ASSESSING COAL MINE ROOF STABILITY THROUGH ROOF FALL ANALYSIS

By Gregory M. Molinda,[1] Christopher Mark, Ph.D.,[2] and Dennis Dolinar[3]

ABSTRACT

In 1999, 2,087 unplanned roof falls were reported from 841 mines. Nearly 55% of all mines reported at least one roof fall, and nearly 17% of the mines reported five or more falls. In order to investigate the variables that contribute to roof falls, the National Institute for Occupational Safety and Health (NIOSH) compiled a national database of roof performance from 37 coal mines. Geotechnical factors and their effect on roof fall rates were compiled from over 1,500 miles of drivage. The factor that is the best predictor of roof fall rate is the Coal Mine Roof Rating (CMRR). For a low CMRR (≤30), almost all cases have high roof fall rates. Conversely, high roof fall rates are rare for strong roof rocks (CMRR ≥ 60). Roof fall rates were also higher in deeper mines, probably because of greater stresses. Intersections were much more likely to fall than roadways, and four-way intersections were more prone to fall than three-way intersections. In a controlled comparison of the effect of increasing bolt length on roof fall rates, it was found that longer bolts reduced the roof fall rates in 11 of 13 cases. A relationship between the roof fall rate, the intersection span, and the CMRR was also found. Finally, a systematic method for tracking roof performance and geotechnical variables was demonstrated.

[1]Research geologist.
[2]Supervisory physical scientist.
[3]Mining engineer.
Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, Pittsburgh, PA.

INTRODUCTION

In 1998, a total of 2,232 unplanned reportable roof falls occurred in 884 U.S. underground coal mines. These falls resulted in 419 injuries and 13 fatalities. According to the Mine Safety and Health Administration's (MSHA) accident database, in 1999 over 55% of underground coal mines reported at least one roof fall and 17% of the mines reported more than five falls. In 1998, an estimated 12,500 miles of entry and 350,000 intersections were excavated. Falls of roof represent a very small proportion of exposed and supported ground. Nevertheless, each roof fall represents a direct threat to life and limb or an indirect threat to ventilation, escape, and equipment.

Through trial and error, operators have generally learned how to mine the coal and support the roof. After mining a certain length of time in a given coal seam, the appropriate entry width, mining height, length of cut, pillar geometry, and support can usually be determined. Roof instability occurs when conditions (usually geology, equipment, or economics) change, and the operator is uncertain how to respond or adapt.

Past studies that focused on detailed measurements at specific field sites have provided a wealth of data on specific roof stability topics, including bolt loads, bed separation, rock strength, mining influences, horizontal stress, and pillar stability [Signer 1998; Dolinar 1997; Chase 1999; Wang 1996]. This approach has been successful in increasing our understanding of the mechanics of roof instability and failure. However, site-specific instrumentation studies have the disadvantage that measurements from that site may not be entirely representative because of local variations in stress, geology, or support installation.

Roof falls, after all, are relatively infrequent events. It is difficult for deterministic rock mechanics models to explain why one intersection collapses while many others nearby remain stable. On the other hand, roof falls seem well suited for study using a probabilistic or empirical approach. The basic concept of the empirical approach is to collect a large quantity of real-world case histories and then use statistics to determine the most important factors.

The empirical approach also requires that the researcher begin with a clear hypothesis, often in the form of a simplified model of the real world that abstracts and isolates the factors that are deemed to be important. It therefore requires, as Salamon [1989] pointed out, "a reasonably clear understanding of the physical phenomenon in question." Without prudent simplification, the complexity of the problem will overwhelm the method's ability to discern relationships among the variables. But a key advantage is that critical variables may be included even if they are difficult to measure directly through the use of "rating scales."

During the past 5 years, modern empirical techniques have been applied to a variety of problems in coal mine ground control. They have resulted in some very successful design techniques, particularly in the area of pillar design, as well as some new insights into pillar and rock mass behavior [Mark 1999a, 1999b].

Much can be learned by observation of roof instability. The geometry, timing, geology, and frequency of roof falls may indicate what caused the failure. If these variables are carefully documented on a mine-wide basis, it may be possible to characterize the combination of factors that may contribute to a high incidence of roof falls. This documentation, expanded with corehole data, at a single mine is called hazard mapping. The hazard map indicates that poor ground conditions are expected. Responses can include bolt changes, narrowing the span, and supplemental support in critical intersections.

Due to highly variable geology and stress regimes, it has been difficult to transfer this knowledge to other mines. To address this problem, the National Institute for Occupational Safety and Health (NIOSH) decided to capture the experience of thousands of miles of existing mine roadways to assess the parameters that influence roof stability.

NATIONAL ROOF FALL DATABASE

Several geotechnical variables are known to influence roof stability. These include geology, mine opening geometry, horizontal and vertical stress regime, abutment load, and support. Through extensive interviews and underground reconnaissance with mine operators, NIOSH documented many of these variables. A national database of roof falls was created from data obtained during visits to U.S. coal mines (table 1). Ultimately, 41 mines in 10 States were visited, representing over 1,500 miles of drivage in most of the major coal basins where underground mining occurs (figure 1). Study mines were selected by computing the roof fall rate from the MSHA accident database. Drivage was estimated by converting annual production (excluding longwall production) into linear feet of advance, assuming an average seam height. Reportable roof falls were then divided by drivage to arrive at the roof fall rate (figure 2). Mines were then selected for study from this distribution to represent the entire range of roof stability from high, to medium, to low roof fall rates. Mines were also selected to represent a wide range of roof geologies, as well as varying size, ranging from large (>1 million tons per year) to small mines (<200,000 tons per year).

Table 1.—Summary of geotechnical data gathered for each case in the study

Mine No.	CMRR	Bolt length, ft	Bolt tension	Bolt grout column	Bolt capacity, kips	Bolts per row	Row spacing, ft	Entry width, ft	PRSUP	Inter-section diagonal, ft	Depth of cover, ft	Mining height, ft	Drivage, 10,000 ft	No. of 3-way	No. of 4-way	No. of segments	Falls 3W	Falls 4W	Segment falls	Roof fall rate
1	59	6.0	0	3	20.50	4	5.0	18.5	5.32	65.90	150.00	6.0	3.50	94	282	705.0	0	0	.0	.00
1	59	6.0	1	3	20.50	4	5.0	18.5	5.32	65.90	150.00	6.0	3.50	95	300	742.5	0	0	.0	.00
2	50	4.0	0	3	17.70	4	4.0	18.0	3.93	60.00	400.00	7.0	3.02	82	175	473.0	0	1	1.0	.66
2	50	6.0	0	3	17.70	4	4.0	18.0	5.90	60.00	400.00	7.0	.93	22	55	143.0	0	1	.0	1.08
2	75	4.0	0	3	17.70	4	4.0	18.0	3.93	60.00	400.00	7.0	2.34	58	116	319.0	0	0	.0	.00
2	75	2.5	1	1	17.70	4	4.0	18.0	2.46	60.00	400.00	7.0	2.32	51	140	356.5	0	0	.0	.00
3	44	6.0	0	3	18.60	4	4.0	18.0	6.20	62.00	350.00	3.5	1.40	28	128	298.0	0	2	3.0	3.57
3	44	6.0	1	2	26.40	4	4.0	18.0	8.80	62.00	350.00	3.5	.44	15	39	100.5	0	0	.0	.00
3	44	4.0	0	3	19.60	4	4.0	18.0	4.36	62.00	350.00	3.5	4.75	122	461	1,105.0	0	0	.0	.00
4	45	6.0	1	1	18.00	4	5.0	19.0	4.55	65.00	350.00	5.5	5.80	148	434	1,090.0	0	24	9.0	5.69
4	41	5.0	0	3	18.00	4	5.0	19.0	3.79	59.00	350.00	5.5	8.60	220	562	1,454.0	1	6	4.0	1.28
4	45	6.0	1	3	18.00	4	5.0	19.0	4.55	59.00	350.00	5.5	6.90	150	444	0	0	2	.0	.29
4	41	4.0	0	3	18.00	4	5.0	19.0	3.03	59.00	350.00	5.5	6.90	0	0	1,113.0	0	0	4.0	.58
4	45	6.0	0	3	18.00	4	5.0	19.0	4.55	59.00	350.00	5.5	21.90	700	1,250	3,550.0	0	2	3.0	.23
5	41	4.0	0	3	20.00	4	4.0	20.0	4.00	61.00	300.00	8.0	8.52	265	690	1,777.5	1	1	.0	.23
5	78	4.0	0	3	20.00	4	4.0	20.0	4.00	61.00	300.00	8.0	4.94	155	445	1,122.5	0	0	.0	.00
6	70	6.0	0	3	20.50	4	4.0	18.0	6.83	60.00	500.00	7.0	2.93	53	203	485.5	0	0	.0	.00
6	50	6.0	0	3	20.50	4	4.0	18.0	6.83	60.00	500.00	7.0	5.24	96	489	1,122.0	1	2	3.0	1.15
6	30	6.0	0	3	20.50	4	4.0	18.0	6.83	60.00	500.00	7.0	5.10	720	3,667	8,414.0	5	17	19.0	8.04
7	40	5.0	0	3	20.00	4	4.0	16.0	6.25	61.00	750.00	7.0	176.70	4,604	5,528	17,962.0	23	23	46.0	.52
8	38	4.0	0	3	20.50	4	4.0	19.0	4.32	60.00	600.00	4.0	39.84	1,000	3,079	7,658.0	3	11	12.0	.65
9	40	5.0	0	3	33.00	4	4.0	16.0	10.31	61.00	500.00	6.5	46.27	1,207	1,684	5,178.5	4	7	7.0	.39
9	40	6.0	1	2	33.00	3	4.0	16.0	9.28	61.00	725.00	6.5	17.12	483	385	1,494.5	3	0	1.5	.26
10 ...	55	6.0	0	3	26.00	4	4.0	19.0	8.21	75.20	1,050.00	10.0	3.79	149	89	401.5	1	2	.0	.79
10 ...	55	5.0	0	3	26.00	4	4.0	19.0	6.84	75.20	1,050.00	10.0	9.77	207	288	886.5	0	0	.0	.00
10 ...	55	4.0	0	3	26.00	4	4.0	19.0	5.47	75.20	1,050.00	10.0	.74	18	36	99.0	0	3	.0	4.05
10 ...	55	5.0	1	2	30.00	4	4.0	19.0	7.89	75.20	1,050.00	10.0	11.34	540	270	1,350.0	0	4	.0	.35
11 ...	42	4.0	0	3	18.40	4	5.0	18.0	3.27	61.00	200.00	5.0	5.90	0	654	1,308.0	0	7	7.0	2.37
11 ...	42	4.0	0	3	18.40	4	5.0	20.0	2.94	70.50	200.00	5.0	.65	0	109	104.0	0	2	3.0	7.69
11 ...	42	5.0	0	3	18.40	4	5.0	18.0	4.09	61.00	200.00	5.0	.49	0	60	120.0	0	0	.0	.00
11 ...	42	5.0	0	3	18.40	4	5.0	20.0	3.68	70.50	200.00	5.0	.05	0	10	10.0	0	0	.0	.00
11 ...	42	4.5	0	3	18.40	4	5.0	18.0	3.68	61.00	200.00	5.0	1.76	0	180	372.0	0	6	5.0	6.25
11 ...	42	4.5	0	3	18.40	4	5.0	20.0	3.31	54.00	200.00	5.0	.20	62	0	.0	0	0	.0	.00
12 ...	45	5.0	1	3	18.60	4	4.0	20.0	4.65	66.00	300.00	6.0	9.53	236	599	1,552.0	11	8	11.0	3.15
13 ...	55	4.0	0	3	17.60	4	4.0	19.0	3.71	62.70	500.00	6.5	1.44	30	58	161.0	0	0	.0	.00
13 ...	55	4.0	0	3	17.60	4	4.0	19.0	3.71	62.70	1,000.00	6.5	14.37	252	647	1,672.0	0	2	2.0	.28
14 ...	45	5.0	0	3	18.40	4	4.0	20.0	4.60	59.00	300.00	10.0	13.00	346	1,036	2,591.0	4	16	9.0	2.23
15 ...	37	6.0	0	3	18.40	4	4.0	20.0	5.52	58.00	400.00	10.0	4.00	114	285	741.0	0	8	1.0	2.25
15 ...	37	6.0	1	2	33.10	4	4.0	20.0	9.93	58.00	400.00	10.0	.58	15	36	94.5	0	4	3.0	12.07
15 ...	37	8.0	1	2	33.10	4	4.0	20.0	13.24	58.00	250.00	10.0	.58	17	46	117.5	0	3	2.0	8.62
16 ...	44	4.0	0	3	17.60	4	4.0	19.0	3.71	64.00	300.00	4.0	5.88	129	423	1,039.5	0	3	1.0	.68
16 ...	46	4.0	0	3	18.40	5	4.0	19.0	4.84	64.50	300.00	3.5	1.90	68	101	304.0	1	4	.0	2.63

Table 1.—Summary of geotechnical data gathered for each case in the study—Continued

Mine No.	CMRR	Bolt length, ft	Bolt tension	Bolt grout column	Bolt capacity, kips	Bolts per row	Row spacing, ft	Entry width, ft	PRSUP	Inter-section diagonal, ft	Depth of cover, ft	Mining height, ft	Drivage, 10,000 ft	No. of 3-way	No. of 4-way	No. of segments	Falls 3W	Falls 4W	Segment falls	Roof fall rate
16 . . .	53	4.0	0	3	18.40	4	4.0	19.0	3.87	62.00	300.00	3.0	.67	22	51	135.0	0	0	.0	.00
17 . . .	58	3.5	0	3	17.70	4	4.0	20.0	3.10	68.60	800.00	6.0	10.20	274	485	1,481.0	0	6	3.0	.88
17 . . .	58	3.5	0	3	17.70	4	4.0	20.0	3.10	75.70	800.00	6.0	1.20	0	137	137.0	0	4	.0	3.33
17 . . .	58	5.0	0	3	17.70	4	4.0	20.0	4.43	68.60	800.00	6.0	8.80	220	330	1,100.0	1	0	1.0	.23
17 . . .	58	5.0	0	3	17.70	4	4.0	20.0	4.43	75.70	800.00	6.0	1.20	0	110	110.0	0	0	.0	.00
17 . . .	58	3.5	0	3	17.70	4	4.0	20.0	3.10	64.80	800.00	6.0	4.80	112	254	681.0	0	0	.0	.00
17 . . .	58	5.0	0	3	17.70	4	4.0	20.0	4.43	64.80	800.00	6.0	8.90	188	418	1,108.0	0	0	.0	.00
18 . . .	42	4.0	0	3	31.00	4	4.0	20.0	6.20	59.00	500.00	6.5	3.10	55	95	272.5	3	2	4.0	2.90
18 . . .	42	6.0	1	2	37.00	4	4.0	20.0	11.10	62.00	500.00	6.5	4.50	47	130	330.5	1	2	2.0	1.11
19 . . .	40	4.0	0	3	17.70	4	4.0	18.0	3.93	63.00	350.00	7.0	4.45	93	236	611.5	3	6	6.0	3.37
19 . . .	40	4.0	0	3	17.70	4	6.0	18.0	2.62	63.00	350.00	7.0	.96	24	60	156.0	3	4	3.0	10.42
19 . . .	50	6.0	0	3	17.70	4	4.0	18.0	5.90	63.00	350.00	7.0	1.28	32	80	208.0	0	0	.0	.00
19 . . .	50	5.0	0	3	17.70	4	4.0	18.0	4.92	63.00	350.00	7.0	.64	16	40	104.0	0	0	.0	.00
19 . . .	75	2.5	1	1	17.70	4	4.0	18.0	2.46	63.00	350.00	7.0	3.74	96	234	612.0	0	0	.0	.00
20 . . .	40	8.0	1	2	33.00	4	4.0	18.0	14.67	65.00	600.00	7.5	17.20	340	820	2,150.0	9	43	32.0	4.88
21 . . .	63	6.0	0	3	26.50	4	4.0	18.0	8.83	69.00	500.00	7.5	.17	21	74	.0	0	1	.0	5.88
21 . . .	63	4.0	0	3	26.50	4	4.0	18.0	5.89	69.00	500.00	7.5	.90	0	0	179.0	0	0	1.0	1.11
21 . . .	45	6.0	0	3	26.50	4	4.0	18.0	8.83	69.00	500.00	7.5	.28	62	96	.0	0	5	.0	17.86
21 . . .	45	4.0	0	3	26.50	4	4.0	18.0	5.89	69.00	500.00	7.5	1.43	0	0	285.0	0	0	5.0	3.51
21 . . .	28	4.0	0	3	26.50	4	4.0	18.0	5.89	69.00	500.00	7.5	2.76	0	0	552.0	0	0	5.0	1.81
21 . . .	28	6.0	0	3	26.50	4	4.0	18.0	8.83	69.00	500.00	7.5	.52	59	232	.0	0	9	.0	17.18
21 . . .	39	4.0	0	3	26.50	4	4.0	18.0	5.89	69.00	500.00	7.5	6.13	0	0	1,225.0	0	0	1.0	.16
21 . . .	39	6.0	0	3	26.50	4	4.0	18.0	8.83	69.00	500.00	7.5	1.14	93	543	.0	0	1	.0	.87
21 . . .	76	4.0	0	3	26.50	4	4.0	18.0	5.89	69.00	500.00	7.5	8.15	0	0	16,292.0	0	0	4.0	.49
21 . . .	76	6.0	0	3	26.50	4	4.0	18.0	8.83	69.00	500.00	7.5	15.26	1,340	7,141	.0	1	10	.0	.72
22 . . .	40	6.0	0	3	17.70	4	4.0	18.0	5.90	63.00	400.00	7.0	3.02	75	185	482.5	0	0	.0	.00
22 . . .	40	6.0	1	2	17.70	4	4.0	18.0	5.90	63.00	400.00	7.0	1.00	24	60	156.0	0	0	.0	.00
22 . . .	40	6.0	1	1	17.70	4	4.0	18.0	5.90	63.00	400.00	7.0	1.10	25	65	167.5	0	3	.0	2.73
23 . . .	50	6.0	0	3	17.70	4	4.0	18.0	5.90	63.00	400.00	7.0	1.28	30	75	195.0	0	0	.0	.00
23 . . .	40	6.0	1	2	17.70	4	4.0	18.0	5.90	63.00	400.00	7.0	.76	18	45	117.0	0	0	.0	.00
24 . . .	42	6.0	1	2	33.00	4	5.0	19.0	8.34	61.00	650.00	6.0	73.20	1,967	2,825	8,600.5	5	34	16.5	.76
24 . . .	42	4.0	1	2	45.00	4	5.0	19.0	7.58	61.00	650.00	6.0	1.04	23	47	128.5	2	11	6.0	18.27
25 . . .	66	4.0	0	3	26.50	4	4.0	20.0	4.71	74.60	1,100.00	7.1	17.90	346	777	2,073.0	0	0	.0	.00
26 . . .	55	6.0	0	3	26.00	4	4.0	20.0	7.80	73.50	500.00	10.0	2.02	48	72	216.0	0	0	.0	.00
26 . . .	30	6.0	0	3	26.00	4	4.0	20.0	7.80	73.50	500.00	10.0	.76	18	27	81.0	3	5	.0	10.53
27 . . .	50	6.0	0	3	18.40	4	4.0	20.0	5.52	60.00	300.00	6.0	.94	80	48	168.0	0	0	3.0	3.19
27 . . .	50	6.0	0	3	18.40	4	4.0	16.0	6.90	50.00	300.00	6.0	4.94	254	221	871.0	0	0	2.0	.40
27 . . .	50	6.0	1	3	26.50	4	4.0	20.0	7.95	60.00	300.00	6.0	.10	26	3	42.0	0	0	2.0	20.00
27 . . .	50	6.0	1	3	26.50	4	4.0	16.0	9.94	50.00	300.00	6.0	.24	40	19	101.0	3	1	.0	16.67
27 . . .	50	4.0	1	2	26.50	4	4.0	20.0	5.30	60.00	300.00	6.0	.04	2	4	11.0	0	0	.0	.00
27 . . .	50	4.0	1	2	26.50	4	4.0	16.0	6.63	50.00	300.00	6.0	.22	13	15	49.5	0	1	2.5	15.91
28 . . .	50	6.0	0	3	26.50	4	4.0	22.0	7.23	78.40	1,000.00	5.0	14.30	396	736	1,914.0	12	24	14.0	3.50

Table 1.—Summary of geotechnical data gathered for each case in the study—Continued

Mine No.	CMRR	Bolt length, ft	Bolt tension	Bolt grout column	Bolt capacity, kips	Bolts per row	Row spacing, ft	Entry width, ft	PRSUP	Inter-section diagonal, ft	Depth of cover, ft	Mining height, ft	Drivage, 10,000 ft	No. of 3-way	No. of 4-way	No. of segments	Falls 3W	Falls 4W	Segment falls	Roof fall rate
29 . . .	35	6.0	0	3	18.00	4	4.0	18.0	6.00	64.00	200.00	7.5	2.90	39	227	512.5	0	0	.0	.00
29 . . .	35	6.0	1	2	18.00	4	4.0	18.0	6.00	64.00	200.00	7.5	.98	11	52	120.5	0	0	.0	.00
29 . . .	35	4.0	0	3	18.00	4	4.0	18.0	4.00	64.00	200.00	7.5	.51	9	52	117.5	0	0	.0	.00
30 . . .	52	4.0	0	3	17.70	4	4.0	18.0	3.93	63.00	400.00	7.0	8.20	179	516	1,300.5	0	21	5.0	3.17
30 . . .	40	4.0	0	3	17.70	4	4.0	18.0	3.93	63.00	400.00	7.0	5.30	117	216	607.5	12	4	10.0	4.91
30 . . .	75	2.5	1	1	17.70	4	4.0	18.0	2.46	63.00	400.00	7.0	.61	27	73	186.5	0	0	.0	.00
31 . . .	32	6.0	0	3	26.00	4	4.0	18.0	8.67	54.00	300.00	10.0	13.50	526	429	1,647.0	4	1	4.0	.67
31 . . .	32	6.0	0	3	26.00	4	4.0	18.0	8.67	54.00	800.00	10.0	2.50	62	93	279.0	1	1	3.0	2.00
32 . . .	51	3.5	0	3	18.50	4	4.0	20.0	3.24	66.00	500.00	3.5	11.80	261	763	1,917.5	0	0	.0	.00
33 . . .	30	5.0	1	2	37.00	4	4.5	18.0	9.14	56.00	300.00	6.0	3.22	64	258	612.0	0	8	1.0	2.80
33 . . .	30	6.0	0	3	20.50	4	4.5	18.0	6.07	57.00	300.00	6.0	12.50	236	873	2,100.0	4	21	25.0	4.00
34 . . .	44	3.5	0	3	20.00	4	4.0	20.0	3.50	68.00	250.00	3.5	6.40	296	506	1,456.0	0	4	6.0	1.56
35 . . .	47	3.0	0	3	26.50	4	4.0	20.0	3.98	61.70	300.00	3.0	7.90	275	701	1,814.5	0	0	.0	.00
35 . . .	47	3.0	0	3	26.50	4	4.0	20.0	3.98	66.30	300.00	3.0	1.20	0	201	402.0	0	0	.0	.00
35 . . .	47	3.0	0	3	26.50	4	4.0	20.0	3.98	61.70	500.00	3.0	3.90	144	402	1,020.0	0	0	.0	.00
35 . . .	47	3.0	0	3	26.50	4	4.0	20.0	3.98	66.30	500.00	3.0	.66	0	127	254.0	0	11	10.0	31.82
35 . . .	47	4.0	0	3	26.50	4	4.0	20.0	5.30	62.90	500.00	3.0	2.80	74	153	417.0	0	0	.0	.00
35 . . .	47	4.0	0	3	26.50	4	4.0	20.0	5.30	67.20	500.00	3.0	.30	0	43	86.0	0	0	.0	.00
36 . . .	49	3.5	0	3	26.50	4	4.0	20.0	4.64	63.00	150.00	3.0	1.00	41	72	205.5	0	0	.0	.00
36 . . .	49	3.5	0	3	26.50	4	4.0	20.0	4.64	57.00	150.00	3.0	.10	0	19	38.0	0	0	.0	.00
36 . . .	49	3.0	0	3	26.50	4	4.0	20.0	3.98	57.00	200.00	3.0	.10	0	16	32.0	0	0	.0	.00
36 . . .	49	3.0	0	3	26.50	4	4.0	20.0	3.98	63.00	200.00	3.0	.80	23	43	120.5	0	0	.0	.00
37 . . .	60	4.0	0	3	18.60	4	4.0	16.0	4.65	60.00	400.00	4.3	17.40	216	1,215	2,754.0	0	0	1.0	.06
37 . . .	39	6.0	0	3	18.60	4	4.0	16.0	6.98	60.00	400.00	4.3	5.50	81	294	709.5	0	1	1.0	.36
37 . . .	40	5.0	0	3	18.60	4	4.0	16.0	5.81	60.00	400.00	4.3	16.80	186	1,601	3,481.0	3	16	11.0	1.79

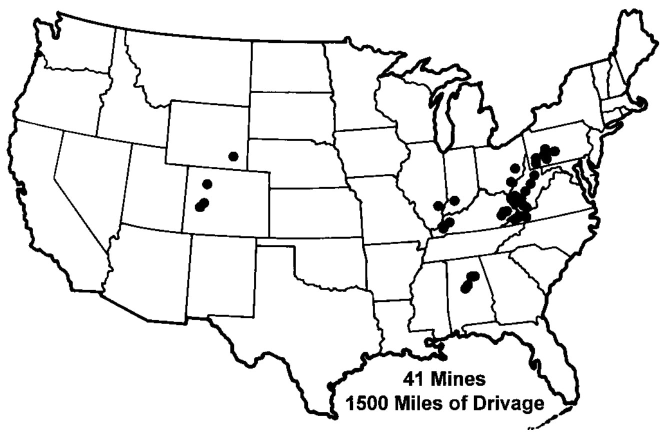

Figure 1.—Location of study mines.

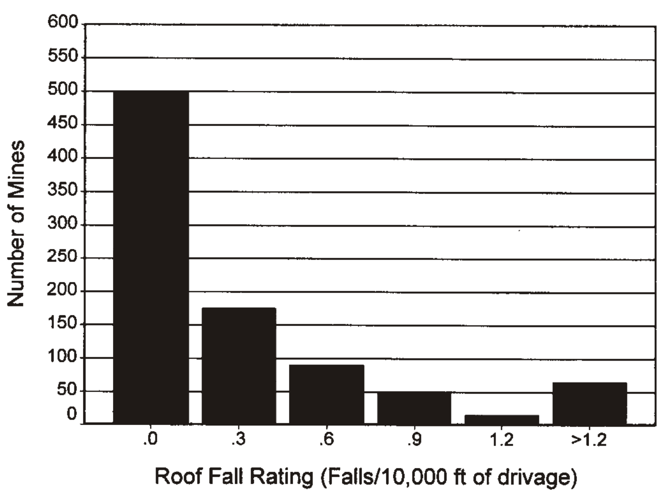

Figure 2.—Distribution of roof fall rates in U.S. coal mines.

At each mine, one or more "case histories" were collected. A case history was a portion of the mine that could be defined by a number of descriptive parameters and an outcome parameter (roof fall rate, falls/10,000 ft of drivage). The outcome parameter was based on the number of reportable roof falls that occurred in that portion of the mine.

According to MSHA regulations at 30 CFR 75.223, a fall of roof is reportable when it—

- Causes injury;
- Falls above anchorage;
- Blocks ventilation;
- Stops production for 30 min; or
- Blocks escape.

It was recognized that not all roof falls should be treated equally because their causes and impacts vary widely. A protocol for filtering roof falls for the study was developed. Tabulated roof falls were restricted to falls less than 18 months old in order to reduce time-dependent effects. Additionally, some mined areas are only accessible for short times (retreat panels or gate roads). To ensure equal treatment, mined areas had to be open a minimum of 18 months for use in the study.

Falls that were associated with longwall recovery, pillaring, multiple-seam effects, or other abutment pressures were also excluded. Falls associated with large-scale geologic dis-continuities, such as faults or sandstone channel margins, were excluded because they represent anomalous conditions and require specialized primary or supplemental support. In any study of roof safety or support performance, falls due to these factors must be treated separately because roof stability will not be achieved by standard support practices.

Because geotechnical parameters vary within mines, it was often not possible to characterize a whole mine by one set of variables. As a result, it was possible to have two or more "cases" within a mine representing a combination of geotechnical variables. The database ultimately included information from 37 of the 41 mines, but actually contained 109 "cases." The changing geotechnical environment of a mine roof was characterized by partitioning sections of a mine into zones with common variables. For example, a single mine might be broken up into three zones, or cases, if three roof bolt lengths were used. If two different roof geologies with different CMRR values were encountered within each of the three bolt length zones, then six cases were created.

ROOF FALL RATE

The roof fall rate was calculated as the outcome variable for each case. It was calculated by dividing the total number of roof falls that qualified for the study by the drivage. In order to quantify the percentage of drivage affected by a roof fall, roof falls were counted not as single entities but by the number of intersections and entry segments involved. A single roof fall covering two intersections and the crosscut between would count as three falls. Figure 3 shows the distribution of roof fall rates for the database. Nearly 60% of the cases in the data set had no roof falls. The other outcome variable was the four-way intersection rate. This number is calculated by dividing the number of four-way falls by the total number of four-way intersections in each case.

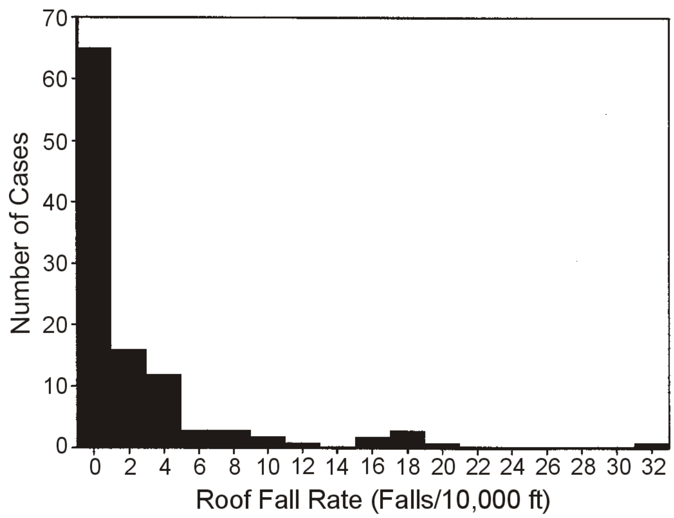

Figure 3.—Distribution of roof fall rates for cases in the study sample.

PRIMARY ROOF SUPPORT

For this study, a careful effort was made to characterize the roof bolts used in each case history. Operators were asked to report what bolts were installed historically through the mine. Where underground access permitted, NIOSH checked the accuracy of the information by reading the roof bolt heads, using a wire brush to clean them as necessary. This was done routinely where access permitted. After underground verification, roof bolt maps were compiled for the entire mine (figure 4). Six bolt variables were documented for each type of bolt used:

- Bolt length.
- Tension.
- Length of grout column.
- Yield capacity (grade of steel times cross-sectional area of the roof bolt).
- Bolts per row.
- Row spacing.

The most common bolt length used at the mines in our study was 5 ft (figure 5). Over 3.2 million feet of drivage was supported by 5-ft bolts (38%). Six-foot bolts were the next common length used (2.4 million feet of drivage, 30%), followed by 4-ft bolts (1.83 million feet of drivage, 22%).

Bolt tension was defined as either tensioned or untensioned. Eighty percent of the drivage was untensioned bolts (6.5 million feet), and 20% of the bolts were tensioned (1.6 million feet) (figure 6). All untensioned bolts were fully grouted, while nearly all tensioned bolts were ungrouted or partially grouted.

Figure 7 shows the distribution of roof bolts in the study by grout column and roof fall rate. The percentage of fully grouted bolts far outweighs the other grout column types, mirroring the national trend [Dolinar and Bhatt 2000]. There seems to be no correlation between roof fall rate and grout column length (roof fall rates are evenly distributed between variables), indicating that other factors are involved in the roof fall rate. Figure 8 shows the distribution of tensioned bolts as related by roof fall rate. Again, there is no correlation between roof fall rate and tension. Yield capacity ranged from 8.8 to 22.5 tons, with 9.5 tons of capacity occurring most frequently. The pattern of bolting in the United States varies little, with four bolts per row across the entry and 4 to 5 ft spacing between rows standard in nearly every case.

A summary variable, PRSUP, was calculated as a rough measure of roof bolt density:

$$PRSUP = \frac{Lb * Nb * C}{Sb * We}, \tag{1}$$

where Lb = length of the bolt, ft;

Nb = number of bolts per row;

C = capacity, kips;

Sb = spacing between rows of bolts, ft; and

We = entry width, ft.

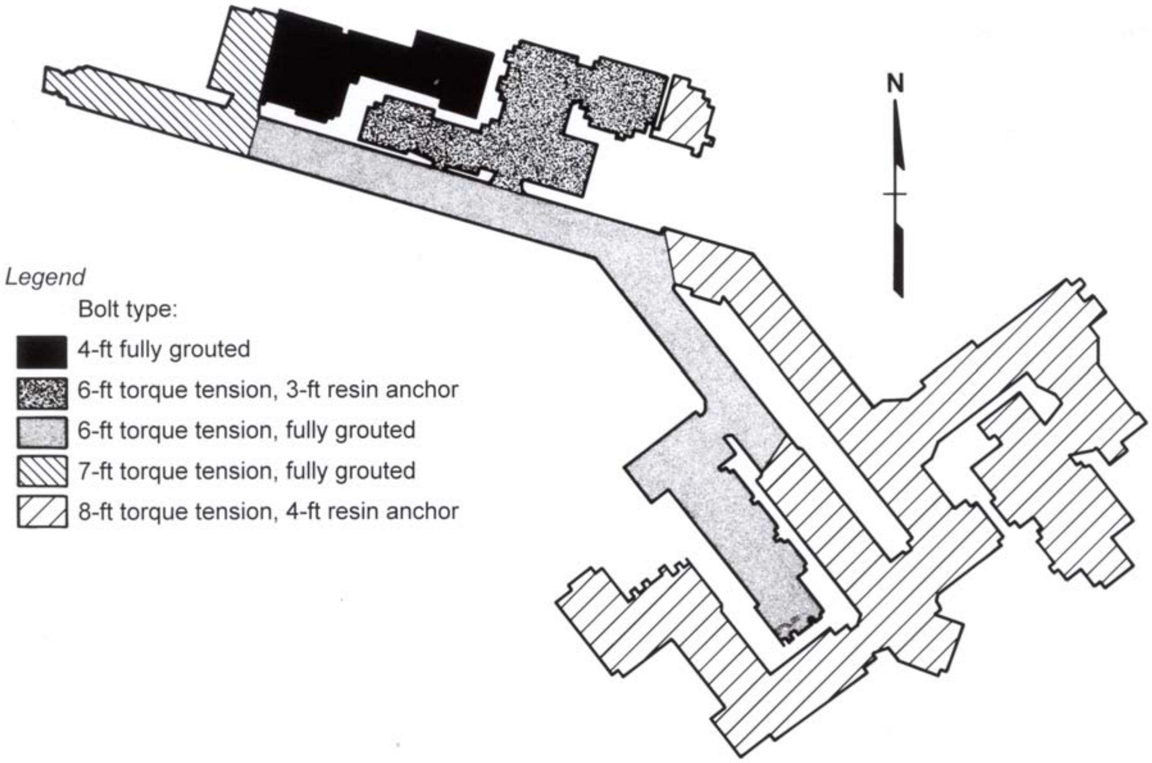

Figure 4.—Roof bolt map for study mine.

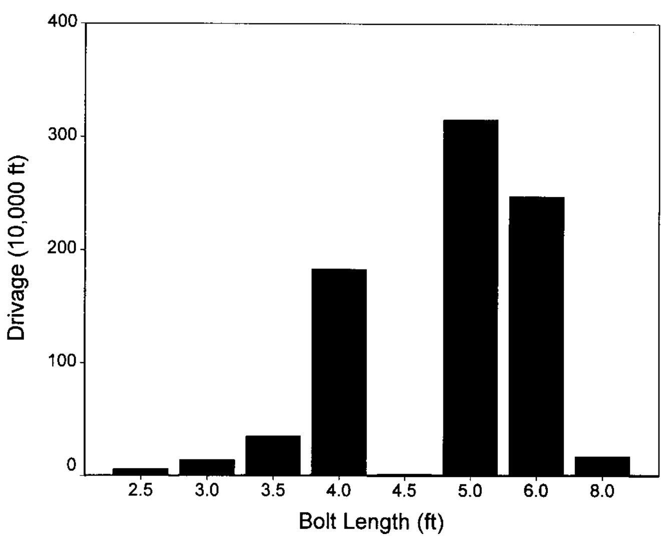

Figure 5.—Bolt length distribution in database as normalized by drivage.

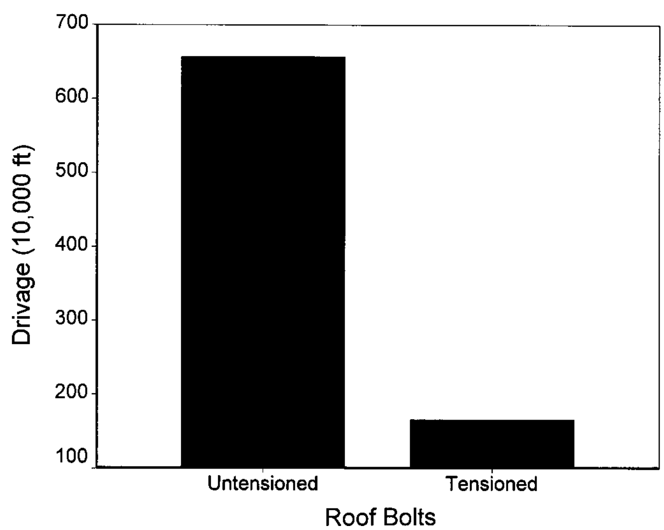

Figure 6.—Distribution of tensioned and untensioned bolts in the study.

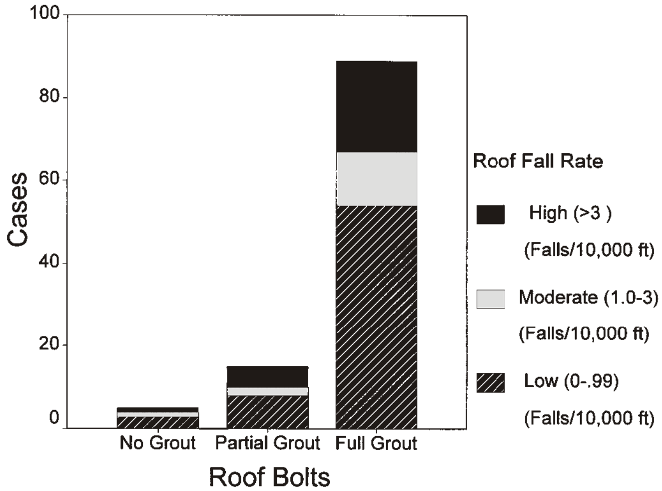

Figure 7.—Relationship between bolt grout column length and roof fall rate.

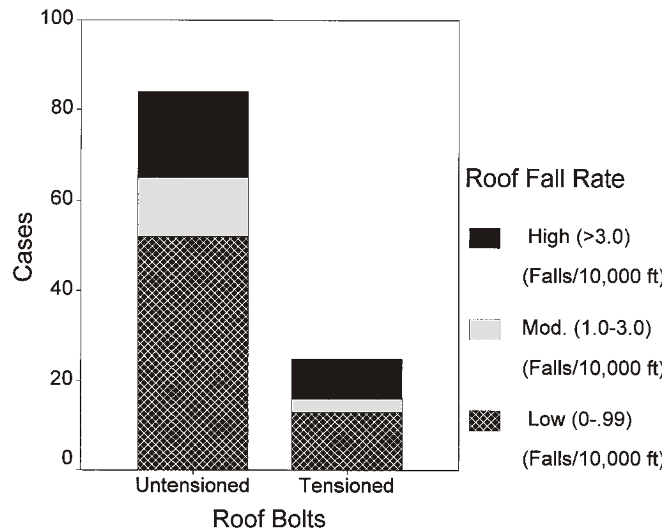

Figure 8.—Relationship between bolt tension and roof fall rate.

Figure 9 shows the distribution of PRSUP of all cases as grouped by roof fall rate. PRSUP is a rough measure of the "intensity" of the support. The more "steel" in the roof, the higher the PRSUP. It does not consider the type of bolt. PRSUP differs from the PSUP used in past studies [Mark et al. 1994] in that the bolt capacity has been substituted for the bolt diameter. The proportion of cases with high roof fall rates increases with increasing PRSUP. Additionally, the average PRSUP for cases with a roof fall rate equal to 0 is 4.4. The average PRSUP for cases with roof fall rate >1 is 6.1 This difference is significant at the ∝ = 0.05 level. This is an indication that operators are responding to poor roof conditions (higher roof fall rates) by adding more roof bolt support (increasing PRSUP) and that they are being only partially successful. The correlation between higher support densities and higher fall rates also presented a problem for the statistical study.

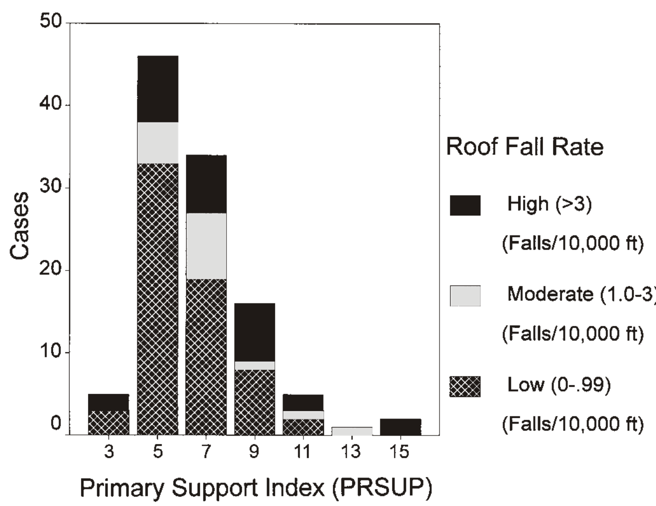

Figure 9.—Relationship between PRSUP and roof fall rate.

ROOF GEOLOGY

Roof geology has historically been difficult to quantify in ground control studies because of the many factors that comprise it. The Coal Mine Roof Rating (CMRR) was designed to quantify the geotechnical elements of the roof and return a number from 0 to 100 that reflects the competence of the roof [Molinda 1994]. The CMRR for each case was determined primarily by underground observation of roof falls, supplemented by drill core when it was available. A roof geology-CMRR map was constructed for each mine (figure 10). Figure 11 shows the distribution of the CMRR in the database. There is a strong correlation between CMRR and roof fall rate, with higher roof fall rates in the weaker roofs (CMRR ≤ 50). For cases with a CMRR ≤ 30, all have high or moderate roof fall rates. Conversely, high roof fall rates are rare for roof rocks with CMRR ≥ 60. If just the cases with no roof falls at all are considered (n = 41), the average CMRR is 52.3. For cases with a roof fall rate ≥ 2.0 (n = 36), the average CMRR is significantly lower at 42.8.

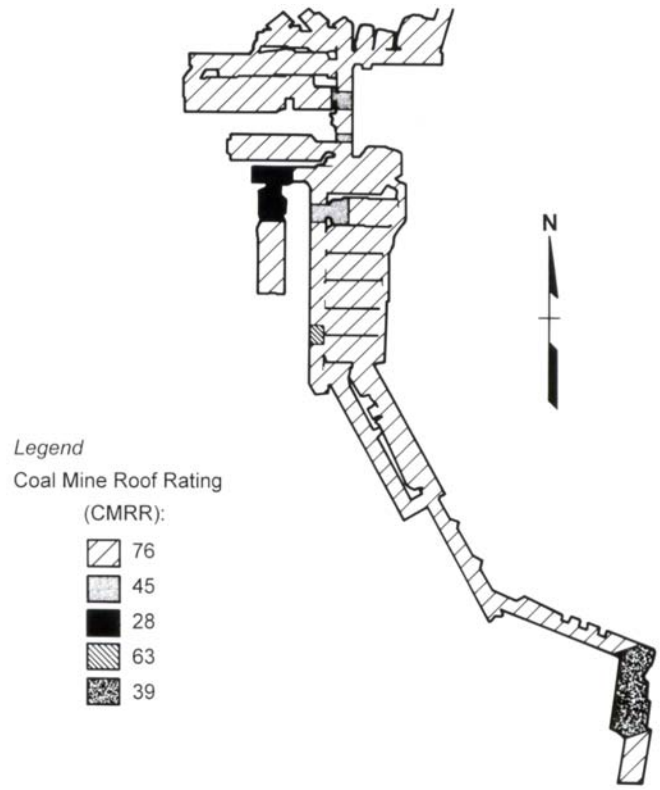

Figure 10.—CMRR map of study mine.

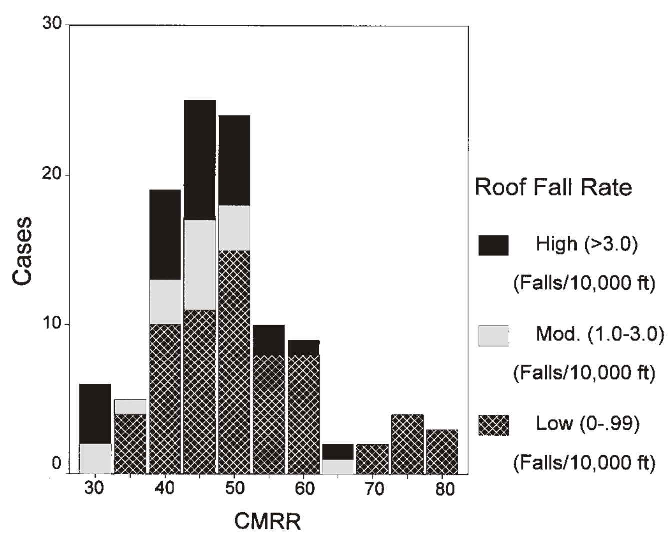

Figure 11.—Relationship between roof fall rate and CMRR.

INTERSECTION SPAN

The intersection diagonals were measured for a sampling of intersections in each mine, and in cleaned-up roof falls when possible. Figure 12 shows the method of measurement of intersections. Measurements were averaged to represent the typical span for each case. Figure 13 shows the distribution of intersection spans and roof fall rate. There is no obvious correlation between roof fall rate and intersection span.

While most (62%) of the falls in the total database occur in intersections, the intersection *fall rate* shows that intersections are much more likely to fall than entry or crosscut segments between intersections (figure 14). Segments are defined as any mined room that is not an intersection. Segments usually are two to three times as long as intersections. Of the intersections, four-way intersections are more likely to fall than three-way intersections (figure 15).

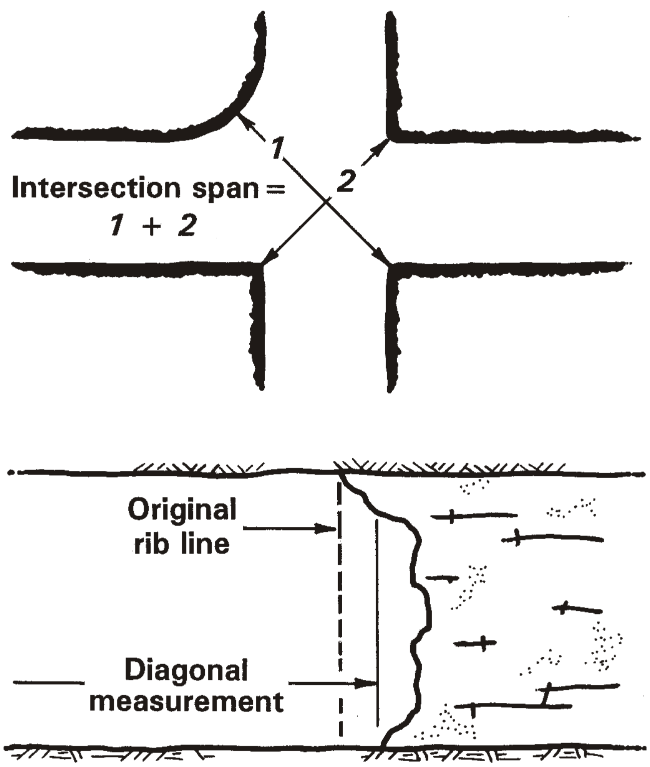

Figure 12.—Method of measuring intersection diagonals.

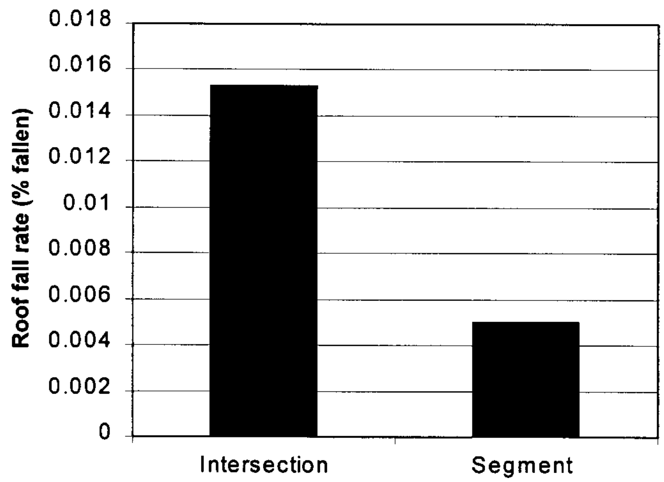

Figure 14.—Comparison of the roof fall rate between intersections and entry segments.

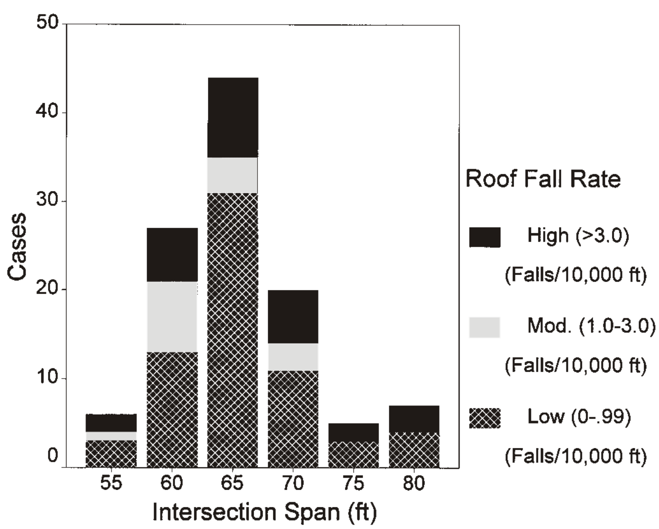

Figure 13.—Relationship between roof fall rate and intersection span.

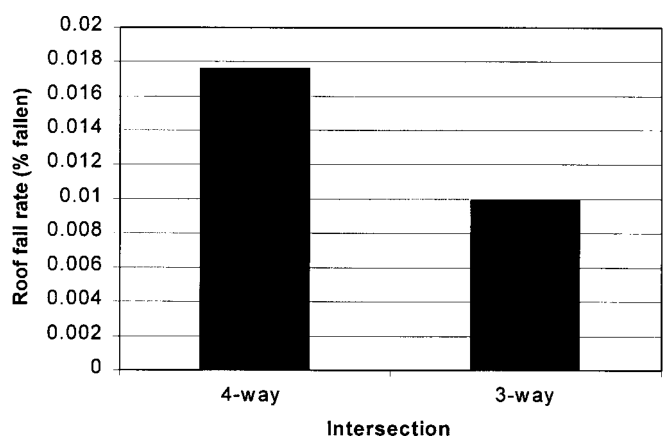

Figure 15.—Comparison between the roof fall rate for four-way and three-way intersections.

DEPTH OF COVER

The depth of cover over the mines in the study ranged from 0 to 1,600 ft. For analysis purposes, the average cover was recorded into three categories: shallow (0 to 400 ft), moderate (400 to 800 ft), and deep (>800 ft). Figure 16 shows the distribution of depth of cover for study cases.

STATISTICAL ANALYSIS

In order to determine the influence of the collected geotechnical variables on roof instability, the database was standardized and prepared for analysis. SPSS was the statistical package used for the analysis.

One goal of the study was to determine if there was a universal design equation that would use all or some of the geotechnical variables to predict the roof fall rate. A linear regression was performed that included all the significant geotechnical variables, including overburden, bolt length, grout length, density, entry width, CMRR, intersection span, tension, and bolt capacity. The regression technique progressively removes variables that are not significant in a stepwise procedure. The resultant regression equation can explain only 29.9% of the variation of the four-way intersection fall rate. More importantly, there is a positive relationship between bolt capacity and the roof fall rate. In other words, when bolt capacity goes up, the roof fall rate goes up. This defies logic, but the explanation is that when roof conditions deteriorate (roof fall rate goes up), higher capacity bolts are generally installed.

There are several explanations for the low overall correlation of the regression equation to the data. A test for intercorrelation of the variables revealed that a number of the variables were correlated to each other. This interdependence reduces the overall correlation of the design equation. Table 2 (Pearson correlation) is a test of the codependence of the geotechnical variables. A value of 1.0 is a perfect correlation, and 0.0 shows no correlation at all. Several bolt parameters—tension and grout indices, capacity and density, and bolt tension and capacity—are related. As roof conditions worsen, operators generally move toward tensioned bolts as well as increased capacity, apparently with only partial success. Intersection span and entry width are naturally related. The CMRR and the bolt length are also related. As expected, as the roof gets stronger (higher CMRR), operators are installing shorter bolts. These intercorrelations of variables confound the overall effect of any one variable on the outcome, which is the roof fall rate. Therein lies the difficulty in producing a reliable roof bolt design equation.

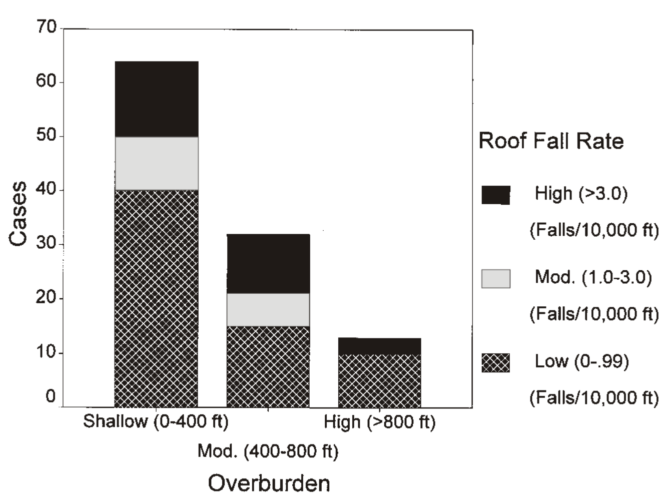

Figure 16.—Relationship between roof fall rate and overburden.

Although a universal design equation was not possible, the data analysis produced other interesting results. Other studies show significant evidence of increasing horizontal stress with depth [Mark 1994]. In this study, there is indirect evidence of the relationship. The data show that there is a statistically significant correlation (Pearson correlation = 0.253, statistically significant at 0.01 level) between CMRR and overburden. It seems that stronger roof rocks are encountered as overburden increases. There is no geologic reason for this, but it seems that operators are unable to mine weak roof at great depth. As overburden increases, stronger roof is encountered. In our database, 10 cases are mining at depths below 800 ft of cover, and 9 are >50 CMRR.

Figure 17 shows the relationship between CMRR and depth of cover for the study data. The individual cases have been divided into three roof fall rate categories; high, borderline, and zero. A line has been drawn on the graph that roughly separates lower roof fall rates from higher roof fall rates. Sixteen of twenty-two cases of zero roof falls fell above the classification line and were correctly classified. Nineteen of twenty-three cases with high roof fall rate (>2.0 falls per 10,000 ft of drivage) fell below the classification line and were correctly classified. The overall correct classification rate was 77%.

It seems likely that in our data, depth of cover is an indirect measure, or surrogate, for horizontal stress level. Horizontal stresses are seldom measured directly because of the difficulty and expense.

Using this assumption, the case histories were divided into two groups by depth of cover. The shallow-cover group included depths <400 ft, and the deeper-cover groups included depths ≥400 ft. Figure 18 shows the relationship between CMRR and PRSUP at high cover. Ten of sixteen "high" roof

Table 2.—Correlation between geotechnical variables in the study

Geotechnical variable	CMRR	Bolt length selected, ft	Tension index	Grout index	Capacity, kips	Bolts per row	Row spacing, ft	Entry width, ft	Density	PRSUP	Intersection span, ft	Overburden index	4-ways rate	Roof fall rate
CMRR	1.000	-.329	-.020	-.081	-.166	.037	-.147	.089	-.134	-.282	[1].233	[2].249	-.257	-.215
Bolt length selected, ft	[1]-.329	1.000	.251	-.059	.134	-.116	.038	-.215	.161	.738	-.067	-.039	.091	.105
Tension index	-.020	.251	1.000	[1]-.811	.326	-.161	.070	-.107	.271	.356	-.204	-.188	.217	.187
Grout index	-.081	-.059	[1]-.811	1.000	-.196	.131	-.012	.123	-.169	-.176	.124	.127	-.192	-.044
Capacity, kips	-.166	.134	[1].326	[2]-.196	1.000	-.178	-.084	.086	[1].907	.686	.043	[1].234	.442	.322
Bolts per row	.037	-.116	-.161	.131	-.178	1.000	.000	.167	-.076	-.132	.042	-.097	.079	.031
Row spacing, ft	-.147	.038	.070	-.012	-.084	.000	1.000	.041	-.375	-.232	-.089	-.248	.182	.075
Entry width, ft	.089	[2]-.215	-.107	.123	.086	.167	.041	1.000	-.172	-.245	[1].359	[1].124	.063	-.011
Density	-.134	.161	.271	-.169	[1].907	-.076	-.375	-.172	1.000	.767	-.016	[2].248	.341	.294
PRSUP	-.282	.738	.356	-.176	.686	-.132	-.232	-.245	.767	1.000	-.049	.154	.273	.266
Intersection span, ft	[1].233	-.067	-.204	.124	.043	.042	-.089	[1].359	-.016	-.049	1.000	[1].600	.060	-.053
Overburden index	[2].249	-.039	-.188	.127	[1].234	-.097	-.248	[1].124	[2].248	.154	[1].600	1.000	.089	.004
4-ways rate	-.257	.091	.217	-.192	.442	.079	.182	.063	.341	.273	.060	.089	1.000	[1].661
Roof fall rate	-.215	.105	.187	-.044	.322	.031	.075	-.011	.294	.266	-.053	.004	[1].661	1.000

[1]Correlation is significant at the 0.01 level (2-tailed).
[2]Correlation is significant at the 0.05 level (2-tailed).

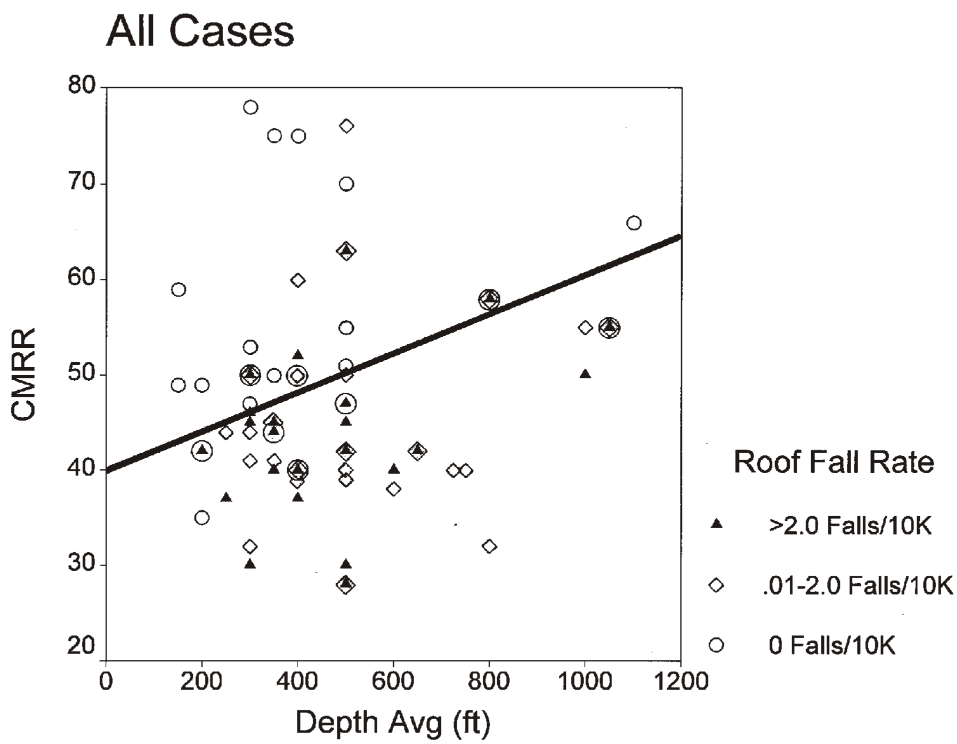

Figure 17.—Relationship between CMRR, depth of cover, and roof fall rate.

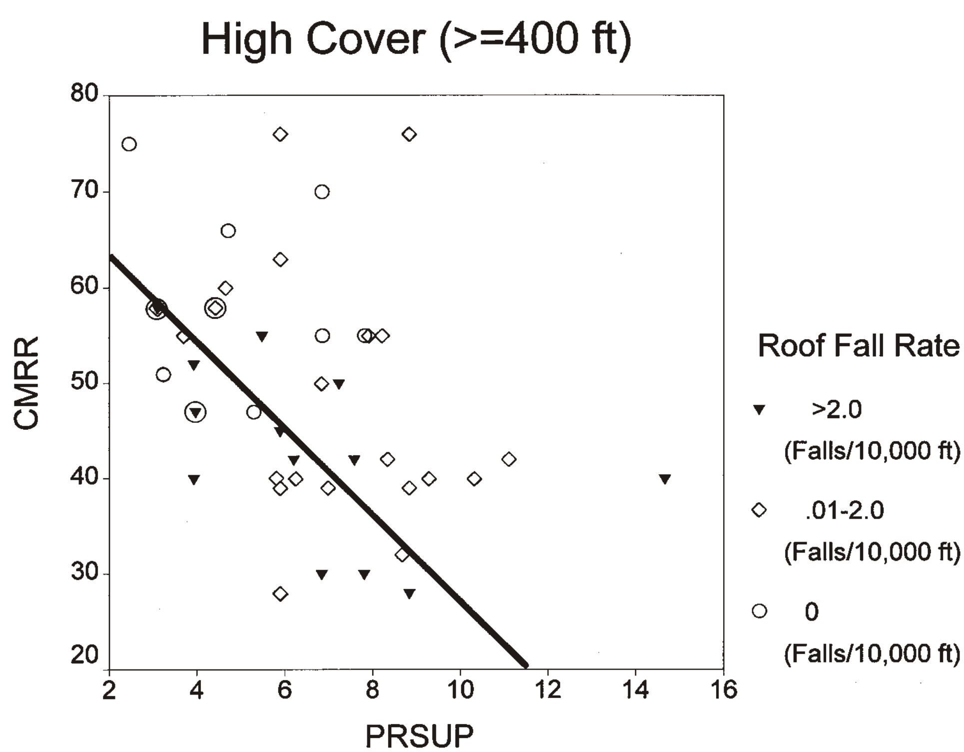

Figure 18.—Relationship between PRSUP, CMRR, and roof fall rate for cases under cover ≥400 ft.

fall rates fell below the classification line and were correctly classified. Eleven of 17 zero roof fall rate cases fell above the classification and were correctly classified. Looking at the "low" cover group, 16 of 17 cases with zero roof falls fell above the classification line, whereas the high roof fall rate cases were approximately evenly split (figure 19).

In both groups, most of the misclassified high-rate cases and the borderline cases plotted fairly close to the classification line. There were also high-roof-fall-rate cases that were misclassified that were also low CMRR. However, it seems that the relationship may break down for the weakest roof.

The relationship between CMRR and PRSUP was used to develop design equations, which are described by Mark [2000].

OTHER VARIABLES AFFECTING ROOF FALL RATE

The data collected during this study showed a considerable amount of scatter, as evidenced in many of the figures presented thus far. The explanation for the scatter is that the mining environment is far from a controlled experiment where all variables may be held constant and varied individually. If this were the case, the change in outcome variable can be observed and attributed to one variable. Moreover, some variables are difficult to measure, particularly over large areas. As a result, the observed roof fall rates may be affected by a number of factors that could not be included in the analysis, including—

Geologic variation: Typically, in an underground coal mine, parameters like geology (CMRR) can vary rapidly. Without systematic roof exposure (test holes), it may be difficult to assign the CMRR accurately to large sections of mine roof. By underground observation of roof falls and other exposures and drill core data, a CMRR was calculated that best represents the case area.

Horizontal stress: The presence of high biaxial horizontal stress is known to affect roof quality adversely [Mucho 1995]. The study used overburden depth as a surrogate for horizontal

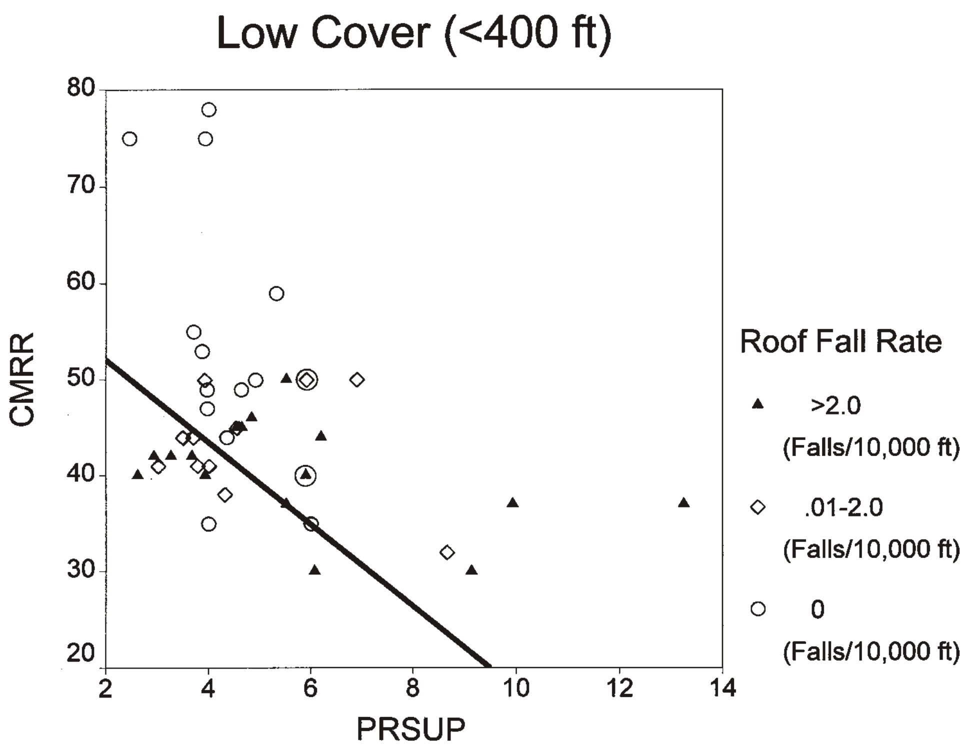

Figure 19.—Relationship between PRSUP, CMRR, and roof fall rate for cases under <400 ft.

stress, but actual stress levels vary by region, direction of mining, and surface topography.

Overwide intersections: It is suspected that in weak rock, small increases in intersection span (3 to 8 ft) can significantly weaken the roof. Many roof falls in the study were either inaccessible or not cleaned up, making it difficult to document accurately any overspans that may have contributed to the fall.

Quality of roof bolt installations: One of the most difficult parameters to measure is the quality of roof bolt installation. It is suspected that some failures can be caused by deficient bolting practices, including loss of tension, large bolt annulus, bent or notched bolts, overdrilled holes, or long lag times before bolting. All of these factors may mask the performance of bolt systems by increasing the roof fall rate.

OTHER RESULTS

As described above, the statistical analysis of data becomes more complicated with increasing numbers of variables. Interdependence of variables and errors in measurement are compounded with large numbers of variables. An alternative was to conduct analyses using "paired data" from individual mines. In these cases, only a single variable changes.

The most successful of these analyses was on roof bolt length. From the large data set, 13 pairs of data where two different lengths of roof bolts were used at the same mine were extracted. The roof bolt lengths differed by at least 1 ft in the pairs. Table 3 shows the bolt lengths, along with the CMRR, the bolt type, the roof fall rate, and the percentage of difference in roof fall rate between the two lengths.

The data show that in 11 of 13 cases, the four-way intersection roof fall rate was less with the longer bolt (figure 20). The roof fall rates for the paired data range from 0.0 to 18.3 and the

Table 3.–Test cases showing the effect of bolt length on roof fall rate

Mine	CMRR	Bolt length, ft	Roof fall rate (falls per 10,000 ft)	% change	Bolt type
1	50	4	1.08		Fully grouted.
		6	.66	-39	Fully grouted.
2	37	6	12.07		Tension.
		8	8.62	-29	Tension.
3	41	5	1.28		Fully grouted.
		6	.23	-82	Fully grouted.
4	55	4	4.05		Fully grouted.
		6	.79	-80	Fully grouted.
5	58	3.5	.88		Fully grouted.
		5	.23	-74	Fully grouted.
6	39	5	1.79		Fully grouted.
		6	.36	-80	Fully grouted.
7	42	4	2.9		Tension.
		6	1.11	-61	Fully grouted.
8	42	4	18.3		Tension.
		6	.76	-96	Fully grouted.
9	44	4	0		Tension.
		6	3.57	+100	Tension.
10	40	5	.52		Fully grouted.
		8	0	-100	Tension.
11	40	5	.39		Fully grouted.
		6	.26	-34	Tension.
12	30	5	2.8		Tension.
		6	4.0	+40	Fully grouted.
13	50	4	2.45		Tension.
		5	1.77	-28	Fully grouted.

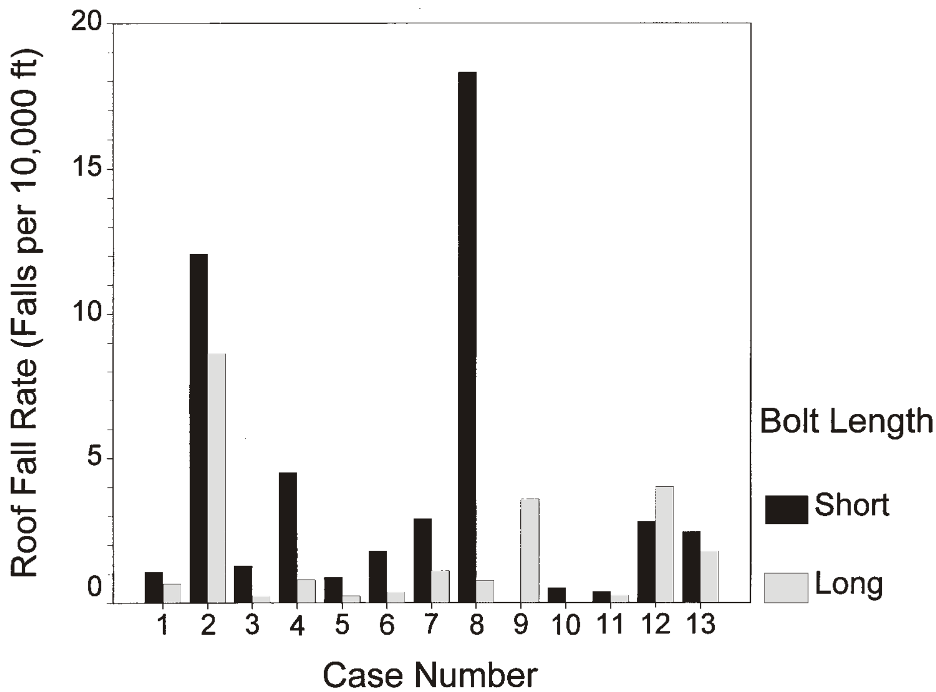

Figure 20.—Paired cases of long and short bolts showing benefits of long bolts and decreasing roof fall rates.

decrease in roof fall rate (average 65%, n = 13) with increasing bolt length holds true even in the high roof fall rate range. Six of the 13 pairs of bolt lengths mixed tensioned bolts with fully grouted bolts and the relationship holds true with both types of bolts. Thus, through a wide range of CMRR (30-58), an increase of at least 1 ft in bolt length can be expected to result in a decrease in four-way intersection roof fall rate.

The paired bolt length data contain four cases comparing longer fully grouted bolts with shorter tensioned bolts. The roof fall rate was lower in just one case and higher in the three other cases when the mine used the shorter tensioned bolts.

The relationship between CMRR and intersection span was also analyzed. The data were partitioned by four-way intersection fall rate into low (0-0.001 falls per 100 four-way intersections), moderate fall rate (0.001-0.05 falls per 100 four-way intersections), and high fall rate (>.05 falls per 100 four-way intersections). Additionally, only fully grouted bolts were used in the analysis. By logistic regression, a line was fitted to the data and presented in figure 21. No cases with high roof fall rates fell to the right side of the regression line. This line can be used to indicate whether smaller spans might be helpful in relieving the incidence of roof falls. It is rare for high roof fall rates to occur in roof with intersection spans less than the equation. The less conservative regression line (span = 31 + 0.66 CMRR) might be an appropriate first approximation design equation. Based on our data, there is also a likelihood that intersection falls will be reduced by a decrease in intersection span. The intersection span measured for the study was taken at the midpoint between the original rib corner and the subsequent sloughage point. This differs from MSHA's measurement point, which is the original rib corner. For this reason, the projected intersection spans will be somewhat conservative.

Intersection diagonals are usually related to entry width. The data were studied to determine the typical intersection spans that are encountered underground. Figure 22 shows the mean of the sum of the diagonals for 16-, 18-, and 20-ft entries. It also shows that in deeper mines, the sum of the diagonals was 3-4 ft wider than in the shallow mines with the same entry width, probably because of greater rib sloughage.

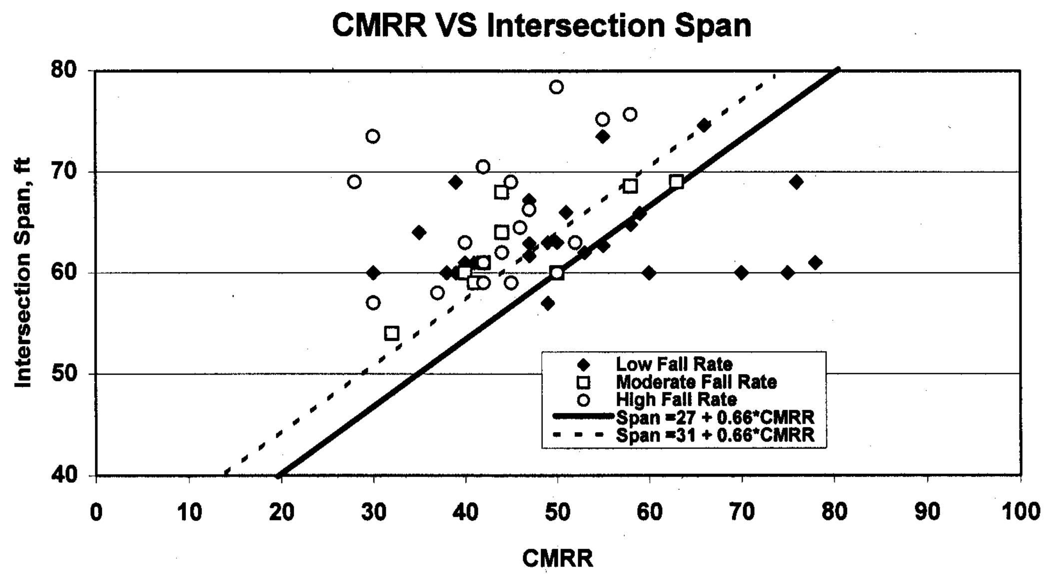

Figure 21.—Relationship between CMRR, intersection span, and roof fall rate.

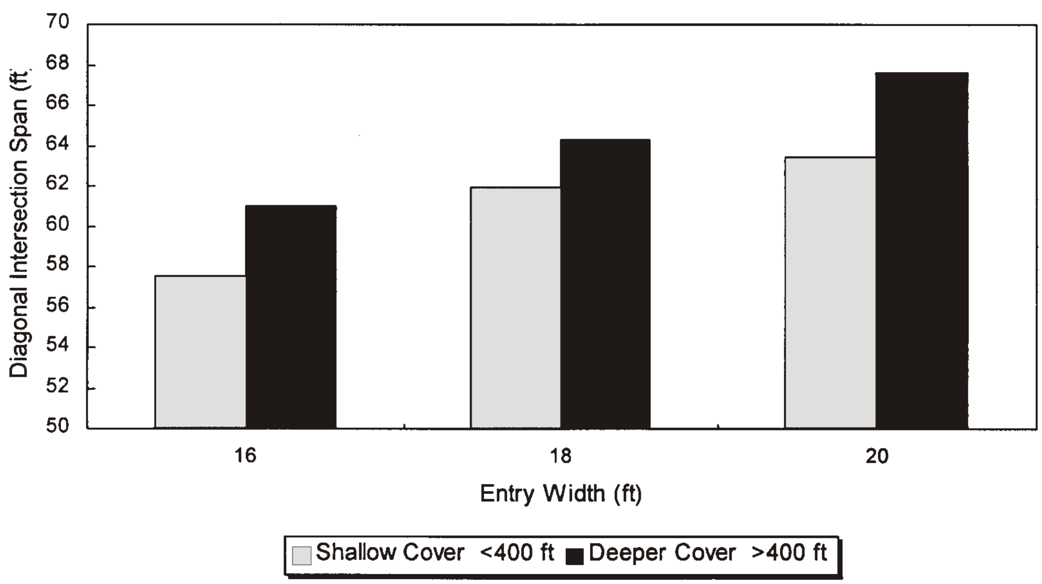

Figure 22.—The effect of overburden on intersection diagonal.

CONCLUSIONS

Data on roof quality and roof bolt performance were collected from interviews and underground reconnaissance at 41 U.S. coal mines. The roof fall rate (falls per 10,000 ft of drivage) and the four-way intersection fall rate (roof falls in four-ways/total number of four-ways) were developed as the outcome variables for analyzing the influence of numerous geotechnical variables on stability. From the data it was determined that higher roof fall rates were more common in the lower CMRR range (CMRR $\leq$ 50). Intersections were much more likely to fall than entry segments, and four-way intersections were more likely to fall than three-way intersections. When the data were divided into two groups by depth of cover, a relationship between PRSUP and the CMRR was determined that could be used in design. The study determined that overburden depth could be used as a surrogate for stress level. Paired data extracted from the database show that increasing bolt length decreased the roof fall rate in 11 of 13 cases over a wide range of roof fall rate and bolt types. A useful relationship between the intersection span and the CMRR was also found. The data showed considerable scatter, which was attributed to variations in roof geology, horizontal stress, and bolt installation quality, none of which could be measured.

The method for constructing historic roof bolt maps and hazard maps using the CMRR was described. These methods of tracking roof quality and support performance will be valuable for individual mine operators.

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