

Article

Stress Distribution and Evolution Characteristics of Hard–Soft Interbedded Floor Strata Subjected to Coal Pillar Loading

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Abstract

To reveal the stress transfer mechanism of overlying coal pillar loads in hard–soft composite floor strata during close-distance coal seam mining, this study comprehensively employed theoretical analysis, similar material simulation, and numerical simulation to systematically investigate the floor stress distribution characteristics under different pillar widths and rock combinations. This study focuses on the instantaneous elastic response of hard–soft composite floor strata under static coal pillar loading, providing a theoretical foundation for pillar design and roadway layout in multi-seam mining. The limitations and future research directions are also discussed. First, based on the elastic layered half-space theory, mechanical models for stress transfer in the floor under narrow coal pillars (unimodal load) and wide coal pillars (bimodal load) were established. Analytical expressions of stress at any point in the floor were derived, and the influence laws of key parameters, including Poisson's ratio, interlayer spacing ratio, and shear modulus ratio, were clarified. Second, two typical physical models, namely “hard–soft–hard” and “soft–hard–soft”, were constructed. Experimental results revealed that the weak interlayer exhibits a significant “barrier effect” in the hard–soft–hard combination, causing the stress contours to contract in a “bulb-like” shape; whereas the hard rock layer plays a “bearing effect” in the soft–hard–soft combination, leading to stress contours diffusing in a “gourd-like” shape. Furthermore, numerical simulation revealed the controlling mechanisms of rock combination and thickness ratio: the hard rock layer dominates stress concentration, with the peak stress zone evolving from an “inverted water droplet” shape to a “platform” shape as the thickness increases; the soft rock layer governs stress diffusion and buffering. The depth of the plastic zone significantly decreases with increasing hard rock thickness ratio, achieving a reduction of 44.4%.

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1. Introduction

As shallow coal resources in China are gradually depleted, mining activities are progressively shifting to deeper coal seams with complex geological conditions [1,2]. In the mining of close-distance coal seam groups, the stability of overlying coal pillars and the mechanical response of the underlying floor strata are key issues for ensuring safe and

efficient extraction [3,4]. The reasonable design of coal pillar width directly determines the long-term stability of roadway surrounding rock, while the mechanical behavior of the pillar is significantly constrained by the mechanical properties and structural characteristics of the underlying floor strata [5,6].

In practice, the coal seam floor is typically composed of hard rocks (e.g., sandstone) and soft rocks (e.g., mudstone) with significantly different strength, stiffness, and deformation characteristics, which are alternately deposited to form a typical “hard–soft interbedded” structure. This heterogeneous and discontinuous layered combination significantly alters the stress transfer path and stress distribution pattern induced by the overlying coal pillar load [7,8]. Traditional coal pillar–floor mechanical models based on the assumption of a homogeneous, isotropic continuum have obvious limitations when applied to such complex layered media [9,10]. Under the abutment stress of the coal pillar, stress concentration tends to occur at the interfaces between hard and soft layers, inducing collaborative deformation or even overall shear failure of the composite floor, which in turn leads to floor heave and large deformation of roadways [11–13].

Extensive research has been conducted on the distribution of abutment stress within coal pillars and its propagation into the floor. The two-zone constraint theory proposed by Wilson [14,15] and the “pressure bulb” theory based on the Boussinesq solution [16–18] are the main theoretical foundations. Peng and Chandra [19] showed that the influence depth of a coal pillar is approximately four times its width. However, most of these studies simplify the floor as a homogeneous elastic half-space and seldom systematically consider the “interface effect” caused by the alternating arrangement of hard and soft layers.

In recent years, the optimization of coal pillar width and its influence on the stability of surrounding rock in gob-side entry driving have also received increasing attention. Chang et al. [20] systematically investigated the determination of narrow coal pillar width and the surrounding rock support technology in gob-side entry driving using limit equilibrium theory and numerical simulation, highlighting the critical role of pillar width in controlling roadway stability. Li et al. [21] further studied the evolution of internal and external stress fields under hard roof conditions and proposed an optimal coal pillar width of 10 m based on the distribution characteristics of stress and plastic zones. However, these studies primarily focused on the coal pillar itself and the immediate roof strata, with less emphasis on the layered structure of the floor and its stress transfer mechanism under coal pillar loading. In particular, the combined effect of hard–soft interbedded floor strata and different coal pillar load patterns (unimodal vs. bimodal) on floor stress distribution has not been systematically addressed. Wessels and Malan [22] developed a limit equilibrium model to simulate the time-dependent scaling of hard rock pillars, providing insights into long-term pillar stability. Similarly, Eremin et al. [23] conducted a numerical analysis of pillar stability in longwall mining of inclined coal seams, which is directly relevant to the stress conditions investigated in our study.

Therefore, this study aims to (1) establish stress transfer mechanical models for hard–soft composite floors under narrow coal pillars (unimodal load) and wide coal pillars (bimodal load) based on the elastic layered half-space theory; (2) reveal the stress distribution characteristics of two typical floor combinations, namely “hard–soft–hard” and “soft–hard–soft”, through similar material simulation tests; and (3) investigate the evolution laws of vertical stress, horizontal stress, and plastic zone in the floor under different rock combinations and hard rock thickness ratios using FLAC3D numerical simulation. The research findings can provide a theoretical basis for determining reasonable coal pillar sizes in multi-seam mining and optimizing the layout of roadways in lower coal seams.

Despite the progress reviewed above, several critical knowledge gaps remain unaddressed. First, most existing analytical models treat the floor as a homogeneous elastic half-space, neglecting the layered structure and interfacial effects that fundamentally alter

stress transfer paths in hard–soft interbedded strata. Second, the combined influence of coal pillar width (which determines unimodal vs. bimodal load patterns) and the specific hard–soft sequence on floor stress distribution has not been systematically quantified. Third, the quantitative relationship between hard rock thickness ratio and plastic zone depth remains unclear, limiting the rational design of floor protection in multi-seam mining.

To fill these gaps, the present work contributes the following novelties (1) an analytical stress transfer model that explicitly incorporates interface depth, Poisson’s ratio, and shear modulus ratio for both narrow (unimodal) and wide (bimodal) pillar loads; (2) systematic experimental validation of the “barrier effect” (hard–soft–hard) and “bearing effect” (soft–hard–soft) using similar material simulation; and (3) quantitative identification of the critical interface depth ($h_1 = D$) and the thickness-ratio-dependent evolution of the plastic zone (44.4% reduction from 1:5 to 1:1). These contributions provide both theoretical guidance and practical criteria for pillar design and roadway layout in multi-seam mining. It should be noted that the present study focuses on static loading conditions and elastic responses; the limitations and corresponding future research directions are discussed in Section 4.4.

2. Materials and Methods

2.1. Theoretical Model of Stress Transfer in Hard–Soft Composite Floor

2.1.1. Load Distribution Pattern of Coal Pillar

As shown in Figure 1a, the distribution of abutment pressure above a coal pillar is significantly controlled by the pillar width. When the pillar width is relatively small (narrow coal pillar), the plastic zones induced by the goafs on both sides merge in the middle of the pillar, and the vertical stress exhibits a unimodal distribution with the peak located at the central axis of the pillar. As shown in Figure 1b, when the pillar width is relatively large (wide coal pillar), plastic zones develop at both edges of the pillar, while an elastic core remains in the middle. The vertical stress then exhibits a bimodal distribution, with two peaks located near the two edges of the pillar.

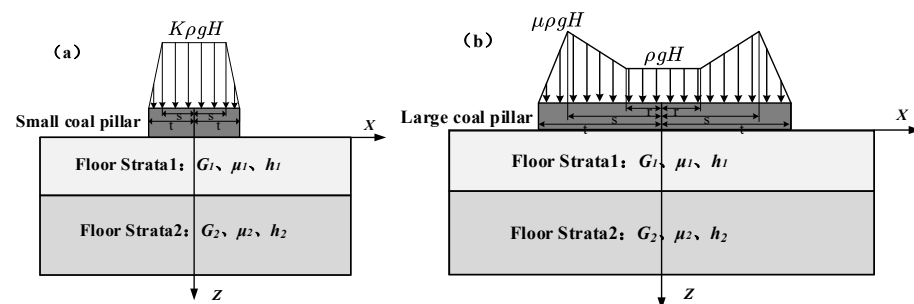


Figure 1. Stress transfer mechanical model of hard–soft composite floor under coal pillar loading: (a) small coal pillar condition and (b) large coal pillar condition.

The two typical load functions are as follows:

Narrow coal pillar (unimodal load):

$$q_1(x) = \begin{cases} \frac{K\rho gH}{t-s}(t+x) & -t \leq x < -s \\ K\rho gH & -s \leq x < s \\ \frac{K\rho gH}{t-s}(t-x) & x \geq t \end{cases} \quad (1)$$

Wide coal pillar (bimodal load):

$$q_2(x) = \begin{cases} \frac{t+x}{t-r} K \rho g H & -t \leq x < -r \\ \frac{\mu(r+x) - K(s+x)}{r-s} \rho g H & -r \leq x < -s \\ \mu \rho g H & -s \leq x \leq s \\ \frac{\mu(r-x) + K(x-s)}{r-s} \rho g H & s < x \leq r \\ \frac{t-x}{t-n} K \rho g H & r < x \leq t \end{cases} \quad (2)$$

where, under narrow coal pillar conditions, t is the half-width of the coal pillar, s is the plastic zone width, K and μ are different coal pillar load coefficients, and $\rho g h$ is the in-situ stress; under wide coal pillar conditions, t is the half-width of the coal pillar, and r is the half-width of the elastic core zone.

2.1.2. Analytical Solution of Stress in Layered Floor

The floor is regarded as an elastic layered half-space consisting of two layers (upper layer: thickness h_1 , Poisson's ratio μ_1 , shear modulus G_1 ; lower layer: thickness h_2 , Poisson's ratio μ_2 , shear modulus G_2), with perfect bonding at the interface. Under an arbitrary distributed load $q(x)$ acting on the surface, the vertical stress at any point (x, z) within the floor can be obtained by the following convolution integral:

$$\sigma(x, z) = \int_{-\infty}^{\infty} q(\xi) F(x - \xi, z) d\xi \quad (3)$$

where G is the Green's function for the layered half-space. Using the Fourier transform and the stiffness matrix method, taking the narrow coal pillar as an example, the vertical stress expressions in each layer can be derived.

Upper layer (above the interface):

$$F_z^1(x, z) = -\frac{1}{2\pi(1+k_1)} \left\{ \begin{aligned} & \frac{32 \frac{G_1-G_2}{k_1 G_2 + G_1} h_1 (h_1 - z)^3 z}{[x^2 + (h_1 - z)^2]^3} \\ & + \frac{4(h_1 + z)^3}{[x^2 + (h_1 + z)^2]^2} + \frac{(h_1 + z)(k_1 - 1)}{x^2 + (h_1 + z)^2} \\ & - \frac{4 \frac{G_1-G_2}{k_1 G_2 + G_1} (h_1 - z) [h_1(h_1 + 5z) - z(h_1 - z)k_1]}{[x^2 + (h_1 - z)^2]^2} \\ & + \frac{2 \frac{G_1-G_2}{k_1 G_2 + G_1} h_1 - \frac{G_1-G_2}{k_1 G_2 + G_1} (h_1 - z) - \frac{G_1-G_2}{k_1 G_2 + G_1} (h_1 + z)k_1}{x^2 + (h_1 - z)^2} \end{aligned} \right\} \quad (4)$$

Lower layer (below the interface):

$$\begin{aligned}
F_z^2(x, z) = & -\frac{1}{2\pi(1+k_1)} \left\{ \frac{32 \frac{G_1-G_2}{k_1 G_2+G_1} h_2 (h_2-z)^3 z}{[x^2+(h_2-z)^2]^3} \right. \\
& + \frac{4(h_2+z)^3}{[x^2+(h_2+z)^2]^2} + \frac{(h_2+z)(k_1-1)}{x^2+(h_2+z)^2} \\
& - \frac{4 \frac{G_1-G_2}{k_1 G_2+G_1} (h_2-z) [h_2(h_2+5z) - z(h_2-z)k_1]}{[x^2+(h_2-z)^2]^2} \\
& \left. + \frac{2 \frac{G_1-G_2}{k_2 G_2+G_1} h_2 - \frac{G_1-G_2}{k_1 G_2+G_1} (h_2-z) - \frac{G_1-G_2}{k_1 G_2+G_1} (h_2+z)k_1}{x^2+(h_2-z)^2} \right\} \quad (5)
\end{aligned}$$

where $k_1 = 3 - 4\nu_1$ and $k_2 = 3 - 4\nu_2$; ν_1 and ν_2 are the Poisson's ratios of the rock layers on both sides of the interface, respectively; and G_1 and G_2 are the shear moduli of the rock layers on both sides of the interface, respectively.

Substituting the above formulas into the previously derived Equation (3), the vertical stress expression at any point in any layer of the layered floor structure under a narrow coal pillar can be obtained as follows:

$$\begin{aligned}
\sigma_z(x, z) = & \int_{-s}^s \frac{q_1(x)}{s-t} (t+\xi) F_z^n(x-\xi, z) d\xi \\
& + \int_{-s}^s q_1(x) F_z^n(x-\xi, z) d\xi + \int_s^t \frac{q_1(x)}{t-s} (t-\xi) F_z^n(x-\xi, z) d\xi \quad (6)
\end{aligned}$$

2.2. Similar Material Simulation Test

2.2.1. Model Design

A plane strain similarity model was adopted with a geometric similarity ratio of 1:50. The model frame was a steel structure (manufacturer: Jinan Kuangyan Testing Instrument Co., Ltd., Jinan, Shandong, China) with internal dimensions of 1.2 m × 0.2 m × 1.0 m. Two typical floor combinations were designed: (1) "sandstone–mudstone–sandstone" (hard–soft–hard, abbreviated as H–S–H); and (2) "mudstone–sandstone–mudstone" (soft–hard–soft, abbreviated as S–H–S). The mass ratios (sand:calcium carbonate:gypsum) of the similar materials were 7:5:5 for sandstone and 8:3:7 for mudstone, with bulk densities of 1.8 g/cm³ and 1.7 g/cm³, respectively. A unimodal load was applied on top of the model through a hydraulic jack and a specially shaped non-uniform loading block (manufacturer: Xi'an LETRY Material Testing Technology Co., Ltd., Xi'an, Shaanxi, China) to simulate the load distribution under narrow coal pillar conditions. Strain and load data during the experiment were recorded in real time by a data acquisition system (manufacturer: Jinan Hengle Xingke Instrument Co., Ltd., Jinan, Shandong, China).

It should be noted that the similar materials used in this study were prepared with isotropic proportions (sand:calcium carbonate:gypsum) for each individual layer, following standard practice in similar material simulation. However, the overall floor model—comprising alternating sandstone and mudstone layers—exhibits transverse isotropy as a layered composite, which effectively replicates the mechanical behavior of sedimentary strata. This layered configuration, rather than the intrinsic anisotropy of the constituent materials, is the primary source of the observed interface effects (stress contraction/expansion at layer boundaries). This approach is consistent with established methodologies in physical modeling of stratified rock masses.

The model was constructed layer by layer from bottom to top. For each layer, the pre-mixed materials (sand, calcium carbonate, and gypsum in the proportions listed in Table 1) were dry-mixed thoroughly, then water was added and the mixture was stirred to a uniform consistency. The wet mixture was placed into the model frame and compacted evenly with a flat rammer to the designed thickness, ensuring that the actual bulk density matched the design value (1.8 g/cm^3 for sandstone and 1.7 g/cm^3 for mudstone). No additional adhesive was applied between layers; the interlayer contact was achieved through physical compaction and the natural cohesion of the material itself. This approach replicates the natural bedding contacts in sedimentary strata, where adjacent layers are bonded by compaction rather than artificial cementation. After all layers were completed, the model was cured indoors for 7–10 days until fully dried and solidified.

Table 1. Similar material simulation proportionality parameters.

Layer No.	Lithology	Thickness	Cumulative Thickness	Bulk Density	Proportion	Material Consumption/kg				
		/cm	/cm	/ $\text{g}\cdot\text{cm}^{-3}$		Total Weight	Sand	CaCO_3	Gypsum	Water
Coal	Coal	10	70	1.7	864	37.4	29.92	2.244	1.496	3.74
F1	Sandstone	30	60	1.8	755	178.2	124.74	8.91	8.91	35.64
F2	Mudstone	20	30	1.7	837	74.8	59.84	2.244	5.236	7.48
F3	Sandstone	10	10	1.7	755	59.4	41.58	2.97	2.97	11.88
Total		70				349.8	256.08	16.368	18.612	58.74

2.2.2. Sensor Layout and Data Acquisition

A total of 20 miniature soil pressure cells were arranged in four rows within the model floor. In the vertical direction (depth), the measuring points were located at 15, 30, 45, and 55 cm. In the horizontal direction, the measuring points were arranged symmetrically about the central axis of the coal pillar at positions of -10 , -5 , 0 , 5 , and 10 cm. The layout of the measurement points is shown in Figure 2. Data acquisition was performed using a DH3815 static stress testing system. Photographs of the test bench and the completed models for the two typical floor combinations (hard-soft-hard and soft-hard-soft) are presented in Figure 3.

The vertical stress contour maps were generated from the 20 discrete measurement points using the ordinary Kriging interpolation method in Surfer software (Surfer 31.2.277). This method provides smooth and statistically robust contouring from sparse point data. The interpolation grid resolution was set to $0.5 \text{ cm} \times 0.5 \text{ cm}$. The contour maps were validated against the raw point data, with deviations within 5%.

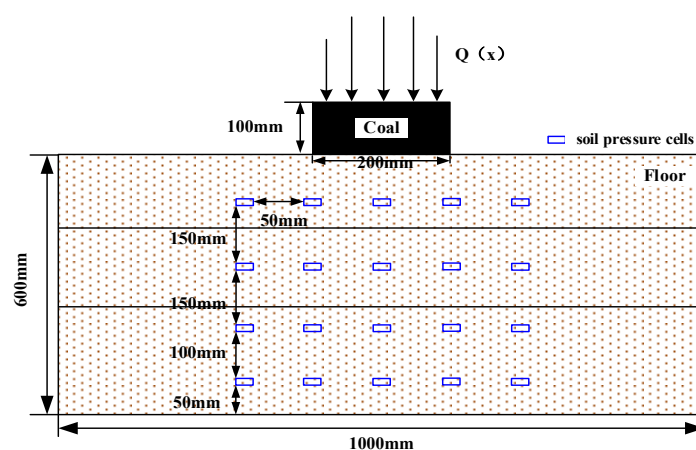


Figure 2. Measurement point layout of similar material simulation model.



Figure 3. Test bench and specific test models.

2.3. Numerical Simulation Scheme

The numerical simulation was performed using FLAC^{3D} 6.0 software. The numerical model has dimensions of 200 m in length (x-direction), 1 m in width (y-direction, to simulate plane strain conditions), and 215 m in height (z-direction). The model consists of approximately 10,000 hexahedral elements with a uniform grid size of 2 m × 2 m. The Mohr–Coulomb failure criterion was adopted with non-associated flow rules for shear failure and associated flow rules for tensile failure. Boundary conditions were applied as follows: the bottom boundary ($z = 0$) was fixed in all directions; the lateral boundaries ($x = 0$, $x = 200$, $y = 0$, and $y = 1$) were restrained in their respective normal directions; and the top surface ($z = 215$) was subjected to a uniformly distributed vertical stress of 8.75 MPa (equivalent to a 350 m overburden with an average unit weight of 25 kN/m³). The Mohr–Coulomb failure criterion was adopted. Two coal pillar widths were considered: a small coal pillar (10 m) and a large coal pillar (40 m). Six floor rock strata combinations were designed: (i) single hard rock (sandstone); (ii) single soft rock (mudstone); (iii) hard over soft; (iv) soft over hard; (v) three-layer hard–soft–hard; (vi) three-layer soft–hard–soft. Furthermore, to investigate the influence of thickness ratio, based on the hard-over-soft sequence, the total thickness of the floor strata was fixed at 90 m, and the thickness of the sandstone layer was varied (15, 18, 22.5, 30, 50 m), corresponding to sandstone/mudstone thickness ratios of 1:5, 1:4, 1:3, 1:2, and 1:1, respectively. The rock mechanical parameters are listed in Table 2.

It is important to clarify the interpretation of the plastic zone indicators in FLAC^{3D}. In this study, the plastic zone refers exclusively to zones that are currently in a yielded state at the end of the calculation, i.e., zones with shear-n or tension-n flags. Zones with shear-p or tension-p flags (which indicate that yielding occurred temporarily during the solution process but the zone has since unloaded) are excluded from the plastic zone statistics. This distinction ensures that our plastic zone analysis reflects the final stable state of the model rather than transient yielding during iteration.

Table 2. General rock mechanics parameters table.

Lithology	Density/kg·m ^{−3}	Elastic Modulus/GPa	Poisson's Ratio	Cohesion/ MPa	Internal Friction Angle/°	Tensile Strength/MPa
Mudstone	2070	0.78	0.28	3.41	40	0.86
Sandstone	2450	5.4	0.24	4.5	30	2.2

3. Results

3.1. Stress Distribution Predicted by the Theoretical Model

Based on the analytical solutions derived in Section 2.1, the vertical stress distributions under narrow (10 m) and wide (40 m) coal pillars were calculated for different hard–soft floor combinations. The lateral half width h^* (defined as the horizontal half width where $\sigma_z \geq 1$ MPa) and the shape of the stress contours were systematically analyzed.

3.1.1. Narrow Coal Pillar (Unimodal Load)

As shown in Figure 4, for a homogeneous sandstone floor, the stress contours exhibit a classic “spindle-shaped” symmetrical distribution with $h^* = 9.0$ m. In the hard-over-soft (sandstone–mudstone) combination, the stress contours contract sharply toward the pillar centerline at the interface, forming a “bulb-shaped” distribution. As the interface depth h_1 increases, the lateral half-width first slightly exceeds that of the homogeneous case ($h^* = 10.2$ m at $h_1 = 5$ m) and then monotonically decreases to $h^* = 5.5$ m at $h_1 = 30$ m. A critical interface depth exists at $h_1 = D$ (10 m). The high-stress core remains inside the hard rock layer and migrates downward as the hard rock thickness increases.

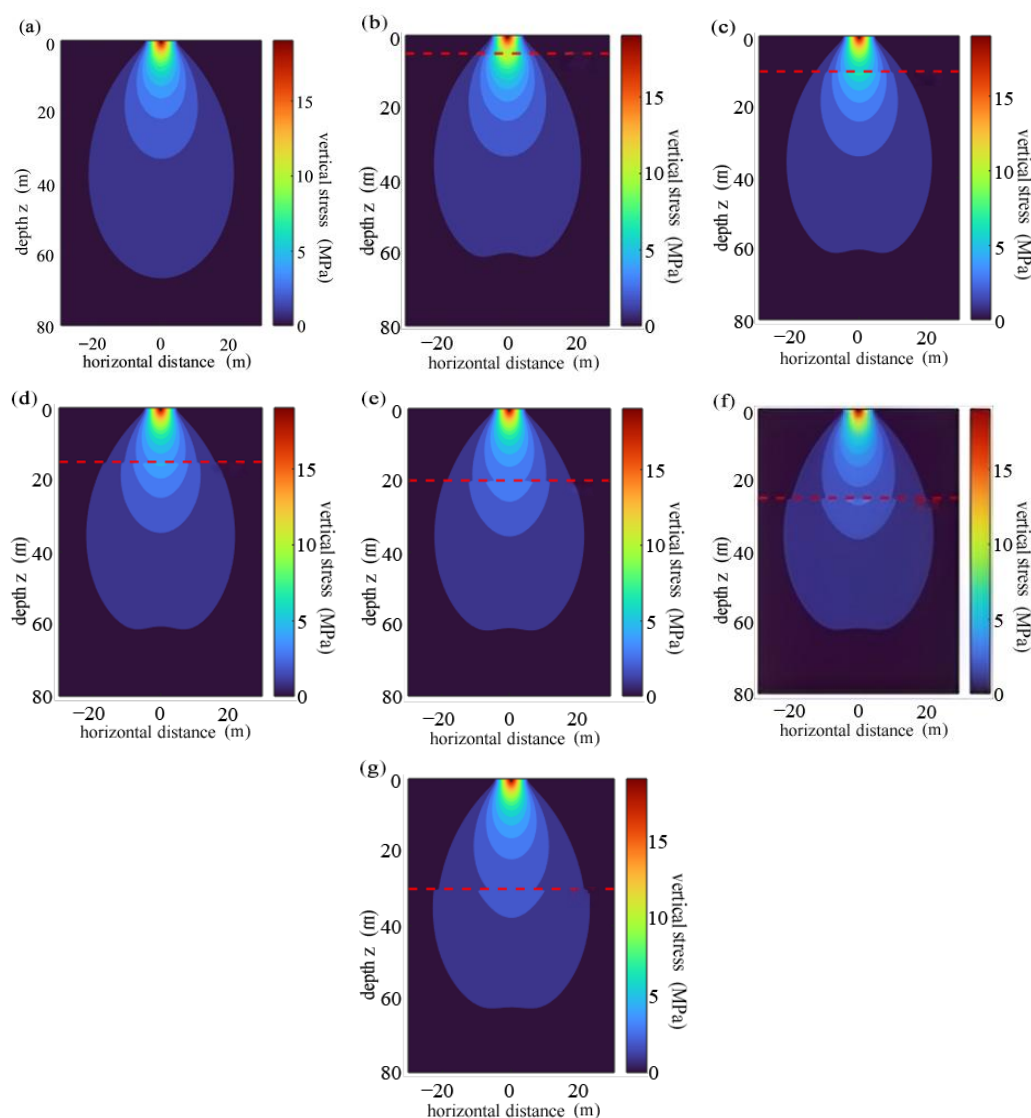


Figure 4. Vertical stress distribution in the hard-above-soft floor: (a) homogeneous floor; (b–g) interface depths of 5 m, 10 m, 15 m, 20 m, 25 m, and 30 m, respectively.

As shown in Figure 5, In the soft-over-hard (mudstone-sandstone) combination, the stress contours expand outward at the interface, forming a “gourd-shaped” distribution. The lateral half-width increases monotonically with h_1 and tends to stabilize at $h^* \approx 12.0$ m when $h_1 = 30$ m. The high-stress core shifts into the hard rock layer below the interface, with a reduced peak but a much wider horizontal extent.

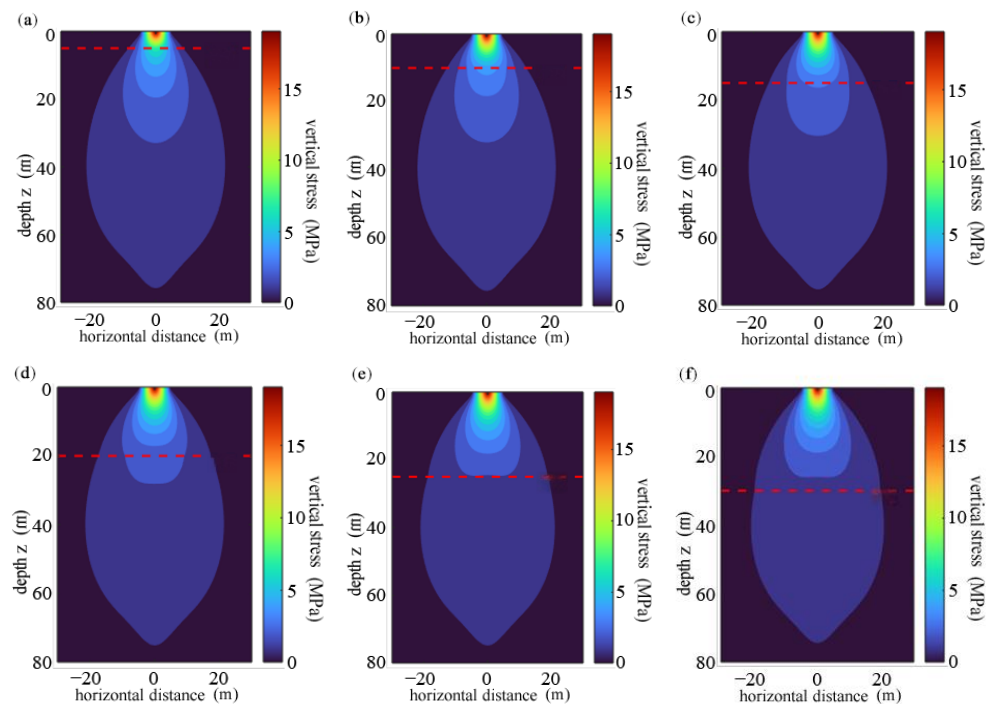
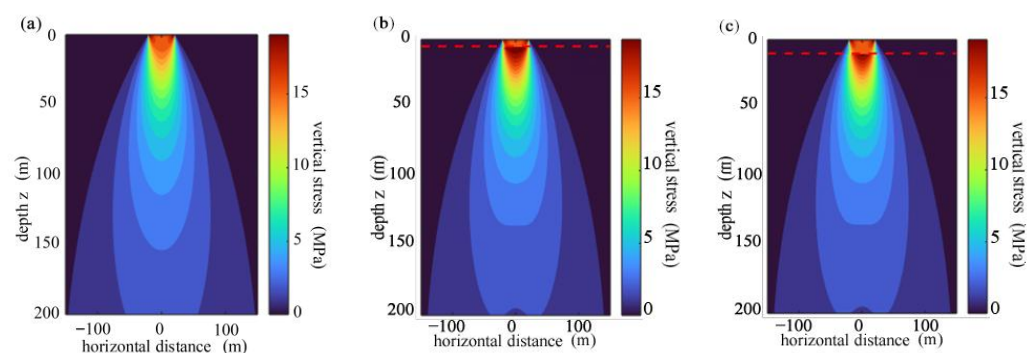


Figure 5. Vertical stress distribution in the soft-above-hard floor: (a–f) interface depths of 5 m, 10 m, 15 m, 20 m, 25 m, and 30 m, respectively.

3.1.2. Wide Coal Pillar (Bimodal Load)

As shown in Figure 6, for a homogeneous sandstone floor under a 40 m wide pillar, the stress contours show a “double-nucleus butterfly-shaped” distribution with $h^* = 25.0$ m. The two high-stress cores are located near the two edges of the pillar (at $x^* \approx \pm 18$ m, depth ≈ 5 –8 m). In the hard-over-soft combination, the stress contracts at the interface, and the lateral half-width first increases to 28.0 m at $h_1 = 5$ m and then decreases to 15.5 m at $h_1 = 30$ m. The two nuclei gradually merge into a single broad high-stress zone at depth. In the soft-over-hard combination, the stress expands outward at the interface; the lateral half-width increases monotonically with h_1 , reaching 34.5 m at $h_1 = 30$ m, and the two nuclei become a wide elliptical disk. Compared with the narrow pillar case, the stress concentration coefficients under the wide pillar are generally lower at the same depth, but the influence zone is larger and the stress decays more slowly.



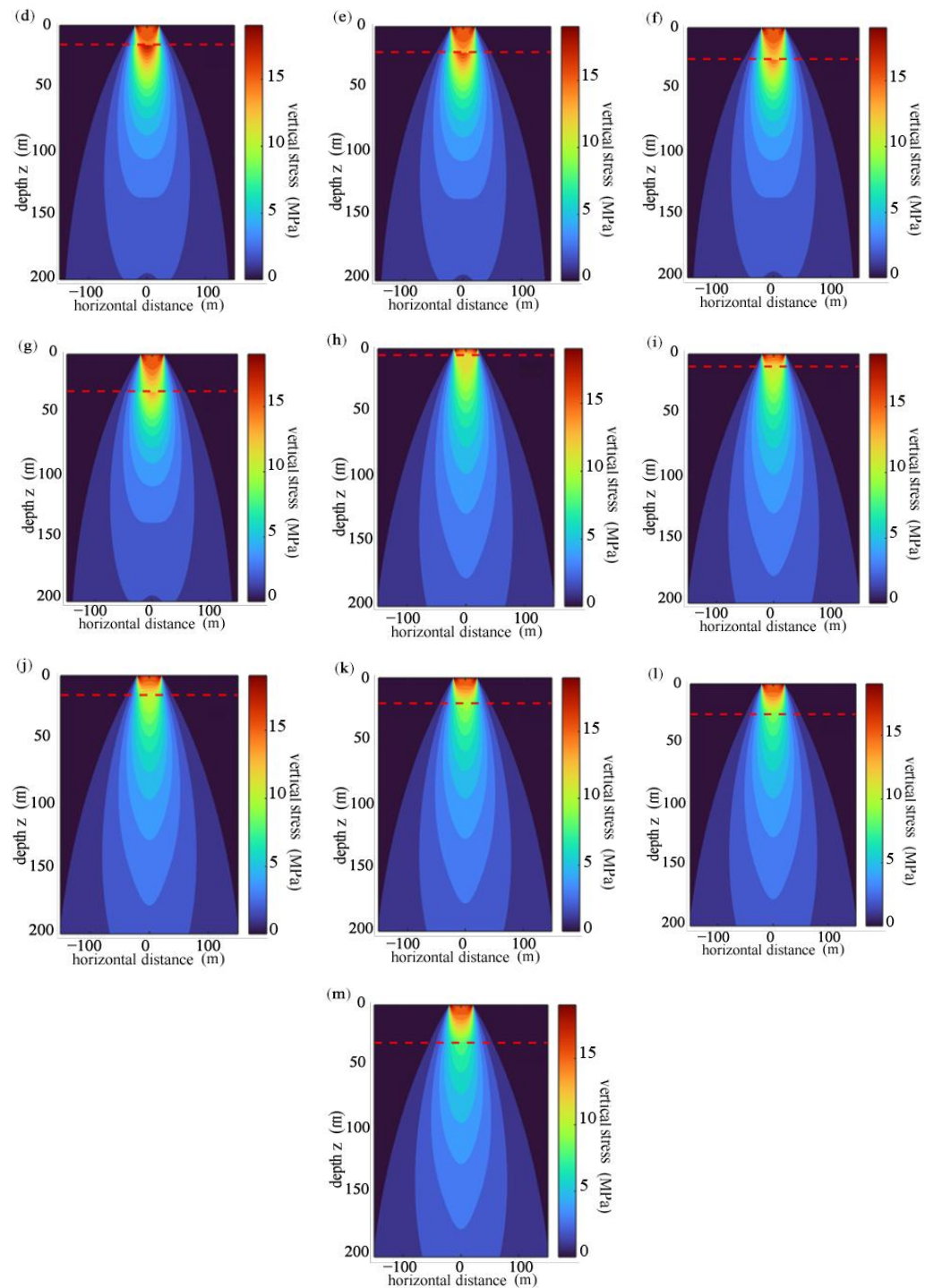


Figure 6. Vertical stress distribution in the hard–soft composite floor under a wide coal pillar: (a) homogeneous floor; (b–g) hard-above-soft floor with interface depths of 5 m, 10 m, 15 m, 20 m, 25 m, and 30 m, respectively; (h–m) soft-above-hard floor with interface depths of 5 m, 10 m, 15 m, 20 m, 25 m, and 30 m, respectively.

3.2. Stress Distribution from Similar Material Simulation

To validate the theoretical predictions, similar material tests were performed on two typical floor structures: (1) sandstone–mudstone–sandstone (H-S-H) and (2) mudstone–sandstone–mudstone (S-H-S), both under a narrow coal pillar (unimodal load).

3.2.1. H-S-H (Hard-Soft-Hard) Floor

The vertical stress contours (Figure 7) exhibit a clear “bulb-shaped” pattern, which agrees well with the theoretical prediction for the hard-over-soft combination. In the shallow sandstone layer (0–10 cm), the contours are dense, indicating strong stress concentration. At the mudstone interlayer (10–30 cm), the contours sharply contract toward the pillar centerline, and the stress decays rapidly—from 16.83 MPa at $z^* = 15$ cm to 13.5 MPa at $z^* = 30$ cm (a drop of 3.33 MPa). This confirms the “barrier effect” of the weak interlayer, which impedes downward stress transmission. Below the mudstone, the lower sandstone layer shows sparse contours, meaning full stress diffusion.

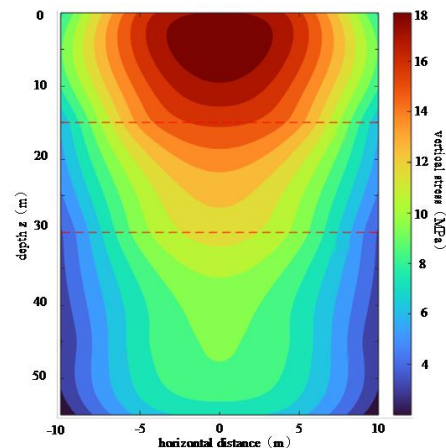


Figure 7. Vertical stress contour map of the sandstone-mudstone-sandstone (hard-soft-hard) combination.

3.2.2. S-H-S (Soft-Hard-Soft) Floor

The vertical stress contours (Figure 8) show a “gourd-shaped” distribution, matching the theoretical soft-over-hard pattern. The shallow mudstone buffers the load, giving a low peak of only 9.85 MPa at $z^* = 15$ cm. When the stress enters the middle sandstone layer, the contours expand outward and the peak stress rises to 14.5 MPa at $z^* = 30$ cm, demonstrating the “bearing effect” of the hard rock. In the deep mudstone, the stress decays slowly and the influence depth is much larger than that of the H-S-H floor.

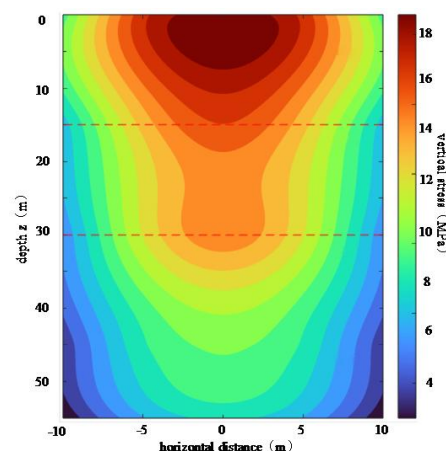


Figure 8. Vertical stress contour map of the mudstone-sandstone-mudstone (soft-hard-soft) combination.

3.3. Numerical Simulation of Stress Evolution

3.3.1. Effect of Floor Strata Combination on Vertical Stress

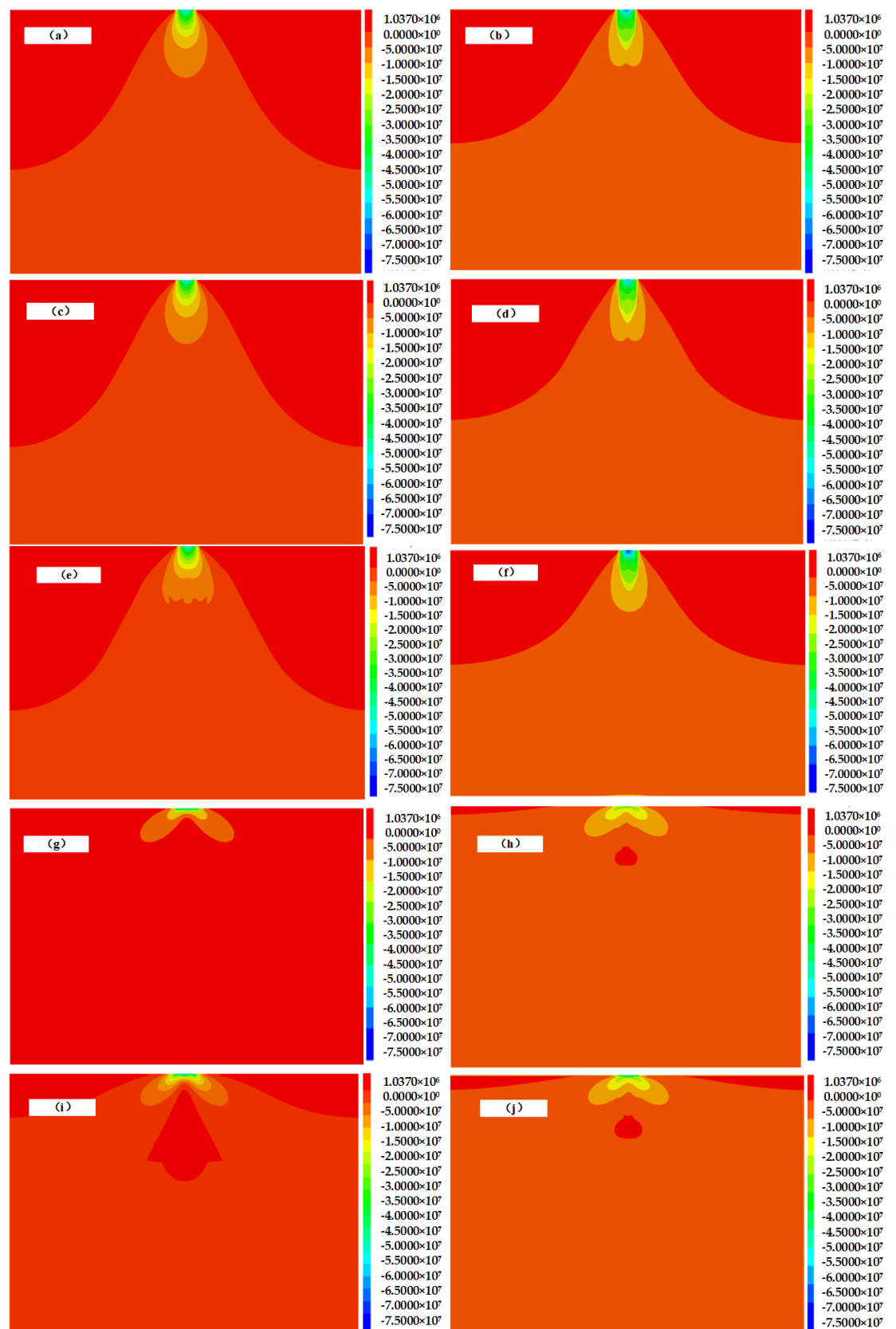
FLAC3D simulations were performed for six floor combinations (single hard rock, single soft rock, hard-over-soft, soft-over-hard, hard-soft-hard (H-S-H), and soft-hard-soft (S-H-S)) under both narrow (10 m) and wide (40 m) coal pillars. The results are presented in Figure 9.

Narrow pillar (10 m, unimodal load). For the homogeneous sandstone floor (Figure 9a), the vertical stress contours exhibit a deep “spindle-shaped” high-stress zone extending downward from the pillar centerline. The peak vertical stress reaches 58.1 MPa at a shallow depth, and the stress decays slowly with increasing depth, indicating strong load transmissibility of hard rock. In contrast, the homogeneous mudstone floor (Figure 9b) shows a flat “elliptical” high-stress zone confined to the shallow depth, with a peak of only 25.9 MPa and rapid decay, reflecting the buffering and dissipating effect of soft rock.

In the two-layer combinations, the lithological sequence significantly controls the stress morphology. For the hard-over-soft (sandstone over mudstone) floor (Figure 9c), the stress contours are “full in the upper part, flattened at the interface, and expanded in the lower part”. The high-stress core resides in the upper hard rock, and a clear stress drop occurs across the interface, where the weak mudstone layer impedes further downward transmission. For the soft-over-hard (mudstone over sandstone) floor (Figure 9d), a secondary deep “bulb-shaped” concentration appears inside the lower hard rock, indicating downward migration of the peak stress. The interface here acts as a stress-focusing plane, transferring the load efficiently into the underlying hard rock.

The three-layer combinations further amplify the “interface effect”. The H-S-H structure (sandstone–mudstone–sandstone, Figure 9e) produces a “bow-tie” shape with two high-stress cores—one in the shallow sandstone and another in the deep sandstone, with the mudstone interlayer causing a clear stress saddle. This configuration exhibits the strongest stress transmissibility and the deepest influence zone. The S-H-S structure (mudstone–sandstone–mudstone, Figure 9f) forms a “sandwich” pattern: a single high-stress core confined within the middle sandstone layer, with the upper and lower mudstone layers acting as buffers that significantly reduce the stress concentration. This combination yields the lowest peak stress among all layered floors.

Wide pillar (40 m, bimodal load). Under the wide pillar (Figure 9g), the stress distribution shares the same lithological control but exhibits a broader influence zone and slower stress decay compared to the narrow pillar case. For the homogeneous sandstone floor, the “spindle” becomes wider and the peak stress (about 40 MPa) is substantially lower than that under the narrow pillar (58.1 MPa). The soft rock floor (Figure 9h) still shows a flat elliptical zone with a peak of about 20 MPa. The hard-over-soft (Figure 9i) and soft-over-hard (Figure 9j) combinations retain their characteristic contraction and expansion patterns, but the interface-induced stress discontinuity is less abrupt due to the wider load distribution. The H-S-H structure (Figure 9k) still presents a double-core “bow-tie” shape, while the S-H-S structure (Figure 9l) maintains the “sandwich” pattern with the lowest stress concentration. Overall, increasing pillar width reduces the stress concentration coefficient at any given depth, but the vertical stress penetrates deeper and affects a larger area.



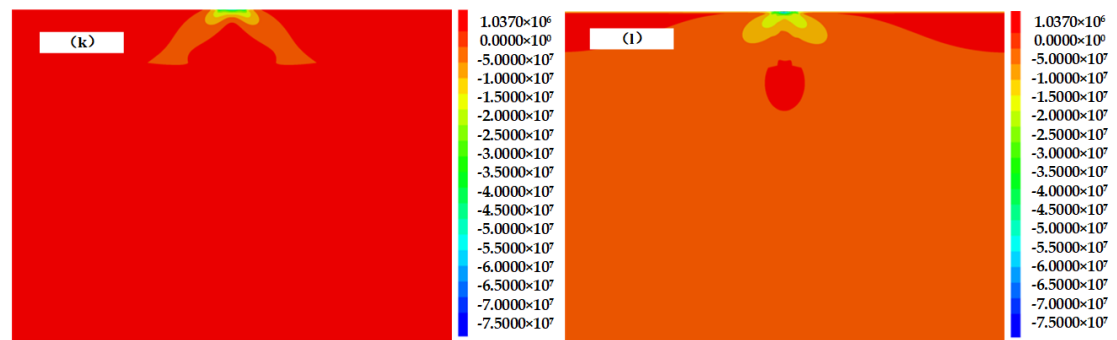


Figure 9. Vertical stress distribution contours of hard–soft composite floors under coal pillars with widths of 10 m and 40 m: (a–f) under a 10 m pillar, and (g–l) under a 40 m pillar, with floor combinations in the order of homogeneous hard rock, homogeneous soft rock, hard-above-soft, soft-above-hard, hard-soft-hard, and soft-hard-soft, respectively.

3.3.2. Effect of Floor Strata Combination on Plastic Zone

The plastic zone distributions presented in Figure 10 are based on zones with shear-n and tension-n flags at the end of the calculation, following the criterion established in Section 2.3. The plastic zone distribution (Figure 10) is intrinsically linked to the vertical stress pattern and follows similar lithological controls.

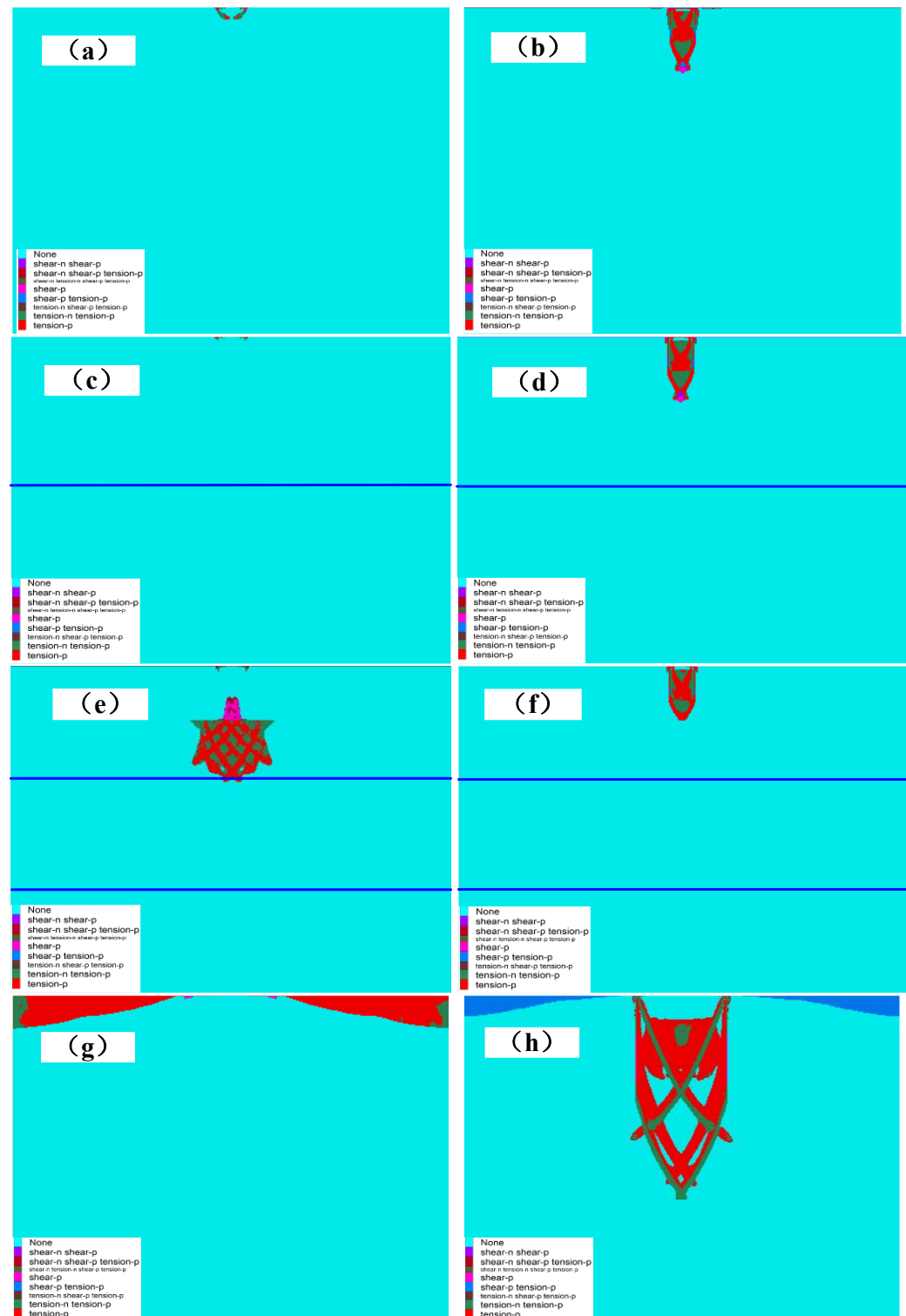
Narrow pillar (10 m). For the homogeneous sandstone floor (Figure 10a), the plastic zone is extremely limited—only a few isolated points of shear failure appear directly beneath the pillar centerline. The high strength and low deformability of hard rock effectively suppress plastic yielding. For the homogeneous mudstone floor (Figure 10b), a continuous tensile plastic zone develops, forming a narrow vertical band that penetrates deep into the floor (up to ~45 m). This reflects the low strength and high ductility of soft rock, which easily undergoes plastic flow under concentrated load.

In the two-layer combinations, the plastic zone morphology is governed by the position of the interface. For the hard-over-soft floor (Figure 10c), the plastic zone is mainly concentrated in the upper hard rock near the pillar centerline, with a limited extension into the underlying soft rock. The interface acts as a barrier that restricts the downward propagation of plastic failure. For the soft-over-hard floor (Figure 10d), the plastic zone is predominantly located in the shallow soft rock layer, forming a thick band; however, once the stress enters the underlying hard rock, plastic yielding is almost completely suppressed. This demonstrates that a hard rock layer can effectively “shield” deeper strata from plastic damage.

The three-layer combinations show the most complex plastic behavior. The H–S–H structure (Figure 10e) develops a “honeycomb”-like plastic zone: shear failure occurs in both the upper and lower sandstone layers, while the middle mudstone interlayer experiences through-going tensile failure that connects the two shear zones. This configuration has the widest and deepest plastic zone among all combinations, indicating the poorest overall stability. In contrast, the S–H–S structure (Figure 10f) confines the plastic zone almost entirely within the middle sandstone layer, with only minor tensile cracks in the adjacent mudstone layers. The plastic zone is thin and laterally restricted, making this combination the most stable for protecting the deep floor.

Wide pillar (40 m). The plastic zone under the wide pillar (Figure 10g) is significantly smaller than that under the narrow pillar for the same floor combination, because the wider load distribution reduces the stress concentration. For the homogeneous sandstone floor, the plastic zone remains negligible. For the homogeneous mudstone floor (Figure 10h), the tensile plastic band is shallower (maximum depth ~30 m) than under the narrow

pillar (~45 m). The hard-over-soft (Figure 10i) and soft-over-hard (Figure 10j) combinations show plastic zones that are more confined to the shallow strata. The H–S–H structure (Figure 10k) still exhibits a double-layer plastic zone but with reduced extent, while the S–H–S structure (Figure 9l) maintains a very limited plastic zone in the middle sandstone layer. These results confirm that increasing pillar width effectively alleviates plastic damage in the floor, especially for soft rock and composite structures.



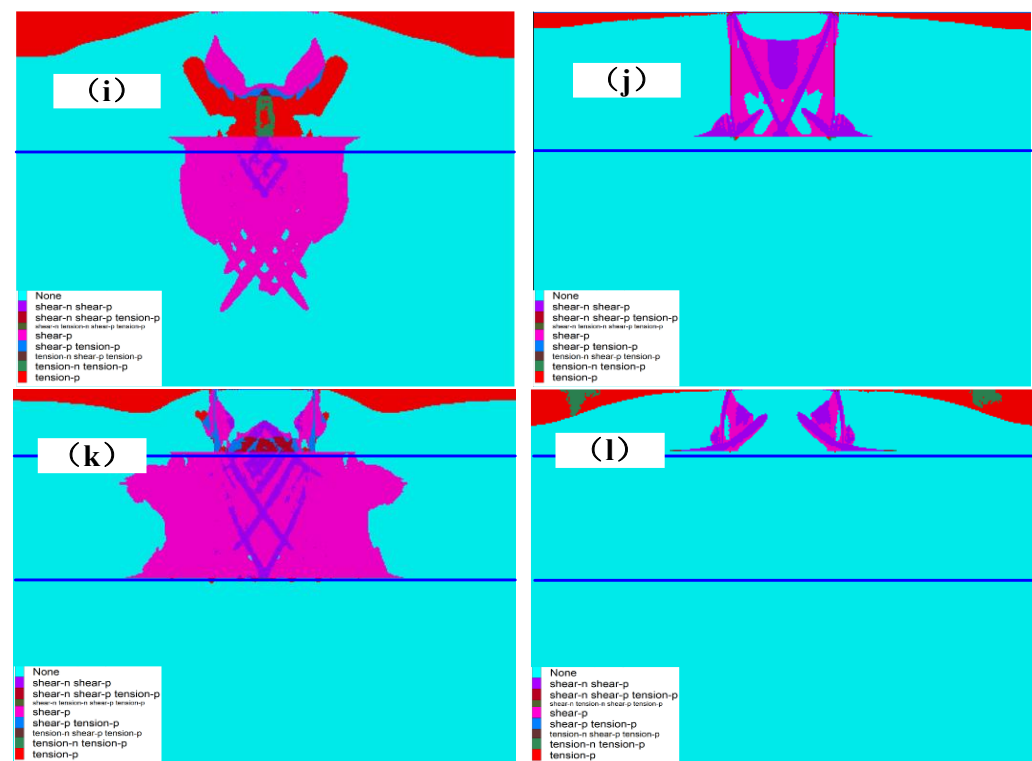


Figure 10. Plastic zone distribution contours of hard–soft composite floors under coal pillars with widths of 10 m and 40 m: (a–f) under a 10 m pillar, and (g–l) under a 40 m pillar, with floor combinations in the order of homogeneous hard rock, homogeneous soft rock, hard-above-soft, soft-above-hard, hard–soft–hard, and soft–hard–soft, respectively.

4. Discussion

4.1. Mechanical Mechanism of the Interface Effect

Through theoretical analysis, physical simulation and numerical simulation, this study consistently reveals two typical patterns of stress transfer in hard–soft composite floors: “bulb-shaped” contraction at a hard–soft interface and “gourd-shaped” expansion at a soft–hard interface. The mechanical essence lies in the significant differences in Poisson’s ratio and shear modulus between the two layers. When hard rock overlies soft rock, the soft rock has a higher Poisson’s ratio ($\nu_2 > \nu_1$) and a lower shear modulus ($G_2 < G_1$), giving it a greater lateral deformation capacity. This inhibits lateral stress diffusion and forces vertical stress to concentrate toward the centerline of the coal pillar, forming an elongated “bulb-shaped” high-stress zone. Conversely, when soft rock overlies hard rock, the low Poisson’s ratio and high shear modulus of the hard rock promote lateral stress transmission, causing the contours to expand outward and produce a wide-flat “gourd-shaped” distribution. These mechanisms are consistent for both narrow and wide pillars, although under the wide pillar the bimodal load delays the intensity of contraction/expansion and leads to merging of the two stress nuclei at depth.

4.2. Comparison with Previous Studies

The classical pressure bulb theory, treats the floor as a homogeneous half-space and predicts smooth “spindle-shaped” or “butterfly-shaped” stress contours, which cannot explain the abrupt stress changes and morphological turning at layer interfaces. By introducing the layered half-space theory and interfacial boundary conditions, this study quantifies, for the first time, the controlling effect of hard–soft interfaces on the stress transfer path, and provides a clear criterion for the critical interface depth ($h_1 = D$ under a narrow pillar).

The comparison (Table 3) demonstrates that all three methods consistently identify the same stress distribution patterns: bulb-shaped contraction for H–S–H and gourd-shaped expansion for S–H–S. The differences in absolute peak stress values are attributable to the different scales and idealizations inherent in each method (theoretical analysis assumes perfectly elastic half-space; similar material simulation uses a 1:50 scaled model; numerical simulation adopts a full-scale Mohr–Coulomb model). Nevertheless, the relative trends—particularly the stress concentration position and the contraction/expansion behavior at layer interfaces—are in good qualitative and semi-quantitative agreement across all three approaches.

Table 3. Comparison of key stress parameters obtained from the three methods (theoretical analysis, similar material simulation, and numerical simulation) for the two typical floor combinations under narrow pillar (10 m) conditions.

Rock Combination	Method	Peak Vertical Stress	Position of Peak	Cohesion/MPa
H–S–H (hard–soft–hard)	Theoretical analysis	~20 MPa	Within hard rock layer	Stress distribution shape
Similar material simulation	16.83 MPa ($z = 15$ cm)	Shallow sandstone layer	Bulb-shaped contraction	Bulb-shaped contraction
Numerical simulation (FLAC3D)	58.1 MPa (shallow depth)	Shallow hard rock layer	Spindle-to-bulb transition	
S–H–S (soft–hard–soft)	Theoretical analysis	~16 MPa	Within hard rock layer (deeper)	Gourd-shaped expansion
Similar material simulation	14.5 MPa ($z = 30$ cm)	Middle sandstone layer	Gourd-shaped expansion	
Numerical simulation (FLAC3D)	25.9 MPa	Middle hard rock layer	Sandwich pattern	

4.3. Implications for Engineering Practice

For downward mining of close-distance coal seams, when the overlying pillar floor has a “hard-over-soft” combination, the roadway in the lower seam should avoid the high-stress contraction zone directly beneath the pillar. It is recommended to place the roadway in the lateral region where the stress is relatively low (i.e., at a distance from the pillar centerline greater than the lateral half-width h). Conversely, for a “soft-over-hard” combination, the lateral stress diffusion range is large and the peak stress is lower, offering more flexibility in roadway layout; nevertheless, attention should still be paid to the wide, gentle high-stress zone that may form inside the deep hard rock. The plastic zone analysis shows that the hard–soft–hard structure has a wide and through-going plastic zone, so grouting reinforcement or a wider pillar should be prioritized; in contrast, the soft–hard–soft structure is most favourable for protecting the floor and represents an ideal underlying rock combination.

4.4. Limitations and Outlook

While this study provides a systematic investigation of stress transfer in hard–soft composite floor strata under coal pillar loading, several limitations should be acknowledged, and future research directions are proposed to address them.

First, the present analytical model assumes perfectly elastic behavior for all rock layers and perfectly bonded interfaces, without considering the time-dependent deformation of soft rocks (e.g., creep) or potential interface degradation such as slip or opening. In deep mining environments, high in-situ stresses and strong mining-induced disturbances may drive soft rocks into a plastic or visco-plastic flow regime, which could significantly alter the stress transfer paths over time. Specifically, progressive yielding of the weak interlayer may weaken the “barrier effect” observed under elastic conditions in the hard–soft–hard combination; meanwhile, interface slip could shift stress concentrations toward the hard rock boundaries, thereby modifying the shape of the stress contours. The “bulb-shaped” contraction and “gourd-shaped” expansion patterns identified in this study represent the

instantaneous elastic response. Under long-term or cyclic loading, these patterns may evolve as the mechanical contrast between layers gradually degrades. To address this limitation, future work should introduce visco-elasto-plastic constitutive models to capture time-dependent deformation, implement non-perfect interface conditions (e.g., Coulomb friction or cohesive zone models) to account for interface slip and opening, and perform coupled mining-creep numerical simulations to evaluate the long-term stability of the composite floor.

Second, this study only addresses static pillar loading and does not consider the dynamic disturbance caused by active extraction of the lower coal seam. In actual close-distance coal seam mining, the extraction process inevitably introduces transient stress redistributions, periodic weighting, and potentially blasting vibrations, all of which could significantly affect the stress state and stability of the underlying floor strata. Such dynamic disturbances may act in combination with static pillar loads to accelerate the deterioration of the floor's bearing capacity, particularly at the hard–soft interfaces where stress concentrations are already high. To overcome this limitation, future research should incorporate dynamic loading conditions into numerical models to simulate stress redistribution during active mining, combine the static analytical framework developed in this study with dynamic finite element or finite difference analyses, and integrate field monitoring data (e.g., microseismic or stress monitoring) to calibrate and validate the dynamic models.

Despite these limitations, the present work provides a fundamental theoretical framework and quantitative insights into the interface-controlled stress transfer mechanisms in layered floor strata. The analytical solutions, experimental validations, and numerical findings reported here lay a solid foundation for future investigations that incorporate more complex material behaviors and loading conditions, ultimately contributing to safer and more efficient design in multi-seam coal mining.

5. Conclusions

- (1) Mechanical models for stress transfer in hard–soft composite floors under narrow (unimodal) and wide (bimodal) coal pillars were established based on elastic layered half-space theory. Analytical stress solutions at any point within the layered floor were derived, and it was clarified that interface depth, Poisson's ratio, and shear modulus ratio are the key parameters controlling stress transfer.
- (2) Theoretical calculations show that for the hard-over-soft combination, the stress contours contract sharply toward the pillar centerline at the interface, forming a “bulb-shaped” distribution, and a critical interface depth $h_1 = D$ (pillar width) exists. For the soft-over-hard combination, the stress expands outward at the interface, producing a “gourd-shaped” distribution; the lateral half-width increases monotonically with interface depth and tends to stabilize. Under a wide pillar, the stress pattern is a “double-nucleus butterfly” shape, but the contraction/expansion behavior at the interface follows the same rules as under a narrow pillar.
- (3) Similar material simulation tests validated the theoretical predictions: the hard–soft–hard floor exhibited “bulb-shaped” contraction, with the mudstone interlayer causing rapid stress decay (a drop of 5.5 MPa), reflecting the “barrier effect”; the soft–hard–soft floor showed “gourd-shaped” expansion, with the stress rising again inside the sandstone layer, reflecting the “bearing effect”.
- (4) Numerical simulations revealed the controlling laws of strata combination on stress evolution: the hard rock layer is the primary stress carrier—stress concentration always resides inside hard rock—while the soft rock layer acts as a buffer and diffuser. The hard–soft–hard structure produces a “bow-tie” vertical stress pattern and a honeycomb plastic zone, which is the most unfavorable for stability; the soft–hard–soft

structure forms a “sandwich” low-stress zone and a confined plastic zone, offering the best stability.

- (5) The depth of the plastic zone is significantly controlled by lithological combination: hard rock floors have a very limited plastic zone, while soft rock floors develop a through-going tensile plastic zone (up to 45 m deep). The hard–soft–hard structure gives the widest and most complex plastic zone; the soft–hard–soft structure confines the plastic zone within the middle hard rock, providing the best overall stability. Increasing the pillar width effectively reduces the plastic zone depth.

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