Engineering Geological Characterization of Brittle Faults and Classification of Fault Rocks

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Most serious geotechnical problems related to rock engineering are generated by brittle faults. Despite the tremendous importance of faults in engineering practice only a little is known about the engineering properties of faults and their engineering geological characterization and identification. The objective of this paper is to discuss aspects of the characterization and investigation of brittle faults and to present a diagnostic engineering geological classification of fault rocks.

Among the numerous attempts by structural geologists to define narrow zones of concentrated, high shear deformation, there is general agreement on the distinction between brittle faults and ductile shear zones according to the physical conditions in which the deformation occurred.

Ductile shear zones are generated in deeper parts of the crust, where metamorphic conditions exist (1) which may or may not change the mechanical properties of the affected rocks. In ductile shearing the material integrity is not lost during deformation. Main deformation mechanisms are crystal plasticity, dynamic recrystallization, solution mass transfer, dislocation creep, diffusion creep and grain boundary sliding.

Faults are common features of the upper crust. They are complex structures resulting mainly from brittle fracturing deformation. Consequently, faults have the highest impact on the rock mass properties. Faults may range from decimetres to hundreds of kilometres in trace length, either continuous as well as discontinuously. The predominant small-scale deformation mechanisms of brittle faults are mechanical damage processes such as micro-cracking, fragmentation, grinding with rigid-body rotation and frictional wear. These processes result in grain size reduction, dilatancy and a dramatical drop in strength as compared to the source rock (“protolith”). Low-temperature solution transfer contributes to the alteration of brittle faulted rocks through transformation and neoformation of clay minerals (2, 3, 4) or other secondary minerals (carbonates, oxides). As a result cohesionless “soil-like” or cemented cataclastic rocks develop, such as gouge, cataclasite, breccia and pseudotachylite (5).

Typical features of brittle faults

Brittle faults are geotechnically problematic because of their complex structure and the tectonically disturbed weak rocks associated with them (6, 7). Typically, a pattern of shear and tensile fractures occur in a brittle fault, reflecting the geometry of the displacement field during faulting, and indicating the orientation of principal stresses. Kinematic indicators such as slickensides (striations) may be evidence of the latest relative movements.

Ingenieurgeologische Charakterisierung spröder Störungszonen und Klassifizierung von Störungsgesteinen

Spröde Störungszonen haben eine außerordentliche Bedeutung im Felsbau. Die geotechnischen Probleme im Zusammenhang mit Störungen sind die enorme Heterogenität in bezug auf ihre interne Struktur, den raschen Wechsel von Gesteinen mit geringer und hoher Festigkeit und die Grundwasserverhältnisse. Die extreme Komplexität von spröden Störungen erschwert ihre geotechnische Charakterisierung und Erkundung. Die Wichtigkeit, bei der ingenieurgeologischen Analyse von Störungsgesteinen geometrische und geomechanische Merkmale zu analysieren, die spezifisch sind für „Block-in-Matrix“ Gesteine, wird hervorgehoben. Basierend auf Erfahrungen aus der Erkundung und dem Bau von Felsbauwerken, wie Talsperren, Felsböschungen und Tunneln, sowie unter Berücksichtigung neuerer Forschungsergebnisse, wird eine funktionelle, diagnostische Klassifizierung von Störungsgesteinen vorgestellt.

Brittle faults are extraordinarily important in rock engineering. The geotechnical problems related to faults include their substantial heterogeneity with regard to internal structure, abrupt variations in weak and strong rocks components, and groundwater. The extreme complexity of brittle faults makes their geotechnical characterization and investigation difficult. The importance of evaluating specific geometrical and geomechanical features of “block-in-matrix“ rocks for the engineering geological characterisation of fault zones is emphasised. A functional, diagnostic classification of fault rocks is introduced, based on experience from investigation and construction of rock structures such as dams, slopes and tunnels, and consideration of the results of recent research.

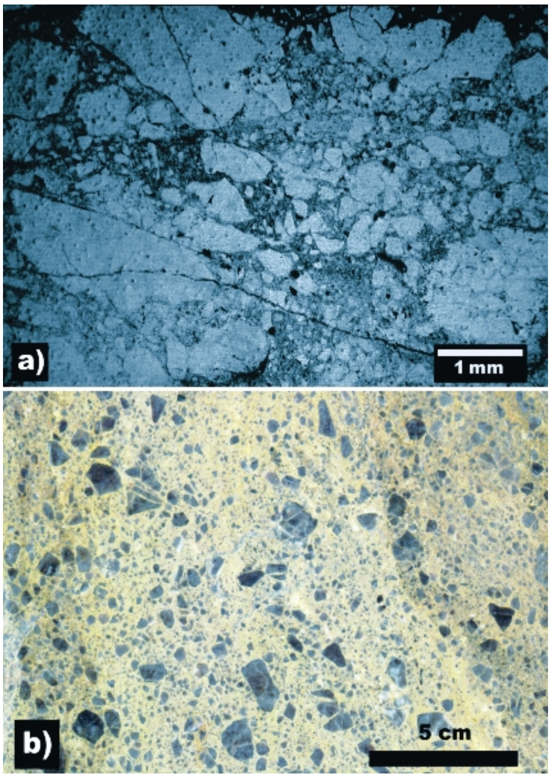

Fig. 1 Blocks embedded in matrix (random distribution of blocks varying in size and orientation); a) microscale (thin section); b) mesoscale (polished surface).

Bild 1 *Blöcke mit unterschiedlicher Größe und Orientierung in Matrix eingebettet (Zufallsverteilung); a) mikroskopischer Maßstab (Dünnschliff); b) mesoskopischer Maßstab (polierte Gesteinsoberfläche).*

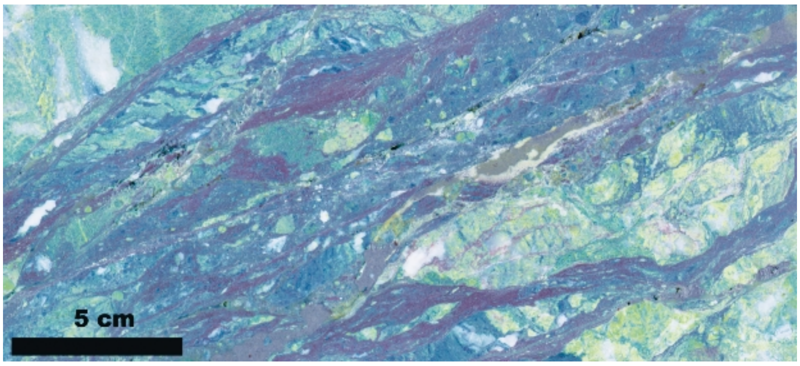

Fig. 2 Lenticular shaped blocks embedded in matrix (anastomosing pattern, significantly anisotropic); mesoscale.

Bild 2 *Linsenförmige Blöcke in Matrix (anastomisierend, anisotrop), mesoskopischer Maßstab.*

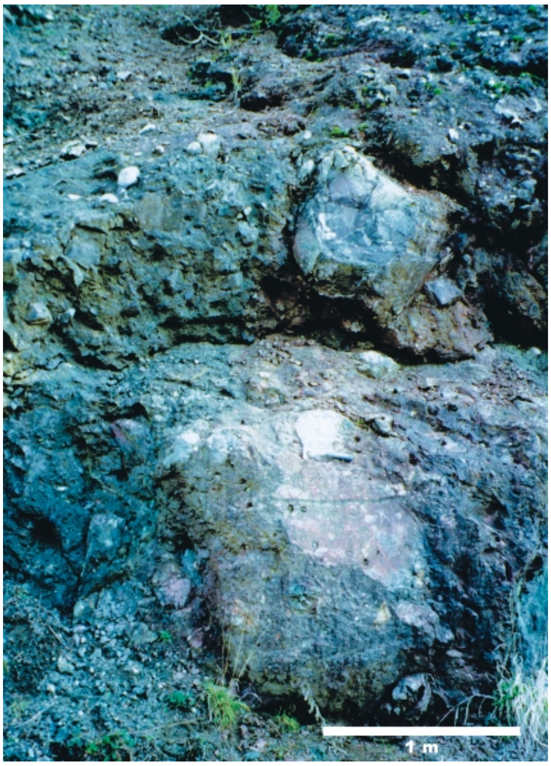

Fig. 3 Randomly distributed serpentinite blocks in an ophiolitic tectonic melange (NW-Greece); macroscale.

Bild 3 *Serpentinitblöcke in ophiolitischer tektonischer Melange; NW-Griechenland; (Zufallsverteilung; makroskopischer Maßstab).*

Fault zones typically exhibit substantial heterogeneity, consisting of randomly occurring units of more or less undeformed, unaltered stiff rock fragments which are surrounded by a mainly soft, weak matrix. Occasionally, the matrix may be cemented by secondary formed minerals, which results in a considerable hardening of the fault rocks.

There is an abundance of geological names for the fragmented fabric of fault zones (gouge, breccia, tectonic chaos, etc.), as well as for the individual hard components (such as horses, knockers, clasts, tectonic inclusions, etc.). These hard fragments are simply termed blocks in this paper. The mainly lenticular shaped blocks embedded in the matrix of fault zones, show a generally fractal distribution of dimensions, ranging from the microscale to hundreds of metres in length (8, 9, 10, 11). The matrix typically consists of highly sheared fine-grained clayey, silty gouge and intensely fractured, brecciated rocks (Figures 1, 2, 3 and 4). The matrix often appears to flow around the blocks in an anastomosing pattern. The ratio of weak gouge matrix to rock blocks of different sizes, shapes and strengths is extremely variable. The distinction between fragments and matrix is basically a matter of the scale of observation and engineering interest. Medley (11) has introduced the term “bimrocks” (“block-in-matrix”-rocks) to avoid the confusingly rich and complex geological terminology related to mixed and fragmented rocks.

Another factor subject to substantial variation in fault zones is groundwater. Groundwater elevation plus pressure head, where confined, as well as flow direction may be very heterogeneous within faults and may naturally destabilise the ground and thus demand suitable drainage and support measures. It is important to understand that a fault may act as both an aquifer and an aquiclude (6, 12).

Investigation

To successfully cope with severe geotechnical problems, which usually are encountered by construction work in a fault zone, a realistic three dimensional geological model based on a geotechnically relevant investigation and characterization of the fault zone has to be established. A sound geotechnical assessment of faults, followed by three dimensional modelling, has to continue through all design stages from feasibility, preliminary, detail and final design to construction.

Brittle faults are often concealed under considerable thicknesses of overburden, and their presence must be inferred indirectly from field evidence. Surface features helping to locate and trace brittle faults are linear depressions associated with seeps or swamps, landslides, creeping areas, or scarped linear relief features (Figure 5).

The typical morphological features which indicate faults can be evaluated prior to any geological field work by the study of satellite images and aerial photographs. Examination of stereo pairs of aerial photographs allows a three-dimensional analysis of fault structures. This results, for example, in the differentiation of low angle thrusts and high angle faults. Occasionally offsets may be observed by imagery analysis. A useful technique in detecting faults and related discontinuity structures is remote sensing such as infrared scanning and airborne radar. A combined morphostructural analysis, based on airborne radar and digital elevation models was successfully performed recently to evaluate Quaternary transfer faulting in Taiwan (13).

Rock exposures may provide important indications such as fault slip data, concentrations of major joints and severe fracturing. As a consequence of the scale independence of most fault structures even small-scale features in outcrops reflect the architecture and significant characteristics of a concealed larger fault.

An important engineering geological undertaking is to estimate whether a fault is tectonically active or not. A fault is commonly considered to be active if fault displacements are verified within the Holocene or Pleistocene period. Geologic field evidence for the recognition of fault activity is provided by stratigraphical and morphological analyses (6).

Detailed structural geologic field investigation on certain fault-related kinematic indicators (e.g. slickenplanes and striae) are the precondition for paleostress analyses which make it possible to reconstruct the deformation history of the project area. Based on such analyses extensional and compressional regions can be distinguished. Such differentiation may have geotechnical implications. For example, in extensional regions, which are characterised by normal or oblique-slip extension faults, an open-jointed rock mass or joints healed by secondary minerals may prevail at depth. The initial stress situation may be characterized by lack of confining pressure, whereas in compressional regions, indicated by thrusting, reverse faults, strike-slip faults and oblique-slip contraction faults, a high confining pressure may exist.

In order to obtain reliable information on the geometry and mechanical properties of faults, we also need subsurface investigations which include trenches, core drilling and geophysical surveys.

Exploring brittle fault zones by means of core drilling is a very exacting job and requires an experienced geologist, a particularly skilled drilling crew, and high-quality drilling equipment. Both equipment and drilling technique must be selected to suit the particular ground conditions of the fault zone. Washing out of fine-grained gouge and disturbance of the shear structures must be avoided. A common example of poor practice in the drilling of "block-in-matrix"-rocks is alternately dry and flush drilling.

Better results have been obtained by drilling in faults continuously with double or triple tube core barrels and using a polymer as a flushing agent which avoids the disintegration of the drill core and promotes drill hole stability by the formation of a transparent filter skin on the bore hole wall.

Core logging by the engineering geologist should in particular record the proportion of fine-grained gouge matrix and blocks, the degree of alteration and fracturing, as well as the surface properties of discontinuities and their inclination to the borehole axis. A kinematic structural analysis has been recently developed which is performed on selected drill cores (14, 15). This is a combined analysis by means of the Acoustic Borehole Televiewer, a visual inspection of the drill cores and a computerised evaluation of the detected distinctive features (surface characteristics and geometric pattern of discontinuities). Together with surface outcrop data the results facilitate the differentiation of structural domains along the borehole axis and the

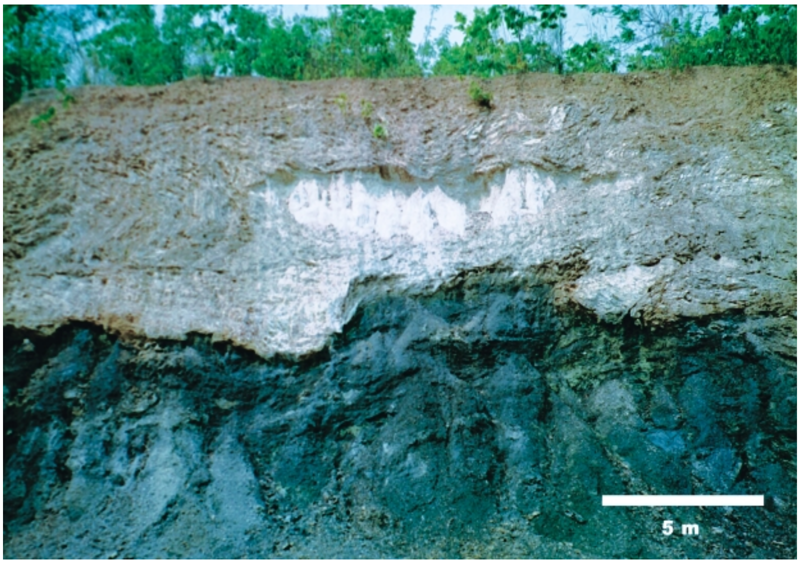

Fig. 4 Lenticular blocks embedded in matrix which shows ductile and brittle deformation features (N-Thailand); macroscale.

Bild 4 *Linsenförmige Blöcke in Matrix mit duktilen und spröden Charakteristika (Nordthailand); makroskopischer Maßstab.*

Fig. 5 Fault escarpment, indicated by steep clear-cut slope (North Eastern Anatolian Fault, Turkey).

Bild 5 *Störungsverlauf markiert durch steile, ebenflächige Hangmorphologie (Nordostanatolische Störung, Türkei).*

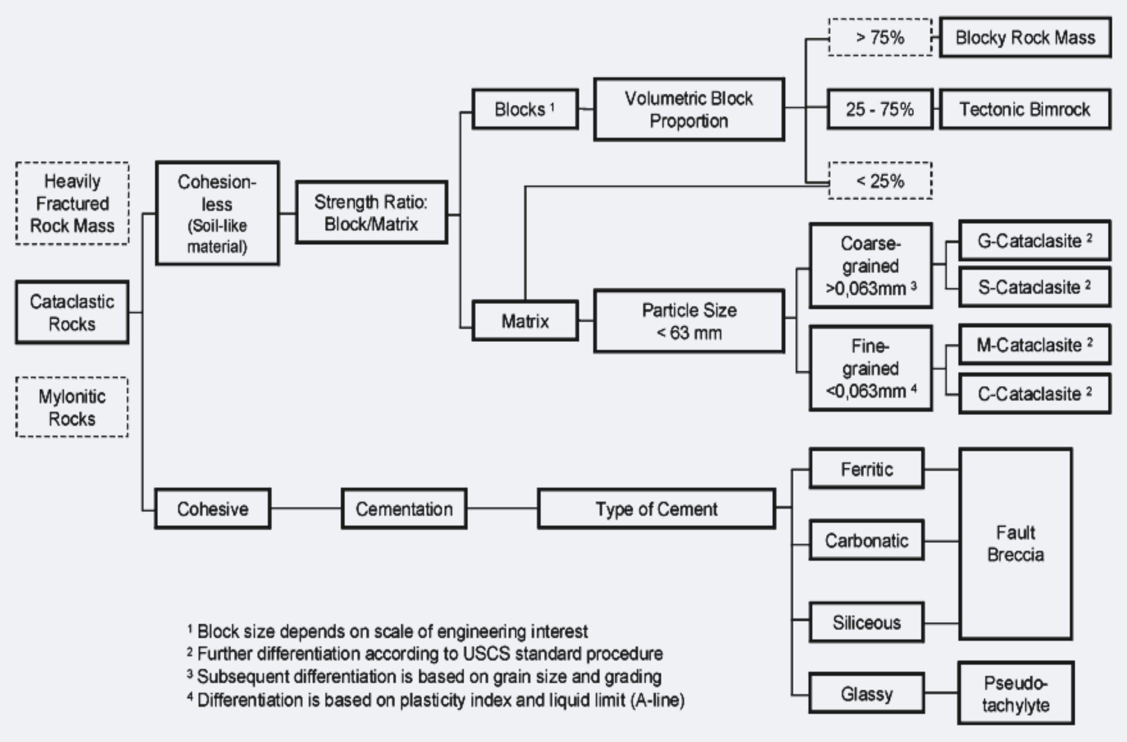

Fig. 6 Engineering geological classification of cataclastic rocks (fault rocks).

Bild 6 *Ingenieurgeologische Klassifizierung von Kataklastischen Gesteinen (Störungsgesteinen).*

establishment of a 3D conceptual model of the rock mass discontinuity-bound kinematics.

Borehole in-situ-testing in faults should routinely be limited to hydraulic tests, such as Lugeon or slug and pulse tests. We do not recommend the performance of dilatometer or pressuremeter tests used in a drill hole to obtain data relating to the deformability of a rock mass. The extreme variability of a fault zone, with alternations of soft and hard rocks, renders the execution of the test both risky and time-consuming, and the data obtained can only be used with high uncertainties.

For an adequate characterization of the mechanical properties of the tectonically disturbed rock mass, one must mainly rely on laboratory testing of core samples. Bear in mind, however, that the reasonable determination of rock mass parameters decreases with increasing weakness of the rock concerned. Conventional laboratory analyses should include triaxial and direct shear tests, swelling tests and quantitative clay mineral analyses. The risk of disturbing core samples, the problems involved in sample preparation and, finally, the extreme variation of test results all make it extremely difficult to obtain representative mechanical data. Experience has shown that, to be on the conservative side, drained direct shear tests on disturbed samples of grain size fraction < 40 µm should be used. However, by focussing only on the fine-grained matrix the potentially substantial mechanical contributions of blocks will be ignored. Medley (11, 16), Lindquist (17, 18) and Goodman & Algren (19) show the vital importance of including blocks in the determination of strength and deformation properties of “block-in-matrix” rocks.

The routine field instrumentation required for the hydrogeological investigation of fault zones are stand pipes or piezometer installations in boreholes, which provide a continuous, long-term check on the groundwater situation. But due to the complex conditions along fault zones, a substantial number of such installations is often needed.

The exploration of fault zones by direct investigation methods should be supplemented by geophysical methods. We recommend gamma-log measurements as suitable geophysical borehole logging. This method facilitates the recording of fault segments dominated by clayey gouges. Conventional geophysical field surveys consist of refraction seismic methods and resistivity methods. More recently reflection seismic methods were successfully applied to get a better understanding of the fault pattern along a tunnel alignment. For the route selection of the Koralm base tunnel (length 32 km, maximum overburden 1 700 m) which will be part of the Austrian high speed railway, high resolution reflection seismics were performed to obtain information of the fault structure at depth (20). A satisfactory image of the fault structure including relative movements could be achieved down to a depth of 2 000 m. A problem with this method is the interpretation of seismic anomalies in terms of significant structural features and the precise allocation of the identified structures.

Classification of fault rocks

The classification of fault rocks as found in structural geology proposals is typically either based on the parameters fabric, texture, clast size and matrix percentage (1, 21) or on a genetic-microstructural description in a rate of strain vs. rate of recovery reference frame (22).

More recent and reasonably applicable schemes, based on the former classifiers, are thought as guidelines to present usage only, since the terminology applied to fault rocks is by no means generally agreed upon (5, 23). An extensive discussion of fault rocks is presented by Snoke et al. (24).

Besides of some problems with definitions in the classifiers, major drawbacks of the mentioned classifications in engineering geological application are that they generally do not contain much geotechnically valuable information and are not applicable to classify the rocks of a brittle fault zones as a whole. The latter is a consequence of the close interlacing and complex relationships of different fault rock types within the fault zone.

The first geotechnical classification of fault rocks was presented by Brekke and Howard (25). An “engineering geological classification of fault rock” was introduced by Zhang et al. (26). In both classifications the heterogeneous nature of rocks generated by brittle faulting is not well defined. D’Elia et al. (27) and Manfredini et al. (28) have classified “structurally complex rocks” but without further differentiation of the category “chaotic mixtures of weathered blocks in a clayey matrix” (which are commonly olistostromes).

Due to the shortcomings of previous attempts to classify the highly complex and variable fault rocks, we here propose a diagnostic functional classification which is based on our experience from investigations for, and construction of, rock structures such as dams, slopes and tunnels; and on the results of recent research (11, 16, 17, 18, 29, 30, 31, 32).

According to conventional engineering geological usage, the term fault rocks generally only applies to the products of brittle faulting and the potential subsequent alteration or cementation of the fault by migrating fluids. Classification proposed here considers both matrix and block characteristics, as well as secondary cementation since all it is the combined contributions of these components together determine the performance and strength of the faulted rock mass.

The basic classification of the rocks produced by brittle faulting, for which we suggest the term cataclastic rocks, consists of the differentiation between the cohesive or noncohesive (cohesionless) character of the faulted rock, i.e. whether it has the properties of hard rocks or else of soil-like material (Figure 6).

For cohesive cataclastic rocks, the strengths of both fragments and cementing material, as well as the degree of cementation, determine the rock properties. Cemented fault rocks (fault breccia, pseudotachylyte) may be subject to the same characterization methods as used commonly for hard rocks. In view of our experience it is geotechnically more important to differentiate fault breccias by their degree of cementation and type of cement than by the size of clasts (megabreccia, breccia, microbreccia), as has been suggested elsewhere in the structural geological literature (5).

The differentiation of cohesionless cataclastic rocks is based on the identification of geotechnically significant blocks, in which blocks have a strength contrast relative to matrix, and the block sizes and block volumetric proportions are sufficient that they influence the mechanical behaviour of the fault rocks (11, 17).

Blocks are mechanically distinct from matrix if there is a contrast between the strength or stiffness of the blocks and the strength or stiffness of the matrix. For example, based on the laboratory experience of Lindquist (17), Medley (11) proposed a minimum strength contrast based on friction angle ratio (tan φ of weakest block)/ (tan φ of matrix) of between 1.5 and 2.0.

The discrimination of block sizes from matrix materials is not a trivially easy task when blocks sizes in fault zones may range between millimeters and hundreds of meters. Indeed, block size distributions in brittle faults will often be fractal; that is, obey negative power laws with relatively few large blocks and increasing numbers

Fig. 7 Transition from blocky rock mass into "bimrock" (central part of picture); mesoscale.

Bild 7 *Übergang von blockigem Gebirge in „Block in Matrix" Gesteine (mittlerer Bildabschnitt); mesoskopischer Maßstab.*

of ever diminishing smaller blocks. Following the procedure of Medley and Lindquist (8) our diagnostic classification proposes the minimum size of blocks to be 6 cm, which is 5 percent of an assumed reasonable scale of engineering interest of 1.2 m. All material with maximum block sizes which do not exceed 6 cm (corresponding to the gravel size limit) would then be defined as "matrix". Within this matrix the parameters grain size distribution, plasticity and content of critical clay minerals are of geotechnical interest.

After defining "block-in-matrix" rocks on the basis of strength contrasts between blocks and matrix as well as block sizes, further differentiation is achieved by determining the volumetric block proportion, which strongly influences the shear strength of a block-in-matrix rock mass (11, 16, 17, 18, 19, 30, 32). Based on the work of Lindquist (17) Medley (11) defined limiting volumetric block proportions in "block-in-matrix" material. Geotechnically significant blocks in a "block-in-matrix" rock mass are influential at volumetric block proportions (proportion of volume of blocks to total rock mass volume) between about 75 % and 25 %. If a "block-in-matrix" rock mass within a brittle fault falls between within these limits, we suggest that the "block-in-matrix" fault rock be called a "tectonic bimrock".

For "block-in-matrix" rocks with volumetric block proportions > 75 % the term "blocky rock mass" can be used (Figure 7). "Block-in-matrix" rocks with a volumetric block proportion of < 25 % are assigned to the matrix independently from block sizes.

As shown by Lindquist for physical model melanges and other "block-in-matrix" materials, as volumetric block proportion increases the total strength of the tectonic bimrock increases. The strength properties of tectonic bimrocks can thus be evaluated using a simple and direct relationship between the angle of internal friction of tectonic bimrocks and the volumetric block proportion (17).

The differentiation of the matrix generally follows the standard procedures used to describe and classify soils in soil mechanics (Unified Soil Classification System, British Standard Institution). The principal classification parameters are particle size distribution (or grading) and plasticity, from which the soil name can be deduced. Following the engineering soil description, we suggest differentiation between gravel, sand, silt and clay dominated cataclasite, to yield one of G-, S-, M- or C-cataclasite. The name cataclasite is used as a generic term for cohesionless, soil-like matrix material which is a product of rock deformation (cataclasis) accomplished by pervasive brittle fracturing and comminution of the grains (5). The name coarse-grained (> 63 µm) or fine-grained (< 63 µm) cataclasite is used if further differentiation is not required, or not possible. Instead of fine-grained cataclasite the term gouge, which is very common in engineering geology, can be used. Gouge can be further differentiated into clayey or silty gouge, if possible.

Conclusions

For the engineering geological characterization and classification of brittle faults and tectonically disturbed rocks a comprehensive knowledge of the fault's internal structure and its material properties are required as this is absolutely crucial in order to establish a reliable engineering geological model of faulted rocks.

Contrary to the common practice in engineering geology of simplifying a fault into a uniform zone limited by planar planes, the complex heterogeneous fault structure has to be investigated and represented in detail. For the assessment of geotechnical properties it is most important to examine fault kinematics, deformation mechanisms and mechanical as well as hydraulic properties.

Despite the problems in characterizing complex fault zone features and the great difficulty to classify the intricate cataclastic rocks a simple functional classification scheme has been introduced. We are convinced that the application of this classification will contribute to the improvement of the engineering geological examination of brittle fault zones. Additionally, detailed investigations in faulted rocks, at the usual scales of engineering interest, will yield data on specific bimrock features such as block size and block volumetric proportion, data which can be used to optimise the design and construction of structures built on or in the faulted rock mass.

References

1. Sibson, R.H.: Fault rocks and fault mechanisms. *J. Geol. Soc. London* 133 (1977), pp. 191-231.
2. Riedmüller, G: Neoformation and transformation of clay minerals in tectonic shear zones. *Tschermaks Min. Petr. Mitt.* 25 (1978), pp. 219-242.
3. Wu, F. T.: Mineralogy and physical nature of clay gouge. *J. Pure and Appl. Geoph.* 116 (1978), pp. 655-689.
4. Klima, K. ; Riedmüller, G. ; Stattegger, K.: Statistical analysis of clay mineral assemblages in fault gouges. *Clays and Clay Minerals* 36 (1988), No. 3, pp. 277-283.
5. Twiss, R.J. ; Moores, E.M.: *Structural Geology.* New York: W.H. Freeman & Co., 1992.
6. Goodman, R.E.: *Engineering geology.* New York: J. Wiley & Sons, 1993.

7. Riedmüller, G. ; Schubert, W.: *Tunnelling in fault zones - Innovative approaches.* Proc 4th NARMS Symp., Pacific Rocks 2000 (Girard et al., eds.). Rotterdam: A.A. Balkema, pp. 113-124, 2000.

8. Medley, E. ; Lindquist, E.S.: *The engineering significance of the scale-independence of some Franciscan melanges in California,* USA. Proc. 35th U.S. Symp. Rock Mechanics Reno/Nevada. Rotterdam: A.A. Balkema, pp. 907-914, 1995.

9. Marone, C. ; Scholz, C. H.: Particle size distribution and microstructures within simulated fault gouge. *J. Struct. Geol.* 11 (1989), No. 7, pp. 799-814.

10. Sammis, C.G. ; Biegel, R.L.: Fractals, fault gouge and friction. *J. Pure Appl. Geophys.* 131 (1989), pp. 255-271.

11. Medley, E.W.: *The engineering characterization of melanges and similar “block-in-matrix”-rocks (bimrocks).* PhD Thesis, Dept. of Civil Engineering, University of California. Berkeley, 1994.

12. Caine, J.S. ; Evans, J.P. ; Forester, C.P.: Fault zone architecture and permeability structure. *Geology* 24 (1996), No.11, pp. 1025-1028.

13. Mouthereau, F. ; Lacombe, B. ; Deffontaines, A. ; Chu, H.T. ; Lee, C.T.: Quaternary transfer faulting and belt front deformation at Pakuashan (Western Taiwan). *Tectonics* 18 (1999), No. 2, pp. 215-230.

14. Harer, G. ; Riedmüller, G.: Assessment of ground condition for the Koralm Tunnel during the early stages of planning. *Felsbau* 17 (1999), No. 5, pp. 374-380.

15. Brosch, F.J. ; Pischinger, G. ; Steidl, A. ; Vanek, R. ; Decker, K.: *Improved site investigation results by kinematic discontinuity analysis on drill cores.* Proc. ISRM Reg. Symp. EUROCK 2001/ Espoo/Finland, 2001. Rotterdam: A.A. Balkema, in print.

16. Medley, E.W.: Systematic characterization of melange bimrocks and other chaotic soil/rock mixtures. *Felsbau* 17 (1999), No. 3, pp. 152-162.

17. Lindquist, E.S.: *The strength and deformation properties of melange.* PhD Thesis, Dept. of Civil Engineering, University of California. Berkeley, 1994.

18. Lindquist E.S. ; Goodman, R.E.: *Strength and deformation properties of a physical model melange.* Proc. 1st NARMS Symp., Austin/Texas: Rock Mechanics Models and Measurements, Challenges from Industry, (Nelson & Laubach, eds.). Rotterdam: A.A. Balkema, 1994.

19. Goodman, R.E. ; Algren, Ch.S.: Evaluating safety of concrete gravity dam on weak rock: Scott dam. *J. Geot. Geoenvironmental Eng.*,May 2000, pp. 429-442.

20. Dörrer,Th. ; Harer,G. ; Lehmann, B. ; Lux, K-N. ; Riedmüller, G. ; Schön, J. ; Seren, S.: Combined application of geophysical measurements – case history Koralm tunnel. *Felsbau* 18 (2000), No.4, pp. 37-47.

21. Heitzmann, P.: Kakirite, Kataklasite, Mylonite – Zur Nomenklatur der Metamorphite mit Verformungsgefügen. *Eclogae Geol. Helv.* 78 (1985), pp. 273-286.

22. Wise, D.U. ; Dunn, D.E. ; Engelder, T. ; Geiser, P.A. ; Hatcher, R.D. ; Kish, S.A. ; Odom, A.L. ; Schamel, S.: Fault-related rocks: Suggestions for terminology. *Geology* 12 (1984), pp. 391-394.

23. Passchier, C.W.; ; Trouw, R.A.J.: *Microtectonics*. Berlin/ New York: Springer, 1996.

24. Snoke, A. W. ; Tullis, J. ; Todd, V. R.: *Fault-related rocks – a photographic atlas.* Princeton, New Jersey: Princeton Univ. Press, 1998.

25. Brekke, T.L. ; Howard, T.R.: *Functional classification of gouge material from seams and faults in relation to stability problems in underground openings.* Univ. of California, Berkeley, Dept. of Civ. Engin.: Final Report to USBR, 1973.

26. Zhang, X.G. ; Han, W.F. ; Nie, D.X.: *Engineering geological classification of fault rocks.* Proc. 5th Int. Congr. Int. Assoc. Engin. Geol. Buenos Aires 1986. Rotterdam: A.A. Balkema, pp. 479-486, 1986.

27. D’Elia, B. ; Distefano, D. ; Esu, F. ; Federico, G.: *Slope movements in structurally complex formations.* Proc. Int. Symp., Engineering in Complex Rock Formations, Beijing, China 1986 (Tan Tjong Kie, Li Chengxiang & Yang Ling, eds.). New York: Pergamon Press, pp. 430-436, 1986.

28. Manfredini, M. ; Bertini, T. ; Cugusi, F. ; Grisolia, M. ; Rossi-Doria, M.: Geological outline of Italy: bearing of the geological features on the geotechnical characterization on the example (sic) of some typical formations. In: *Geotechnical Engineering in Italy*, (Capuzzo, M:G: Japelli, R. ; Martinetti, S. ; Nova, R. ; Troiano, V. ; Viggiani, C.: eds.). Rome: AGI-Associazione Geotecnia, 1985.

29. Medley, E.W.: *Order in chaos: the geotechnical characterization of melange bimrocks.* Proc. 1st Int. Conf. Site Characterization - ISC´98/Atlanta/Georgia/USA 1998. Rotterdam: A.A. Balkema, pp. 201-206, 1998.

30. Lindquist, E.S.: *The mechanical properties of a physical model melange.* Proc. 7th Congr. Int. Assoc. Eng. Geol., Lisbon, Portugal 1994. Rotterdam: A.A. Balkema, pp. 819-827, 1994.

31. Medley, E.W. : *Uncertainty in estimates of the block volumetric proportion in melange bimrocks.* Proc. Int. Symp. IAEG, Athens, Greece. Rotterdam: A.A. Balkema, pp. 267-272, 1997.

32. Medley, E.W. ; Goodman, R.E.: *Estimating the block volumetric proportions of melanges and similar “block-in-matrix” rocks (bimrocks).* Proc.1st NARMS Symp. Rock Mechanics, Austin, Texas: Models and Measurements, Challenges from Industry (Nelson, P.P. ; Laubach, S.E.: eds.). Rotterdam: A.A. Balkema, pp. 851-858, 1994.

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