CHAPTER THREE
THE EXPERIMENTAL STAGE OF THE STUDY

3.1 Rock types tested

During the planning stage of the study of the shear strength of joints in rock it was envisaged to select as many of the rock types covering the surface and near surface in southern Africa as possible. Potential sites where rock material samples could be taken were identified. These sites were in most cases dam sites, although road cuttings and quarry sites were also included. Various rock types were sampled and subsequently tested. Figure 3.1 shows the origins of the samples discussed in this chapter.

Figure 3. 1 **Location where samples of rock material with joints were taken**

Block samples for shear testing in the large shear box were taken at the sites of dams under construction as well as at one road cutting. The purpose of the large scale testing was to determine the peak and residual shear strength and the influence of the surface characteristics (mainly hardness and roughness) and scale on the shear strength. Large shear tests were carried out on block samples with surface areas ranging from approximately 100 x 100 mm to 300 x 300 mm. Table 3.1 presents the rock types and origins of the block samples that were tested.

During the taking of large-scale samples for shear test care must be taken as not to damage the shear surface. Large shear tests were carried out on block samples with surface areas ranging from approximately 100 x 100 mm to 300 x 300 mm. The samples are extremely sensitive to disturbance during sample taking, transportation, preparation, and testing. During sampling, transportation and preparation of samples extreme care was taken as not to damage samples and it can be reported that damage to surfaces were very limited and it can be stated that joint surfaces tested were very similar to joints conditions in situ, with the exception of moisture content. Samples were taken from the sites that were of a small enough size to fit the laboratory shear box so that cutting and associated damage to the shear surface was limited to a minimum. Generally joint fill material got dried out during the period between sample taking and testing that could have been as much as eighteen (18) months. During the final phase of testing water as added to the shear box to test the shear strength under saturated conditions.

ROCK TYPE	GEOLOGICAL SUCCESSION	SITE
Basalt	Karoo Supergroup	Lesotho Highlands Water Scheme
Dolerite	Post Karoo	Qedusizi Dam, Ladysmith
Granite	Archaean	Driekoppies Dam
Sandstone	Natal Group	N3 Cutting, Darnall
Mudstone(Shale)	Karoo Supergroup	Qedusizi Dam, Ladysmith
Quartzite	Cape Supergroup	Skuifraam Dam site, Franschhoek
Granite	Archaean	Nandoni Dam

Table 3. 1 **Selected rock types (large rock samples) tested with the large shear box**

Only six rock types were tested in the large shear box apparatus due to the difficulties in obtaining samples as well as the duration of the testing process. The quartzite samples from Skuifraam dam site, Franschoek were very brittle and disintegrated during sample preparation and testing. No results for this rock type could be obtained. Samples tested went through three phases of testing. The first phase was carried out dry and could, in hindsight, be seen as part of the learning curve for the new large shear apparatus. The second phase was carried out after problems with the machine were eliminated. Each sample was tested three times dry and then three times under saturated conditions. Eventually third phase tests were conducted on three additional granite specimens.

3.2 Apparatus used in testing

The different apparatus used in this research is discussed in this paragraph.

3.2.1 Shear boxes

Two types of shear tests were conducted. The tests were conducted on

(i) samples with saw cut surfaces tested on a modified soil shear box and

(ii) large samples with natural joint surfaces tested on the large shear box of the Department of Water Affairs and Forestry.

3.2.1.1 The small shear box.

Basic shear strength and shear strength of joints (peak and residual) of NX size core samples were tested on this test apparatus. A Soiltech soil shear box was modified for this purpose. The original sample box was removed and replaced by a clamp mechanism to accommodate the NX size rock core samples. The bottom sample holder is fixed to the frame of the apparatus while the upper sample holder can move along the line of shear. The normal load is applied through a yoke and hanger system where the normal load is increased by adding additional weights. The shear load is applied by a motorized worm drive acting on a load cell transferring the load to the upper sample holder assembly. Vertical dilation and horizontal movements are measured by means of linear variable displacement transducers (LVDT's).

Three loading cycles were carried out on each sample. Normal stresses of 55 kPa, 105 kPa and 1,55 MPa were applied and the corresponding shear loads were measured.

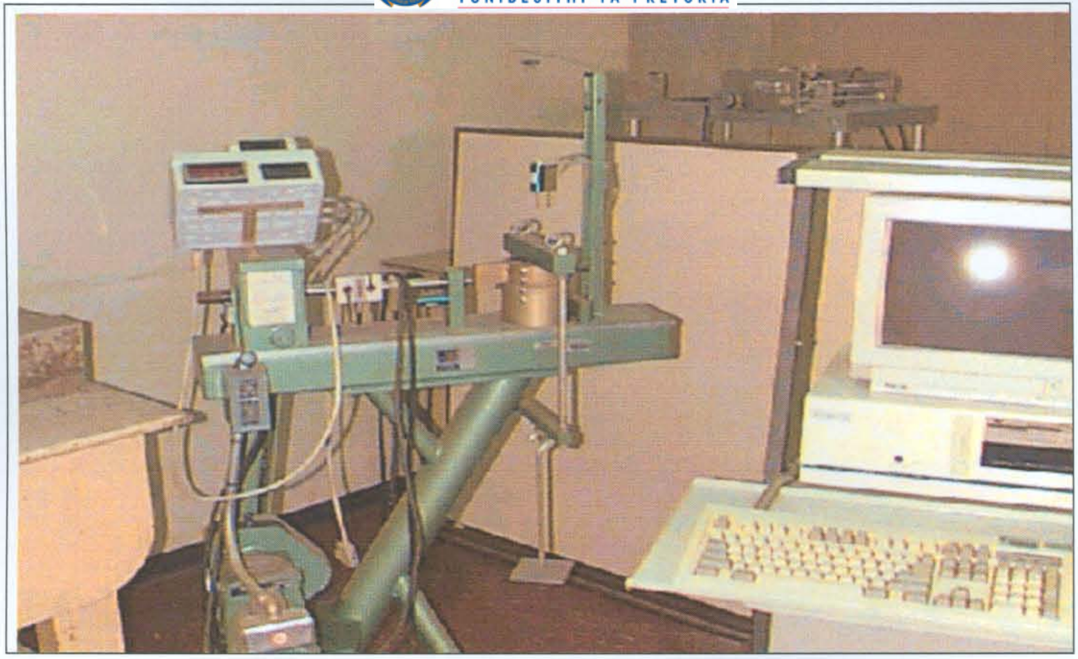

Figure 3. 2 **The modified soil shear box for shear testing of NX-size rock core samples.**

The shear process is computer controlled and data retrieval is done through a data acquisition unit connected to a PC. Figure 3.2 shows the laboratory set-up. The maximum displacement was 10 mm. After each cycle the upper sample holder containing the sample was returned to its original position before applying the next higher load. The measurements are illustrated in graphic form as shear load vs. shear displacement and shear stress vs. normal stress available in Appendices A and B. Results of the testing are discussed in chapter four. Raw data in the form of tables and graphs are in Appendixes A and B.

3.2.1.2 Large shear box of the Department of Water Affairs and Forestry

The apparatus

The machine was designed and built in such a way, that specimens of rock or soil of a maximum size of 350 x 350 mm can be tested under normal loads of up to 200 kN and shear loads of up to 500 kN - illustrated in Figure 3.3.

The machine consists essentially of an arrangement to accommodate the specimen to be tested, a mechanism to apply different constant vertical loads on the specimen and a mechanism to apply shear loads, in a direction perpendicular to the normal load.

Figure 3.3 **The large shear testing machine**

A line drawing of the machine is presented in Figure 3.4 (side view) and Figure 3.5 (front view). Suitable instrumentation to measure and record forces and displacements is also provided.

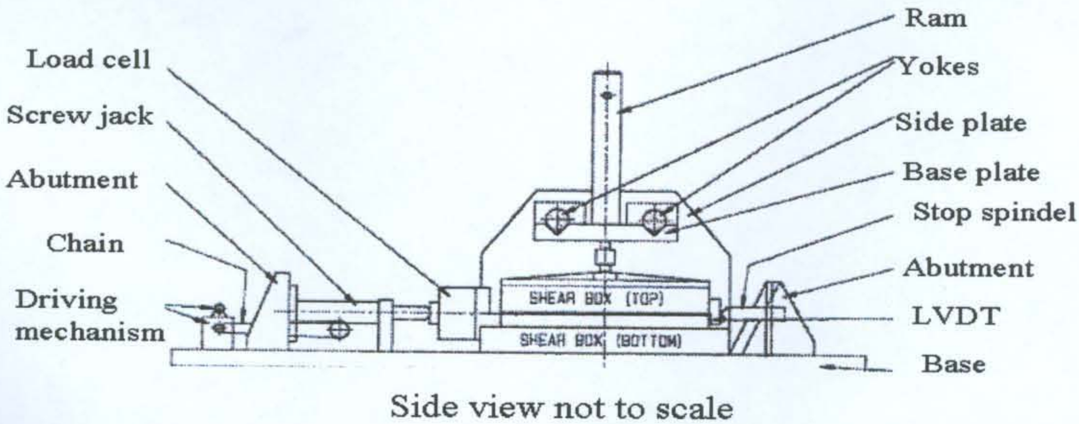

Figure 3.4 **Schematic sketch of large shear testing machine (side view)**

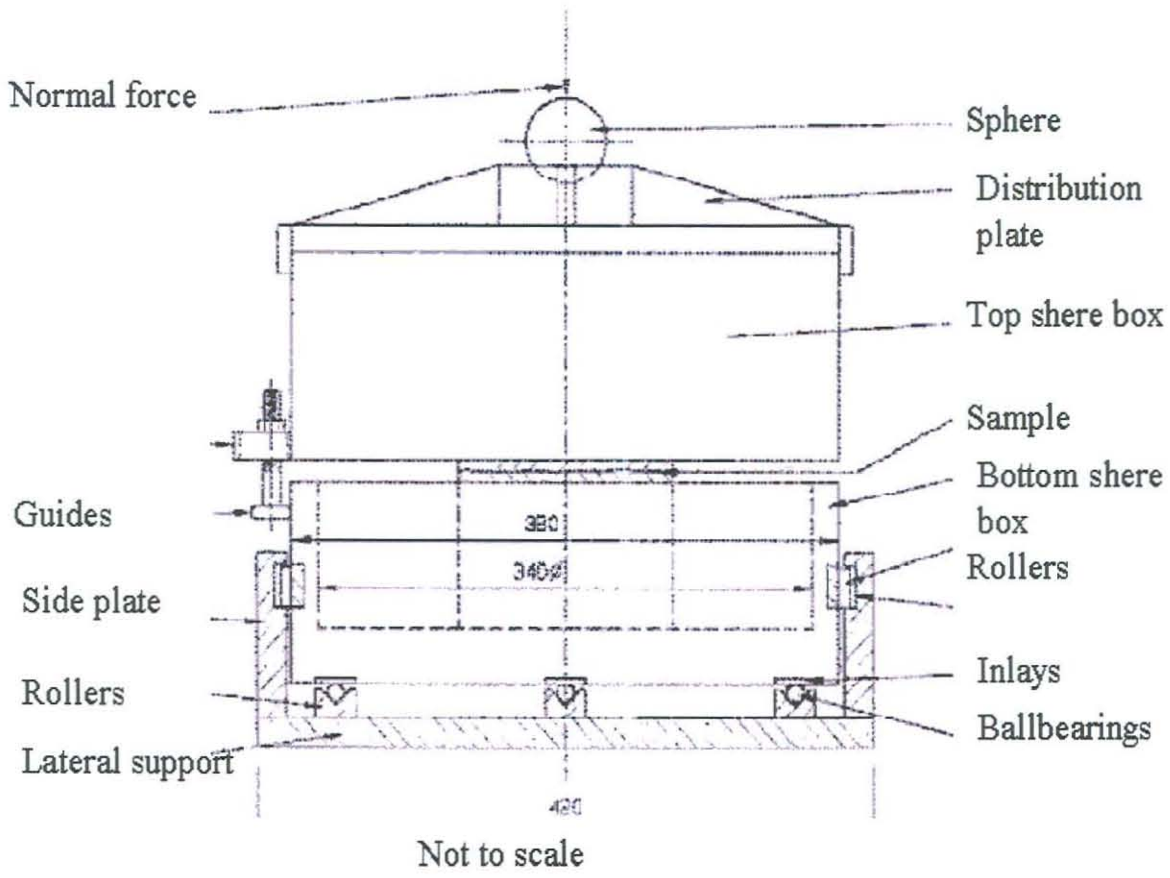

Figure 3. 5 **Schematic sketch of large shear testing machine (front view)**

Shear box assembly (specimen accommodation)

The shear box assembly consists of two different parts, a lower half and a top half. The lower half accommodates one half of the specimen and represents the mobile part of the shear box i.e. shearing takes place underneath the top half, which is kept horizontally stationary. Via a yoke the bottom part is in direct contact with the mechanism which provides the force necessary for shearing.

Suitable roller bearings ensure low friction gliding of the lower half over a rigid, machined base plate. The base plate is fitted to a strong frame, to which all other stationary machine components are fitted. The lateral support of the bottom part is provided by needle bearings.

The top half accommodates the other half of the specimen and is separated from the bottom part by a gap, which is aimed to be 5 mm.

The direction of the shear force is in line with the shear plane. Provision is made for adjusting the gap between the bottom and top parts of the shear box and for adjusting the direction of the shear force to suit the specimen as described above.

To prevent side way drifting of the top part during testing side, guides are provided which are in firm touch with the corresponding outside flats of the bottom part.

Provision is made for testing the sample under wet conditions by a water bath. The water bath allows for immersion of the entire test sample in water. The water bath is designed not to interfere with either the transfer of loads onto the specimen or with the measuring of displacements.

Provision is made to protect the lower shear-box assembly from water and moisture when testing specimens under wet conditions.

Both shear box parts are equipped with clamps for temporary immobilization and hooks are provided at suitable positions on both parts to facilitate the handling of the equipment during assembly, testing and dismantling.

Three shear box assemblies were manufactured, having the following inside dimensions:

Box No. 1: 350 x 350 mm Square
Box No. 2: ø 350 mm Round
Box No. 3: ø 150 mm Round

All three boxes have sufficient wall thickness to minimise deformations caused by loads acting on them. Figure 3.6 illustrates the square box.

Figure 3.6 **Bottom half of shear box assembly with test specimen**

Load distribution plate

On the top part of the shear box assembly a stiffened load distribution plate is placed. In the geometrical center of the stiffened plate a spherical seating is provided through which the normal loads are applied.

For each of the square or round boxes, two different load distribution plates were manufactured:

(a) one plate which fits loosely over the outside of the top part and

(b) one which fits with enough clearance into the respective square or round cavity of the top part.

The clearance of the plates on the sides of the shear box and the method of providing for vertical movement of the plates is sufficient to ensure free unhindered vertical travel of the load plates up to 10 mm.

Application of normal loads

The normal load is applied on the seating of the load-distribution plate by means of a hydraulic cylinder. The maximum capacity is 200 kN. During the test the mechanism is able to maintain any specified load of up to 200 kN constant, to ± 2 %, regardless of any volume change of the specimen. The apparatus was designed so that no tilting of the shear box with the specimen during testing was allowed. The reason for this is that on this scale, no tilting takes place under a dam foundation as a result of confinement.

Application of shear forces

The shear force is applied in the horizontal direction. The mechanism that generates the force is a hydraulically operated and strain-controlled hydraulic jack. The shear force is applied continuously and can reach up to 500 kN.

The rate of shearing, i.e. the horizontal displacement, measured at the bottom part of the shear box assembly within a certain period of time, can be pre-selected in steps of 0.2 mm/min. from 0.2 mm/min. to 5.0mm/min. The maximum shear displacement is 50 mm.

Data measurement and acquisition

All forces and displacements are measured electronically. The recording of the voltage outputs is recorded continuously. The measurement of the normal and the shear forces are done by means of suitable load-cells.

A total of five interchangeable load cells with capacities of 50, 100, 150, 200 and 500 kN can be used. Suitable mountings for the load cells are provided. The combined error for linearity and hysteresis of each load cell is less than 0,10 % of the RO (rated output mV/V ± 0,1 %).
The measurement of the relative horizontal movement between the two halves of the shear box assembly (shear displacement) is measured by two LVDT's (linear variable differential transducers), with a stroke of 50 mm and a linearity of better than 0,25 % RO. The LVDT's are positioned at the upper left and right hand corners of the bottom part of the shear box assembly. The electrical wiring of the LVDT's is done in such a way that their combined output represents the average displacement. The mountings (clamps) for the bodies of the LVDT's are rigid and shock resistant. The contact points for the spring-return armatures are smoothened.

The vertical displacement (dilation) is measured by two LVDT's with a stroke of 20 mm and a linearity of better than 0,25 % RO. The two LVDT's are positioned in the middle and at opposite ends of the load distribution plate.

3.2.2 Apparatus for the measurement of roughness

3.2.2.1 Laser apparatus

During the course of this investigation a laser-scanning device was developed and built.

The apparatus

The laser is built on a sturdy frame 750 mm long by 500 mm wide, allowing samples up to 600 mm by 350 mm. Figure 3.7 clearly shows the scanner head which moves in a longitudinal direction above the sample.

A laser displacement sensor is attached to this head, which is moved along the guide rails by a stepper motor driving a toothed belt by means of two toothed gear wheels.
The rotational movement of the stepper motor produces an incremental movement of the

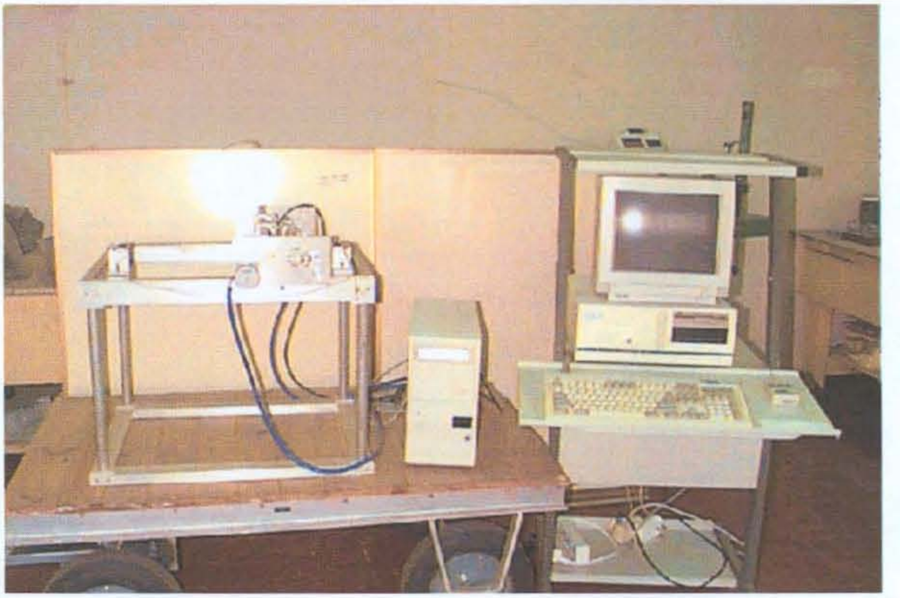

Figure 3. 7 **The laser scanning device**

scanning head which in turn allows the rock sample to be scanned in steps in the X-direction. This longitudinal scanning frame is attached, on one side, to the transverse moveable carriage, which allows movement in the Y-direction. The other end of the longitudinal frame is supported on a linear bearing, along which it moves. The transverse moveable carriage is driven along two guide rails by a second stepper motor arrangement.

The size or number of steps and thus the speed of rotation of the stepper motors are determined by the number of electrical pulses and the frequency of the input signal respectively. The laser displacement sensor uses a 3 mW helium-neon semiconductor laser diode producing a light with a wavelength of 780 nm and a spot diameter less than 2 mm. It can measure distances between 50 and 130 mm, with a resolution of 50 μm at a 100 ms response time, or 150 μm with a 10 ms response time. The light is reflected off the surface to be measured and is received by a position sensing diode, which allows a stepped incremental signal to be output. This voltage output is directly related to the distance measured so that the latter may be simply determined.

Method of operation

The sample to be scanned is placed on the base plate against a reference bar in order to ensure accurate positioning and is oriented such that the direction of shearing is parallel with the longitudinal scanning head. A wide range of sample thicknessess can be accommodated because of the large measuring range of the laser sensor. Once the sample has been positioned the longitudinal and transverse scanning ranges of the apparatus can be set by positioning the micro switches appropriately. In this way only as small an area as required is scanned. The working sequence of the scanner is programmed and completely automated by the use of a PC connected to a control box via an RS-232 serial port.

Once the scan program has been started and the relevant information entered, scanning can commence. Both stepper motors are initially moved so that the laser displacement sensor is positioned at the starting point as dictated by the positions of two micro switches. This point is to the left and below the actual sample to be scanned. The scanning head is then moved incrementally to the right in the X-direction by applying pulses to the stepper motor. When the scanning head reaches a limiting micro switch the head returns to the left limit of its travel and the entire longitudinal scanning frame is moved by one increment in the Y-direction. The scanner head then again begins to move to the right in the X-direction and the process is repeated until a fourth micro switch triggers the end of the scanning process.

The profile of the sample is only measured as the scanner head moves from left to the right in the X-direction. The X- and Y- coordinates are determined from the number of pulses fed to each of the stepper motors and the distance between the scanner head and the joint surface is measured at each increment directly by the laser sensor.

The increment in the X- and Y-directions can be set separately, such that the Y-direction increment can be any multiple of the X-direction increment. For a small joint surface approximately 80 mm by 55 mm in size, and using a scan increment of 0.5 mm, the entire surface can be scanned in 25 minutes, producing a data file containing approximately 18 000 data points.

The accuracy and relevance of the results that are obtained from the scanner are influenced by the increments between individual data points. A large increment will produce a coarse and largely non-representative profile whereas a very small increment may provide too much information for processing and will greatly increase the time taken to build up a complete three dimensional picture of the surface roughness.

3.2.2.2 Alternative method of determining joint roughness.

An alternative method to measure joint roughness is with the use of a carpenter's comb. The carpenter's comb consists of a number of vertical steel or plastic pins that can individually move up or down to resemble the face of a two dimensional surface. This tool can be used to determine the unevenness of a joint surface in two dimensions by placing it directly onto the surface. Fig 3.8 illustrates this principle. This apparatus was used to measure and record the roughness profiles of joint surfaces. These roughness profiles were then compared to Barton's roughness profiles (Figure 2.9) and the joint roughness coefficient (JRC) for each sample determined.

Figure 3. 8 **Carpenter's comb on rough joint surface**

3.3 Tests methods for basic, peak and residual shear strength

Barton (1993) states that both angles of basic (ϕ_b) and residual (ϕ_r) friction represent minimum shear resistance. Conceptually ϕ_b refers to smooth planar surfaces in unweathered rock and can be considered as a material constant. The residual friction angle (ϕ_r) refers to the residual condition of natural joint surfaces, which is attained after large shear displacements. If the natural surface is unweathered, ϕ_r can be taken to be equal to ϕ_b.

3.3.1 Testing basic friction angle with the small shear box

Methods for basic angle of friction (ϕ_b) characterization include the direct shear test or tilt tests on saw cut surfaces (Barton and Choubey, 1977).
These tests were carried out with the converted soil shear box, as described in paragraph 3.2.1.1, on saw cut surfaces of NX size core samples. NX size core samples were cut perpendicular to the core axis with a diamond saw. The saw cut surface was then shaved by brushing the sample under its own weight on a fine sanding paper. The test was carried out under dry conditions. Results of this testing are discussed in chapter four.

3.3.2 Testing shear strength with the large shear box

Sampling procedure

Sampling of rock specimens with associated joint surfaces is a difficult procedure because a joint surface is delicate and that must be preserved in its original state for testing.

The size of the final sample is determined by the size of the shear box assembly. Two boxes were used with the following dimensions: 350 x 350 mm square and 350 mm diameter. Samples were carefully selected in a rock mass on site and the surrounding rock material removed. Samples were taken out by hand with the use of a handspike "koevoet" and "Hilti" drill. Then the two rock material pieces with associated joint surface were carefully wedged out and placed on the floor and packaged for transport to the laboratory. Extra rock samples were taken as to compensate for damage during transportation and casting.

Sample preparation

In the laboratory a suitable sample was selected and tied up with wire, with the joint surfaces in their original relative position. Figure 3.9 illustrates this principle.

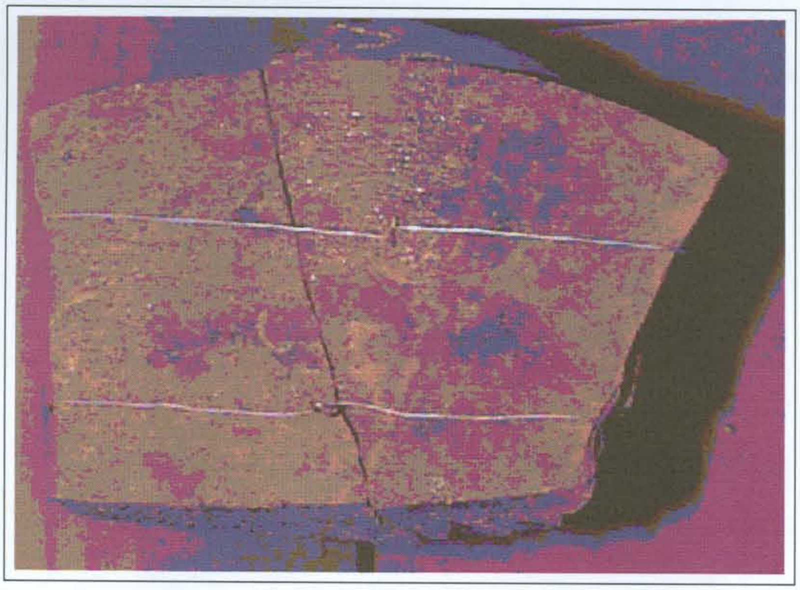

Figure 3. 9 **Rock sample with associated joint surface tied, up with wire ready to be cast**

The sample is then placed into the top box (upside down position) and the joint surface orientated parallel to the shear plane. It is positioned such that the shear surface is approximately 10 mm above the top of the shear box rim. A casting agent (cement grout) is then prepared and cast into the top half of the box with the sample in position. The grout is poured into the box to about 20 mm below the rim of the box. The grout is made up of the following ingredients: 20 kg building sand, 5,25 kg cement, 2,25 kg slagment, 10 ml plastisizer, and ± 3,9 liters water. The grout is then left for two days to set. Figure 3.9 illustrates a rock sample with joint cast in the shear box.

The bottom part of the box is then bolted onto a special jig to keep it in position and filled with grout to about 40 mm below of the rim of the box. The top part of the box with the sample in place can now be turned around and gently lowered onto the bottom part until the joint surface is about 10 mm above the rim of the bottom part. Now it can be bolted to the jig and left for two days to set. When completely set, the wire holding the sample together can be cut and the moulds removed from the jig and moved to the testing machine.

Testing procedure

The prepared sample in the shear box assembly is placed into the shear box machine. The whole testing operation is computer controlled.

The software supports a variety of shear testing procedures as well as keeping record of all the results. Mounted inside the PC is an ADC/DAC card, which interfaces the software to the testing machine. This interface enables the software to read the load signals and controls the speed of the drive motor. When the software is loaded, the first menu is activated on the screen. Selecting the options on the screen and entering the required information carries out the test by keyboard.

The normal load is applied for at least 20 seconds before the shear load is activated. Normal stresses of 0.6, 0.9 and 1.2 MPa were decided upon and depending on the area of the sample to be tested, the corresponding loads were calculated and fed into the programme. The mass of the top half including the plate for transferring the load to the sample was determined and included in the calculation of the normal load. Shear load is applied at a rate of 2 mm per minute.

The data acquisition unit captures data every two seconds. These data consist of normal load by means of a pressure transducer, vertical movement by means of two vertical LVDT's, horizontal movement by means of two horizontal LVDT's and shear load by means of a load cell. The test was terminated when the horizontal movement reached a maximum of approximately 20 mm.

A test cycle was conducted for each normal load and the corresponding shear load obtained. Thereafter graphs of shear stress vs. normal stress were plotted and values for the angle of friction and cohesion were calculated.

Tests were carried out on basalt, dolerite, granite, sandstone and mudstone samples. Samples were tested a first time through three cycles dry and then photographed (Appendix F). After interpretation of the results, it was decided to run another three cycles of dry testing and then three cycles wet. (Submerged under atmospheric conditions). After the completion of a the "dry" tests, the same samples were saturated and "wet" tests were done to compare the results and to get a "dry - wet" relationship.

Evaluation of the large shear apparatus

The large shear apparatus is the only shear test apparatus of its kind in southern Africa. The **advantages** of the machine are that it can be used to determine the shear strength parameters of relative large rock specimens. The expertise has now been developed to prepare samples, execute the test procedure and interpret the results. The machine can also be used to determine the shear strength parameters of other materials such as gravel's or even simulated rock fill materials.

The **disadvantages** of the method are that it is difficult to take specimens from rock mass while ensuring that both joint surfaces remain intact. Great care should also be taken with transportation. The preparation and testing process is very time-consuming.

It should be noted that the true peak shear strength of a joint could theoretically only be measured if at least three identical specimens can be tested at different normal stresses.
Since three or more identical specimens are never available, true peak shear strength can not be determined in practice. If a single specimen is used, some of its peak shear strength (roughness) is removed after the first shear failure. The second and further shear failures

therefore represent "post-peak" shear strength. After many tests on the same specimen, most of the roughness has been removed, and the residual or basic shear strength is approached.
In this test programme, the "maximum post-peak" (max p-p) friction angle is considered to be an conservative measure of the true peak friction angle. The "minimum post-peak" (min p-p) friction angle is taken to fall somewhere between the peak and the basic friction angles.

3.3.2.1 Phase 1 testing

The first phase consisted of three tests at different vertical stresses, i.e. at approximately 600, 900 and 1200 kPa on dry rock samples. It was expected that this test phase would result in the determination of the max p-p shear strengths.

After analysis of the data it was decided to check the large shear apparatus for any possible defects since the results were difficult to interpret. After adjustments to the apparatus and amendments to the software controlling the machine the second and third phases were carried out. Adjustments to the apparatus included repositioning of LVDT attachments, while the software was partially rewritten to change the commands regulating the horizontal and vertical forces. During the first phase of testing the shear and normal forces were initiated simultaneously, which meant these forces, increased simultaneously to the set levels. This was changed to allow the normal force to reach its predetermined level before the shear force was initiated. Results of this testing phase are presented in Appendices C and D, and on the compact disc (CD) included in this report.

The results obtained during the first phase of testing must be regarded as unreliable as they were not conducted in accordance with standard testing methods due to the way the software controlling the application of stresses on the sample. The results are however included and compared with residual shear strength results as obtained from the second and third phases of testing.

3.3.2.2 Phase 2 testing

The second phase consisted of two sub phases, referred to as phases 2A and 2B. Phase 2A was conducted on the same rock specimens as tested in Phase 1. This was done after adjustments to the large shear machine and software controlling the shear process had been made. The same normal stresses as used during Phase 1 were applied. At the beginning of this stage each specimen had already been sheared three times and it was accepted that the results obtained were approaching the residual shear strength. Supportive documentation is available in Appendix E and F.

Phase 2B was carried out immediately after Phase 2A, without removing the specimen from the apparatus. All tests were conducted in the same manner as during phase 2A but the shear box was filled with water to simulate submerged conditions. Supportive documentation is available in Appendices E and F.

3.3.2.3 Shear strength of joints in Granite - Phase 3

The third phase of the investigation involved the taking of the three new samples. A suitable site for sampling specimens for the third phase of testing was located at the Nandoni Dam presently under construction in the Limpopo (Northern) Province near Thohoyandou. A number of large samples were taken for shear testing in the laboratory. These samples were all taken from the quarry at the dam site as no suitable samples could be found in the dam foundation. They were all excavated from the rock mass with hand held tools. Care was taken that the joint surfaces were not damaged during the sampling process. Table 3.2 gives a description of the three granite specimens tested.

They were numbered Granite 1C, 2C and 3C and prepared as described in chapter two of this report.

Specimen	Surface characteristic	Schmidt rebound Number	JRC
Granite 1C	Rough clean	62	6 – 8
Granite 2C	Rough - FeO_2 stained	61	4 – 6
Granite 3C	Rough - hard joint fill	58	10 – 12

Table 3. 2 **Granite specimens tested during the third phase of the investigation**

Although the three samples were taken from the same granite site it was not possible to get samples from the same continuous in situ joint surfaces. On closer inspection it was found that there were some variations in the characteristics of the joint surface sampled. Granite 1C had the smallest surface area of 15950 mm^2. The surface was not stained or covered by any joint fill. Granite material formed the contact surface. Granite 2C had a surface area of 30600 mm^2. The surface was lightly stained with iron oxide. No joint fill was present. Slightly weathered granite material formed the contact surface. Granite 3C had a surface area of 31500 mm^2. The surface was covered with joint fill in the form of a greenish secondary mineral. The joint fill material formed the contact surface. The joint roughness (JRC) of the three samples was approximately the same.

Testing during Phase 3A was carried out at effective normal stresses of approximately 600, 900, 1200 and 1500 kPa. It was decided to use four normal loads as this would give greater accuracy with four points on the shear stress vs. normal stress graph. Testing was carried out in a forward direction and then the sample was cleaned (all debris of the previous test removed by blowing it off the surface), turned 180° around, and tested in the opposite direction (reverse). The reverse tests were also carried out at the same normal stresses. Thereafter the samples were tested in the forward direction under submerged conditions, using the same four normal loads. This was Phase 3B of the investigation. Supportive documentation is available in Appendices G and H.

3.4 Self evaluation

In hindsight, the following aspects of the project is worth noting:

- A project of this magnitude should be approached as a team effort and preferably on a full time basis. This project was carried out by on a part time basis over a long period. The minority of research projects in South Africa is carried on a full time basis due to the shortage of expertise. In contrast to researchers in the USA, UK and Europe the majority of researchers (Masters and Doctorate students) at South African tertiary educational institutions are enrolled in a part time capacity. This means that the have divided interests and that the research project is secondary to their daily occupation and responsibility to their employer. This results in many projects taking much longer and initially planned and loss of coherent ness of data and information in such reports.

- It is important to define the scope of a project at the start of the project and not allow the project to 'grow' during the course of the project. When additional interesting research aspects emerge during the project they should be treated as separate projects.

- A large shear-testing machine was designed and built as part of the research project. This was a time consuming task and many people were involved. These included staff of the Department of Water Affairs and Forestry, different members of the steering committee of the Water Research Commission, the researcher and a contractor. Looking back at the process from initiation to commissioning of the machine, it can be concluded that the whole process was very well organized and the end product very suitable for the purpose it was built. The only problem identified was that the software controlling the stresses, which was rectified after interpretation of the first set of results was analyzed.

- During the taking of large-scale samples for shear test care must be taken as not to damage the shear surface. Large shear tests were carried out on block samples with surface areas ranging from approximately 100 x 100 mm to 300 x 300 mm. The samples are extremely sensitive to disturbance during sample taking, transportation, preparation, and testing. During the project extreme care was taken as not to damage samples and it can be reported that damage to surfaces were very limited and it can be stated that joint surfaces tested were very similar to joints conditions in situ, with the exception of moisture content. Samples were taken that were of a small enough size to fit the laboratory shear box so that cutting and associated damage to the shear surface was limited to a minimum. Generally joint fill material dried out during the period between sample taking and testing that could have been as much as eighteen (18) months. During the final phase of testing water as added to the shear box to test the shear strength under saturated conditions.

- During 1995 a laser-scanning device was built to determine the 3D roughness of joint surfaces. In hindsight, this apparatus should have been used more extensively in the determination of the volume of material that was removed from the joint surface during each shear. The relationship between volume of material removed during each shear and friction angle will give interesting results and should be investigated further.