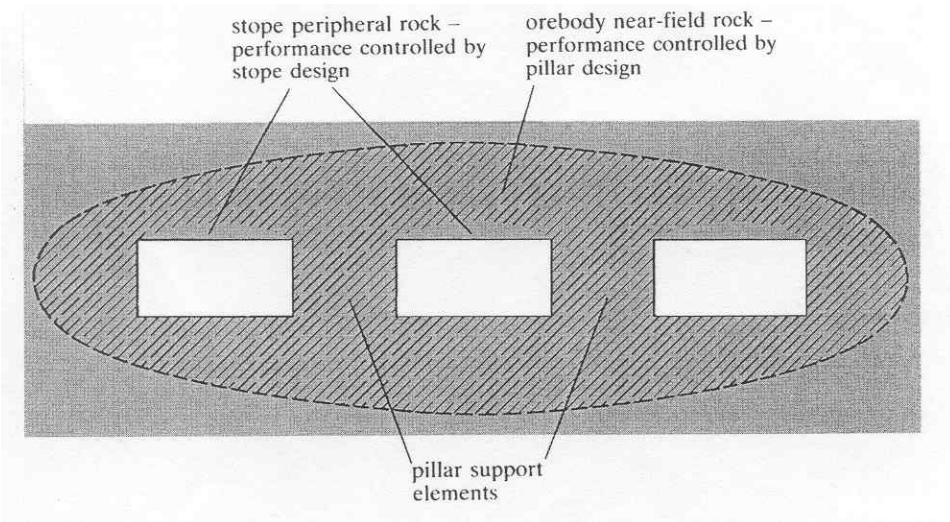
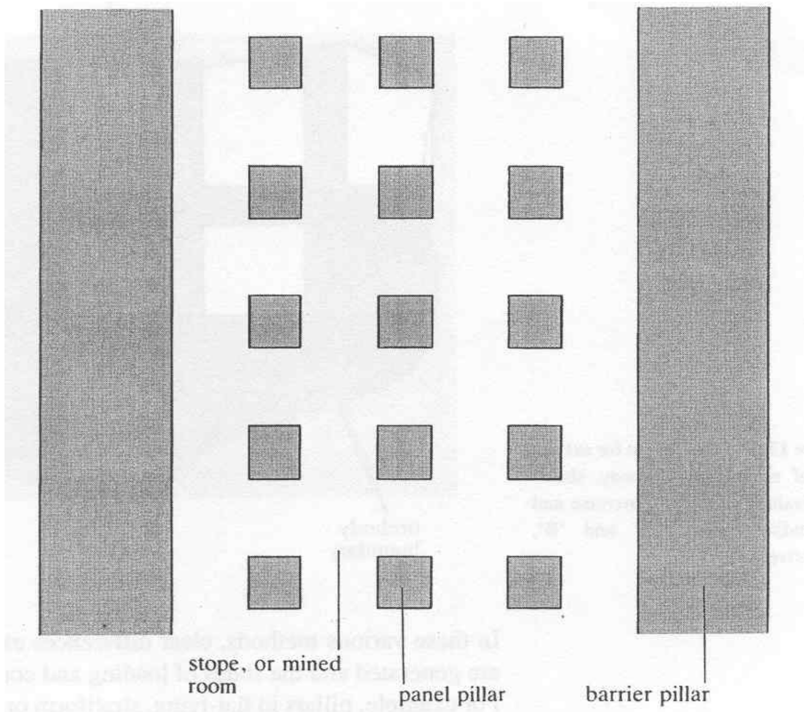
13. Pillar supported mining methods

13.1 Components of a supported mine structure

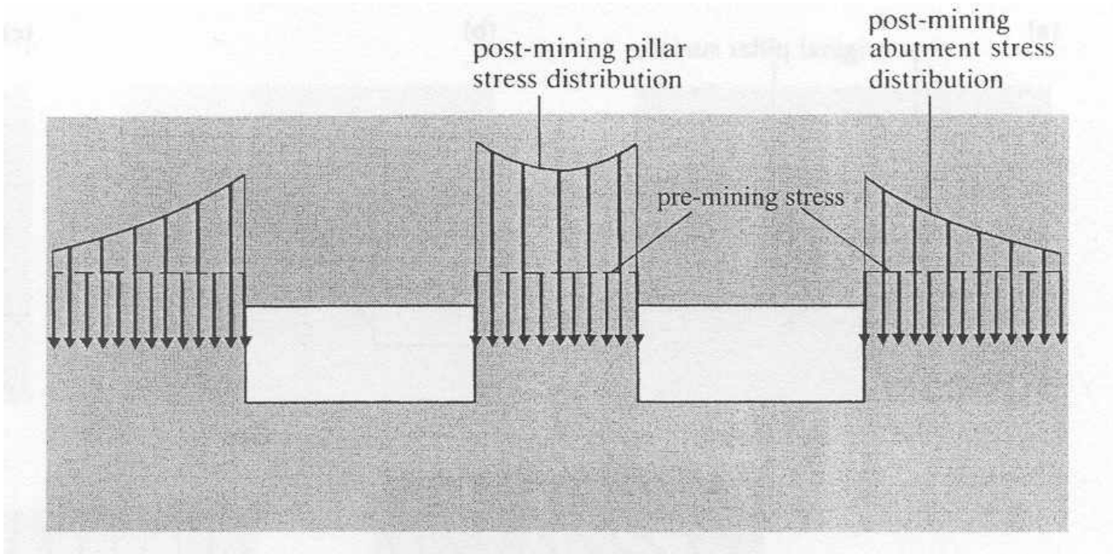
- Economic design of a support system
- Minimizing pillar support while assuring the stability of the mine structure
- Pillars
- Panel pillars and barrier pillars





13.2 Field observation of pillar performance

- Stress distribution in a pillar
- Concentration of stress on the surface of pillars and host rock
- Response of pillars depends on
- Rock material properties, geological structure, pillar dimension etc.



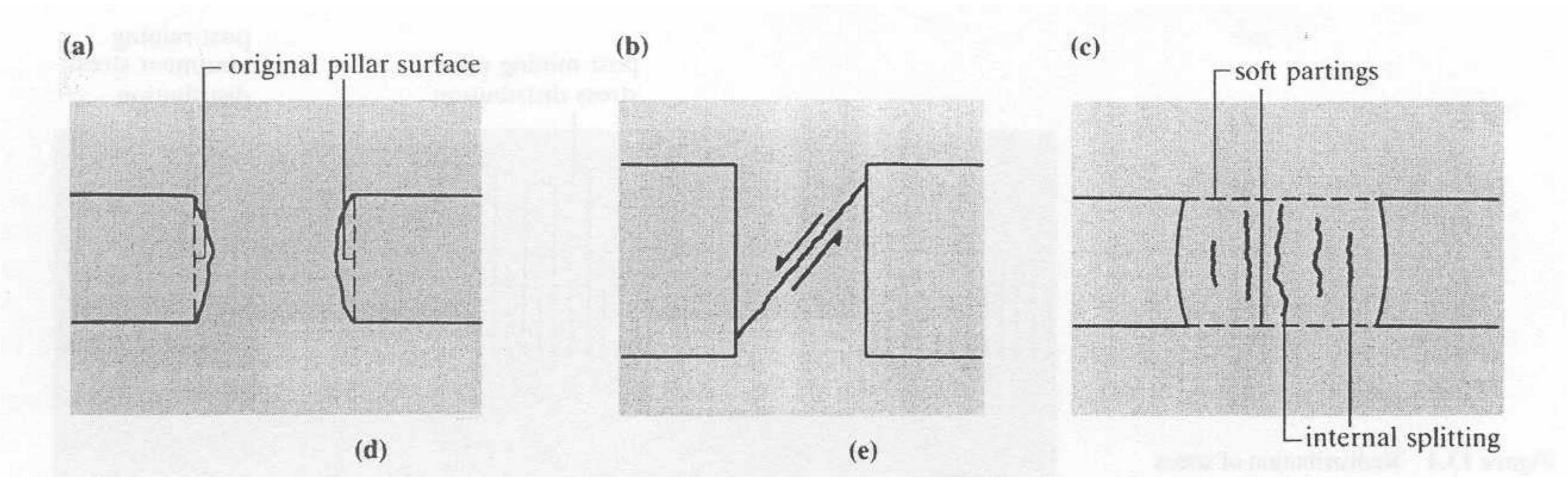
13.2 Field observation of pillar performance

- Three main modes of pillar behavior under stress close to its strength (massive rock)

  (a) Spalling (necking or fretting)

  (b) Shear failure (especially at high pillar height/width ratio)

  (c) Lateral bulging (barrelling) with internal splitting when transverse weak planes exist between the pillar and adjacent country rock

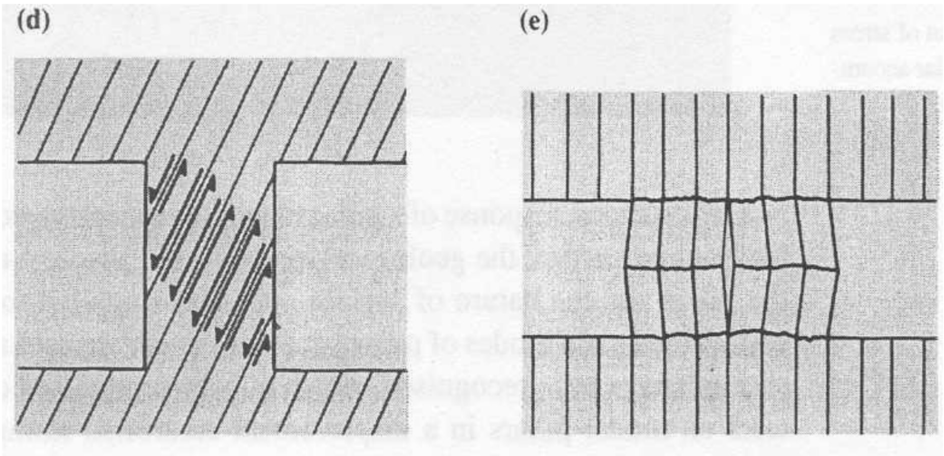


13.2 Field observation of pillar performance

- Pillars with a set of natural transgressive fractures or foliation (schistosity)

(d) Slip along the fractures when the fracture dip angle exceeds the friction angle

(e) Buckling failure



13.2 Field observation of pillar performance

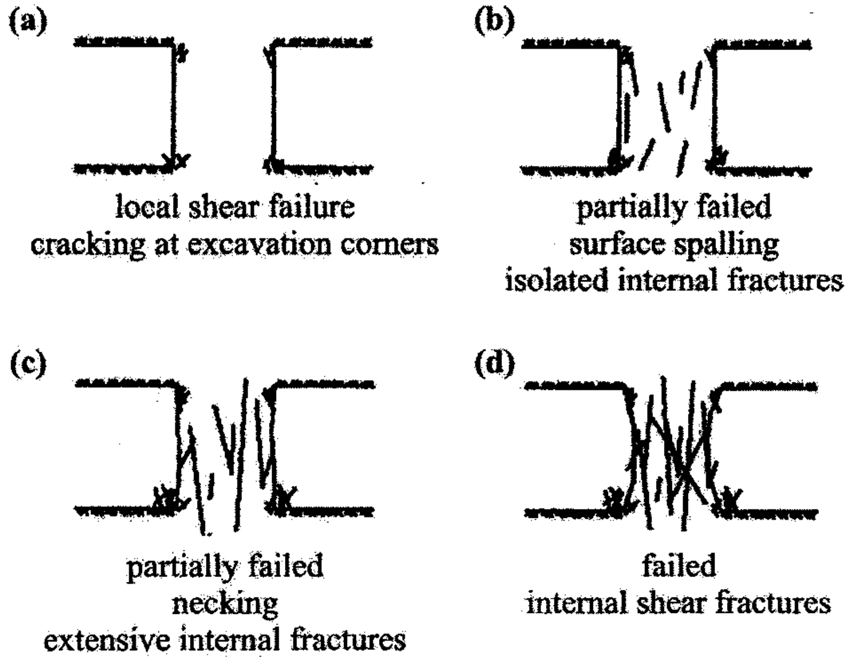
- Evolution of fracture and failure in a pillar in massive rock

  (a) Local shear failure

  (b) Surface spalling

  (c) Network of cracks making extensive fractures

  (d) Failure



13.3 Elementary analysis of pillar support

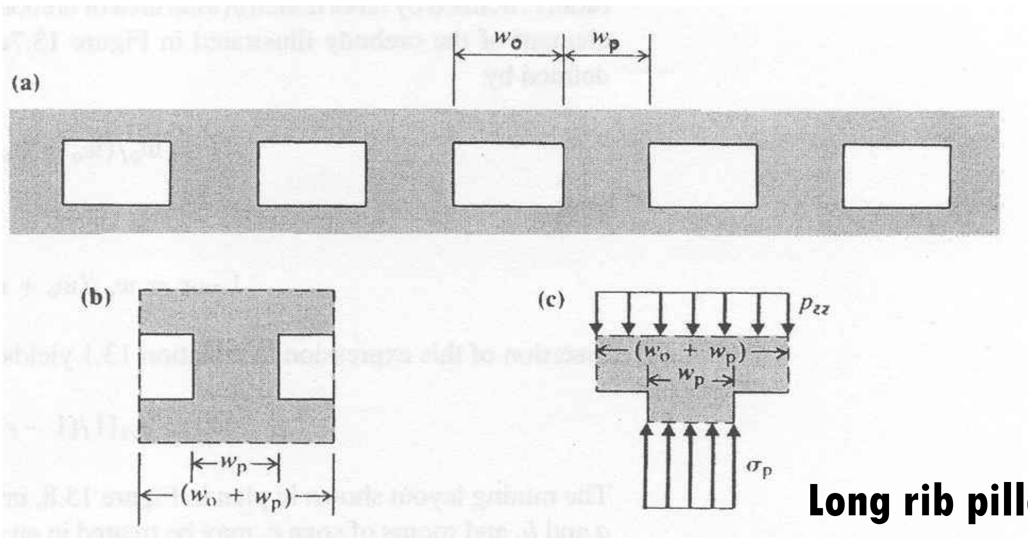
- Tributary area method
- Showing an average axial pillar stress (σ_p)
- The same formula of pillar stress is applied to both of the long rib pillars and column pillars

$$\sigma_p w_p = p_{zz}\left(w_o + w_p\right) \rightarrow \sigma_p = p_{zz}\left(w_o + w_p\right)/w_p$$

$$r = w_o/\left(w_o + w_p\right) \rightarrow 1 - r = w_p/\left(w_o + w_p\right)$$

$$\sigma_p = p_{zz}\left[1/(1-r)\right]$$

r: extraction ratio



Long rib pillars

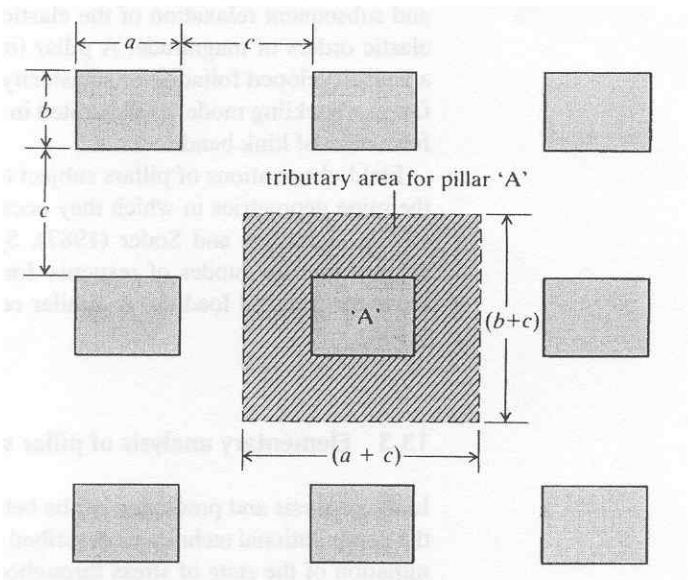
13.3 Elementary analysis of pillar support

$$\sigma_p ab = p_{zz}(a+c)(b+c) \rightarrow \sigma_p = p_{zz}(a+c)(b+c)/ab$$

$$\left(\sigma_p = p_{zz}\left[\left(w_o + w_p\right)/w_p\right]^2 \text{ when } a = b = w_p \text{ and c} = w_o\right)$$

$$r = \left[(a+c)(b+c) - ab\right]/(a+c)(b+c) \rightarrow 1 - r = ab/(a+c)(b+c)$$

$$\sigma_p = p_{zz}\left[1/(1-r)\right]$$



Column pillars

13.3 Elementary analysis of pillar support

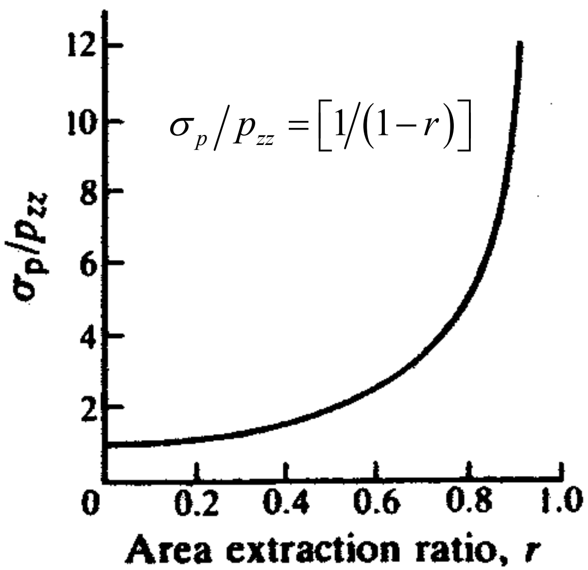
- Pillar stress soars at a certain high level of extraction ratio.
- Extraction ratios greater than 0.75 are rare in natural pillar support.
- Limitation: only the average axial pillar stress is obtained;
  only the pre-mining normal stress component is considered.
- Pillar volume (v)and shape affect its strength (S):

$$S = S_o v^a \left(w_p/h\right)^b = S_o v^a R^b \text{ or } S = S_o h^\alpha w_p{}^\beta : \text{ at } R \le 5$$

$\left(a,\ \alpha < 0 \text{ and } b,\ \beta > 0 \text{ refer to Table 13.1}\right)$

$$S = S_o v^a R_o^b \left[\frac{b}{\varepsilon} \left(\left(\frac{R}{R_o} \right)^\varepsilon - 1 \right) + 1 \right], \quad R > R_o \approx 5 \ (\varepsilon = 2.5)$$

S_o: strength parameter obtained by retro-spective analysis or insitu loading tests

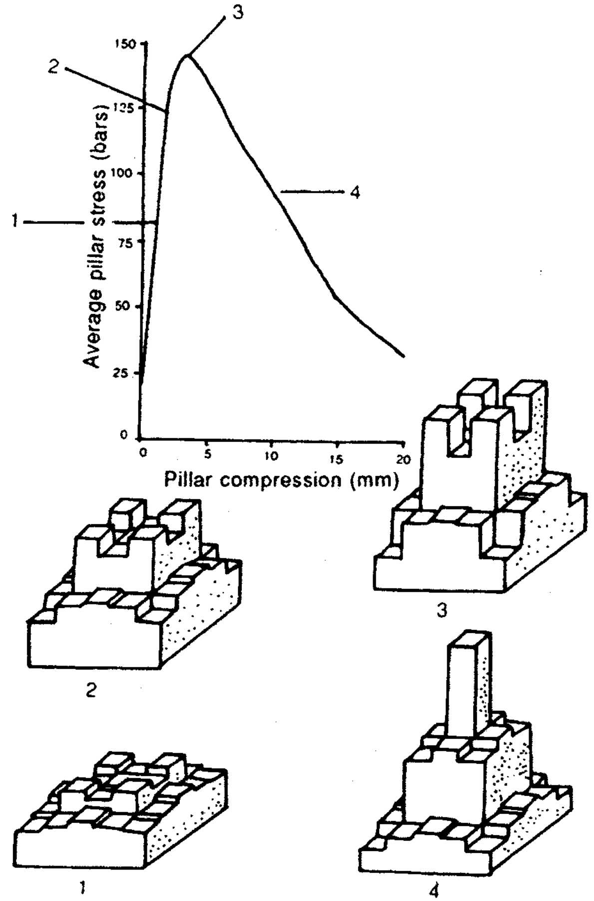


13.3 Elementary analysis of pillar support

- Failure starts at pillar boundary and migrates towards the center.
- Effective width is useful for pillars of irregular shape:

$$w_p^e = 4A_p / C$$

$$\left(w_p^e = 2w_p \text{ for long rib pillar} \right)$$



13.3 Elementary analysis of pillar support

- Width of parallelepiped pillars (Galvin et al., 1999):

For $R < 3$

$$w_e = w = w_1 \sin\theta \quad \text{(min. width)}$$

For $R > 6$

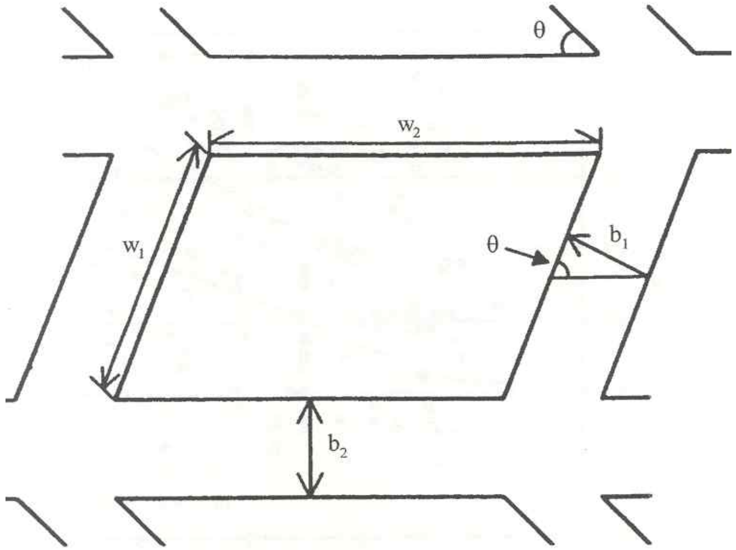
$$w_e = w_{eo} = \Theta_o w, \quad \Theta_o = 2w_2/(w_1 + w_2), \quad 1 \le \Theta_o < 2$$

For $3 \le R \le 6$

$$w_e = \Theta_o^{(R/3-1)} w = \Theta w$$

$$S = S_o h^{\alpha} w_p^{\beta} \rightarrow S_o h^{\alpha} w^{\beta} \Theta^{\beta}$$

$$S = S_o v^a R_o^b \Theta^b \left[\frac{b}{\varepsilon} \left(\left(\frac{R}{R_o} \right)^{\varepsilon} - 1 \right) + 1 \right]$$



13.3 Elementary analysis of pillar support

- Pillar strength in hard rock mines (Lunder and Pakalnis, 1997)

$$S = K\sigma_c\left(C_1 + C_2\kappa\right) \quad \left(\rightarrow S = 0.44\sigma_c\left(0.68 + 0.52\kappa\right)\right)$$

S: pillar strength

K: scale factor relating pillar strength to laboratory scale strength

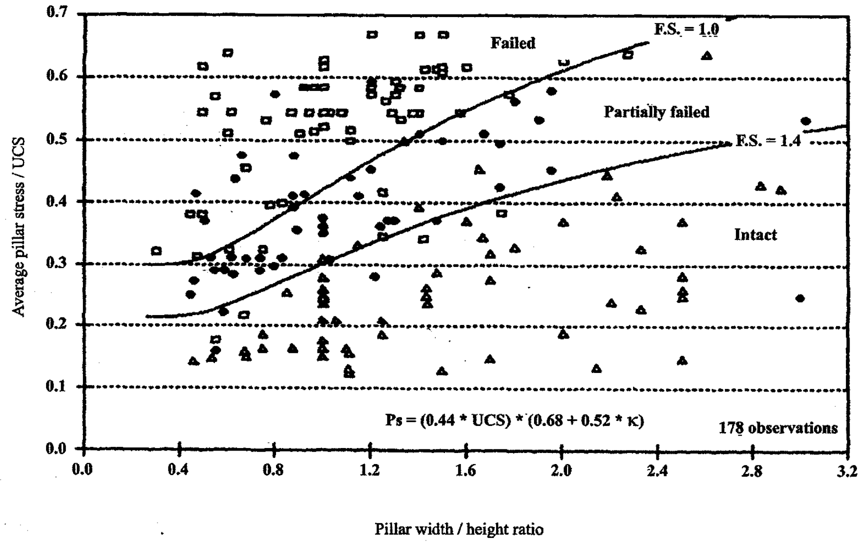
C_1, C_2 : empirical constants

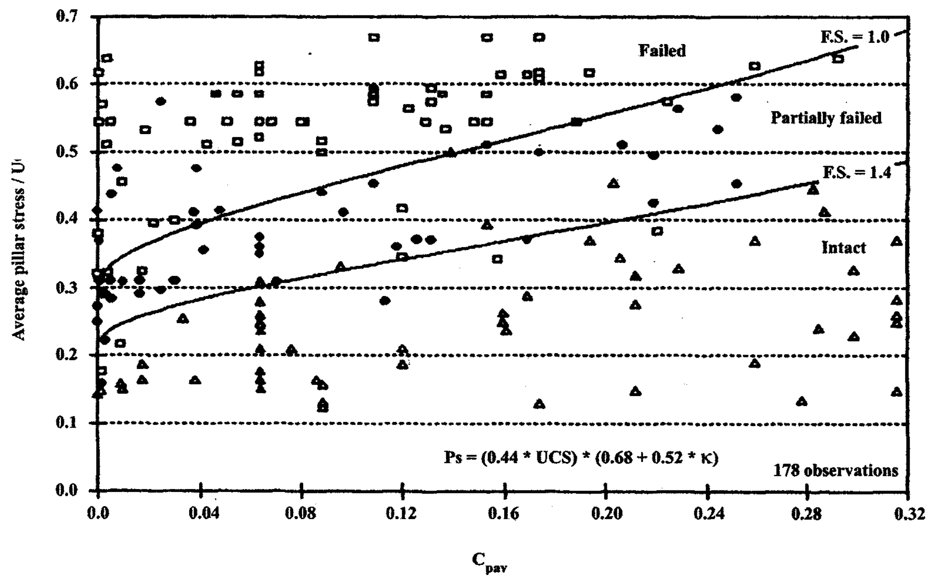
κ : factor of friction mobilized in the pillar core under confining stress

$$\kappa = \tan\left[a\cos\left(\frac{1-C_{pav}}{1+C_{pav}}\right)\right]$$

$C_{pav} = 0.46\left[\log\left(w/h\right) + 0.75\right]$: average pillar confinement

13.3 Elementary analysis of pillar support





13.4 Design of a stope-and-pillar layout

- Ex) Thickness and depth of an orebody: 2.5 m and 80 m
  Unit weight of rock cover: 25kNm^{-3}
  Span of a room and square pillar: 6 m, and 5 m
  Formula of pillar strength: $S = 7.18h^{-0.66}w_p^{0.46}$

  (a) Pre-mining stress: $P_{zz} = 80\,m \times 25\,kNm^{-3} = 2.0MPa$

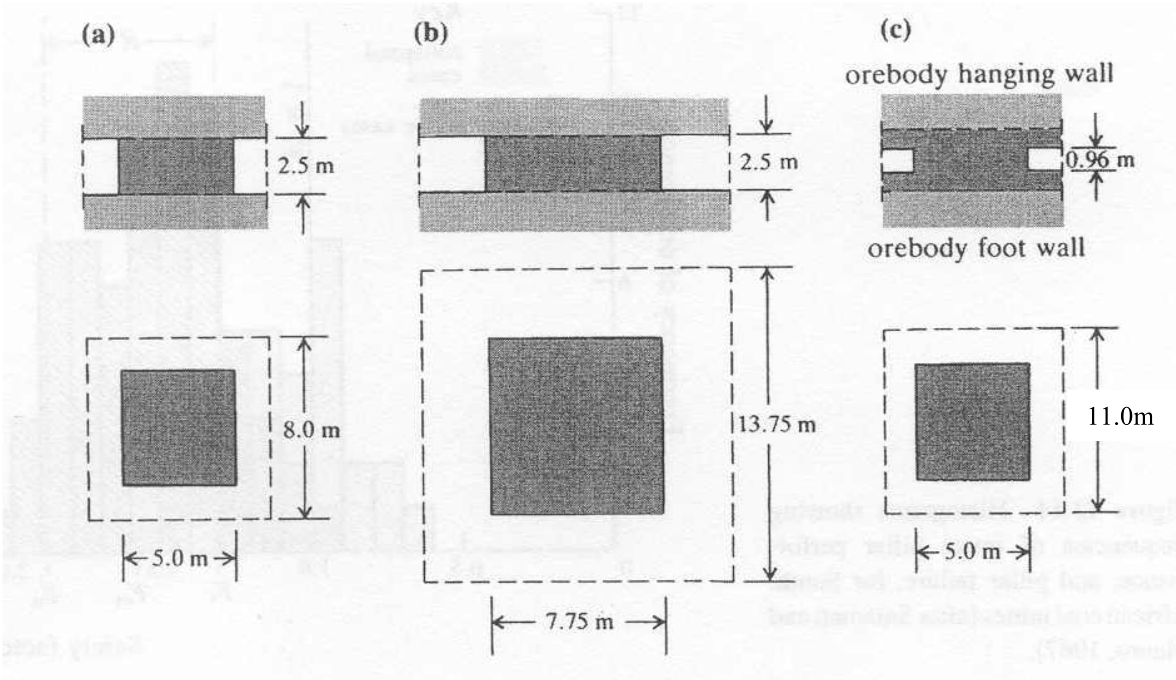
  (b) Average axial pillar stress: $\sigma_p = 2.0MPa \times \left[(6m + 5m)/5m\right]^2 = 9.68MPa$

  (c) Pillar strength: $S = 7.18 \times 2.5^{-0.66} \times 5^{0.46} = 8.22MPa$

  (d) Safety factor: $F = 8.22/9.68 = 0.85$

- To increase the safety factor (→1.6, refer to Fig.13.14)
  (i) to reduce the room span and therefore pillar axial stress
  (ii) to increase pillar width
  (iii) to reduce the pillar height

13.4 Design of a stope-and-pillar layout



(a) $w_o = 3.0\,m,\ \ w_p = 5.0\,m,\ \ h = 2.5\,m$

(b) $w_o = 6.0\,m,\ \ w_p = 7.75\,m,\ \ h = 2.5\,m$

(c) $w_o = 6.0\,m,\ \ w_p = 5.0\,m,\ \ h = 0.96\,m$

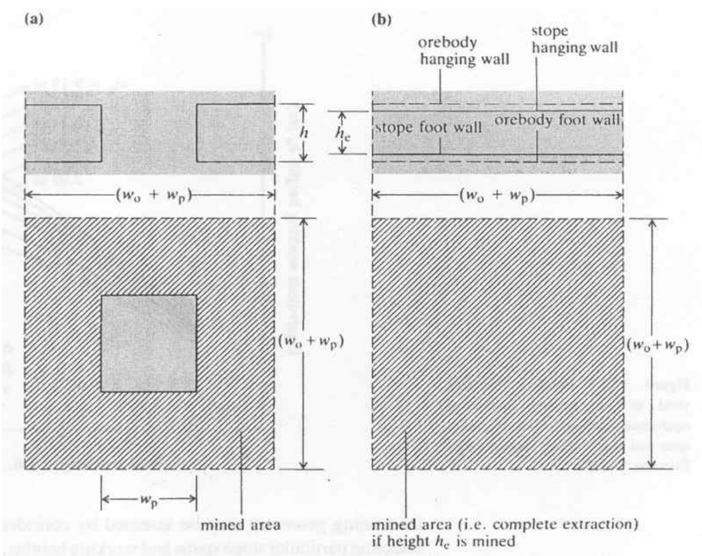
13.4 Design of a stope-and-pillar layout

- Extraction volume and equivalent working height (square pillar)

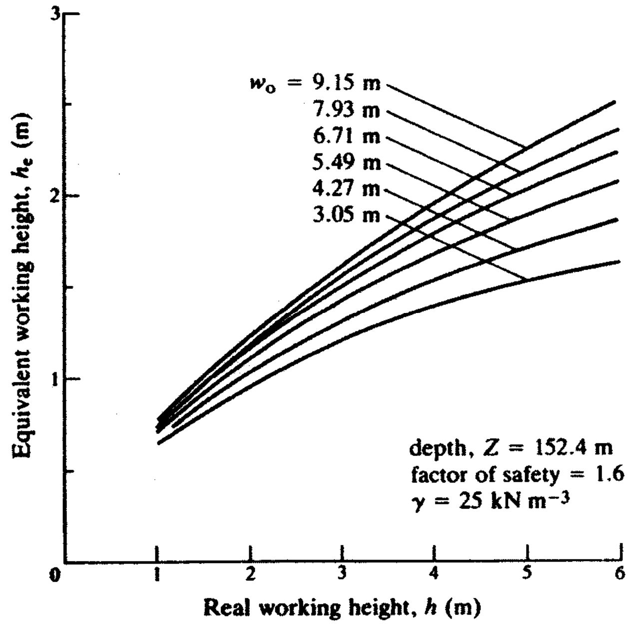
$$V_e = h\left[\left(w_o + w_p\right)^2 - w_p^2\right]$$

$$h_e = h\left[1 - \left(w_p / \left(w_o + w_p\right)\right)^2\right] \quad \because h_e\left(w_o + w_p\right)^2 = V_e = h\left[\left(w_o + w_p\right)^2 - w_p^2\right]$$

- Increased h_e indicates an increased orebody recovery



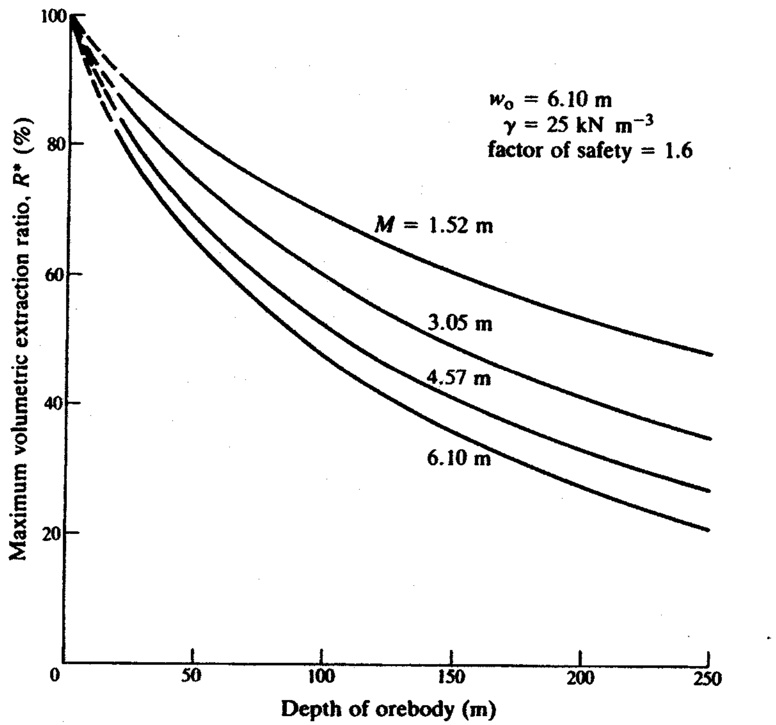
13.4 Design of a stope-and-pillar layout



- Increase of w_o or h increases h_e (and therefore orebody extraction).

→ To maximize the orebody recovery
(S.F. remains constant)
(a) The complete thickness of orebody (M) is mined.
(b) The maximum room span is mined.

13.4 Design of a stope-and-pillar layout



- Volumetric extraction ratio, $R = h_e / M$

- The maximum extraction ratio decreases with increasing depth of the orebody and with increasing thickness of the orebody.

- General conclusions in pillar design:
  (1) With singe phase of mining, the stopes must have the largest stable spans.
  (2) Fully supported methods using pillars are limited to low stress or hard rock conditions.
  (3) Thick orebody in weak rock masses may be mined in successive phases.

13.5 Bearing capacity of roof and floor rocks

- Roof or floor rocks can be punched by pillars

- Capacity and F.S.

- Long rib pillars:

$$q_b = \frac{1}{2}\gamma w_p N_\gamma + cN_c$$

$$N_c = \left(N_q - 1\right)\cot\phi,\ \ N_\gamma = 1.5\left(N_q - 1\right)\tan\phi \quad \text{(bearing capacity factors)}$$

$$N_q = e^{\pi\tan\phi}\tan^2\left[\frac{\pi}{4} + \frac{\phi}{2}\right]$$

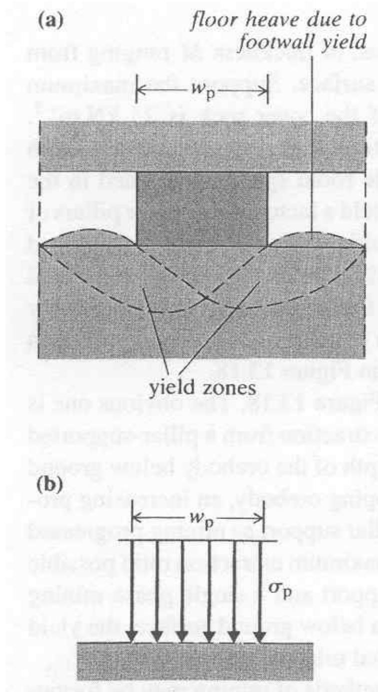
where γ = unit weight, c = cohesion, ϕ = friction angle

- Panel pillars:

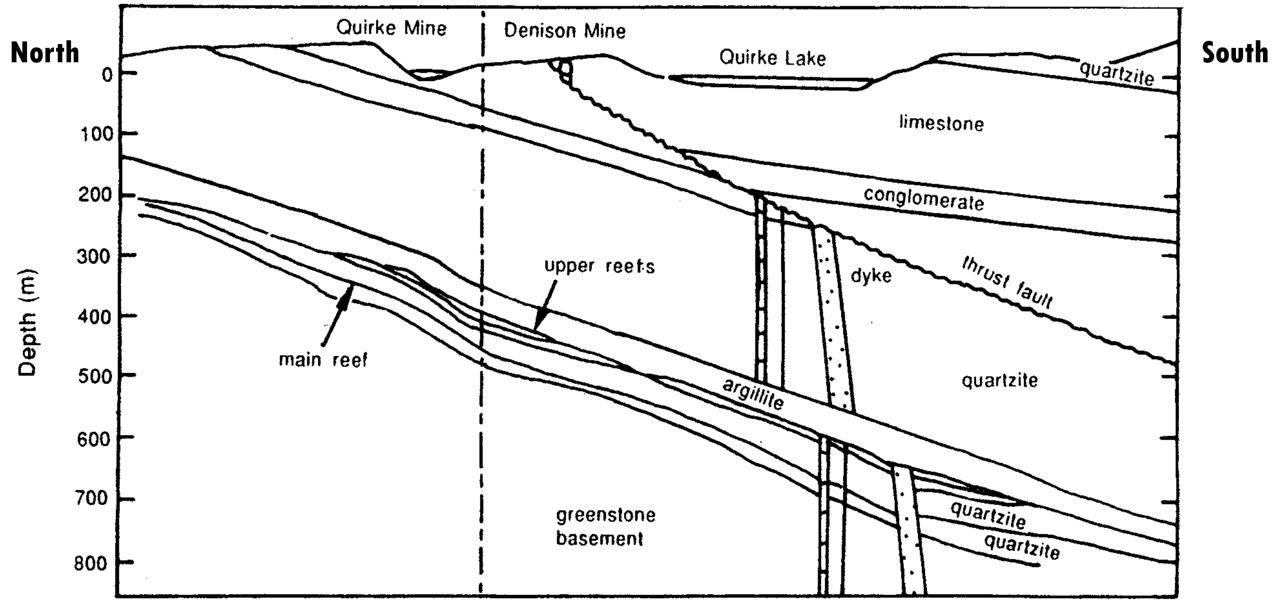
$$q_b = \frac{1}{2}\gamma w_p N_\gamma S_\gamma + c\cot\phi N_q S_q - c\cot\phi$$

$$S_\gamma = 1 - 0.4\left(w_p/l_p\right),\ \ S_q = 1 + \sin\phi\left(w_p/l_p\right) \quad \text{(shape factors)}$$

$$F.S. = q_b/\sigma_p$$

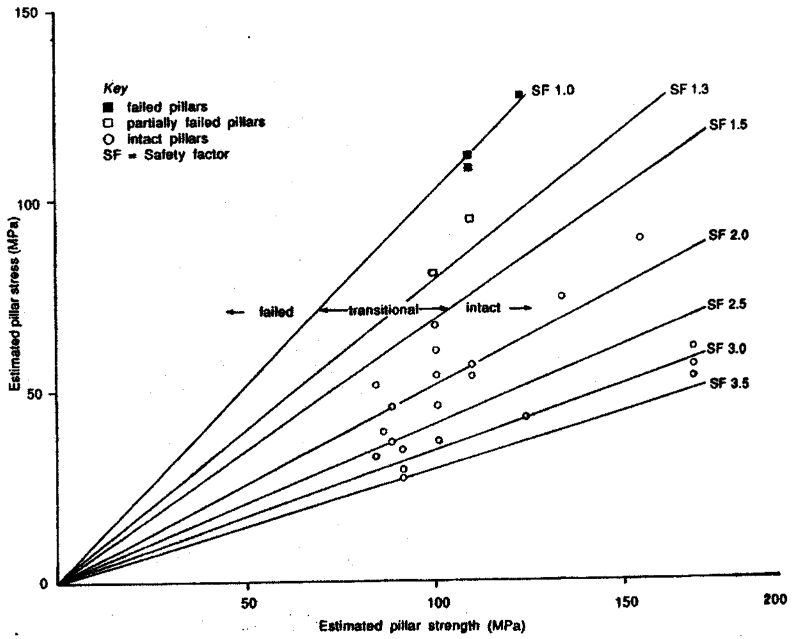


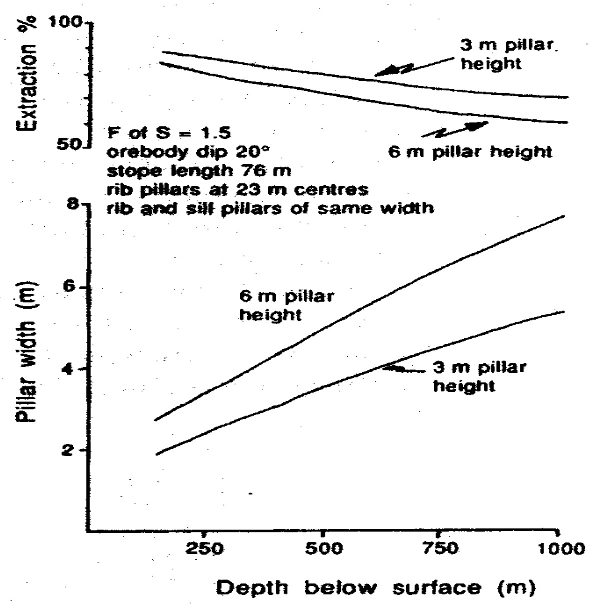
13.6 The Elliot Lake room-and-pillar mines



- Uranium-bearing orebodies: 3 m ~ 8 m thick, dip south 15° ~20°, 1,050m deep at max.
- Transport drift: along strike, at 47 m vertical interval (→ 76 m of stope length)

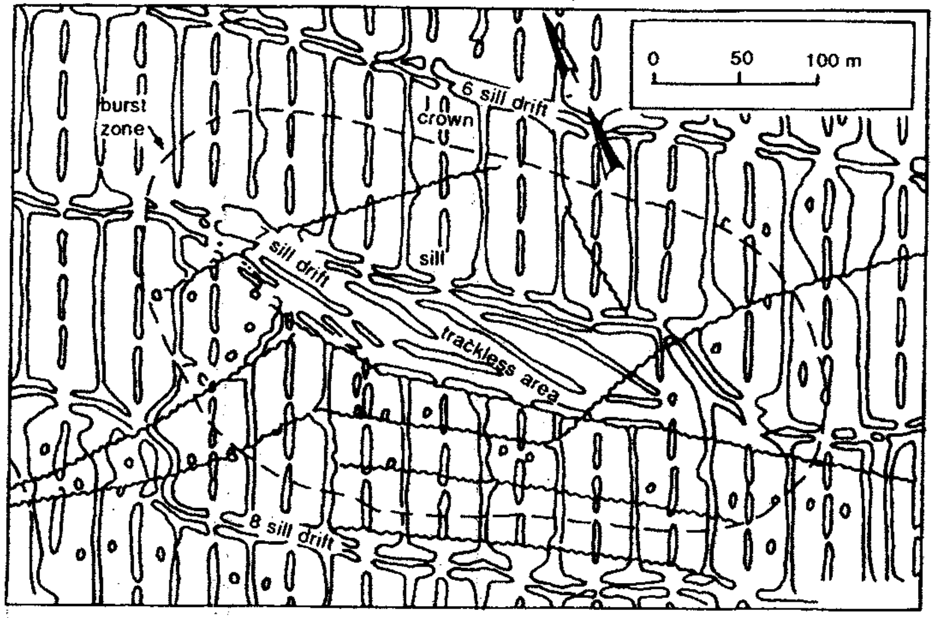
13.6 The Elliot Lake room-and-pillar mines

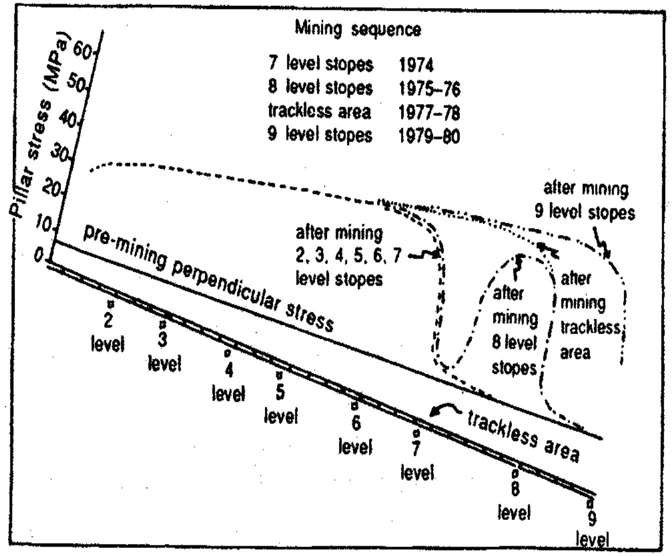




- Rib pillar: Strength, $S = 133\ h^{-0.75}\ w_p^{0.5}$, 23 *m* apart on strike (S.F.=1.5 adopted)
- Extraction ratio: 70~85% until 1981

13.6 The Elliot Lake room-and-pillar mines

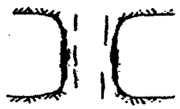




- Pillar failure: in trackless area when 9 level stopes were in progress and bursting in the seven level sill pillars
- Cause of the failure: local increase in orebody thickness and pillar height reduced pillar strength and safety factor (especially at trackless area having relatively high extraction ratio)

13.6 The Elliot Lake room-and-pillar mines

Table 13.2 Doe Run pillar condition rating system (after Roberts *et al.*, 1998).

Pillar rating	Pillar condition	Appearance
1	No indication of stress induced fracturing. Intact pillar.	
2	Spalling on pillar corners, minor spalling of pillar walls. Fractures oriented sub-parallel to walls and are short relative to pillar height.	 Plan
3	Increased corner spalling. Fractures on pillar walls more numerous and continuous. Fractures oriented sub-parallel to pillar walls and lengths are less than pillar height.	
4	Continuous, sub-parallel, open fractures along pillar walls. Early development of diagonal fractures (start of hourglassing). Fracture lengths are greater than half of pillar height.	
5	Continuous, sub-parallel, open fractures along pillar walls. Well developed diagonal fractures (classic hourglassing). Fracture lengths are greater than half the pillar height.	
6	Failed pillar, may have minimal residual load carrying capacity and be providing local support to the stope back. Extreme hourglassed shape or major blocks fallen out.