ROCK MASS CLASSIFICATION IN GERMAN HARD-COAL MINING: STANDARDS AND APPLICATION

By Holger Witthaus, Dr.-Ing.,[1] and Nikolaos Polysos, Dr. rer. nat.[1]

INTRODUCTION

The classification system for German coal mining is the result of approximately 100 years of experience in roadway development and longwall mining. It is also based on different research projects covered by national and European research programs.

Over the past 30 years, more then 600,000 m of roadways have been driven and employed for mining activities. To properly describe the German rock mass classification system, therefore, it is useful to take a look at the main geomechanical preferences and common support systems.

The decision about the most effective development technique and support system is based on a synthesis of rock mass classification and geomechanical analysis. The properties of surrounding rock, the in situ stress, and the influence of mining activities in several seams at each German mine must be considered for the evaluation of the expected deformation of the roadway.

The mine layout, the requirements of ventilation and fire prevention, as well as the need to maintain emergency escape routes for the miners, require that the gate roads remain usable after the passage of the longwall face in most cases. Moreover, the gate roads must be maintained despite the high stresses that are applied during longwall retreat mining. Therefore, gate road design must address a broad spectrum of potential deformation environments.

In the past, when gate roads were supported solely with yielding steel arches, lithologic descriptions of the surrounding strata conditions were adequate for the dimensioning of support and the prediction of the roadway deformation. The current conditions of multiple-seam mining at depths of up to 1,700 m require combined support systems, including pattern bolting and backfilled steel arches.

Rock bolt support is used for development, after which (typically 50–100 m outby the face) the steel arches are installed and backfilled with building material (concrete) in order to achieve an optimized development rate.

The rock mass classification system described below was developed especially for the conditions of German hard-coal mining. It includes the stress distribution caused by multiseam workings (including crossing goaf edges of former longwalls), as well as in situ stresses due to great depth and the presence of tectonic faults. It is based on the evaluation of four parameters:

- Geotechnical analysis of drill cores
- Geotechnical observation of the development face
- Geotechnical classification of tectonic structures (faults)
- Standard classification derived from geotechnical assessment and evaluation of stress conditions (using numerical modeling for stress calculation)

ROCK STRENGTH

One of the most important input parameters for describing strata conditions is the strength of the rock. The German classification system is based on a description of lithotypes. This method has been used successfully since the 1950s and is based mainly on the uniaxial compressive strength (UCS) of the material.

An evaluation of the rock strength observed in a survey of approximately 82,500 samples of rock core yielded the results shown in Figure 1. The three most common coal measure rock types are mudstone, siltstone, and sandstone. Each shows a specific mean UCS level and a different spread between the minimum and maximum values. Sandstones, in particular, have a wide spectrum of compressive strength, ranging from approximately 40 MPa to greater than 130 MPa, with an average of 85 MPa. The causes of this wide range include different sedimentological preconditions, facies, and digenetic processes.

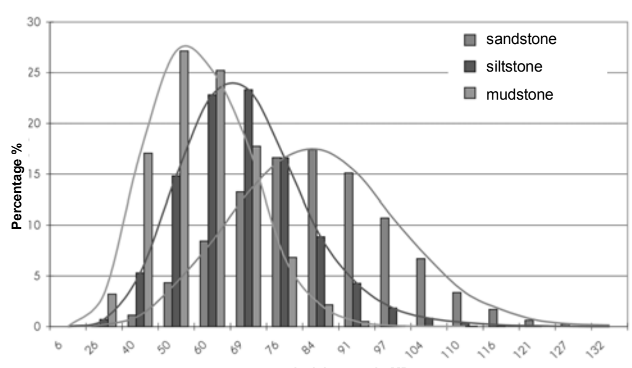


Figure 1.—Frequency distribution of uniaxial strength for typical lithotypes from German coal mines.

[1]Certified expert in geomechanics and support systems, Deutsche Steinkohle AG (DSK), Herne, Germany.

GEOTECHNICAL ROCK EVALUATION

The assessment of strata conditions, which can be conducted either by analyzing drill cores or by evaluating the development face, requires data on 14 parameters. Figure 2 gives an overview of this system of rock evaluation. Each parameter is rated as “poor,” “mean,” or “good,” depending on the characteristic that is being analyzed. For example, the intensity of stratification is rated according to the structure of bedding, as follows:

- *Good conditions:* No significant stratification or no regular stratification;
- *Mean conditions:* Some typical regular bedding areas; or
- *Poor conditions:* Regular stratification of thin beds in a banded bedding structure.

While parameters 1–8 and 13 can be determined either from drill core or from observations made in the headings, parameters 9–12 and 14 can only be obtained from underground observations.

The evaluation focuses on the rock properties to provide some idea of the rock strength, the character of the stratification, and the description of separation. These elements are used for description of the expected deformation of a roadway under the influence of high stress.

Geotechnical rock evaluation	
1.	**Structure of bedding**
1.	ug = massive
2.	ur = irregular bedded
3.	re = regular bedded
4.	we = alternate bedding with Sandstone bands
5.	gb = banded
2.	**Bed thickness structure**
1.	B100 > 0,80 [m]
2.	B80 0,80 - 0,60 [m]
3.	B60 0,60 - 0,40 [m]
4.	B40 0,40 - 0,20 [m]
5.	B20 0,20 - 0,10 [m]
6.	B10 < 0,10 [m]
3.	**Rock properties**
1.	ko = compact
2.	ab = sanding (rubbing)
3.	ge = friable
4.	zr = fractrured/ sheared
5.	le = lettenlike/ mylonitized
4.	**Character of separation plane surface**
1.	ra = rough
2.	FA = fossil separation planes (e.g. plant layer, shell bank)
3.	ar = abrasion
4.	SH = slickenside surface
5.	KA = coaly layers (e.g. vitrain, coal streaks)
5.	**Additional description of separation planes**
1.	ag = stepped
2.	wl = undulating
3.	gg = bent
4.	gr = straight
5.	ha = conchoidal
6.	**Character of separation plane**
1.	g = closed
2.	o = open
3.	k = cavernous
4.	z = fractured
5.	m = mylonitized
7.	**Character of tectonic separation**
1.	ra = rough
2.	e = straight
3.	ar = abrasion
4.	H = slickenside surface
5.	SpH = polished slickenside

8.	**RQLD (Rock Quality Lithologic Designation)**
1.	> 90
2.	> 75
3.	> 50
4.	< 50
5.	> 25
9.	**Degree of natural internal separation**
1.	I
2.	II
3.	III
4.	IV
5.	V
10.	**Relative elongation of separation planes**
1.	< 0,2
2.	0,2 up to 0,4
3.	0,4 up to 0,6
4.	0,6 up to 8
5.	0,8 up to 1
11.	**Relative degree of bedding**
1.	> 1
2.	1 to 0,5
3.	0,5 to 0,3
4.	0,3 to 0,2
5.	< 0,2
12.	**Relative degree of tectonic separation**
1.	< 1
2.	1 up to 2
3.	2 up to 3
4.	3 up to 4
5.	4 up to 5
13.	**Water resistance**
1.	No influence
2.	Debonding
3.	Loosening
4.	Decomposition
5.	Collapse
14.	**Formation water**
1.	dry
2.	moist
3.	wet
4.	dripping
5.	running

1 2 3 4

good mean poor

Figure 2.—Matrix for geotechnical rock evaluation.

The strata evaluation is conducted in three areas around a roadway:

- The floor area (0–6 m below the roadway);
- The mined strata (between floor and roof of the roadway); and
- The roof area (0–6 m above the roof of the roadway).

For larger roadways, with widths of more than 6 m, the area evaluated is increased to a distance equal to the roadway width above and below the roadway.

RATING STRUCTURAL FAULTS

The typical German hard-coal deposit includes a lot of tectonic faults. The panel layout has to consider these features, but, in some cases, it is not possible to avoid having a longwall cross a fault. Experience has shown that faults can cause a wide range of effects on the mining process and the supports. The rating matrix shown in Figure 3 was developed to evaluate faults. The fault classification is based on a geometrical description of the fault itself, together with underground observations of the separation and strength of surrounding strata.

The objective of the fault classification is to provide an idea of the consequences for the roadway, in terms of the expected deformation and support requirements for the face and the face entry T-junction, in the area of the tectonically disturbed strata.

ROCK MASS CLASSIFICATION USING BOREHOLE GEOPHYSICS

Data collection for classification includes applied geophysical methods. Borehole geophysics provides information about the lithologic and physical parameters of the strata.

The most important geophysical logs include natural gamma, density, electrical resistance, seismic velocity and reflection, acoustic imaging, and caliper. By combining these logs and processing them together with information about the lithology, it is possible to obtain data on the structure of the rock mass, the elastic parameters of rock, and the location and properties of weak areas. Table 1 gives an overview of the criteria used in the geophysical classification of coal measure strata in German coal mines.

EVALUATION AND REPORTING OF GEOTECHNICAL PARAMETERS

The strata assessment method described above allows a comparison between geotechnical data derived from drill core and underground observations made in the headings. The results can be used to optimize the support system. In addition, the universal character of the classification method allows for a broad range of applications, including:

Mine:			
Exploration:			
Drilling depth/roadway section:			
Fault type/displacement:			
	Good	Medium	Poor
Strike relative to direction of drivage	perpendicular	diagonal	parallel
Dip relative to direction of drivage	in	against	transverse
Width of fault relative to roadway width (W)	< 1 W	1 W	> 1 W
Fault characteristic	Slickenside surface	Fractured zone	Gouge zone
Tectonic stress of rock strata	low	medium	strong
Fault associated structure	parallel	diagonal	perpendicular
Structure characteristics	Slickenside surface	Fractured zone	Gouge zone
Water delivery	dry	moist	trickling
Seam distance	W heading face	W floor	W roof
Potential caving	≤ ¼ W	Up to ½ W	≥ 1 W
Degree of rock separation (ahead of fault)	II	III	IV
Degree of rock separation (beyond fault)	II	III	IV
Rock strength (N/mm^2)	≥ 67	66–41	≤ 40
Roof			
Heading face			
Floor			

Figure 3.—Geotechnical fault rating matrix.

Table 1.—Criteria for geophysical classification of coal measure rock in German mines

	Classification		
	Good	Mean	Poor
Caliper (mm)..	127–128	127–135	130–135
Stiffness modulus M (GPa)	90–95	40–50	<40
FEL (Ωm)...	1.5–1.9	1.3–1.5	<1.4
DipLog Spur 1..	<9,000 (FEL > 1.6 and reflectivity >2,000)	9,000–11,000	>11,000 (FEL <1.3 and reflectivity <1,700)
BHTV reflectivity......................................	1,700–2,500	1,300–1,700	<1,300
dtvp (μsec/m)...	260–230	260–230	>250
dtvs (μsec/m)...	350–410	450–410	>430
Density (g/cm^3)..	2.6–2.7	2.5–2.6	2–2.5

- Estimation of critical support loads;
- Analysis of strata movement after development and during retreat mining activities; and
- Roof control in the face and in the area of face end T-junction.

The goal of geological and geotechnical description is to quantify the relevant rock properties. The description has to be coordinated with the mining activities and roadway development, and it has to include the survey by drill core analysis. A special method based on COREDAT software was developed for German coal mining, taking into consideration the parameters shown in Figure 4. The form provides a matrix of description that includes the orientation of separation planes, a geotechnical description of lithological elements and stratification, and different classification elements for the bedding separations.

In addition to the core description, the geotechnical parameters can be derived from an evaluation of a development face using the form shown in Figure 5. The evaluation includes the amount of caving in the roof and sides, the lithotypes observed, the presence of separation planes, and relevant geometrical data. The degree of separation can be classified very simply by measuring the spacing between the lithologic and tectonic separation planes. Another important piece of information is the inclination and orientation of jointing. This information is used to estimate the maximum support loads from potential wedges within the sides and roof of the roadway, and it can be compared to the output from the drill core analysis.

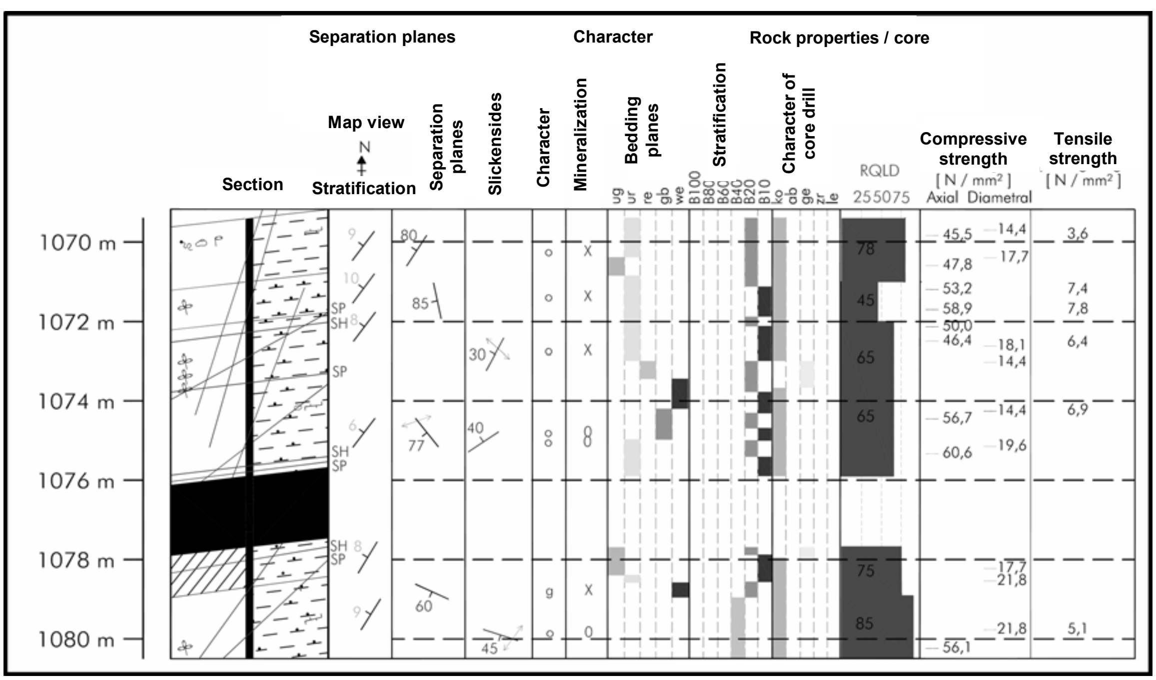


Figure 4.—Form of geotechnical analysis from drill cores by COREDAT software (DMT).

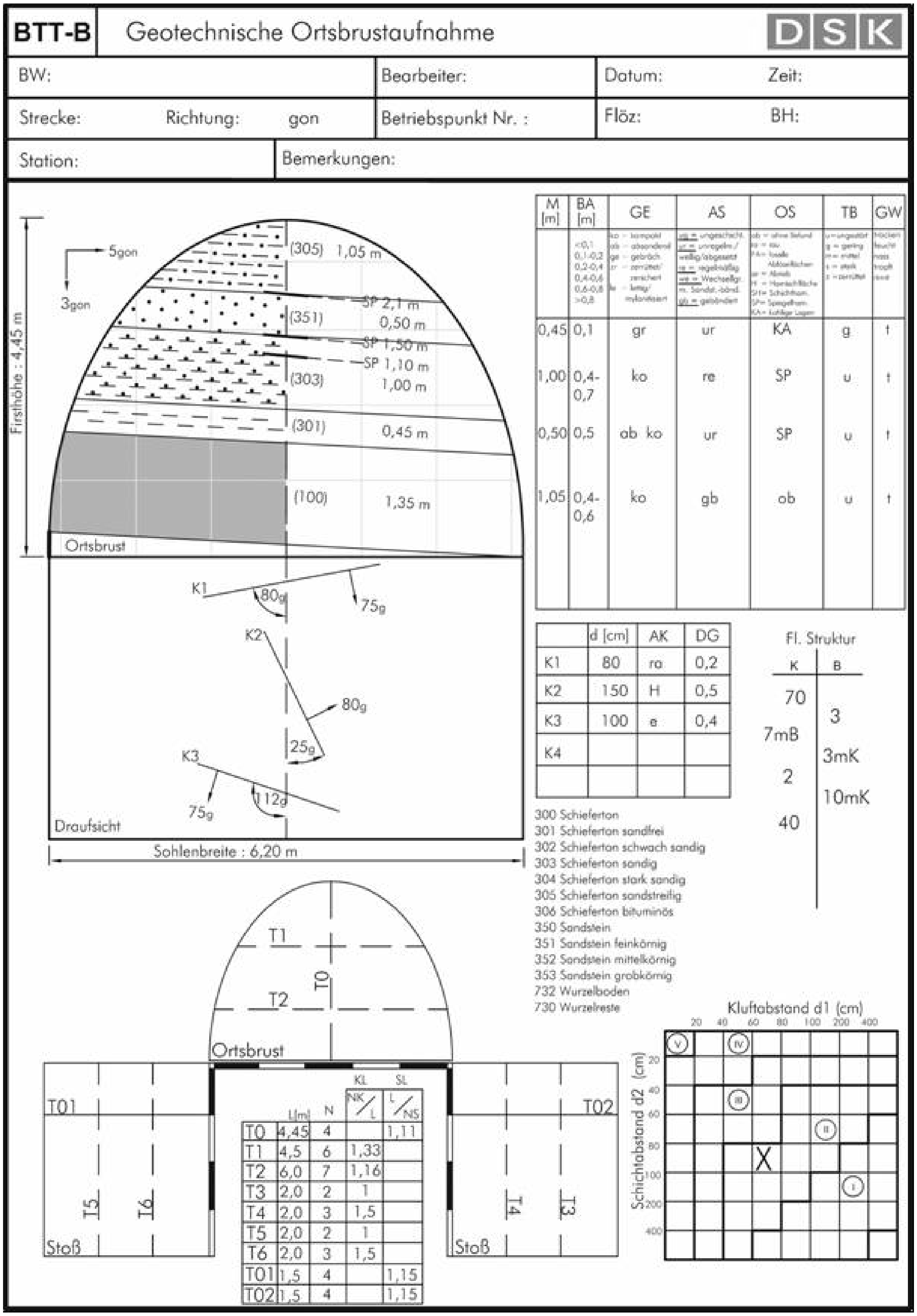
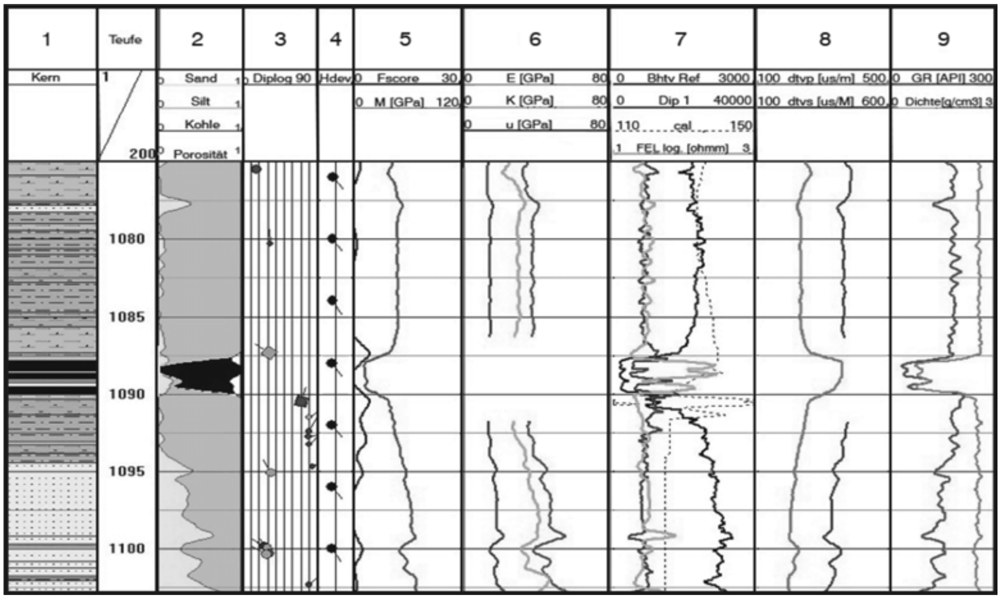


Figure 5.—Form for geotechnical observation of a heading front.

The form shown in Figure 5 was developed to complement basic geotechnical engineering and allows a comparison to the information obtained from the survey. The combined data set gives a detailed overview of the rock properties in, above, and below the roadway section.

The synoptic imaging of an analyzed geophysical drill core is shown in Figure 6. The meaning of each curve is described in the figure. Taken together, these data provide the basic information needed for geological engineering, design of panel layouts, dimensioning of roadway support, and support of the face T-junction.



Column No.	Heading note	Description
1	Core	Core description
2	(composite log)	Porosity - sand, clay, coal
3	Diplog	Dipping
4	Hdev	Horizontal orthographic deviation
5	Fscore M	Fissures / m Stiffness modulus
6	E K U	Elastic modulus Compression modulus Poisson - rate
7	BHTV ref Dip 1 Cal FEL	Reflectivity from BHTV measurement resistance Diplog Pad 1 borehole caliper Focused Electric Log
8	dtvp dtvs	Run duration P – wave Run duration S – wave
9	GR Density	Gamma ray Density

Figure 6.—Geophysical drill core analysis.

RELIABILITY OF GEOMECHANICAL PARAMETERS

In geomechanical planning work, it is important to know how reliable the data are for the specific strata being evaluated. The probability of occurrence is mainly influenced by the lithofacies, the tectonic conditions, and the density of survey. When the degree of reliability is known, a risk analysis can be conducted by analyzing each measured input parameter.

Table 2 shows a reliability ranking based on the density and quality of the survey. The five classes reflect the different levels of reliability and give a simple scheme for assessing geologic and geotechnical information. Combining the information from boreholes and roadway observations normally leads to a reliability rating of "confident" or "probably."

Table 2.—Influence of exposure-density on probability of occurrence

	Probability of occurrence	Distance of exposures
1	*Confident* Margin of error 10% Probability of occurrence 90%	Up to 200 m.
2	*Probably* Margin of error 20% Probability of occurrence 75%–90%	Up to 300 m.
3	*Potential* Margin of error 30% Probability of occurrence 50%–75%	Up to 400 m.
4	*Indicated* Margin of error >30% Probability of occurrence 30%–50%	Up to 500 m.
5	*Supposed* Margin of error >50% Probability of occurrence <30%	More than 200 m.

For any specific pattern of boreholes, the need for additional boreholes can be determined by evaluating the characteristics of the deposit and the longwall panel layout with respect to the sedimentologic analysis and lithofacies. This is particularly important when dealing with layers of sandstone whose thickness can change over short distances.

The result of the geomechanical classification is only as good as the quality of the information on which it is based. An important part of the process is to identify the remaining risk and manage it. Therefore, the current geomechanical planning standard is designed not only with the aim of defining the operational required parameters, but also to point out the risks that could arise during the development and use of the roadways. The procedure provides a basis for the design of support and the engineering of reinforcement measures.

ROCK MASS CLASSIFICATION

The German rock mass classification system includes both geotechnical rock analysis and geomechanical prediction of stress and roadway convergence. The prediction of the stress level is based on numerical modeling of the stress field under the influence of multiple-seam mining. A system of equations for predicting convergence and roadway deformation during development and longwall mining is based on empirical analysis of measurements that have been collected since the 1960s.

The most important issue for classification is that it must be flexible enough to adapt to a broad range of mining scenarios (e.g., panel design and dimensioning of support). It must also be able to adapt to the different types of input data that are available from drill cores and underground observations. Since the rock rating system can use data from either drill cores or underground observations, it provides maximum flexibility in advance of mining for optimization of support or panel layout.

Drawing upon mining experience gained in the past 5 decades, the German rock mass classification system represents a compromise between practicality and the best possible characterization. The parameters that are included are sufficient to represent the actual geological and rock mechanics conditions, and they can be determined from the currently available technical survey methods.

The rock rating clearly identifies the critical combination of geotechnical parameters within a large quantity of data. However, using it requires experience and a multidisciplinary knowledge. In doing so, one has to recognize that each parameter has different influence on the different mining tasks. The rating system developed by Deutsche Steinkohle AG (DSK) contains 21 parameters, each of which is evaluated individually.

Figure 7 shows how the process works. Each parameter is given one of five rating levels (A through E). Associated with each individual rating is a numerical evaluation index. The 21 individual evaluation indices are then summed to obtain an overall rating for the rock. Depending on the overall rating, the rock is classified into one of five types, ranging from "stable" to "squeezing," as shown on the bottom line of Figure 7. The rating for the example in Figure 7 is 535.5, which is considered "squeezing" rock quality.

Rock Classification											
No.	Parameters	A	Index	B	Index	C	Index	D	Index	E	Index
1	Bonding strength Roof [N/mm²]	80	4.6	60	9.3	45	18.5	30	37	≤25	74
2	Bonding strength Face [N/mm²]	80	4.1	60	8.3	45	16.5	30	33	≤25	66
3	Bonding strength Floor [N/mm²]	80	3.7	60	7.3	45	14.5	30	29	≤25	58
4	Driving-pressure [MPa]	0.4 Bs R	4.5	0.6 Bs R	9.0	0.8 Bs R	18.0	1 Bs R	36	>1 Bs R	72
5		0.4 Bs F	3.9	0.6 Bs F	7.8	0.8 Bs F	15.5	1 Bs F	31	>1 Bs F	62
6		0.4 Bs Fl	3.3	0.6 Bs Fl	6.5	0.8 Bs Fl	13.0	1 Bs Fl	26	>1 Bs Fl	52
7	Course and no. of working boundaries	0	4.1	FAB	8.3	PAB	16.5	SAN	33	PAN	66
8	Distance to bound. of overlying workings [m]	≥350	4.4	>200	8.8	>100	17.5	>50	35	≤50	70
9	Distance to bound. of underlying workings [m]	≥350	4.5	>200	9.0	>100	18.0	>50	36	≤50	72
10	Age of working boundaries	≥10 years	4.5	≥5 years	9.0	≥2 years	18.0	≥1 years	36	during driving	72
11	Distance between fault and roadway	≤4B	3.0	≤3B	6.0	≤2B	12.0	≤B	24	≤0.5B	48
12	Distance between fold and roadway	≤4B	2.5	≤3B	5.0	≤2B	10.0	≤B	20	≤0.5B	40
13	Seam distance roof	≤3B	4.1	≤2B	8.3	=B	16.5	≤0.5B	33	≤0.25B	66
14	Seam distance floor	≤3B	2.5	≤2B	5.0	=B	10.0	≤0.5B	20	≤0.25B	40
15	Bed thickn. structure	thick-bedded	2.7	bedded	5.3	laminated	10.5	thin-lamin.	21	flaky	42
16	Character of separat. plane surface	irregular	2.2	undulating	4.3	even	8.5	slickensided	17	polished	34
17	Degree of natural internal separation	I	3.2	II	6.3	III	12.5	IV	25	V	50
18	Slickensided/ "Lösen"-surfaces	≤2B	3.0	≤B	6.0	≤0.5B	12.0	≤0.25B	24	In roadway cross-section	48
19	Room to move of jointed rock body relative to roadway	joints and bedding visible	3.2	along bedding	6.3	along bed. and 1 joint direction	12.5	along bed. and 2 joint directions	25	Along bed. And several joint directions	50
20	Formation water	dry	4.4	moist	8.8	wet	17.5	dripping	35	running	70
21	Resistance to water	not soluble	2.7	sanding	5.3	loose	10.5	deconsolid.	21	Disintegrate d	42
	Remarks									$\sum_{\text{Indices}}$: 535.5	

Figure 7.—German mining standard rock mass rating matrix.

The evaluation is done continuously, and the results are merged into a single rock quality class for the analyzed section of roadway during drivage. The aim of the rock rating, besides determining the rock quality class, is to define the support class. Both the rock quality and support classes are dependent on mining technology and excavation technique. Increasing rock quality means lower support requirements. Depending on the required support, it may be possible to optimize the support installation timing, for example, by installing temporary bolting at the time of initial installation and completing the bolting pattern later with the setting of long tendons. The rock quality can also indicate the maximum allowable distance between the face and where the arches must be backfilled, which can help optimize the mining method to achieve the best development rate.

APPLICATION OF GEOTECHNICAL ANALYSIS AND ROCK MASS RATING

Today, the German rock mass rating system is used in geomechanical planning work for design of development headings, selection of support classes, and risk management. Rock mass rating is an important element of a closed loop of planning work for strata control. This closed loop was defined in the 1970s for German coal mining when it was recognized that optimized planning is based on performance review by monitoring. Another aspect is the successful development of planning tools and support systems. Both require a performance review because they are based on empirical processing.

Operational experience with the application of the rock mass rating system gives the results summarized in Table 3. A rating of up to 131 points indicates stable rock quality. Only minimal roadway deformation is expected, and just a few local displacements are likely. The separation planes, either joints or bedding planes, are closed and maintain high frictional strength. These conditions require the lowest level of support system with, in principle, only a need for lagging to prevent small pieces of rock from falling out of the roof. Unfortunately, these conditions are seldom encountered in German hard-coal mining.

The next class of rating, between 132 and 264 points, indicates caving rock quality. Poor rock quality is designated as "friable" (264–521) or "squeezing" (>521). Increasing roadway deformation that starts within the heading process must be taken into account. In most cases, combined support systems with both rock bolt systems and additional backfilled steel arches are used for roadway support.

Table 3.—Rock classification and rock types

Rating index	Class	Rock type
Up to 80	Ia	*Stable rock:* Local displacement, closed joints and bedding elements (separation planes)
Up to 131	Ib	
Up to 196	IIa	*Caving rock:* Local displacement and sporadic caving areas up to decimeter size in the roof and the upper sides, particular separation planes
Up to 264	IIb	
Up to 304	IIIa	*Friable rock:* Increased separation results in displacements and caving up to meter size, separation planes pronounced and partially opened
Up to 347	IIIb	
Up to 434	IVa	*Very friable rock:* High density of jointing and intensive transaction results in regular displacement caving up to 1 m sliding gravity wedges
Up to 521	IVb	
Up to 621	Va	*Squeezing rock:* Local gouge zones and squeezing areas, opened separation plane, high density of separation and intensive transaction, loosening of strata, and high mobility of gravity wedges
>621	Vb	

The rock mass rating has to be interpreted for different assignments of tasks. Looking at the roadway support for gate roads, for example, a rating of 434 is the limit of the applicability of backfilled steel arches as exclusive support. Below this rating, for rectangular starting rooms, it is typical to employ combined support with rock bolts and additional steel canopies and hydraulic props. For detailed design of support patterns in this range, it is necessary to take a close look at the geomechanical parameters.

As the rock mass rating increases, the quality of the rock decreases. This results in an increasing effort for roadway support. Table 4 gives some examples of the rock bolting densities required in different rock qualities. The example shown is for an arched-shaped roadway with a width of 6.4 m and a height of 4.5 m.

Table 4.—Required bolting density for support depending on rock mass quality

Rock mass quality	Bolting density in bolts/m^2 of bolted roof and side	Number of bolts per meter of roadway length	Support resistance of bolting pattern (kN/m^2)
Stable	0.8	6.5	231
Caving	1.3	10.5	370
Friable	1.6	13	463
Very friable	2.0	15.6	552
Squeezing	2.4	19	678

In this case, for stable rock (i.e., competent strata condition), a bolt density of approximately 0.8 bolts/m^2 of arch peripheral area is specified. This bolt density is only one-third of that needed for the squeezing rock quality, which requires approximately 2.4 bolts/m^2.

In Figure 8, the range of common support classes for German coal mines is assigned according to the rock mass rating and rock quality. The increasing effort required for support is clear in this figure. An optimized roadway development rate can be achieved with a multiphased support installation. The sequential installation of different support measures behind the face requires quite good rock conditions. In contrast, poor conditions require immediate support during development.

CONCLUSIONS

The German rock mass rating system for hard-coal mining has been developed particularly for application in multiple-seam mining at great depth and for use with a variety of support systems. It takes into account the service function of the roadways, including not only retreat longwall mining, but also reuse of the roadways after the passage of one longwall face.

The system is a compromise between the best possible rock mass description and the practical limitations of available measurement methods. Because the aim of classification is to provide the basic information needed for dimensioning of support, it takes into account both the in situ stress and the stresses caused by multiple-seam mining activities. Basic experiences from German hard-coal mining are included in the system through lithologic descriptions.

The system has been routinely applied in all DSK mines for the past 3 years. The class number determined by the rock classification provides the essential information needed for a detailed support design. It also provides an opportunity for comparing different seam conditions across borderlines between mines and panel layouts. The classification is an important addition to the descriptive geologic parameters.

The class number also gives a sense of rock quality and, therefore, it helps in assessment support requirements. However, it is not possible to predict roadway convergence with a single number, particularly for the later phases of roadway use. This means that it is still necessary to analyze the classification parameters and measure deformation to determine the maximum amount of convergence during roadway use. It is important to consider that the German method of mining employs single roadway systems and requires reuse of the roadway after passage of the face.

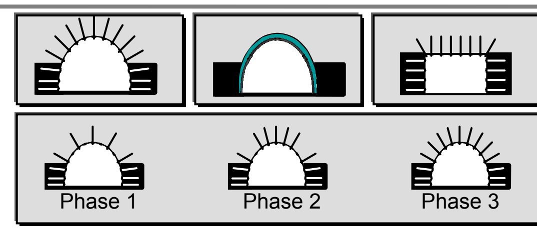
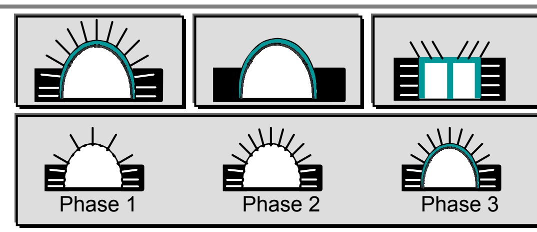
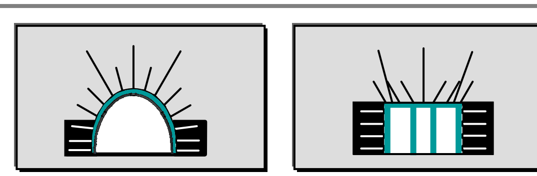
Rock mass rating	Rock mass quality	Support class/ support system
≤ 196	stable – caving	
≤ 434	friable – very friable	
> 434	very friable – squeezing	

Figure 8.—Rock mass quality and support measures.

Every time the standard is used, the classifying parameters from drill cores and roadway observations allow a retrospective evaluation of the main factors influencing support performance. This information is documented and maintained in a central data pool for knowledge management within DSK and, therefore, serves as an important tool for future support designs.

BIBLIOGRAPHY

Everling G, Meyer A-G [1972]. Ein Gebirgsdruckrechenmodell als Planungshilfe (in German). Glückauf-Forschungshefte *33*:81–88.

Jacobi O [1981]. Praxis der Gebirgsbeherrschung (in German). 2. Aufl. Essen, Germany: Verlag Glückauf.

Junker M, et al. [2006]. Gebirgsbeherrschung von Flözstrecken (in German). Glückauf-Verlag.

Müller W [1989]. Messung der absoluten Gebirgsspannungen im Steinkohlenbergbau (in German). Glückauf-Forschungshefte *50*:105–112.

Opolony K, Witthaus H [2003]. Comparison of multiple- and single-entry roadway systems for highly stressed longwalls. In: Peng SS, Mark C, Khair AW, Heasley KA, eds. Proceedings of the 22nd International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 33–36.

Opolony K, Polysos N, Bartel R, Lüttig F [2000]. Ankertechnik bei der DSK Theorie und Praxis (in German). Glückauf *136*.

Polysos N, Peters S [2002]. Application of geotechnical and geophysical parameters to improve planning certainty in roadway driving. In: Peng SS, Mark C, Khair AW, eds. Proceedings of the 21st International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 302–309.

Polysos N, Brandt K–H, Peters S [2003]. Geotechnische Gebirgsbewertung im Hinblick auf die Hangendbegherrschung im Strebraum (in German). 2. Intern. Colloquium on High-performance Mining Production (Aachen, Germany).

Witthaus H [2001]. Die Planung von Ankerausbau in Flözstrecken (in German). 4. Intern. Colloquium: Ankerausbau im Bergbau (Aachen, Germany).

Witthaus H [2006]. Entwicklung einer Planungsmethode für Ankerausbau im deutschen Steinkohlenbergbau unter Berücksichtigung der Gebirgsstruktur und der Gebirgsbeanspruchung [Dissertation] (in German). Aachen, Germany: Verlag Mainz.

Witthaus H, Adams M, Junker M [2000]. Die ausbautechnische Planung für vorbauartig und doppelt genutzte Ankerstrecken (in German). Glückauf *136*.

Witthaus H, Polysos N, Peters S [2006]. Applied geomechanics for support design in German deep coal mines. In: Peng SS, Mark C, Finfinger GL, Tadolini SC, Khair AW, Heasley KA, Luo Y, eds. Proceedings of the 25th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 208–212.