

Supplementary Information

Rockburst proneness evaluation and pressure relief technology for deep heterogeneous rock masses: a case study of the Sanshandao Gold Mine

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Supplementary Figures

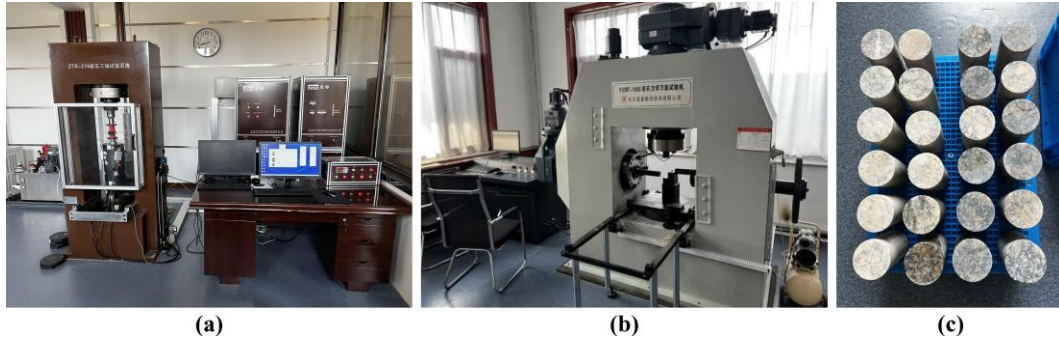


Figure S1. Laboratory testing equipment and specimens: (a) ZTR-276 rock triaxial testing system; (b) YUMT-1000 rock mechanics universal testing machine; (c) rock specimens

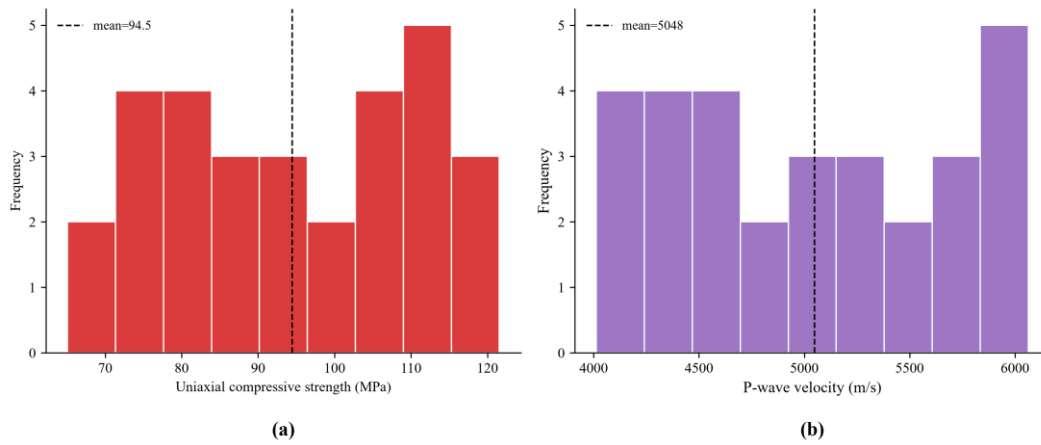


Figure S2. Statistical distributions of the measured parameters of the 30 calibration specimens: (a) uniaxial compressive strength; (b) P-wave velocity.

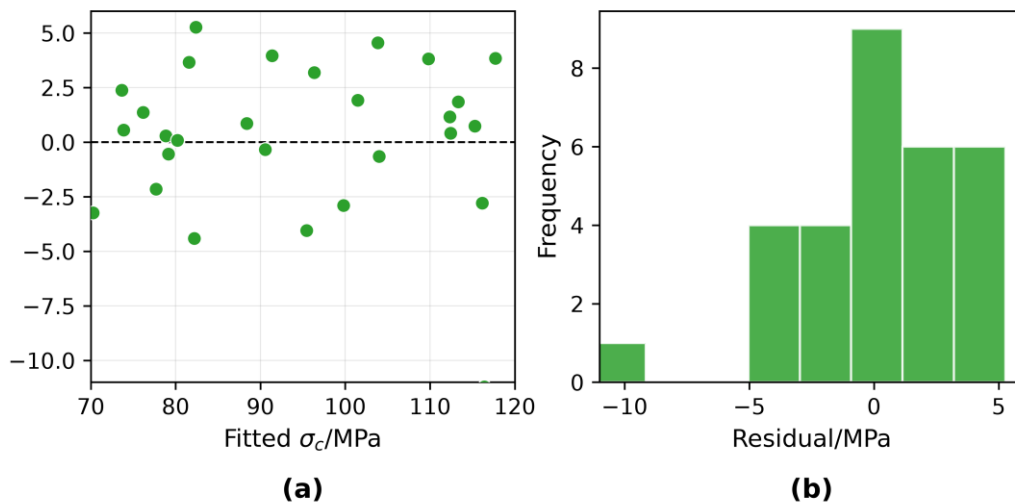


Figure S3. Residual analysis of the power-law model: (a) residuals versus predicted strength; (b) histogram of residuals.

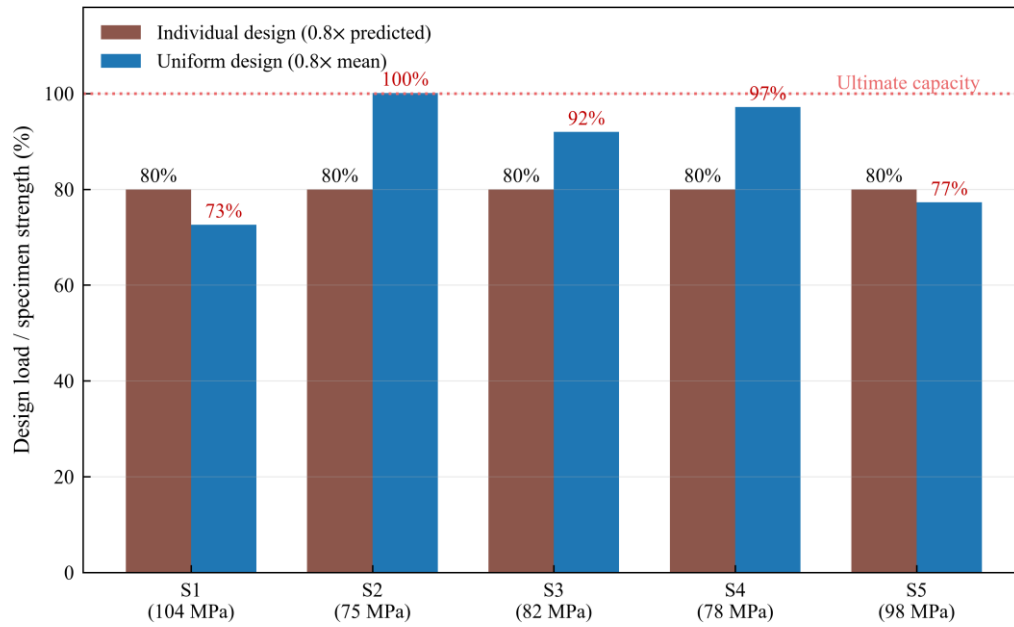


Figure S4. Comparison of the stress-level ratio (design stress/specimen strength) between the conventional mean-strength scheme and the proposed individualized scheme.

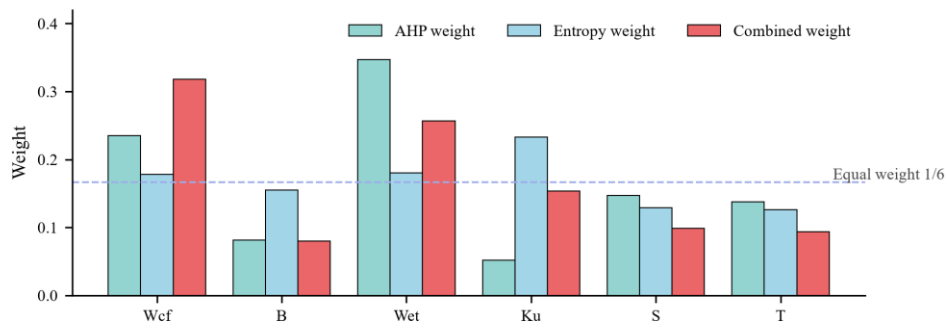


Figure S5. Comparison of the AHP, entropy and combined weights of the six evaluation indices.

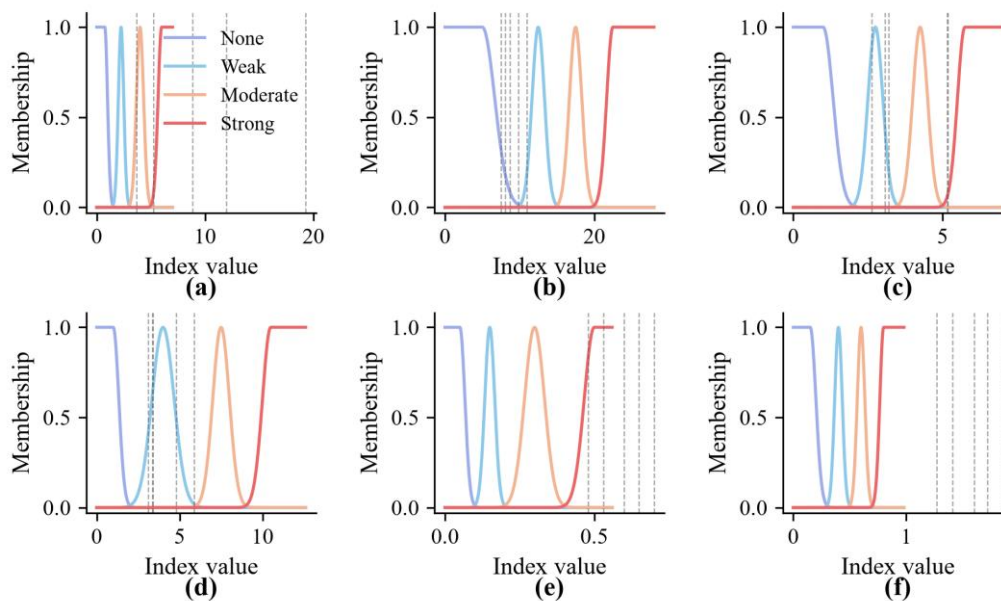


Figure S6. Standard normal cloud membership curves of the six evaluation indices (grey dashed lines denote the measured values of the five samples).

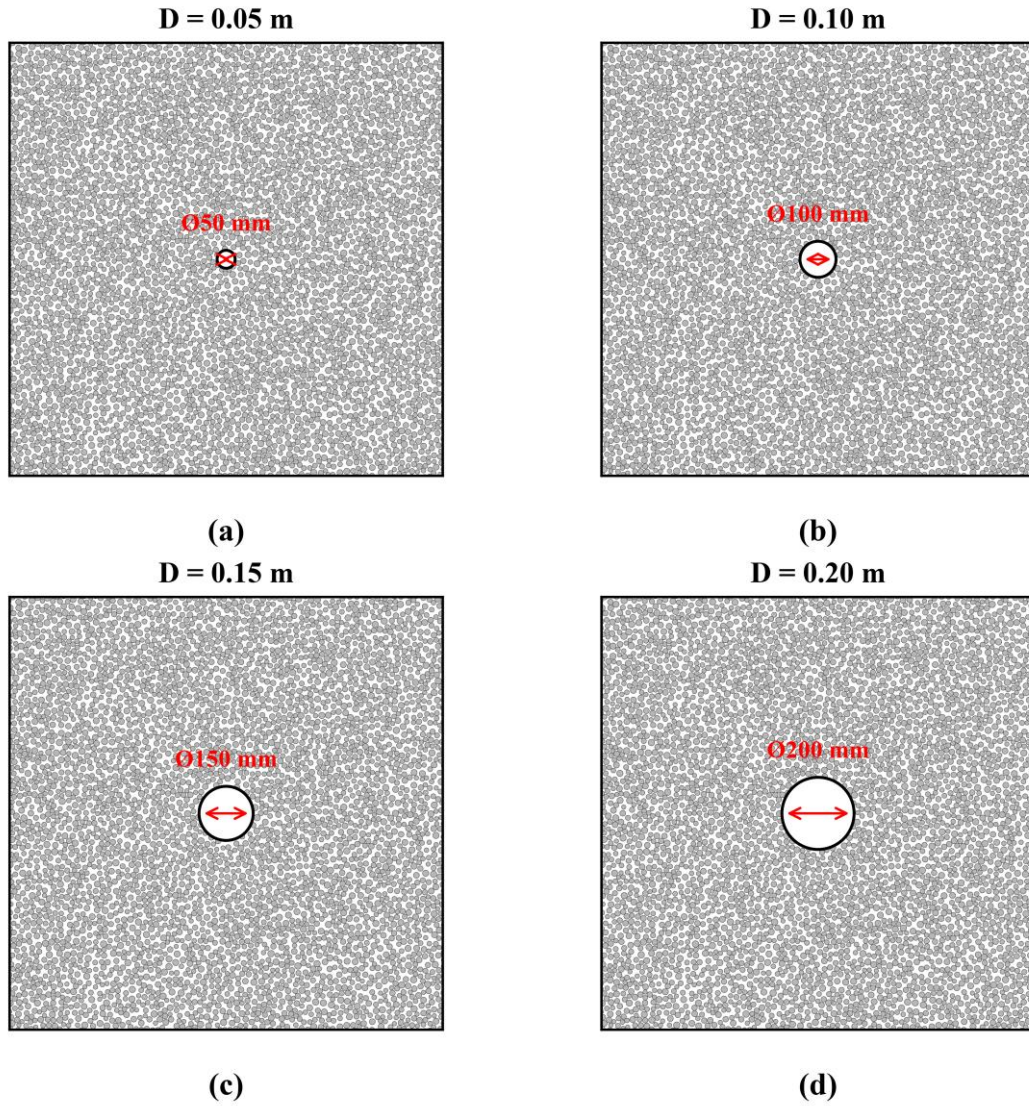


Figure S7. PFC2D particle model of the four borehole diameters after excavation (27,289 balls, $r = 0.006\text{--}0.009 \text{ m}$): (a) $D = 0.05 \text{ m}$; (b) $D = 0.10 \text{ m}$; (c) $D = 0.15 \text{ m}$; (d) $D = 0.20 \text{ m}$.

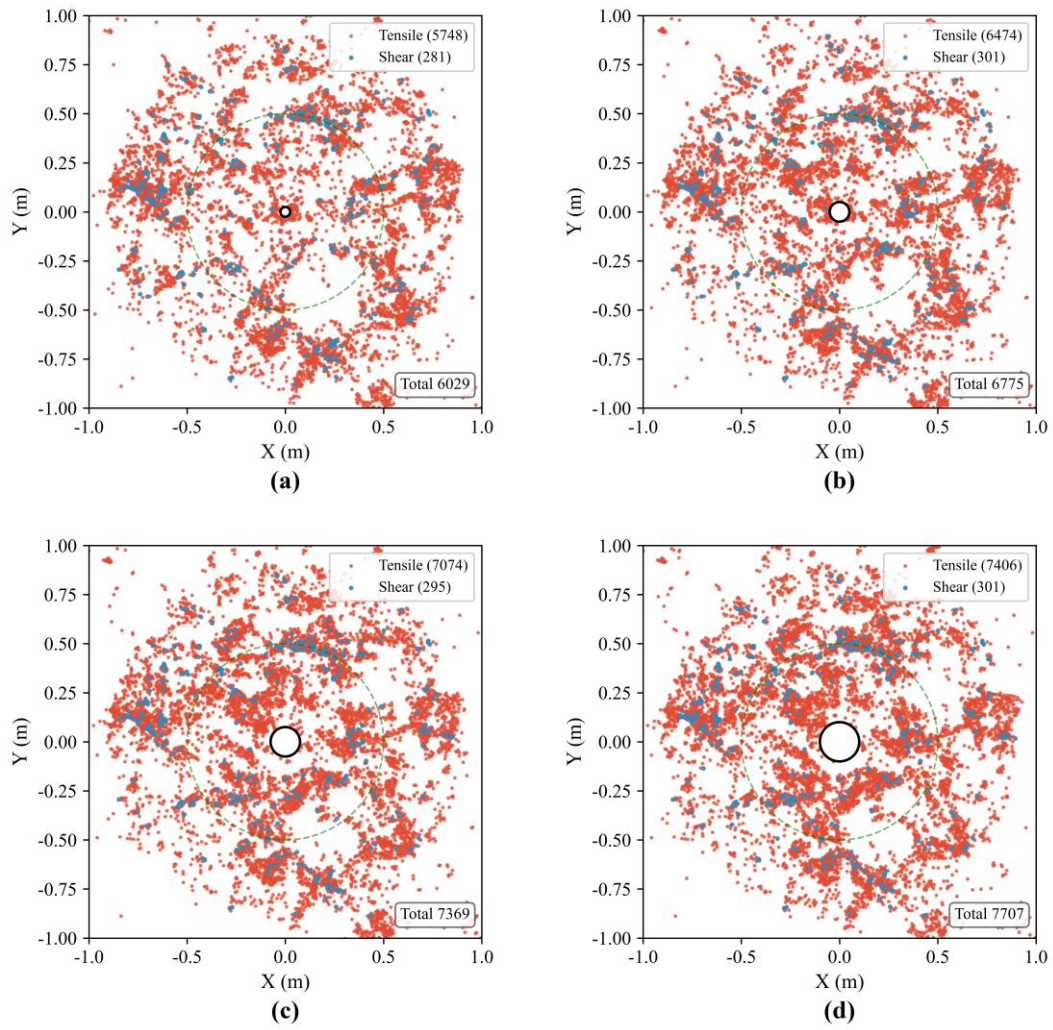


Figure S8. PFC2D crack (plastic zone) distribution after excavation for the four borehole diameters: (a) $D = 0.05$ m; (b) $D = 0.10$ m; (c) $D = 0.15$ m; (d) $D = 0.20$ m. The dashed green circle denotes the connectivity threshold ($r_p = 0.5$ m).



Figure S9. Pressure relief drilling construction and layout location. (a) Drilling construction site; (b) The relative position and arrangement parameters of pressure relief borehole and bolt tray.

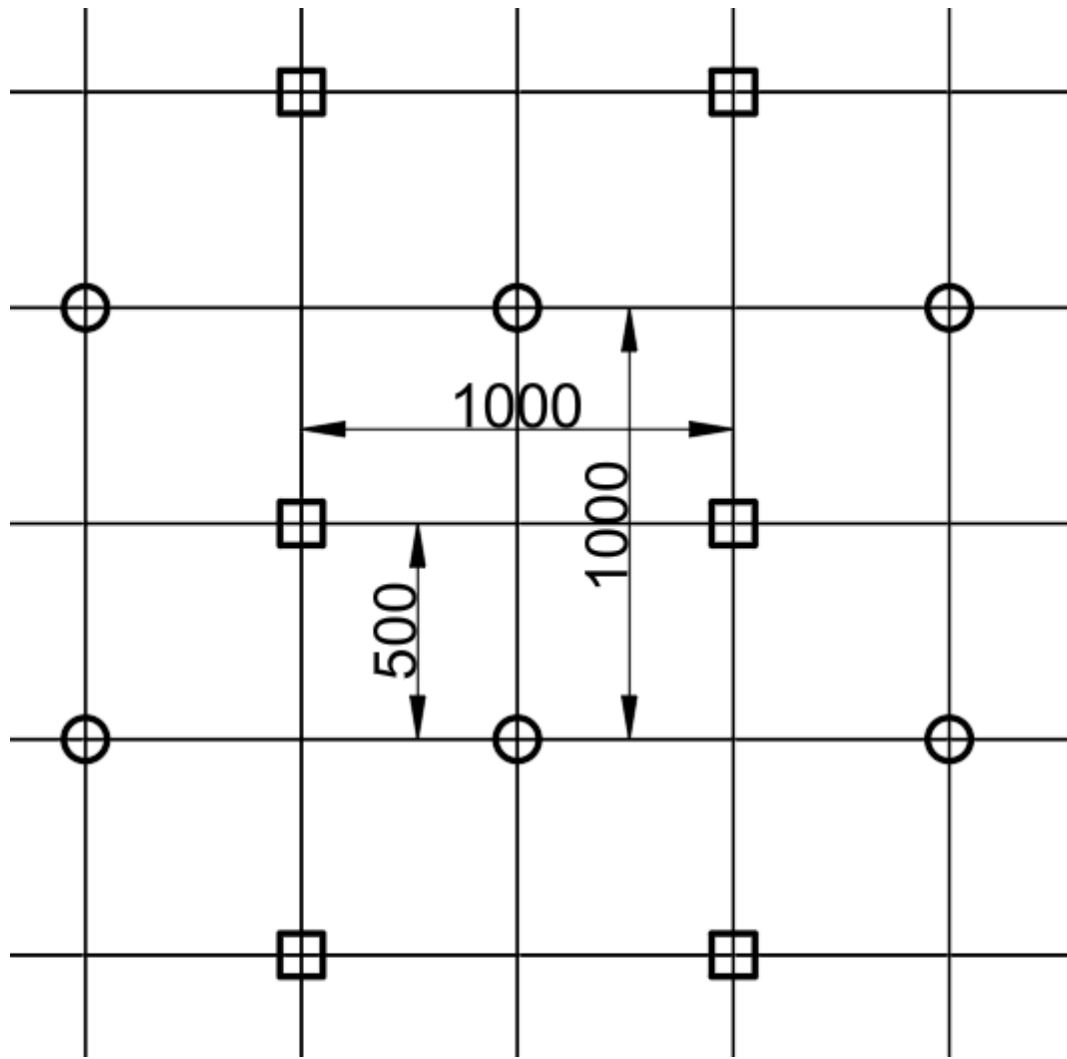


Figure S10. Resin bolt and vibrating wire steel bar dynamometer. (a)Resin bolting; (b) Vibrating wire steel bar dynamometer.



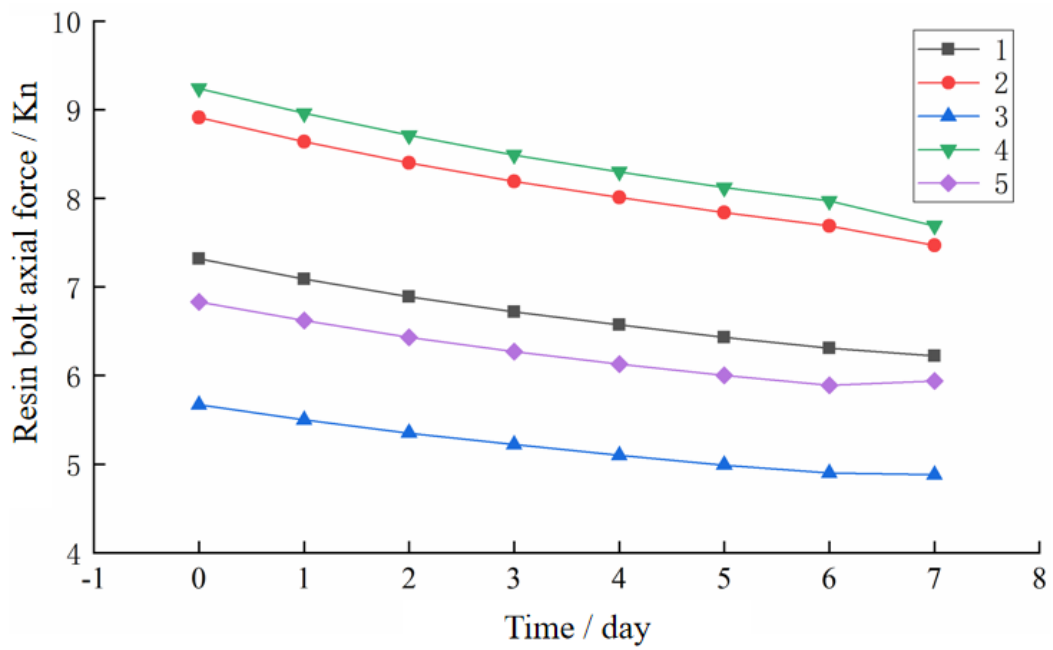


Figure S11. The variation trend of bolt axial force with time

Supplementary Tables

Table S1. Physical and mechanical parameters of the 30 calibration specimens.

Sample	ρ (g·cm ⁻³)	ν (m/s)	σ_c (MPa)	E (GPa)	μ
D1	2.72	4567.16	85.24	31.71	0.24
D2	2.73	5771.02	115.19	42.22	0.20
D3	2.74	4440.33	79.13	30.55	0.22
D4	2.76	5302.86	103.41	49.69	0.29
D5	2.75	5083.11	91.39	37.72	0.26
D6	2.78	5090.03	99.53	40.29	0.18
D7	2.75	5249.33	96.92	42.00	0.20
D8	2.80	6062.64	120.18	41.72	0.31
D9	2.72	4410.02	75.54	29.73	0.23
D10	2.66	5009.18	95.32	43.93	0.31
D11	2.79	5367.31	103.35	43.40	0.27
D12	2.63	5984.63	113.37	44.53	0.23
D13	2.66	5918.54	116.03	53.16	0.24
D14	2.64	4413.24	77.53	31.32	0.30
D15	2.73	4504.10	80.30	37.95	0.22
D16	2.64	4909.78	89.24	42.05	0.28
D17	2.74	4228.49	76.02	33.02	0.24
D18	2.70	4617.00	87.67	34.46	0.20
D19	2.75	4230.10	74.43	31.60	0.27
D20	2.70	5766.25	113.50	48.90	0.27
D21	2.79	4533.77	77.78	24.81	0.26
D22	2.68	5937.30	105.19	41.82	0.22
D23	2.76	4436.48	78.60	31.13	0.27
D24	2.72	5940.55	121.55	54.33	0.25
D25	2.75	4081.27	67.03	24.22	0.27
D26	2.79	4860.74	90.24	33.19	0.29
D27	2.71	4013.02	65.07	26.20	0.27
D28	2.79	5580.29	113.62	40.60	0.29
D29	2.80	5665.01	112.82	45.59	0.25
D30	2.69	5459.79	108.39	44.63	0.26
Mean $\pm$ SD	2.73 $\pm$ 0.05	5047.78 $\pm$ 639.46	94.45 $\pm$ 16.70	38.55 $\pm$ 7.96	0.25 $\pm$ 0.03
CV/%	1.81	12.67	17.68	20.66	13.32

Table S2. Brazilian splitting specimen data and tensile strength.

Sample	d /mm	h /mm	F /kN	σ_t /MPa
P1	48.84	25.98	22.57	11.33
P2	49.29	26.06	30.10	14.93
P3	49.38	26.28	14.68	7.21
P4	49.21	25.79	25.50	12.80
P5	49.36	26.48	22.42	10.93
P6	48.98	26.15	11.92	5.93
average	49.18	26.12	21.20	10.52

Table S3. Predicted uniaxial compressive strength and designed peak load of specimens for loading-unloading tests.

Sample	ρ /kg·m ⁻³	ν /m·s ⁻¹	d /mm	Predicting uniaxial strength/MPa	80 % uniaxial strength/MPa	peak load/kN
1	2.74	5417.70	48.99	104.13	83.30	157.02
2	2.71	4326.71	49.49	75.52	60.42	116.22
3	2.67	4633.36	49.54	82.23	65.78	126.80
4	2.70	4429.70	49.55	77.84	62.27	120.08
5	2.64	5279.42	48.86	97.87	78.30	146.81

Table S4. In-situ stress test results in the study area.

Principal stress	Value (MPa)	Direction (°)	Dip angle (°)
Maximum principal stress	55.0	329	7
Intermediate principal stress	25.4	61	15
Minimum principal stress	18.7	214	73
Tangential stress	146.3	—	—

Table S5. The calculation results of each index of rockburst proneness.

Sample	W_{cf}	B	W_{et}	K_u	S	T
1	8.85	8.10	5.18	4.80	0.65	1.72
2	3.68	10.95	3.07	3.37	0.48	1.27
3	19.29	7.52	3.19	3.38	0.70	1.85
4	5.23	9.83	2.62	3.11	0.53	1.41
5	11.97	8.69	5.16	5.87	0.60	1.60

Table S6. Evaluation results of rockburst proneness.

Sample	W_{cf}	B	W_{et}	K_u	S	T	Grade
1	Strong	None	Strong	Weak	Strong	Strong	Strong
2	Moderate	Weak	Weak	Weak	Strong	Strong	Weak
3	Strong	None	Weak	Weak	Strong	Strong	Strong
4	Strong	None	Weak	Weak	Strong	Strong	Weak
5	Strong	None	Strong	Weak	Strong	Strong	Strong

Table S7. Weights of the six evaluation indices obtained by different methods.

Method/Index	W_{cf}	B	W_{et}	K_u	S	T
Entropy value e_i	0.714	0.751	0.710	0.625	0.792	0.797
Coefficient of variation CV_j	0.633	0.153	0.320	0.290	0.150	0.149
AHP weight	0.235	0.081	0.347	0.052	0.147	0.138
Entropy weight w_j^1	0.178	0.155	0.180	0.233	0.129	0.126
CV weight w_j^{cv}	0.374	0.090	0.189	0.171	0.089	0.088
Objective weight w_j^{kbrj}	0.376	0.079	0.193	0.225	0.065	0.063
Combined weight w_j^*	0.318	0.080	0.257	0.153	0.099	0.094

Table S8. Rockburst grading criteria and cloud digital characteristics (E_x , E_n , H_e) of the six evaluation indices.

Index	Grade	Interval	E_x	E_n	H_e
Wcf	None	<1.5	0.75	0.250	0.025
	Weak	1.5-3	2.25	0.250	0.025
	Moderate	3-5	4.00	0.333	0.033
	Strong	≥ 5	6.00	0.333	0.033
B	None	<10	5.00	1.667	0.085
	Weak	10-15	12.50	0.833	0.042
	Moderate	15-20	17.50	0.833	0.042
	Strong	≥ 20	22.50	0.833	0.042
Wet	None	<2	1.00	0.333	0.033
	Weak	2-3.5	2.75	0.250	0.025
	Moderate	3.5-5	4.25	0.250	0.025
	Strong	≥ 5	5.75	0.250	0.025

Ku	None	<2	1.00	0.333	0.032
	Weak	2-6	4.00	0.667	0.064
	Moderate	6-9	7.50	0.500	0.048
	Strong	≥9	10.50	0.500	0.048
S	None	<0.1	0.05	0.017	0.001
	Weak	0.1-0.2	0.15	0.017	0.001
	Moderate	0.2-0.4	0.30	0.033	0.002
	Strong	≥0.4	0.50	0.033	0.002
T	None	<0.3	0.15	0.050	0.002
	Weak	0.3-0.5	0.40	0.033	0.002
	Moderate	0.5-0.7	0.60	0.033	0.002
	Strong	≥0.7	0.80	0.033	0.002

Table S9. Comprehensive certainty degrees (mean ± SD) and judgment grades of the five samples..

Sample	b_1 (None)	b_2 (Weak)	b_3 (Moderate)	b_4 (Strong)	Grade
Sample 1	0.014±0.003	0.074±0.010	0.001±0.001	0.530±0.010	Strong
Sample 2	0.000±0.000	0.223±0.029	0.198±0.019	0.176±0.002	Weak
Sample 3	0.025±0.003	0.153±0.025	0.000±0.000	0.510±0.000	Strong
Sample 4	0.001±0.001	0.286±0.018	0.001±0.001	0.216±0.012	Weak
Sample 5	0.007±0.002	0.004±0.003	0.002±0.002	0.527±0.009	Strong