CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 The objectives of this research project were to determine and to analyze the shear strength of joints in a number of rock types, sampled at different locations. The objective was also to link these strengths to the conditions of the foundations and in particular the condition of the surfaces of the rock joints. The information so obtained can then serve as a data bank for the design of new dams and for the evaluation of the safety of existing dams. The results were obtained for a number of rock types, including dolerite, granite and mudstone and to some extent for basalt and sandstone

6.2 A comprehensive literature study was conducted and it showed that although engineering characteristics of rock material are investigated on a continuous basis for civil and other engineering applications, this information is not readily available to the engineering community because clients and contractors regard it as confidential information. This thesis is a source that describes the shear strength characteristics of southern African rock types available today.

6.3 The emphasis was placed on the shear strength of discontinuities in rock. The basic shear strength parameters of the different rock materials were determined as part of the determination of rock material characteristics. The angles of friction obtained for the different materials correspond very well with those in the literature.

6.4 It was also envisaged to determine the peak and residual shear strength parameters of important southern African rocks. To achieve this objective the Department of Water Affairs and Forestry, in association with a technical subcommittee of the Water Research Commission, had a large shear box apparatus built that was used for the testing of large specimens as well as rock fill material for this project. This thesis describes the design and construction of the apparatus, the test method, the results as well as the interpretation and application of shear testing on large specimens.

6.5 It was impossible to determine the true peak and residual shear strength due to practical limitations. Peak values are therefore approximated by determining the "maximum post-peak" strength, whilst residual values were approximated by "minimum post-peak" values.

6.6 The testing of the specimens with the large shear box apparatus was conducted in three phases. During the first phase the "maximum post-peak" shear strength parameters were determined under dry conditions. The second phases (2A and 2B) involved determination of the "minimum post-peak" shear strength parameters under dry and submerged conditions and the third phase (granite) a record of the polishing effect after repeated testing of three granite samples under dry and submerged conditions. The same specimens were used through phases 1, 2A and 2B.

6.7 The first phase was carried out between 28 September 1995 and 10 June 1996. It was intended to determine the peak shear strength parameters during this phase. This phase of testing consisted of three cycles of shear testing under increasing normal stress. Normal stresses for the testing were in the order of 600, 900 and 1200 kPa.

6.8 Evaluation of the test results of the first phase revealed certain problems. The shear load vs. shear displacement graphs was difficult to interpret. Further detailed investigation discovered a problem with the software controlling the shear- and normal load actuators. It was found that at the start of the shear test, the normal and shear loads increased simultaneously. The normal load should have been at a set maximum before the shear load was applied.

6.9 Before the second and third phases the shear apparatus was inspected and all the bolts and LVDT's were fastened properly. The software used to drive the apparatus was scrutinised to ensure correct instruction during testing.

6.10 The second and third phases were carried out between 25 March 1998 and October 2000. The aim was to determine the residual shear strength parameters during this phase. These tests were conducted under dry and submerged conditions. Each phase of testing consisted of three cycles of shear testing under increasing normal stress.

Normal stresses for the testing were in the order of 600, 900 and 1200 kPa for Phase 2 and 600, 900, 1200 and 1500 kPa for Phase 3.

6.11 The results showed that the shear strength parameters of joints in rock are mainly influenced by (i) the hardness and (ii) the roughness of the joint surfaces. Both these parameters were measured during the study. The hardness of each joint surface was determined with a Schmidt hammer and related to the uniaxial compressive strength as reported by Barton and Choubey, 1977.

6.12 As part of this research project a three-dimensional laser-scanning device was developed. The Department of Civil Engineering of the University of Natal was commissioned to build this apparatus to measure the roughness of joint surfaces. This device measures x, y and z co-ordinates on a rock joint surface on a grid pattern. This information can be manipulated with software on a computer to produce a contour diagram of the joint surface area. From this joint roughness profiles can be obtained.

6.13 A third phase of investigation was undertaken to determine the validity of the test results during the second phase of testing. This was the final phase and concluded the project during October 2000. Three Granite samples were tested in detail. Every sample was tested in a forward as well as reverse direction. Tests were also carried out with the sample saturated. Four normal loads were applied to have four observation points on the graph. It was concluded that although problems were encountered during the second phase of testing, the results obtained can now be used with confidence.

6.14 Emphasis was placed on the shear strength parameters of joints, especially the angle of friction. Two types of joints are recognised in nature: (a) joints with no or little fill material where the shear strength is strongly influenced by the characteristics of the rock material and (b) joints with fill material where the shear strength is determined by the characteristics of the fill material. The major part of this research concentrated on (a) joints with no or little fill material. The three major characteristics determining the shear strength parameters of this type of joint are (i) the base shear strength of the rock material, (ii) the roughness profile along the joint surface and (iii) the hardness of the material on the joint surface.

6.15 A classification system for joints in terms of hardness and roughness were developed. The classification system is described in Table 5.20

6.16 The relationship between joint roughness (in this case JRC was used) and shear displacement was investigated during this study. The influence of high normal stresses were not taken into consideration as testing was limited to normal stresses of maximum 1 MPa. An exponential regression was fitted to the points plotted. After a cumulative shear displacement of more than 2,0 meter will the joint surface be smooth as a result of friction. Then only will the friction angle be equal to the residual friction angle.

6.17 A reasonable correlation (with a confidence limit of 70%) between joint roughness and friction angle exists for the rock types tested. The rock types tested varied in hardness, origin, structure and strength. The conclusion that can be made from this is that rough joints have higher friction angles, with a minimum (basic) friction angle at 30° under dry conditions. In practice this means that a rock mechanics practitioner can measure joint surface roughness on site with a carpenters comb, determine the joint roughness coefficient (JRC) with Barton's joint roughness profiles and use the graph to read of the friction angle of the joint surface for rocks with a hardness of approximately 200 MPa.

6.18 This research has provided the framework from which further research can be undertaken. The infrastructure is now available in South Africa to investigate the relationship between shear displacement and joint roughness. Testing should be carried out under the conditions of low (1 MPa) to high (10 MPa) normal stresses. This could provide a graph showing the relationship of joint roughness (JRC) vs. shear displacement. A reasonable correlation (with a confidence limit of 70%) between joint roughness and friction angle exists for the rock types tested. The rock types tested varied in hardness, origin, structure and strength. The relationship between friction angle and JRC under dry conditions can be expressed as follows:

$\phi = \phi_b + f(JRC)$ where $\phi_b = 30°$

and $f = 1{,}43$

The graph can be used to estimate the friction angle (dry) when the joint roughness coefficient (JRC) is known. In practice this means that a rock mechanics practitioner can measure joint surface roughness on site with a carpenters comb, determine the joint roughness coefficient (JRC) with Barton's joint roughness profiles and use the equation to estimate the friction angle of the joint surfaces.

6.19 This study contributes to the knowledge of shear strength on southern African rock types, in particular on the sampling of specimens, preparation of specimens for testing in the large shear apparatus, the measurement of the roughness and hardness of the joint surface, the testing procedure and the interpretation and application of the results. The roughness index developed from this research as a measure of joint roughness was developed during this research project. To a lesser extent the study provides typical values of the shear strength characteristics of the rock joints.

6.20 It is recommended that a further research be initiated to investigate the shear strength of representative southern African rock types in further detail in a systematic manner. Such an investigation can build on the knowledge obtained in this investigation. It is important to keep the variables such as rock type, weathering, and hardness as few as possible and to investigate the influence of joint roughness.

6.21 A simple tool has been developed that will be of use to engineering geologists and rock mechanics practitioners who require a rapid method to determine the peak angle of friction of a joint surface in the field. If it is accepted that $\sigma_n = 1$ MPa (equal to the stresses normally associated in the foundations of dams and other civil engineering structures) then the value of *i* can be calculated for different JRC vs. JCS values and a graph be drawn as shown in Figure 4.19 on page 4.34.

6.22 Any experienced engineering geologist or rock mechanics engineer can now estimate [by estimating (or measuring) in the field] the JRC and the JCS (in terms of UCS) of a joint surface and by using this chart, determine the contribution of the surface characteristics to the portion of peak angle of friction. By adding the contribution of the waviness (Table 4.23 on page 4.35) as well as the basic friction angle, the total peak friction angle can be calculated.

6.23 Where fill is present on a joint surface, the fill thickness is of great importance. It is postulated that there is a relationship (FTC) between fill thickness JRC which has a value between 0 – 1.

For filled joints the modified Barton & Choubey equation becomes:

$$\tau = c_t + c_b + \sigma_n \tan [JRC . \text{JMC} .(1\text{-FTC}) \log_{10} (\text{JCS}/\sigma_n) + (1+\text{FTC}) \phi_b + (\text{FTC} . \phi_f) + i]$$

Where: τ = peak shear strength; σ_n = effective normal stress

JRC	= joint roughness coefficient	JCS	= joint wall compressive strength
ϕ_f	= friction angle of fill	JMC	= joint matching coefficient
c_t	= true cohesion (fill)	c_b	= bridging strength
i	= effect of waviness resulting in change of direction		
FT	= Fill thickness in mm	FTC	= -0,07 ln (JRC+1/FT+1) + 0,5
ϕ_b	= basic friction angle of rock.		

This relationship could further be investigated.