CHAPTER 7
CASE HISTORIES AND APPLICATIONS

7-1. General. This section summarizes underground rock reinforcement experience on a number of major underground projects completed since the year 1950. A more general background and history on rock reinforcement is presented in Appendix A. In this section, detailed information is presented which may be useful because the design and construction of new underground projects is largely based on previous experience. The data presented are not intended to substitute for the extensive study of past projects required of rock reinforcement designers. However, one of the objectives of summarizing the tabulated data is to present design parameters which are presently useful or which may become useful as additional data become available from new projects.

7-2. Data on Underground Chambers, Tunnels, and Shafts.

a. Table 7-1 presents data patterned after the manner used by Cording, Hendron, and Deere,[29] except that somewhat more detail is included in table 7-1. The information presented was gathered from the literature or from the designers of projects. In addition to factual information identified by the column headings, calculated values useful for establishing design parameters are also shown. These include element length to opening span (width or height) ratios, estimated average confining pressure exerted on the rock surface by the reinforcing element when initially tensioned, and a projected value for average confining pressure at the yield strength of the element. The confining pressure is then related to the unit weight of the rock and the opening width (or height) by a factor n (or m), which is defined below.

b. Cording, et al., stated that in a rock mass having both frictional resistance and cohesion, acted upon by its own body forces, the internal pressure, P_i, required to maintain stability would be:

$$P_i = nB\gamma - \text{(rock mass cohesion)}$$

where n is a function of the frictional resistance of the rock mass, B is the width of the opening, and γ is the unit weight of the rock. The rock mass cohesion should be related to the ratio of joint spacing to B. For a given joint spacing, increasing B will decrease the rock mass cohesion. Thus, a small opening may be stable with no internal pressure while a large opening may require support.

c. For large openings, if the rock mass cohesion is assumed to be zero, the relation becomes $P_i = nB\gamma$. In terms of measurable rock properties, n can be considered a function of (1) rock quality, (2) displacement along discontinuities, (3) strength and orientation of discontinuities, and (4) the ratio of intact unconfined compressive strength to the maximum natural stress, q_u/σ . Values of (q_u/σ) less than 5.0 are indicative of stress conditions where new fractures will form around the opening upon excavation and where shearing and crushing of irregularities on discontinuities is likely to take place as rock wedges displace.

d. Figure 7-1 compares cavern width, B , with the average support pressures which have been used in the crowns of chambers. The support pressure, P_i , is defined as the yield capacity of the bolt divided by the square of the bolt spacing. Support pressures generally fall within the range of n = 0.1 to 0.25 , equivalent in a 100-foot-wide cavern to supporting 10 to 25 feet of rock. Figure 7-2 compares height of caverns with average pressure used on walls. Wall support pressures are generally lower than crown pressures with values of m ranging from 0.04 to 0.13 and above.

e. Figures 7-3 and 7-4 summarize bolt lengths used in underground openings. Most of the bolts used in the crowns of large openings fall within the range of 0.2B to 0.4B with the ratio increasing for tunnels under 25 feet in diameter. Bolt lengths used in sidewalls range, widely, from 0.1H to 0.5H.

7-3. Anchorage of Structures. Rock bolts and rock anchors have been used to anchor several types of structures. In civil engineering projects, uses have included anchoring concrete walls to rock, anchoring retaining walls, anchoring spillway weirs and stilling basins, and anchoring several other types of miscellaneous structures. Stability analyses for these types of structures are covered in other Engineering Manuals and will not be discussed here.

Table 7-1. Reinforcement in Underground Chambers, Tunnels and Shafts

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$		$n = P_i/B\gamma$ $m = P_i/H\gamma$		Bolt Length / Span		Comments
							Initial	Yield	Initial	Yield	$\frac{\ell}{B}$	$\frac{\ell}{H}$	
1	East Delaware Tunnel New York, N. Y.		Aqueduct 1950	H = B = 13 L = 63,360 D = Circular	Shale, red, flat bedded Sandstone, gray, thinly laminated	Ungrouted, 1-in.-diam by 6-in.-long slot and wedge rock bolts. S = approximately 3 ft but varied to meet local conditions. Steel channels and ties used on rock surface					0.46		Approximately 30,000 ft of tunnel reinforced. Gunite placed after bolts were installed
2	Nechako-Kemano-Kitimat British Columbia, Canada Aluminum Co. of Canada, Ltd.	British Columbia International Co., Ltd.	Kemano power development, underground hydro-electric power-plant chamber 1952	H = 120 B = 82 L = 700 D = 1500, cover Parabolic arch roof mined with rise of 37 ft and span of 103 ft Vertical walls	Granodiorite containing many small feldspar - aplite and diorite dikes; two dominant and two minor faults intersect chamber q_u = 16-25 ksi γ = 171 pcf	Ungrouted "fishtail" slot and wedge bolts, 12-16 ft long in walls. Following a massive fallout in west wall, over 1500 "fishtail," 1-1/2-in.-diam by 30- to 40-ft-long bolts placed in inclined diamond drilled holes filled with fluid sand cement grout, wedges driven tight, and bolts stressed with torque wrench						0.25 0.33	Rock bolts provide permanent reinforcement of walls. Continuous reinforced concrete arch supports roof. 2,200 temporary "fishtail" rock bolts and 11,000-cu-yd gunite were used during roof mining to assure personnel safety
3	Glendo Dam Glendo, Wyo. U.S.Bureau of Reclamation	U. S. Bureau of Reclamation C.F. Lytle Co. Green Construction Co.	Intake tunnel 1955-1958	H = B = 24.5 L = 1150 D = Circular	Sandstone, shale γ = say 165 pcf	Ungrouted, 3/4-in.-diam by 6-ft-long expansion shell rock bolts. 6,267 lin ft installed at 4-ft spacing where considered necessary. Bearing plates: 6 in. triangular by 1/2 in. thick. F_y = 15k		7		0.25	0.24		
4	Hills Creek Dam Oak Ridge, Ore. CE, Portland District	Corps of Engineers Shea Co.	Diversion tunnel 1956	H = B = 27 L = 1150 D = Horseshoe	Lapilli tuff, with areas of weak faults and joints γ = 134 pcf q_u = 5-7 ksi	Ungrouted, 1-in.-diam slot and wedge rock bolts, 10 ft long in crown, 8 ft long to springline, placed in 800 ft of tunnel. S = 5 ft each way. T_n = 250-300 ft-lb, F_i = 10k, F_y = 24k	3	7	0.12	0.28	0.30 0.37		Remainder of tunnel supported with steel sets. Tunnel is lined with reinforced concrete
5			Regulating tunnel 1959	H = B = 18 L = 545 D = Circular	Lapilli tuff, massive, with minor faults	Ungrouted, 1-in.-diam-slot and wedge rock bolts, 10 ft long in crown, 6 ft long to springline. S = 4 by 5 ft. T_n = 200-300 ft-lb, F_i = 8k, F_y = 24k	3	8	0.12	0.32	0.33 0.44		Tunnel is lined with reinforced concrete
6			Penstock tunnel 1959	H = B = 16 L = 667 D = Circular	Lapilli tuff with 20-ft-wide fault gouge zones	Ungrouted, 1-in.-diam slot and wedge, 10 ft long in crown and faults, 8 ft long to springline, 6 ft long in faults below springline. S = 4 by 4 ft above springline and 4 by 6 ft below. T_n = 100-200 ft-lb in fault zones, F_i = 4k; T_n = 200-300 ft-lb in intact rock, F_i = 8k, F_y = 24k	4 2 (faults)	13	0.19	0.45	0.50 0.63		Tunnel is lined with reinforced concrete

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Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$ Initial	 Yield	$n = P_i/B\gamma$ $m = P_i/H\gamma$ Initial	 Yield	Bolt Length / Span $\frac{\ell}{B}$	 $\frac{\ell}{H}$	Comments
7	Cougar Dam Eugene, Ore. Corps of Engineers	CE, Portland District Merritt, Chapman, & Scott, Inc.	Diversion tunnel 1956	H = B = 20 L = 1834 D = Horseshoe	Bedded Lapilli tuff Basalt near portal γ = 160 pcf q_u = 7-21 ksi	Ungrouted, 1-in.-diam slot and wedge rock bolts, 8 ft long in crown, 6 ft long to springline, and below springline in faulted areas. S = 4 by 5 ft. F_y = 24k, T_n = 250-300 ft-lb, F_i = say 10k	3.5	8.4	0.19	0.45	0.30 0.40		Temporary diversion tunnel, unlined
8			Penstock tunnel 1960	H = B = 16 L = 1028 D = Circular	Part Lapilli tuff, bedded; part basalt with vertical joints and faults	Ungrouted, 3/4-in.-diam expansion shell rock bolts, 6 ft long, S = 5 by 5 ft, T_n = 150-200 ft-lb, F_i = say 6k, F_y = 15k	1.7	4.2	0.11	0.28	0.33		Tunnel is lined with reinforced concrete
9			Regulating tunnel 1960	H = B = 22 L = 993 D = Horseshoe	Basalt, some widely spaced vertical joints with some oxidation and water seeps	Same as penstock tunnel, except 8-ft-long bolts used in crown, 6 ft long to springline	1.7	4.2	0.07	0.20	0.27 0.36		Tunnel is lined with reinforced concrete
10	Haas Hydroelectric Power Project 50 miles north of Fresno, Calif. Pacific Gas & Electric Co.	Pacific Gas & Electric Co. Morrison-Kaiser-Macco-Ferini	Underground power plant chamber 1957	H = 100 B = 56 L = 173 D = 500	Massive granite (widely spaced fractures) γ = say 170 pcf	Fully grouted perforated-sleeve rock anchors, 1-in.-diam deformed reinforcing bar with Portland cement-sand grout, 10, 12.5, and 15 ft long spaced at 3.5 ft each way. Installed in arch roof. Gunite mesh, 4 by 4 in. by No. 6, attached to bars and 4-in.-thick gunite to surface of roof. 2,000 rock anchors and 13,000-sq-ft gunite placed. Steel yield unknown, say 36k	0	20	0	0.30	0.18- 0.27		First large underground hydroelectric power plant constructed in the U.S.A.
11	Binga Hydro-electric Project Luzon, Republic of Phillipines National Power Corp.	National Power Corp. & Engineering Development Corp. of Phillipines Phillipine Engineers Syndicate, Inc., & Platzer, AB, Stockholm	Underground power plant chamber Prior to 1959	H = 93.5 B = 50 L = 255 D = 300	Metamorphosed andesites and sedimentary rocks intruded in places by diorite and other igneous rocks	Rock bolts consisting of deformed reinforcing bar, 10-20 ft long, inserted in grout mortar placed by the Swedish SN method. Lower portions of walls reinforced at 3.3-ft spacing each way. Generally installed pointing upward, 30-45 deg from horizontal, with some horizontal		12.9			0.11- 0.21		Size, strength, and initial load on bars unknown. In pull tests, an embedment of 3-5 ft developed full bar strength (in excess of 20k) in a variety of rock types, including the softer rocks
12	Broken Bow Dam Broken Bow, Okla. CE, Tulsa District	Corps of Engineers Nello L. Teer	Diversion tunnel 1962	H = B = 18 L = 1090 D = Circular	Argillite, shale, limestone	Ungrouted 3/4-in.-diam headed rock bolts with expansion shell, S = 5 ft longitudinal by 4.5 ft perimetrical, 6- by 6- by 3/8-in.-bearing plate, 4- by 4-in.- by No. 6 wire mesh on rock surface, F_y = 15k, T_n = 150 ft-lb, F_i = 6.5k	2	4.5	0.1	0.22	0.44		

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Table 7-1. (Continued)

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								Initial	Yield	Initial	Yield	ℓ/B	ℓ/H	
13	NORAD Cheyenne Mountain Complex Colorado Springs, Colo. North American Air Defense Command	CE, Omaha District; Parsons, Brinkerhoff, Quade & Douglas; A. J. Ryan & Associates Utah Mining & Construction Co.	Parallel chambers A, B, and C, typ.	H = 60.5 B = 45 L = 1368, total	Coarse-grained biotite granite intruded by fine-to-medium-grained granite and thin basalt dikes Pegmatite dikes may occur locally. Granite is closely fractured (3 in.-3 ft) and mostly unaltered. Predominant fracture system composed of two steeply dipping sets, striking NE and NW γ = 174 pcf q_u: Coarse-grained 19-29 ksi Fine- to- medium grained, 24-35 ksi Coarse-grained, highly altered, 4.8-8.6 ksi RQD: Coarse-grained, good Fine-grained, fair to good	S, Length Arch: 4 by 4 ft, 10 ft Walls: 5 by 5 ft, top 1-12 ft, bottom 2-8 ft, remainder-10 ft	Fully grouted slot and wedge rock bolts, 3/8-in.-thick bearing plates by 8-in. square or equilateral triangle. Chain link fabric, 2 by 2 in. by No. 6 gate, over rock surface. Some mine ties used to support rock between bolts. T_n = 275 ft-lb, F_i = 9k, F_y = 26k	Arch 3.9 Walls 2.5	Arch 11.3 Walls 7.2	n 0.07 m 0.03	n 0.21 m 0.10	0.22	0.17	*Construction period: 1961-1964 **Shape of chambers and tunnels on this sheet consists of semicircular arch with vertical sidewalls At intersection corners of large chambers, 12-, 14-, and 18-ft-long bolts used in lieu of those shown for a distance of 16 ft from the corners
14			Power plant chamber	H = 56 B = 50 L = 132				"	"	n 0.07 m 0.04	n 0.19 m 0.11	0.20	0.18	
15			Parallel building chambers 1, 2, and 3, typ.	H = 56 B = 32 L = 600, total		Arch: 4 by 4 ft, 8 ft Walls: 5 by 5 ft, 10 ft except bottom 2-8 ft		"	"	n 0.10 m 0.04	n 0.29 m 0.11	0.25	0.18	
16			Chambers A and B between 3 and 4	H = 36 B = 45 L = 200		Arch: 4 by 4 ft, 10 ft Walls: 5 by 5 ft, Upper one-12 ft, Others - 8 ft		"	"	n 0.07 m 0.06	n 0.21 m 0.17	0.22	0.22 0.33	
17			Chamber 4	H = 36 B = 32 L = 200		Arch: 4 by 4 ft, 8 ft Walls: 5 by 5 ft, 8 ft Upper two-10 ft		"	"	n 0.10 m 0.06	n 0.29 m 0.17	0.25	0.22 0.28	
18			North access tunnel	H = 22.5 B = 29 L = 1094, total			Same as above except bolts ungrouted and no chain link fabric	3.9	11.3	n 0.11	n 0.32			North access lined with 2-ft-8-in.-thick reinforced concrete for 269 ft beginning at portal
a			Pattern No. 1 (minimum reinforcement)	L = (498)		4 by 4 ft, 3-8 ft at crown, 6 ft at haunches and one below springline						0.21 0.28	0.27	
b			Pattern No. 2	L = (328)		4 by 4 ft, 14 ft over arch and one below springline						0.48	0.62	
19			North access transition tunnel	H = 22.5-25 B = 29-45 L = 324		4 by 4 ft, three 8 ft at crown, 6 ft at haunches	Same as north access tunnel, except 192 ft covered with chain link fabric	"	"	n 0.07 0.11	n 0.21 0.32	0.18 0.28	0.24 0.27	
20			Turn-around tunnel	H = 20.5 B = 32 L = 50		4 by 4 ft, 8 ft over arch to within 5 ft of springline. 10 ft long at springline	Same as north access tunnel, except chain link fabric over entire length	"	"	n 0.10	n 0.29	0.25	0.39 0.49	

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Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period*	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape**	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)		Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$		$n = P_i/B\gamma$ $m = P_i/H\gamma$		Bolt Length / Span		Comments
								Initial	Yield	Initial	Yield	$\frac{\ell}{B}$	$\frac{\ell}{H}$	
21	NORAD Cheyenne Mountain Complex Colorado Springs, Colo. North American Air Defense Command	CE, Omaha District; Parsons, Brinkerhoff, Quade & Douglas; A. J. Ryan & Associates Utah Mining & Construction Co.	Central access tunnel Pattern No. 1	H = 25 B = 45 L = 591 L = (156)	See page 7-3	S, Length 4 by 4 ft, 16 ft long at crown and upper haunch, 14 ft @ midhaunch, 12 and 10 ft lower haunch	Ungrouted 1-in.-diam slot and wedge rock bolts, 3/8-in.-thick bearing plates by 8-in.-square or equilateral triangle. Chain link fabric, 2- by 2-in. by No. 6 gage, over the rock surface T_n = 275 ft-lb, F_i = 9k, F_y = 26k	3.9	11.3	n 0.07 m 0.13	n 0.21 m 0.37	0.31 0.31	0.40 0.48	*Construction period: 1961-1964. **Shape of all tunnels or adits on this sheet consists of semicircular arch with vertical sidewalls
a			Pattern No. 2	L = (93)		4 by 4 ft, 10 ft @ crown, 8 ft @ upper haunch, 6 ft @ midhaunch				n 0.07	n 0.21	0.13 0.18 0.22		**Portions of central access tunnel were supported with steel sets and lined with reinforced concrete**
b			Pattern No. 3	L = (138)		4 by 4 ft, 18 ft long over entire arch	Grouted expansion shell hollow core deformed bar rock bolts, 1-in.-diam, 3/8- by 8-in.-square bearing plates on mortar pads T_a = 250 ft-lb, T_n = 275 ft-lb, F_i = 9k, F_y = 36k	3.9	15.6	n 0.07 m 0.13	n 0.29 m 0.52	0.40	0.72	200 ft of central access tunnel reinforced with Patterns Nos. 3 and 4 was treated with 2-in. thickness of shotcrete reinforced with 2- by 2-in. by No. 12 wire mesh over entire arch
c			Pattern No. 4	L = (120)		Same as Pattern No. 3	**Same as Pattern No. 3, except solid deformed bar used**							
22			South access tunnel	H = 17.5 B = 15 L = 2171										
a			Pattern No. 1	L = (1423)		4 by 4 ft; 5 each, 6 ft long over crown and upper haunch	Ungrouted slot and wedge rock bolts, 1 in. diam. No fabric over rock surface T_n = 275 ft-lb, F_i = 9k, F_y = 26k	3.9	11.3	n 0.21	n 0.62	0.40		270 ft of south tunnel was supported with steel sets and lined with reinforced concrete
b			Pattern No. 2	L = (346)		4 by 4 ft, 8 ft in arch, 6 ft in walls				n 0.21 m 0.18	n 0.62 m 0.54	0.53	0.34	
c			Pattern No. 3	L = (132)		4 by 4 ft, 8 ft over arch and walls	Fully grouted perforated sleeve rock anchors, 1-in.-diam deformed bars. Rock surface covered with 8-in.-thick shotcrete reinforced with 1 layer 2 by 2 in. by No. 12 and 2 layers 2 by 2 in. by No. 10 wire mesh. F_y = 30k	0	13.0	0	n 0.73 m 0.62	0.53	0.46	
23			Pedestrian and access adit	H = 24 B = 32 L = 390		4 by 4 ft, 8 ft in crown and upper haunch, 6 ft at midhaunch	Ungrouted 1-in.-diam slot and wedge rock bolts. Chain link fabric over rock surface	3.9	11.3	n 0.10	n 0.29	0.19 0.25		
24			Reservoir adit	H = 16 B = 20 L = 246		Ungrouted 1-in.-diam slot and wedge rock bolts, 6 ft long in arch. Chain link fabric over rock arch. S = 4 by 4 ft. T_n = 275 ft-lb, F_i = 9k, F_y = 26k		3.9	11.3	n 0.16	n 0.47	0.30		
25			Reservoir access adit	H = 16 B = 32 L = 48		Same as reservoir adit, except 8-ft-long rock bolts used		3.9	11.3	n 0.10	n 0.29	0.25		

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Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period*	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape**	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$: Initial	Yield	$n = P_i/B\gamma$ $m = P_i/H\gamma$: Initial	Yield	Bolt Length / Span: $\frac{\ell}{B}$	$\frac{\ell}{H}$	Comments
26	NORAD Cheyenne Mountain Complex Colorado Springs, Colo. North American Air Defense Command	CE, Omaha District; Parsons, Brinkerhoff, Quade & Douglas; A. J. Ryan & Associates Utah Mining & Construction Co.	Adits A and B	H = 18.75 B = 17.5 L = 679	See page 7-7 for general rock description at NORAD Cheyenne Mountain Complex	Fully grouted hollow core deformed bar, No. 8 (1-in.-diam) 10-ft-long expansion shell rock bolts over 195 ft of adits. S = 4 by 4 ft over arch. Ungrouted solid deformed bar No. 8 expansion shell rock bolts, 10 ft long, over 484 ft of adits. S = 4 by 8 ft over arch. T_a = 250 ft-lb, T_n = 275 ft-lb, F_i = 9k, F_y = 36k	3.9 2.0	15.6 7.8	n 0.18 n 0.09	n 0.74 n 0.37	0.57		*Construction period: 1961-1964. **Shape of tunnels, adits and chambers on this sheet consist of semi-circular arch with vertical walls
27			Air exhaust tunnel	H = 12 B = 12 L = 4675									108 ft of tunnel supported with steel sets and 2-in. shotcrete on rock surface
a			Pattern No. 1	L = (3900)		Ungrouted 1-in.-diam slot and wedge rock bolts, 6 ft long. 3 bolts at 4 ft installed in upper arch at locations determined in field					0.50		
b			Pattern No. 2	L = (449)		Ungrouted slot and wedge bolts, 8 ft long in arch, 6 ft long at springline. S = 4 by 4 ft	3.9	11.3	n 0.27	n 0.78	0.67		
c			Pattern No. 3	L = (158)		Fully grouted perforated sleeve-type anchor bars. No. 8 by 8-ft-long deformed bars. S = 4 by 4 ft. Rock surface covered with 6-in.-thick shotcrete. F_y = 30k	0	13	0	n,m 0.90	0.67	0.67	Rock surface covered with 6-in.-thick shotcrete reinforced with one layer 2- by 2-in. by No. 12 and two layers of
d			Pattern No. 4	L = (60)		Same as Pattern No. 3, except that at every 12-ft interval along tunnel, anchor bar length increased to 12 ft and spacing decreased to 2 ft	0	13 26	0	n,m 0.90 1.80	0.67 1.0	0.67 1.0	2- by 2-in. by No. 10 welded wire mesh. Rock surfaced covered with 1/2-in. minimum thickness shotcrete
28			Cooling tower chamber	H = 30 B = 45 L = 53		Fully grouted slot and wedge rock bolts, 12 ft long in arch, 10 ft long at springline, 8 ft long in wall. S = 4 by 4 ft. Shotcrete on rock surface, 2 in. thick, reinforced with one layer 2- by 2-in. by No. 12 welded wire mesh	3.9	11.3	n 0.07 m 0.11	n 0.21 m 0.31	0.27	0.27	Shotcrete, 2-in. thick, reinforced with 2- by 2-in. by No. 12 wire fabric over rock surface
29			Exhaust shaft adit	H = 34.5 B = 22 L = 36		16 ft of adit reinforced 12-ft-long fully grouted No. 11 (1-3/8-in.-diam) hollow core deformed bar rock bolts with expansion shells. T_a = 375 ft-lb, T_n = 600 ft-lb, F_i = 25k, F_y = 70k 20 ft of adit reinforced with fully grouted perforated sleeve-type rock anchors, No. 10 (1-1/4-in.-diam) by 12-ft-long deformed bars. S = 4 by 4 ft, F_y = 52k	10.8 0	30.4 22.6	n 0.41 m 0.25 0	n 1.14 m 0.70 n 0.85 m 0.52	0.55	0.35	Shotcrete, 4 in. thick, reinforced with two layers wire fabric over rock surface. Surface of shotcrete painted with epoxy
30			Central exhaust shaft 1961-1964	Vertical shaft, 12 ft square by 91 ft high		Fully grouted 1-in.-diam slot and wedge rock bolts, 6 ft long. S = 4 by 4 ft. T_n = 275 ft-lb, F_i = 9k, F_y = 26k	3.9	11.3	Does not apply		Does not apply		Surface of rock covered with 4-in. thickness of shotcrete reinforced with two layers 2- by 2-in. by 12-gage welded wire fabric

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Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$ Initial	 Yield	n = P_i/B γ m = P_i/H γ Initial	 Yield	Bolt Length / Span $\frac{\ell}{B}$	 $\frac{\ell}{H}$	Comments
31	NORAD Cheyenne Mountain Complex Colorado Springs, Colo. North American Air Defense Command	CE, Omaha District; Parsons, Brinkerhoff, Quade & Douglas, A. J. Ryan & Associates Utah Mining & Construction Co.	Intersection of Chamber B and Chamber 2 1963-1964	Chambers initially mined to dimension shown in Items 13 and 15, page 7-7	Intersection of two shear zones created the necessity for special reinforcement and support of the B-2 intersection See page 7-7 for general rock properties	In circular chamber sections: Fully grouted recessed rock anchors, perforated sleeve type, No. 10 (1-1/4-in.-diam) by 18-ft-long deformed bars over roof and walls to midway between springline and invert. S = 8 by 8 ft. Superposed at S = 4 by 4 ft are recessed rock anchors, No. 10 by 12 ft long in area beginning midway between invert and springline and extending to midway between springline and crown. Superposed in remaining roof at S = 4 by 4 ft are No. 8 by 12-ft-long fully grouted hollow core deformed bar expansion shell rock bolts	Roof No. 8 3.9	Roof No. 8 15.6 No. 10 5.6	n 0.05	n 0.24	0.17 0.25	0.17 0.25	B-2 intersection consists of circular tunnels leading to an intersection mined with a domed roof and domed invert Recessed rock anchors were placed before enlargement of the excavation
a			Chamber B	H = B = 72 L = 58 (total in two legs) circular			No. 10 0	Total 21.2	m 0	m 0.32			
b			Chamber 2	H = B = 63 L = 40 (total in two legs)			Walls and invert 0	Walls and invert 28.2	n 0.05 m 0	n 0.28 m 0.37	0.19 0.29	0.17 0.29	Following reinforcement of rock, intersection and chambers were lined with reinforced concrete
c			Intersection	H = 84 B = 104 (at diagonal) Invert and roof consist of spherical segments See comments		In intersection: Domed roof reinforced with recessed rock anchors, No. 10 deformed bar with perforated sleeve by 24 ft long. S = 5 ft-8 in. by 5 ft-8 in. Superposed are fully grouted hollow core deformed bar bolts, No. 8 by 8 ft long with S = 4 by 4 ft. For No. 10 deformed bars, F_y = 52k. For No. 8 rock bolts, T_a = 250 ft-lb, T_n = 275 ft-lb, F_i = 9k, F_y = 36k	No. 8 3.9 No. 10 0	No. 8 15.6 No. 10 11.2 Total 26.8	n 0.03 m 0.04	n 0.21 m 0.27	0.17 0.23	0.21 0.29	Walls created by chamfering the intersection corners are reinforced similar to domed roof except that adjacent anchor lengths alternate from 24 to 18 ft Upper portion of domed invert reinforced with 18- and 24-ft-long recessed rock anchors; No. 10 gravity grouted deformed bars, at 4-ft spacing
32			Corner of intersection, Chamber A and pedestrian adit 1963-1964	H = 60.5	Rock movement along fractures cutting and dropping into the corner required additional rock excavation and specially designed reinforcement	173 rock bolts, 24 and 30 ft long, consisting of No. 11 (1-3/8-in.-diam) deformed bars grouted in 12-ft-long perforated sleeves installed to stabilize rock at corner. Bolts tensioned with T_n = 600 ft-lb and grouted with neat cement or epoxy grout. Bearing plates: 8 by 8 by 1/2 in. set on mortar pad. F_i = 25k, F_y = 117k, S^2 varies from 4.5-36 sq ft. 36 additional fully grouted (neat cement or epoxy) hollow core deformed rock bolts used. T_a = 250 ft-lb, T_n = 375 ft-lb, F_i = 20k	Max. 39	Max. 1.80	Max. 0.54	Max. 2.47	Does not apply	0.40	After the corner was stabilized with rock bolts, consolidation grouting of open fractures was done by pumping epoxy grout through bore holes and through hollow core rock bolts. Some filling of open fractures also took place during neat cement grouting of rock bolts intersecting open fractures
33	Snowy Tumut Development, Tumut-1 Snowy Mountains, Australia Snowy Mountain Hydro-Electric Authority	Snowy Mountain Hydro-Electric Authority, Australia CITRA Enterprises	Machine hall, underground power plant 1955-1957	H = 110 B = 77 L = 306 D = 1100 Curved roof, vertical sidewalls	Biotite granite, granite gneiss q_u = 20,000 psi RQD = fair to good	Arch: Ungrouted 1-in.-diam slot and wedge rock bolt, 15 ft long. S = 4 by 4 ft. F_y = 23k		10		n 0.11	0.20		Ungrouted rock bolts installed in roof prior to installation of permanent concrete ribs
						Walls: Grouted 1-in.-diam slot and wedge, 12 ft long. S = 5 by 5 ft		6		m 0.05	0.11		

(Continued)

Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$		n = P_i/B γ m = P_i/H γ		Bolt Length / Span		Comments
							Initial	Yield	Initial	Yield	ℓ/B	ℓ/H	
34	**Eklutna Dam** **Anchorage, Alaska** **U. S. Bureau of Reclamation**	U. S. Bureau of Reclamation A & B Construction Co.	**Intake** tunnel 1952-65		**Mostly sound argillite and greywacke in rock bolted sections**	**Expansion shell rock bolt,** 1 in. diam							**Rock bolts used during early stages of excavation, but due to numerous seams, thin bedding planes and poorly cemented joints, bolts proved to be ineffective and use was discontinued**
35	**Gilham Dam** **Gilham,** Ark. CE, Tulsa District	CE, Tulsa District	**Outlet** works tunnel 1965	H = 13 B = 13 L = 1100	**Sandstone**	Ungrouted expansion shell type rock bolts, 7/8-in.-diam by 6-15 ft long. Rock surface covered with 2- by 2-in. by No. 9 gage wire mesh							
36	**Carters Dam** **Carters, Ga.** CE, Mobile District	Corps of Engineers; Tippetts, Abbett, McCarthy, and Stratton **Cowin & Co.**	**Diversion** tunnel 1963	H = 23 B = 23 L = 2410 D = **Horseshoe**	Quartzite, phyllite q_u = 10,000-27,000 psi γ = 165-170 pcf	Ungrouted 1-in.-diam by 8-ft-long slot and wedge rock bolts, S = 6 by 4.7 ft, 6- by 6- by 3/8-in. bearing plate. F_y = 26k, T_n = 170 ft-lb, F_i = 7k	2	6	0.07	0.22	0.35		
37			4 penstock tunnels 1968	H = B = 23 L = 3044, total D = **Circular**	Quartzite q_u = 11,000-43,000 psi γ = 170 pcf	Ungrouted 1-in.-diam by 8-ft minimum length expansion shell rock bolts, no set spacing, 6- by 6- by 3/8-in. bearing plate, 2- by 3-in. by No. 6 wire mesh on rock surface					0.35		
38	**Morrow Point Dam** Montrose, Colo. **U.S. Bureau of Reclamation**	U. S. Bureau of Reclamation Al Johnston Construction Co., Morrison-Knudsen Co.	**Underground** power plant chamber 1963	H = 100 to 138 B = 57 L = 206 D = 400	Micaceous quartzite, mica schist, some pegmatite intrusions. Two shear zones present in vicinity of chamber. RQD = good to excellent q_u = 6000-16,000 psi γ = say 165 pcf	Fully grouted 1-in.-diam expansion shell rock bolts, S = 4 by 4 ft, 20 ft long in roof, 12 ft long in walls. 4-Special reinforcement to stabilize sidewall: 9 each, 135k grouted rebars, 60-100 ft long; 25 each, 250k tendons; 27 each, 1-3/8-in.-diam rock bolts, 26-78 ft long tensioned to 60k. Based on 7500-sq-ft wall area reinforced, P_i estimated at 8 psi. Average length of specified reinforcement approximately = B		**Crown Walls, 13** **Spec Wall 8**		**n 0.20** **m 0.11** **Spec Wall 0.07**	0.35	0.12 **Spec 1.0**	Special reinforcement on sidewall intersected by 1- to 5-ft-thick shear zone dipping 32 deg. A 100-ft-wide wedge moved 2 in. into chamber, along a 17-deg component of shear zone dip. Grouted rebars installed during excavation stopped movement; tendons and long bolts added after excavation was complete
39	**Laurel Dam** Kentucky CE, Nashville District	CE, Nashville District **Feenix & Scisson**	**Power** tunnel 1966	H = B = 24.5 L = 670 **Circular**	Sandstone, occasional zones of coal and shale	Fully grouted, 1-in.-diam by 12-ft deformed bar, perforated sleeve rock anchor, S = 3 ft along and 5 ft around 70 ft of tunnel	0				0.47		
					Sandstone, occasional coal stains **γ = say 160 pcf**	Fully grouted, 1-in.-diam by 10-ft hollow core deformed bar rock bolt, S = 5 ft along and 7 ft around 600 ft of tunnel. F = 36k	7			n 0.26	0.41		

(Continued)

Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$ Initial	 Yield	n = P_i/B γ m = P_i/H γ Initial	 Yield	Bolt Length / Span ℓ/B	 ℓ/H	Comments
40	**Oroville Dam and Reservoir** **State of California**	California Department of Water Resources **Oro Dam Constructors, McNamara-Fuller**	Underground power plant chamber 1964-1966	H = 88 to 137 B = 69 L = 550 D = 300 Parabolic arch roof, 24 ft high by 69 ft wide vertical sidewalls	Amphibolite, fine-to-coarse grained, generally massive, but with a slight schistosity. Steeply dipping fractures, spaced 5-20 ft apart with most 1-6 in. wide containing crushed rock, schist, and lenses of clay gouge γ = 185 pcf RQD = fair to good	Fully grouted expansion shell rock bolts, 1 in. diam by 20 ft long. S = 4 by 4 ft in roof, 6 by 6 ft in walls. Additional bolts angled across slabby rock where shears intersect roof. Surface covered with chain link fabric or steel headers. Pneumatic mortar, 4 in. thick, F_y = say 36k		Roof 16 Walls 7		n 0.18 m 0.04- 0.06	0.29	0.15- 0.23	40-ft-long rock bolts installed at junction of access tunnel with power plant chamber where large overbreak occurred Specifications called for installation of pattern bolts within 5 ft of advancing face and within 3 hr of blasting permanent surface. Later lengthened to 48 hr
41	**Foster Dam**	CE, Portland District	**Diversion** tunnel 1965	H = 32 B = 32 L = 565 **Horseshoe**	**Basalt. Tuff at downstream portal**	Ungrouted expansion shell-type rock bolts, 5/8 and 3/4 in. diam by 6-10 ft long. S = 5 by 5 ft. T_n = 250-300 ft-lb					0.19 to 0.31		**Temporary tunnel**
42	**Blue River Dam**	CE, Portland District	**Diversion** and regulating tunnel 1965	H = 24 B = 24 L = 7797 **Horseshoe**	**Andesite with platy joints and vertical fault zones**	Ungrouted 1-in.-diam slot and wedge rock bolts over 1547 ft of the tunnel. Length = 6-10 ft, S = 5 by 5 ft. T_n = 200-250 ft-lb					0.25 to 0.41		
43	**Boundary Dam Metaline Falls,** Wash. **City of Seattle**	**Bechtel-Leeds-Hillard City of Seattle** **Mannix Contractors, S.G.S. Constructors, Frontier Construction Co., McLaughlin, Inc.**	**Underground** power plant chamber 1965	H = 175 B = 76 L = 477 D = 500 **Arched roof, vertical side walls**	**Dolomitic limestone** **q_u = 10,000 psi** RQD = good to excellent (est.)	Fully grouted, 1-in.-diam hollow core or solid expansion shell rock bolts. In roof, S = 6 by 6 ft, length = 15 ft. Three rows of rock bolts, 15 and 20 ft long, S = 5 by 5 ft at extreme top of sidewalls. Remainder of walls bolted only where required In draft tube pillars: 8-636k tendons per pillar.							Additional 30-ft-long bolts placed in roof where joints appeared to form wedges Wire mesh and some shotcrete used Attention given to reinforcement of rock around reentrants 636k tendons placed to reinforce jointed and slickensided rock

(Continued)

Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element. S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$: Initial	Average Confining Pressure: Yield	$n = P_i/B\gamma$, $m = P_i/H\gamma$: Initial	n, m: Yield	Bolt Length / Span: $\frac{\ell}{B}$	Bolt Length / Span: $\frac{\ell}{H}$	Comments
44	**Ranier Mesa** **Nevada Test Site, Mercury** **Atomic Energy Commission**	**Fenix & Scisson, Inc.** **Reynolds Electrical Engineering Co.**	**Test Cavity I** 1964-65	H = 140 B = 80 (because of cavity geometry, span is taken as 100 ft) L = diam = 120 D = 1300 Shape approximate spherical segment with plane surface inclined 68 deg from horizontal	**Alternating layers of red to yellow-white porous tuff of low intact strength.** Tuff is predominantly thick-bedded (dipping 8-15 deg) and massive, except for occasional thin beds (3-18 in.) of soft, friable white tuff q_u = 1500 psi γ = 125 pcf RQD = 95-100 percent	Grouted anchorage type rock bolts, No. 9 (1-1/8-in.-diam) deformed bars, grouted length = 7-9 ft with gypsum ("Sulfaset," Ranco F-181) liquid grout mix pumped to back of hole. Grout length controlled with use of polyfoam packer In curved surface: Roof, bar length = 32 ft, S = 3 by 3 ft Middle portion, length = 24 ft, S = 3 by 3 ft Lower portion, length = 16 ft, S = 6 by 6 ft In plane surface: Length = 24 ft, S = 6 by 6 ft Bearing plate size = 8 by 8 by 1/2 in. with cement mortar pad under plate T_n = 400 ft-lb, F_i = 30k, F_y = 59k	23 23 6 6	45 45 11 11	n,0.26 n,0.26 m,0.05 m,0.05	0.52 0.52 0.09 0.09	0.32 0.24	0.11 0.17	In Cavities I and II: Extra bolts were **spotted as required particularly where joint sets were present. Shotcrete was applied in roof to prevent drying and to support rock slabs between rock bolts. Some chain link fabric supported from** 6-ft-long perforated sleeve-type grouted **rock bolts was also placed to provide temporary support prior to placing long rock bolts**
45			**Test Cavity II** 1965	**Same as Cavity I.**	**Same as Cavity I, except high angle joint systems were much more prevalent**	**Initially reinforced the same as Cavity I. During construction, instability of the plane** face required additional reinforcement, and 48-ft-long rock bolts (same type as in Cavity I), S = 3 by 3 ft, were installed over large areas	**Same as Cavity I except in plane surface** 23	45	m,0.19	0.37		0.34	**Grouted rock bolt anchorages were used in both cavities because the tuff was incapable of supporting standard expansion shell anchors** In Cavity II, stabilization was required because deep-seated movements occurred **along the steeply dipped joint and bedding planes intersecting the plane surface. In addition to placing additional reinforcement, approximately 1100 bags of cement (neat cement grout) were pumped into open joints and fault zones**
46			**Test Cavity III** 1965	H = 80 B = 50 (because of cavity geometry, span is taken as 60 ft) L = 75 D = 350 Similar to Cavity I except plane surface inclined 74 deg from horizontal	Quartz monzonite, iron-stained joints form rock blocks approximately 2 ft on a side. Major joint set parallels plane face of cavity **q_u = 27,000 psi** **γ = 167 pcf** RQD = 63-85 percent	**Fully grouted** 1-1/8-in.-diam deformed bar rock **bolts with expansion shells. Grouted with gypsum grout after tensioning** **In curved surface:** Roof, bar length = 24 ft, S = 3 by 3 ft Middle portion, bar length = 16 ft, S = 3 by 3 ft Lower portion, bar length = 8-16 ft, S = 6 by 6 ft In plane surface, bar length = 16 ft, S = 6 by 6 ft T_n = 275 ft-lb, F_i = 20k, F_y = 59k	15 15 4 4	45 45 11 11	n,0.29 n,0.29 m,0.03 m,0.03	0.86 0.86 0.06 0.06	0.40 0.27	.13-.27 0.20	**Extra bolts placed normal to predominant joints and fault zones as required**
47	**Poatina Power Station** **Tasmania** **Hydro-Electric Commission of Tasmania**	**Hydro-Electric Commission of Tasmania** **Same**	Underground power plant chamber 1962	H = 85 B = 45 L = 300 D = 500 Trapezoidal arch, vertical sidewalls	Mudstone. Roof is thinly bedded, highly fossiliferous, calcareous mudstone. Remainder is massive mudstone with occasional thin shale bands. No faults; joints sealed with calcite and are watertight. In situ compressive strength = 5000 psi, measured parallel to bedding γ = 163 pcf	Fully grouted slot and wedge rock bolts Roof: 14 ft long, S = 3 by 3 ft Roof, near haunches, slabby rock: 14 ft long, S^2 = 4.5 sq ft Haunches and top of walls: 12 ft long, S = 3 by 3 ft Midheight of walls: 14 ft long, S = 3 by 3 ft Lower walls: 8 ft long, S = 3 by 3 ft Mesh and 4-in. gunite over rock surface		10 20 10 10 10		0.20 0.40 0.20	0.31 0.31	0.14 0.16 0.09	**For roof rock, q_u = 5,000 psi. saturated,** q_u = 10,000 psi, air dried. For wall rock, q_u = 16-19 ksi, air dried. 3-ft-deep stress relief slots cut at junction of flat roof and sloping haunches. Shear failure developed on horizontal bedding plane at intersection of haunch and crown and caused 1/8-in. displacement of haunch into chamber

(Continued)

Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$ Initial	 Yield	n = P_i/B γ m = P_i/H γ Initial	 Yield	Bolt Length / Span ℓ/B	 ℓ/H	Comments
48	El Toro Chile			H = 126 B = 80 L = 335	Granodiorite, orthogonal joints	Roof: Tendons, 400k, S = 20 by 20 ft, length = 49-55 ft		7		0.08	0.61-0.69		
						Roof: Rock bolts, 40k, S = 8 by 8 ft, length = 13 ft		6		0.06	0.16		
						Roof, total		13		0.14			
						Walls: Tendons, 400k, S = 20 by 20 ft, length = 50 ft		7		0.05		0.4	
49	**Churchill Falls** **Labrador, Canada** **Churchill Falls Labrador** Corp.	**Acres Canadian Bechtel**	Surge chamber 1968-1971	H = 150 B = 64 L = 760 D = **Circular shaped arch, vertical walls**	Gneiss, intruded by gabbro, diorite, syenite, and pegmatites Excellent quality mass rock, no major fault zones. Rock cut by persistent joint sets. Minor shear zones, joints generally planar and rough, alteration by gypsum, nematite, chlorite, and talc	Arch: Fully grouted hollow core deformed bar rock bolts with expansion shells, No. 11 (1-3/8-in.-diam) by 15-20 ft long, S = 5 by 5 ft. Rock surface covered with 2- by 2-in. by No. 10 gage wire mesh. F_i = 45k, F_y = 68k	12.4	19	n 0.16	n 0.25	0.24 to 0.31		One half of bolt pattern installed within 8 hr of blasting and to within 10 ft of working face. Remainder installed within three days following first half installation and to within 60 ft of working face. In poor rock, bolts specified to be installed within 5 ft of working face In walls, bolts were angled 20 deg from vertical and 20 deg from horizontal to enable reinforcement of maximum number of rock joints Direct pull tensioning or by torquing specified, but contractor elected to tension bolts by torquing. Torque values up to 1000 ft-lb used to achieve tension loads of 45k in 1-3/8-in.-diam bolts
						Walls: Fully grouted (1-1/8-in.-diam), expansion shell type solid, bar rock bolts. Length = 15-25 ft, S = 7 by 7 ft. F_i = 30k, F_y = 45k. No mesh on walls	4.2	6.4	m 0.02	m 0.04		0.10 to 0.16	
50			**Powerhouse** chamber 1968-71	H = 145 B = 81 L = 1000 **Circular shaped** arch, vertical walls	**q_u = 16,000 psi** **γ = say 170 pcf** RQD = > 94 percent	Arch (15 ft each side of crown): Fully grouted No. 11 hollow core, S = 10 by 5 ft, length = 25 ft. Superposed on No. 11 pattern are fully grouted No. 9 solid rock bolts, S = 10 by 5 ft, length = 15-25 ft	6.2 4.2 10.4	9.3 6.3 15.6	n 0.14	n 0.21	0.31 0.18 to 0.31		Additional rock bolts, up to 75 ft long, installed and tensioned to 60k in surge chamber wall to prevent possible movement of rock wedges formed by intersection of joint sets and "foliation shears" dipping about 50 deg into excavation
						Remainder of Arch: Same as above, except No. 11 bolts are 20 ft and No. 9 bolts are 15-20 ft. Entire arch covered with 2- by 2-in. by No. 10 wire mesh	10.4		n 0.14	n 0.21	0.18 to 0.24		
						Walls: Fully grouted No. 9 solid bar rock bolts, S = 7 by 7 ft, length = 15-20 ft	4.2	6.4	m 0.02	m 0.04	0.10 to 0.14		
51			**Transformer** gallery 1968-71	H = 55 B = 45 L = 800 D =		Arch: Fully grouted No. 11 hollow core rock bolts, S = 5 by 5 ft, length = 15 ft. Arch covered with 2- by 2-in. by No. 10 wire mesh	12.4	19	n 0.24	n 0.35	0.33		
52	**Libby Dam, Flathead Tunnel** **Libby**, Mont. **Great Northern Railroad**	CE, Seattle District	**Railroad** tunnel 1969	H = 29 B = 21 L = Semihorseshoe	**Argillite moderately fractured to blocky, with local zones of closely shattered rock**	Ungrouted, 3/4-in.-diam, high-strength, expansion shell-type rock bolts, S = 4 by 5 ft, length = 10 ft in arch, 6 and 8 ft in walls, welded wire fabric over arch. T_n = 200-250 ft-lb, F_i = 8k, F_y = 21.5k							Bolts were installed right after blasting and carried within 5 ft of face before shooting next round

(Continued)

Table 7-1. (Continued)

Item No.	Project / Location / Responsible Agency	Designer / Construction Contractor	Location of Reinforcing Elements / Construction Period	Excavation Dimensions (H = Height, ft; B = Width, ft; L = Length, ft; D = Depth, ft) Shape	Rock Properties (q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation)	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)		Average Confining Pressure on Rock Surface, P_i, psi ($P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$) Initial	Yield	$n = P_i/B\gamma$, $m = P_i/H\gamma$ Initial	Yield	Bolt Length / Span $\frac{\ell}{B}$	$\frac{\ell}{H}$	Comments
53	NORAD Cheyenne Mountain Complex Addition Colorado Springs, Colo. North American Air Defense Command	CE, Omaha District Tiro Construction Corp.	Air intake delay path tunnel	H = B = 18 L = 502 **Circular**	See page 7-7 for general rock description at NORAD Cheyenne Mountain Complex	No. 8 by 10-ft rock bolts, S = 4 by 4 ft over upper 204-deg arc of tunnel surface. Tensioned by direct pull or by nut torquing. Chain link fabric over a portion of roof	Rock bolts: Fully grouted hollow core deformed bar, expansion shell type rock bolts, No. 8 (1-in.-diam) with 8- by 8- by 3/8-in. bearing plates. T_a = 325 ft-lb, F_y = 36k, T_n (where used) = 350 ft-lb, F_d (where used) = 24k, F_i = 20k Rock anchors: No. 10 (1-1/4-in.-diam) deformed bars grouted full length with use of 1-3/4-in.-diam perforated sleeves in 2-in.-diam drill holes. Generally recessed behind trim burden prior to shooting trim round. Trim burden varied from 15- to 45-in. thickness. F_y = 51k Rock anchors: No. 8 (1-in.-diam) deformed bars grouted full length with use of 1-1/4-in.-diam perforated sleeves in 1-1/2-in.-diam drill holes. F_y = 32k Chain link fabric: 2 by 2 in. by No. 6	8.7	15.6	n 0.4 m 0.4	n 0.72 m 0.72	0.56	0.56	The NORAD Cheyenne Mountain Complex was constructed during 1961-1964. During 1971, the size of the complex was increased by mining additional chambers, tunnels and shafts to house a new power plant, air-cooling and air-handling facilities Rock bolts were placed and tensioned to within 2 ft min. and 10 ft max. of heading. Initially, rock bolts were retensioned and grouted to within 10 ft min and 30 ft max of heading. This procedure was modified to allow grouting of bolts immediately after the first tensioning
54			Air exhaust delay path tunnel and raise	H = B = 19 L = 374 **Circular**		No. 8 by 10-ft rock bolts, S = 4 by 4 ft over upper 194-deg arc of tunnel surface and over 360 deg of raise. Tensioned by torquing nut		8.7	15.6	n 0.38	n 0.68	0.53		
55			Air exhaust valve chamber	H = 27 B = 20 L = 140 Semicircular **roof, vertical walls**		No. 8 by 10-ft-long rock bolts, S = 4 by 4 ft over roof and walls. Tensioned by direct pull or by nut torquing. 30 ft of chamber rock covered with chain link fabric		8.7	15.6	n 0.36 m 0.22	n 0.65 m 0.48	0.50	0.37	
56			Cooling tower chamber	H = 45 B = 38 L = 185 Semicircular roof, vertical **walls**		No. 10 by 16-ft-long recessed rock anchors installed over 135-deg arc of roof. Installed inclined at 60 deg from direction of excavation advance. S = 4.67 by 4.67 ft		0	16.3			0.42		
						After shooting trim round, No. 8 by 16-ft-long rock bolts installed and tensioned by direct pull in roof. S = 4.67 by 4.67 ft		+6.4 / 6.4	+11.5 / 27.8	n 0.14	n 0.6	0.42		
						Walls: No. 8 by 16-ft rock bolts, S = 4.67 by 4.67 ft tensioned either by direct pull or by nut torquing		6.4	11.5	m 0.12	m 0.21	0.36		
						Chain link fabric over roof and 65 percent of wall area								

(Continued)

Table 7-1. (Continued)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$		$n = P_i/B\gamma$ $m = P_i/H\gamma$		Bolt Length / Span		Comments
							Initial	Yield	Initial	Yield	$\frac{\ell}{B}$	$\frac{\ell}{H}$	
57	NORAD Cheyenne Mountain Complex Addition Colorado Springs, Colo. North American Air Defense Command	CE, Omaha District Tiro Construction Corp.	Power plant chamber	H = 53 B = 67 L = 172 Circular segment > semicircle	See page 7-7 for general rock description at NORAD Cheyenne Mountain Complex	No. 10 by 16-ft-long recessed rock anchors installed over 110-deg arc of roof. Anchors inclined at 60 deg from direction of advance. S = 4.67 by 4.67 ft	0	16.3			0.24		See page 7-23 for general description of reinforcing elements used in the NORAD Cheyenne Mountain Complex Addition
						No. 8 by 24-ft-long rock bolts spaced at 4.67 by 4.67 ft installed over roof and walls after shooting trim rock. Bolts tensioned by direct pull	+6.4 6.4	+11.5 27.8	n 0.08 m 0.10	n 0.34 m 0.43	0.36	0.45	
						Chain link fabric over roof and 35 percent of wall area below springline							
58			Power plant access adit	H = 25 B = 32 L = 113 Semicircular roof, vertical walls		Typical Section: No. 8 by 10-ft-long rock bolts spaced at 4.67 by 4.67 ft over arch and one row in walls below springline. Chain link fabric over arch	6.4	11.5	n 0.17 m 0.21	n 0.30 m 0.38	0.31	0.4	
59			Cooling tower access adit	H = 16.5 B = 12 L = 120 Semicircular roof, vertical walls		No. 8 by 8-ft-long rock bolts spaced at 4 by 4 ft over arch and one row in walls below springline	8.7	15.6	n 0.6 m 0.44	n 1.1 m 0.78	0.67	0.49	
60			Air intake shafts	Vertical shafts, 8 ft diam 3 at 46 ft Total L = 138		No. 8 by 6-ft-long rock anchors. S = 4 by 4.2 ft Shafts were later steel lined	8.3	14.9	Does not apply		Does not apply		Shafts mined mechanically by raised bore drilling
61			Air exhaust shafts	Vertical shafts 8 ft diam 4 at 31 ft Total L = 124		Bottom 14 ft of each shaft: No. 8 by 6-ft-long rock bolts tensioned by torquing nut. S = 4 by 4.2 ft	8.3	14.9	Does not apply		Does not apply		Shafts mined mechanically by raised bore drilling
						Remainder of each shaft: No. 8 by 6-ft-long rock anchors. S = 4 by 4.2 ft. Top 15 ft of each shaft was later steel lined	0	13.2					
62			Pipe adit No. 1	H = 12 B = 12 L = 47		No. 8 by 8 ft rock bolts, S = 4 by 4 ft over arch and walls	8.7	15.6	n 0.6 m 0.6	n 1.1 m 1.1	0.67	0.67	

(Continued)

Table 7-1. (Concluded)

Item No.	Project Location Responsible Agency	Designer Construction Contractor	Location of Reinforcing Elements Construction Period	Excavation Dimensions H = Height, ft B = Width, ft L = Length, ft D = Depth, ft Shape	Rock Properties q_u = Unconfined Compressive Strength, γ = Unit Weight, RQD = Rock Quality Designation	Description and Properties of Reinforcing Elements (F_y = Yield Strength of Element, T_a = Anchorage Setting Torque Used, T_n = Tensioning Torque Used, F_d = Direct Pull Tension Force Used, F_i = Estimated Initial Tensile Stress in Installed Element, S = Spacing of Elements, k = 1000 lb)	Average Confining Pressure on Rock Surface, P_i, psi $P_i = \frac{F_i}{S^2}$ or $\frac{F_y}{S^2}$ Initial	 Yield	$n = P_i/B\gamma$ $m = P_i/H\gamma$ Initial	 Yield	Bolt Length / Span $\frac{\ell}{B}$	 $\frac{\ell}{H}$	Comments
63	**NORAD Cheyenne Mountain Complex Addition** Colorado Springs, Colo. **North American Air Defense Command**	CE, Omaha District **Tiro Construction Corp.**	Pipe adit No. 2	H = 18 B = 12 L = 48	See page 7-7 for general rock description at NORAD Cheyenne Mountain Complex	No. 8 by 10-ft rock bolts, S = 4 by 4 ft, and chain link fabric over arch and walls	8.7	15.6	n 0.6 m 0.4	n 1.1 m 0.72	0.83	0.56	See page 7-23 for general description of reinforcing elements used in the NORAD Cheyenne Mountain Complex Addition
64			New to old power plant adit	H = 25 B = 20 L = 57		No. 8 by 10-ft rock bolts, S = 4.67 by 4.67 ft, and chain link fabric over arch and walls	8.7	15.6	n 0.36 m 0.29	n 0.65 m 0.52	0.5	0.4	
65			Diesel exhaust tunnel (2)	H = 12 B = 12 L = 87 + 78=165		No. 8 by 8-ft rock bolts, S = 4 by 4 ft, over arch with one row in walls below springline	8.7	15.6	n 0.6 m 0.6	n 1.1 m 1.1	0.67	0.67	
66			Combustion air tunnel	H = 6.25 B = 6.25 L = 84 Circular		No. 8 by 6-ft rock bolts, 3 bolts per station in roof, S = 4 by 4 ft	8.7	15.6	n 1.1	n 2.1	0.96		
67	**Northfield Mountain Pumped Storage Project** **Northfield and Irving, Franklin County, Mass.** Connecticut Light & Power Co., The Hartford Electric Light Co.,Western Massachusetts Electric Company	**Stone and Webster Engineering** Corp. **Morrison-Knudsen-Northfield Associates**	Underground powerhouse chamber 1968-1970	H = 155 B = 70 L = 328 Circular arch roof (19-ft rise), vertical walls	**Interbedded layers of gneiss and schist with varying amounts of quartz and mica. Two major joint sets, generally widely spaced, dipping steeply and striking** NE and NW predominant q_u = 16,000-22,000 psi γ = say 175 pcf	Roof: 1-in.-diam high strength expansion shell fully grouted rock bolts, S = 5 by 5 ft, 35 ft long in central part of arch, 25 ft long in lower arch. Bolts tensioned by direct pull Walls: Same except top row of bolts, 20 ft long, remainder are 16 ft long. Bolts tensioned by torquing the nut							
68	**Bloomington Lake Dam** Mineral County, W. Va./Garrett County, Md. CE, Baltimore District	CE, Omaha District **L.G. Defelice, Inc.**	Outlet works tunnel 1973-74	H = B = 19.33 L = 1619 D = 200 **Circular**	Sandstone, thin medium bedded (1-4 ft), fine-to-medium grained sub-graywacke, lightly jointed q_u = 30,000 psi γ = 165 pcf Shale, sandy-clayey	Fully grouted rock bolts, 12 ft long, consisting of No. 8 (1-in.-diam) deformed bars anchored in 1-1/2-in.-diam holes with the use of 1-1/4- by 12-in.-long polyester resin cartridges. Approximately 4-ft fast-setting grout at back of hole set (hardened) prior to stressing bars. Slower setting grout in remainder of hole. F_y = 39k, F_d = 36k, F_i = 30k, S = 4 by 4 ft over top 135 deg of tunnel surface. Rock bolts anchored primarily in sandstone Fast-setting grout: 1-min set Slow-setting grout: 25 to 30-min set	10.8	14.0	n 0.49	n 0.63	0.62		Rock bolts carried to 1-4 ft of heading. Bolts installed, tensioned and grouted prior to shooting next advance Portal face immediately above and extending to 45 ft above portal crown reinforced with No. 11 (1-3/8-in.-diam) rock bolts, 25-50 ft long, S = 10 by 10 ft, installed downward from face at 45 deg from horizontal. Deformed bars fully grouted with 1-1/2-in.-diam polyester resin cartridges installed in 1-3/4-in.-diam holes. F_d = 70k. Tunnel lined with 1-1/2-in.-thick reinforced concrete following excavation and rock reinforcement

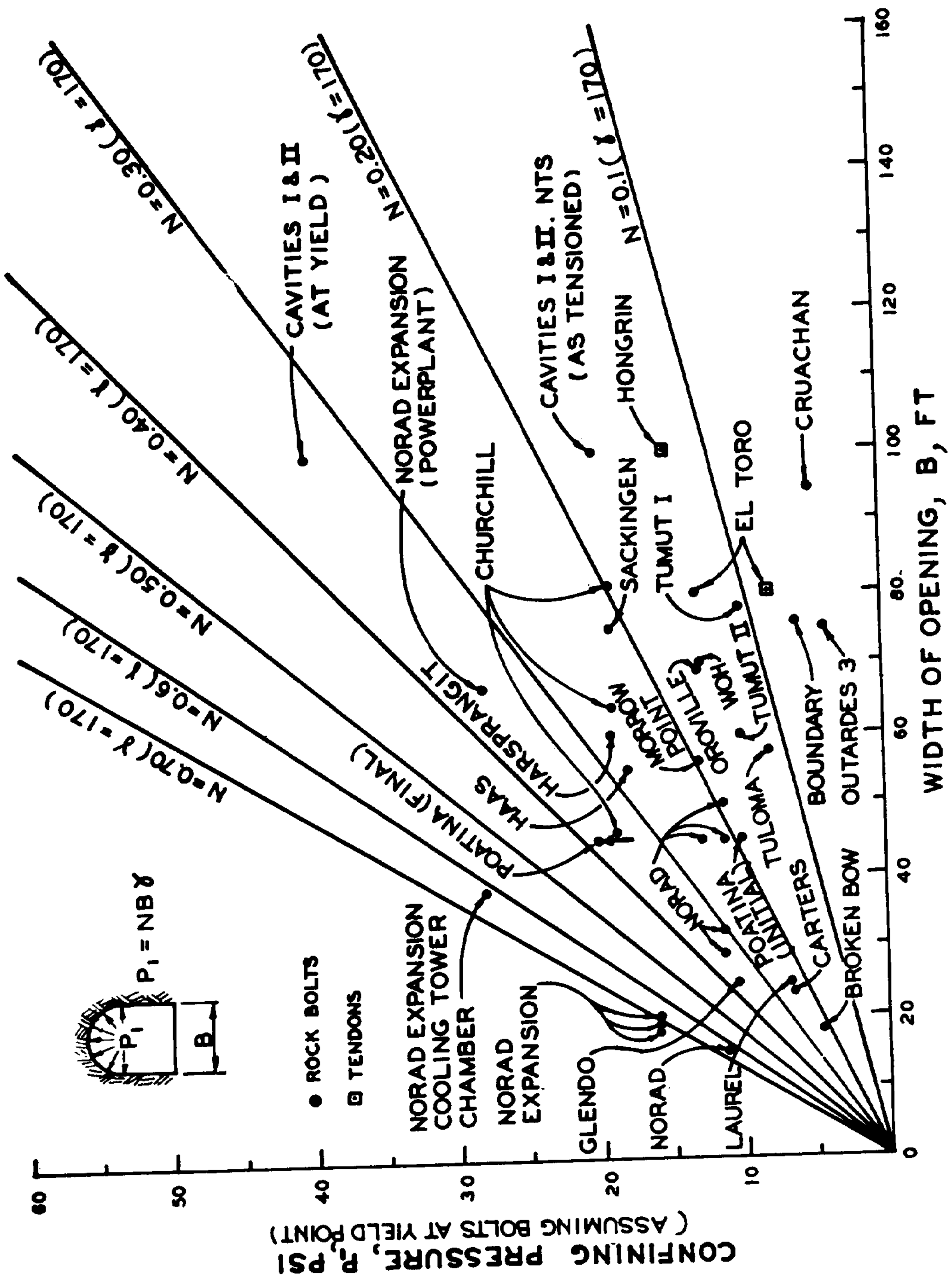

Figure 7-1. Confining pressures used in crown of caverns.

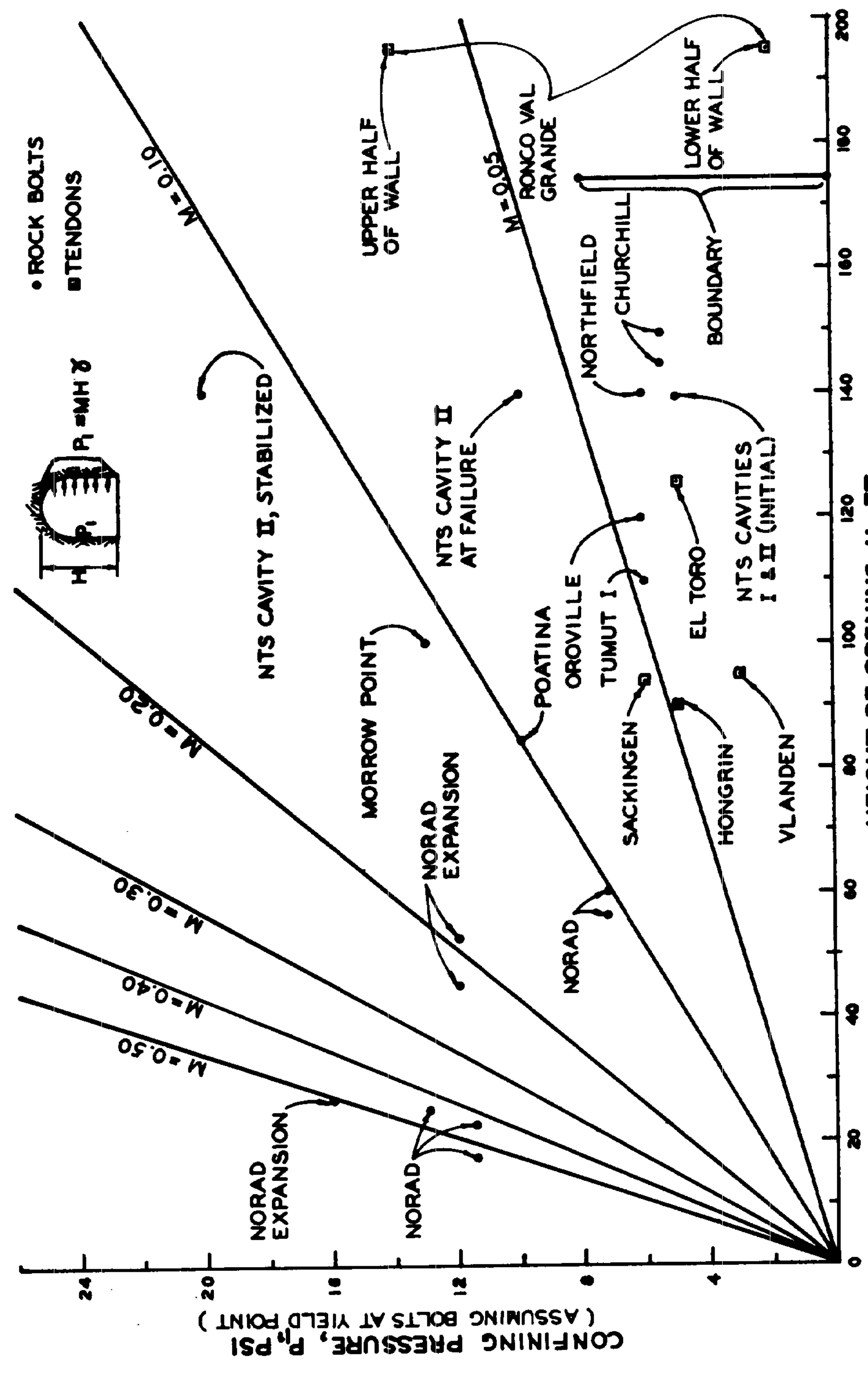

Figure 7-2. Confining pressures used on cavern walls.

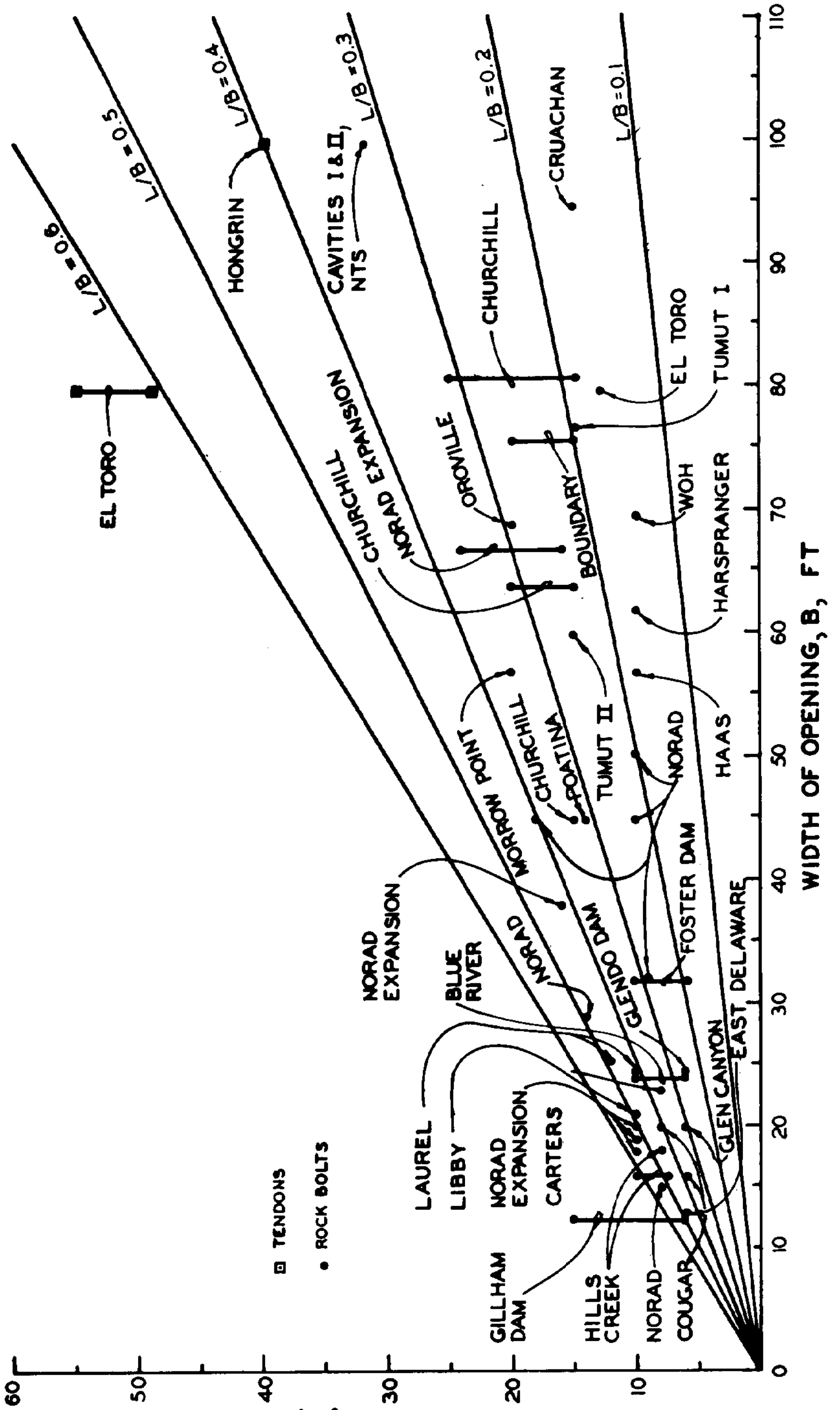

Figure 7-3. Bolt lengths used in crowns of caverns.

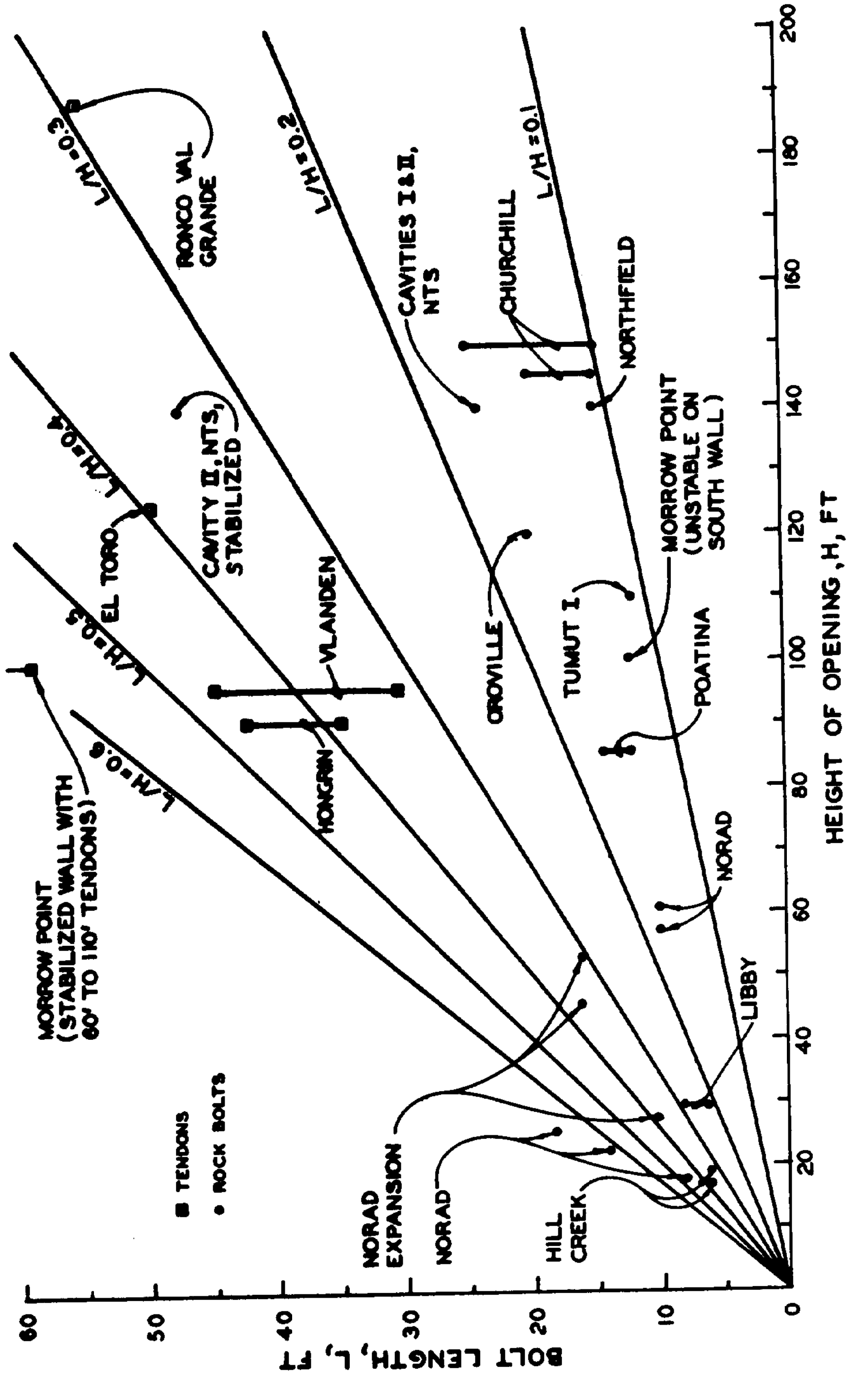

Figure 7-4. Bolt lengths used on cavern walls.