LAW AND MECHANISM OF SUBSIDENCE REDUCTION OF GROUTING IN MINING GOAF AREA

by

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Similar material simulation experiments on grouting in the goaf, aiming to investigate the damage characteristics of the overburden and the movement behavior both before and after grouting were conducted. The results demonstrate that after grouting the goaf, large fissures, fractures, holes, and other cavities are effectively sealed by the slurry. Compared to untreated goaf, grouting significantly reduces subsidence, with a reduction rate of up to 92.3%. The slurry grouting compacts the residual voids in the goaf, slowing the further subsidence of the collapsed area. It also provides lateral support and a barrier to water infiltration in the residual coal pillars. Additionally, the slurry improves the stress conditions of these coal pillars, transforming the initial unidirectional (or bidirectional) stress state into a bidirectional (or triaxial) stress state. This significantly enhances the support strength and stability of the coal pillars.

Key words: *goaf, grouting, similar simulations, subsidence laws, reduction subsidence mechanism*

Introduction

Grouting within abandoned mining areas is an effective method for managing subsidence, preventing ground settlement, and mitigating surface collapse. Using the Suncun Coal Mine as a case study, Ma *et al*. [1] utilized a variety of techniques to evaluate the efficacy of goaf grouting. This assessment provides valuable insights into determining optimal grouting parameters and selecting suitable water-blocking strategies. To address the complex challenges associated with coal mining beneath structures, Yin [2] utilized a syringe to inject slurry into the specified rock stratum during a physical similarity simulation experiment. This approach effectively replicated the grouting process, enabling an in-depth investigation into the movement patterns of the overburden and the mechanisms of grouting control. Teng *et al*. [3] utilized a similar material simulation methodology to examine the evolution patterns of quarry fractures both before and after grouting. Bai *et al*. [4] addressed the challenges of grouting reinforcement in old goaf areas, particularly those with structures constructed above them. They proposed utilizing a positioning quantitative grouting technique based on a 3-D geological model to effectively mitigate these issues. In geotechnical engineering research, similar material simulation

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experiments are of paramount importance and serve as a critical methodology for investigating grouting control in goaf areas. However, accurately replicating the slurry injection process in goaf regions through physical similar material simulation presents significant challenges. This study presents the development of a specialized grouting simulation apparatus tailored for goaf environments. This advanced device enables the comprehensive emulation of the entire grouting procedure, including slurry preparation, transportation, and injection into the goaf, while preserving the integrity of the model's seal.

Development of goaf grouting simulation experimental system

As depicted in fig. 1, the goaf grouting simulation experimental system comprises three main components: a goaf simulation test unit, a grouting simulation unit, and an information monitoring unit. The Goaf simulation test unit consists of a 2-D similar material simulation test bench and a geotechnical model. The similar material simulation test bench dimensions are 2000 mm in length, 300 mm in width, and 1800 mm in height. The geotechnical model employs a mixture of aggregates, cement, and additives to replicate real geological formations, scaled according to specific similarity ratios for both size and strength. The grouting simulation unit is divided into three primary components: slurry preparation, transportation, and injection, designed to accurately simulate the processes involved in preparing, transporting, and injecting slurry into rock layers during grouting operations. The information monitoring unit integrates strain gauges, pressure sensors, and fracture detection mechanisms to monitor various parameters throughout the simulation.

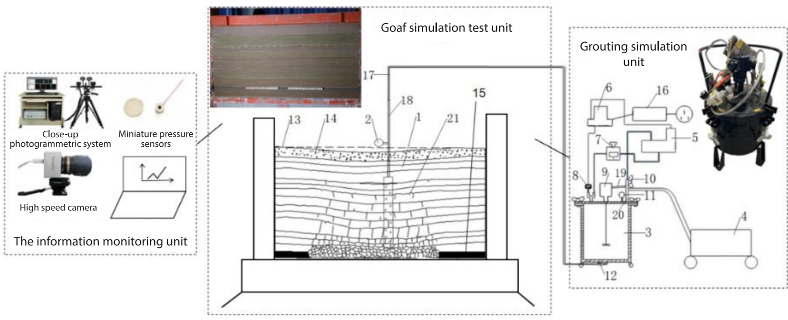

Figure 1. Schematic diagram of the goaf grouting simulation experimental system

Geotechnical similar materials simulation design

This simulation test was conducted based on the Bucun coal mine situated in Jinan, Shandong Province. The main focus of mining operations is the 3 coal seam of the Shanxi Formation, which has a total thickness of 6.0 m and displays a nearly horizontal dip angle. The overlying rock strata are primarily composed of sandstone, shale, and sandy shale. Furthermore, the Quaternary System in this area is relatively thin, with an approximate thickness of 15 m.

This study establishes two comparable material simulation models under uniform geological and mining conditions. In one model, grouting is implemented in the goaf, while the other model remains ungrouted. Both models incorporate fully enclosed mining faces with a mining thickness of 6 m, a mining width of 100 m, an isolation coal pillar width of 20 m, and a mining depth of 170 m. The selected geometric similarity ratio is 1:200. For the geotechnical model, river sand serves as the aggregate, gypsum and calcium carbonate function as binders, and mica powder is employed as the stratification material [5]. A series of observation-lines are strategically positioned along the upper section of the model, with measurement points horizontally spaced at 100 mm intervals. To satisfy the requirements for slurry fluidity, the following material ratios were selected: a water-to-solid ratio of 1:1.5 and a fly ash-to-cement ratio of 9:1. [6] .

Overburden damage characteristics and movement laws before and after grouting of the goaf

Before grouting of the goaf

Upon the complete extraction of the working faces on both sides of the model, the overlying rock strata within the goaf experience substantial collapse and fracturing. Due to the isolating effect of the strip coal pillar, the damaged areas of the two goafs remain independent from each other. The damage zones in the overlying rock strata of both goafs exhibit a trapezoidal profile that is narrow at the top and wide at the bottom, with a development height of approximately 11 cm.

The fracture spaces exhibit diverse dimensions and distinct zonal characteristic in the evolution of damages. Vertical fractures are observed along the boundaries of the damaged region, while separation cracks form at the top. In the central area, a compaction zone of caved rock is present, although micro-fractures and interlayer separation cracks persist.

Figure 2 presents the surface subsidence curve observed prior to grouting in the mined-out area following coal seam extraction. As illustrated, after the completion of coal seam mining, the observation-line indicates the formation of an overall subsidence basin on the surface. The magnitude of subsidence is most significant at the center and diminishes towards the periphery, with the maximum recorded subsidence being 0.437 m.

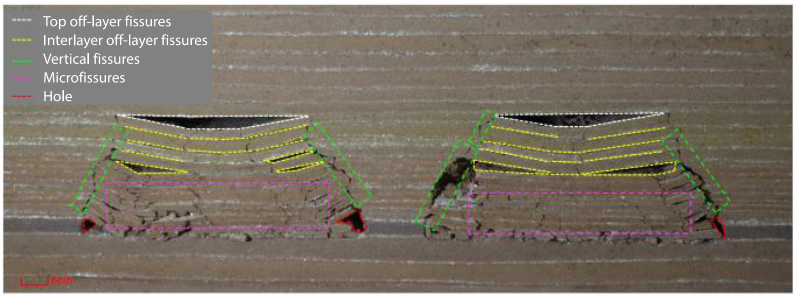

Figure 2. Characteristics of overburden damage after coal seam mining in non-grouting model

After grouting of the goaf

In the goaf, large pores and fissures-including those in the overlying rock strata of the mining damage zone, interstratal layers, vertical fractures on both sides, and openings along the coal pillar edges-are injected with grout, fig. 3. The central compaction region achieves enhanced stabilization due to the grouting pressure originating from the overlying rock strata, which helps mitigate the formation of microfractures. However, due to the relatively narrow dimensions of some channels, the grout cannot fully penetrate and fill these smaller spaces.

Figure 4 depicts the surface subsidence curves before and after grouting in the goaf area. As illustrated, after grouting in the goaf the maximum surface subsidence measures approximately 0.405 m. Compared with the ground settlement before grouting in the goaf, the overall surface subsidence has marginally decreased by about 0.032 m.

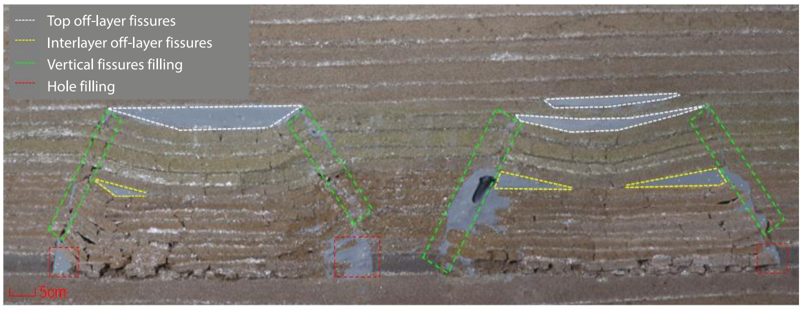

Figure 3. Characteristics of overburden damage after coal seam mining with grouting

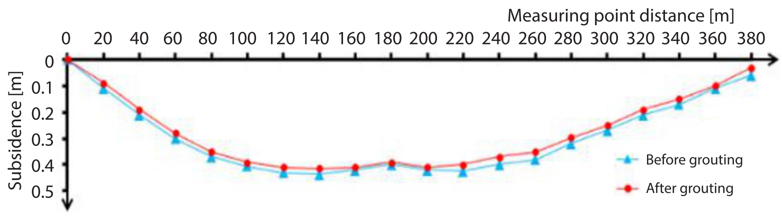

Figure 4. Subsidence curve of A survey line before and after grouting in the goaf

Overburden damage characteristics and movement laws with and without grouting of the goaf

Following the extraction of coal seams, residual coal pillars and void spaces commonly remain in the mined-out areas. These structures are susceptible to destabilization or damage from external factors, while the void spaces may experience further compaction. This study investigates the effects of water injection on the isolation coal pillars within the mined-out area, leading to their saturation and subsequent deterioration. Furthermore, it evaluates the comparative effectiveness of grouting in mitigating subsidence within these areas.

Non-grouting of the goaf

In the absence of grouting in the goaf, prolonged exposure of the isolated coal pillar to water leads to creep-induced destabilization, resulting in a loss of its load-bearing capacity. Consequently, this triggers comprehensive *activation* and movement of the overlying rock strata. The collapse and fracture zones on both sides of the goaf extend upward, reaching heights of up to 15.6 cm.

Following the injection of water into the isolated coal pillar, its structural integrity is significantly compromised, resulting in pronounced *activation* subsidence within the overlying rock strata of the goaf. As a consequence, the overlying rock strata layers spanning both goafs underwent extensive subsidence, leading to the formation of a considerable surface subsidence basin. The maximum surface subsidence was recorded at 0.852 m, with an additional peak subsidence of 0.415 m, as depicted in fig. 5.

Grouting of the goaf

Under the influence of high pressure flow slurry that densely fills most fractures, off-layers, cavities, and other relatively large voids within the goaf, the isolated coal pillar retains its stability even after prolonged water exposure. Following the grouting process, no significant signs of additional collapse are observed in the goaf.

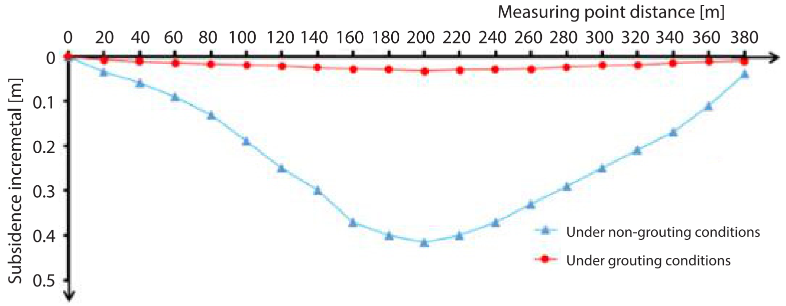

Figure 5. Comparison diagram of subsidence increment after instability of coal pillar

Despite the reduction in coal pillar strength due to water immersion, no significant *activation* movements have been observed on either side of the mined-out area. The maximum increase in surface *activation* subsidence is merely 0.033 m. Compared to the scenarios without grouting in the mined-out area, the implementing grouting can significantly reduce subsidence, achieving a reduction efficiency of up to 92.3%.

Coal pillar and slurry filling body support system subsidence reduction mechanism

The aforementioned similar material model test underscores the pivotal role of grouting in the goaf for mitigating residual deformation in subsidence areas. Specifically, when external factors induce instability in the remaining coal pillars and trigger movement in the overlying rock strata within the goaf, grouting can effectively prevent further significant residual deformation of the collapse area surface. The grouting treatment of the goaf yields several significant outcomes.

Compaction of the goaf by slurry fillers

Due to the presence of numerous voids in the goaf, when these voids are filled with compacted material, they eliminate the space available for the overlying rock strata within the goaf to subside. Upon solidification of the slurry, it provides a supportive function. The filling material, in conjunction with the coal pillars, shares a portion of the load-bearing responsibility of the coal pillars, thereby forming an integrated load-bearing structure characterized by the coal pillar-filling body combination. Then, there is [7]:

$$h\gamma(s+b) = bp_1(x) + sp_2(x) \tag{1}$$

where h is the depth of overlying rock strata mass, γ – the bulk weight of overlying rock strata mass, $p_1(x)$ – the supporting force of coal pillar, $p_2(x)$ – the supporting force of grouting backfill, s – the length of the stope working face, and b – the width of the remaining coal pillar.

Side protection effect of filling body on coal pillar

After grouting the goaf, the surrounding coal pillars undergo expansion due to the compressive forces exerted by the overburden. This results in mutual pressure between the coal pillars within the filling material. Consequently, the filling material exerts lateral stress on the coal pillars, transforming their initial uniaxial or biaxial compression state into a triaxial compression state [7], the triaxial compression and uniaxial compression of coal rock have the relationship:

$$\sigma = \sigma' + K\sigma_a \tag{2}$$

where σ is the triaxial compressive strength of coal pillar, K – the coefficient, σ' – the uniaxial compressive strength of the coal pillar, and σ_a – the lateral stress of grouting body to coal pillar.

According to the aforementioned formula, the bearing capacity of the coal pillar increases, when the goaf is grouted and not grouted, is given:

$$\Delta\sigma = \frac{K\sigma_a}{H\left[0.64 + 0.36\left(\frac{a}{H}\right)\right]^{1.4}} \tag{3}$$

where a is the coal pillar width and H – the coal pillar height.

Following grouting in the goaf, the integrated load-bearing structure formed by the coal pillar and the filling body, along with the lateral forces exerted by the filling material, significantly enhances the load-bearing capacity of the coal pillar. This suggests that through the optimization of grouting techniques and the selection of suitable materials, the self-supporting strength and lateral pressure of the filling body can be improved, thereby effectively increasing the load-bearing capacity of the coal pillar. Additionally, the dimensions of the coal pillar, including its width and height, are critical factors influencing the enhancement of load-bearing capacity. Therefore, in practical engineering design, the optimal determination of coal pillar dimensions and grouting parameters is essential for maximizing the effectiveness of subsidence reduction.

Conclusion

Two distinct similar material simulation models were developed to simulate conditions within a goaf. These models facilitated a comparative analysis of the characteristics and movement patterns of the overlying rock strata before and after grouting. The results demonstrated that the overburden above the goaf exhibited a slight uplift compared to its pre-grouting state. When external forces impacted the isolated coal pillars, the ungrouted residual coal pillars within the goaf became unstable, leading to significant reactivation of both the overlying rock strata and the ground surface. However, after grouting, there was minimal residual settlement, with the rate of sedimentation reduction reaching up to 92.3%. The grout formed solidified bodies that provided support and controlled the settlement of the overlying rock strata layers in the voided area, thereby significantly reducing the residual settlement of the collapsed area surface. For the residual coal pillars, the grout filled the voids within the goaf, creating a supportive structure. This action reduced stress concentration on the coal pillars, preventing collapse and subsidence within the goaf, and substantially enhancing the overall support strength and stability.

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Nomenclature

h – depth of overlying rock strata mass, [m]
p – supporting force, [Pa]
s – length of stope working face, [m]

Greek symbol

γ – bulk weight of overlying rock strata mass, [Nm^{-3}]

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