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# Key Technologies for and Cases of Open-Stope-to-Backfill Transition in China's Small and Medium Mines

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## Abstract

Globally, the open-stope method is used in over 60% of small- and medium-sized mines because of its low cost and high initial efficiency, but it has issues like high ore loss and a great goaf-collapse risk, becoming a core bottleneck for mines' green and sustainable development. Thus, accelerating its transition to the green backfilling method is an urgent industry need. This study focuses on Shishudi Gold Mine, Xingan Fluorite Mine, and Suichang Gold Mine, adopting a "problem diagnosis–scheme design–case verification–experience extraction" framework to analyze their economic and ecological indicators pre- and post-transition. Our results show remarkable effects: Shishudi's ore recovery rose from 75% to 88.5%, with 300,000 tons of residual ore recovered and 100% tailing utilization; Xingan's ore loss dropped by 12%, annual output increased by 60,000 tons, and 200,000 tons of tailings was consumed to achieve a "tailless mine"; and Suichang's mining capacity rose from 30 tons per day (t/d) to 120 t/d, using 150,000 tons of cyanide-free tailings yearly. In this paper, the key problems of open-stope mining are identified and a transition path of "process innovation–system construction–tailing utilization–mechanization support" is summarized. Our results provide promotable technical solutions and practical references for global small- and medium-sized mines that are of great significance for driving their green and sustainable development.

**Keywords:** open-stope method; filling method; green mines; tailing treatment; transformation of mining methods

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## 1. Introduction

The mining method is a core element in the mining production process, and whether the mining method adopted by the mine is reasonable will directly affect the economic benefits and service life of the mine. According to different methods of controlling ground pressure, current mining methods can be divided into three categories: open-stope method, filling method, and collapse mining method [1]. The open-stope method is one of the earliest and most widely used mining methods in underground mines [2]. According to statistics, there are currently nearly 50,000 non-oil and -gas mineral mining rights in China, of which less than 15% are large mines [3]. Traditional mining techniques such as the retention method, room and pillar method, and collapse mining method are still used in many small- and medium-sized underground mines [4]. In Northeast China, Inner

Mongolia, Shandong, Hebei, and other places, the vast majority of colored metals and gold mines are mined using the open-stope method [5].

Globally, significant regional and technological disparities exist in the costs and losses of mining methods and mineral production: open-pit mining accounts for over 60% of applications in small- and medium-sized mines (SMMs) worldwide due to low initial investment, yet it has an average ore loss rate of 20% and dilution rate of ~10% [6]. By contrast, traditional open-stope mining has a higher loss rate (15–30%), while only backfilling mining can control it below 10%.

In cost structure, labor, equipment depreciation, and energy are core expenditures, collectively accounting for 70–80% of direct costs (labor, 30–40%; equipment depreciation and maintenance, 20–30%; and energy consumption, 15–25%) [7]. Notable differences also exist across mineral types: The global comprehensive gold mining cost in 2025 was ~CNY 375/g, soaring to CNY 500/g for deep shaft mines in South Africa (due to high extraction difficulty) but only CNY 270/g for high-grade ore mines in Australia. For open-pit copper mines, the full process (exploration to smelting) incurs a mining cost of ~CNY 950/ton of concentrate and a mineral-processing cost of CNY 1795/ton.

In environmental and resource losses, the global cumulative stock of mine tailings exceeds 22 billion tons. In China, mining forms ~809,600 hectares of goafs annually, leading to 352,200 hectares of ground subsidence [8]. Mines without systematic management face issues like soil/groundwater pollution from surface tailing stockpiling, with a typical tailing utilization rate below 60%.

In China, small- and medium-sized mining enterprises account for as much as 90% [9]. Many small- and medium-sized mines (SMMs) adopt extensive mining methods. This extensive mining method has low resource utilization, serious environmental damage, poor production efficiency, and prominent safety hazards, making it difficult to achieve efficient resource utilization and sustainable economic development [10,11]. The filling method is a mining method that uses filling slurry to manage the goaf. As a part of mining, filling is used to fill the slurry into the mining area, providing a stable working platform for miners. The filling body can also support the goaf, prevent collapse, and effectively eliminate safety hazards created by the goaf [12]. At the same time, the filling method can fully recover the ore pillars and improve the ore recovery rate. Also, during the mining process, the flexibility of the filling method reduces ore impoverishment to a certain extent. Moreover, most mines use tailings as filling materials to fill the goaf, which can store a large amount of tailings underground (about 50%), greatly reducing the operating costs of tailing storage, alleviating daily management pressure, reducing the impact of surface tailing storage on the environment, and effectively avoiding the problem of using the open-stope method [13].

With the global advancement of mining technologies and the growing demand for green mine development in the modern era, the transition from extensive mining operations to green mining has become an inevitable trend for small- and medium-sized mines (SMMs) worldwide [14]. However, a common challenge persists during this transition: many SMMs, both in China and globally, only adopt superficial adjustments—such as merely adding backfilling processes to the ore extraction stage or making isolated changes to mining methods—rather than implementing systematic overhauls. While these partial measures can marginally improve mining safety and achieve limited tailing utilization, they fall far short of meeting the comprehensive standards of green mining, which emphasize integrated efficiency, safety, and environmental sustainability.

On the basis of fully summarizing previous research results, this study sorts out and summarizes three aspects: transformation conditions, program effects, and outstanding achievements of mines. On this basis, in this paper, the key scientific issues in the current

research on the transition from using the open-stope method to using the filling method are summarized, and the future development trends are discussed in order to provide useful references and ideas for the transformation of mining methods in SMMs.

## 2. Literature Review

The development of China's mining industry has a long history, dating back to the Paleolithic era, when mining activities were already underway for mineral resources such as stone, clay, jade, copper, and coal [15]. However, the modernization process of China's mining industry is relatively lagging behind, and the overall foundation of mining technology and equipment level is relatively weak. At present, many small- and medium-sized underground mines still use traditional mining techniques from the last century, mainly including the following typical methods:

(1) Room pillar mining method

This mining method divides the mining units into alternately arranged ore chambers and pillars, and retains the pillars to support the roof of the goaf during the mining of the chambers. Pillars can be arranged continuously or intermittently, with intermittent pillars usually not being mined, as shown in Figure 1a.

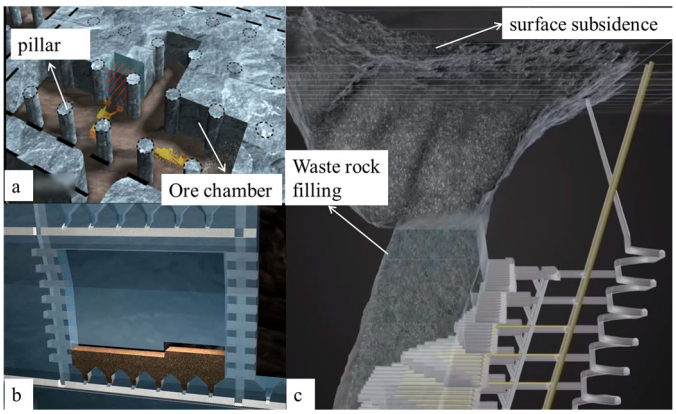



**Figure 1.** Schematic diagram of mining method: (**a**) room pillar mining method, (**b**) retention mining method, and (**c**) collapse mining method.

(2) Retention mining method

This method first divides the ore block into ore chambers and ore pillars. The mining room adopts a bottom-up layered operation method for backfilling, and the ore is dropped through shallow-hole blasting. After each blasting, only about one-third of the ore is released, and the remaining part is temporarily stored in the mining room as a working platform for subsequent mining. The final mining is carried out after the mining room is fully mined, as shown in Figure 1b.

(3) Collapse mining method

As a special mining technique, the collapse method does not distinguish between mining chambers and pillars during the mining process; instead, it uses forced or natural methods to cause the surrounding rock to collapse and form a covering layer. The ore is mined under the cover layer, and as the mining face advances, the collapsed waste rock immediately fills the fill area, thereby achieving effective management of ground pressure in the mining area, as shown in Figure 1c.

As an efficient underground mining method, the open-stope method has been widely used in metal mining, both domestically and internationally. This method maintains the stability of the goaf by reserving mining pillars or manual support, and it has the

characteristics of high mining intensity, low cost, and strong flexibility. In recent years, with the increasing demand for deep mining, digital mining, and safety and environmental protection, the theoretical research and technical application of the open-stope method have continued to deepen, showing a trend of interdisciplinary integration.

The research on the open-stope method in China began in the 1980s, and in recent years, some progress has been made in theoretical innovation, numerical simulation, monitoring technology, etc. Wang Xinmin established a strength calculation model for open-stope pillars based on elastic–plastic mechanics and proposed a dynamic optimization method for pillar-size design [16]. The Cai Meifeng team revealed the distribution pattern of ground pressure in deep mining areas through three-dimensional numerical simulations (FLAC3D), providing a theoretical basis for preventing rock bursts [17–19]. Chen and Wu proposed the "synchronous filling concept" in mining technology; their concept solves the problem of loss and impoverishment in the ore-drawing process of the retention method by setting flexible barriers and filling methods. Based on this method, many in-depth studies have been conducted [20,21]. As the mining depth increases (>1000 m), the risk of void collapse increases in high-stress environments. Academician Xie Heping proposed the concept of "deep depressurization mining", which weakens the stress of the ore pillar through directional blasting and provides new ideas for the application of the deep open-stope method [22–24].

Developed mining countries such as Europe, America, and Australia place greater emphasis on refined design and green mining in the study of open-stope mining methods. Canada has proposed the "Q-system based Mining Site Size Design Guidelines" and developed professional software such as Stope CAD and MAP3D to achieve parametric designs [25]. Abdellah and Hefni studied the factors affecting impoverishment in goaf mining of extremely inclined ore veins [26]. The comprehensive ore retention method is proposed to adapt better to changes in the dip angle of the ore body, while the wall-cutting and filling method is proposed to solve the problem of impoverishment in the recovery of high-grade ultra-thin ore veins [27].

Although the open-stope method has been developed to a certain extent both domestically and internationally, it still faces problems such as low mechanization, low labor efficiency, safety hazards, high pressure on tailing surface storage, high loss and impoverishment rates, and accumulation of ore funds, which are no longer suitable for China's safety production and green mining development concept. Figure 2 below presents a comparison of the technical and economic indicators between the traditional open-stope shrinkage method and the mechanized upward horizontal cut-and-fill stoping method adopted in a Chinese mine.

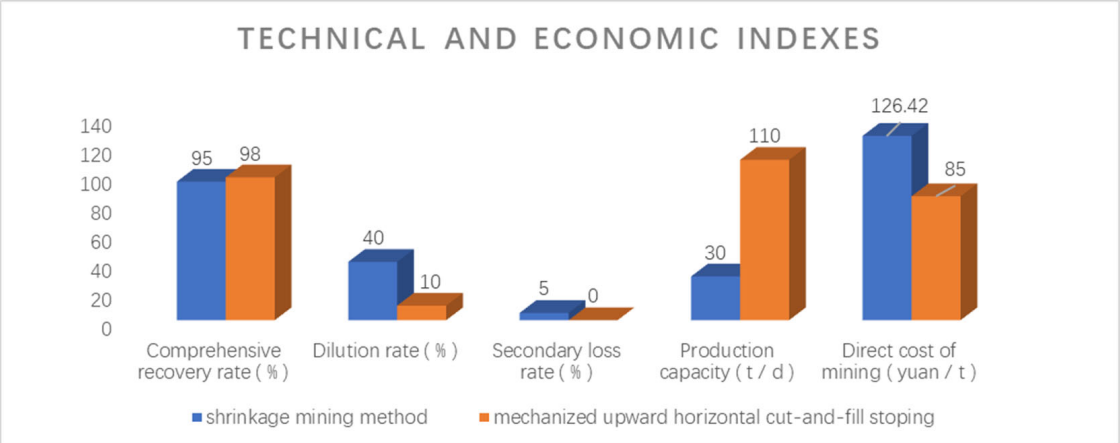



**Figure 2.** Comparison table of technical and economic indicators.

With the Chinese government's increasing emphasis on safety and environmental protection, the open-stope method is gradually being replaced by green and efficient filling methods. The new policy advocates accelerating the upgrading and transformation of mines; promoting the mechanization of SMMs; and stipulating that the construction, renovation, or expansion of metal and non-metal mines should generally adopt the filling method. If there are special circumstances where it cannot be applied, a strict argumentation procedure must be followed.

## 3. Transition Pathways for Traditional Mining Methods

When changing mining methods in extensive small- and medium-sized underground mines, it is necessary to seek backfill mining methods with high recovery rates, good safety, and environmental friendliness [28]. In the process of applying the filling method, the use of trackless equipment such as rock-drilling rigs, loaders, and pry machines can greatly improve the safety and efficiency of operations, and reduce the labor intensity of workers. Therefore, the filling method is a very good option to transition toward using for the ore retention method.

### *3.1. Change the Open-Stope Method to a Safer, More Efficient, and Environmentally Friendly Backfill Mining Method*

The open-stope method has poor applicability for changes in ore occurrence from thin to thick, grade from low to high, and dip angle from inclined to steeply inclined. It is also not suitable for complex mining technology conditions such as poor rock stability and "three down mining". In regard to its practical use, the open-stope method has many safety, economic, and technical issues. A large number of practical applications have proven that changing the open-stope method to the filling method can not only increase the ore recovery rate by more than 20% but also fundamentally eliminate safety hazards in goaf areas, effectively reduce tailing ground emissions, and significantly improve the safety production level of mines. Its comprehensive benefits are extremely significant.

### *3.2. Build a Tailing Filling System and Create Necessary Conditions for the Transition from the Open-Stope Method to the Filling Method*

The key to the backfill mining method lies in the backfill process and backfill system. The constructed filling system not only needs to meet the needs of filling mining, goaf management, and tailing disposal at the same time; it also needs to meet the high standards of "reliable operation, capacity matching, low operating costs, and controllable investment" (see Figure 3). Therefore, key technical parameters such as tailing pipeline transportation and filling ratio should be obtained through experimental research, theoretical analysis, and scheme comparison to determine a suitable low-cost filling-process plan, optimize a suitable filling-preparation site plan, ensure the reliability of the filling system, and control filling costs in order to reduce investment and operating costs.

### *3.3. Carry Out Filling Treatment of Goaf and Eliminate Safety Hazards in Goaf*

Using the newly built filling system to fill and treat the goaf can fundamentally eliminate safety hazards, protect the surface environment, ensure the safety of subsequent mining production, and achieve good economic benefits, all of which have practical significance (see Figure 4d,e).

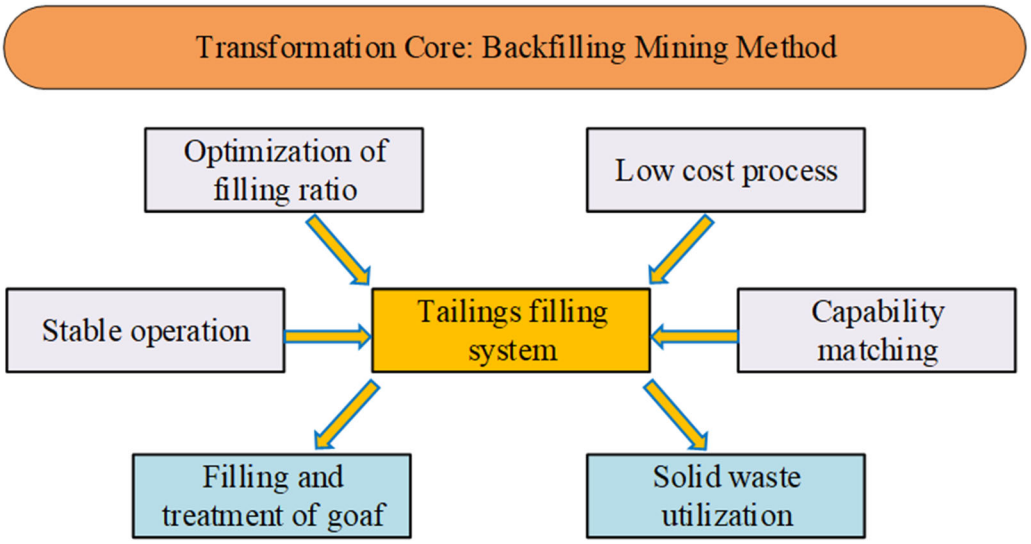



**Figure 3.** Key technologies and construction standards for tailing filling system.

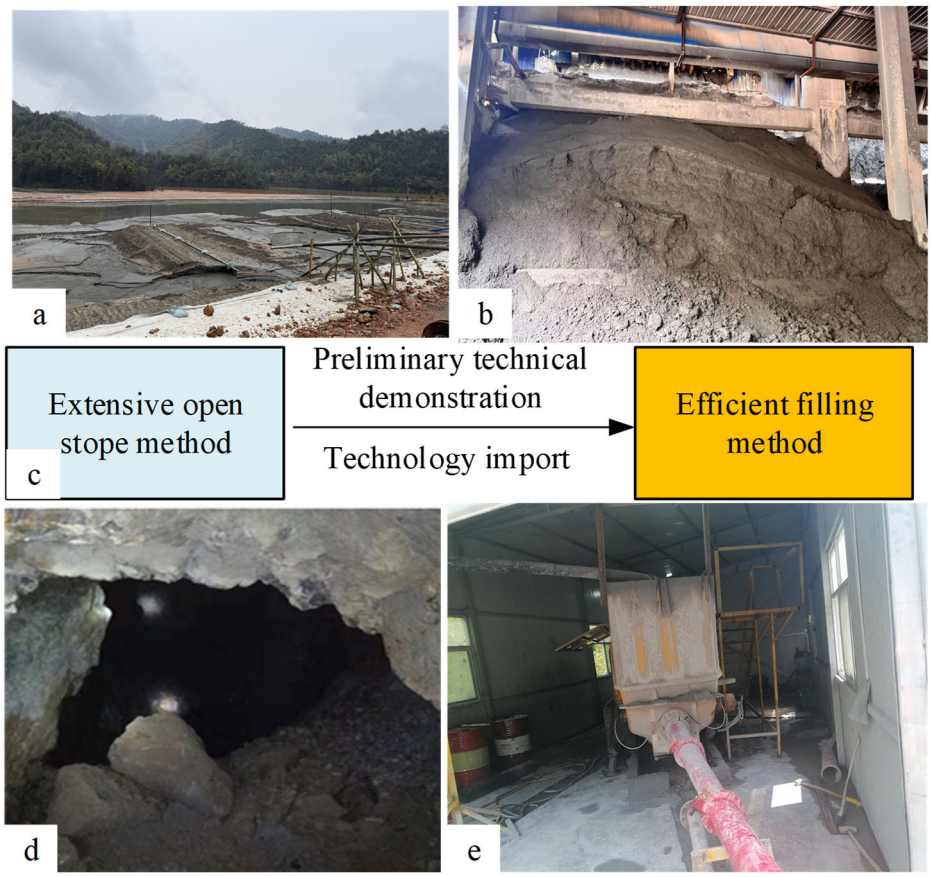



**Figure 4.** Tailing filling treatment diagram: (**a**) tailing pond is full; (**b**) fine-grained tailing production; (**c**) mining-method transformation; (**d**) underground mining voids; and (**e**) filling slurry pumping device.

### *3.4. Strengthen the Comprehensive Utilization of Tailings and Waste Rocks, and Achieve Zero Surface Discharge of Solid Waste*

On the basis of filling mining and the filling treatment of the goaf to absorb a large amount of tailings, researchers in the mining industry need to further strengthen the research on the comprehensive utilization technology of residual tailings and waste rock,

achieve the reduction and resource utilization of mine solid waste, and solve the problem of tailing pond capacity depletion and huge investment in new tailing pond construction (see Figure 4a,b).

### 3.5. Introduce Mechanized Mining Equipment and Promote Mechanized and Intensive Mining

Based on the resource-endowment conditions of each mine, researchers in the mining sector need to develop new high-efficiency and low-cost backfill mining technologies that meet the existing mining-technology conditions, introduce mechanized mining equipment, and maximize the recovery efficiency and mining intensity of resources. They also need to realize the full process mechanization of mining, excavation, loading, transportation, lifting, and beneficiation, reducing labor costs and safety risks; promote mechanized and intensive integrated development; and transform resource advantages into economic advantages (see Figure 5).

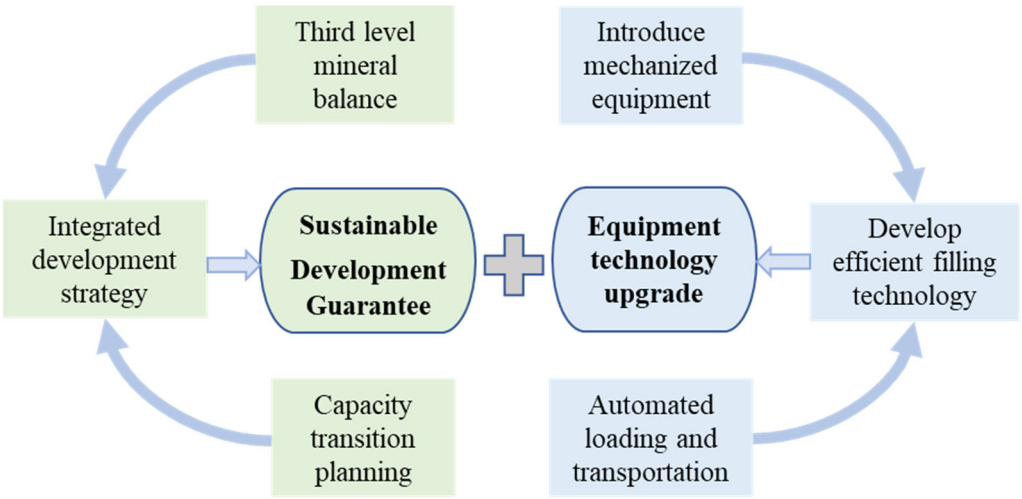



**Figure 5.** Equipment technology upgrade and sustainable development support.

### 3.6. Conduct Scientific and Rational Overall Planning for Resource Exploitation and Achieve Sustainable and Balanced Development

On the basis of detailed statistics and analysis of recoverable reserves, scientific and reasonable resource development plans should be carried out in the short, medium, and long term, and a transition plan for infrastructure production capacity should be formulated based on mining technology and production capacity, so as to form a reasonable three-level mineral quantity in the mine, enable the mine to achieve sustainable and balanced development, and provide the necessary technical and economic benefits (see Figure 5).

There are numerous examples both domestically and internationally of the transition from open-stope methods to efficient, environmentally friendly, safe, and economical filling methods. In the 1950s, Canada began to develop filling technology and subsequently adopted the filling method instead of the retention method to mine extremely inclined thin veins [29]. As another example, the Jaduguda underground mine in India transitioned from the initial retention method to the filling method in the 1980s [30]. Due to the increase in mining depth and difficulty, the Jiashi Tonghui Copper Mine in China, which is fractured and contains water, has also shifted from the original retention method to the filling method [31]. This article elaborates in more detail on the good results achieved after the transition from open-stope method to filling method through specific cases of Shishudi Gold Mine, Xingan Fluorite Mine, and Suichang Gold Mine in Zhejiang Province.

## 4. Construction of a Green Mine at Shishudi Gold Mine

### *4.1. Mine Overview*

Henan Zhongkuang Energy Co., Ltd., owns the Shishudi Gold Mine, located in Niutougou, Dazhang Township, Song County. It is an underground mine with a mining area of 19.8830 $km^2$, a designed production capacity of 120,000 t/a, an average thickness of 3.39 m, and a dip angle of 30°, as shown in Figure 6.




**Figure 6.** Geological map of Shishudi mining area.

Since its establishment in 2002, the Shishudi Gold Mine has been using a combination of adit blind vertical shaft development and room pillar mining methods (as shown in Figure 7a). The total amount of ore extracted during this period is over 3 million tons, and the amount of tailings and waste rock generated is nearly 80% (of the total extracted materials). During the long-term mining process, a large number of pillars and walls undergo significant changes in stability over time. Due to the fact that the room pillar method mainly relies on the stability of the ore rock itself and the support of the mining pillars for the goaf, as the mining area expands, the area of the goaf continues to increase. According to incomplete statistics, the volume of the underground goaf reaches 1.5 million cubic meters. A large number of mining pillars are subjected to long-term ground pressure, resulting in cracks, deformations, and other situations that may cause large-scale collapse at any time, seriously endangering the safety of the production system. Meanwhile, the open-stope mining method results in a lower ore recovery rate, with a large amount of ore remaining in the pillars that cannot be effectively recovered, leading to a prominent problem of resource waste.

### *4.2. Transformation Plan and Full Tailing Filling System*

In response to the many problems in open-stope mining, in 2018, Shishudi Gold Mine embarked on a technological breakthrough. The transformation filling method adopts a mechanized upward horizontal-layered filling method, with a stage height of 30 m, a layer height of 3.3 m, a mining-room length of 50–100 m, and a spacing-column width of 35 m. This method first mines the room; it then recovers the mining column; and it then recovers the mining room layer by layer, from top to bottom. After the recovery is completed, a non-

cemented filling and a high-grade rubber surface-layer filling are used, and the remaining spacing columns are no longer recovered (as shown in Figure 7b). During rock drilling, the Boomer K41 hydraulic rock-drilling rig (as shown in Figure 7c) is used, horizontal blasting holes are employed for blasting, and an underground loader is used for ore extraction (as shown in Figure 7d).

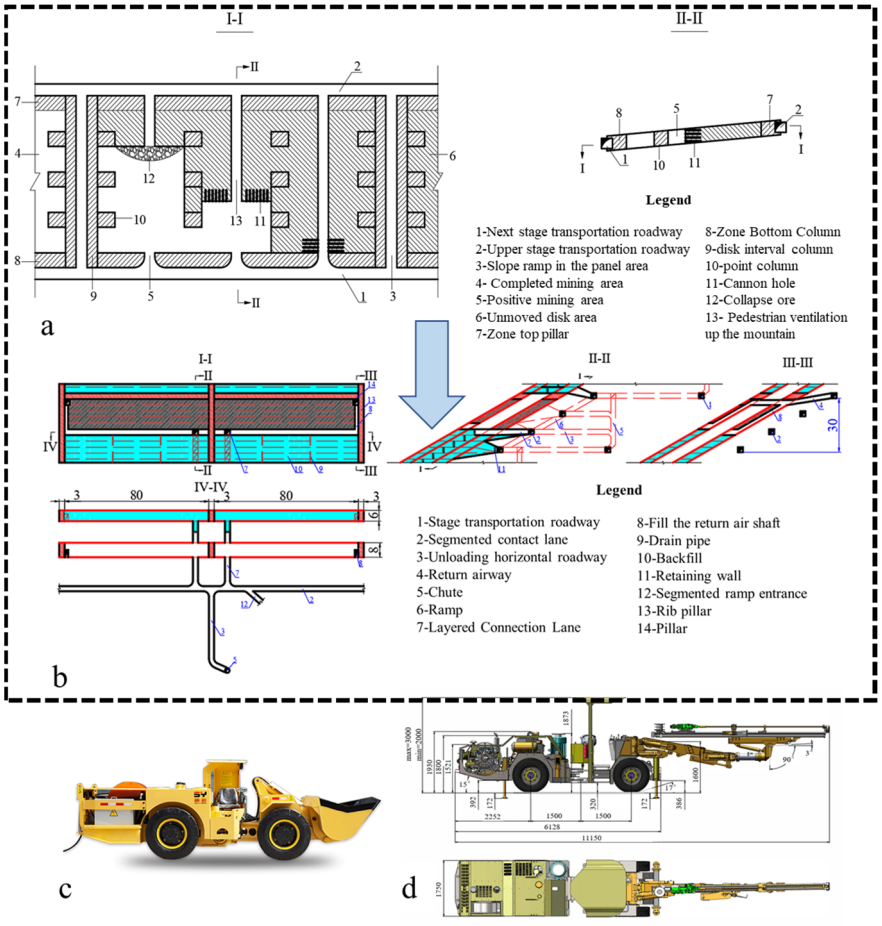



**Figure 7.** Transformation plan and mechanized equipment: (**a**) room and pillar method, (**b**) mechanized upward horizontal-layered filling method, (**c**) load–haul–dump unit, and (**d**) Boomer K41 hydraulic rock-drilling rig.

At the same time, after 3 years of construction, the first low-cost full tailing filling system in China, covering an area of 6840 square meters, was built, with a total investment of RMB 12 million, as shown in Figure 8a,b. Supporting facilities included a filtration room (Figure 8c), vibrating screen room (Figure 8d), tailing storage shed, cement silo, batching silo, etc. This filling system will vibrate and screen the flotation tailings, and use medium-to-fine-grained tailings for filling the underground goaf. Coarse-grained tailings are rich in elements such as iron and silicon, and after dehydration, they will be sold as building materials, achieving zero discharge of tailings on the surface.

The filling system adopts a paste-like filling process with fully dehydrated tailings. By thickening and dehydrating the tailings and mixing them with cement in a certain proportion, a filling slurry with a concentration of 75% is prepared and transported to the underground goaf through a combination of gravity flow and pumping. At the same time, the supporting automation control system monitors real-time parameters such as slurry concentration, flow rate, and pumping pressure to ensure a stable and efficient filling process.

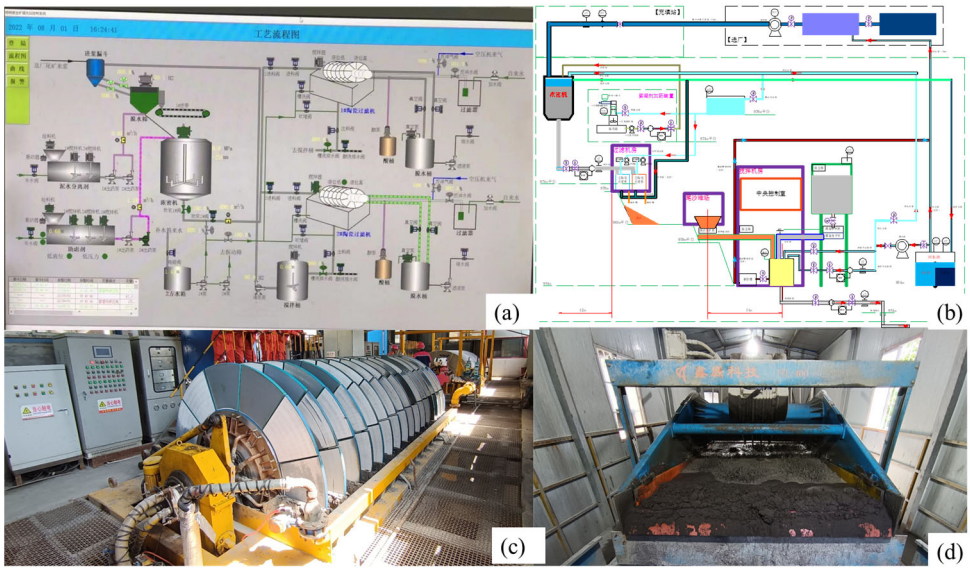



**Figure 8.** Low-cost fully dehydrated paste-like filling system for tailings: (**a**) automatic control system for filling system; (**b**) process flow diagram A for filling system; (**c**) ceramic filter (fine tailing dewatering to moisture content $\leq$ 15%); and (**d**) HFLS-11-2160A series linear high-frequency vibrating screen (separation and 250 μm coarse particles).

### *4.3. Achievements of Green Mine Construction*

After the transformation of the filling method, Shishudi Gold Mine established a full tailing filling system to utilize fine-grained tailings for goaf management and safe recovery of residual mineral resources. Coarse sand was sold to the construction industry, achieving 100% tailing treatment and utilization. The recovery rate of underground ore has increased from 75% to 88.5%, and the recovery amount of residual ore in the middle section has reached 300,000 tons. At the same time, the filling and treatment rate of the goaf has reached 72%, and the ground pressure activity in the deep middle section has been effectively controlled, achieving zero discharge of tailings on the surface and saving CNY 1.545 million in environmental tax annually, approximately USD 220,000.

## 5. Construction of Tailless Mine in the Xingan Fluorite Mine

### *5.1. Mine Overview*

The Xingan Fluorite Mine (see Figure 9) is located in Xingan County, Ji'an City, Jiangxi Province. The mining area has integrated the original Xinheng Fluorite Mine and the original Dachang Fluorite Mine, with a mining depth of and 260.00 m~−206.00 m and a production scale of 200,000 tons per year. The ore body is controlled by the F1 fault structure, with a complex shape, an inclination angle of 64–85°, an average of 78°, and a large variation in thickness, belonging to the unstable thickness type [17].

The quality and value of Xingan fluorite ore resources are excellent, and advanced mining technology and efficient mining equipment should be prioritized to improve resource-extraction efficiency and effectively control ore loss and impoverishment. However, in the actual mining process, the retention method used has a series of safety, economic, and technical issues:

(1) Ore-body applicability of the retention method is poor, and the safety risk is high.
(2) High ore loss rate and serious waste of high-quality resources.
(3) The high ore impoverishment rate restricts the normal production of mines and severely compresses profit margins.
(4) The efficiency of mining equipment is low, and the rate of large ore blocks is high.

(5) The tailing pond is closed, and the mining and filling are unbalanced.

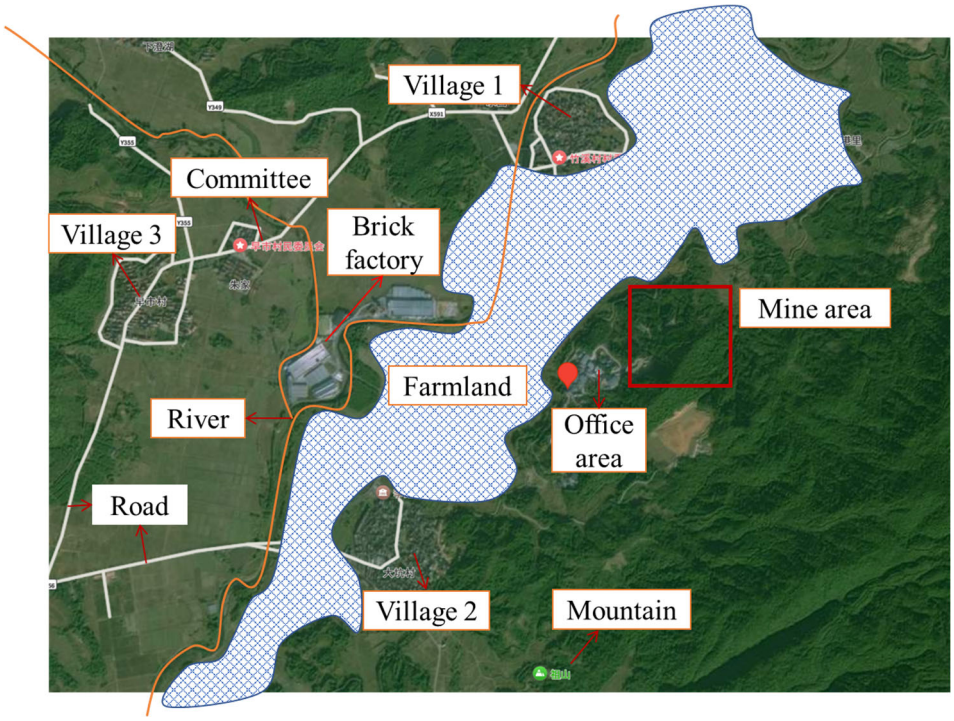



**Figure 9.** Geological map of Xingan mining area.

### *5.2. Transformation Plan and Comprehensive Utilization of Tailings*

Xinheng Mining has innovated the traditional shallow-hole retention mining method into a safer and more efficient two-step mechanized upward horizontal-layered filling mining method, while adopting a vertical layout strategy to strictly control the exposed area and time of the mining site to ensure the safety of the production process. Given the current situation of the third and fourth sections, the stage height is set at 50 m, and a segment is divided every 10 m within the stage. Each segment is further refined into three layers, with the layer height maintained between 3.3 and 3.4 m. In addition, a 3.4 m high top pillar and a 3.3 m high bottom pillar are installed every other stage, as shown in Figure 10.

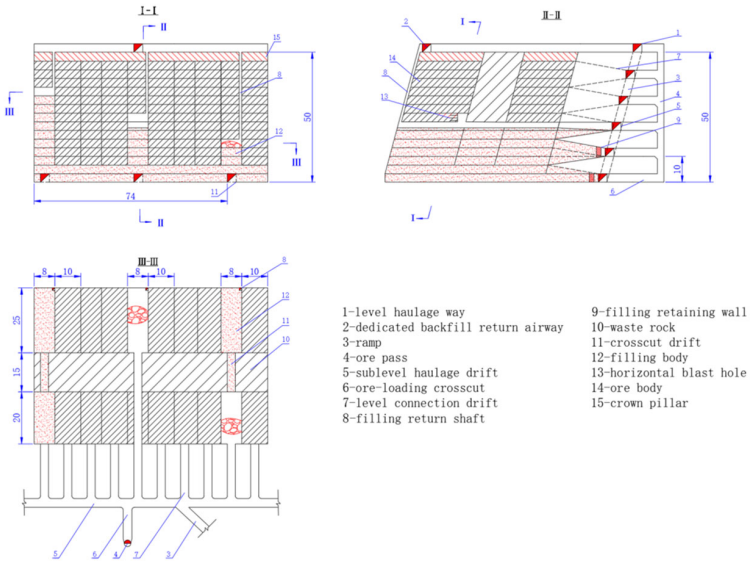



**Figure 10.** Upward horizontal-slicing backfill method.

To address the problem of low efficiency in mining equipment, the company has abandoned traditional drilling and blasting equipment (Figure 11a) and instead introduced supporting mechanized equipment (Figure 11b). Rock-drilling rigs are used for rock-drilling operations, and loaders are responsible for ore extraction, thus achieving an integrated process of high-intensity mining, ore extraction, and filling.

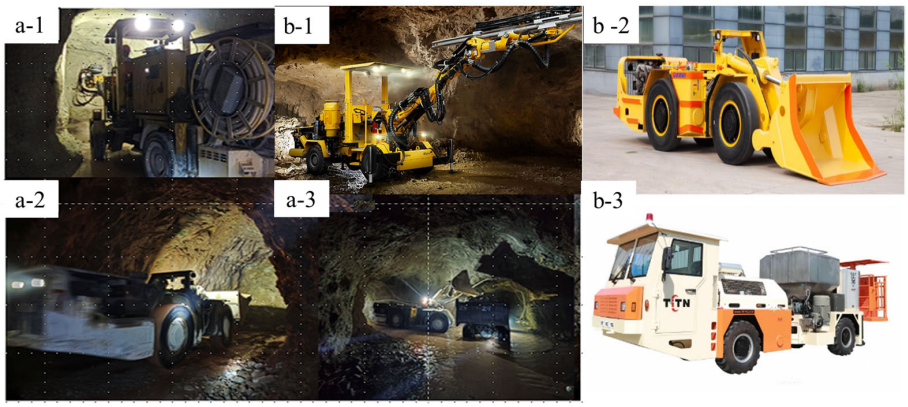



**Figure 11.** (**a**) Equipment configuration for conventional drill-blast and mechanical cutting. (**a-1**): Traditional drilling and rock drilling machine. (**a-2**): Traditional cutting machine. (**a-3**): Traditional Scraper (**b**) Mechanized mining equipment. (**b-1**): Mechanized rock drill. (**b-2**): Mechanized electric loader. (**b-3**): Mechanized medication trolley.

Due to the presence of fluoride in fluorite tailings, groundwater is polluted. In areas where fluorite mining is carried out, mercury pollution may occur due to the inability to properly handle fluorite-processing waste [32]. Considering the harm of fluorite-mine tailings to the environment and human health, as well as the current situation of there being no storage space for tailings on the surface of the Xinheng Mining site, the tailings generated from ore recovery must be fully utilized as resources. The upgrading of the filling method utilizes fine-grained tailings for filling operations (see Figure 12b,c for filling equipment and process flow), achieving partial consumption of tailings. However, due to ore depletion, the filling operation still cannot fully absorb all tailings. A plan for the reuse of tailings has been proposed to address this issue.

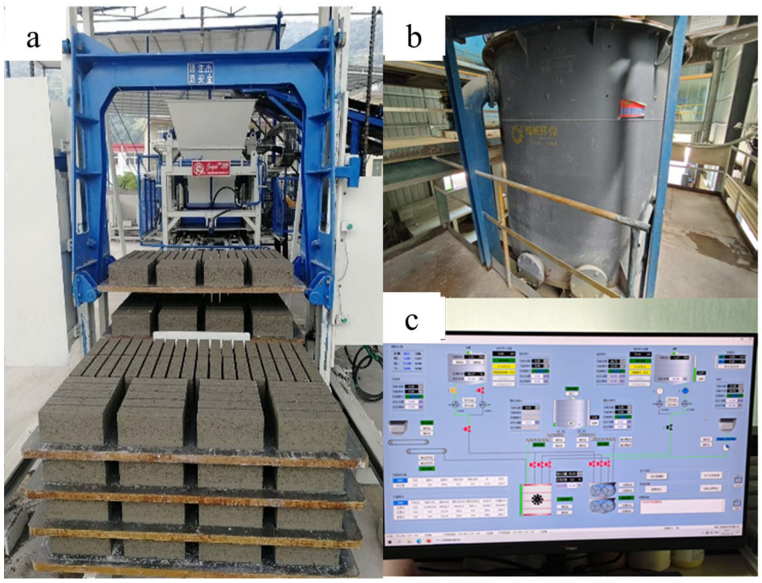



**Figure 12.** Tailing brick-making and mine-filling system diagram. (**a**) Results of tailing brick making. (**b**) Horizontal sand storage. (**c**) Filling-process flow.

Xinheng Mining adopts a graded utilization strategy based on the physical and chemical properties of tailings: fine-grained tailings are used for filling the goaf underground, while coarse-grained tailings are used for preparing environmentally friendly building-material bricks (see Figure 12a). Through the collaborative mode of "filling and brick making", the enterprise not only solves the safety hazards in the goaf and avoids the environmental risks caused by the surface storage of tailings; it also achieves the goal of green mine construction with zero tailing emissions.

### *5.3. Results of Tailless Mine Construction*

Through the implementation of mining-method innovation; equipment mechanization transformation; and comprehensive utilization measures such as "tailing filling and tailing brick making", the Xingan Fluorite Mine has not only achieved safe and efficient mining; it has also significantly improved its ore recovery rate, the loss rate shall be controlled below 5%, the dilution rate shall be less than 9%, and the stope production capacity shall be increased to 60.32 tons per day (t/d). Xingan Fluorite Mine has achieved the environmental goal of zero tailing emissions, and it has also created certain economic benefits through tailing brick making, successfully transforming itself into a tailing-free mine.

## 6. Comprehensive Utilization of Cyanide Tailings from Suichang Gold Mine

### *6.1. Mine Overview*

The Suichang Gold Mine (see Figure 13) is located in Suichang County, Lishui City, Zhejiang Province, and is a mine with a long history of mining. The occurrence conditions of its ore body are complex, with an inclination angle mostly between 45° and 55°, and a large variation in horizontal thickness ranging from 2 to 20 m, with an average thickness of about 4 m. The mining area adopts a joint development method of adit blind vertical shaft.

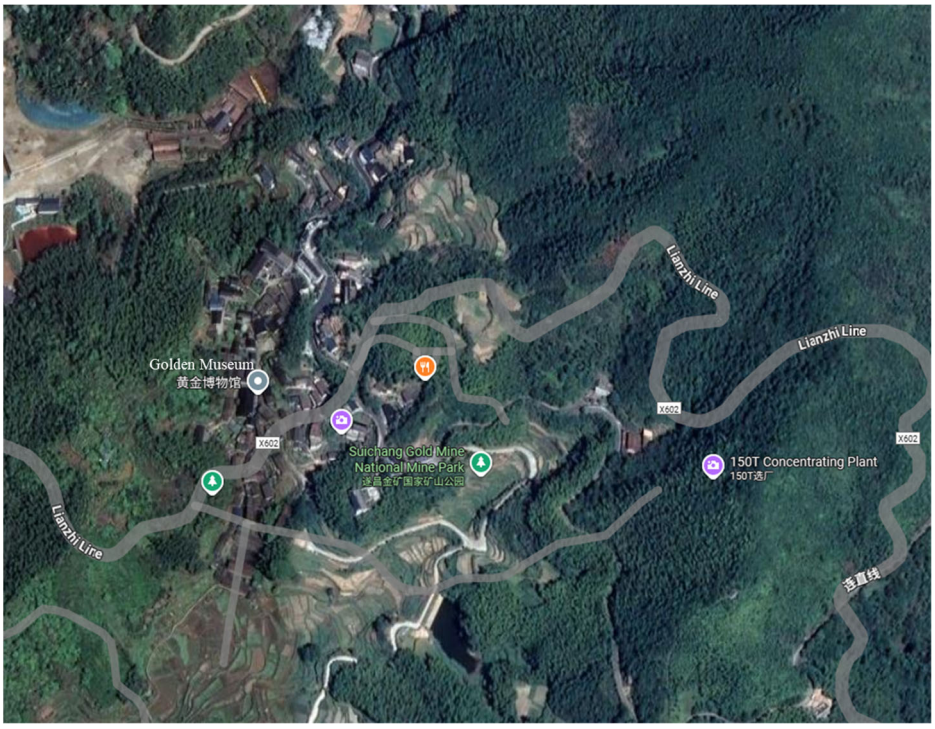



**Figure 13.** Geological map of the Suichang Gold Mine area.

Due to the high ore grade of the Suichang Gold Mine, in order to improve the recovery rate, the retention method of mining first uses concrete to replace the ore pillars, and then it mines the ore room, resulting in a complex mining process and low efficiency [18]. At the

same time, the use of pneumatic rock drills and electric rakes in production results in low mining efficiency, with a production capacity of only 30 t/d. The primary impoverishment rate in mining is as high as 40%, while there is a secondary impoverishment rate of up to 5% [33]. The continuous use of the retention method for mining has generated a large amount of tailings after beneficiation, and these tailings cannot be used to backfill the goaf; in addition, the tailing pond of the Suichang Gold Mine is approaching its design height, leading to the possibility of mine shutdown. Therefore, Suichang Gold Mine plans to use tailings to form filling bodies to treat the existing goaf and the goaf mined by the shallow-hole retention method; transform the existing mining method into an upward horizontal-layered filling method that can utilize tailings; and equip it with mechanized mining equipment to achieve mechanized mining and filling and underground trackless transportation.

### 6.2. Harmless Filling of Cyanide Tailings

Suichang Gold Mine uses the cyanide method to extract gold. After cyanide leaching of gold-containing materials, the resulting cyanide-tailing slurry undergoes solid–liquid separation to form solid cyanide gold slag, mainly including gold cyanide tailings, gold-concentrate cyanide tailings, and heap-leaching cyanide tailings. This type of cyanide gold slag contains a large amount of highly toxic cyanide, which usually accumulates on the surface of tailings or is stored in tailing ponds. This cyanide can easily infiltrate groundwater and soil, or form toxic gases that can escape into the atmosphere, causing serious environmental pollution and even threatening human health [34].

Due to the special hazards of cyanide tailings, the mine has implemented decyanation treatment. Due to the introduction of highly toxic cyanide ions in the cyanide gold-extraction process, it is necessary to reduce the cyanide concentration in the tailing solution to below the national standard of 5 mg/L through decyanation. For this purpose, the Jingjin filter press is selected, and its process flow can achieve continuous operation of "one-filter-press back blowing–back washing/blowing". The key process parameters include a feed pressure of 3 kg, backwashing pressure of 5.2 Mpa, and blowing pressure of 8 kg.

The decyanation process adopts an integrated design of all-mud cyanide washing, and cyanide reduction and dehydration, and it is divided into three stages based on the actual production of the mine:

(1) Poor-liquid gold-washing stage: Use poor liquid to recover residual gold;
(2) Water washing stage: Use water to further remove gold and cyanide;
(3) Sodium metabisulfite cyanide reduction stage: Adding sodium metabisulfite for chemical decyanation effectively reduces cyanide concentration.

The Suichang Gold Mine has transitioned to using a backfill mining method for mining operations, using tailings that have undergone decyanation treatment as cemented backfill aggregates for backfill mining in the mine (see Figure 14b,c). This plan aims to achieve large-scale resource utilization of decyanized tailings, while effectively protecting the surface environment and eliminating safety hazards in goaf areas, thereby ensuring the safety, environmental protection, and economic benefits of the mine.

The particle size of the decyanized tailings after process treatment is relatively fine, resulting in low early strength of the filling material prepared with it as an aggregate. When using it for underground filling, the maintenance period needs to be extended to meet the strength requirements. To address this issue, the Suichang Gold Mine system conducted experiments on the exploration and optimization of the formula for cyanide-removal tailing filling materials. The study ultimately determined a high-performance cemented filling formula: the optimal ratio of high-concentration cemented filling material is a cement-to-sand ratio of 1:4 and a mass concentration of 70%. Meanwhile, the low-

concentration cemented filling material should have a cement-to-sand ratio of 1:15 and a mass concentration of 70%.

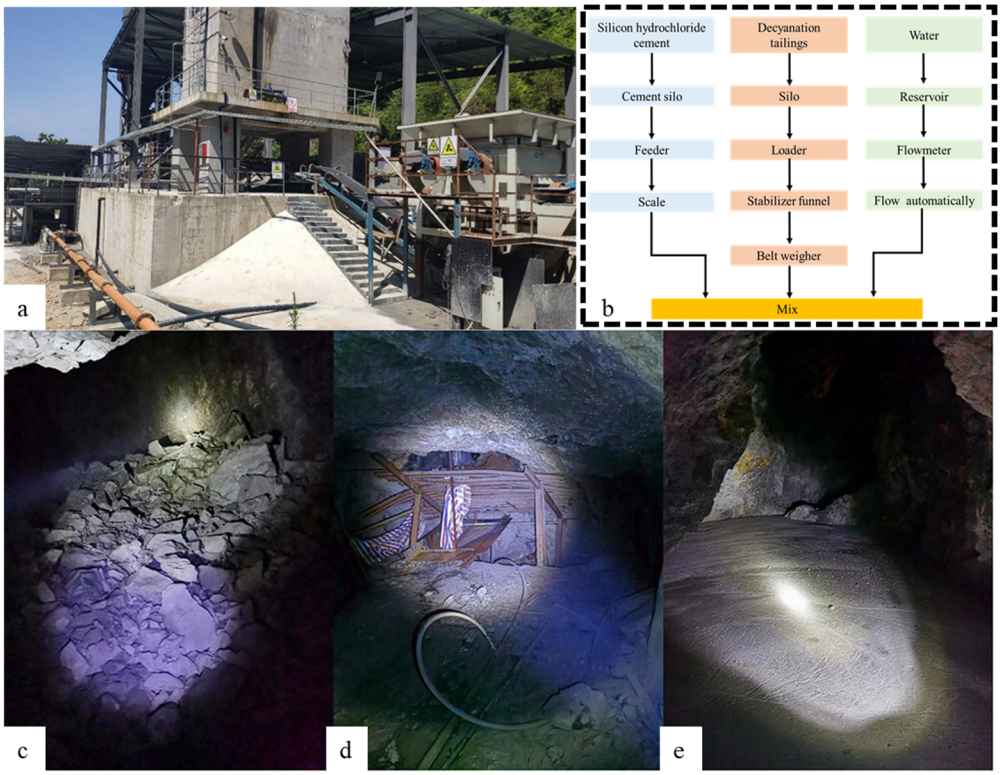



**Figure 14.** Mechanized mining in the Suichang Gold Mine: (**a**) tailing backfill system; (**b**) process flowchart of cyanide-removal tailing backfilling; (**c**) bottom structure of 528 m level; (**d**) the chute of 540 m level; and (**e**) the condition of the baseplate after filling the goaf [35].

### *6.3. Utilization Results of Cyanide-Removal Tailings*

The challenge faced by Suichang Gold Mine in utilizing cyanide tailings is to study the use of decyanized tailings as cemented filling aggregates for mine filling and mining. Through an integrated process of all-mud cyanide tailing washing, cyanide reduction, and dewatering, and experimental research on filling ratios, toxic and harmful cyanide tailings are transformed into usable filling materials, achieving large-scale utilization of decyanized tailings. As shown in Figure 14c, the bottom structure of the 528 middle section is piled up with crushed stones. After the crushed stones are transported through the chute depicted in Figure 14d, filling operations are carried out. The current state of the bottom plate of 540 after filling is shown in Figure 14e. After optimizing operations, the daily production capacity of Suichang Gold Mine increased from 30 t/d to 110 t/d, the impoverishment rate decreased from 40% to 10%, and the comprehensive recovery rate increased from 95% to 98%. This method can effectively protect the surface environment; eliminate safety hazards in mining goaf; and ensure the safety, environmental protection, and economic exploitation of the mine.

## 7. Discussion and Conclusions

After years of practice, China has continuously innovated filling technology, transitioning from traditional dry filling to advanced processes such as full tailing paste filling and high-concentration cemented filling. These new processes have improved the conveying performance of the filling slurry and the strength of the filling body.

A series of advanced pieces of mining equipment are applied in backfill mining. The popularization of mechanized equipment such as rock-drilling rigs, loaders, and anchor rod

rigs has achieved mechanization and automation of mining operations, greatly improving production efficiency. In terms of filling materials, we need to actively explore the use of industrial waste to replace some cement and cementitious materials, thus reducing filling costs, reducing carbon emissions in the cement production process, and achieving the dual goals of comprehensive resource utilization and environmental protection. This study provides technical support for the transformation of solutions for SMMs today.

Through the practices of the abovementioned mines, in this paper, we summarized a set of experiences that can be promoted, from the open-stope method to the filling method. In the process of transformation, it is necessary to fully carry out the preliminary technical demonstration and select appropriate filling processes and mining methods based on the geological conditions of the mine and the occurrence status of the ore body. At the same time, we need to strengthen talent cultivation and technology introduction, and enhance the operational and management capabilities of mining-technology teams for new equipment and processes. We also need to pay attention to the construction and optimization of the filling system to ensure the stability and efficiency of the filling process.

During the transformation process, Shishudi Gold Mine, Xingan Fluorite Mine, and Suichang Gold Mine successfully achieved the transition from the open-stope method to the filling method through reasonable planning and scientific implementation, and they achieved significant benefits, providing valuable reference experience for other mines to be transformed and upgraded.

Many mines have only added filling techniques or changed their mining methods during the transition to filling methods. Although these measures can improve the safety of mining and achieve partial utilization of tailings, they often overlook the chemical properties of tailings, and the utilization rate of tailings has not yet reached 50%, which does not meet the standards for green mine construction.

(1) The three mines fully reflect the "problem-oriented, resource-adapted" principle. For mines with prominent safety risks from goaf accumulation (Shishudi Gold Mine), the priority should be to build a stable and efficient full tailing filling system while improving recovery rate through reasonable filling-method parameters; for mines facing dual pressures of ore-body adaptability and tailing disposal (Xingan Fluorite Mine), the "multi-channel utilization" model, combining filling with downstream industrial chains, can maximize resource value; and for mines with special hazardous tailings (Suichang Gold Mine), the core prerequisite is to develop targeted harmless treatment technology and then match the filling process to achieve environmental protection and economic benefits. However, many mines currently taking part in the transformation only simply add filling technology or change mining methods, ignoring the matching between tailing properties and utilization paths, resulting in a tailing utilization rate of less than 50%, which fails to meet green mine standards. The three typical cases summarized in this paper provide a "classified solution library" for the transformation of SMMs, covering general tailing classified utilization, industrial chain extension, and hazardous tailings' harmless treatment, which can provide more direct and targeted references for different types of mines.

(2) This article summarizes advanced tailing treatment solutions from three typical cases of tailing treatment and utilization, including full tailing filling and utilization, filling and brick making, and tailings' decyanation treatment. It provides a scientific method for the comprehensive utilization of tailings after the transformation of filling methods in other SMMs.

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visualization, Z.L. and Z.D.; writing—original draft, Z.L.; writing—review and editing, S.L., Z.D. and T.Y. All authors have read and agreed to the published version of the manuscript.

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