Engineering Classification of Rock Materials

Course No: G05-007
Credit: 5 PDH

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This course was adapted from the U.S. Department of Agriculture, National Resources Conservation Service, Engineering Classification of Rock Materials, Part 631 of the Geology National Engineering Handbook, which is in the public domain.

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Classes of Rock Properties

In order to use rock in engineering applications, certain properties of the rock must be assessed to reasonably predict performance in the as-built condition. The properties of rock fall into two broad classes: rock material properties relating to the rock itself, and rock mass properties relating to the in-place rock mass, including its discontinuities.

Rock Material Properties

Rock material properties that are essential in assessing hydraulic erodibility of rock include rock type, color, particle size, texture, hardness, and strength. Seismic velocity, weathering, and secondary porosity are properties related to both the rock material and the rock mass.
Rock material properties can be described in the field using qualitative methods and simple classification tests, or, if necessary, in the laboratory using standardized tests. The results are applicable to hand-specimens and representative samples of rock material.

Rock Mass Properties

Rock mass properties are comprised of features generally observed, measured, and documented in the field for in-place rock.

Discontinuities are distinct breaks or interruptions in the integrity of a rock mass that convert a rock mass into a discontinuous assemblage of blocks, plates, or irregular discrete rock particles. A discrete rock particle is an intact fragment of rock material whose shape and size are initially defined by the discontinuities that form its margins. Discrete rock particles may occur in their place of origin, such as fractured, broken, or jointed in situ rock, where particles retain their original form and size; or moved from their place of origin with subsequent modification of size and shape occurring in the transport process. Naturally occurring examples include stream cobbles, talus, and glacial boulders; or they can be manufactured, as in the case of quarried rock.

The properties of a rock mass are significantly different from the material properties of samples of the same rock mass. The strength and mechanical behavior of the rock mass are commonly dominated more by the nature of its mass properties than by its material properties. A rock mass comprised of even the strongest intact rock material is greatly weakened by the occurrence of closely spaced discontinuities. Material properties, however, tend to control the strength of the rock mass, if discontinuities are widely spaced or if the intact rock material is inherently weak or altered. Discontinuities within a rock mass therefore reduce its strength and stability and reduce the energy required to excavate or erode it.

It is important to recognize that many rock properties interact under performance conditions. A performance assessment for any given engineering application must be viewed in the broader context of these interactions.

Rock Material Properties

Evaluating Rock Material Properties

Rock material properties are measurable or describable lithologic properties of rock material that can be evaluated in hand specimens or tested in the laboratory. Rock material properties are related to the physical properties of the rock-forming minerals and the type of mineral bonding. Properties are determined from hand specimens, core sections, drill cuttings, outcroppings, and disturbed samples using qualitative procedures, simple classification tests, or laboratory tests. The results are applicable to hand specimens and representative samples of intact rock material. They do not account for the influence of discontinuities or boundary conditions of the rock.

Typical classification elements include:

- Principal rock type
- Mineralogy (estimate percentage of principal and accessory minerals; note grain size or crystal size, texture, type of cement and presence of alterable minerals)
- Primary porosity (free draining or not)
- Hardness (rock material strength) and unconfined compressive strength categories (v)
- Weathering
- Unit weight (dry)
- Color (Munsell color)
- Discrete rock particle size (use D_{50} or cube root of the product of its three dimensions)

Rock Unit Identification

The rock unit is the basic mapping unit for the rock material field classification (RMFC) system. It is defined as a body of rock that is identified in the field and mapped according to measurable or otherwise describable physical properties or features at a scale useful for project analysis.

A rock unit is consistent in its mineralogical composition, geologic structure, and hydraulic properties. Its boundaries are delineated by measurable or otherwise describable physical properties or features. It is traced in the field by surface and subsurface mapping techniques. Because the mapping criteria are performance-based engineering characteristics, rock units need not conform to formally recognized stratigraphic rock formations.

The term “rock unit” is similar to “lithosome” in that the body of rock has consistent, mappable characteristics, but differs in that lithosomes are formed under uniform physicochemical conditions.

Identify each rock unit at the site by either its proper formation name (e.g., St. Peters Sandstone) or by an alpha-numeric designation (e.g., Rock Unit L-6), whichever is the most useful. If a formation has multiple beds or units of differing engineering behavior, the alphanumeric designation is preferable.

Describe the location of each rock unit by station, elevation, and position in the stratigraphic section. Indicate its location and extent on a geologic evaluation map of the spillway site.

Rock Type

Rock type is a simplified geologic classification of rock based on its genetic category, structure, composition, and grain size. Table 1 is a rock type classification that uses common rock type names that can be assigned in the field without need for detailed lab tests or thin sections (after GSL, 1977).

The equipment needed to identify rock type includes a geologist's hammer with pick end, 10x hand lens, hydrochloric acid (10 N solution: 1-part acid to 3 parts distilled water), pocket knife, 15 cm (6-inch) scale, and American Geologic Institute (AGI 2009) Data Sheets.
Using standard field identification procedures and table 1 as a guide, all rock units are identified and the rock type name recorded for each unit on a Rock Description Data Sheet (Appendix D).

Use more detailed mineralogical and rock descriptors only if they are needed for correlation purposes or to describe engineering properties of the rock. Use common terminology, such as “schist,” instead of technically correct, but jargon-rich terms, such as “albite-epidote-amphibolite-schist.” If more detailed guidance is required, refer to the AGI (2009) Data Sheets.

Table 1. Rock type classification (Geological Society of London 1977)

Genetic group	Predominant grain size, mm (sieve no.)	Detrital sedimentary			Chemical organic	Metamorphic		Pyroclastic	Igneous			
Usual structure		Bedded			Bedded	Foliated	Massive	Bedded	Massive			
Composition		Grains of rock, quartz, feldspar, and clay minerals		At least 50% of grains are of carbonate	Salts, carbonates, silica, carbonaceous	Quartz, feldspars, micas, dark minerals	Quartz, feldspars, micas, dark minerals, carbonates	At least 50% of grains are of igneous rock	Quartz, feldspars, micas, dark minerals		Feldspar; dark minerals	Dark minerals
									Acid	Intermediate	Basic	Ultrabasic
Very coarse-grained		Rudaceous	Grains are of rock fragments Rounded grains: CONGOMERATE (11) Angular grains: BRECCIA (12)	LIMESTONE (undifferentiated) (21) CALCIRUDITE (23)	CLINKER (31) SALINE ROCKS Halite (32) Anhydrite (33) Gypsum (34)	TECTONIC BRECCIA (41) MIGMATITE (42)	METACONGLOMERATE (51)	Rounded grains: AGGLOMERATE (61) Angular grains: VOLCANIC BRECCIA (62)	PEGMATITE (71)			PYROXENITE (01)
Coarse-grained	75 (3")					GNEISS (43)	MARBLE (52)		GRANITE (72)	DIORITE (81) GRANODIORITE (82)	GABBRO (91)	
Medium-grained	4.75 (4)	Arenaceous	Grains are mainly mineral fragments SANDSTONE (13) ARKOSE (14) GRAYWACKE (Argillaceous ss) (15)	CALCARENTIE (27)	CALCAREOUS ROCKS	SCHIST (44)	GRANULITE (53) QUARTZITE (54)	TUFF (63)	SYENITE (73)	ANORTHOSITE (83)	DIABASE (92)	PERIDOTITE (02)
Fine-grained	0.074 (200)					Amphibolite (45) PHYLLITE (46)			APLITE (74)	MONZONITE (84)		
Very fine-grained	0.005	Argillaceous or Lutaceous	MUDSTONE (16) SHALE: fissile mudstone (17) SILTSTONE>50% fine-grained particles (18) CLAYSTONE>50% very fine grained particles (19)	MARLSTONE (22) CALCISILTITE (25) CHALK (26) CALCILUTITE (27)	LIMESTONE (35) DOLOMITE (36)	Mylonite (47) SLATE (48)	HORNFELS (55)	Fine-grained TUFF (64) Very fine-grained TUFF (65)	RHYOLITE or FELSITE (75)	Dacite (85) ANDESITE (86)	BASALT (93)	DUNITE (03) NEPHELINE-BASALT (04)
Glassy amorphous					SILICEOUS ROCKS Chert (37) Flint (38) CARBONACEOUS ROCKS LIGNITE/COAL (39)	Ultramylonite (49)		Welded TUFF (66) PUMICE (67)	VOLCANIC GLASSES OBSIDIAN (76)	PITCHSTONE (87)	TACHYLYTE (87)	

Engineering Significance of Rock Type

Geologic names and geologic classifications may not always relate directly to engineering properties of rock but are useful for identification and correlation purposes.

Rock type may also indicate what processes acted on the rock during and after its formation. These facts may be valuable in predicting mass properties such as the size, shape, extent, and location of beds, lenses, and stringers that may be discontinuities. Rock type can indicate mineralogical and textural characteristics which may provide insight into the physical and chemical interaction between the grains. Some near-surface or exposed granites, for example, form horizontal stress relief fractures with reduced confining pressures as erosion removes overlying materials.

Engineering properties can vary within a rock formation. Published values can be a guide but cannot be solely relied upon.

Hardness

Hardness is the subjective description of the resistance of an earth material to permanent deformation, particularly by indentation (impact) or abrasion (scratching) (ASTM D 653). Rock hardness is not the same as mineral hardness. The Mohs scale is a qualitative scale for a set of empirical tests used to differentiate minerals in hand specimens by scratching. The scale has no useful application in describing most rock material for engineering purposes because most rock types are aggregates of more than one mineral.

For each igneous or crystalline metamorphic rock unit, the rock texture is recorded using the descriptors in table 2 as a guide. Refer to the AGI Data Sheets if more detailed descriptors are needed.

Table 2. Texture descriptors for igneous and crystalline metamorphic rocks

Textural term	Description
Aphanitic	Crystalline components cannot be seen with the naked eye (syn.: cryptocrystalline, or microcrystalline)
Crystalline	Composed entirely of contiguous or interlocking crystals
Glassy	Certain extrusive igneous rocks that cooled rapidly, without distinct crystallization. (syn.: vitreous)
Pegmatitic	Very coarse-grained, crystals >10 mm in diameter
Porphyritic	Large crystals set in a fine-grained ground mass that may be glassy or crystalline

Hardness is simply a qualitative expression of earth material strength. The hardness categories form a scale of ranges in strength values obtained from the laboratory test for strength (see the section below for Strength of materials).

Field tests for rock hardness are given in table 3 for the evaluation of excavation characteristics and hydraulic erodibility of rock and for classifying rock for excavated auxiliary spillways. The equipment needed to perform the field tests for hardness includes a pocketknife, a geologist's hammer with pick end, and a common 20d steel nail. For each rock unit, the hardness category is determined by using the field tests given in table 3.

Engineering Significance of Hardness of Rock
The hardness of rock material is a function of the individual rock type but may be modified (weakened) by chemical or physical weathering (see section on Weathering and Alteration). Hardness categories provide reasonable estimates of rock material strength, for classifying earth material as rock in excavated auxiliary spillways. The designer must carefully consider the characteristics of the rock mass before reaching a decision on alignment and location of a rock spillway.

Strength

Strength is the ability of a material to resist deformation induced by external forces. The strength of a material is the amount of applied stress at failure (ASTM, D 653). The laboratory uniaxial (unconfined) compressive strength is the standard strength parameter of intact rock material.

If strength is to be determined by correlating with hardness, table 3 is used as a guide for hardness and unconfined compressive strength of rock materials. Results and the test method used are recorded on the Rock Mass Description Data Sheets for each identified rock unit (Appendix D).

The strength of rock is influenced by the mineralogical composition, shape of grains, texture, crystallinity, stratification, lamination, modification by heat or pressure, and other factors. Secondary processes of cementation and weathering strongly influence rock strength.

Table 3. Hardness and unconfined compressive strength of rock materials

Hardness category	**Typical range in unconfined compressive strength (MPa)**	**Strength value selected (MPa)**	**Field test on sample**	**Field test on outcrop**
Soil*	< 0.60	———	Use USCS classifications	
Very soft rock or hard, soil-like material	0.60–1.25	———	Scratched with fingernail. Slight indentation by light blow of point of geologic pick. Requires power tools for excavation. Peels with pocket knife.	
Soft rock	1.25–5.0	———	Permits denting by moderate pressure of the fingers. Handheld specimen crumbles under firm blows with point of geologic pick.	Easily deformable with finger pressure.
Moderately soft rock	5.0–12.5	———	Shallow indentations (1–3 mm) by firm blows with point of geologic pick. Peels with difficulty with pocket knife. Resists denting by the fingers, but can be abraded and pierced to a shallow depth by a pencil point. Crumbles by rubbing with fingers.	Crumbles by rubbing with fingers.
Moderately hard rock	12.5–50	———	Cannot be scraped or peeled with pocket knife. Intact handheld specimen breaks with single blow of geologic hammer. Can be distinctly scratched with 20d common steel nail. Resists a pencil point, but can be scratched and cut with a knife blade.	Unfractured outcrop crumbles under light hammer blows.
Hard rock	50–100	———	Handheld specimen requires more than one hammer blow to break it. Can be faintly scratched with 20d common steel nail. Resistant to abrasion or cutting by a knife blade, but can be easily dented or broken by light blows of a hammer.	Outcrop withstands a few firm blows before breaking.
Very hard rock	100–250	———	Specimen breaks only by repeated, heavy blows with geologic hammer. Cannot be scratched with 20d common steel nail.	Outcrop withstands a few heavy ringing hammer blows but will yield large fragments.
Extremely hard rock	> 250	———	Specimen can only be chipped, not broken by repeated, heavy blows of geologic hammer.	Outcrop resists heavy ringing hammer blows and yields, with difficulty, only dust and small fragments.

Method used to determine consistency or hardness (check one):

Field assessment: _____ Uniaxial lab test: _____ Other: __________ Rebound hammer (ASTM D5873): _____

* See NEH631.03 for consistency and density of soil materials. For very stiff soil, SPT N values = 15 to 30. For very soft rock or hard, soil-like material, SPT N values exceed 30 blows per foot.

Weathering and Alteration

Weathering of rock is an important secondary process influencing its strength. Weathering is the process of mechanical or chemical degradation; and can significantly affect the engineering properties.

Weathering effects generally decrease with depth. A summary of description of weathering terminology is shown in table 4.

Table 4. Weathering terminology

Term	**Weathering description**	**Grade**
Fresh	No visible sign of weathering: perhaps slight discoloration on major discontinuity surfaces.	I
Slightly weathered	Discoloration indicates weathering and discontinuity surfaces. May be discolored and somewhat weakened by weathering.	II
Moderately weathered	Less than half is decomposed or disintegrated to a soil material. Fresh or discolored rock is present either as a continuous framework or as core-stones.	III
Highly weathered	More than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework or as core-stones.	IV
Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact	V
Residual soil	All rock material is converted to soil material. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported	VI

Cementation

Cementation of rock is an important secondary process influencing its strength. Principle cementing materials are silica, calcium carbonate, iron oxide, and clays. Most durable are bonds of silica, whereas clay bonds are weakest, particularly when saturated. It is important, therefore, to note the nature of cementing material when describing rock. Table 5 shows a summary description of terminology to describe cementation conditions of rock.

Table 5. Rock cementation chart

Cementation	Behavior
Weak	Crumbles or breaks with handling or little finger pressure
Moderate	Crumbles or breaks with considerable finger pressure
Strong	Will not crumble or break with finger pressure

Dry Density
Information provided by the accessory minerals in the name of a rock can provide clues to properties that have engineering significance. For example, a mica schist might indicate potentially weak rock because the sheet silicates (the micas and chlorite) impart low shear strength to the rock mass. See table 6.

Table 6. Dry density (unit weight) of rock

lb/ft³	Mg/m³	lb/ft³	Mg/m³	lb/ft³	Mg/m³
< 60	< 0.96	90–100	1.44–1.60	130–140	2.08–2.24
60–70	0.96–1.12	100–110	1.60–1.76	140–150	2.24–2.40
70–80	1.12–1.28	110–120	1.76–1.92	150–160	2.40–2.56
80–90	1.28–1.44	120–130	1.92–2.08	> 160	> 2.56

Engineering Significance of Rock Material Strength
Rock material strength and rock material hardness are used in classifying earth material as rock in earth spillways. Rock material strength can be reasonably estimated from the rock hardness scale (table 3) without conducting a laboratory strength test (NEH Part 628 Dams, Chapter 52, Field Procedures Guide for the Headcut Erodibility Index).

Rock mass strength is largely affected by the discontinuities within the rock mass. The field strength of the in-situ rock mass will always be less than the laboratory rock mass strength.

Color

Rock color is an attribute of visual perception that can be described by color names (ASTM, 1986). In wide use are the Munsell Soil Color Charts (Munsell 2018) and Rock Color Chart (Munsell 2017). For rapid field logging purposes, e.g., reconnaissance investigations, table 7 can be used as an alternative.

Color is difficult to describe, because a perceived color greatly depends not only on the spectral power distribution of the color stimulus, but also on the size, shape, structure, and envelop of the stimulus area. For example, a given color will appear differently when seen next to other colors; grey appears bluish when seen next to orange or brown earth colors. Perceived color also depends on the observer's experience with similar observations; hence, a color may often be named differently by different persons.

When using table 7, a color from column 2 can be supplemented, if needed, with a term from column 1, column 3, or column 4. Terms such as banded, mottled, streaked, speckled, and stained may be used as modifiers. Record the color of each rock unit in both its wet and dry states. Indicate whether the sample is fresh or in an altered condition since these conditions can affect color.

*Table 7. Rock color**

1st descriptor	**2nd descriptor**	**3rd descriptor**	**4th descriptor**
Condition: _______	Fresh - Dry	___________	___________
Condition: _______	Fresh - Wet	___________	___________
Condition: _______	Altered - Dry	___________	___________
Condition: _______	Altered - Wet	___________	___________
light ___________ dark ___________ very dark _______	yellowish buff reddish orangish brownish pinkish purplish olive greenish greyish bluish	white yellow buff orange brown pink red blue purple green olive grey black	banded mottled streaked speckled stained

* Modified from GSL 1977.

Engineering Significance of Rock Color

Color can be an indication of the weathered state of the rock. Discoloration of rocks to shades of red, yellow, orange, and brown indicates leaching of iron, Fe^{2+}, from unstable minerals and its fixation as Fe^{3+} in oxide pigments. The degree of discoloration may therefore provide an indication of the degree of stability of minerals in rocks.

Color changes may indicate changes in the rock's mineral assemblage, texture, organic carbon content (shales), or other properties.

Particle Size and Texture

Particle size refers to the size of the particles that make up a sedimentary or pyroclastic rock. Texture refers to the crystallinity and granularity of igneous and crystalline metamorphic rocks. The particle sizes used in the description of rocks for engineering purposes should be consistent with those used for soils (ASTM D422, D2488, and D653). The format of table 8 is modified after USBR (1989) and GSL (1977). The lithified product is the name for the equivalent sedimentary or pyroclastic particles after lithification of the material. A hand lens is usually sufficient to identify particle size and rock texture.

Use the rock particle size descriptors given in table 8 for sedimentary and pyroclastic rock types. Record the particle size or lithified product of each rock unit and the descriptive system used.

The strength of rock masses is greatly influenced by the presence of bedding, cleavage, schistosity, and similar features, as well as by the presence of joints and fractures. The spacing, pattern, attitude, and other characteristics of these features are important in evaluating strength of a rock mass. The presence of bedding, cleavage, schistosity, joints, fractures, and faults can affect the rock strength by increasing or decreasing the fracturing density.

Engineering Significance of Particle Size
Bonding strength may determine material properties as the rock weathers.

Chemical weathering not only influences strength of rocks but also the characteristics of derived soil materials. Some rocks break down into equidimensional grains, whereas others break down into platy grains such as clay minerals. Rocks that contain minerals of variable resistance to chemical weathering may become highly permeable through the alteration and removal of easily weathered materials, leaving the more resistant materials. Rainfall and runoff that percolate through soil and fractured limestone, and other carbonate rocks may develop solution channels and collapse features, or karst terrain.

Table 8. Particle size descriptors for sedimentary and pyroclastic rocks

Descriptive term (rocks)	inches	U.S. standard sieve no.	mm	Unified soil classification system[1/]	Sedimentary particle or fragment	Sedimentary lithified product	Volcanic fragment	Volcanic lithified product
			4026					
			2048	boulder			block	volcanic breccias (angular grains)
very coarse-grained			1024		boulder	boulder conglomerate		
			512					
	12		300					
	10		256	cobble			bomb	agglutinate (round grains)
	6		128		cobble	cobble conglomerate		
	3		75					
			64				splatter	agglutinate
			75	coarse gravel				
	1		25.4					
	0.75		19					
coarse-grained			16					
	0.5		12.7		pebble	cobble conglomerate	lappilus	
	0.375		9.5	fine gravel				lapillistone tuff
			8					
	0.25		6.35					
		4	4.76					
			4	coarse sand				
		10	2		granule	granule conglom		
			1		course sand			
medium-grained			0.5	medium sand		sandstone (v. coarse, coarse, medium, fine or very fine)	coarse ash	coarse tuff
		40	0.425		medium sand			
			0.25					
			0.125	fine sand				
		200	0.074		fine sand			
			0.0625					
			0.05					
fine-grained			0.031		silt	sitlstone or silty shale		
			0.0156	silt or clay			fine ash	fine tuff
			0.0078					
			0.005					
			0.0039		clay	claystone clay shale		
very fine-grained			0.0010					

1/ Unified Soil Classification System, ASTM D2487

Rock Mass Properties: General

Classification Elements

Rock mass properties are measurable or describable lithologic properties, characteristics, or features of the rock mass that are evaluated on a macroscopic scale in the field. They include fractures, joints, and faults, as well as abrupt changes in lithology due to erosion or deposition. Rock mass properties are too large or extensive to be observed directly at a single outcrop and are difficult or impossible to sample for laboratory analysis. Bedding, however, can be seen at the outcrop scale.

The properties of a rock mass are often significantly different from the properties of intact rock samples of the same rock mass. The mechanical behavior and strength of a rock mass are commonly dominated more by mass properties than by material properties. For example, a rock mass composed of the strongest intact rock material is weakened in proportion to the number of discontinuities in a given volume. Material properties, on the other hand, dominate the strength of a rock mass where discontinuities are widely spaced or nonexistent. Discontinuities lower the strength and stability of a rock mass and reduce the amount of energy required to excavate, erode, remove, or blast the rock mass.

Hydraulic Conductivity vs. Permeability

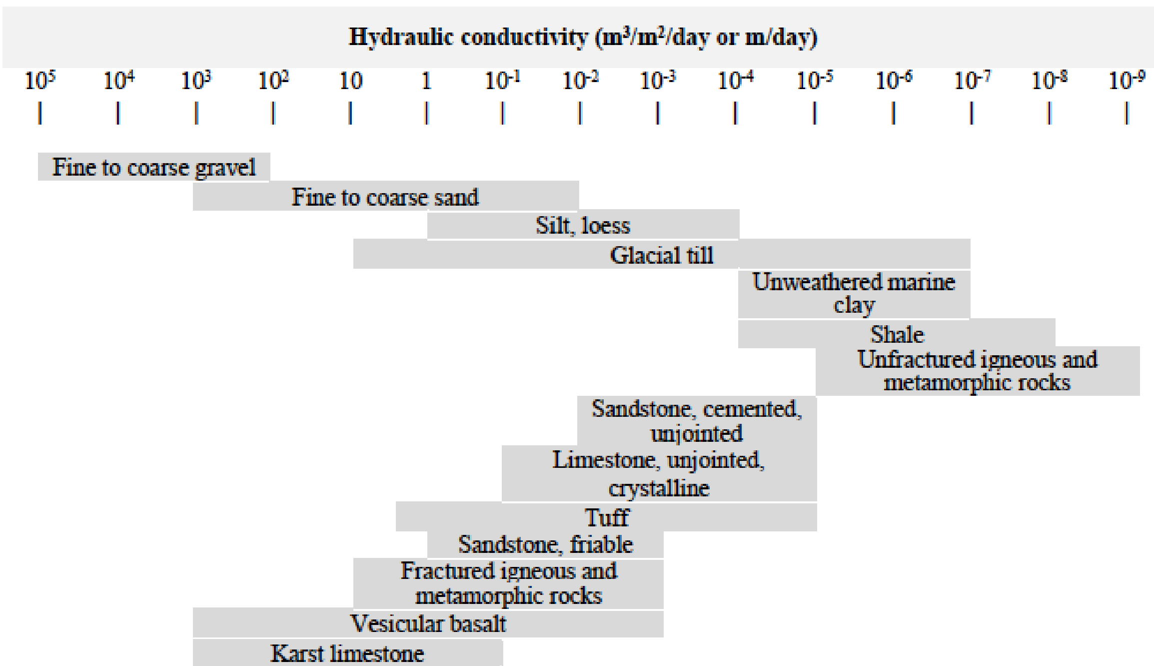
Hydraulic conductivity (K) describes how easily a volume of water flows through a cross-sectional area in unit time, under a given hydraulic gradient. Saturated hydraulic conductivity (K_s, K_{sat}) describes the rate that water flows through a saturated media such as soil. Saturated hydraulic conductivity is affected by both soil and fluid properties and depends on the soil pore geometry as well as the fluid viscosity and density. Hydraulic conductivity and saturated hydraulic conductivity are expressed using various units. NRCS commonly expresses hydraulic conductivity in cubic feet of water per day. For more information about hydraulic conductivity, see NEH Part 631 Geology, Chapter 31 – Groundwater Investigations.

Permeability (k) refers to the rate at which water flows through a material. Permeability is controlled solely by pore geometry of interconnected porosity, and is independent of fluid viscosity and density. Permeability is calculated by multiplying hydraulic conductivity (K) by the fluid viscosity divided by fluid density and the gravitational constant. Units are expressed as the dimension of area (e.g., cm^2). For more information about permeability, see NEH Part 631 Geology, Chapter 31 – Groundwater Investigations.

Foundations, abutments, and reservoir basins that are highly fractured and contain solution channels, or are the products of differential weathering, may be highly permeable. A low porosity rock mass may be highly permeable due to fractures and joints. Jointing is not restricted to any particular type of rock, but certain types of rocks may locally exhibit larger or more closely spaced joints. Surficial joints and cracks are termed lineaments.

The hydraulic conductivity ratings for various rock materials are shown in table 9.

Table 9. Typical hydraulic conductivity (K) values for consolidated and unconsolidated aquifers



(Adapted from Freeze and Cherry, 1979)

Differential weathering may be found in many types of igneous and metamorphic rocks and certain sedimentary rocks. Differential weathering of cherty limestones, for example, may result in highly permeable rock foundations. It is important that the rate of permeability and the depth and direction of water movement be determined as closely as possible to determine requirements for foundation treatment. Field investigation may require angular test borings, pressure testing, use of dyes or other tracer compounds, or other methods to properly determine permeability of rock.

Consolidation

The bearing strength of rock is normally adequate to support dams designed by NRCS. However, consolidation may be a problem in certain types of rock such as weakly-cemented shales and siltstones, and rocks which have been altered to clay minerals. In each instance, samples of questionable materials must be obtained for laboratory analysis, following the same procedures used for soil materials.

Caverns or mines may present a problem of bearing or stability, depending on the size and location of openings. Their locations must be mapped and evaluated for site feasibility, design, and construction.

Rock Texture

Texture is defined as the geometrical aspects of the component particles of a rock, including size, shape, and spatial arrangement. Texture is also applied to unconsolidated materials as an alternate description of particle gradation. Texture is important for field identification purposes and for predicting behavior of rock under load.

Texture refers to the crystallinity and granularity of igneous and crystalline metamorphic rocks. Although specific geologic terms such as "phaneritic" and "aphanitic" imply specific descriptions of igneous rock, simpler terms such as "coarse-grained" and "fine-grained" are useful for sizes of crystals in the rock matrix. See table 10 for crystal sizes for igneous and metamorphic rocks.

Descriptions of mineral constituents, degree and type of cementation, conditions of weathering, fracture system, and other properties influence engineering properties. These descriptors offer more engineering value than merely the type of rock. Standard symbols are available in the Federal Geographic Data Committee (FGDC) Digital Cartographic Standard for Geologic Map Symbolization (FGDC, 2006) documentation (http://ngmdb.usgs.gov/fgdc_gds/geolsymstd/download.php).

Table 10. Igneous and metamorphic crystal size descriptions

Descriptor	**Average crystal diameter**
Very coarse-grained or pegmatitic	> 10 mm (3/8 in.)
Coarse-grained	5 – 10 mm (3/16 – 3/8 in.)
Medium-grained	1 – 5 mm (1/32 – 3/16 in.)
Fine-grained	0.1 – 1 mm (0.04 – 1/32 in.)
Aphanitic (cannot be seen with the unaided eye)	< 0.1 mm (<0.04 in.)

Adapted from chapter 4 of Engineering Geology Field Manual, 2nd Edition. Bureau of Reclamation

Shearing Resistance

Problems related to shear may result from poorly cemented shales and siltstones or highly weathered rock of low shear strength. Materials that dip in an adverse direction and are subject to saturation or unloading of toe supports by excavation are of particular concern. This includes strata dipping downstream in foundations, or strata dipping toward the centerline (parallel to the slope of the abutment) of proposed auxiliary spillway excavations. Rock strata of low shear strength must be thoroughly delineated and evaluated for design and construction.

Rock Structure

The structure of rocks can usually be given a few simple terms describing holes, cavities, joints, bedding planes, fractures, cleavage, schistosity, lenses, and similar features. Rock structure is an important factor affecting the amount and direction of groundwater flow, as well as actual sliding or slipping of any embankment under investigation.

The term "rock structure," as applied to engineering geology, refers to all of the geologic structures at the practice location which could affect the site. These features include faults, folds, joints, rock cleavage, and discontinuities and unconformities. Structure has an important influence on the geologic conditions of a site and the ultimate stability and safety of an engineered structure. Problems of leakage, sliding of embankments, uplift pressure in foundations, and differential settlement are often traced back to inadequate delineation and consideration of the geologic structure at the site.

Attitude

Attitude is the orientation of strata, faults, fractures, and other features relative to a horizontal plane. Attitude is usually expressed in terms of measured dip and strike. In more complex geologic structures, such as plunging anticlines, special conditions may require more elaborate descriptions including pitch and plunge, as well as dip and strike.

Discontinuities

The term "discontinuity" applies to any distinct break or interruption in the integrity of a rock mass. Discontinuities are classified as either stratigraphic or structural, according to their mode of formation.

Stratigraphic discontinuities can be either depositional or erosional. They represent a significant interruption of the orderly sequence of deposition, most frequently marked by a considerable time interval of erosion or non-deposition. The bedding planes above and below the disconformity are usually parallel. These features can be found in all stratified sedimentary rocks, most volcanic flows and deposits, and some low-grade metamorphic rocks. Zones of weathering or alteration may also be considered discontinuities.

Structural discontinuities develop after the initial formation of the rock mass as a result of external processes acting on it. These features are produced by the mechanical deformation or displacement of rock by natural stresses within the Earth's crust. They include fractures of all types, planes or zones of weakness, faults, and shear zones, most of which have little to no tensile strength. The deformation of rock falls into three broad categories: elastic, plastic, and fracture deformation.

Elastic deformation is deformation from which the rock mass instantaneously recovers its original shape on removal of the external forces acting on it. The passage of earthquake waves or tidal stresses may cause elastic deformation. Since no permanent structural discontinuities are produced by elastic deformation, this chapter addresses discontinuities associated only with plastic and fracture deformation.

Plastic deformation exceeds the strain limit for elastic deformation and results in a permanent change in shape of the rock mass. Folds, foliations (such as schistosity and gneissosity) and other linear and planar structures result. The orientation of such features is related to flowage and grain rotation accompanying compression and shearing forces, which ultimately lead to metamorphism.

Fracture deformation results in rupture of the rock mass. Rupture produces discontinuities such as faults, joints, and cleavage. Fractures focus the influence of weathering processes along the fracture surfaces that further weaken the rock mass over time. Caves and solution features are examples of chemical weathering that has progressed along joint systems in karst terrain [see section Rock Material Properties: Strength – *Weathering & Alteration*].

Rock Mass Properties: Stratigraphic Discontinuities

Stratigraphic Discontinuities

Using all available outcrop and subsurface data, geologic maps, cross-sections, fence diagrams, or sketches, as appropriate, are prepared illustrating all significant stratigraphic discontinuities. See table 11 for discontinuity types.

Table 11. Discontinuity types

Discontinuity category			
Stratigraphic		**Structural**	
Lithosome:	Blanket	Plastic deformation:	Folded rock
	Tongue		Banded rock
			Foliation: schistosity
Shoestring			gneissosity
Lens		Fracture deformation:	Random
Slump feature		Systematic joint set	
Unconformity		Bedding plane parting	
			uniformly bedded
			cross-bedded
			rhythmic bedding
			interfingered
			graded bedding
			current bedding
		Sheeting joint	
			Slaty cleavage
			Fault
			Other (put in notes)

Discontinuities are to be recorded on the Discontinuity Survey Data Sheets (Appendix F). Map and identify each discontinuity. If the beds are parallel, record as a stratigraphic discontinuity. If the beds are discordant, the discontinuity should be recorded as an unconformity.

Lithosomes

A lithosome is a rock unit of essentially uniform or uniformly heterogeneous lithologic character, having intertonguing relationships in all directions with adjacent rock masses of different lithologic character. Features that characterize a lithosome include the size, shape, and lateral extent of a rock unit that formed under uniform physio-chemical conditions.

In addition to sedimentary lithosomes, discontinuities may be related to contact metamorphism. For example, high temperature magma may penetrate sedimentary rocks (or zones of weakness in other rock types), extrude onto the Earth's surface, or form an intrusive body at depth. Heat can metamorphose the mineralogical and textural makeup of the adjacent host rock, creating a “baked” contact zone composed of hornfels. Hornfels is a dense, hardened, flinty, fine-grained material, sometimes with one or more minerals prominent as larger crystals. The width of the contact zone varies according to the size of the intrusion from a feather edge around thin basaltic dikes and sills to several kilometers in the case of large, granitic igneous plutons.

When describing a lithosome, use the descriptors in table 12 as a guide.

Table 12. Descriptors for shape of lithosome

Feature	Description
Blanket	A sheet-like, tabular body with one dimension considerably thinner or shorter than the other two dimensions. Syn.: seam.
Tongue	A prism or tongue-shape body with the shortest dimension thinning in one direction. Syn.: pinch-out; wedge.
Shoestring	One dimension is considerably larger than the other two; the term "columnar" is appropriate if the long dimension is vertical. Syn.: stringer.
Lens	A body with tapering edges.
Slump feature	A post-depositional slump, fold, or buckle produced by downslope movement of somewhat more competent layers which maintain their continuity and are not pulled apart or disrupted. Common in the thin-bedded, sand/shale sequences.

Sedimentary Rocks

Because stratified sedimentary rock is so common throughout the United States, the identification of stratigraphic discontinuities in detailed engineering geological mapping is essential for a thorough geologic investigation, particularly for earthen auxiliary spillways designed by the NRCS. The aspect and appearance of sedimentary rock facies provide clues about the origin of the rock unit. The conditions of origin include the environment of deposition, the provenance and availability of sediments, as well as the physical, chemical, climatological, and other environmental characteristics that prevailed during deposition and lithification. These factors collectively determine the size, shape, continuity, and vertical and lateral extent of the rock unit or lithosome.

Depositional environments for sedimentary rocks are classified as alluvial, shore zone, marine, inland basin, lake, swamp, and glacial. Each depositional environment uniquely determines the development of stratigraphic discontinuities and bed correlations with the rock unit.

Paleontology is the study of fossilized ancient life. Fossils show how life, landscapes, and climates evolve over time and how life responds to those changes. Fossils are irreplaceable keys to correlation of rock strata. Plant and animal remains may have a very marked influence (usually adverse) on engineering properties.

Descriptions of fossils, where they have little or no influence on the engineering properties of the material, should be briefly noted. Follow local, state, federal and tribal regulations when fossils of significant scientific value are observed.

Igneous Rocks

Igneous dikes and sills can be considered types of lithosomes with engineering significance. These igneous bodies interrupt the continuity of the country (host) rock, resulting in the juxtaposition of materials that may have widely different engineering properties. This can affect the strength, erodibility, and excavatability of a rock mass. Dikes and sills can erode differentially, especially as portions of flow in an auxiliary spillway are directed initially in the direction of the strike of the sill or dike.

Unconformities

An unconformity is a surface separating two rock units that are not in stratigraphic sequence, representing a substantial break in geologic time. In general, the younger strata do not "conform" to the strike and dip of the underlying, older rocks, implying geologic uplift and erosion. The soil-rock interface is an example of a common unconformity. The engineering geologist is primarily concerned where earth materials of widely different engineering properties are juxtaposed, such as sandstone over shale.

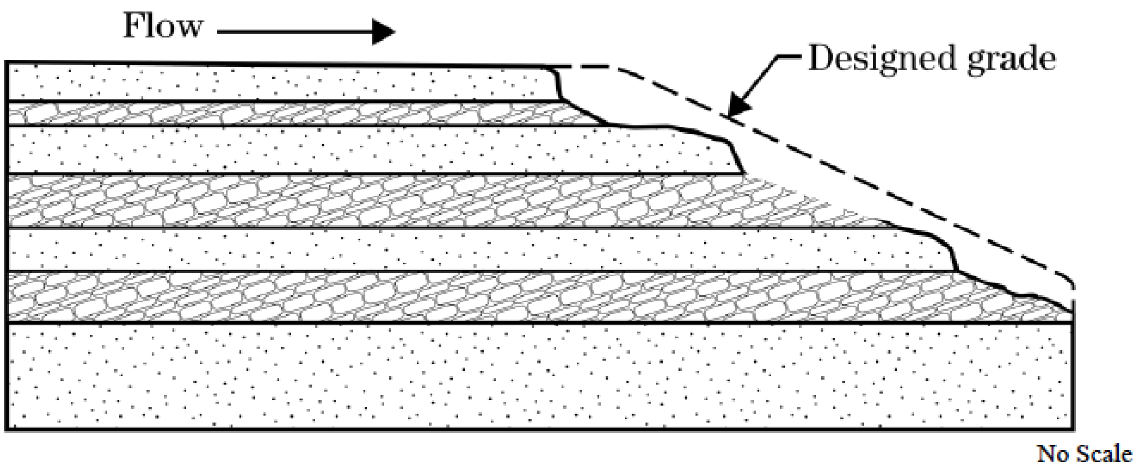
Detailed mapping of the location, size, shape, continuity, orientation, and lateral extent of lithosomes and unconformities is essential for prediction of the locations of potential knickpoints, overfalls, and scour holes. This is particularly important in exit channels that discharge onto steep hillslopes. The designer needs to know the location and erodibility characteristics of identified stratigraphic discontinuities.

Engineering Significance of Stratigraphic Discontinuities

Engineering significance of juxtaposition of geologic materials with widely different mechanical behavior and erodibility can result in abrupt lateral or vertical changes in composition, texture, or hardness associated with discontinuities or variations in sedimentary facies. For example, interfingered thin seams and lenses of inherently weak materials such as bentonite or other expansive clay shales, calcite, gypsum, or organic shales in sedimentary rock masses can significantly increase the hydraulic erodibility of the rock mass. Another example is ashfall deposits (that can turn into bentonite). These layers can be continuous and create significant hazards in dam design.

Detailed mapping should include the location of the discontinuity by stationing and elevation. The orientation of the discontinuity should be measured and recorded as well, as both an azimuth from true north and also as an azimuth relative to direction of spillway flow.

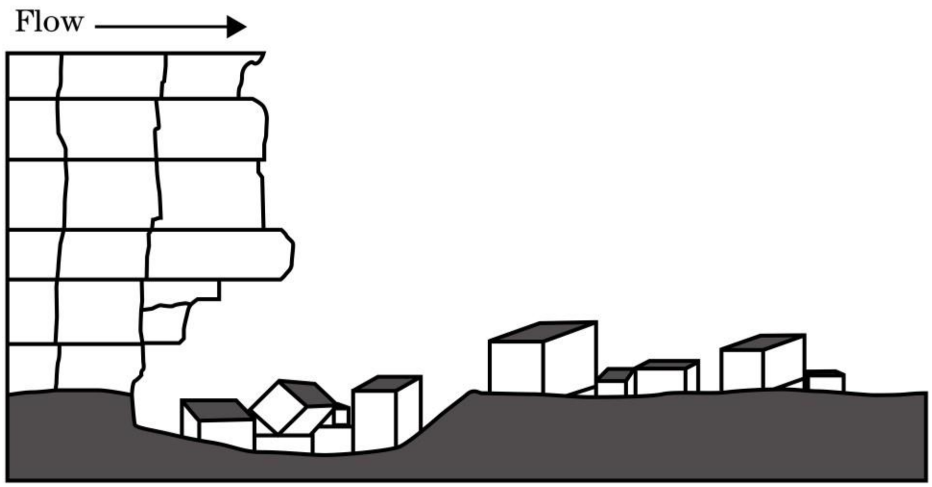
Many spillways exit channels are designed with the outlets discharging onto significantly steeper, natural hillslopes where turbulence can form a head cut, usually in the form of a waterfall or scour hole. The head cut formation represents a transition from a condition of surface attack to an overall condition. In flat-lying, alternating sequences of dissimilar rock types, such as sandstones and shales in beds of roughly equal thicknesses, erosion produces a “stairstep” pattern that results in a comparatively gradual dissipation of flow energy down the hillslope (figure 1).



Adapted from TR-78, 1991

Figure 1. Stairstep erosion pattern in flat-lying rocks of variable resistance

Overfall conditions can develop when resistant units are significantly thicker than the less resistant units they overlie. Less resistant units in the plunge area are subject to the full, undissipated attack of the energy in the spillway flow. As the underlying units are scoured out, the upper units become undermined and collapse, usually in large, discrete blocks (figure 2). Structural discontinuities (e.g., joints) in the upper unit control the size and shape of the eroded blocks. The process proceeds upstream, resulting in headward migration of the overfall until either the resistant unit collapses and is eroded away, or the flow in the spillway stops. Then, as the base level lowers, continued flow and its associated erosion will cause the headcut to proceed in the direction of dip.

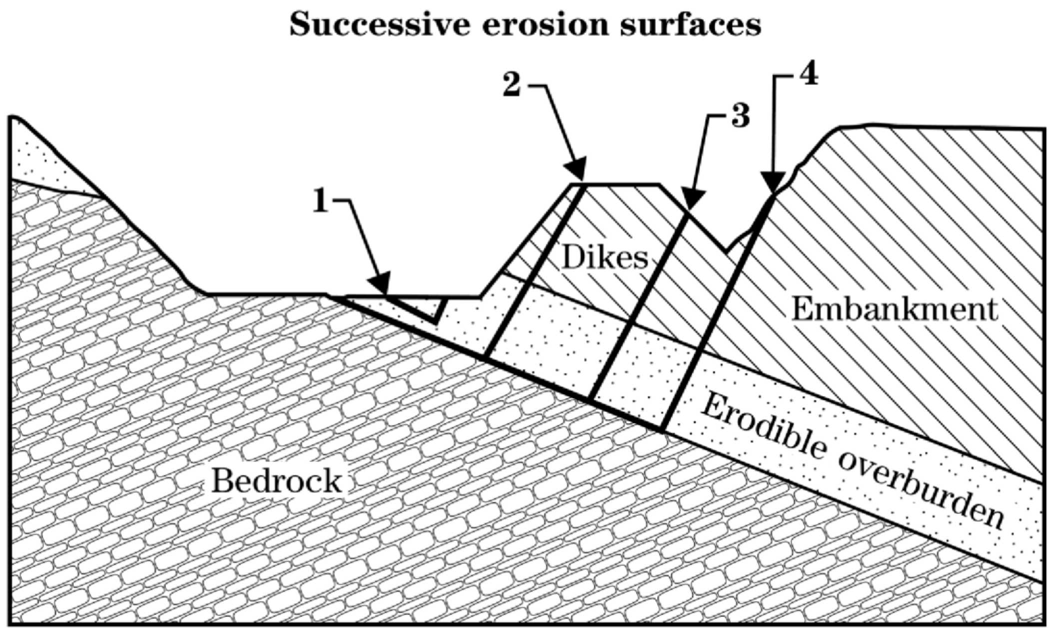


Adapted from Cameron, et. al., 1988 No Scale

Figure 2. Undermined and collapsed rock

A common unconformity found in excavations for auxiliary spillways, particularly in the exit channels, is the soil/rock interface. Ordinarily, the surface of the rock is approximately parallel with the slope of the valley wall and, therefore, slopes toward the dam. Exceptions include sites located in areas of superimposed drainage patterns where the slope of the rock surface (i.e., the configuration of the buried topography) bears no relationship to the surface topography. Gullies typically begin either in the lower reaches of the constructed outlet channel or downstream below the constructed channel.

Once initiated, gullies migrate upstream toward the control section. Gullies form in the overburden materials that cover the underlying bedrock. These materials may be residuum, colluvium, talus, alluvium, or constructed fill. Such materials are generally more erodible than the embankment, which is composed of compacted materials. Once a downward-eroding gully encounters rock surface, the gullying process is forced to progress down the slope of the rock surface, which is toward the retaining dike or the dam. The concentrated flow in the gully then impinges on and attacks the dike or dam (figure 3).



Adapted from TR-78, 1991

No Scale

Figure 3. Rock surface under spillway exit channel directs gullying toward dike and embankment

Rock Mass Properties: Structural Discontinuities

Discontinuities Related to Plastic Deformation

Apply standard geological mapping techniques to determine strike and dip of folded structures (e.g., bedding) and strike and plunge of linear aspects (e.g., fold axes). Use standard mapping symbols for strike and dip, fold axes, and related structures on the geologic evaluation map or sketch of the site (for standard symbols, see FGDC 2006, and AGI Data Sheets 2009).

Folded Structures

A fold is a curve or bend of a planar structure such as rock strata, bedding planes, foliation, or cleavage. It is usually the product of plastic deformation. Although any layered, banded, or foliated rock may display folds, they are most conspicuous in stratified sedimentary or volcanic rocks or their metamorphic equivalents. Folds may range in size from a few millimeters to hundreds of kilometers in wavelength (the distance between adjacent crests of folds).

Regional folding may extend over large areas, resulting in an apparently uniform strike and dip at a particular site. Smaller local folds, however, are usually of more concern than those of a regional character. Minor folds that create channels for substantial water movement may escape detection in a geologic investigation of a dam site. Where such folds are suspected, and anomalies are found in test holes, additional borings may be required to determine the location and size of the folds for design considerations. Descriptions of folds should indicate their size, location, type (anticline, syncline, monocline, drag) and the attitude of the limbs and axial plane.

Foliated and Banded Rocks

Foliation is the planar arrangement of textural or structural features It is commonly associated with the planar or platy structure that results from flattening of the constituent grains of a metamorphic rock. A foliated rock tends to break along approximately parallel surfaces. Schistosity and gneissosity are the two main types of foliations.

Schistosity is a type of foliation or cleavage formed by dynamic metamorphism resulting in a parallel, planar arrangement of mineral grains of the platy, prismatic, or ellipsoidal types, such as mica and hornblende. Rocks of this type cleave readily. Schistosity is a function of compositional differences in the strata that developed in layers parallel to the foliation.

Gneissosity is a type of foliation formed by dynamic metamorphism that is regional in nature, resulting in coarse-textured lineations or distinct banding composed of alternating layers, bands, or streaks of siliceous and mafic minerals.

Banded Rocks consist of assemblages of parallel, tabular layers of rocks differing in composition, texture, or mineralogy, associated with igneous and metamorphic activity. Banding is analogous to bedding in sedimentary rocks. Banding may be inherited from bedding in source sediments or from layering in igneous rocks.

Engineering Significance of Structural Discontinuities

Folded stratified rocks in auxiliary spillways, where beds dip at an angle greater than 2° (3.5 percent), require specific engineering designs. Resistant beds that form the surface (or near surface) of rock spillways can redirect spillway flow in the direction of the dip. Figure 4 illustrates some of the effects of strike and dip in rock spillways.

Corrugations and tight folds with wavelengths of approximately one-half the spillway width or less can also have engineering significance. Where the crest of a tight fold consists of an elevated prominent ridge of resistant rock, portions of the spillway flow can be diverted in the direction of the strike of the fold axis.

The orientation of foliation can have an effect on spillway flow that is analogous to the effect of corrugations and tight folds. Portions of spillway flow can be diverted in the direction of the strike of the foliation. The most favorable orientation of foliation (applies as well to the strike of fold axes of corrugations/tight folds) is within an arc ranging from 15° to 75° in the quadrant pointing away from the dam. The least favorable orientation is within an arc ranging from 105° to 165° in the quadrant pointing toward the dam (figure 5A, B and C).

The following generalizations usually apply in folded rock terrain:

(i) A rock unit dipping away from the dam is more favorable than a rock unit dipping toward the dam. Where the dip is consistent across the valley, consideration should be given to locating the spillway on the abutment that is underlain by rock dipping away from the dam.

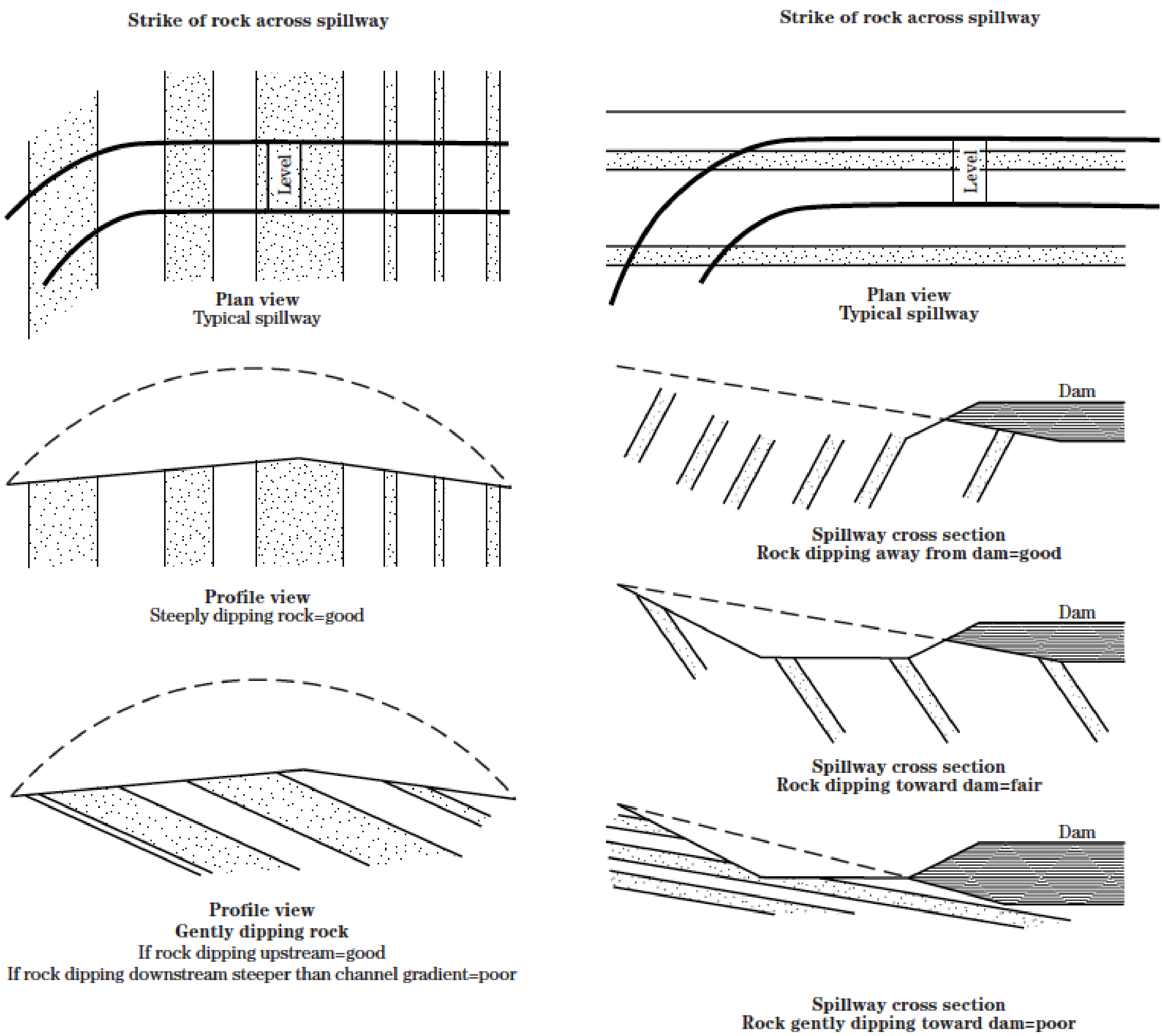
(ii) Relative favorability of the orientation of rock structure with respect to flow direction and location of dam is as follows:

15° – 75º	best
0º – 15º	good
75º – 90º	good
90º – 105º	fair
165º – 180º	fair
105º – 165º	poor

(iii) A rock unit dipping in the upstream direction is more favorable than in the downstream direction.

(iv) A rock unit that dips in the downstream direction, but less than the slope of the exit channel, tends to be more favorable than downstream dips that are greater than or equal to the channel gradient.

Rock structures include trends of axes of tight folds or corrugations, trends of foliation, and strikes of interbedded rocks of variable resistance.



Adapted from TR-78, 1991

Figure 4. Effects of strike and dip in spillways

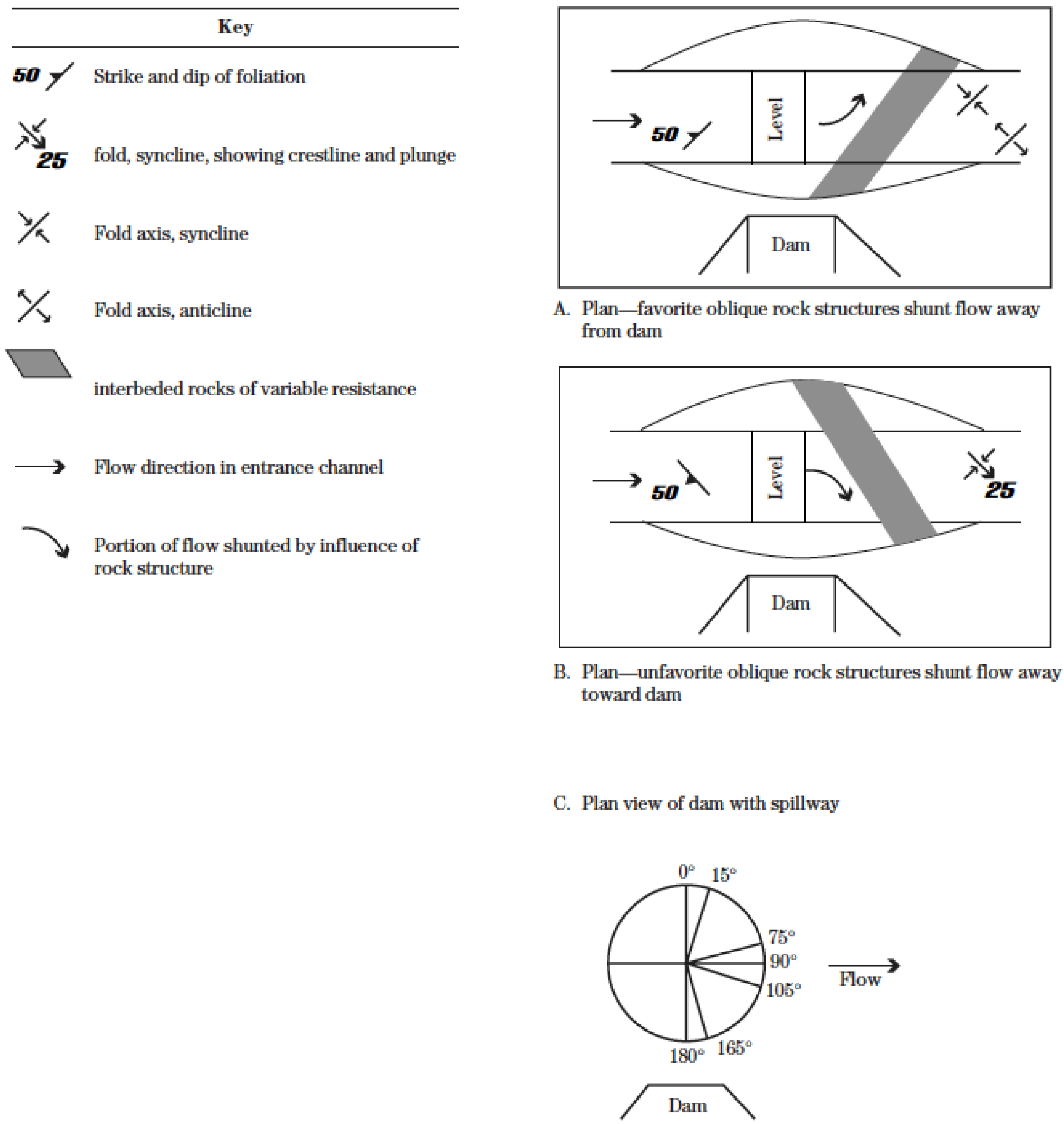


Figure 5. Effects of rock structure on spillway flow

Adapted from TR-78, 1991

Discontinuities Related to Fracture Deformation

A fracture (also called a crack, fissure, rupture, or parting) is any mechanical break in a rock mass. Fractures occur in all rock types in virtually all structural domains. The characteristics of fractures strongly affect the engineering performance of rock.

Rock fractures can occur randomly or systematically and with or without relative displacement across the faces. A joint is a planar or near-planar surface of fracture or parting without visible displacement due to mechanical failure induced by stress in a rock mass. A fault is a fracture with visible relative displacement of opposite faces due to mechanical failure induced by stress.

General Engineering Significance of Attributes of Fractures

Hydraulic erodibility of rock is a function of complex interactions between rock material, rock mass properties, and the hydraulic conditions of flow. Fracture-type discontinuities greatly influence rock mass erodibility. Although several important attributes of fractures have been identified and their engineering significance discussed individually in this chapter, in order to predict engineering performance of excavated rock spillways, these attributes must be considered in an interdependent and interactive context. Table 13 summarizes the range in influence of attributes of fractures/joints on the erodibility of a rock mass.

Table 13. Summary of the influences of fracture attributes on erodibility of a rock mass

Joint/fracture attribute	**Most favorable**	**Least favorable**
Orientation	Parallel to flow or away from dam	Perpendicular to flow or toward dam
Joint pacing	Extremely wide	Fissured
Bedding plane partings	Massive or unstratified	Fissile
Aperture width	Extremely narrow	Wide
Infilling	Filled	Open
	Plastic	Non-plastic
	Inactive clay	Swelling clay or sheet silicates, talc, graphite, or gypsum
Joint face	Unaltered	Altered
Persistence	Very low	Very high
Joint end type	Terminates in rock	Terminates against another joint

Random Fractures

A random or nonsystematic fracture is a unique break in the rock with no obvious relationship to any other nearby fracture. A random fracture can originate as a fault or a joint. Random fractures are usually rough and highly irregular and have nonplanar surfaces with no apparent displacement. Patterns in apparently random fracturing in complex structural domains can often be differentiated by the application of stereographic projection techniques and by the analysis of joint orientation diagrams (see Appendix C, Joint Orientation Diagrams).

Systematic Joints

Joints are defined as breaks in the rocks of the earth's crust along which no movement has occurred. Joints may be from the induration process or may be the product of tectonic activity. Joints usually occur in systematic patterns. They may allow movement of groundwater through otherwise impermeable material, which may create problems in design, construction, or functioning of the structure. The number and orientation of joint systems and their spacing also influences the ease of rock excavation. Description of joints should include their attitude, spacing, estimated depth of jointing, type of joints (strike, dip, or oblique) and kind of joint system.

Systematic joints are fractures that are generally evenly spaced and oriented in consistent patterns. Dips of systematic joints are typically high angle to vertical. They cross other joints, with planar or broadly curved surfaces.

Partial exposures of joint faces are revealed by erosion, natural spalling, or excavation of the rock mass. A joint set is a group of more or less parallel joints, comprised of two or more intersecting joint sets.

Bedding Plane Partings

Bedding plane partings are planar joints or fissures that split the rock along bedding planes. Bedding plane partings reflect changes in depositional conditions that differentiate successive layers in stratified sedimentary rock.

Sheeting Joints

Sheeting joints (also called stress relief joints) form by expansion or dilation accompanying release of load (pressure) during erosion or removal of overburden. Sheeting joints tend to form roughly parallel to the surface topography and tend to become more widely spaced, flatter, and more regular with depth. They rarely occur more than a few hundred meters deep. In horizontal sedimentary strata, sheeting joints often induce additional dilation on pre-existing bedding plane partings. In massive igneous rocks such as granite, sheeting joints can be spectacularly well developed by exfoliation. They tend to increase the erodibility of a rock mass and can be used advantageously in rock excavation.

Slaty Cleavage

Slaty cleavage is closely spaced, planar, parallel jointing developed in slates, phyllites, or tightly folded, homogeneous sedimentary rocks by low-grade metamorphism and deformation. The engineering significance of slaty cleavage is similar to fissility [see section Discontinuities Related to Fracture Deformation – *Random Fractures*].

Faults

A fault can occur as a single break or as a fault zone. A fault zone consists of numerous subparallel and interconnecting, closely spaced fault surfaces. The length of faults and shear zones and the amount of relative displacement can range from a few millimeters to hundreds of kilometers.

A fault is defined as a break in the earth's crust along which movement has taken place. Displacement may be a few inches or many miles. Faults may be detected by discontinuity of strata and by surface features. Aerial photographs often provide evidence of the presence of faults. Active faults may present serious hazards at a structural site. Inactive faults may also present special problems in design, construction, or functioning of the proposed structure. Faults encountered at sites should be described in detail, including type, such as normal or reverse, attitude of the fault plane, and the direction and amount of displacement. Of critical importance to the design of the structure is the activity of the fault.

Faulting may bring together materials with different engineering properties and also modify groundwater conditions. Rock shattering, alteration of minerals, and fault gouge may also occur, presenting challenges for design of the structure.

USGS Fault Classification Category

Class A – Geologic evidence demonstrates the existence of a Quaternary fault of tectonic origin, whether the fault is exposed for mapping or inferred from liquefaction or other deformational features.

Class B – Geologic evidence demonstrates the existence of a fault or suggests Quaternary deformation, but either (1) the fault might not extend deeply enough to be a potential source of significant earthquakes, or (2) the currently available geologic evidence is too strong to confidently assign the feature to Class C but not strong enough to assign it to Class A. (https:://www.usgs.gov/natural-hazard-hazards/earthquakehazards/faults).

Class C – Geologic evidence is insufficient to demonstrate (1) the existence of tectonic fault, or (2) Quaternary slip or deformation associated with the feature.

Class D – Geologic evidence demonstrates that the feature is not a tectonic fault or feature; this category includes features such as demonstrated joints or joint zones, landslides, erosional or fluvial scarps, or landforms resembling fault scarps, but of demonstrable non-tectonic origin.

The USGS Quaternary Fault and Fold Database separates the faults into the following age brackets:

- Historic (<150 years)
- Latest Quaternary (>150 <15,000 years)
- Late Quaternary (>15,000 <130,000 years)
- Middle and Late Quaternary (>130,000 <750,000 years)
- Undifferentiated Quaternary (>750,000 <1,600,000 years)
- Unspecified

It is important to note that at the time the Quaternary Fault and Fold database was established in 1993, the Quaternary time period was defined as less than 1.6 million years (Myr) by the 1983

Geologic Time Scale. In 1999, it was updated to 1.8 Myr; and in 2009, it was revised to 2.6 Myr. Most recently, in 2018 it was revised again to 2.58 Myr.

Faulting may bring together materials with different engineering properties and also modify groundwater conditions. Rock shattering, alteration of minerals, and fault gouge may also occur, presenting challenges for design of the structure.

Attributes of Fractures

Fracture Characteristics
Characteristics of fractured rock include orientation, joint spacing, aperture width of joint face surfaces, type of infilling material, fracture healing descriptions, fracture openness, roughness, linear persistence, and type of joint ends.

Fracture types and density descriptions are shown in tables 14 and 15.

Table 14. Fracture type

	Fracture type
1	Random fracture
2	Systematic joint (high-angle)
3	Bedding plane parting
	a) uniformly bedded
	b) cross-bedded
	c) rhythmically bedded
	d) interfingered
	e) graded bedding
	f) current bedding (ripples, etc.)
4	Sheeting joint
5	Slaty cleavage, or fissile bedding
6	Fault

Table 15. Fracture density description chart

Fracture density	
Fracturing	**Size range of pieces**
Crushed	< 1 ft
Intensely fractured	1/16-inch –0.1 ft
Closely fractured	0.1–0.5
Moderately fractured	0.5–1.0 ft
Little fractured	1.0–3.0 ft
Massive	> 3.0

Note the presence or absence of fines in the fractures.

Orientation

Orientation is the establishment of the correct relationship in direction, usually with reference to points of the compass. Use a geological compass, such as a Brunton, to measure the orientation of joints and fractures. If the three-dimensional expression of the joint surface is clear, express its orientation in terms of strike and dip. If the outcrop is so smooth and flat that only the trace of the joint is discernible, measure only the trend.

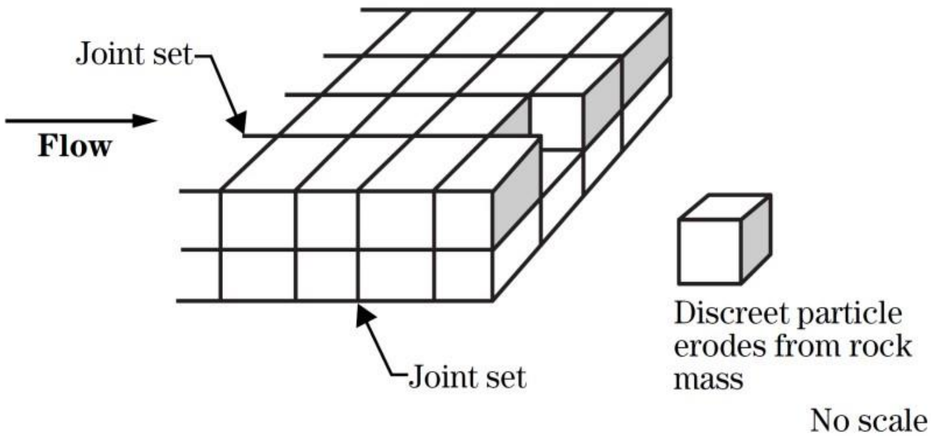
Identify the measurement locations and elevations on a geologic evaluation map using standard symbols for strike and dip or trend. For presentation of orientation data for analysis, see Appendix C, Joint Orientation Diagrams.

Engineering Significance of Orientation of Rock Joints and Fractures

The orientation of joints and fractures within a rock mass relative to the direction of spillway flow strongly influences the anisotropic strength of the mass. If the direction of spillway flow is oriented perpendicular (± 15°) to a persistent systematic joint set, the erosive attack acts against the weakest aspect of the rock mass. This relative orientation is the least desirable for the rock mass in resisting erosion. Once hydraulic erosion is initiated, headcutting tends to proceed in a consistent manner as discrete rock particles are eroded from the rock mass, typically in sizes defined by the spacing of the joint sets (figure 6). The erodibility of a rock mass increases as joint spacing decreases (see next section on Joint Spacing).

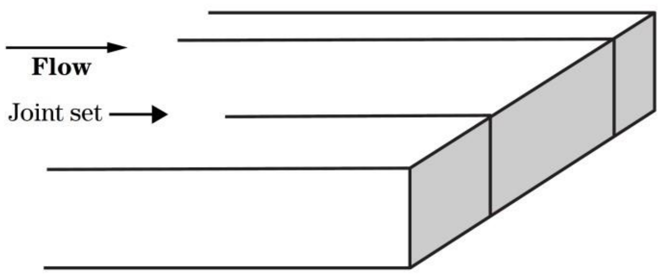
Conversely, for spillways oriented parallel (± 15°) with a single persistent systematic joint set, the erosive attack acts against the most erosion-resistant aspect of the rock mass. This relative orientation is the most favorable for the rock mass in resisting erosion, if there are no persistent systematic joint sets-oriented perpendicular to flow (figure 7).

For two sets of persistent systematic joints, orient the spillway so that both sets are oblique to the direction of flow; i.e., neither set is within ± 15° of the direction of flow. This orientation improves discrete particle interlock and provides a more stable position for the center of mass of any given particle (figure 8).



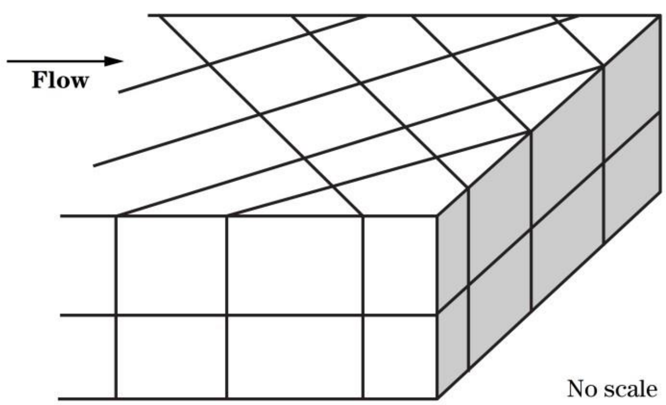
Adapted from TR-78, 1991

Figure 6. Joint system with one joint set perpendicular to flow (prone to erosion)



Adapted from TR-78, 1991 No scale

Figure 7. One joint set parallel to flow (resists erosion)



Adapted from TR-78, 1991

Figure 8. Joint system with both sets oblique to flow (resists erosion)

Joint Spacing

Joint spacing is the average spacing of joints within a joint set expressed in meters (or millimeters). The spacing and orientation of joints and bedding plane partings determine the size and shape of discrete rock particles.

Use the fixed line survey method (Appendix B) to determine joint spacing. For systematic joints, place a 10-meter tape perpendicular to the trend of each joint set, count the number of joints that intersect the survey line, and divide the number counted by 10 to determine the average joint spacing. For random fractures, measure in three mutually perpendicular directions, if possible. If the vertical component is not available because of outcrop constraints, use data from drilling logs or rock core samples, if available, to estimate the spacing.

Descriptive terms should be consistent with the usage in table 16. Record the spacing of joints in each set and use table 16 as a guide for defining the spacing category.

Determine the mean diameter (D_{50}) of discrete rock particles by taking the cube root of the product of the average joint spacing of the three most prominent intersecting joint sets. For example, a rock mass with two intersecting vertical joint sets, one with an average spacing of 1.00 meter and the other 2.00 meters, and with bedding plane partings of 0.10 meter, produces discrete rock particles with a mean diameter of 0.6 meter. A mean diameter greater than or equal to 0.20 meter is used in the definition of rock in excavated earth spillways.

Table 16. Joint set spacing categories

Spacing Descriptors		**Spacing**
Bedding Plane Partings	**Joint sets**	**(meters)**
Massive/unstratified	Extremely wide	> 6.000
Very thick bedded	Very wide	2.0–6.0
Thick bedded	Wide	0.6–2.0
Medium bedded	Moderately wide	0.2–0.6
Thin bedded	Moderately close	0.06–0.20
Very thin bedded	Close	0.020–0.060
Laminated	Very close	0.006–0.020
Thinly laminated	Shattered	0.002–0.006
Fissile	Fissured	< 0.002

Engineering Significance of Size and Shape of Discrete Rock Particles

The size and shape of discrete rock particles are initially determined by the joint spacing of intersecting joint sets and bedding plane partings. The size of discrete rock particles strongly affects the erodibility of a rock mass. As the spacing of bedding plane partings and joints decreases, the erodibility and excavatability of a rock mass tend to increase.

Fissility is a primary foliation feature that is common in some fine-grained sedimentary rocks, particularly shales. Most shales are fissile or laminated. Fissility distinguishes shale from claystone or siltstone. In many shales the most prominent fissility is parallel to the bedding, but in others it is not. Fissility is responsible for the unravelling of shales under hydraulic attack and is a qualifier of material strength as it predisposes rock to mechanical weathering processes (wetting and drying, freezing and thawing, etc.) that can cause the rock to slake and disintegrate between flow events.

Aperture Width of Joint Face Surfaces

Aperture refers to the opening between opposing faces of a joint, fracture, or fault. In most instances, the width of an aperture is not constant along the trace of any given fracture or joint; therefore, a range category is recommended in table 17. Determine the aperture width category of each selected joint by measuring the aperture width at a sufficient number of places along the trace of the joint. If the width of an aperture of a particular joint varies through more than one range, state the length of the trace for which the aperture width category applies. For example, a 20-meter-long joint has a narrow aperture width (6-20 mm) for 13 meters and widens to moderately narrow (20-60 mm) for seven meters. Clarify the variability by describing the joint in separately labeled segments on the Discontinuity Survey Data Sheets (see Appendix F) and show the location of the joint on the geologic evaluation map.

Table 17. Aperture category

Aperture Width Category	**Width Range (mm)**
Wide	> 200
Moderately wide	60–200
Moderately narrow	20–60
Narrow	6–20
Very narrow	2–6
Extremely narrow (hairline)	< 2

Engineering Significance of Joint Aperture Width

Aperture width of a joint affects the movement of water into the opening. The wider the aperture, the greater the potential for movement of the particle by uplift forces and pore pressure.

Infilling

Infilling is the material occupying the aperture between joint faces. It is often referred to as gouge, breccia, or mylonite (for faults). The materials deposited in an opening can include airborne or washed materials, such as silt, clay, calcite, iron oxides, quartz, and other organic and mineral matter; or may include partially or completely re-mineralized vein deposits. If not infilled, that should be recorded.

Soil materials in open fractures should be described according to standard soil logging terminology and classified by ASTM D2488 in the field or D2487 in the lab (Unified Soil Classification System). Chemically precipitated or re-mineralized material in fractures should be identified by composition (quartz, carbonate, gypsum, etc.). The thickness of the infilling is usually the same as aperture width.

For each evaluated joint, record the general nature of the infilling according to the scheme in table 18. Report any range in variability in the notes.

Record the classification of the material according to the Unified Soil Classification System, ASTM D2488.

Table 18. Nature of joint infilling

Nature of joint infilling
Clean, open joint; no infilling present.
Non-plastic silt (PI > 10), sand, or gravel; with or without crushed rock.
Inactive clay or clay matrix; with or without crushed rock.
Swelling clay or clay matrix; with or without crushed rock.
Chlorite; talc; mica; serpentine; other sheet silicate; graphite; gypsum. Specify type in notes.

Engineering Significance of Joint Characteristics

The resistance to sliding of adjacent joint blocks affects excavatability, slope stability, and hydraulic erodibility.

Coatings or infillings of chlorite, talc, graphite, or other low strength materials need to be identified because they increase the erodibility of the rock mass, especially when wet. Infillings that are dispersive or micaceous can squeeze or erode under fluid flow, contributing to increased erodibility and instability of the rock mass. Montmorillonite clays can swell or cause swelling pressures. Fluid flow can readily remove cohesionless silts and sands, allowing for the entry and passage of moving water which can cause uplift and sliding pressures on the discrete rock particles.

Resistance to sliding can be either increased or decreased, depending on:

- aperture width
- continuity, texture, plasticity, consistency, permeability, and unconfined compressive strength of the infilling
- the character of the joint walls (Kirsten, 1988)

Linear Persistence
Linear persistence is the extent to which an individual fracture can be traced within a plane.

Persistence is one of the most important factors in rock performance evaluation. However, it is usually difficult to measure adequately because joints often extend beyond the outcrop area. Persistence can be quantified by measuring the discontinuity trace lengths on the surface of exposures. The joints of some sets are often more continuous than those of other sets. Minor sets tend to terminate against primary sets or may terminate in solid rock (figure 9).

Measure, in meters, the lengths of all selected joint traces in the direction of strike and in the direction of dip, if discernable. Note whether it is a strike, dip, or apparent trace. Using table 19 as a guide, record the persistence category of each identified joint.

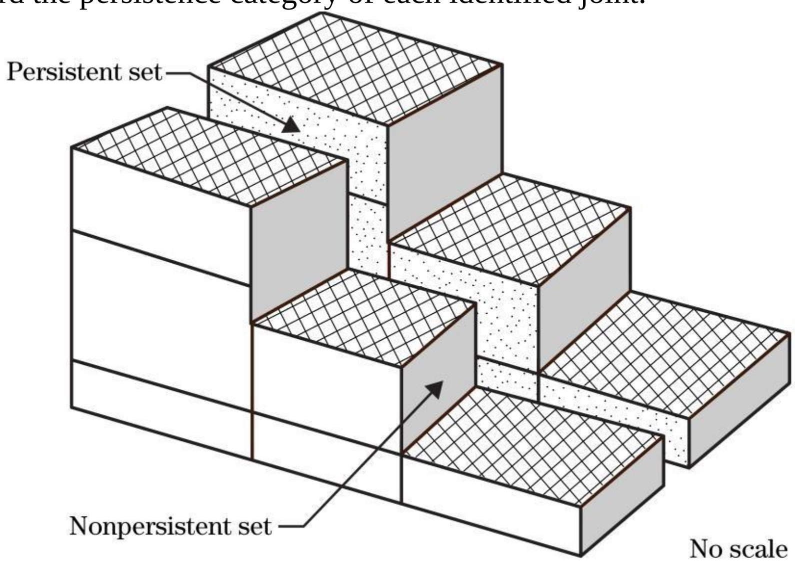


Figure 9. Persistent and non-persistent joint sets

Table 19. Joint persistence categories

Joint trace persistence category	**Trace length range (meters)**
Very low	< 1
Low	1—3
Medium	3—10
High	10—20
Very high	> 20

Engineering Significance of Linear Persistence of Joints
Linear persistence strongly affects the hydraulic erodibility of a rock mass. A rock mass interrupted by highly persistent joints is potentially more erodible than a rock mass with less persistent joints. The higher the persistence category of systematic joint sets in a rock mass upstream of the crest of a slope or overfall, the greater the tendency for the development of

tension cracks during flow. The persistence factor determines the height and width of a step which would occur between adjacent joints for a tension (failure) surface to develop and for the process to repeat itself.

Joint Ends

Joint ends refer to the nature of the terminations of a joint. Joints can terminate in solid rock, or they can terminate against another joint (like the letter "T"). Intersecting or through-going joints (like the letter "X"), are not considered to terminate at the intersection.

Record the type of joint termination for both ends of each joint according to the scheme in table 20. Figure 10 provides illustrated examples of joint terminations. Note that all length measurements in Type B joints are minimum values since the ends are not observable.

Table 20. Types of joint ends

Joint type	Description
R	Joint end terminates in solid rock
J	Joint end terminates against another joint
B	Joint end extends beyond outcrop area

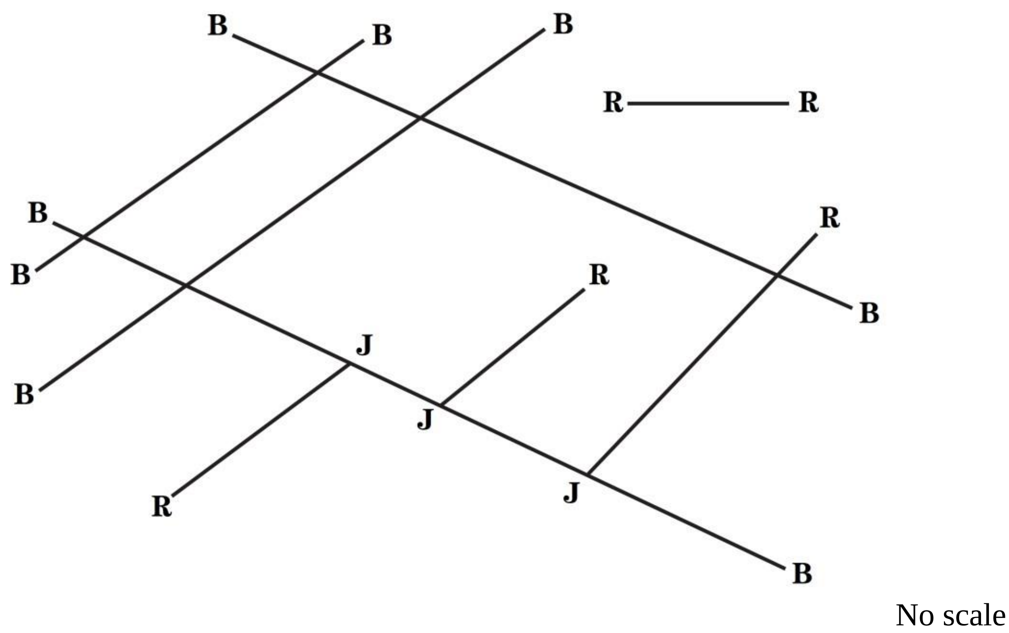


Figure 10. Types of joint ends in a rock outcrop

How the spillway channel is laid out relative to rock features can greatly affect its performance. Small changes in layout can either take advantage of favorable rock characteristics or avoid adverse features, resulting in significant improvement in spillway performance.

Engineering Significance of Joint Ends

The type of joint end strongly influences the erodibility of a rock mass. Joints that terminate in solid rock have the least potential for forming a discrete rock particle. Joints that terminate against other joints greatly increase the erodibility of the rock mass, particularly if a persistent systematic joint set is oriented perpendicular to flow (± 15°).

Systematic joints and random fractures within a rock mass reduce its integrity and stability and increase its excavatability and erodibility. Additionally, by increasing the surface area on the rock mass, jointing increases the susceptibility to physical and chemical weathering which will further weaken the rock mass over time.

Properties Related to Both Rock Materials and Rock Mass

Physical Properties

Physical properties related to both the rock material and the rock mass include seismic velocity, weathering, and secondary cavities. Each of these characteristics can affect the hydraulic erodibility and excavation characteristics of rock.

Seismic Waves, in General

Primary (P) waves are compressional waves with particle motion parallel to the direction of wave propagation.

Secondary (S) waves are shear waves with particle motion perpendicular to the direction of wave propagation. S-waves do not propagate through liquids due to the lack of shear strength in liquids. S-waves and P-waves are body waves that travel through a medium at depth, as opposed to surface waves which travel along the surface of the medium.

Surface waves are low frequency acoustic energy that travel through the earth's surface. Surface waves are a result of earthquakes, landslides, volcanic eruptions, and man-made explosions. Rayleigh waves (R-waves) are surface seismic waves that propagate along the plane of the surface of a homogenous elastic solid. Ground roll is the dominant type of wave. Love waves (Q-waves) are surface seismic waves in which particles of an elastic medium vibrate transversely to the direction of travel.

Seismic Primary (P) Wave Velocity

Seismic P-Wave velocity (V_p) is the velocity of propagation of compressional waves through a rock mass. Seismic P-wave velocity (V_p) is a function of many rock material properties, including density, porosity, mineral composition, and the degree of cementation and consolidation; and rock mass properties, including degree of fracturing and degree of weathering. Different seismic velocities are also obtained for wet and dry joint apertures in rock masses which are otherwise identical.

Seismic P-Wave velocity (V_p) of an earth material is determined by a seismic survey using standard active source seismic refraction techniques conducted by personnel with appropriate training and experience.

Engineering Significance of Seismic P-Wave Velocity
Generally, the lower the seismic P-wave velocity (V_p) of a rock mass, the greater the erodibility and excavatability of the rock mass. Most earth materials with seismic velocities less than 1,000 m/sec are prone to particle-by-particle erosion (Caterpillar Tractor Company 1983, Kirsten 1982). An obvious exception is highly plastic, nondispersive clay. The "Little Bear Residuum"

in the Lower Mississippi River Valley is an example of an extremely erosion resistant residual soil associated with limestone parent material.

Seismic refraction surveys are routinely conducted during preliminary dam site investigations to provide a rapid assessment of depth to rock, configuration of the rock surface, and an indication of the relative integrity of foundation materials, including a way to estimate rock rippability. The results of a seismic survey must be considered provisional until supplemented with “ground-truth” information provided by conventional drilling and excavation techniques in subsequent detailed investigations.

Seismic Secondary (S) Wave Velocity

Seismic S-Wave velocity (Vs) is the velocity of propagation of shear waves through a rock mass. Seismic S-wave velocity (Vs) is a function of many rock material properties (including density, porosity, mineral composition, and the degree of cementation and consolidation) and rock mass properties (including degree of fracturing and degree of weathering). Seismic velocities are also different for wet and dry joint apertures in rock masses which are otherwise identical. Seismic S-waves travel through a medium at a slower velocity than compressional (P) waves (as seen in table 21).

Engineering Significance of Seismic S-Wave Velocity
S-wave velocities (Vs), in conjunction with other material properties, can be used to characterize the shear strength of the material.

Site classifications (as seen in table 22) are correlated to a range of seismic S-wave velocities (Vs). Generally, the higher the seismic S-wave velocity (Vs) of a rock mass, the less ground shaking will occur during seismic events. The S-wave velocity and site classification are used for calculation of the peak ground acceleration (pga) to assess seismic hazards of a site.

Weathering

Weathering is the physical disintegration or chemical decomposition of earth materials, resulting in changes in the color, texture, composition, density, or form, with little or no transport of the loosened or altered material. In this section, the scope of weathering is limited to the condition of the joint face rock material. The effects of weathering tend to diminish with depth and are best assessed on a macroscopic scale in the field.

The rate and type of rock weathering depend on climate, topography, vegetation, time, and the physical and chemical composition of the rock.

Physical weathering is the disintegration of rock into chemically unaltered pieces by the following processes:

- differential expansion by pressure release when rock is exposed at the surface or confining forces are reduced
- growth of crystals, such as ice or salt, in cracks and pores
- differential expansion and contraction during cyclic heating and cooling
- the prying action of roots

Table 21. Typical sound-travel velocities of earth materials

Type of formation	P wave Velocity (V_P)		S wave Velocity (V_S)		Density
	(m/s)	(ft/s)	(m/s)	(ft/s)	(g/cm^3)
Scree, vegetal soil	300 – 700	330 – 2300	100 – 300	330–985	1.7 – 2.4
Dry sands	400 – 1200	1310–3940	100 – 500	330–1640	1.5 – 1.7
Wet sands	1500 – 2000	4920–6560	400 – 600	1310–1970	1.9 – 2.1
Saturated shales and clays	1100 – 2500	3610–8200	200 – 800	655–2625	2.0 – 2.4
Marls	2000 – 3000	6560–9840	750 – 1500	2460–4920	2.1 – 2.6
Saturated shale and sand sections	1500 – 2200	4920–7220	500 – 750	1640–2460	2.1 – 2.4
Porous and saturated sandstones	2000 – 3500	6560–11480	800 – 1800	2625–5905	2.1 – 2.4
Limestones	3500 – 6000	11480–19685	2000 – 3300	6560–10825	2.4 – 2.7
Chalk	2300 – 2600	7545–8530	1100 – 1300	3610–4265	1.8 – 3.1
Salt	4500 – 5500	14765–18045	2500 – 3100	8200–10170	2.1 – 2.3
Anhydrite	4000 – 5500	13125–18045	2200 – 3100	8860–10170	2.9 – 3.0
Dolomite	3500 – 6500	11480–21325	1900 – 3600	6235–11810	2.5 – 2.9
Granite	4500 – 6000	14765–19685	2500 – 3300	8200–10825	2.5 – 2.7
Basalt	5000 – 6000	16405–19685	2800 – 3400	9185–11155	2.7 – 3.1
Gneiss	4400 – 5200	14435-17060	2700 – 3200	8860–10500	2.5 – 2.7
Coal	2200 – 2700	7220–8860	1000 – 1400	3280–4595	1.3 – 1.8
Water	1450 – 1500	4760–4920	–	–	1.0
Ice	3400 – 3800	11155–12465	1700 – 1900	5575–6235	0.9
Oil	1200 – 1250	3940–4100	–	–	0.6 – 0.9

Table 22. Engineering Significance of Seismic S-Wave Velocity Site Classifications[1]

Site Classification	V_s[2] (ft/s)	V_s[2] (m/s)	N[3]	*Su*[4](psf)
A. Hard rock	> 5,000	> 1,500	NA	NA
B. Rock	2,500 to 5,000	760 to 1,500	NA	NA
C. Very dense soil and soft rock	1,200 to 2,500	360 to 760	> 50	> 2,000
D. Stiff soil	600 to 1,200	180 to 360	15 to 50	1,000 to 2,000
E. Soil[5]	< 600	< 180	< 15	< 1,000
F. Soils requiring site specific evaluations[6]				

Modified from: NEHRP/FEMA 450 Section 3.5.1 "Site Class Definitions" (2003) Notes:
1. Parameters used to define Site Class are based on the upper 100 ft (30 m) of site profile.
2. V_s – Shear wave velocity
3. N – Standard Penetration Test (SPT) blow count per foot, ASTM D1586-2018
4. S_u – Undrained shear strength, ASTM D2166–2016 or D2850–2015
5. Soil profile with more than 10 ft (3 m) of soft clay with PI > 20, water content ≥ 40 percent and S_u < 500psf.
6. Site specific evaluations for vulnerable to failure or collapse with liquefiable soils and collapsible soils.

Other soils include peat and/or highly organic soils (thickness > 10 ft), very highly plastic clays (thickness > 25 ft with PI >75), and very thick, clays (thickness > 120 ft) with S_u < 1,000 psf.

Chemical weathering is the decomposition of the chemical structure of the mineral grains that make up a rock. All chemical weathering reactions use water as either a reactant or the carrier of reactant products. The chief chemical weathering processes are hydration, hydrolysis, oxidation, carbonation, and solution.

Use descriptors in table 23 to classify the weathering condition of the joint face rock material of identified joints.

Table 23. Descriptors for weathering condition of joint face rock material

Descriptor	Weathering condition of joint face rock material
Fresh	No sign of weathering of joint face rock material
Discolored	Joint face rock material is iron-stained or discolored, but otherwise unweathered
Disintegrated	Joint face rock material is physically disintegrated to a soil condition with original fabric still intact. Material is friable and mineral grains are not decomposed
Decomposed	Joint face rock material is chemically altered to a soil condition with original fabric still intact; some or all of mineral grains are decomposed

Adapted from ISRM, 1978

Engineering Significance of Weathering of Rock

Physical weathering results in the widening of existing discontinuities, the creation of new discontinuities by rock fracture, the opening of grain boundaries, and the fracture or cleavage of individual mineral grains.

Chemical weathering results in staining of rock surfaces in its early stages. Long term chemical weathering results in the formation of clay minerals and chemical changes in the original minerals. In soluble rocks, it results in the widening of joints and the development of caves, sinkholes, and other karst features.

Weathering of rock material lowers the integrity of the rock and reduces its resistance to erosion and excavation. Where rock materials are known to weather rapidly (e.g., some shales in the Appalachian States or the Plains States), clay liners have been applied to the rock surface to inhibit weathering processes.

Secondary Porosity

Secondary porosity is characterized by open holes and voids, such as pits, vugs, and vesicles that form from chemical or mechanical processes acting on the rock mass after its formation. These types of secondary porosity are exclusive of fractures, jointing, and other open, planar, secondary features.

Identify the type of secondary porosity, if present, using the descriptors in table 24 as a guide.

Table 24. Descriptors for secondary porosity

Secondary Porosity	Description
Pitted	Small openings, 1–10 mm
Vuggy	Openings often lined with crystals, 11–100 mm
Cavitied	Openings > 100 mm
Honeycombed	Only thin walls separate pits or vugs
Vesicular	Small openings in volcanic rocks of variable shape formed by entrapped gas bubbles during solidification

Engineering Significance of Secondary Porosity
Secondary porosity reduces the integrity of the rock mass by decreasing block size, allowing water into the system, changing the engineering properties. By increasing the surface area of the rock mass, secondary porosity increases its susceptibility to physical and chemical weathering, which further weakens the rock mass over time.

Hydrogeologic properties

Hydrogeologic properties are attributes of a rock unit that affect the mode of occurrence, location, distribution, and flow characteristics of subsurface water within the unit.

Hydrogeologic properties include material and mass properties, but also account for the interaction and behavior of subsurface water within the rock mass.

Field tests are typically used to evaluate hydrogeologic properties of the rock mass, including secondary porosity, hydraulic conductivity, transmissivity, and other hydraulic parameters. See NEH Part 631–Geology, Chapter 31–Groundwater, for more information on field tests and hydrogeologic properties of rock units. Laboratory tests are used to evaluate hydrogeologic properties of the rock material, such as primary porosity and permeability.

Typical classification elements include:

- Primary porosity (use data collected for rock material properties)
- Secondary porosity (use data collected for rock mass properties)
- Hydraulic conductivity (aquifer tests, published information)
- Transmissivity (aquifer tests, published information)
- Storativity/specific yield (aquifer tests, published information)
- Soluble rock (occurrence of limestone, gypsum, or dolomite) (see data collected for rock material properties)
- Water table/potentiometric surface (measured in field, published data, date of measurement)
- Aquifer type (unconfined, confined, leaky artesian, perched)
- Electrical conductivity or resistivity (geophysical survey)

Rock Material Field Classification System

Scope

The NRCS uses the Rock Material Field Classification (RMFC) system to classify rock and assess rock performance for engineering applications of rock. Classification alone does not preclude or replace laboratory testing for specific engineering design purposes.

History of RMFC system

The RMFC system was first issued in 1984 as SCS Technical Release 71. It was prepared by Louis Kirkaldie (SCS), Peter V. Paterson (SCS), and Douglas A. Williamson (USDA Forest Service). The second edition of TR-71, issued in 1987, had revisions made by John S. Moore. A critique of this edition was published in ASTM STP-984 (Moore, 1988). The 2012 edition of NEH, Part 631, Chapter 4–Engineering Geology, was prepared under the guidance of John S. Moore, NRCS national geologist (retired). Classification criteria for two engineering performance objectives, hydraulic erodibility in earth spillways and excavation characteristics, were updated to reflect recent findings from field and laboratory research. Other performance objectives were updated to conform to the field procedures for describing various rock parameters presented in NEH Part 628 - Dams, Chapter 52 – Field Procedures Guide for the Headcut Erodibility Index. The present edition of NEH, Part 631, Chapter 4, was prepared under the guidance of Jo Ellen Johnson, NRCS national geologist and others.

Rock Unit

The rock unit is the basic mapping unit for the RMFC system. It is defined as a body of rock that is identified in the field and mapped according to measurable or otherwise describable physical properties or features at a scale useful for project analysis.

A rock unit is consistent in its mineralogical composition, geologic structure, and hydraulic properties. Its boundaries are delineated by measurable or otherwise describable physical properties or features. It is traced in the field by surface and subsurface mapping techniques. The body is prevailingly, but not necessarily, tabular in form. Uniformity in thickness is not a determining factor. Because the mapping criteria are performance-based engineering characteristics, rock units need not conform to formally recognized stratigraphic rock formations.

The term “rock unit” is similar to lithosome in that the body of rock has consistent, mappable characteristics, but differs in that the body need not have been formed under uniform physicochemical conditions.

Outcrop confidence level

Outcrop confidence is the relative measure of the predictability or homogeneity of the structural domain and the lithology of the rock unit from one exposure to another or to the proposed site of investigation. The three levels of outcrop confidence are defined as:

- *Level I:* High—Rock units are massive and homogeneous, vertically and laterally extensive. Site geology has a history of low tectonic activity.
- *Level II:* Intermediate—Rock characteristics are generally predictable but have expected lateral and vertical variability. Structural features produced by tectonic activity tend to be systematic in orientation and spacing.
- *Level III:* Low—Rock conditions are extremely variable because of complex depositional or structural history, mass movement, or buried topography. Significant and frequent lateral and vertical changes in rock units can be expected.

Once a rock unit has been established, it can be defined by classification elements and analyzed for performance in relation to selected performance objectives.

Classification elements

Classification elements are objective physical properties of a rock unit that define its engineering characteristics. Engineering classification of a rock unit considers the material properties of the rock itself, the structural characteristics of the in situ rock mass, and the flow of water contained in the rock or within the system of discontinuities.

The RMFC system uses three major types of classification elements: rock material properties, rock mass properties, and geohydrologic properties.

Rock Material Properties

Rock material properties are measurable or otherwise describable lithologic properties of intact rock material that can be evaluated in hand specimens and in the laboratory. Rock material properties are related to the physical properties of the constituent minerals and the type of mineral bonding. The properties are determined from examination of hand specimens, core sections, drill cuttings, outcroppings, and disturbed samples, using qualitative procedures and simple classification tests, or in the laboratory using standard test methods. The results are applicable to hand specimens and representative samples of intact rock material. They do not account for the influence of discontinuities or boundary conditions of the rock.

Typical classification elements include:

- Principal rock type (use table 1)

- Mineralogy (estimate percentage of principal and accessory minerals; note type of cement and presence of alterable minerals)
- Primary porosity (free draining or not)
- Discrete rock particle size (use D50 or cube root of the product of its three dimensions)
- Hardness category (use table 3)
- Unconfined compressive strength (table 3)
- Unit weight (table 6)
- Color (table 7)

Rock Mass Properties

Rock mass properties are measurable or otherwise describable lithologic properties, characteristics, or features of the rock mass that must be evaluated on a macroscopic scale in the field. They include many types of discontinuities, such as fractures, joints, and faults, as well as abrupt changes in lithology because of erosion, deposition, or the effects of its mode of emplacement. Normally, rock mass properties are too large or extensive to be observed directly in their entirety at a single outcrop and are difficult or impossible to sample for laboratory analysis. Typical classification elements include:

- Discontinuity type (use table 11)
- Joint set spacing category (use table 16)
- Joint persistence category (use table 19)
- Aperture category (use table 17)
- Joint count number (use NEH 628, Chapter 52, table 52-6)
- Join roughness condition (use NEH 628, appendix 52C, table 9)
- Type of joint infilling (gouge) (use table 18)
- Large geomorphic features (karst topography, lava flows, lineaments, exfoliation)
- Large geologic structures (folds, faults, unconformities)
- Types of major voids (caverns, vugs, sink holes, lava tubes)
- Seismic velocity (seismic refraction survey, use ASTM D5777, Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation)
- RQD (use ASTM D6032, Standard Test Method for Determining Rock Quality Designation (RQD) of Rock Core)
- Other geophysical survey parameters (ground penetrating radar, gravity, electromagnetic, resistivity, use ASTM D6429, Guide for Selection of Surface Geophysical Methods)

The properties of a rock mass are often significantly different from the properties of intact rock samples of the same rock mass. The mechanical behavior and strength of a rock mass are commonly dominated more by mass properties than by material properties. For example, a rock mass composed of the strongest intact rock material is weakened in proportion to the number of discontinuities in each volume.

Material properties, on the other hand, dominate the strength of a rock mass where discontinuities are widely spaced or nonexistent. Thus, discontinuities inevitably lower the strength and stability of a rock mass and reduce the amount of energy required to excavate, erode, remove, blast, or otherwise destabilize the rock mass.

Rock Material Classification Process

The classification process consists of identifying the rock units at the site of investigation, describing them in terms of appropriate classification elements, and conducting the performance assessment. The performance assessment includes selecting the performance objectives for the proposed engineering uses of the rock and classifying the rock material within each selected objective. Figure 11 schematically illustrates the basic steps in the process.

Determine class of rock or each selected performance objective:

Step 1: Identify rock units

- Rock unit identification includes determining the location and extent of each mappable unit in the outcrop or in the stratigraphic section at and near the site. When done in conjunction with a review of available data, maps, and literature, this field work should provide the outcrop confidence level.
- If a formally recognized geologic formation is expected to perform as a homogeneous mass for engineering purposes, it may be considered a rock unit (as defined in this chapter) and identified by its formal stratigraphic name, such as Vishnu schist. All other mappable rock units should be assigned alphanumeric designations, such as Rock Unit L-6.
- Each unit should be located on a geologic map by stationing, depth, and elevation. The outcrop confidence level should be determined and recorded in the notes.

Step 2: Describe rock units by classification elements

- Each rock unit is characterized in terms of specific classification elements that affect performance of the rock for its intended use.
- The investigator may include any additional elements considered necessary for further clarification and refinement.
    - *Rock material properties*—Determined by examining and classifying hand specimens, core sections, drill cuttings, outcroppings, and disturbed samples using conventional geologic terminology.
    - *Rock mass properties*—Determined by geologic mapping, fixed line survey, geophysical survey, remote imagery interpretation, core sample analysis, and geomorphic analysis.
    - *Geohydrologic properties*—Determined by pressure testing; review of logs/data from water wells, observation wells, drill holes, and piezometers; review of published and unpublished maps and reports; interpretation of rock material and rock mass properties; and dye tests.

Step 3: Select performance objectives

- This step involves the selection of performance objectives (engineering uses) of the rock for which an assessment of engineering performance is needed.

- Figure 11 and tables 25 through 29 provide the criteria for applicable classification elements that define each class for the five performance objectives considered in this system.

Step 4: Classification by objective

- Determining the class of the rock material for all identified performance objectives is the final step in the procedure.
- Each of the five performance objectives has three classes of rock material (figure 11 and tables 25 through 29). A class defines the expected capabilities and limitations of the rock for each engineering use. End member classes I and III for each performance objective are intentionally defined restrictively. Therefore, rock material that classifies as class II is usually an indication that additional evaluation may be needed.
- Rock units assigned to the same class within a given performance objective can be expected to perform similarly.

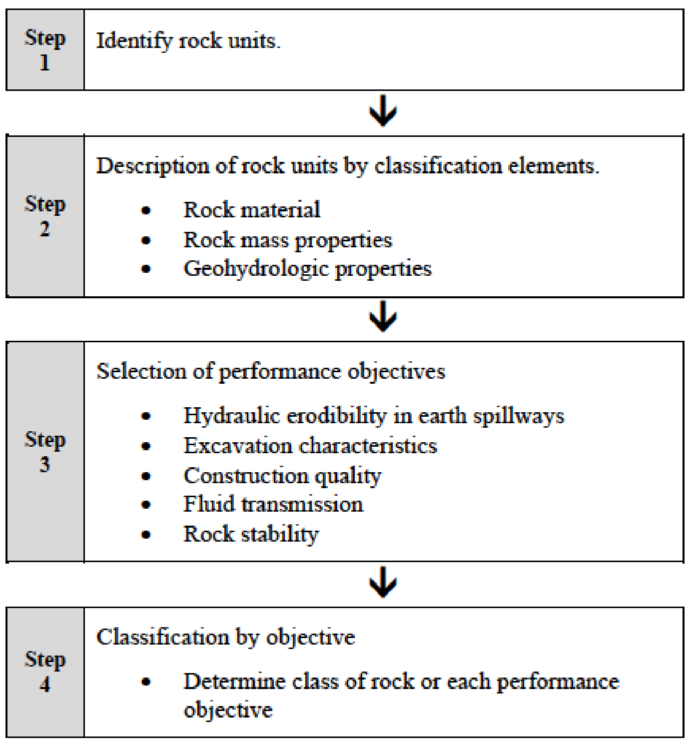


Figure 11. Process for using the Rock Material Field Classification System (RMFC)

Evaluation of Earth Material for Excavation by a Ripping Index

Purpose

NRCS Construction Specification 21, Excavation, provides criteria for defining rock excavation and common excavation for pay purposes. One of the criteria defining rock excavation is the need to use either heavy ripping equipment (rated above 250 flywheel horsepower) or blasting for excavation.

This section describes the ripping index method for predicting the excavatability of any earth material. The index allows estimation of the minimum energy or effort required for excavation, on a scale ranging from hand tools to drilling and blasting. A relationship may exist between rippability and hydraulic erodibility of rock, although no definitive study has been published to date. Caterpillar Tractor Company (1983) correlates the seismic velocities of some broad categories of earth materials with ripping performance of tractors.

Background

An earth material classification system developed by Kirsten (1988) was field-proven by ripping trials to reasonably and accurately predict the excavation characteristics of a broad range of earth materials. Kirsten's ripping index, k_n, allows earth material to be classified on a continuous basis from soft soil through hard rock.

Moore, Temple, and Kirsten (1994) developed the concept of a headcut erodibility index based on the analogy between bulldozer drawbar power required for ripping earth material and the hydraulic power associated with turbulent hydraulic energy dissipation at a headcut in a concentrated flow channel. Both indexes comprise the same parameters for rock material and rock mass. The classification system for the headcut erodibility index, k_h, (Temple and Moore, 1997) is presented in NEH, Part 628 – Dams, Chapter 52 – Field Guide for the Headcut Erodibility Index.

Hydraulic Erodibility in Earth Spillways
For hydraulic erodibility in earth spillways, use table 25, which covers evaluation of erodibility of rock subject to intermittent flowing water. For performance objectives for spillways in rock, please refer to NEH, Part 628 – Dams, Chapter 52 and its appendices. Classification criteria included in this chapter are consistent with or are taken from NEH, Part 628 – Dams, Chapter 52.

Excavation Characteristics of Rock
Cost of rock excavation may be greatly influenced by the nature of rock and secondary alteration. The geologist must describe the properties, quality, and quantity of rock proposed for excavation in terms translatable into workability by construction equipment, so that the amounts of rock excavation can be determined.

Table 25. Hydraulic erodibility in earth spillways

Classification elements	Class I	Class II	Class III
	Highly erosion resistant	**Erosion resistant**	**Moderately erosion resistant**
	Rock material experiences headcut erosion rates less than 0.3 m/hr (1 ft/hr) at a unit discharge of 9.2 $m^3/s/m$ (100 $ft^3/s/ft$) and 9 m (30 ft) of energy head. **Must fulfill the following condition:**	Rock material experiences headcut erosion rates from 0.3 to 3.0 m/h (1 to 10 ft/h) at a unit discharge of 9.2 $m^3/s/m$ (100 $ft^3/s/ft$) and 9 m (30 ft) of energy head. **Must fulfill the following condition:**	Rock material experiences headcut erosion rates > 3.0 m/h (10 ft/h) at a unit discharge of 9.2 $m^3/s/m$ (100 $ft^3/s/ft$) and 9 m (30 ft) of energy head. **Must fulfill the following condition:**
Headcut erodibility index, k_h (NEH628.52), which comprises: Material strength Block size Discontinuity shear strength Relative ground structure	$k_h \geq 100$	$10 < k_h < 100$	$1 \leq k_h \leq 10$

For further details on classification of rock for excavation, see NEH, Part 642 – Specifications, Chapter 2 – National Construction Specifications and Chapter 3 – National Standard Material Specifications.

For excavation characteristics, use table 26, which covers evaluation of excavation characteristics of rock.

Construction Quality of Rock

For construction quality, use table 27, which shows rock quality classification for riprap, aggregate, embankment fill, and road armor for construction applications.

Transmission of Water Through Rock

For water transmission, table 28 shows the potential for water transmission through primary and secondary porosity in rock units underlying reservoirs, canals, and dam foundations; for excavation dewatering; for drainage for slope stability and for point and nonpoint source pollution; for ground water yield for water supply development (water wells, springs, aquifers, basins) for groundwater recharge or disposal; and for saltwater intrusion.

Rock Mass Stability

Table 29 shows rock mass stability of natural or constructed slopes for gravity or seismic activity.

Table 26. Excavation characteristics

Classification elements	Class I **Very hard ripping to blasting**	Class II **Hard ripping**	Class III **Easy ripping**
	Rock material requires drilling and explosives or impact procedures for excavation may classify[1] as rock excavation (NRCS Construction Spec. 21). **Must fulfill *all* conditions below:**	Rock material requires ripping techniques for excavation may classify[1] as rock excavation (NRCS Construction Spec. 21). **Must fulfill *all* conditions below:**	Rock material can be excavated as common material by earthmoving or ripping equipment may classify[1] as common excavation (NRCS Construction Spec. 21). **Must fulfill *all* conditions below:**
Headcut erodibility index, k_h (NEH628.52)	$k_h \geq 100$	$10 < k_h < 100$	$k_h \leq 10$
Seismic refraction velocity (V_p), approximate (ASTM D5777 and Caterpillar Handbook of Ripping, 1997)	≥ 2,450 m/s (≥ 8,000 ft/s)	2,150–2,450 m/s (7,000–8,000 ft/s)	≤ 2,150 m/s (≤ 7,000 ft/s)
Minimum equipment size (flywheel power) required to excavate rock. All machines assumed to be heavy-duty, track-type backhoes or tractors equipped with a single tine, rear-mounted ripper.	260 kW (350hp), for $k_h < 1,000$ 375 kW (500hp), for $k_h < 10,000$ Blasting, for $k_h > 10,000$	185 kW (250 hp)	110 kW (150 hp)

1. The classification is a general guide and does not prescribe the actual contract payment method to be used, nor supersedes NRCS contract documents. The classification is for engineering design purposes only.

Table 27. Construction quality

Classification elements	Class I **High grade**	Class II **Medium grade**	Class III **Low grade**
	Rock material is suitable for high-stress aggregate, filter and drain material, riprap, and other construction applications requiring high durability. **Must fulfill all conditions below:**	Rock material is potentially suitable for construction applications. **May require additional evaluation if at least one condition below is fulfilled:**	Rock material is unsuitable for aggregate, filter and drain material, or riprap. Reacts essentially as a soil material in embankments. **Must fulfill at least one condition below:**
Strength (table 3)	> 50 MPa (> 7,250 lb/in^2)	12.5–50 MPa (1,800–7,250 lb/in^2)	< 12.5 MPa (< 1,800 lb/in^2)
Hardness (table 3)	Hard to extremely hard rock	Moderately hard rock	Moderately soft to very soft rock
Unit weight (table 6)	> 2.24 g/cm^3 (> 140 lb/ft^3)	2.08–2.24 g/cm^3 (130–140 lb/ft^3)	2.08 g/cm^3 (<130 lb/ft^3)

Table 28. Fluid transmission

Classification elements	**Class I** **Slowly permeable**	**Class II** **Moderately permeable**	**Class III** **Highly permeable**
	Rock material has low capability to transmit water. **Must fulfill *all* conditions below.**	Rock material has potential to transmit water, generally through primary porosity. **May require additional evaluation if *at least one* condition below is fulfilled.**	Rock material has high capability to transmit water, generally through secondary porosity. **Must fulfill *at least one* condition below.**
Soluble rock	No soluble rock occurs in the rock mass.	Soluble rock, if present, occurs as a minor or secondary constituent in the rock mass.	Soluble rock, such as limestone, gypsum, dolomite, marble, or halite, is the predominant rock type.
Primary porosity	Very low primary porosity; pores not interconnected or free draining	Pores visible under 10x hand lens; slowly free draining	Pores visible to naked eye; rapidly free draining
Number of joint sets (include bedding plane partings)	1 joint set and random fractures; or rock mass intact and massive	≤ 2 joint sets and random fractures	≥ 3 interconnecting joint sets
Joint aperture category (NEH 628.52, appendix 52C, table 14)	Extremely narrow, hairline (< 2 mm)	Very narrow to narrow (2–6 mm)	Narrow to wide (≥ 6 mm)
Infilling (including gouge)	Joints tight or filled with cohesive, plastic clay or swelling fines matrix	Joints open or filled with non-plastic, non-swelling fines matrix	Joints open or filled with sand or gravel with <15% cohesionless, non-plastic fines matrix
Major voids, solutional (caverns, sinkholes, enlarged joints), depositional (lava tubes or interbedded gravels and lava beds) or structural/tectonic (faults, stress relief joints)	No major voids occur in rock mass		Any types of major voids occur in rock mass
Hydraulic conductivity (dams and other structures)	$< 10^{-6}$ m/s (< 0.3 ft/d)		$> 10^{-5}$ m/s (> 3 ft/d)
Transmissivity (irrigation wells)	$< 10^{-3}$ m^2/s ($< 10^3$ ft^2/d)		> 1 m^2/s ($> 10^5$ ft^2/d)
Transmissivity (domestic/ stock wells)	$< 10^6$ m^2/s (< 1 ft^2/d)		$>10^{-4}$ m^2/s ($>10^2$ ft^2/d)

Table 29. Rock mass stability

Classification elements	Class I **Stable**	Class II **Potentially unstable**	Class III **Unstable**
	Rock material has very low potential for instability. **Must fulfill *all* conditions below:**	Rock material has potential for instability. **May require additional evaluation if *at least one* condition below is fulfilled:**	Rock material has significant potential for instability. **Must fulfill *at least one* condition below:**
Strength (table 3)	> 50 MPa (> 7,250 lb/in^2)	12.5–50 MPa (1,800–7,250 lb/in^2)	< 12.5 MPa (< 1,800 lb/in^2)
Hardness (table 3)	Hard to extremely hard rock	Moderately hard rock	Moderately soft to very soft rock
RQD (ASTM D6032)	> 75	25–75	< 25
Number of joint sets in rock mass (include bedding plane partings)	1 joint set and random fractures, or rock mass intact and massive; no adverse component of dip	≤ 2 joint sets plus random fractures; no set contains adverse component of dip	≥ 3 interconnecting joint sets; and > 1 set contains adverse component of dip
Joint water condition	Unconfined	Unconfined	Confined

Ripping Index Method

Excavation characteristics of any given earth material are readily established by calculating the material's ripping index. The ripping index is determined by following the same procedures used in determining the headcut erodibility index (NEH, Part 628, Chapter 52).

Table 30 correlates various parameters that indicate the excavatability of the full spectrum of earth material. In the first column, earth material is delineated by hardness. The second column provides the minimum tools required for excavation. The excavation class (rock or common), as defined in NRCS Construction Specification 21, Excavation, is provided in parentheses. Determining the ripping index or seismic velocity allows prediction of the minimum size machine needed (expressed in flywheel horsepower) to excavate the material. The final column indicates the class of rock for excavation characteristics in the RMFC system.

Table 30. Correlation of various indicators of earth material excavatability

Earth material hardness	Excavation description excavation class	Ripping index[1] (kn)	Seismic Refraction velocity (V_p) [2] (ft/s)	Equipment[3] needed for excavation (hp)	RMFC system class (table 25)
Very soft through firm cohesive soil or very loose through medium dense cohesionless soil (Table G-1 & G-2, Appendix G)	Hand tools (common [4])	< 0.10	< 2,000 (< 610 m/s)	—	—
Stiff cohesive soil or dense cohesionless soil through very soft rock or hard, rock-like material (Table G-1 & G-2, Appendix G)	Power tools (common [4])	0.10–1.0	2,000–5,000 (610-1525 m/s)	≥ 100	—
Soft through moderately soft rock (Table G-3, Appendix G)	Easy ripping (common [4])	1.0–10	5,000–7,000 (1525-2135 m/s)	≥ 150	III
Moderately hard through hard rock (Table G-3, Appendix G)	Hard ripping (rock [5])	10–100	7,000–8,000 (2135-2440 m/s)	≥ 250	II
Very hard rock (Table G-3, Appendix G)	Very hard ripping (rock [5])	100–1,000	8,000–9,000 (2440-2745 m/s)	≥ 350	I
Extremely hard rock (Table G-3, Appendix G)	Extremely hard ripping to blasting (rock [5])	1,000–10,000	9,000–10,000 (2745-3050 m/s)	≥ 500	I
	Drilling and blasting (rock [5])	> 10,000	> 10,000 (> 3050 m/s)	—	I

Note:

1. Because ripping index, kn, (Kirsten, 1988) is equal to headcut erodibility index, kh (NEH628.52), use k_h.
2. Seismic velocity values are approximate, taken from ASTM D5777 and Caterpillar Handbook of Ripping (1997).
3. Flywheel horsepower, machines assumed to be heavy-duty, track-type backhoe or tractor equipped with a single tooth, rear-mounted ripper.
4. Meets criteria for common excavation in NRCS Construction Specification 21, Excavation.
5. Meets criteria for rock excavation in NRCS Construction Specification 21, Excavation.

Note: The classification is a general guide and does not prescribe the actual contract payment method to be used, nor supersedes NRCS contract documents. The classification is for engineering design purposes only.

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Appendix A: Definitions

Bedrock	A general term for in-place (in situ), usually solid rock that is exposed at the surface of the Earth or overlain by unconsolidated material. Colloquial syn.: ledge. See Rock mass.
Bedding plane	A bedding plane is a planar or near planar interface that reflects a change in depositional conditions indicated by a parting, color difference, or both, and defines successive layers of stratified rock.
Cleavage	The property or tendency of a rock to split along secondary, aligned fractures or closely spaced, planar structures produced by deformation or metamorphism.
Clastic	Pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals and that have been transported some distance from their places of origin. See Pyroclastic.
Corrugations	Small-scale, tight folds; wrinkles; or furrows.
Density	The mass of a unit volume of substance at a specified temperature, expressed in SI units of kilograms per cubic meter, but often is reported in grams per cubic centimeter. Syn.: unit weight, weight per unit volume.
Discontinuity	Any distinct break or interruption in the integrity of a rock mass. See Stratigraphic discontinuity; Structural discontinuity.
Discrete rock particle	An intact, sound fragment of rock material whose shape and size is defined by the discontinuities that form its margins. The mean diameter of a rock particle is defined as the cube root of the product of its three dimensions (length, width, and thickness). Syn.: rock block, intact block.
Durability	The resistance of discrete rock particles to breaking down over time due to weathering processes, hard wear, and abrasion. Syn.: weatherability.
Earth material	The entire spectrum of soil and rock materials. See table 3 for the ranges in strength and hardness of earth materials.
Earth spillway	An open channel spillway in earth materials without vegetation.
Fault	A fracture or fracture zone along which there has been relative displacement of opposite faces, due to mechanical failure by stress in a rock mass.
Fissility	The tendency of a rock to split or part into thin layers or plates. Bedding fissility is a primary feature inherited from the time of deposition; it is the result of compaction with concomitant recrystallization, and to some degree, is due to the parallel arrangement of platy or elongated, fine-grained mineral particles.
Fold axis	The intersection (which is a line) of the axial surface of a fold with any bed. The axial surface is the plane or surface that divides the fold as symmetrically as possible.
Fracture	A general term for any physical break in a rock mass without regard to the nature of the origin of the break. Syn.: crack, fissure, rupture, parting.
Freeboard hydrograph	The hydrograph used to establish the minimum settled elevation of the top of dam; also used to evaluate the structural integrity of the spillway system.
Geologic evaluation map (GEM)	A plan view diagram or drawing representing a given area depicting the orientation and location of selected geologic features using appropriate signs

	and symbols at a chosen scale and projection. See Sketch map.
Groundmass	[igneous] The glassy or fine-grained crystalline material between the larger crystals of a porphyritic igneous rock.
Intact rock	Rock containing no discontinuities. Syn.: rock material.
Joint	A planar or near-planar surface of fracture or parting without visible displacement, due to induced mechanical failure by stress in a rock mass.
Joint set	A group of more or less parallel joints.
Joint system	Two or more joint sets that intersect.
Knickpoint	Any interruption or break of slope; especially a point of abrupt change or inflection in the longitudinal profile of a stream or of its valley, resulting from rejuvenation or the outcropping of a resistant bed.
Lithosome	A lithosome is a body of sedimentary rock of uniform character that has intertonguing relationships with adjacent masses of different lithology. There is no implication of formal rock-stratigraphic nomenclature.
Master joint	A persistent joint plane of greater than average extent. Syn.: main joint, major joint, regional joint.
Pyroclastic	Pertaining to clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; it is not synonymous with the adjective “volcanic.” See clastics.
Rock mass	Rock as it occurs in situ, including its system of discontinuities, and weathering profile. Syn.: bedrock, rock outcrop. Colloquial: ledge.
Rock mass properties	Measurable or otherwise describable lithologic properties, characteristics, or features of the rock mass that must be evaluated on a macroscopic scale in the field. Normally, rock mass properties, such as joints and faults, are too large to be observed directly in their entirety and are difficult to impossible to sample for laboratory analysis (NRCS, TR–71, Feb 1987).
Rock material	An intact, natural body or aggregate of solid mineral matter that is free of discontinuities, such as joints. Syn: intact rock, intact rock material.
Rock material properties	Measurable or otherwise describable properties of intact rock material that can be evaluated in hand specimen (and, in many instances, in outcrop) and, therefore, can be subject to meaningful inquiry in the laboratory. The properties of rock material depend on the physical properties of the constituent minerals and their type of bonding to one another. The properties can be determined from the examination of hand specimens, core sections, drill cuttings, outcroppings, and disturbed samples.
Rock unit	An identifiable body of rock that is consistent in mineral, structural, and hydraulic characteristics. A rock unit can be considered essentially homogeneous for engineering performance analysis and for descriptive and mapping purposes. A rock unit can be delineated by measurable or otherwise describable physical properties or features. The term is similar to lithosome in that the body of rock has consistent, mappable characteristics, but differs in that the body need not have been formed under uniform physicochemical conditions.
Sheeting joint	A joint that forms by expansion (also called dilation, scaling, and exfoliation) accompanying release of load (pressure) during geologic erosion. Syn.:

	pressure release joint, stress relief joint, sheeting.
Sketch map	A map drawn freehand from observation or uncontrolled surveys showing only approximate space, scale, and orientation relationships of the main features of an area.
Slaty cleavage	Closely spaced, planar, parallel jointing of fine-grained, platy minerals developed in slates and phyllites by low-grade metamorphism; or in tightly folded, homogeneous sedimentary rocks by deformation. Slaty cleavage is perpendicular to the direction of greatest shortening of the rocks in which it is formed.
Standard practice	A definitive procedure for performing one or more specific operations or functions that does not produce a test result.
Stratigraphic discontinuities	Features that originate contemporaneously with the formation of a rock mass. Syn.: primary discontinuities, first order discontinuities, syngenetic discontinuities.
Structural discontinuities	Features that develop after the initial formation of the rock because of external processes acting on the rock mass. Syn.: secondary discontinuities, second order discontinuities, epigenetic discontinuities.
Structural domain	A geologic locality having rock masses with similar major lithologic and structural features. Syn.: structural region.
Tight folds	Fold with an interlimb angle between 0° and 30°.
Trace	The intersection of a geological surface with another surface, e.g., the trace of a fault on the ground. The trace is a line. Syn.: trend, strike.
Unconformity	The surface separating two rock units that are not in stratigraphic sequence representing a substantial break in geologic time. Often, but not always, the younger stratum does not “conform” to the dip and strike of the underlying; it usually implies geologic uplift and erosion.
Vein	An epigenetic mineral filling or deposit in the aperture of a fracture, in a rock mass, in tabular or sheet-like form. Quartz and calcite are the most common vein minerals.

Appendix B: Rock Surveys

The fixed line surveys

A fixed line survey is an inventory of all structural discontinuities that intersect a linear traverse of specified length and orientation. In structural domains where joint set patterns are obvious, the fixed line survey can be used to make rapid determinations of joint set spacings, which, in turn, are used to determine mean diameter and shape of discrete rock particles.

In complex structural domains where joints and fracture patterns are difficult to discern, the fixed line survey can be applied to differentiate subtle joint patterns and to inventory a representative sample of the joints for assessment of joint attributes.

If the survey line is parallel with the trend of a dominant joint set, the method is subject to potential under-sampling and data bias.

The procedure for the fixed-line survey is as follows:

(i) The rock outcrop in the area of interest must be well exposed, clean, and accessible for measurement and study. Cleaning can be accomplished using power equipment, hand tools, or pressurized air or water.

(ii) To determine the average spacing of a persistent systematic, high-angle joint set, orient a measuring tape perpendicular to the trend of the joint set. The length of the survey line depends on the spacing of the joints and the amount of outcrop available for measurement. As a rule of thumb, 10 meters or 10 joints, whichever is greater, is the recommended length of the survey line. Widely spaced joints require a longer line to obtain a meaningful average. In some instances, outcrop limitations necessitate shorter lines. Determine the spacing for each persistent joint set. To measure the number of bedding plane partings or sheeting joints on steep outcrops, place a weighted tape or telescoping range pole against the face. Where the vertical component is not exposed, estimate the spacings using test hole logs or core samples in the spillway near the survey line.

(iii) For complex structural domains with abundant unique fractures, establish three mutually perpendicular axes for survey lines—one axis parallel with the spillway flow direction and another perpendicular to the flow. The third axis, the vertical component, is described in the previous paragraph. The discrete rock particle mean diameter is determined by taking the cube root of the product of the average joint set spacings in the three surveyed directions.

(iv) To improve the determination of the average joint set spacing in a given dimension, survey more than one line. For example, use three parallel survey lines 5 meters apart and average the results. The number of lines needed is a function of the size and geologic complexity of the site.

Documentation
Show the location of each line on a geologic evaluation map and record its orientation, elevation, and ground coordinates or stationing on the Discontinuity Data Sheets (Appendix F).

The attributes of all structural discontinuities that intersect the fixed lines are then measured according to procedures described in this chapter and recorded on the Discontinuity Data Sheets (Appendix F).

The fixed area survey

A fixed area survey is an inventory of all structural discontinuities of specified area and shape. The fixed area survey is a detailed assessment of structural discontinuities at a project site.

The specified area may include: the entire auxiliary spillway; selected reaches between the control section and the outlet of the exit channel; or offsite areas that are considered germane to the study objectives. The shape of the survey area is usually square or rectangular; however, in some instances, a circular or rhomboidal shape may be useful.

The procedure for the fixed area survey is as follows:

(i) The rock outcrop in the area of interest must be well exposed, clean, and accessible for measurement and study. Cleaning can be accomplished using power equipment, hand tools, or pressurized air or water.
(ii) For mapping large areas or areas with a high density of fractures, subdivide the study area into manageable sub-areas. For square or rectangular areas, the sub-areas can be quarters, ninths, sixteenths, twenty-fifths, etc., of the total area. These sub-areas must be labeled appropriately.
(iii) To avoid measuring the same joint or feature twice, it is helpful to trace out with chalk the full length of each joint after it is measured.

Documentation
The attributes of all structural discontinuities within the survey area are evaluated according to procedures described in this course and recorded on the Discontinuity Data Sheets (Appendix F).

Show the location of each feature on the geologic evaluation map, sketch, or on the corresponding sub-area map.

Appendix C: Joint Orientation Diagrams

Joint orientation diagrams

Joint orientation diagrams are useful statistical tools in the analysis of orientation data of joints, faults, and unique fractures. Preferred orientations can often be determined from data collected in complex structural domains.

Structural orientation data can be summarized in pole diagrams, pole-density diagrams, rose diagrams, and strike histograms.

Joint analysis

The analysis of joint data consists of standard and well known procedures in geological mapping. The information presented below is an overview of joint orientation diagrams.

Three-dimensional plots

Pole diagrams are spherical projections (stereographic displays) of three-dimensional, strike, and dip data. Two types of stereographic diagrams are displayed in figures C–1 and C–2. The Wulff net is an equal-angle projection in which the angular relationships between features are accurately represented (Wulff 1902). The Schmidt net (Lambert projection) (Sander and Schmidegg 1926; Lambert 1772) is an equal-area projection in which the spatial distribution of data is accurately represented.

The Schmidt net is the preferred stereographic projection for joint analysis; the Wulff net is not recommended because it has a built-in bias that invalidates the statistical distribution of plotted points.

All joint pole data are plotted onto a Schmidt net to distinguish joint set patterns. Contouring the values of the density of the poles (the concentration or number of points per unit area) on the resulting scatter diagram provides a measure of the degree of preferred orientation of structures in complex rock masses.

Where three-dimensional control on the attitude of the joints cannot be attained, either due to the nature of the surfaces of the outcrop or due to the collection of joint orientations from aerial photos, the orientation data can be plotted on two-dimensional plots, such as rose diagrams or strike histograms. In preparing rose diagrams and strike histograms, the trend or strike data are first organized into intervals of 5 or 10 degrees, encompassing the orientation range from west through north to east. The number (or percentage) of readings within each interval is summed. Data can then be plotted as either a rose diagram or a strike histogram.

Rose diagrams

The number (or percentage) of joints that occur in each 5° (or 10°) interval is plotted in a family of concentric circles radiating outward from a common point. The data can also be plotted on the north side of a semicircle with similar graphic effect.

Strike histograms (frequency diagrams)

The intervals are plotted along the y-axis, and the number (or percentage) of joints occurring within each 5° (or 10°) interval is plotted on the x-axis of an x-y plot. The advantage of two-dimensional plots is that dominant or preferred joint set orientations can be readily recognized at the high-frequency peaks. The disadvantage is that a given peak can mask two sets of joints of distinctly different inclination and/or dip direction.

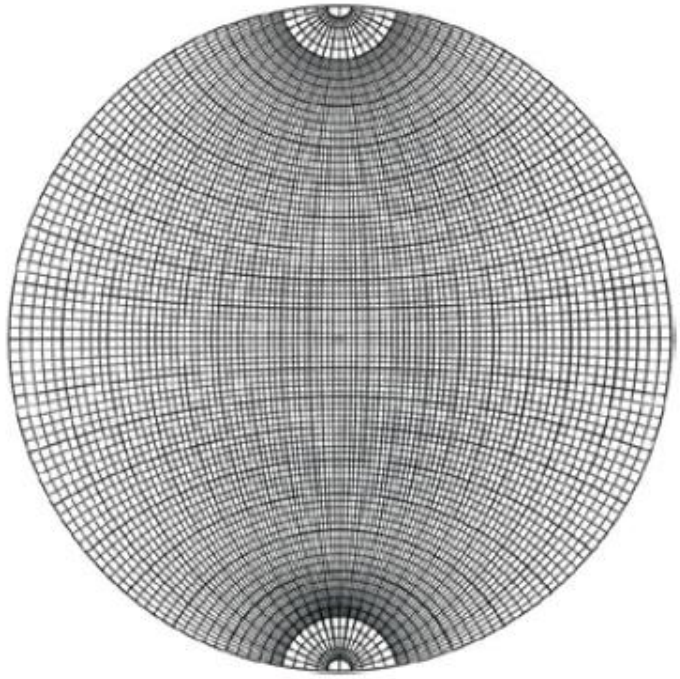

Figure C- 1. Wulff net, an equal-angle projection

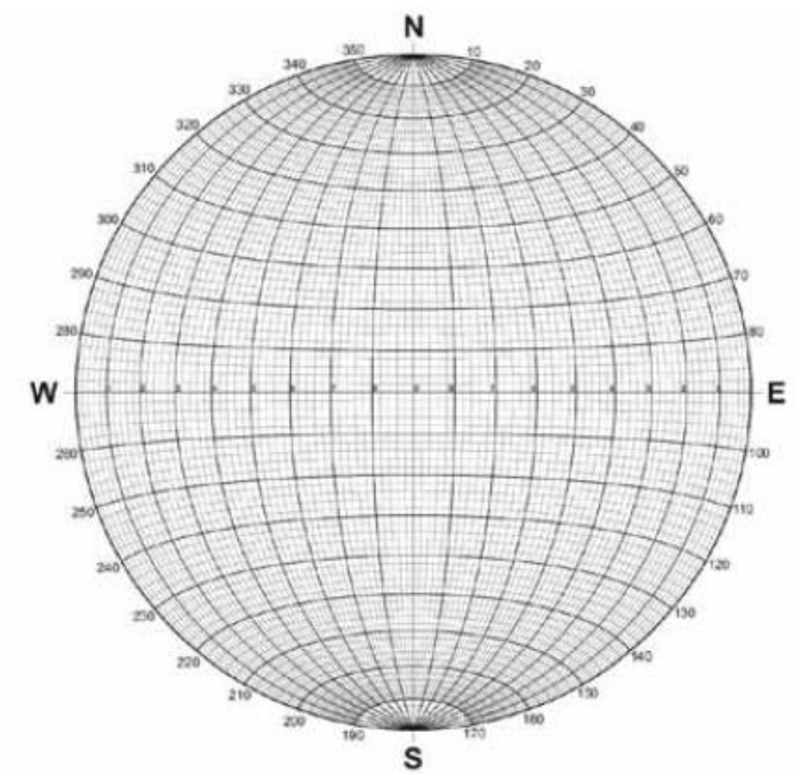

Figure C- 2. Schmidt net (Lambert projection), an equal-area projection

Appendix D: Rock Description Data Sheets

Sheet 1 of 3

(See also NEH628.52C, data sheets for headcut erodibility index)
(Use one set of sheets for each material) Set ____ of ____

General Information

Watershed name: ____________________________________ Site number: ________ State: ______ Investigator: ______________________________ Title: _____________________ Date: _________

Type of investigation: Intensity of investigation:

Reconnaissance __________ Subjective survey _________ Detailed/design ______
Preliminary ______________ Objective survey __________
As-built/construction ______ Photograph numbers: _________________________
Spillway performance __________

Earth Material (Soil/Rock) Unit Identification

Formal rock type name or alphanumeric designation: ____
Soil group name (ASTM D2488): ____________________________ Unified classification symbol: _____
Location (show on geol. map/sketch): Station ________ Offset (lt) _____ Offset (rt) _____ Elevation ____
Locality type (check one): Natural exposure_______ Channel side slope ______ Channel floor _____

Earth Material Properties

Table D- 1. Color (choose from up to three columns for selected condition below).

Color			
Condition	Fresh:_____	Dry:_____	_______
	Fresh:_____	Wet:_____	_______
	Altered:____	Dry:_____	_______
	Altered:____	Wet:_____	_______
1st descriptor		2nd descriptor	3rd descriptor
light dark very dark		yellowish buff orangish brownish pinkish reddish bluish purplish orange olive greenish greyish	white yellow buff orange brown pink red blue green purple olive grey black

Other notes: ________________________________

____

____

____

Table D- 2. Grain size (for sedimentary and pyroclastic rocks, check one below).

Descriptor	**Grain size (mm/ sieve size)**
Very coarse	> 75 mm/ 3 in. (cobble-size+)
Coarse	4.75–75 mm/ #4–3 in (gravel-size)
Medium	0.075–4.75 mm/ #200–#4 (sand-size)
Fine	0.005–0.075 mm (silt-size)
Very fine	< 0.005 mm (clay-size)

Table D- 3. Texture (for igneous and crystalline metamorphic rocks), check one below:

Descriptor	**Description of texture**
Aphanitic	Components cannot be seen with naked eye
Crystalline	Composed of interlocking crystals
Glassy	Vitreous; without crystallization
Pegmatitic	Very coarsely crystalline (> 10 mm diameter)
Porphyritic	Large crystals set in fine-grained ground mass

Table D- 4. Secondary cavities

Secondary cavities	**Description**
Pitted (1–10 mm)	Small openings, 1–10 mm
Vuggy (11–100 mm)	Openings often lined with crystals
Cavitied (> 100 mm)	Openings > 100 mm
Honeycombed	Only thin walls separate pits or vugs
Vesicular	Small openings in volcanic rocks of variable shape formed by entrapped gas bubbles during solidification

Table D- 5. Rock type classification

Sheet 2 of 3

Genetic group	Predominant grain size, mm (sieve no.)	Detrital sedimentary				Chemical organic	Metamorphic		Pyroclastic	Igneous			
Usual structure		Bedded				Bedded	Foliated	Massive	Bedded	Massive			
Composition			Grains of rock, quartz, feldspar, and clay minerals		At least 50% of grains are of carbonate	Salts, carbonates, silica, carbonaceous	Quartz, feldspars, micas, dark minerals	Quartz, feldspars, micas, dark minerals, carbonates	At least 50% of grains are of igneous rock	Quartz, feldspars, micas, dark minerals: Acid	Quartz, feldspars, micas, dark minerals: Intermediate	Feldspar; dark minerals: Basic	Dark minerals: Ultrabasic
Very coarse-grained	75 (3")	Rudaceous	Grains are of rock fragments			CLINKER SALINE ROCKS Halite Anhydrite Gypsum	TECTONIC BRECCIA MIGMATITE	METACON-GLOMERATE	Rounded grains: AGGLOMERATE	PEGMATITE			
Coarse-grained	4.75 (4)	Rudaceous	Rounded grains: **CONGLOMERATE** Angular grains: BRECCIA		CALCIRUDITE		GNEISS	MARBLE GRANULITE	Angular grains: VOLCANIC BRECCIA	GRANITE	DIORITE GRANODIORITE	GABBRO	PYROX-ENITE
Medium-grained	0.074 (200)	Arenaceous	Grains are mainly mineral fragments SANDSTONE ARKOSE GRAYWACKE (Argillaceous ss)		CALCARENITE	CALCAREOUS ROCKS	SCHIST	QUARTZITE	TUFF	SYENITE	ANORTHOSITE	DIABASE	PERIDO-TITE
Fine-grained	0.005						Amphibolite			APLITE	MONZONITE		
Very fine-grained		Argillaceous or Lutaceous	MUDSTONE SHALE: fissile mudstone	SILTSTONE>50% fine-grained particles CLAYSTONE>50% very fine grained particles MARLSTONE	LIMESTONE (undifferentiated) CALCISILTITE CHALK CALCILUTITE	LIMESTONE DOLOMITE	PHYLLITE SLATE Mylonite	HORNFELS	Fine-grained TUFF Very fine-grained TUFF	RHYOLITE or FELSITE	Dacite ANDESITE	BASALT	DUNITE NEPHELINE-BASALT
Glassy amor-phous						SILICEOUS ROCKS Chert Flint CARBONACEOUS ROCKS LIGNITE/COAL	Ultramylonite		Welded TUFF PUMICE	VOLCANIC GLASSES OBSIDIAN	PITCHSTONE	TACHYLYTE	

Sheet 3 of 3

Table D- 6. Hardness and unconfined compressive strength

Hardness category	Typical range in unconfined compressive strength (MPa)	Strength value selected (MPa)	Field test on sample	Field test on outcrop
Soil*	< 0.60	———	Use USCS classifications	
Very soft rock or hard, soil-like material	0.60–1.25	———	Scratched with fingernail. Slight indentation by light blow of point of geologic pick. Requires power tools for excavation. Peels with pocket knife.	
Soft rock	1.25–5.0	———	Permits denting by moderate pressure of the fingers. Handheld specimen crumbles under firm blows with point of geologic pick.	Easily deformable with finger pressure.
Moderately soft rock	5.0–12.5	———	Shallow indentations (1–3 mm) by firm blows with point of geologic pick. Peels with difficulty with pocket knife. Resists denting by the fingers, but can be abraded and pierced to a shallow depth by a pencil point. Crumbles by rubbing with fingers.	Crumbles by rubbing with fingers.
Moderately hard rock	12.5–50	———	Cannot be scraped or peeled with pocket knife. Intact handheld specimen breaks with single blow of geologic hammer. Can be distinctly scratched with 20d common steel nail. Resists a pencil point, but can be scratched and cut with a knife blade.	Unfractured outcrop crumbles under light hammer blows.
Hard rock	50–100	———	Handheld specimen requires more than one hammer blow to break it. Can be faintly scratched with 20d common steel nail. Resistant to abrasion or cutting by a knife blade but can be easily dented or broken by light blows of a hammer.	Outcrop withstands a few firm blows before breaking.
Very hard rock	100–250	———	Specimen breaks only by repeated, heavy blows with geologic hammer. Cannot be scratched with 20d common steel nail.	Outcrop withstands a few heavy ringing hammer blows but will yield large fragments.
Extremely hard rock	> 250	———	Specimen can only be chipped, not broken by repeated, heavy blows of geologic hammer.	Outcrop resists heavy ringing hammer blows and yields, with difficulty, only dust and small fragments.

Method used to determine consistency or hardness (check one):
Field assessment: _____ Uniaxial lab test: _____ Other: __________ Rebound hammer (ASTM D5873): _____

* See NEH631.03 for consistency and density of soil materials.

Appendix E: Line Survey Data Sheet

Sheet 1 of 2

Rock Mass Properties

Line survey to determine average spacing of joint sets

(i) Plot location of surveyed lines on a geologic evaluation map or sketch.

(ii) Notes: For systematic joint sets:

- Lines 1 and 2 are for the two most persistent, high-angle, intersecting joints.
- Line 3 is for bedding plane partings or sheeting joints (the vertical axis).

(iii) Notes: For apparently random fractures:

- Line 1 is perpendicular to spillway flow direction.
- Line 2 is parallel to spillway flow direction.
- Line 3 is for bedding plane partings or sheeting joints (the vertical axis).

Spacing Categories (for column f):

Table E- 1. Line survey data

Survey line	**a**	**b**	**c**	**d**	**e**	**f**
(axis)	**Plunge of Line**	**Trend (Azim)**	**Line Length (meters)**	**No. of Joints**	**Average Spacing d/c**	**Spacing Category**
Line 1 (x)						
Line 2 (y)						
Line 3 (z)						

Table E- 2. Joint set spacing categories

Spacing descriptors		**Spacing (meters)**	**Category**
Bedding plane partings	**Joint sets**		
Massive/unstratified	Extremely wide	> 6.000	**1**
Very thick-bedded	Very wide	2.000–6.000	**2**
Thick-bedded	Wide	0.600–2.000	**3**
Medium bedded	Moderately wide	0.200–0.600	**4**
Thin-bedded	Moderately close	0.060–0.200	**5**
Very thin-bedded	Close	0.020–0.060	**6**
Laminated	Very close	0.006–0.020	**7**
Thinly laminated	Shattered	0.002–0.006	**8**
Fissile	Fissured	< 0.002	**9**

Discrete rock particle mean diameter (use values in table E–1, column e):

$$\sqrt[3]{e_x\, e_y\, e_z} = \_\_\_\_\_\_ \text{ meters}$$

Other observations/notes on rock mass properties:

____

____

____

Sheet 2 of 2

Table E- 3. Sketch map of auxiliary spillway

Spillway flow direction

- On both circles, plot azimuths of spillway flow direction using an arrow.
- On left circle, plot strike and dip of rock.
- On right circle, plot trends and plunges of major joint sets.
- Indicate approximate location of dam (i.e., left side or right side).

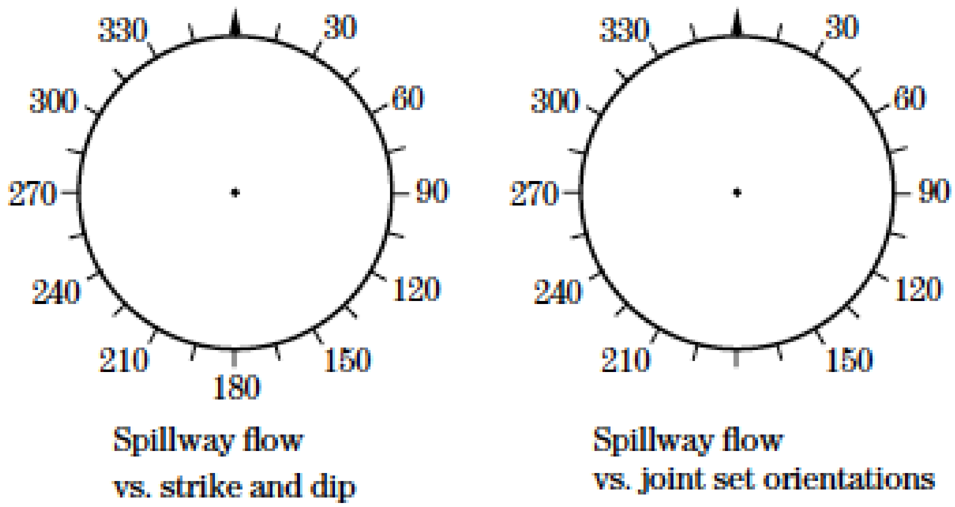

Figure E- 1. Plotted azimuth of spillway flow direction

Appendix F: Discontinuity Survey Data Sheets

Notes: Sheet 1 of 2

1. Assign each discontinuity an ID number and show location on geologic evaluation map or sketch.
2. Use codes numbers from the following tables and enter data on the form at the bottom of this sheet and on Sheet 2 of 2.
3. Use code from table D–6, Rock Description Data Sheets for classifying compressive strength of infilling.
4. Classify infilling according to ASTM D2488 (UNRCS), record soil symbols on data sheet.

Table F- 1. Discontinuity category

Discontinuity category	Code
Stratigraphic	
Lithosome	
Blanket	1
Tongue	2
Shoestring	3
Lens	4
Slump feature	5
Unconformity	6
Structural	
Plastic deformation	
Folded rock	7
Foliation	
schistosity	8
gneissosity	9
Banded rock	10
Fracture deformation	
Random fracture	11
Systematic joint set	12
Bedding plane parting	
Uniformly bedded	13
Cross-bedded	14
Rhythmic bedding	15
Interfingered	16
Graded bedding	17
Current bedding	18
Sheeting joint	19
Slaty cleavage	20
Fault	21
Other (put in notes)	22

Table F- 2. Joint persistence category

Joint persistence category	Trace length (meters)	Code
Very low	<1	1
Low	1-3	2
Medium	3-10	3
High	10-20	4
Very high	>20	5

Table F- 3. Joint end category

Joint end category	End 1	End 2
Joint end extends beyond the exposure area	x b	x b
Joint end terminates in solid rock inside exposure area	t r	t r
Joint end terminates against another joint	t j	t j

Table F- 4. Aperture category

Aperture category	Width range (mm)	Code
Wide	> 200	1
Moderately wide	60-200	2
Moderately narrow	20-60	3
Narrow	6-20	4
Very narrow	2-6	5
Extremely narrow (hairline)	> 0-2	6

Table F- 5. Nature of joint infilling

Nature of joint infilling	Code
Clean, open joint; no infilling present	1
Non-plastic silt (PI >10), sand, or gravel; with or without crushed rock	2
Inactive clay or clay matrix; with or without crushed rock	3
Swelling clay or clay matrix; with or without crushed rock	4
Chlorite; talc; mica; serpentine; other sheet silicate; graphite; gypsum. Specify type in notes	5

Table F- 6. Weathering condition of joints

Descriptor	Weathering Condition of Joint Face Rock Material	Code
Fresh	No sign of weathering.	1
Discolored	Iron-stained or discolored, but otherwise un-weathered.	2
Disintegrated	Physically disintegrated to a soil condition with original fabric still intact. Material is friable and mineral grains are not decomposed.	3
Decomposed	Chemically altered to a soil condition with original fabric still intact. Some or all mineral grains are decomposed.	4

Sheet 3 of 3

Table F- 7. Work sheet for discontinuities

	F-1	**Discontinuity Measurement**				**F-2**	**F-3**		**F-4**	**F-5**	**Table 3**	**D2488**	**F-6**
Discon. ID No.	**Discon. Type Code**	**Trend (Azim)**	**Dip** (°)	**Dip Direction (Azim)**	**Joint Persist. (m)**	**Joint Persist. Code**	**End 1 Code**	**End 2 Code**	**Aper. width Code**	**Nature Infill. Code**	**Strength Infill. Code**	**Infill. Classif. (USCS)**	**Joint Wea. Code**
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													
11													
12													
13													
14													
15													

Other notes:

Appendix G: Material Strength Number

Table G- 1. Material strength number, M_S, for cohesionless soil

Relative density	Field identification tests	SPT[2,5] (blows/0.3m)[4,5]	In situ deformation modulus (IDM) (MPa)[5]	M_s[3]
Very loose	Particles loosely packed. High percentage of voids. Very easily dislodged by hand. Matrix crumbles easily when scraped with point of geologic pick. Raveling often occurs on excavated faces.	< 5	< 0.005	< 0.02
Loose	Particles loosely packed. Some resistance to being dislodged by hand. Large number of voids. Matrix shows low resistance to penetration by point of geologic pick.	5 - 10	0.005 - 0.01	0.02 - 0.05
Medium dense	Particles closely packed. Difficult to dislodge individual particles by hand. Voids less apparent. Matrix has considerable resistance to penetration by point of geologic pick.	10 - 30	0.01 - 0.03	0.05 - 0.10
Dense	Particles very closely packed and occasionally very weakly cemented. Cannot dislodge individual particles by hand. The mass has very high resistance to penetration by point of geologic pick. Requires many blows of geologic pick to dislodge particles.	30 - 50	0.03 - 0.08	0.10 - 0.20
Very dense	Particles very densely packed and usually cemented together. Mass has high resistance to repeated blows of geologic pick. Requires power tools for excavation.	> 50	0.08 - 0.2	0.20 - 0.45

Notes:

1. Cohesionless soil is a material with a plasticity index (PI) less than or equal to 10. Use table B-2 for cohesive soils.
2. Standard Penetration Test, SPT (ASTM D 1586) used for most sandy-type cohesionless soils. In situ deformation modulus (IDM) (ASTM D 1194) used for most gravel-type soils and coarse detritus.
3. M_s of a cohesionless soil is approximately determined from results of IDM testing by the following relationship:
   $$M_s = 1.7\ (IDM)^{0.832} \text{ for IDM in MPa}$$
4. Cohesionless soils in which blow counts are greater than 50 or IDM is greater than 200 kPa to be taken as rock, for which the hardness may be obtained from table B-3.
5. Correlation between SPT and IDM should be used as a guide only as results may vary in different geologic areas. Lab strength tests are recommended on soil materials to support SPT or field assessment tests.

Table G- 2. Material strength number, M_S, for cohesive soil

Consistency	**Field identification tests**	**SPT (blows/0.3 m)**	**Unconfined compressive strength (UCS) (kPa)**	**M_s**
Very soft	Exudes between fingers when squeezed in hand.	< 2	< 40	< 0.02
Soft	Easily molded with fingers. Point of geologic pick easily pushed into shaft of handle.	2 - 4	40 - 80	0.02 - 0.05
Firm	Penetrated several centimeters by thumb with moderate pressure. Molded by fingers with some pressure.	4 - 8	80 - 150	0.05 - 0.10
Stiff	Indented by thumb with great effort. Point of geologic pick can be pushed in up to 1 centimeter. Very difficult to mold with fingers. Just penetrated with hand spade.	8 - 15	150 - 300	0.10 - 0.20
Very stiff	Indented only by thumbnail. Slight indentation by pushing point of geologic pick. Requires hand pick for excavation.	15 - 30	300 - 625	0.20 - 0.45

Notes:

1. Cohesive soil is material with a plasticity index (PI) greater than 10. Use table B-1 for cohesionless soils.
2. 1 kPa equals 1 kN/m^2.
3. Vane shear strength (ASTM D 2573, field; ASTM D 4648, lab) also may be used for unconfined compressive strength (ASTM D 2166).
4. Cohesive soils in which blow counts are greater than 30 or strengths greater than 625 kPa are to be taken as rock, for which the hardness can be obtained from table B-3.
5. Cohesive soils must be evaluated for hardness in the saturated condition.
6. M_s of a cohesive soil also can be determined as the product of unconfined compressive strength (in MPa) times its coefficient of relative density. For most cohesive soils, M_s is approximately determined by:
   $$M_s = 0.78\ (UCS)^{1.09} \text{ for } UCS \leq 10 \text{ MPa, and } M_s = UCS \text{ for } UCS > 10 \text{ MPa}$$
7. Correlation between SPT and UCS should only be used as a guide, as results may vary in geologic areas. Lab strength tests are recommended on soil materials to support SPT or field assessment tests. Vane shear strength values also are applicable in the lower strength ranges.

Table G- 3. Material strength number, M_S, for rock

Rock material hardness[1]	**Uniaxial compressive strength (MPa)**[2]	**Field identification tests**	M_s[3]
Very soft rock or Hard, soil- like material	0.6 - 1.25	Scratched with fingernail. Slight indentation produced by light blow of point of geologic pick. Requires power tools for excavation. Peels with pocket knife.	0.45 - 1.0
Soft rock	1.25 - 5.0	Hand-held specimen crumbles under firm blows with point of geologic pick.	1.0 - 4.5
Moderately soft rock	5.0 - 12.5	Shallow indentations (1 to 3 mm) produced by light blows with point of geologic pick. Peels with pocket knife with difficulty.	4.5 - 12.5
Moderately hard rock	12.5 - 50.0	Cannot be scraped or peeled with pocket knife. Intact hand-held specimen breaks with single blow of geologic hammer. Can be distinctly scratched with 20d common steel nail.	12.5 - 50
Hard rock	50.0 - 100.0	Intact hand-held specimen requires more than one hammer blow to break it. Can be faintly scratched with 20d common steel nail.	50 - 100
Very hard rock	100.0 - 250.0	Intact specimen breaks only by repeated, heavy blows with geologic hammer. Cannot be scratched with 20d common steel nail.	100 - 250
Extremely hard rock	> 250.0	Intact specimen can only be chipped, not broken, by repeated, heavy blows of geologic hammer.	> 250

Notes:

1. Hardness categories are based solely on hardness characteristics, not geologic origin. For example, a highly weathered shale may classify as firm cohesive soil, and a partially lithified recent soil may classify as moderately soft rock. The transition, however, generally occurs within the 0.60 to 1.25 MPa range.
2. 1.0 MPa approximately equals 145 pounds per square inch, or 10.4 tons per square foot.
3. M_s is equal to the product of uniaxial compressive strength, UCS (ASTM D 2938), and coefficient of relative density. For most rock or rocklike materials, M_s is approximately determined by:

$$M_s = 0.78\,(UCS)^{1.09} \text{ for UCS} \leq 10 \text{ MPa, and } M_s = UCS \text{ for UCS} > 10 \text{ MPa}$$