Slope Instability – In-situ and Laboratory Testing

By Manfred Blümel and Stephan Semprich

In order to estimate the risk of slope instabilities, representative parameters to describe the soil and rock material behaviour are needed. Geotechnical parameters could be separated into different groups, like geophysical, mineralogical, hydrological, and mechanical parameters in addition to parameters that describe the rock mass structure. However, these groups should not be separated, because they are all part of a sphere of influence on the material behaviour. For instance, a variation in the mineralogical and hydrological parameters influences the mechanical parameters. The relevant boundary conditions and parameters for a certain project should be discussed in the investigation phase. For this complex matter, teamwork between geologists, geophysicists, and engineers is necessary to adequately characterize complex geologic situations for engineering purposes. Apparently simple questions like: “What are the adequate test methods, the location of the test or specimen, the amount of tests and how can we get appropriate samples?” are important.

To achieve a realistic evaluation, specifying representative procedures and the testing programme is necessary. The determination of parameters in laboratory and in-situ tests is an essential part of the characterization process. Because rock and the rock mass is inhomogeneous, one have to deal with wide distributions in the parameter values and to determine which parameters are necessary for a given rock mass

Böschungsinstabilität – In-situ- und Laborversuche

Mit Hilfe von In-situ- und Laborversuchen können boden- und felsmechanische Parameter bestimmt werden. Welche Versuchsmethoden geeignet sind, hängt von den jeweiligen Randbedingungen ab. Böschungsuntersuchungen stellen für die Versuchstechnik eine besondere Herausforderung dar, da oft stark gestörtes, verwittertes Material angetroffen wird und herkömmliche Methoden der klassischen Boden- beziehungsweise Felsmechanik nicht ausreichend geeignet sind. Eine umfassende Betrachtung der jeweiligen Randbedingen ist daher besonders wichtig. In dieser Arbeit werden einige Beispiele von Versuchsmethoden vorgestellt.

The mechanical parameters for soil and rock can be determined with in-situ and laboratory tests. The appropriate methods are dependent on the boundary conditions expected in the field. Especially slope stability analysis are a challenge for testing techniques, because one often have to deal with faulted, weathered rock masses where the classical soil and rock mechanics approaches are not sufficient enough. Therefore, a comprehensive view considering the relevant boundary conditions is of utmost importance. This paper shows some examples of advanced testing methods, which begin to address some of these insufficiencies.

- Stress level
- Boundary conditions (e.g. constant normal load, constant normal stiffness, volumetric strain behavior)
- Loading rate, loading direction
- Strain rate
- (Pore) Water pressure
- Swelling or shrinking materials
- Chemical- physical change
- Temperature
- Weathering
- Time dependence (e.g. loss of cohesion in course of time)
- Vibrations (e.g. earthquake, blasting)
- Scale effect

Fig. 1 Some exemplary factors of influence on strength.

Bild 1 *Einige Einflussfaktoren auf die Festigkeit.*

Fig. 2 In-situ direct shear test.

Bild 2 *Direkter In-situ-Scherversuch.*

Fig. 3 Results of direct shear tests.

Bild 3 *Ergebnisse der direkten Scherversuche.*

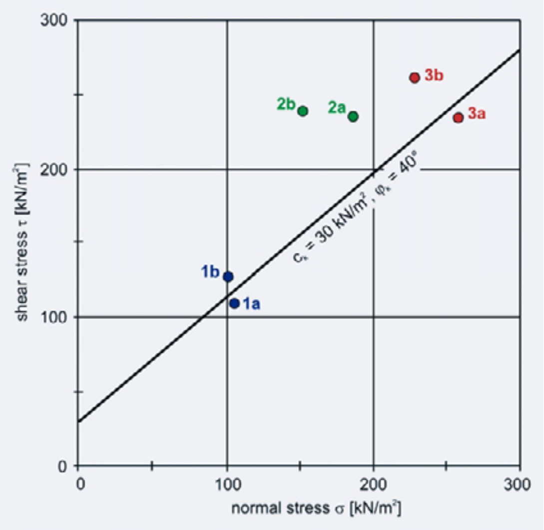
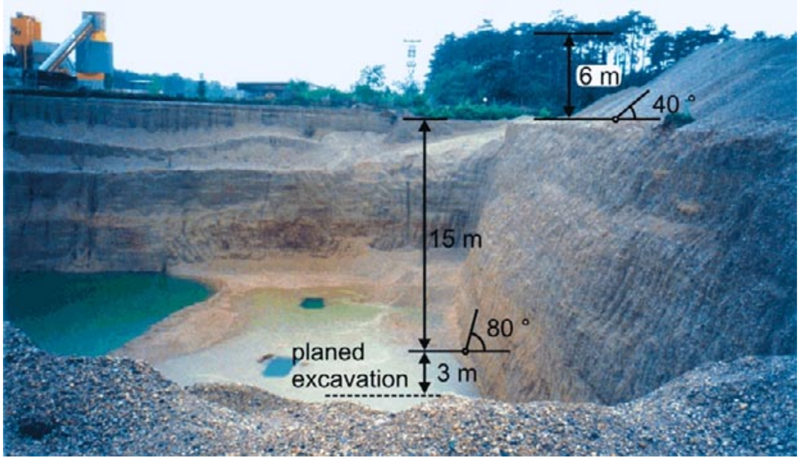


Fig. 4 Gravel pit with a slope inclination of 80°.

Bild 4 *Schottergrube mit einer Böschungsneigung von 80°.*

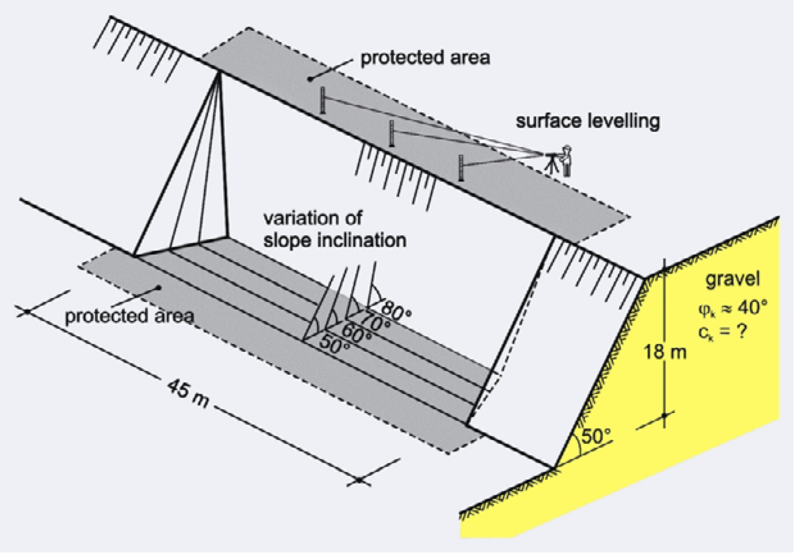


to properly convey lab behaviour to the real situation.

The shear strength is the main parameter for slope stability analysis and can be described by either a linear or non-linear failure criterion. One must recognize that strength is not an independent parameter. Strength can only be described if the boundary conditions are defined. This is also valid for a differentiation between the peak and residual strength.

Fig. 5 Large scale in-situ test for waste removal at Fischer Deponie, Theresienfeld, Austria.

Bild 5 *In-situ-Großversuch für die Räumung der Fischer Deponie, Theresienfeld, Österreich.*



Some exemplary factors that influence the strength are shown in Figure 1. Each of these influence factors can change the strength parameter. If a non-comprehensive view is considered reasonable results we cannot be expected. To formulate the facts there are different stages, identification, classification, characterization, interpretation and verification. Quantifying the rock and rock mass behaviour will always be a challenge; appropriate testing procedures and analyses are the first step for a more realistic evaluation. Therefore, testing and the testing results should not be irrespective of the entire project.

Testing methods can be divided into two groups, in-situ and laboratory tests, depending on where the tests are performed. Typical in-situ tests, performed without removing samples from their natural position, are geophysical tests, piezometer tests, large-scale tests (e.g. in-situ shear test, embankment test), tilt test, torque vane test, penetrometer or dilatometer tests. The usual laboratory tests are direct shear tests, unconfined and confined compression tests, determination of water content, density, plasticity, mineral composition, permeability tests, (particle) grain size analysis, thin sections, swelling tests, etc.

The classical mechanical parameters for slope stability analysis are cohesion, friction, dilatancy, shear stiffness (hardening and softening), (joint) compressive strength, joint asperity geometry (roughness coefficient). Because the failure mechanisms are a very complex process and influenced by the boundary characteristics, as mentioned before, it is often necessary to leave standardized procedures.

This paper shows some examples of tests to determine the mechanical parameters for slope stability problems.

In-situ tests of quaternary soil

The first example describes test procedures used to investigate the shear strength of quaternary soil. The most relevant strength parameters, the cohesion and friction angle, of fine-grained soil such as clay or silt are very often investigated by direct shear tests or triaxial tests. These tests are carried out on undisturbed soil samples in a laboratory. For cohesive soils, sampling and test preparation is typically unproblematic. However, retrieving high quality, undisturbed samples in cohesionless materials is very difficult and often requires additional techniques such as freezing. Besides, coarse soils, such as gravels, require relatively large sample dimensions and respectively the test equipment.

With respect to economical reasons investigations of the shear strength of coarse soils are mostly performed on disturbed probes, which consist only of the soils fine grain portion because the coarse grains are removed by sieving previously. Consequently the expressiveness of results

Urgent Subscription

Technical journals with competence

**Delhi Mass Rapid ransport System
Metro Corridor MC1B
Chawri Bazar Station**

- Geological Investigation
- Detailed Design
- Assistance during Construction

Due to the very densely populated area Chawri Bazar Station is designed and constructed according to the New Austrian Tunnelling Method. The station complex consists of two large shafts with cross sections of 1500 m², two platform tunnels and several cross adits and service tunnel . Overburden above crown level is approx. 15 m.

**GEOCONSULT ZT GmbH
S ERNECKS RASSE 52
A-5020 SALZBURG
TEL. 0662-65 9 65-0
FAX 0662-65 9 65-10
E-mail: office@geoconsult.at
www.geoconsult.at**

VGE
Verlag Glückauf Essen

P.O.Box 18 56 20
D-45206 Essen
Montebruchstraße 2
D-45219 Essen
Phone
+49 (0) 20 54 / 92 41 21
Telefax
+49 (0) 20 54 / 92 41 29
E-Mail vertrieb@vge.de
Internet www.vge.de

Journal for Engineering Geology, Geomechanics and Tunnelling

Edited by Austrian Society for Geomechanics (ÖGG)

Published in English thrice annually

International subscription
65.50 EUR
(airmail, overseas)

The leading Austro-German technical journal contains contributions from the field of international rock and loose rock structures and reports on current tunnelling projects from surveying via planning to construction work.

ORDER COUPON

Please fax to: +49 (0) 20 54 / 92 41 29

I would like to subscribe to the international edition of **Felsbau · Rock and Soil Engineering**.

☐ at an annual subcription price of 65.50 EUR

☐ I like to order the **Rock and Soil Engineering 2002 CD-ROM** at a price of 50.00 EUR

☐ I would like to familiarize myself with **Felsbau · Rock and Soil Engineering**. Please send me a specimen copy free of charge.

☐ I am interested in advertising in **Felsbau · Rock and Soil Engineering**. Please send me your media information.

Date, Signature

My address

Fig. 6 Rock mechanic laboratory equipment.

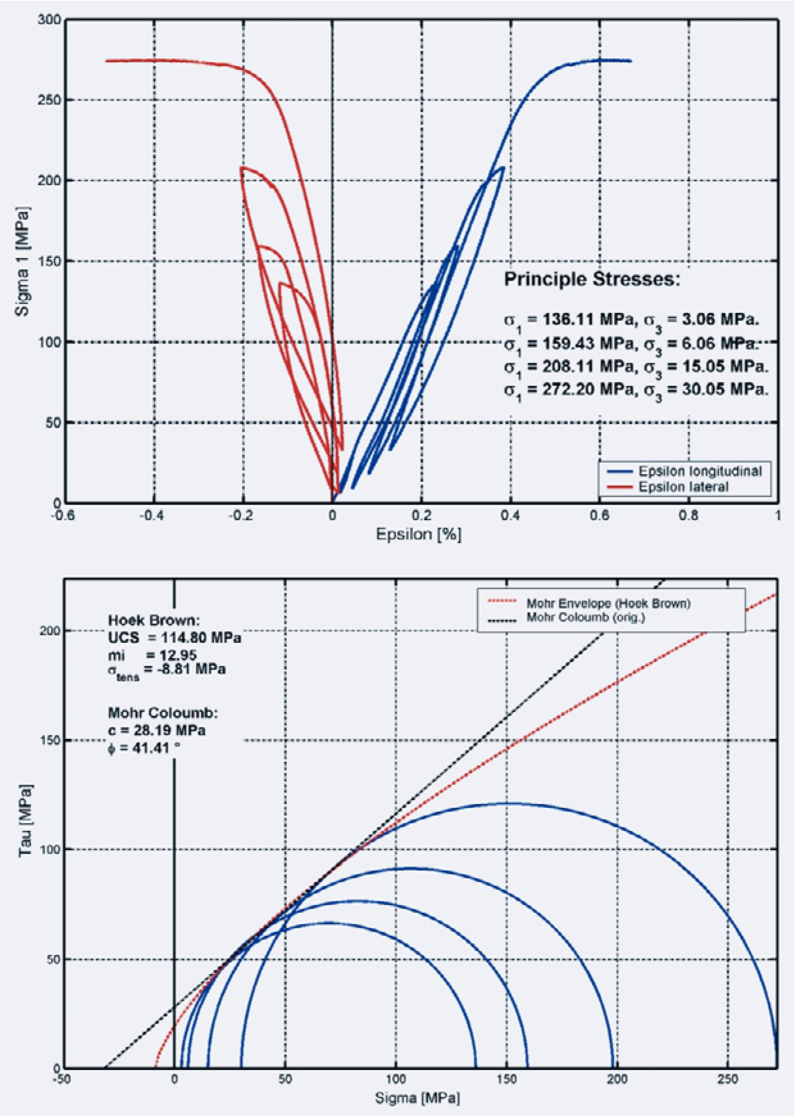
Bild 6 *Felsmechanik Laborausstattung.*

from laboratory shear tests of coarse grain soils is limited and in important cases in-situ shear tests are necessary.

Figure 2 shows an in-situ shear test carried out on a construction site 50 km south of Vienna using simple test equipment. In this test, quaternary gravel of the Vienna Basin has been investigated. This sandy gravel respectively very sandy gravel fills up the Vienna Basin down to 80 m and is very often used as an aggregate for concrete mixing. In an undisturbed soil condition, the grains are slightly cemented with calcium precipitates.

Fig. 7 Multiple failure triaxial test results.

Bild 7 *Ergebnisse eines Mehrstufen-Triaxialversuchs.*



The results of six in-situ shear tests performed with different normal stresses are shown in Figure 3. Based on these results, a cohesion $c_k = 30$ kN/m² and a friction angle $\varphi_k = 40°$ have been derived. These figures have been used for stability analyses of slopes for several gravel pits (Figure 4).

A similar task appears at waste disposal site, the „Fischer Deponie“, located 20 km east from the above mentioned construction site with the same subsoil conditions. At the Fischer Deponie slopes with heights up to 20 m have to be designed. However, for the first phase of stability analyses no site-specific strength data from shear tests either in the laboratory or in-situ were provided. Consequently, strength parameters were chosen with conservative values: $c_k = 26{,}5$ kN/m³ and $\varphi_k = 35°$.

For a second phase of analyses investigating more economical solutions undisturbed site specific shear strength values are desired. These revised values will be derived from a large-scale in-situ test, which includes a variation of the inclination of a 18 m high slope up to 80° (Figure 5). This test will be executed in March 2003. Because of the relatively high failure risk, people are not allowed to stay within a fenced-off protected area, which could be covered by soil in case of a slide. This unusual procedure is chosen to derive representative shear parameters for the gravel layer of Vienna Basin. No other method leads to more realistic results when considering sample disturbance and scale effects. This test even accounts for the potential disturbance due to the construction methods.

Rock mechanic laboratory tests

State-of-the-art testing equipment allows new types of testing procedures to determine the mechanical parameters of joints and intact rock. High-response servo hydraulic systems (Figure 6) with digital control technology, strain measurement equipment mounted onto the specimen and programmable control modes, enable new types of test procedures to be performed, which are tailored to the specific problem (1). The correct interpretation of test results depends on the quantity and especially on the quality of the laboratory tests with the goal of obtaining as much information as possible about the rock properties from each test or group of tests.

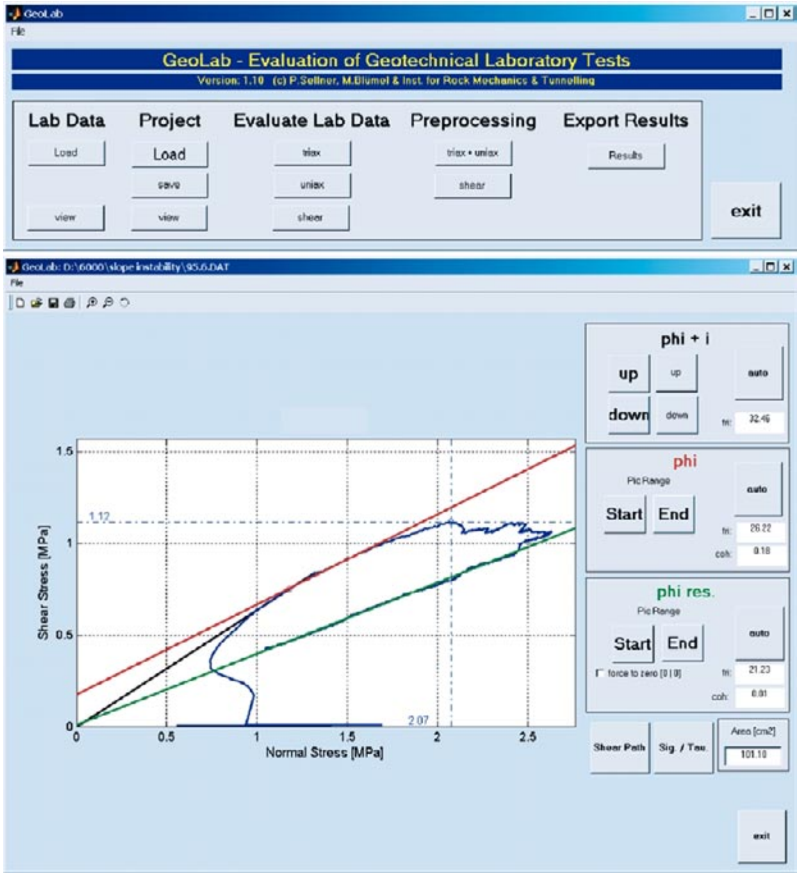
Specimens for rock testing that are representative of the rock mass behaviour are extremely difficult to obtain. Even drilling cores, which are suitable for uniaxial or triaxial tests, often cannot be used due to sample defects. Therefore, this biased selection of the specimens can have a great influence on the results. This is especially true for weak rock or highly fractured rock, where the mechanical parameters are even more important for stability investigations.

Compression tests

The ability to apply different stress paths and boundary conditions to a given sample or suite of samples allows different failure modes to be investigated in the laboratory. The uniaxial test is the most frequently used rock mechanics test, but provides only elastic properties and a single failure value derived from a very simple stress path (2). With computer controlled feedback it is possible to follow different stress paths by varying the axis symmetric confining pressure and the axial compression of a rock cylinder. The use of computed automated controls allows to perform multiple loading cycles on the same specimen. After each peak load for a given confining pressure, the deviatoric stress is reduced to zero and the sample is loaded hydrostatically to the next confining level. Thus, the progressive stress history of a single sample can be monitored instead of using different samples (with different microstructure?) at each stress state and combining the results to estimate the progressive stress behaviour of the "intact" rock (Figure 7). This allows a more realistic evaluation of the intact rock strength, and thus the rock mass strength, resulting in more realistic predictions and interpretations of the in-situ rock mass behaviour.

Shear tests

The simplest case for shear failure is a single block resting on a plane. With this simple case a failure criterion is needed in which the principal stress



GeoLab

GeoLab - Evaluation of Geotechnical Laboratory Tests

Version: 1.10 (c) P.Sellner, M.Blümel & Inst. for Rock Mechanics & Tunnelling

GeoLab: D:\6000\slope instability\95.6.DAT

fri: 32.46

fri: 26.22

coh: 0.18

☐ force to zero [0|0]

fri: 21.23

coh: 0.01

Area [cm2] 101.10

Fig. 8 Stiffness controlled shear test evaluation.

Bild 8 *Auswertung eines steifigkeitskontrollierten Scherversuchs.*

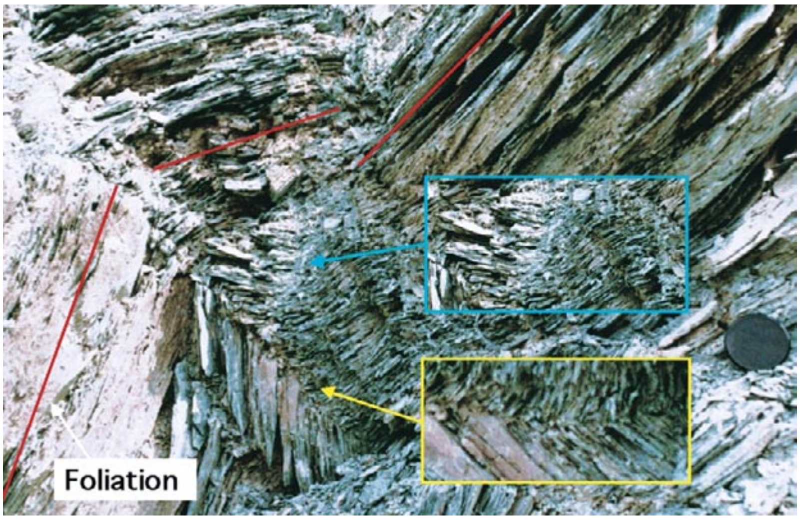


Fig. 9 Foliated rock, shear zone.

Bild 9 *Geschiefertes Gestein, Scherzone.*

Deformations of weak faulted phyllite Brittle cataclastic flow- interlayer shear

Deformations of hard intact phyllite tensile fractures, interlayer shear and ridged block rotation

Fig. 10 Pictures of specimen taken after a constant normal stiffness test.

Bild 10 *Probenbilder nach steifigkeitskontrollierten Scherversuchen.*

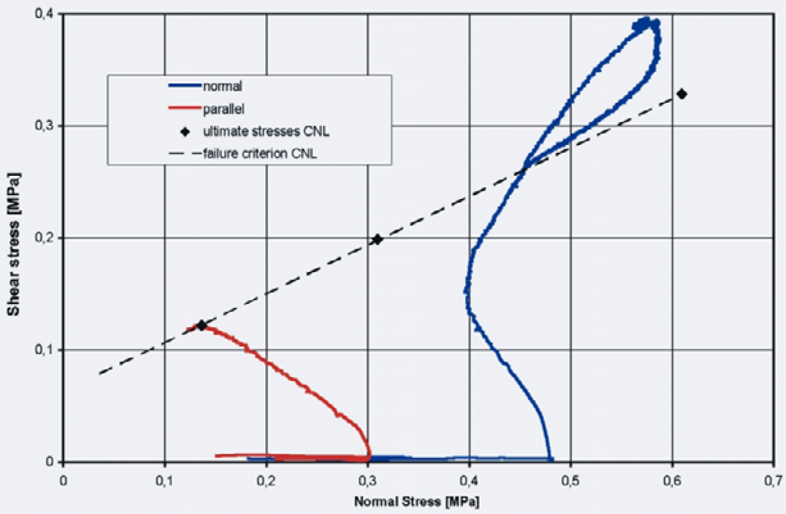


Fig. 11 Diagram of the stress paths depending on the shear direction and test control mode.

Bild 11 *Spannungspfade in Abhängigkeit von der Scherrichtung und der Versuchsprozedur.*

situation is not changed. This can be performed in the laboratory with a constant normal load direct shear test. In many slopes, the failure mechanism will not be this simple and more representative boundary conditions should be used. To investigate the shear behaviour and failure characteristics of both fracture surfaces and weak intact rock automated testing procedures are used to perform tests with different boundary conditions (3). This enables the execution of modified shear tests, which are behaviour specific. Usually one have to deal with embedded blocks side by side where the acting normal forces on the joint planes change and so the overall principal stress distribution varies. For example, stiffness controlled tests can be used to evaluate the ultimate shear strength for different boundary conditions, and also allows the recognition of the different failure modes that occur during shearing. The volumetric strain behaviour, the so-called dilation or contraction is used as the feedback control mode for the vertical stress. This test method is the most appropriate test method for evaluating a material´s shear behaviour yielding the shear and normal stiffness, dilation potential, cohesion, and the initial and ultimate friction angles (4). In Figure 8, a screenshot of the laboratory data evaluation programme for a stiffness controlled shear test is shown. Multi failure state shear tests (under constant normal loads) as well as various combinations of test control procedures can be performed on a single sample eliminating the effects of sample variability on the failure envelope.

For highly anisotropic and weak rocks, such as Phyllites (Figure 9), the acquisition and preparation of samples for compression tests often results in a highly biased selection of stronger samples due to difficulties in specimen preparation. The preparation effort is much less for direct shear testing, thus allowing the testing of the weaker material, as well as the highly competent material using the same procedures. To determine the anisotropic behaviour, a sample can be placed at any orientation within the shear box to evaluate the strength and failure processes associated with a shear direction that is not directly parallel to the preexisting discontinuity structures (5). In Figure 10 pictures of a weak faulted Phyllite specimen, and a hard intact Phyllite tested normal to the foliation, are shown, which were taken after a constant normal stiffness test. The observed failure modes look similar to different zones within the failing rock mass shown in Figure 9. The evaluation of such shear tests shows that the strength is influenced by a complex interaction between sliding friction, dilation, and cohesion. The use of constant normal load shear tests (CNL) does not really test the rock strength but the resistance to shear at a certain normal load, which may be appropriate under certain boundary conditions. Constant normal stiffness testing procedures (CNS) can be used to define a sample´s “ultimate shear strength” which is the natural response to simple shearing (Figure 11). For completely destroyed specimens, like sheared loose rock material, a frame shear laboratory test can be done on the disturbed samples. For a standard soil mechanic shear test the maximum grain size is 4 mm. In a larger shear frame it is possible to test a remolded rock-soil mixture, like is often found in natural shear zones (Figure 12). The different results of both shear tests are shown in Figure 13. In this case, the determined friction angle and the cohesion on the sieved material was almost the same, but the residual friction of the fine grained material after shearing several times on the shear joint was about half the value when compared to the material that still contained blocky material in the matrix.

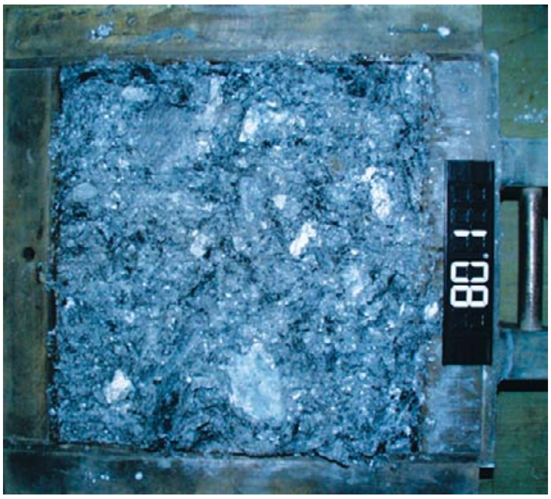


Fig. 12 Picture of large-scale shear box test for remolded specimens (30 cm x 30 cm).

Bild 12 *Foto eines Großscherrahmenversuchs für gestörtes Probenmaterial (30 cm x 30 cm).*

References

1. Blümel, M.: *Improved Procedures for Laboratory Rock Testing*. EUROCK 2000 ISRM Symposium Aachen 2000, pp. 573-578. Essen: Verlag Glückauf GmbH, 2000.
2. Brosch, F.J. ; Schachner, K. ; Blümel, M. ; Fasching, A.; Fritz, H.: *Preliminary investigation results on fabrics and related physical properties of an anisotropic gneiss*. In: Journal of Structural Geology 22 (2000) 1773-1787.
3. Blümel, M. ; Bezat, F.A.: *Advanced Control Techniques for Direct Shear Testing of Jointed Rock Specimens*. Nondestructive and Automated Testing for Soil and Rock Properties, ASTM STP 1350, W.A. Marr and C.E. Fairhurst, Eds., American Society for Testing and Materials, 1998.
4. Blümel, M. ; Button, E.A. ; Pötsch, M.: *Steifigkeitsabhängiges Scherverhalten von Fels*. In: Felsbau · Rock and Soil Engineering 20 (2002), No. 3, pp. 22-32.
5. Button, E.A. ; Blümel, M.: *Servo-Controlled Direct Shear Tests on Phyllites*. Proceedings of the 5th North American Rock Mechanics Symposium, Toronto, 2002.

Authors

Dipl.-Ing. Dr. Manfred Blümel, Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Rechbauerstrasse 12, A-8010 Graz, Austria, o. Univ.-Professor Dipl.-Ing. Dr.techn. Stephan Semprich, Institute for Soil Mechanics and Foundation Engineering, Graz University of Technology, Rechbauerstrasse 12, A-8010 Graz, Austria, E-Mail tunnel@ tu-graz.ac.at

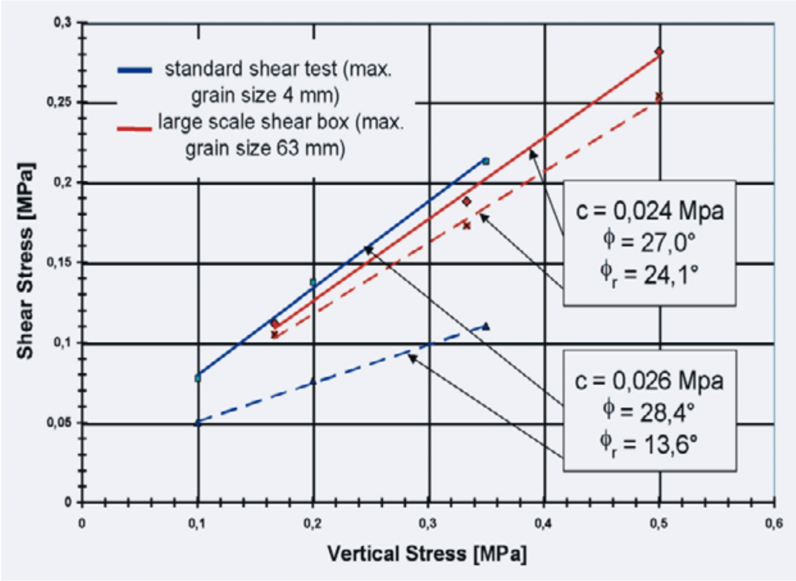


Fig. 13 Mohr-Coulomb envelope for large-scale shear box test for remolded specimens (maximum grain size 63 mm) and standard shear test (maximum grain size 4 mm).

Bild 13 *Mohr-Coulomb Bruchkriterium für den Großscherrahmenversuch (maximale Korngröße 63 mm) und Standard-Scherversuch (maximale Korngröße 4 mm).*