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Preliminary Design Parameters Based on Laboratory Shear Test of Core Samples

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Abstract

It is essential that the preliminary design data for a civil engineering structure is reliable and can be acquired at minimal cost. For a structure that requires excavation of rock mass, the shear strength of critical rock joints is among the fundamental data required. Rock core samples collected during preliminary sub-strata investigation of a project site are the most appropriate source of information for the *in situ* rock. In the laboratory, specific equipment can be used to test these core samples. However, the reliability of laboratory data as design parameters greatly depends on how they are assessed and interpreted. With regard to joint shear strength, the assessment must include consideration on factors which affect shear behaviour of the joint.

Parameter Rekabentuk Awalan Berdasarkan Kajian Ricih Sampel Teras

Abstrak

Data rekabentuk awalan bagi struktur kejuruteraan awal seharusnya tepat, bersesuaian dan melibatkan kos yang terendah. Bagi aspek struktur yang memerlukan pemecahan jasad batuan, kekuatan ricih kekar kritikal merupakan di antara data asas yang diperlukan. Sampel teras batuan yang dikumpul semasa penyiasatan awal sub-strata di lapangan merupakan sumber maklumat batuan in-situ yang paling sesuai. Di makmal, peralatan yang khas digunakan untuk menguji teras batuan ini. Walau bagaimanapun, ketepatan data makmal sebagai pembina parameter, bergantung kepada bagaimana ia dinilai dan ditafsirkan. Merujuk kepada kekuatan ricih kekar, penilaian juga memerlukan pertimbangan faktor yang mempengaruhi sifat ricih pada rekahan.

INTRODUCTION

Geological discontinuities in the rock mass often affect the stability of a civil engineering structure involving excavation of rocks. At the preliminary design stage, this necessitates verification of parameters such as shear strength. However, at this stage the acquisition of design data is often inhibited by limited financial allocation. This situation compels the utilisation of readily available information. The procedures adopted in obtaining the data must be geared toward acquiring optimum information at a minimal cost.

Rock core samples collected during preliminary sub-strata investigation of the project site are the most appropriate source of reliable information of the *in situ* rock. It is an advantage if these samples can be utilised in evaluating the strength and fundamental characteristics of the *in situ* rock. This paper discusses a method for laboratory shear test on core sample using the portable shear box. For shear strength verification, the apparatus used proves to be versatile. The test in general, involves routine sample preparations and testing procedures and therefore, it is relatively inexpensive and simple to conduct. Relevant documentation of the samples and observation made during testing are also discussed, specifically on the characteristics of the joint surface that are related to shear behaviour.

JOINT CHARACTERISTICS AND SHEAR STRENGTH

Laboratory data used in assessing the *in situ* strength of rock is only valid after each contributing factor to its strength is carefully considered (Richards and Cowland, 1982). Although most these factors are best verified in the field however, some pertinent details would help in interpreting and documenting the test result. For example, joints selected for laboratory testing must first be verified to be persistent. Bridging across joint surfaces is an interruption to joint persistency and may lead to cohesion, an area dependent strength.

Joints are fractures of geological origin in intact rock mass. Being a discontinuity plane joints affect significantly the rock mass strength and frequently, are points of initiation of failure in rock. Joints are generally characterised by their geometry/orientation, persistence, surface roughness and infilling (ISRM, 1981). Persistent, non-dilating planar joints normally exhibit purely frictional resistance proportional to the applied normal stress. Therefore, the shear strength parameter like basic friction is scale independent (Hencher and Richards, 1989) and can be accurately determined in the laboratory using small samples.

However, joints are invariably non-planar and exhibit a certain degree of surface roughness. Joint roughness is classified into two, namely large-scale (undulations) and small-scale (asperities) roughness (Stavros and Bandis, 1993). Undulations (a scale of few m) determines the direction of shear and its effect on joints are usually determined by *in situ* testing. Asperities (a scale of few cm) is due to mineral boundaries and surface texture. It is the main concern in laboratory testing because it affects the strength and deformational behaviour of joints under shear loading (Richards and Cowland, 1982; Power and Hencher, 1996).

For shearing of rough joints with typical surface asperities shown in Figure 1, additional strength (besides friction) will be needed to overcome interlocking by over-riding and/or shearing of surface irregularities. The mechanics of shear failure for a rough joint can be idealised as Figure 2 (Richards and Cowland, 1982). The additional stress to overcome over-riding of asperities, as normally encountered in test with low normal stress, is due to the displacements perpendicular to the direction of shear, i.e. dilation angle i. However, in tests with higher normal stress or tests on weathered joint surfaces, shearing of asperities may occur. In this case, the additional stress for shearing of asperities will give rise to shear strength intercept, c. It must also be noted that the final surface texture and the nature of debris resulting from shearing of the asperities have a significant effect on the residual frictional strength of the joints.

Figure 3 represents contact area between joint walls during shearing of a smooth and rough joint. For rough joints, the area of contact is very much smaller than the gross projected area of the joints as contact only occurs at the peaks of the interfacing joint walls. Consequently, the actual normal stress acting on the joint is much higher than the applied stress. This stress concentration may lead to the fracturing of surface irregularities. Although the actual contact area is impossible to determine however, a close approximation will certainly help in interpreting the shear strength (Power and Hencher, 1996 and Xiaoqing Sun *et al.*, 1995). For instance, examination of the sample after the test can give an indication of the surface area actually involved in shearing.

It can be inferred that joint asperities is one of the most important aspects in assessing joint strength in the laboratory. It should be accordingly quantified and included in the documentation of laboratory shear tests. For laboratory documentation, joint asperities can be measured using the profiler. At present, a research is being undertaken at UTM to study the possibility of using photogrammetry for joint roughness measurement (Mustaffar and Mohd Amin, 2000). Quantification of the influence of other factors like weathering condition is also relevant. For example staining or discoloration of joint surfaces may indicate the encroachment of weathering effect into the rock mass.

SHEAR STRENGTH VERIFICATION FOR PRELIMINARY DESIGN

Depending on factors like project size, construction stage and degree of criticality of joints, joint strength can be determined using various methods. These include computer modeling, *in situ* and laboratory testing (Hencher and Richards, 1989; Skinas *et al.*, 1990; Bandis, 1993). At the preliminary design stage, joint strength can be assessed using computer modeling and laboratory testing. The former however, requires reliable input parameters, which are normally scarce at this stage, particularly for a new project site. Therefore, laboratory tests using the conventional and portable shear box are the customary choice. These tests, if properly conducted with correct simulation of the *in situ* loadings, can provide reliable strength data. Yet at this stage, the conventional shear box test may be expensive and time consuming as it requires specific sampling procedures and extensive preparation work (Bandis, 1993).

The type of samples available for laboratory testing is another constraint at the preliminary stage. Usually, rock cores collected during the preliminary investigation of the project site are the only representative samples for the *in situ* rock mass. Besides RQD and detailed description of critical joints, a number of index tests can be conducted on these samples to provide strength indication. For example, a Schmidt hammer test conducted on the joint surface is a

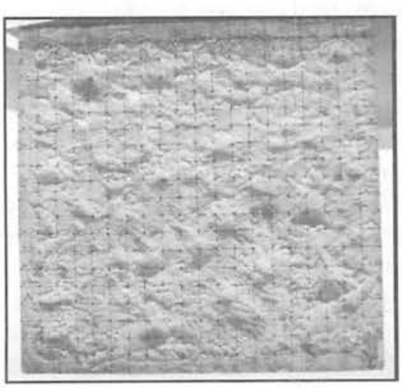

Figure 1: Joint asperities.

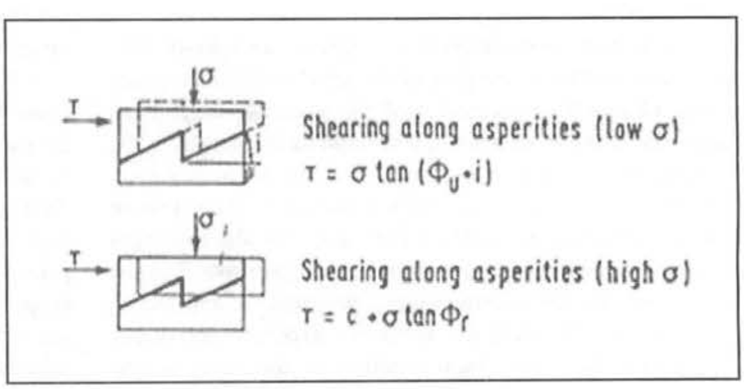

Figure 2: The mechanics of failure of rough joint

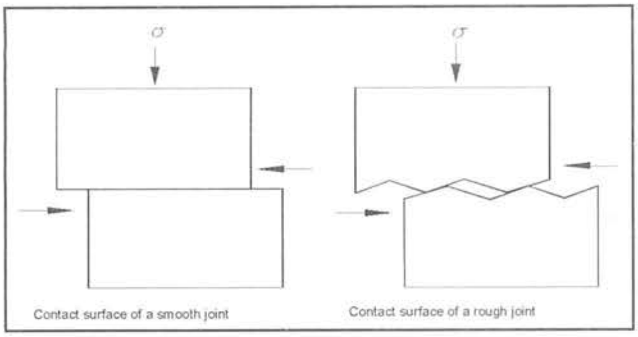

Figure 3: Gross contact area of joint surface.

means of assessing the joint compressive strength (JCS) as proposed by Barton (1977):

$$\text{Log } 10\ (\text{JCS}) = 0.00088\gamma R + 1.01 \qquad (1)$$

JCS indicates two important characteristics of the joint surface. These are the weathering degree and the crushing strength of the asperities.

The above qualitative and quantitative information derived from the core samples only allow for inferences on basic characteristics and index properties and are not directly related to the shear strength. Unfortunately, core samples are not suitable to be tested on the shear box mainly due to the problem in mounting the sample and loading configuration of the apparatus.

Laboratory Test

The testing method discussed here is appropriate for rocks that are sufficiently strong for consolidation effects to be insignificant under the applied normal loads. The testing program and related observations during the test were aimed at providing the design engineer as much information as possible on the characteristics of the joints being tested. Specifically these focus on the following aspects:

- Identification and quantification of surface characteristics that control joint shear strength.
- Range of peak and residual strength of critical joints in the range of applied normal stress.
- Observation of performance and contribution to strength made by asperities during shear, i.e. whether they are sheared through or over-ridden at particular stress levels.

Phi-10 Roctest Assembly

The rig assembly consists of a loading frame and shear box sections (Figures 4 and 5). The rigid vertical U-shaped loading frame helps to reduce fluctuations of normal load in the case of dilating joints. This frame together with the roller carriage sitting in the upper half of the shear box help to minimise tilting of the loading cap thus, allowing for single point measurement of vertical displacement. Hydraulic rams, which are operated using hydraulic pumps, provide the horizontal and vertical load. To ensure a constant normal load throughout the test, the hydraulic circuit for the vertical load is equipped with a pressure maintainer. The shear box sections consist of two halves cylinder and can handle rock sample with a dimension of 115∞115 mm or cores up to 115 mm diameter. The rock sample to be tested must be immersed in a suitable casting material before it is mounted into the shear box. This is done using a casting mould and a minimum of 4 sets of this mould is recommended to speed-up the casting process.

Sample Documentation and Preparation

Test samples were 54 mm diameter cores obtained from rotary drilling on a cut slope at APMC Rawang, Selangor. In the laboratory, joint roughness was measured using the profile gauge and profiled along the direction of shear. However, the effective roughness and the corresponding correction for asperities angle (i), if required, can be verified from the actual dilation measurements during testing (Hencher and Richards, 1989). Measurements obtained shows that a majority of the joint exhibit a typical rough undulating profile (Figure 6). Schmidt hammer tests were also conducted on the samples. The JCS values estimated using equation (1), ranges between 55 and 75 MPa. To facilitate the identification of the surface area involved in shearing and crushing of surface irregularities, all joint surfaces were photographed before and after testing. Typical sample description and documentation for laboratory shear test is shown in (Mohd Amin, 1995 and Hencher and Richards, 1989).

The typical jointed rock core is shown in Figure 7 and this was cut at both ends to required length. The length depends on the orientation of the joint plane to the core axis however, sufficient length should be embedded in the casting material (35 to 50 mm on either side of the joint). The prepared core sample that was ready for casting was matched and held together using thin metallic wire (Figure 8).

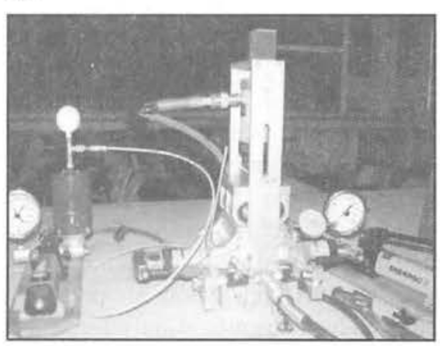

Figure 4: Phi-10 Roctest assembly.

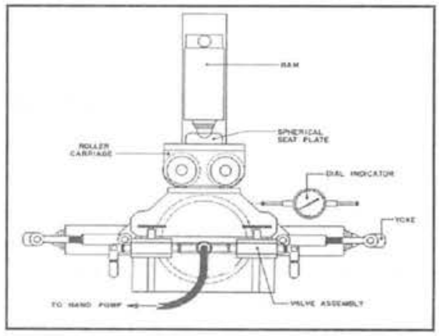

Figure 5: Shear box and loading rams.

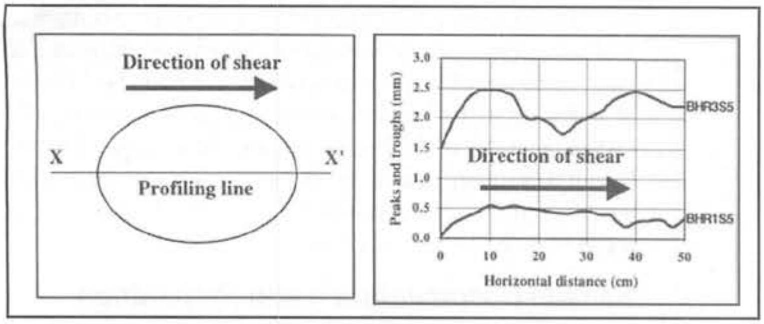

Figure 6: Typical joint roughness profiled along the direction of shear.

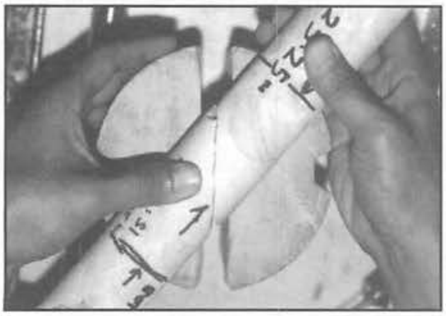

Figure 7: Jointed core sample.

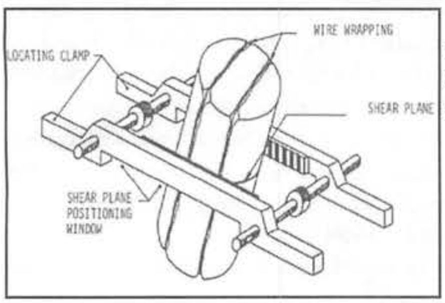

Figure 8: Matched sample and locating clamp.

The correct orientation of the sample in the mould is important before casting so that the joint plane is symmetrical and normal to the vertical load. This is achieved using a sample locating clamp shown in Figure 8. Casting material used is Ordinary Portland Cement with 1:2.5:2.5 water:cement:sand ratio. Superplasticiser and silica fumes (about 1% of cement content) were added to the mix to increase its workability and to enhance strength development. Casting was done in two stages: casting of the lower half and the upper half of the mould. For the type of mix used, it takes about 3 hours before the second casting can be carried out. Care must be exercised so as not to contaminate the joint surfaces. Details on casting procedure are discussed in Roctest (1991). Once the cast material has set (about 6 hours under room temperature) the cast sample is removed from the mould and mounted in the shear box.

Shear Testing Program

Test procedures were according to ISRM (1981) and samples were tested under dry condition. The natural moisture content and dry density of samples were also determined. The *in situ* stress field ($\mathbf{P_c}$) of each sample was approximated using the hydrostatic state of stress. For each sample, this was calculated based on the average unit weight of rock and topsoil (27 and 18kN/m^3, respectively) and the respective depth of each sample (23 to 70 m inclusive of 10 m topsoil). Parameters $\mathbf{P_c}$, shear area ($\mathbf{A_s}$) and ram piston area ($\mathbf{A_p}$) were used to calculate the respective normal load (see Table 1 for selected samples). Most of the joints tested were inclined at an angle to the core axis thus, giving elliptical shaped shear planes. The inclination of the joint plane to the vertical axis was also considered in calculating the applied normal stress during testing.

A total of 15 samples were tested at different normal load. Each sample was sheared well beyond the peak strength at the rate of 0.1mm/min. The shear stress and vertical displacement (measured using pressure transducers and LVDT) were continuously recorded using the TDS301 Tokyo Sikki data logger.

DISCUSSION OF TEST RESULTS

Typical test results are shown in Figure 9 and 10. These are *raw data* as no correction for the dilatation effect will be considered in this discussion.

Depending on the normal stress and joint roughness, the peak shear strength varies between 0.6 and 2.3 MPa. The numerous secondary peaks observed in Figure 9 are due additional strength to overcome joint surface irregularities during shear. Sample BHR1S5 seems to exhibit a lower strength than BHR3S5 despite having similar normal stress (about 2.8 MPa). Examination on the surface roughness shows that BHR3S5 displays a larger asperities size compared to BHR1S5 thus, a higher peak strength due to a larger dilatation. The drop in peak strength for tests at higher normal stress (sample BHR3S5 and BHR2S5) is more abrupt than those at lower stress. This can be attributed to shearing of asperities as shown in Figure 11 for these samples. However, JSC values imply that the joint surface strength is much higher that the applied normal stress of 2.8 MPa. This phenomenon is explained in Figure 3 where in rough joints, the actual contact area during shear is much smaller. Observation made after the test shows that only 20 to 30% of the joint surface is actually involved in shearing. This leads to a higher contact stress at the asperities and consequently, crushing of surface irregularities.

The residual strength varies between 0.3 to 1.6 MPa. Despite the difference in surface roughness and applied stress, it is thought that the variation is relatively higher for samples of similar rock type. For tests at lower stresses,

Table 1: Sample depth and estimated normal stress during shear. Note: A_p is piston area of vertical ram = $2.026\infty10^{-3}m^2$. $\mathbf{P_c}$ = depth∞unit weight of sample.

Sample no.	Depth (m)	*In situ* stress (P_c), kPa	Shear area, A_s ($10^{-3}m^2$)	Normal load $Ln = P_c x A_s$ (kN)	Normal stress $\sigma_n = P_c/A_P$ (kPa)
BHR1S1	23.25	451.6	2.695	1.217	600.7
BHR1S5	69.35	1521.5	3.793	5.771	2848.5
BHR2S1	34.89	721.8	2.529	1.825	900.8
BHR2S5	65.24	1426.2	2.879	4.106	2026.7
BHR3S2	39.10	819.5	3.285	2.692	1328.7
BHR3S5	69.73	1530.4	3.793	5.805	2865.3

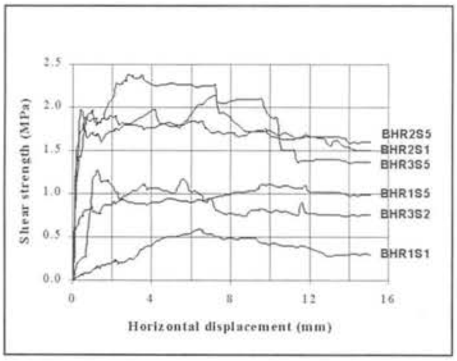

Figure 9: Shear strength vs. shear displacement.

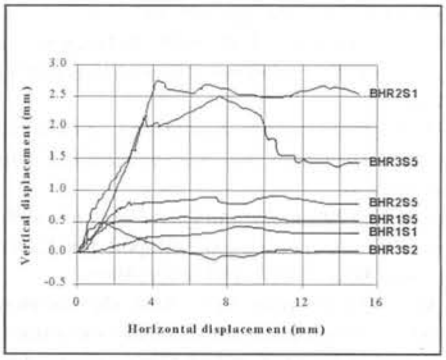

Figure 10: Vertical displacement vs. shear displacement.

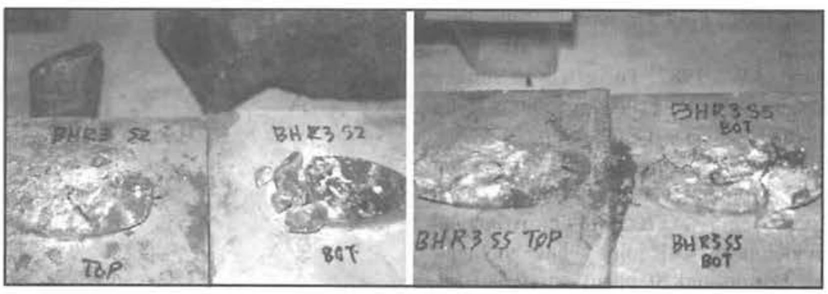
Figure 11: Crushing of joint asperities.

this could be due to incomplete shearing of surface roughness. On the other hand, for tests at higher stresses, debris due to crushing of asperities, as shown in Figure 11, may lead to a higher frictional resistance at residual state.

For rough joints, shearing must be carried out beyond the peak strength. This is to verify whether the drop in strength is really a residual state or, merely a stress relief due to overriding of asperities. Figure 10 shows the vertical displacement of each joint, which is also the effective joint roughness under the applied normal stress. A majority of the joints dilate upon shearing and this correspondingly this results in an abrupt strength increase. Joints with lower residual strength (BHR1S1, BHR1S5, BHR3S2) tend to have a constant volume behaviour towards the end, indicating less effect of joint roughness after certain amount of shearing.

CONCLUSIONS

A total of 15 core samples were tested successfully using Phi-10 apparatus. The whole apparatus is portable thus permitting rapid set-up and testing time. The mix used in the casting process is an important factor. Its curing time and strength help to speed up the testing process and this can be achieved using cement additives.

Besides shear strength data, quantification on the factors that affect shear strength is also important when documenting laboratory test results. This in particular includes the characteristics of surface roughness which has a significant control on joint strength and deformational behaviour. Although most of these factors are best verified in the field however, some pertinent details would help in interpreting the data and facilitates the final assessment of the *in situ* rock mass strength. These should include:

- descriptions related to the surface mineralogy and roughness;
- the nature of the joint surfaces before and after testing; and
- definition of the normal stress level at which crushing of asperities occurs.

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