technology of geomorphology-soil-vegetation in the discharge site, the soil water content in the demonstration area has been increased by 52%, the survival rate of plants has been increased by 34%, and the vegetation coverage has been increased by more than 40%.

Social media summary. Damage-reducing mining and systematic ecological restoration in open-pit coal mining are essential for the safe, efficient and green development of coal.

1. Introduction

Coal-rich, oil-poor, gas-poor is China's fossil energy resource endowment, over a significant duration, coal serves as a 'ballast' for energy security, but more than 80% of the coal production originates from the Yellow River Basin. Including the northern sand belt and other ecologically fragile areas, the ecological protection and restoration of coal mining areas are directly related to ecological and energy security, which are essential requirements for modernization (Huertas, Huertas, & Izquierdo, 2012; Li, 2019; Li, She, & Zhou, 2019; Song, Bi, Zhang, Gong, & Zhang, 2019). Open-pit mining offers the advantages of safety and high efficiency, high resource recovery rate and large capacity flexibility, which is an important support for China's energy security. The primary production areas of open-pit coal mines are characterized by water scarcity, high evaporation rates, and fragile ecology. The stripping of uncovered rock and soil in open-pit mining causes excavation and damage to vegetation, topsoil, submerged, and bedrock aquifers, which leads to systematic damages such as groundwater loss, decline in the water table, and degradation of soil ecological functions (Bian, 2000; Liu, Guo, Li, & Zhou, 2021; Xue, Guo, & Zhang, 2021; Yan et al., 2022; Yang, 2021; Yang et al., 2022). Therefore, the task of ecological restoration and management in mining areas is increasingly urgent, and reducing mining damage has become a hot topic of research.

Numerous scholars have conducted extensive studies on the ecological impacts and restoration techniques of open-pit mining. Song, Fan, and Wang (2016) and Wang, Dong, & Jia (2020a, 2020b) studied the adverse effects of surface mining on land, water, atmosphere and ecology, and established a coordinated relationship between surface mining and ecological environmental protection; Fan, Xiang, & Peng (2016), Zhao, Wang, and Wang (2019), Gao (2019), Liu (2020), and Wang et al. (2020a, 2020b) analyzed the impacts of surface mining on groundwater level and water quality across different ecological types, and concluded that high-intensity mining is the primary driving factor for the decline of the groundwater levels in the study area; Cai, Liu, and Chen (2012), Cai, Gao, and Shang (2002a) and Cai, Ma, Han, and Shen (2002b) proposed a calculation method for greenhouse gas emissions from surface coal mines, and established a systematic model for integration production and ecological reconstruction. Li et al. (2022a, 2022b) summarized the soil and water conservation engineering measures and vegetation conservation measures in the restoration area, and proposed the ecological restoration technology model for the Yimin open-pit mine; Xia, Li, Li, Bian, and Lei (2022) developed hydrologically integrated geomorphic remodeling optimization technology for grassland open-pit mine discharge site; Li (2016) developed and created a crucial technology system for the ecological restoration of surface mine dumps based on the integration of mining and drainage restoration, vegetation restoration, and landscape reclamation based on source damage reduction.

The previous research on ecological restoration of surface coal mines has conducted relatively systematic and in-depth studies, especially focusing on vegetation and soil restoration. However, these studies have primarily focusing on superficial vegetation restoration, neglecting to address damage reduction at the source. Consequently, technical challenges such as groundwater loss and ecosystem restoration remain unresolved, severely constraining the safe, efficient, and green development of open-pit coal mines. Based on this, this paper elaborated on the concept and essence of 'coal ecological open-pit mining', and proposes the theory of ecological reduction and systematic restoration within the technical system of open-pit mining. Engineering demonstration are conducted to establish a coal ecological open-pit project, providing technological support for the integrated development of open-pit coal mining, ecological protection, and restoration in China.

2. Coal ecological protection mining concept

This paper introduces the concept of coal ecological protection mining (Figure 1), which centers on damage-reducing mining, three-dimensional protection of water resources, restoration of groundwater level, and emphasizes ecological reconstruction of strata and systematic restoration of ecological elements, reveals the damage conduction mechanism of the ecological elements of 'rock-soil-water' in surface mining, and proposes a comprehensive set of technological based on this mechanism. These technologies aim to provide scientific and technological support for the safe, efficient, and environmentally sustainable development of surface coal mines.

2. Key technologies for derogation mining

2.1 Mechanisms of damage transmission to ecological elements in open-pit mining

To address the unclear damage propagation mechanism of rock-soil-water ecological elements caused by open-pit mining, a three-dimensional simulation test platform for fissure seepage field in open-pit mining was developed (Figure 2). It comprehensively adopts the means of theoretical analysis, simulation testing, numerical calculations and on-site research, and based on the law of the evolution of stress fields, fissure fields, and seepage fields, it elucidates the mechanism of 'rock-soil-water' ecological element damage propagation under the concept of 'damage to rock-soil-water' (Figure 3). This research provides theoretical support for reducing damage in mining operations.

2.2 Seasonal coordination of work gangs and end gangs to save land and reduce damage by gangs

Aiming at the technical problems of efficient resource recovery and reduction of land excavation damage and slope safety, we have elucidated the slope destabilization mechanism involving 'the overall negative exponential relationship of rock and soil strength decreasing with time and seasonal strong-weak fluctuation' under the freezing and thawing cycles in cold regions (Figures 4, 5), and established the soft rock slopes stability

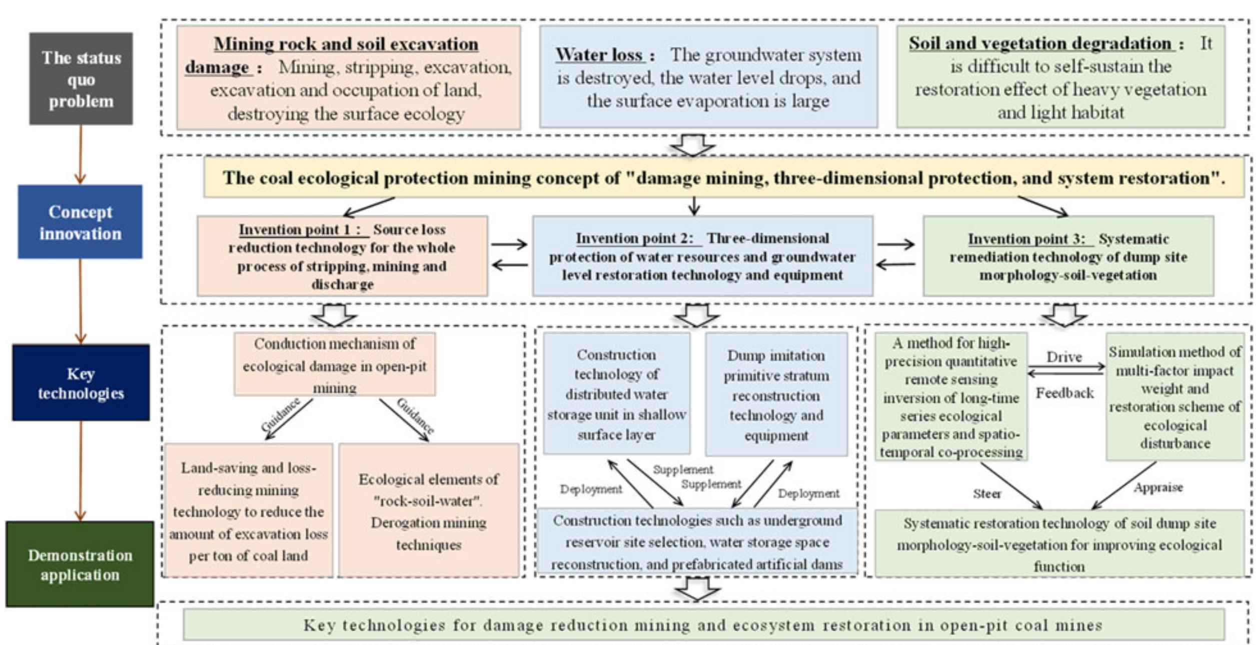

Figure 1. Overall technical route.

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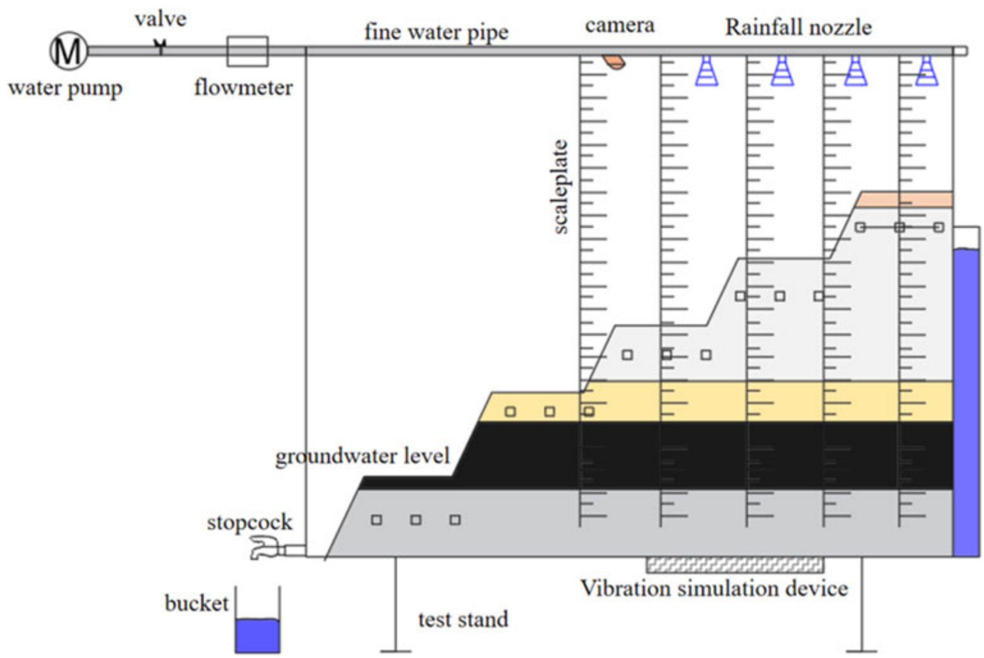

Figure 2. Three-dimensional simulation test platform for open-pit mining.

coefficient by freezing and thawing fluctuations. The formula for calculating the stability coefficient of soft rock slopes under the influence of freezing and thawing strength-weakening (Eq. 1) was developed, Additionally, a seasonal coordination method for the working gang and the end gang was devised based on adjusting slope angles according to the seasonal changes in slope strength in cold regions. As a result, the slope angle of soft rock in winter was increased by 11% to 16%. The mine has developed methods of multi-working face, multi-equipment cooperative arrangement and transportation system adjustment under the limitation of working space: 'convex' working line mining with variable section length, longitudinal combination of mining and stripping bridge transportation channel arrangement, and multi-working line parallel operation and cooperative soil discharging. The Shengli open-pit mine employs seasonal intensified mining technology, reducing land occupation (pit area/yearly output) is reduced by 26% for a million tons of coal output.

$$F_{\mathrm{sn}} = \frac{R\sum_{i-1}^{j}(C_n l_i + W_{ni}\cos\beta_i\tan\varphi_n) + \sum_{i-1}^{m}\tau_{ndi}}{R\sum_{i-1}^{j}W_{ni}\sin\beta_i} \quad (1)$$

where F_{sn} is responsible for the stability of the slope after n freeze-thaw cycles ; R is the radius from the center to the sliding surface, m; C_n is the cohesive force of rock after n cycles of freezing; l_i is the length of the bottom edge of the i-th block; W_{ni} is the gravity of the i-th block after n freeze-thaw cycles; β_i is the inclination angle of the bottom sliding surface of the i-th block; φ_n is the internal friction angle after n freeze-thaw cycles,°; τ_{ndi} is the tangential force acting on the i-th anti slip block after n freeze-thaw cycles.

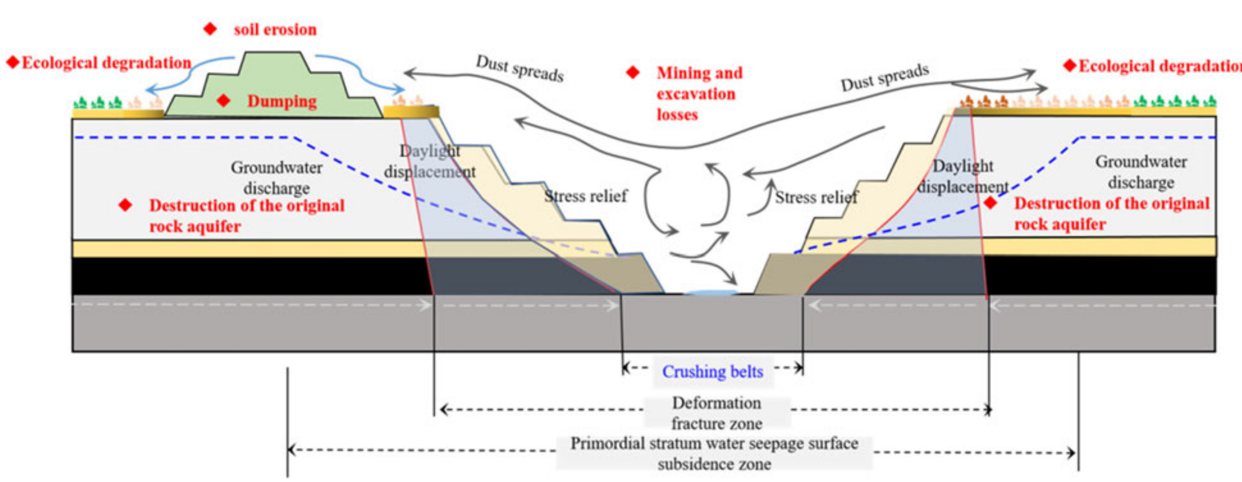

Figure 3. Mechanism of ecological damage conduction in open-pit mining.

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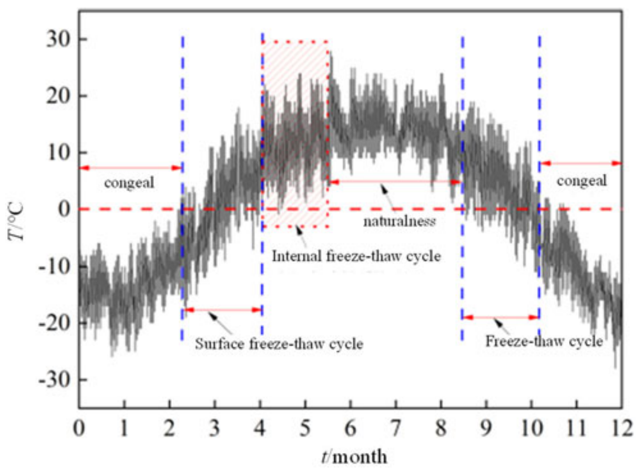

Figure 4. Freeze-thaw cycle of slope in Shengli mining area.

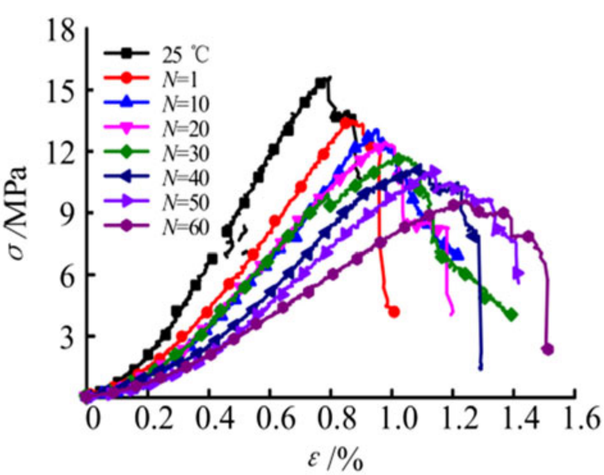

Figure 5. Freeze-thaw cycle of slope rock and soil mass (−10 °C).

2.3 'Rock-soil-water' ecological factor mitigation technology based on the mining damage transmission chain

The in-situ test system for consolidated loose bodies and the method of advance internal drainage of inclined coal seam base plate step shaping – segmented centralized drainage-reverse channel anti-discharge sliding (Figure 6) were developed, which improved the capacity of the internal drainage field and reduced the external drainage area by 16%; and the method of constructing soil and rock retaining wall in the internal drainage field by using geotechnical hierarchical layer-by-layer drainage and grouting to strengthen seepage blockage was invented, which realizes the combination of the mining and drainage synergistic control of seepage surface of the aquifer and the dam body. The method of constructing soil and rock retaining wall inside the discharge site was invented, and the combination of mining and discharge to regulate the seepage surface of the aquifer and dam body to prevent seepage and preserve water was realized, and the amount of groundwater loss was reduced by 25%.

3. Technologies for three-dimensional storage of water resources and water level restoration

3.1 Underground water banking technology for open pit coal mines

To address the issues of mine pit water pooling affecting safe production, large surface reservoir footprint, and significant water resource evaporation, we proposed a technical approach for constructing underground water reservoirs in open-pit coal mines. This method involves regulating the particle gradation of discharged rock and soil to create water storage spaces. We also developed reservoir siting technology that considers the integrity of the reservoir bottom under mining influence, slope stability, and reservoir safety. Preference is given to stripped sand and gravel to enhance void space and permeability, thereby achieving a storage coefficient more than one times larger than natural gravel strata (Figure 7). Additionally, we invented the wedge-shaped seepage control assembly dam structure (Figure 8, Eq. 2), enhancing the overall dam body safety coefficient by approximately 75%. A combined construction process was devised involving prefabrication of the wedge-shaped sealing top beam on the ground and on-site casting of the dam base. This innovation resolves seepage control challenges associated with quarrying and reduces construction costs by about 40% compared to traditional dam construction methods.

$$B = \frac{(h - 1.5)\eta}{2\tan\alpha}\ln\left(\frac{k\gamma H + (C/\tan\alpha)}{(C/\tan\alpha) + (P/\eta)}\right) + 2.8 \qquad (2)$$

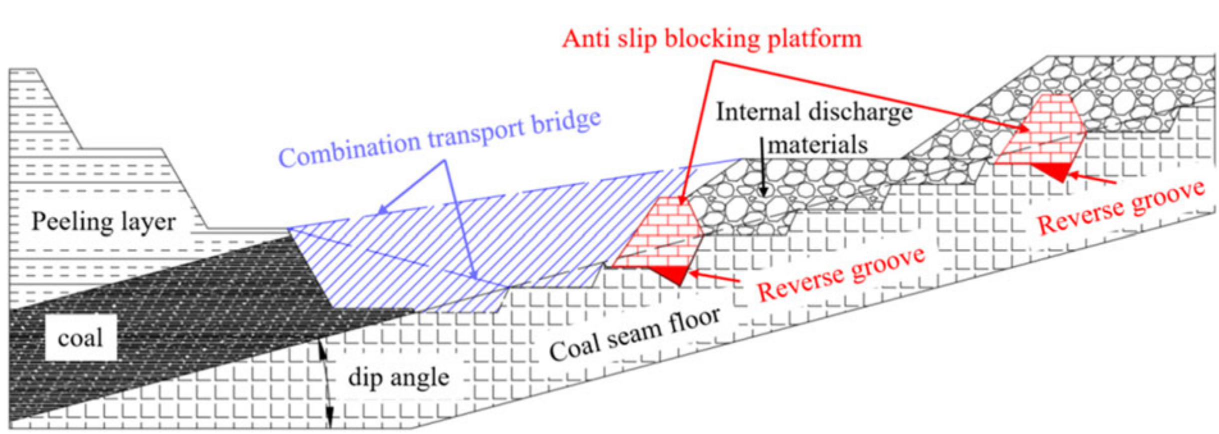

Figure 6. Early internal drainage method for loose body consolidation and step shaping.

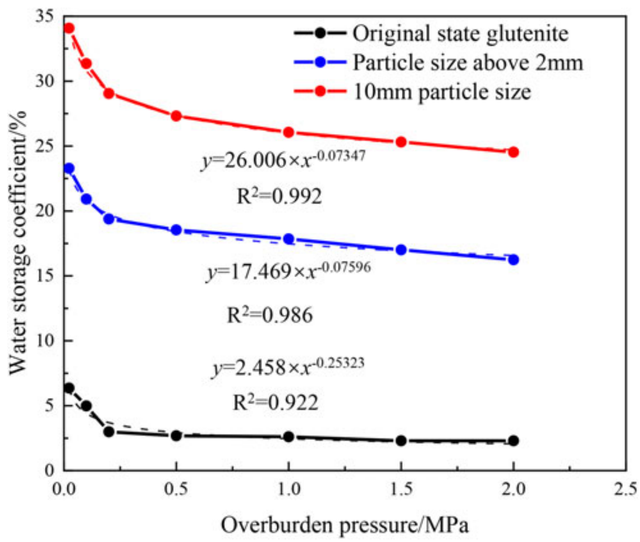

Figure 7. Relationship between grain size and water storage coefficient.

where B is the base thickness of the artificial dam body, m; h is the thickness of the coal seam, m; η is the lateral pressure coefficient; α is the internal friction angle,°; γ is the average bulk density of the rock layer, KN/m^3; K is the concentration factor; H is the burial depth of the coal seam, m; C is the cohesion between the artificial dam body and the coal seam roof and floor, MPa; P is the pressure of the coal pillar dam on both sides on the artificial dam body, MPa.

3.2 Techniques and equipment for reconstructing the original stratigraphy of the exhumation fields

A reconstruction model imitating the original stratigraphy of the inner earth discharge site was established (Figure 9), and the method of storage and transportation of stripped materials coordinated with mining and drainage, and the stratigraphy construction method of reconstructing water barrier layer in mudstone and water aquifer layer in sandstone were invented, realizing the reconstruction of water-bearing and water barrier layer and effective connection with the original water-bearing and water barrier layer. The wavy water barrier layer construction method of determining the elevation and thickness based on the water level was invented, and the pumping and injecting method of adjusting the speed of water transportation of water from connected water aquifers was researched and developed. A water level restoration technology was developed, which realizes the coordination between the restoration of groundwater level and slope safety protection in the earth discharge site. It has invented an intelligent drive system adapted to all working conditions for the construction of strata reconstruction, and developed a high-powered grader and a cold regeneration machine that efficiently mixes loose materials and water-insulating materials on the spot to rapidly construct a water-insulating layer (Figure 10), thus realizing the rapid construction of strata reconstruction imitating natural strata. Monitoring at the Shengli open-pit coal mine discharge field indicates that: the permeability coefficient of the water barrier constructed with stripped mudstone is less than 10md, the water level in the internal discharge field has risen by 2.6–6 meters, and the rate of groundwater level recovery in the mining-affected area has improved by over 70%.

3.3 Construction of shallow surface distributed water storage units and three-dimensional allocation technology of underground water reservoirs in the earth discharge site

To address severe soil erosion in discharge fields, the instability of slopes during heavy rainfall, and the challenge of sustaining reclaimed vegetation in dry seasons due to water scarcity, we have developed innovative technologies. Our shallow surface water storage unit construction, featuring layers of humus planting, gravel water storage, and clay seepage control, effectively prevents erosive slope runoff, underground seepage, and undercurrents during rainfall. Additionally, we have pioneered a construction method involving continuous non-uniform flexible seepage control and water barrier layers tailored to accommodate settlement volumes in discharge fields (Eq. 3). We have also developed advanced construction technologies to further enhance our approach. Our continuous non-uniform flexible anti-seepage water barrier technology, tailored to the settlement dynamics of discharge fields, effectively prevents seepage at reservoir bottoms. Additionally, we have innovated segmental pre-burial techniques for large-diameter pumping and injection wells, carefully coordinated with stripping, mining, and drainage operations. This integration establishes hydraulic connections between surface water

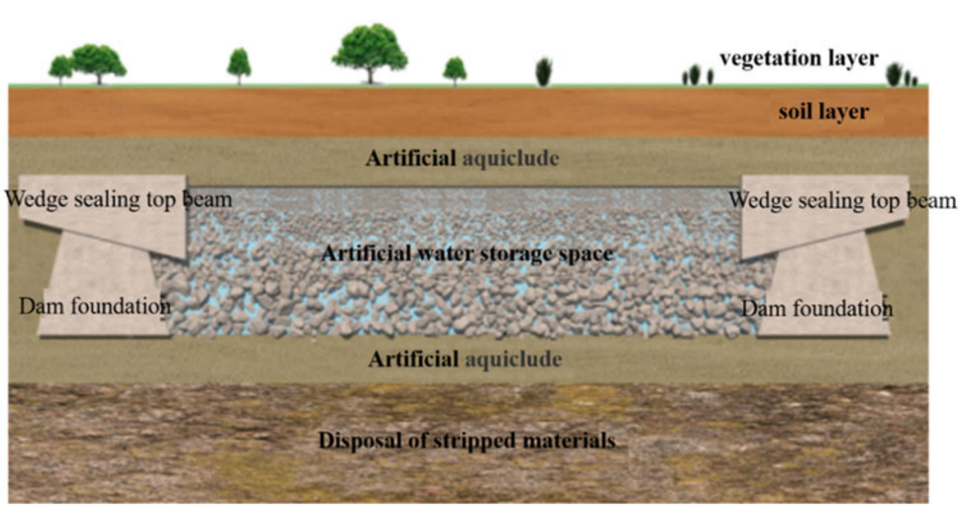

Figure 8. Drawing of dam construction of underground reservoir.

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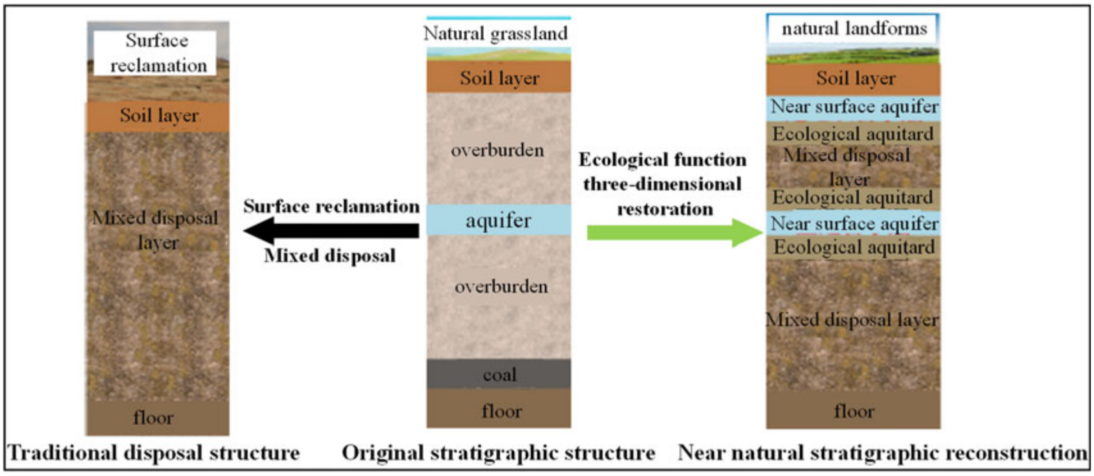

Figure 9. Structural reconstruction model of internal soil dump and nearby natural strata.

storage units and underground reservoirs, ensuring the integrated deployment of water resources and enhancing reservoir safety through controlled pumping and injection of water (Figure 11 and Eq. 4).

$$w_{\max} = \frac{5P_1a^4}{24EI} \tag{3}$$

where $w_{\max}$ is the maximum subsidence amount at the distance a from the slope surface of the waste disposal site, m; EI is the bending stiffness of the beam, GPa*m^4; P_1 is the uniformly distributed load on the waste disposal site, KN/m; a is the distance between the slope surface of the waste dump and the aquiclude, m.

$$W \geq K_1/\gamma_y + [(K_1/\gamma_y)^2 + (K_1 \cdot W_b + \gamma \cdot h^2)/\gamma_y]^{1/2} \tag{4}$$

$$K_1 = \frac{e \cdot \gamma_y}{(1-e)\tan\beta} \tag{5}$$

where W is the safe distance from the dumping face to the dam body, m; K_1 is the lateral force of the abandoned rock-soil, KN/m^3; h is the water level height, m; γ_y is the weight of the abandoned rock-soil, KN/m^3; W_b is the bottom width of the dam body, m; γ is the weight of stored water, KN/m^3; β is the angle of the inner slope, °.

4. Systematic remediation techniques

4.1 High-precision quantitative remote sensing inversion and spatial-temporal synergistic processing of long time-series ecological parameters in surface coal mines

To address the challenge of monitoring and quantifying the scope and extent of ecological damage caused by open-pit mining, we

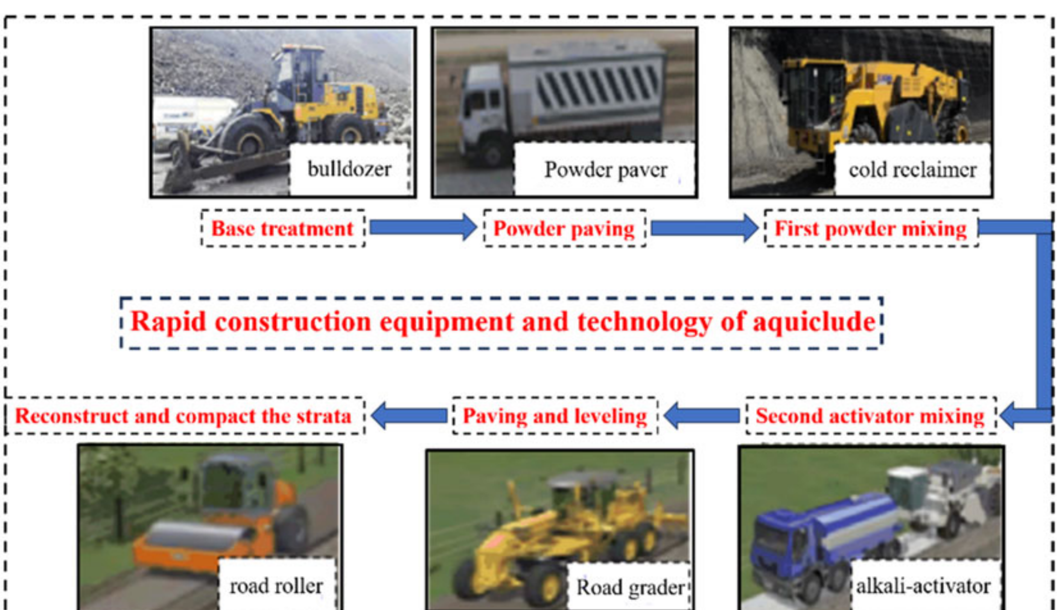

Figure 10. Rapid construction equipment and technology of water barrier layer.

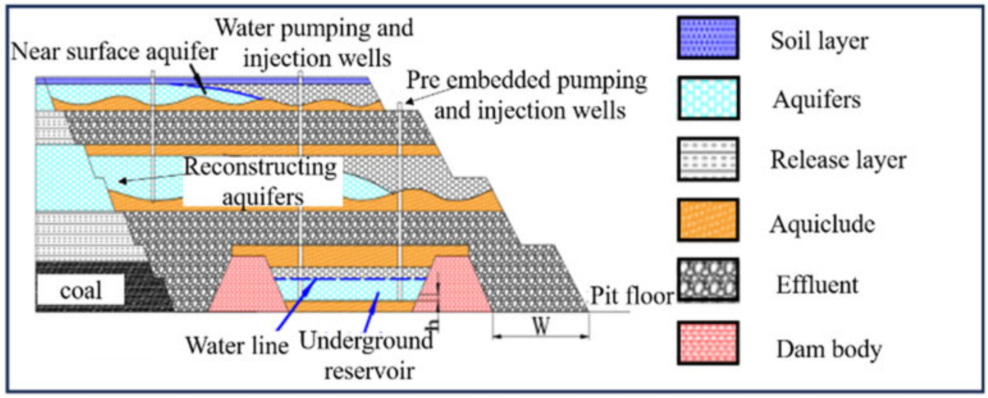

Figure 11. Three-dimensional water storage mode of internal soil dump.

have developed a pioneering method. This method involves dynamic and detailed identification of key feature elements and utilizes advanced quantitative remote sensing techniques to precisely invert ecological parameters related to soil, water, and vegetation. This approach is specifically tailored to the considerable spatial variability inherent in open-pit mining areas, resulting in a significant enhancement in measurement precision of approximately 20%. We have invented a time-consistent correction method for ecological parameters based on the similarity of cumulative distribution function, and a high-precision interpolation technique for bidirectional correction of missing ecological data, and constructed a large ecological dataset that is long time-series, time-consistent, and spatially-continuous. We invented a method for quantifying the scope of ecological damage from mining and identifying the main control factors based on the residual method, and quantified the scope of ecological impacts of open-pit mining on the ecological impacts and the main control factors for the first time, with an impact range of 2 km for the vegetation in the eastern grassland area, an impact range of less than 1 km for the soil, and an impact radius of 4 km to 12 km for the 5 m drop in the underground dive level, and weights of anthropogenic ecological impacts: 35% for mining, 28.5% for grazing, and other 36.5%.

4.2 Multi-factor weight quantification of ecological disturbances in open pit mines and simulation methods for restoration programs

To address the challenges of accurate decision-making, evaluation, and quantitative prediction in ecological restoration programs for open-pit mines, innovative methodologies have been developed. A geographically weighted artificial neural network model and weight quantification method (Figure 12) was introduced. This breakthrough addresses issues such as distance attenuation and nonlinear modeling of complex disturbance processes, resulting in a 42.8% reduction in error. Additionally, a multiscale temporal and spatial grid coding method was devised for managing multi-source large-scale mine data, significantly improving data storage and computing efficiency by 1–2 orders of magnitude. Furthermore, a digital twin simulation technology

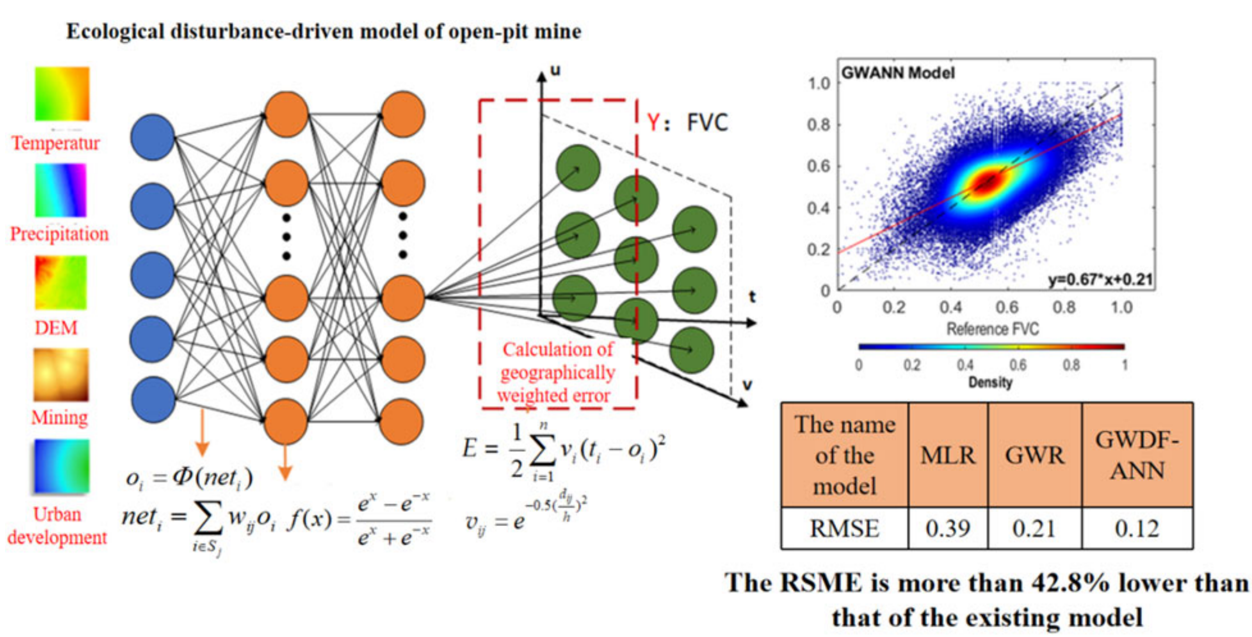

Figure 12. Modeling and weighting quantification of multiple drivers of ecological disturbances.

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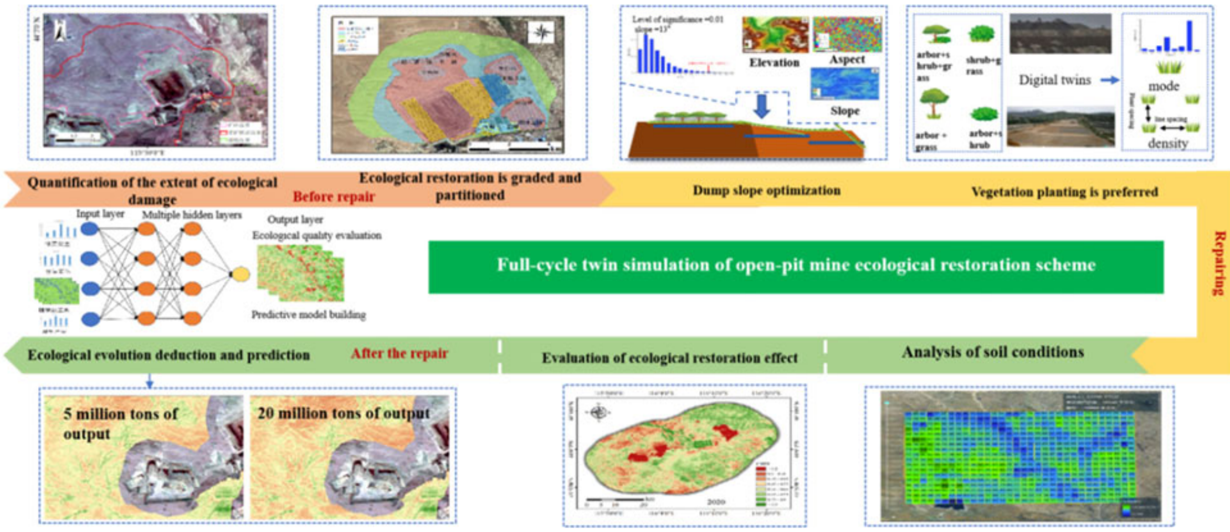

Figure 13. Twin simulation technique for ecological rehabilitation program of open pit mines.

and platform for ecological restoration planning in open-pit mines (Figure 13) enables precise ecological restoration through hierarchical zoning, optimized slope angles for discharge sites, soil condition evaluations for suitable plants, selection of plant species combinations and planting modes, assessment of restoration effectiveness, and prediction of ecological evolution trends (Li et al., 2022a, 2022b). Application of this simulation technology has shown a 34% higher vegetation survival rate in demonstration mine areas compared to control areas.

4.3 Systematic restoration technology of geomorphology-soil-vegetation ecological elements of the discharge site for the enhancement of ecological functions of open-pit mines

A method has been developed to assess the ecological resilience of drainage fields, considering climate, topography, soil quality, irrigation volume, and microbial community characteristics. Additionally, an ecological systematic restoration technology for drainage fields has been introduced. This technology integrates near-natural geomorphological adjustments to reduce surface runoff and erosion, distributed water conservation and erosion control through a system of 'slope guide ditches' for water diversion, 'platform submerged ditches' for water catchment, and underground storage units for water retention. It also includes soil restructuring, moisture content regulation, and restoration of appropriate vegetation (see Figure 14). Soil reconstruction and moisture regulation are key components of the ecological restoration techniques at the discharge site. In a demonstration at an open-pit mine restoration area, slope erosion has decreased by 60%, soil moisture content has risen from 6% to 9%, and vegetation cover has increased by over 40%. These improvements were achieved alongside a reduction of over 50% in water consumption for maintenance purposes.

5. Coal ecological open pit mining technology application effect

Addressing the significant challenge posed by balancing the efficient development of coal resources with ecological environmental protection in the grassland area of Mengdong in eastern China, we conducted theoretical research on ecologically sustainable open-pit coal mining. This encompassed the development of key technologies and the demonstration of their integrated application, leveraging the coal bases in Hulunbeier and Xilinguole. Our efforts successfully mitigated ecological issues such as declining groundwater levels, land degradation, soil erosion, reduced vegetation cover, and landscape damage caused by intensive coal mining in environmentally fragile areas. This initiative provides crucial scientific and technological support for the sustainable development of large-scale surface coal mines and regional ecological security in China.

5.1 Demonstration of ecological mining technology for surface coal mining in semi-arid grassland area

5.1.1 Overview of the demonstration area

The Shengli Coalfield, situated in the Xilinguole region of Inner Mongolia, plays a crucial role as a primary capacity source for China's East (Northeast) Coal Base. The mining area experiences a semi-arid grassland climate, characterized by an average annual precipitation of 295 mm and evaporation of 1,795 mm. The humus layer thickness ranges from 0 to 30 cm, and the average soil moisture content varies between 3% and 10%. These conditions reflect typical grassland climate and ecological characteristics (Li, Han, Zhao, Lin, & Wang, 2021).

5.1.2 Technology integration models and application effects

In response to the ecologically fragile conditions characterized by poor soil, limited water resources, and an arid climate in the Xilinguole grassland area, the company has established a 12,146 mu demonstration project for ecological mining technology in semi-arid zones. This initiative focuses on achieving ecological damage control and efficient restoration, concurrently with the steady enhancement of surface coal mine production capacity.

(1) By comprehensively applying technologies such as gang mining and rapid backfilling, coordinating seasonal operations, reconstructing ecological strata, discharging soil along mining boundaries, strengthening internal drainage channels within

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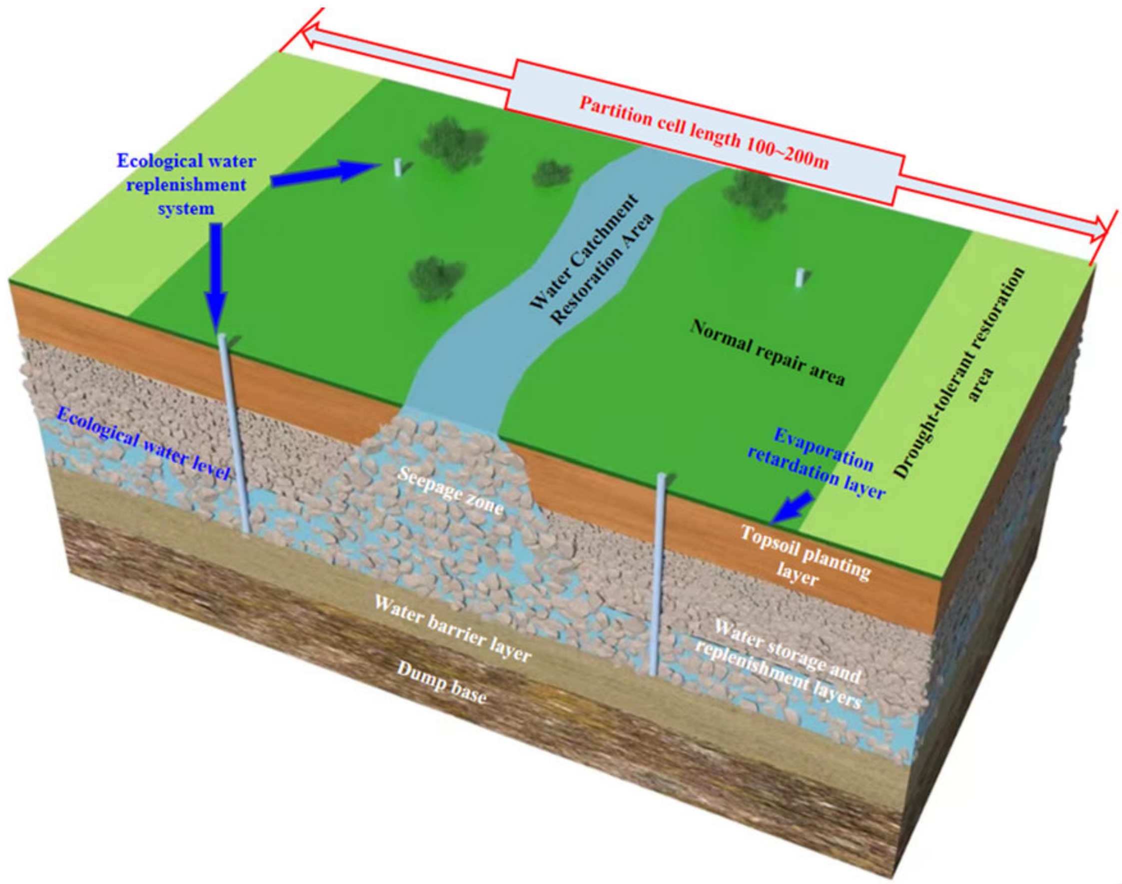

Figure 14. Technical system for systematic restoration of geomorphic soil vegetation.

the central mining area, and synergistically utilizing the 'ecological restoration window period,' we have developed an integrated model for reducing ecological damage through mining, discharge, and recovery. As a result, the demonstration Shengli open-pit coal mine has doubled its production capacity. Concurrently, it has reduced annual land excavation and loss by 60 mu, decreased the quarry area by 1,128 mu, and accelerated the ecological restoration timeline of discharged fields by over a year.

(2) According to the concept of synergistic restoration of water, soil, air, plants, and landscape, a comprehensive ecological restoration model has been developed for open-pit mine discharge areas in semi-arid grasslands. This model integrates technologies such as ground reservoir water storage, water resource purification and efficient utilization, soil fertility improvement and reconstruction, selective planting and promotion of microorganisms, natural landform shaping at discharge sites, and creation of three-dimensional landscape isolation zones using trees, shrubs, and grasses in a vertical arrangement. Additionally, it enhances slope stability through hay restoration, among other techniques. As a result of implementing this model, the demonstration open-pit mine has achieved zero discharge of pit water. Vegetation coverage has increased by 41.78% compared to baseline values, and plant diversity in the discharge area has improved by 50%. The rehabilitation rate of the degraded site has reached 100% Figure 15.

5.2 Engineering practice

5.2.1 Overview of the demonstration area

Baorixile Coal Field, situated in the Hulunbeier area of Inner Mongolia, represents a significant coal mining region notable for its high latitude within China. It serves as a crucial source of coal supply for Heilongjiang Province. The area experiences an average annual precipitation of 315 mm and evaporation of 1,345 mm. The grassland soil layer ranges from 20 to 50 cm in thickness, with soil water content typically falling between 8% and 16%. The prolonged and severe winter conditions impose considerable challenges on both the operational logistics of the open-pit mine and the ecological restoration efforts (Li, 2023).

5.2.2 Technology integration models and application effects

Given the ecological challenges posed by the Hulunbeier Coal Base, characterized by cold, semi-arid conditions and infertile soil, a project has been implemented. This project encompasses a 10,394-acre ecological mining technology demonstration area in the cold grassland region. Its aim is to achieve synergistic enhancement of ecological damage control at surface coal mines and systematic restoration during the post-mining period.

(1) We have developed an ecological damage-reducing mining approach tailored to the characteristics of a cool climate by comprehensively implementing several advanced technologies. These include strip-type gang mining during freezing

Figure 15. Effect of ecological mining in Shengli open pit coal mine.

periods, coordinated seasonal operations, combined bridge transportation within the open-pit mine, relocation of the raw coal crushing station to the inner mine row, ecological stratum reconstruction refined through meticulous management of mining, transportation, and stripped material drainage, as well as optimized deployment strategies for mining, transportation, storage, and utilization of topsoil layers. This innovative model has been demonstrated in an open-pit mine, achieving an annual recovery of over 600,000 tons of coal from sloped areas. Furthermore, it reduces the mining footprint by 500 mu, shortens the distance between end gangs and inner rows of stripping by nearly 200 m, and optimizes the deployment of approximately 460,000 meters of soil layer reconstruction materials for ecological restoration purposes. .

(2) To mitigate the impact of cold climates on pit water throughout its lifecycle – from generation and transportation to storage and utilization – the company has implemented integrated technologies. These include natural seepage prevention on the surface of open pit mine discharge fields, ensuring the safety of water barrier dams with earth and stone core walls, constructing near-surface water barriers using stripped materials from open pit mines, enhancing loose material water storage capacity, and strategically locating underground reservoirs for open pit mine discharge sites. Measures such as reservoir bottom seepage prevention, dam construction, and continuous safety monitoring have been employed. These efforts have established a synergistic three-dimensional storage and quality separation model for surface water reservoirs, ecological aquifers, and underground reservoirs at discharge fields. Notably, the company has pioneered the world's first underground reservoir for open pit coal mines, boasting a storage capacity of 1,220,000 m^3 and achieving 100% utilization of mine pit water.

(3) By integrating slope imitation natural micro-geomorphic land shaping, meticulous reconstruction of near-surface soil layers, and enhancement of soil quality and capacity through plant selection and microbial promotion, a comprehensive remediation and ecological restoration model has been developed for drainage fields adapted to the freeze-thaw cycle in cool zones. In the demonstration area of the open pit mine, these efforts have increased the utilization rate of rainfall to over 75%, boosted soil water content by approximately 10%, reduced annual erosion rates by about 60%, and elevated vegetation

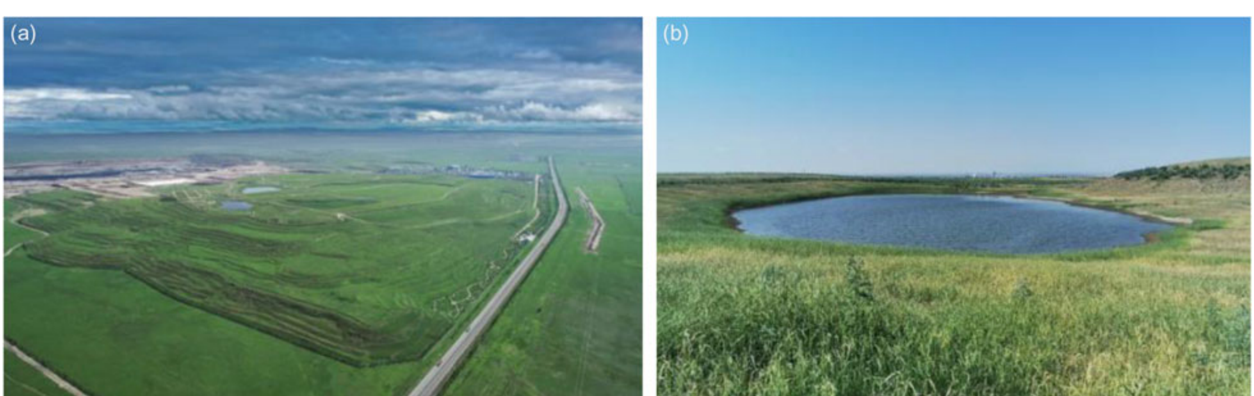

Figure 16. Effect of ecological mining in Baorixile open-pit coal mine. (a) Effectiveness of ecological restoration of soil disposal sites (b) Water storage works at soil disposal sites.

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cover by 37% compared to baseline levels. This achievement underscores a significant 37.96% increase in vegetation coverage from the original background value Figure 16.

6. Conclusion

(1) Revealed the damage transmission mechanism of 'rock-soil-water' ecological elements in surface coal mining, and developed holistic source damage reduction mining technologies. These include rapid stripping of rock and soil along the 'convex' shaped working line of surface coal mines, seasonal coordination of coal extraction operations to align with gang cycles, and early internal drainage of large volumes of stripped materials in inclined basins.
(2) Developed three-dimensional water resource storage and utilization and water level restoration technologies for underground water reservoirs in open-pit coal mine drainage fields. These include three-dimensional methods for aquifer reconstruction and reconnection to the original aquifer, as well as shallow surface distributed water storage units. These technologies have been successfully implemented at the Shengli and Baorixile open-pit coal mines, leading to significant improvements in the ecological environment of the mining areas.
(3) Developed a high-precision quantitative remote sensing inversion and spatial and temporal synergistic processing method for long time-series ecological parameters of open-pit coal mines. This method quantifies the impacts of multiple ecological disturbance factors and simulates remediation programs. Additionally, I devised systematic techniques for geomorphology-soil-vegetation remediation at discharge sites to enhance ecological functionality.

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