DATA ACQUISITION AND ANALYSIS SYSTEM FOR THE APPLICATION OF TRIAXIAL TEST AND DIRECT SHEAR TEST IN DETERMINING THE RESIDUAL SHEAR STRENGTH OF CLAYS FROM LANDSLIDE SITE

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CHAPTER I

INTRODUCTION

Large scale landslides are usually categorized as catastrophic and are generally well documented. On the other hand, smaller scale backslope slides in highway constructions are less dramatic, however, they constitute a large maintenance problem for transportation departments. For routine highway construction programs with limited budgets, it is unlikely that a thorough geotechnical survey or slope stability analyses will be conducted along the entire route. Consequently, remedial measures are frequently required for the associated smaller scale landslides. In order to establish a feasible remedial plan, it is necessary to study the stability of slopes after the occurrence of the landslides.

Researchers have shown that the stability of a slope with a pre-existing failure surface is closely related to the residual shear strength of the soil[1,2,3,4,5,6,7,8]. The residual shear strength, defined as the ultimate post-peak strength of soils after large strain, poses several problems for determination of strength parameters in the soil mechanics laboratory. First of all, the conventional testing apparatus may not be able to provide the large strains required for the soil sample to reach its residual shear strength. Second, the testing period becomes lengthy. Finally, the data analysis procedures require modifications to accommodate the large strain condition. Laboratory automation, in this case, is an acceptable solution to the problems.

In recent years, laboratory automation has become a major trend in most disciplines of engineering. The main benefit for employing a laboratory automation scheme is to increase the productivity of engineers. The engineer can be released from constantly monitoring the test. In addition, the probability of human errors can be reduced in both data acquisition and data analysis, thus the results from computerized data collection can be reduced in a more standardized and efficient manner.

When evaluating the feasibility of a laboratory automation scheme, laboratory test equipment and required testing time are the two most important factors to be considered. That is, the longer the time required the more engineering effort can be saved. In addition, a laboratory test which was originally conducted mechanically is easy to convert to computer control and automatic data acquisition.

Although there are apparatus developed solely for the determination of the residual shear strength of soils, modifications made to the existing testing machines serve the same purpose in a more convenient and economical manner. Triaxial compression tests and direct shear tests are two common testing procedures used in determining the strength characteristics of soils. Consequently, they become the prime candidates for the application of laboratory automation.

This research includes three phases, 1) development of a data acquisition and analysis system including modifications to the direct shear and triaxial compression test apparatus, 2) applying the system for determination of the residual shear strength of clay samples taken from a landslide site in Eastern Oklahoma, 3) evaluation of the stability of the slope after previous landslide. In addition, the effects of different sample preparation methods, laboratory test methods and data reduction schemes will be discussed.

CHAPTER II

LITERATURE REVIEW

Shear Strength Concept

Stresses at a point within a solid can be represented as the combination of principal stresses, see Figure 1a. At this specific point, shear and normal stresses change with different orientation in space (Fig. 1b). In soil mechanics, σ_2 and σ_3 are considered equal to each other. This reduces the 3-dimensional problem to 2-dimensional plane stress problem. The corresponding 2-D stress diagram is shown in Figure 2a. For this 2-D stress condition, Mohr's circle (Fig. 2b) represents the normal and shear stresses combinations for all possible planar orientations.

All materials fail under certain stress condition. This specific condition is defined as the failure criteria, and the corresponding stresses relationship indicates the strength of the material. If all possible principal stresses at failure are plotted in the principal stress space, see Figure 3a, a failure envelope (strength envelope) will be formed. For an assumed failure criteria, the failure envelope marks the limit of principal stresses that could exist in the material.

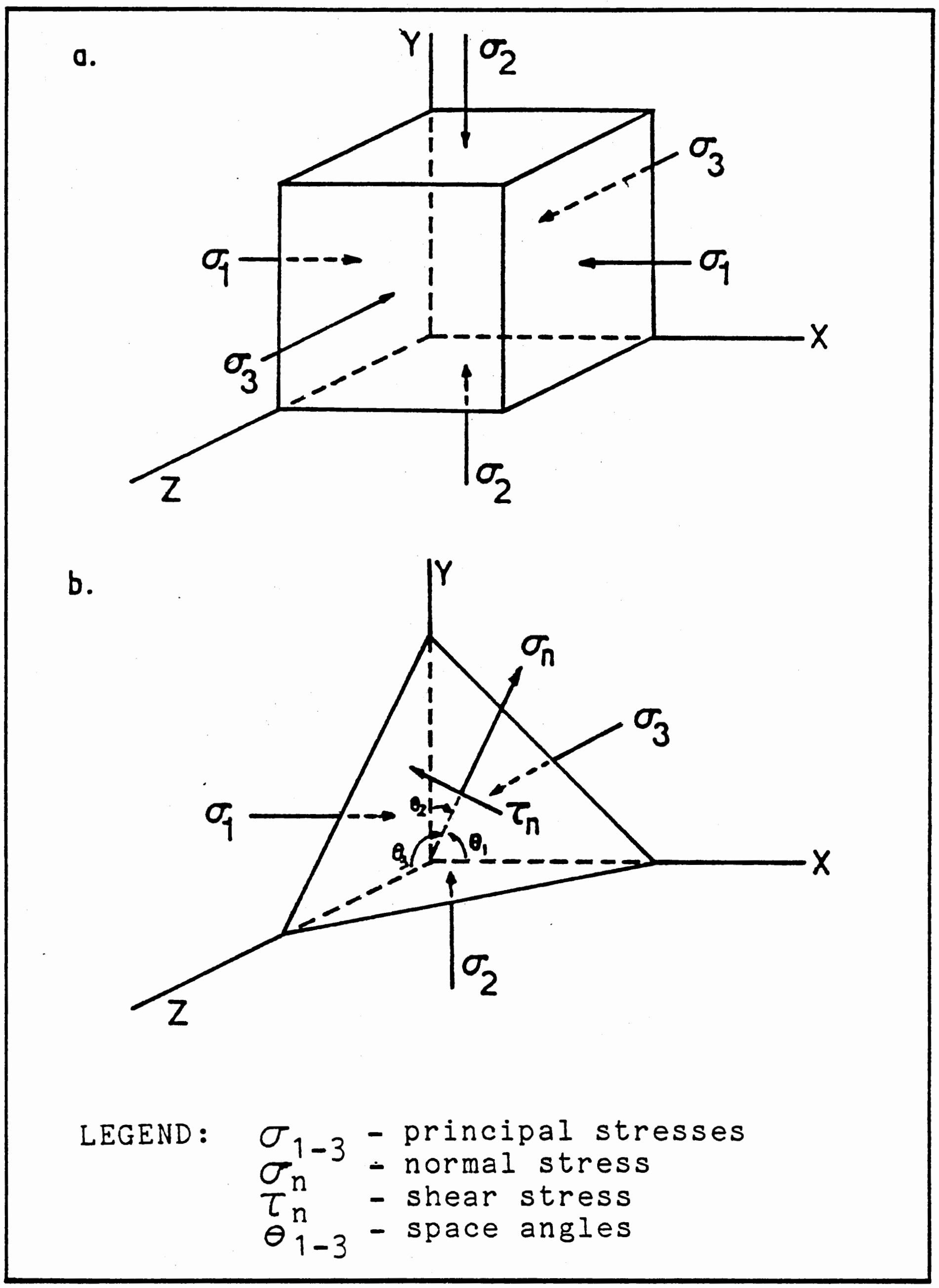


Figure 1a. Three-Dimensional Principal Stresses Acting on A Point.
1b. Three-Dimensional Shear and Normal Stress at Arbitrary Space Direction.

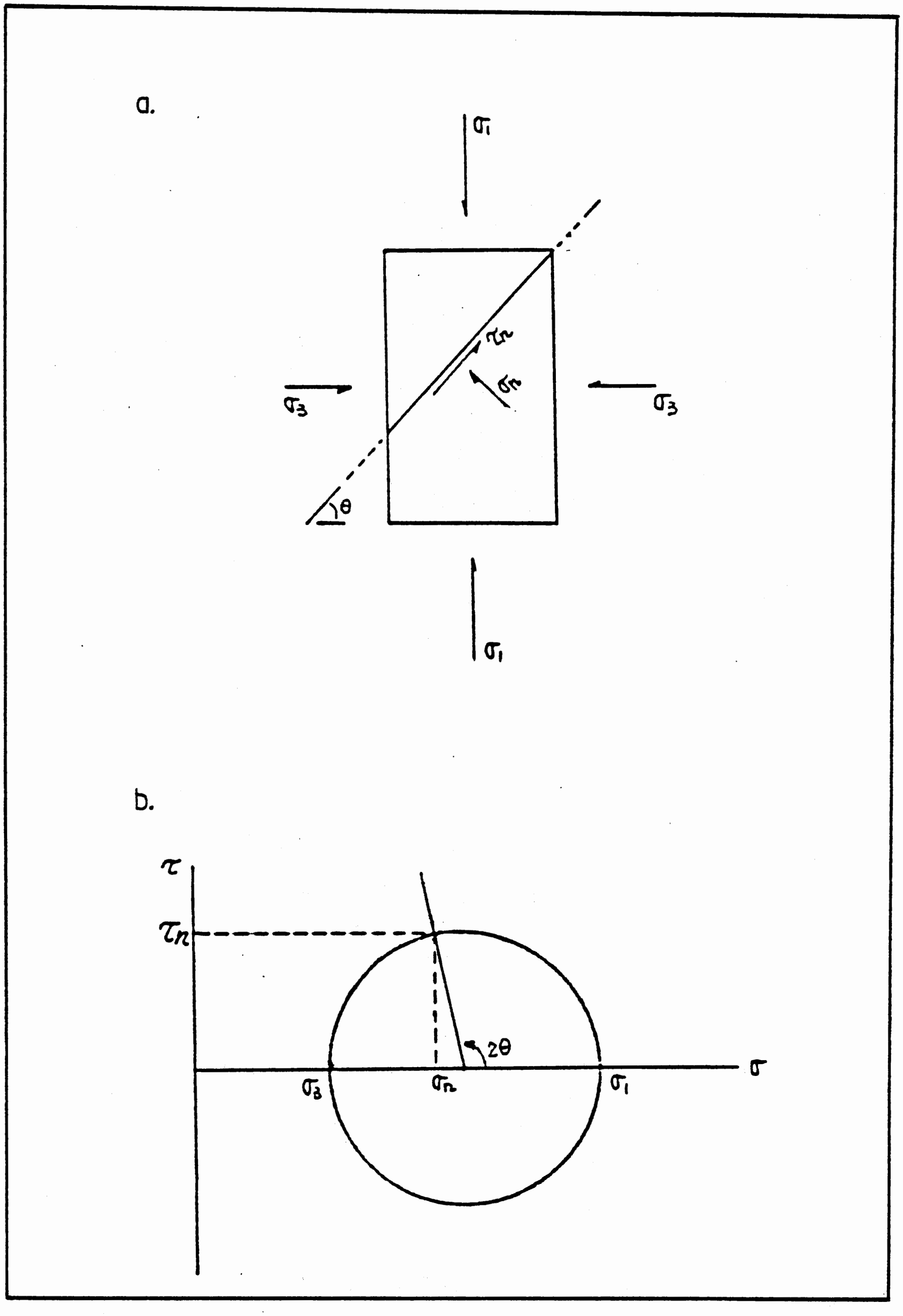


Figure 2a. Two-Dimensional Principal Stresses Acting on A Point.
2b. Mohr's Circle for Plane Stress Condition.

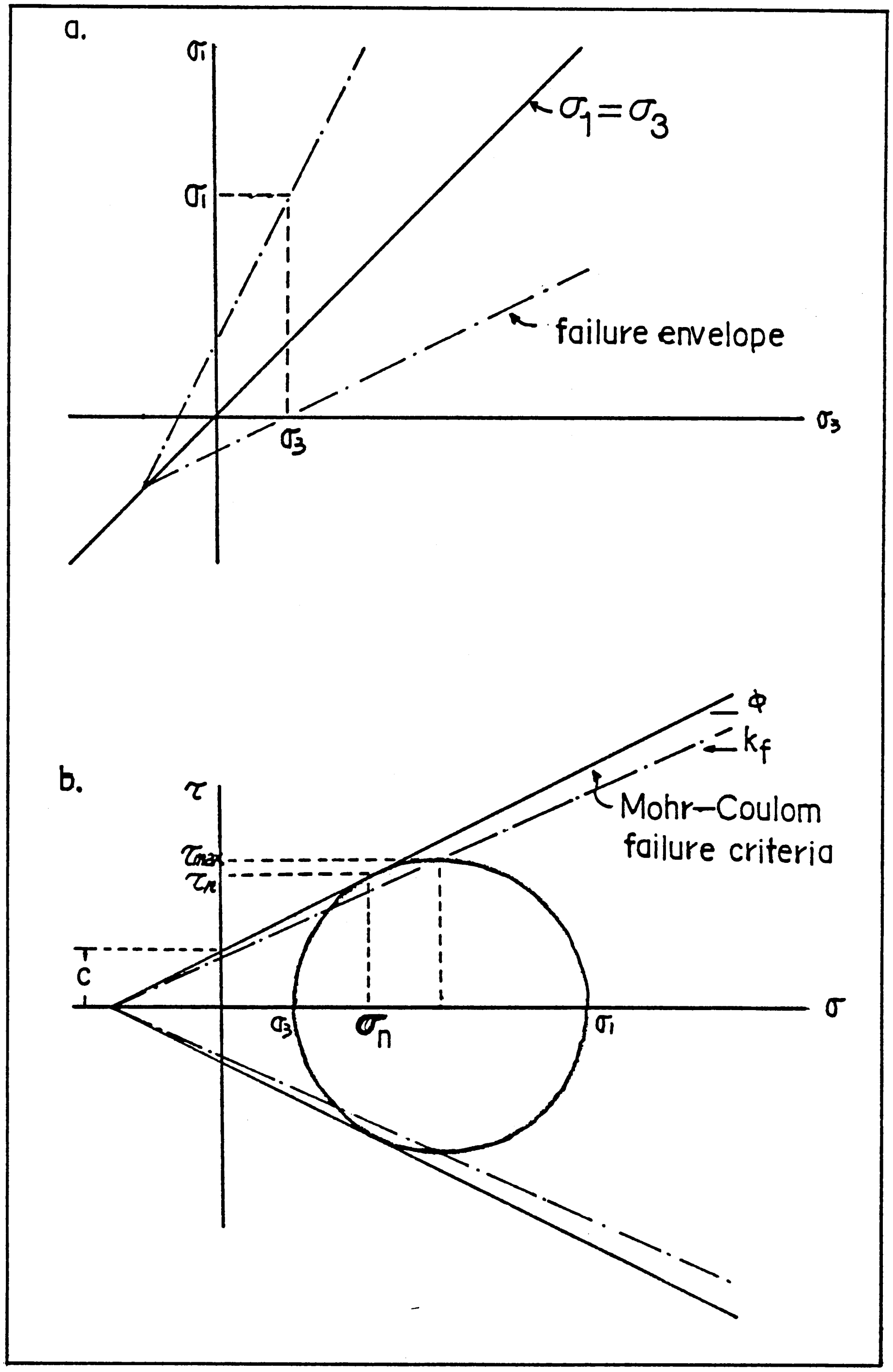


Figure 3a. Failure Envelope on Principal Stresses Space.
3b. Mohr-Coulomb Failure Envelope.

The Mohr-Coulomb failure criteria, defined as,

$$\tau = c + \sigma \tan\phi \quad . . . . \quad (1)$$

where,

τ : shear stress,

c : cohesion,

σ : normal stress,

ϕ : friction angle.

The Mohr-Coulomb failure envelope (Figure 3b), is used to represent the shear strength of soils. The corresponding shear strength parameters, cohesion "c" and internal friction angle "ϕ", define the strength of the soil.

For saturated soil, Terzaghi introduced the effective stress concept, which modified the Mohr-Coulomb failure criteria to,

$$\tau = c + \sigma' \tan\phi' \quad . . . . \quad (2)$$

in which σ' is the effective normal stress and ϕ' is the effective friction angle. The effective stress concept describes the shear strengths of two phases materials such as saturated soils (Fig. 4a). Considering an inter-particle contact point within a soil mass (Fig. 4b), the pore water pressure acts on all directions and thus balances itself. Therefore, it is the effective normal stress instead of the total normal stress which contributes to the

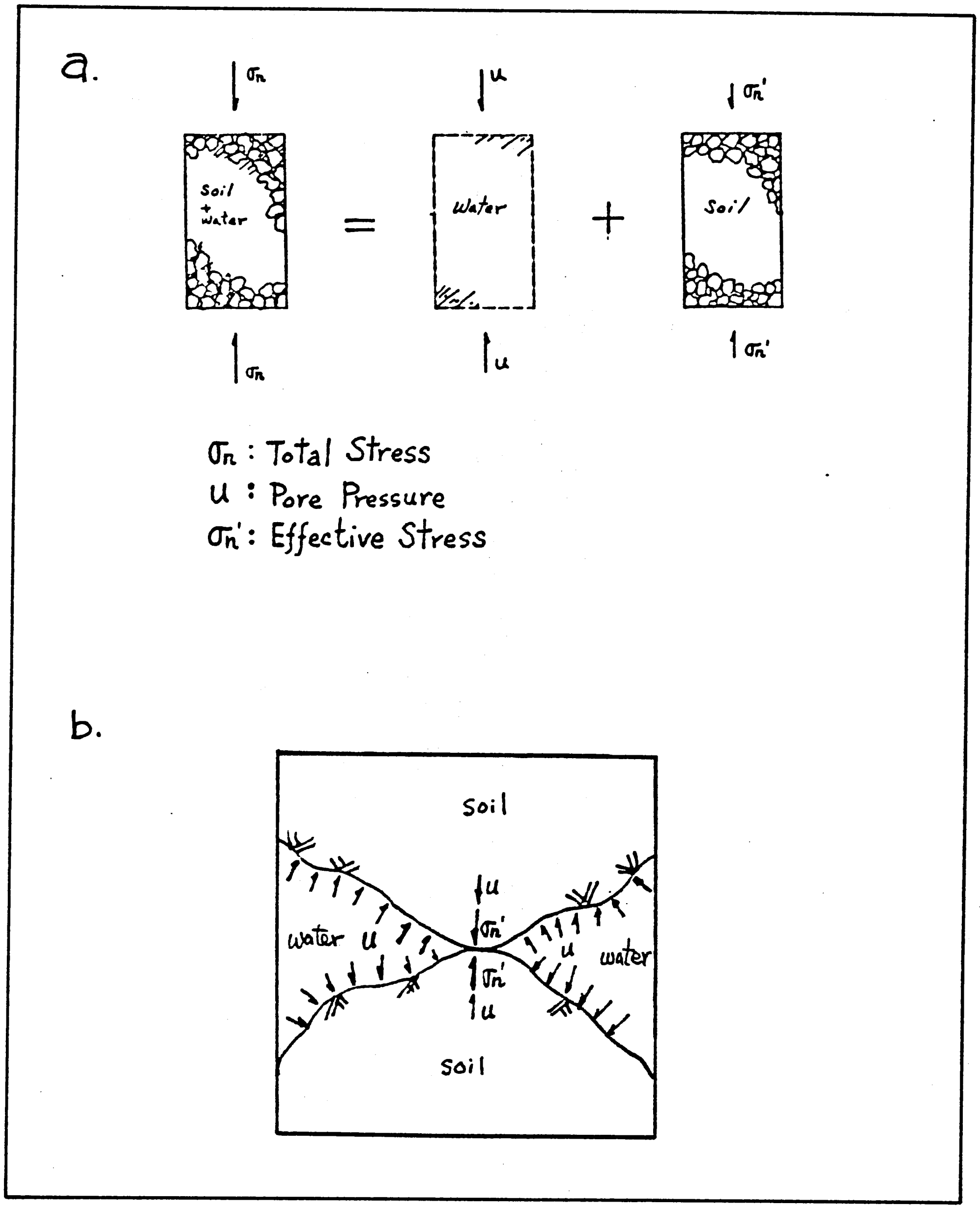


Figure 4a. Terzaghi's Effective Stress Concept.
4b. Microscopically View of Inter-particle Contact.

internal friction within soil mass.

Residual Shear Strength Concept

Residual shear strength, defined as the post-peak resistance of soil to shear stresses, can be described using mechanical models[19]. As shown in Figure 5, two kinds of basic units (elastic units and plastic units) are combined to simulate the stress strain behavior of soils. First, all elastic units together form the peak strength. Then, elastic units which represent the unrecoverable inter-particle bondings, start to break down and result in the post-peak drop of shear stress. Finally, all elastic units are broken down and only plastic units remained.

As an analogy from the above model, Figure 6 shows typical stress-strain curves for overconsolidated and normally consolidated clays which exhibit the relative post peak drop in shear strength. Skempton[8] concluded that the the post-peak drop in shear strength of an over-consolidated clay may be considered to occur in two stages. First, at relatively small displacements, the strength decreases to the "fully softened" or "critical state" value, owing to an increase in water content (dilatancy). This is due to the break down of inter-particle bondings which is analogous to elastic unit break-down. Second, after larger displacements, the strength falls to the residual value, as a result to the re-orientation of plate shaped clay minerals parallel to the direction of shearing failure plane. In

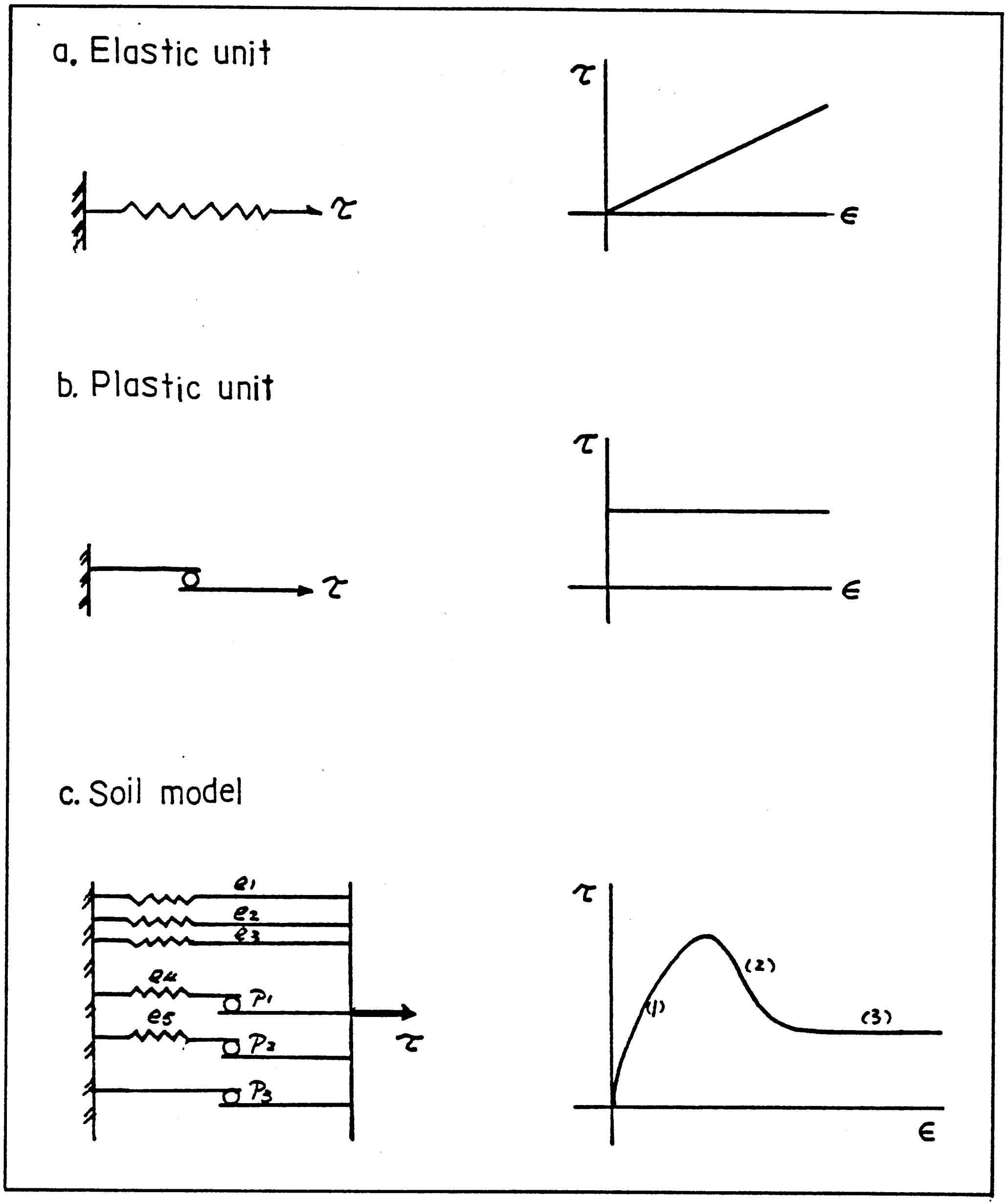


Figure 5. Idealized Model Illustrating Residual Shear Strength Concept.

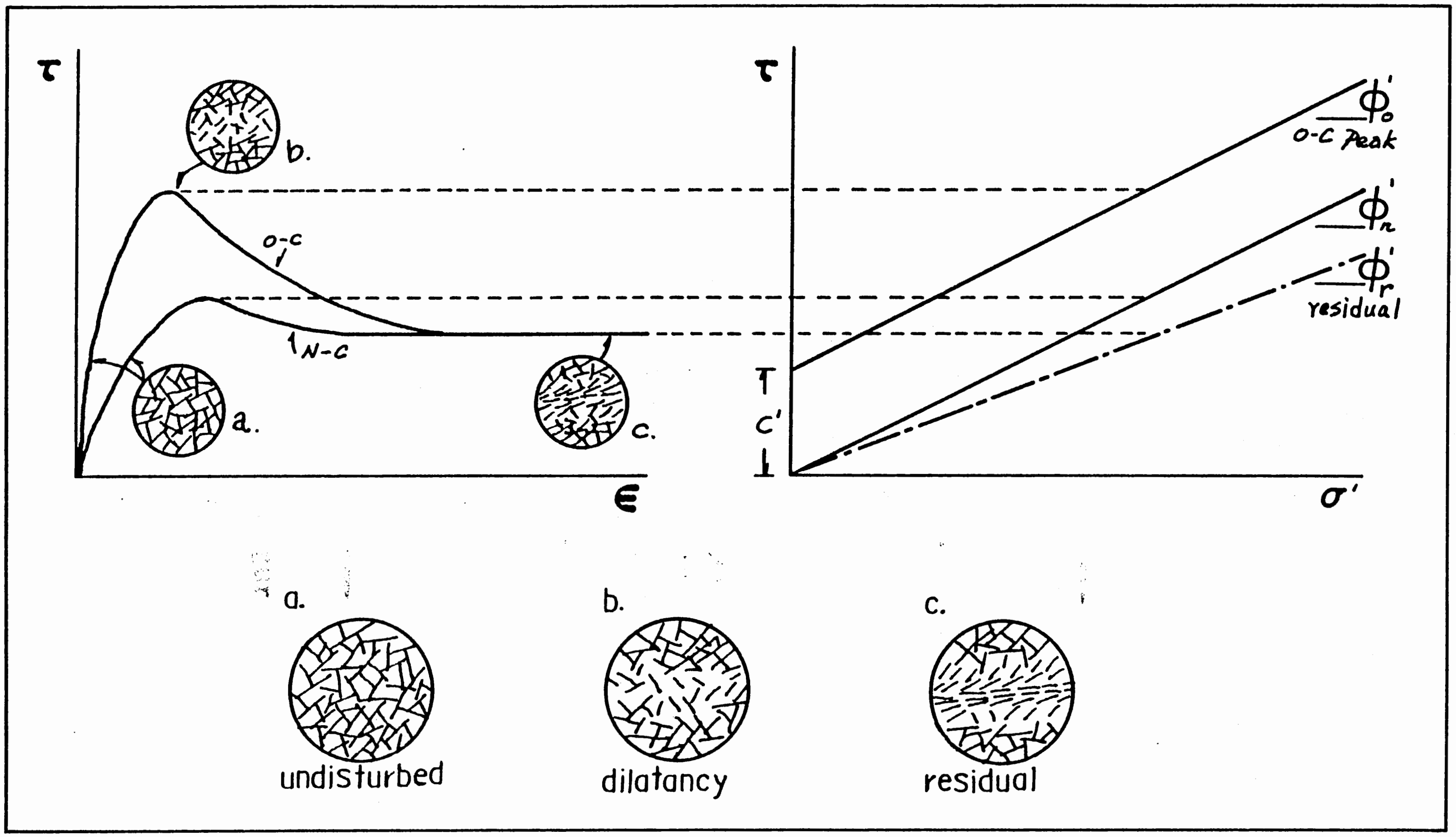


Figure 6. Typical Stress-Strain Curves for Normal Consolidated and Overconsolidated Clay.

this stage, similar to the plastic unit, only plate to plate friction exists. For normally consolidated soils in which inter-particle bondings are weaker, the post-peak drop is due mostly to the reorientation of clay particles.

There are two important factors which govern the re-orientation of plate shaped clay particles and are important in determination of the residual shear strength. The first factor is the required large strain for clay particles to re-adjust their orientation. The second factor is the magnitude of the normal stress which forces the re-orientation of clay particles. Generally, for larger normal stress, less strain is required for the reorientation[21]. On the other hand, if the normal stress is too low, clay particles may still remain in their natural clusters. As a consequence, the measured ultimate strength represents the inter-cluster shear resistance instead of the residual shear strength.

Measurement of Residual Shear Strength

The common procedures used in the soil mechanics laboratory for shear strength measurement are the triaxial shear and direct shear tests. Since engineers have used these two testing procedures for a long time, they have sufficient data and experience to support engineering judgment based on the results of the tests. Researchers have also developed the annular shear test (ring shear test) machine for large displacement shear strength testings[2,12,13].

Triaxial Test

The triaxial shear test is the most widely used test in determining the shear strength of soil samples. It can closely reproduce the in-situ stress conditions using the all around cell pressure to simulate the geostatic pressure. Because no pre-determined failure plane is involved, the samples are failed in their weakest direction. Through special testing procedures, the triaxial tests can include the pore water pressure effects.

There are arguments against using the triaxial test for residual shear strength measurement. Most of them concern the amount of displacement triaxial test machines can provide. However, Webb[14] proposed a correction method for the test results from the triaxial shear test and concluded that it is valid for residual shear strength measurements. The correction method is summarized in Appendix E. Other researchers[11] have used precut surfaces for samples so that the particle re-adjustment can start without passing the peak strength.

Other concerns about the triaxial shear test, such as the restrictions from the rubber membrane and filter paper, have been studied by various researchers and results indicate the errors are still within the accuracy acceptable in engineering practice[15,16].

Direct Shear Test

The direct shear test is the oldest shear strength test used by engineers. Through the years, enough experience has been collected to correlate the results with the actual values. It was the first test adopted by many researchers to measure the residual shear strength[1,4,12,15].

There are several assumptions imbedded in the original design of the direct shear test machine. First, it forces the soil sample to fail on a pre-determined surface. Lamb and Whitman[22] have shown that for the stress condition imposed on the soil sample, the plane of highest shear stress is slightly oblique to the pre-determined failure surface. Hvorslev[23] also found similar phenomenon, see Figure 7, and attributed it to the progressive failure along the shear plane. Second, the shear stress distribution on the failure plane is far from uniform. Stress concentration at the edge of the sample is generally believed to be the cause of the progressive failure in the sample. Finally, the cross-section area subjected to shear stresses is not constant during the test. This could be corrected using formula derived in Figure 8. Despite the limitations described above, the results from direct shear tests are widely accepted by practicing engineers.

Other concerns about the direct shear test include possible soil to shear box friction and shear box to shear box friction during the test. Furthermore, under high

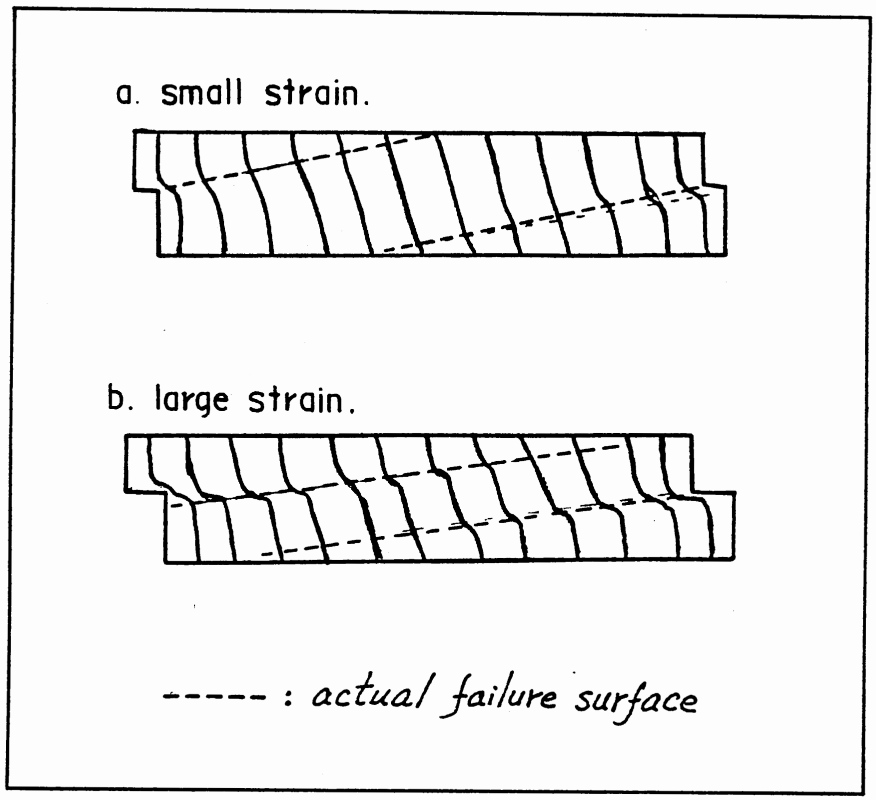
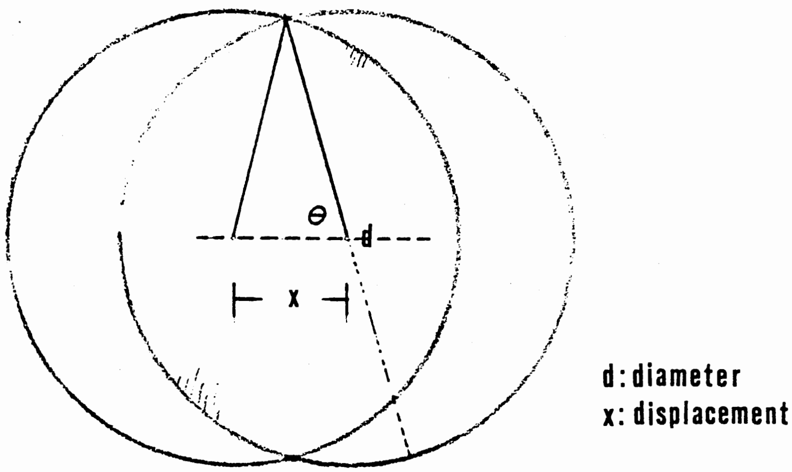


Figure 7. Inclination of the Actual Failure Surface to the Predetermined Failure Surface.



EQUATION:

$$\theta = \cos^{-1}\left(\frac{X}{d}\right)$$

$$\text{Area} = \left(\theta d^2 - X\sqrt{d^2 - X^2}\right)/2$$

Figure 8. Cross Section Area Correction for Round Direct Shear Sample.

normal stress, soil may be extruded out from the separation between the upper and lower part of the shear box[20]. The errors from the above considerations are operation dependent and are generally considered as negligible.

In addition, conventional direct shear machines are limited in the capacity for providing large displacement. It is accomplished by modifying the direct shear machine to change the shearing direction. This repetitive reversal motion cumulates the strain to the desired large displacement. Skempton[18] questioned that the reversal of the shear box would force the soil particles to re-align in the opposite direction for each shearing cycle. Laboratory test results[11,17] showed that it is true for the first few reversal of shear box and gradually faded as the number of reversal motion increased.

<u>Annular Shear Test</u>

As the annular shear test machine was designed to provide large displacement without changing shearing direction, it appears to be the most rational approach for measuring the residual shear strength of soils. However, there are difficulties involved in applying the annular shear test. Preparation of the ring shaped sample is one of the difficulties. Special trimming devices are needed for the hollow samples used in the annular tests. The other difficulty concerned about the interpretation of the test results. Complex data reduction procedures are required to convert the rotational shearing resistance to shear stresses.

Although supporters of the annular shear test have compared the testing results with various landslide cases[3,4,7], the annular shear test is still not widely accepted by the practicing engineers. It is generally believed that annular shear tests measure the lower limit of the residual shear strength and tend to under-estimate the value. This is because the particle reorientation is so complete as compared with the field observations. The measured residual strength parameters are thus lower than values obtained from back analysis of slope failure.

Factors Affecting Residual Shear Strength

Based on the residual shear strength concept, the ultimate strength is the internal friction angle of plate shaped clay particles. Consequently, it is natural to correlate residual shear strength and indices which describe the clay portion of soils. The indices are, percent clay particles, liquid limit, plasticity index, and clay mineralogy. Since all the indices listed above are related to each other, no single index can be used alone for comparison. In addition, shear strength is usually dependent on strain rate and effective normal stress.

Percent Clay Sized Particles

Correlations between the percent clay sized particles and residual shear strength were presented by Skempton[17] and other researchers[5,21], see Figure 9. Although there is a trend showing that the higher the percentage the lower the residual angle of friction, it is generally considered only a qualitative comparison. Skempton[18] suggested that for soils with clay size percentage less than 25%, the clay particle orientation may not have an effect. While for soils with clay percentage greater than 50% the residual strength is controlled by the plate to plate sliding friction of the clay minerals.

Hawkins[7] pointed out that there is no standardized method for the determination of the clay percentage in a soil. Different dispersion methods are employed in the hydrometer analysis. If high energy was used in dispersing the soil particles, some particles may be broken down to finer particles[20]. On the other hand, if less effort was involved, some clay particles stay in clusters.

Clay Mineralogy

Table I shows the residual friction angles of the most common types of clay minerals[10]. This could be viewed as the lowest value to be expected when any of the clay minerals are dominant in a soil.

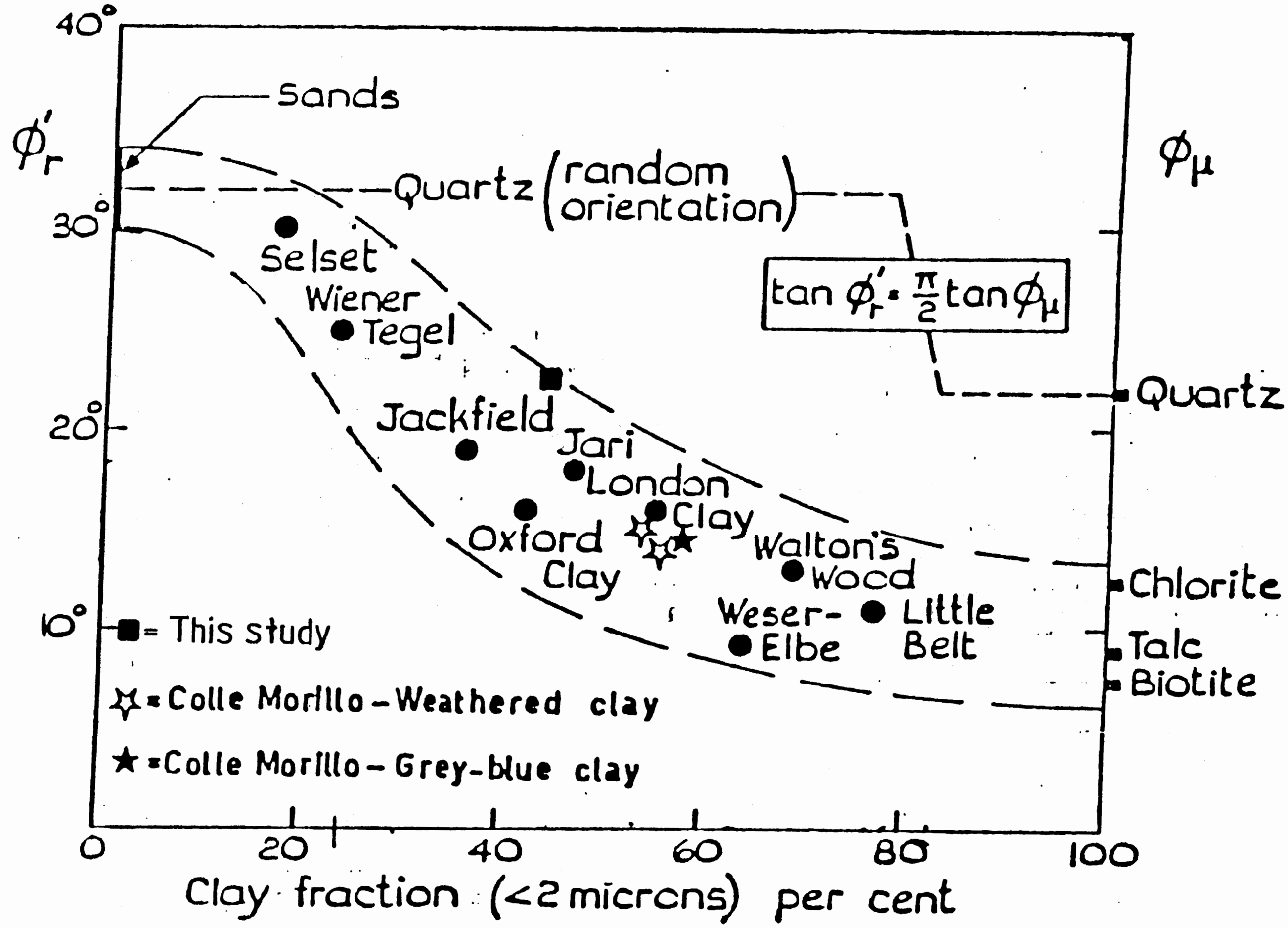


Figure 9. Correlation Between Residual Friction Angle with Percent Clay Size Particles (17).

TABLE I

RESIDUAL FRICTION ANGLE FOR PURE CLAY MINERALS

Mineral	Residual Friction Angle
Kaolinite	27.5°
Ca illite	24.0°
Na illite	19.0°
Ca montmorillonite	12.5°
Na montmorillonite	2.0°
Muscovite Mica, 5% < 2μm, 95% < 50μm	30.0°
Microcrystalline silica 20% < 2μm, 90% < 50μm	34.0°
Quatz, silt size, rounded, uniform	30.0°
Montmorillonite in carbon tetrachloride, aggregated	31.0°
Kaolinite in carbon tetrachloride, aggregated	30.0°

Liquid Limit

Liquid limit is affected by the clay mineralogy and the percent clay sized particles in a soil. It is not surprising to find the trend of lower residual shear strength for higher liquid limit as shown in Figure 10.

Plasticity

Plasticity is also a combined effect of clay percentage and clay mineralogy. Therefore, correlations between plasticity and residual strength are given by several researchers[10,17,21], as shown in Figure 11. There is a general trend showing that the higher the plasticity the lower the residual friction angle.

Strain Rate

Skempton[18] showed that strain rates faster than about 100 mm/min. qualitatively change the residual shear strength. The strain rate controls the time for pore water pressure to dissipate. Therefore, if the strain rate is slow enough to prevent the build up of pore water pressure, further decrease of strain rate would certainly show no significant effect.

Effective Normal Stress

The residual shear strength of clay is dependent on the effective normal pressure applied on it. Instead of a

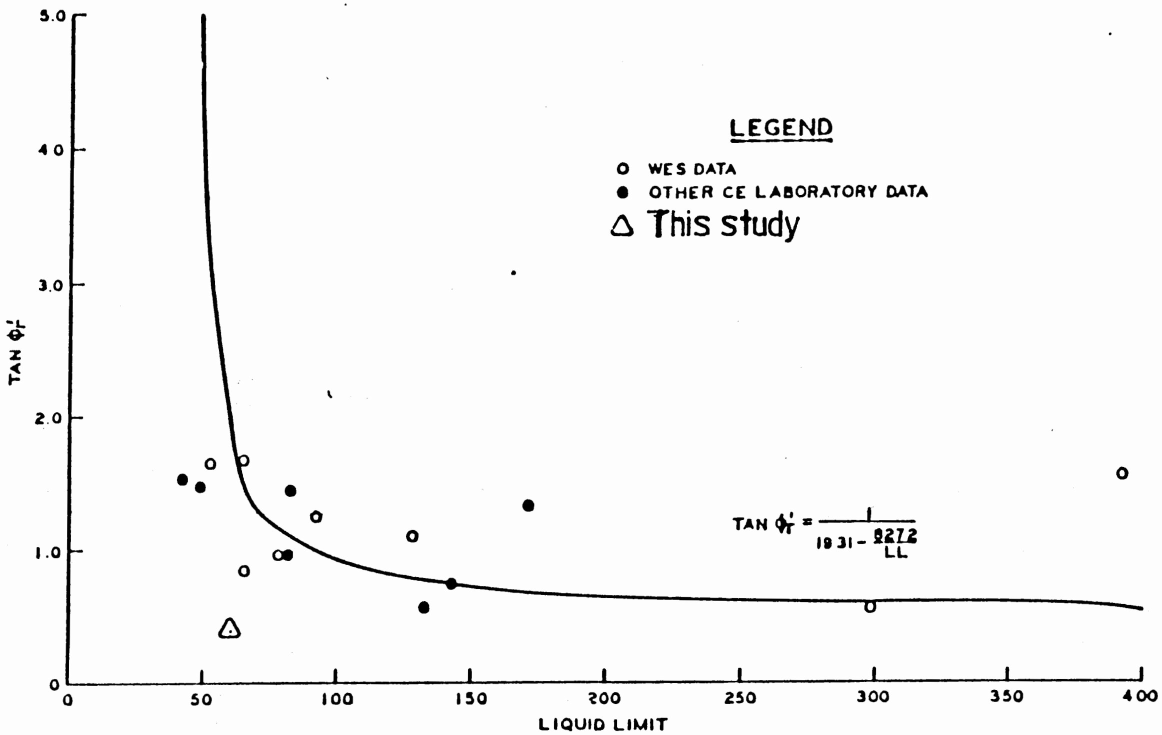


Figure 10. Correlation Between Residual Friction Angle with Liquid Limits (21).

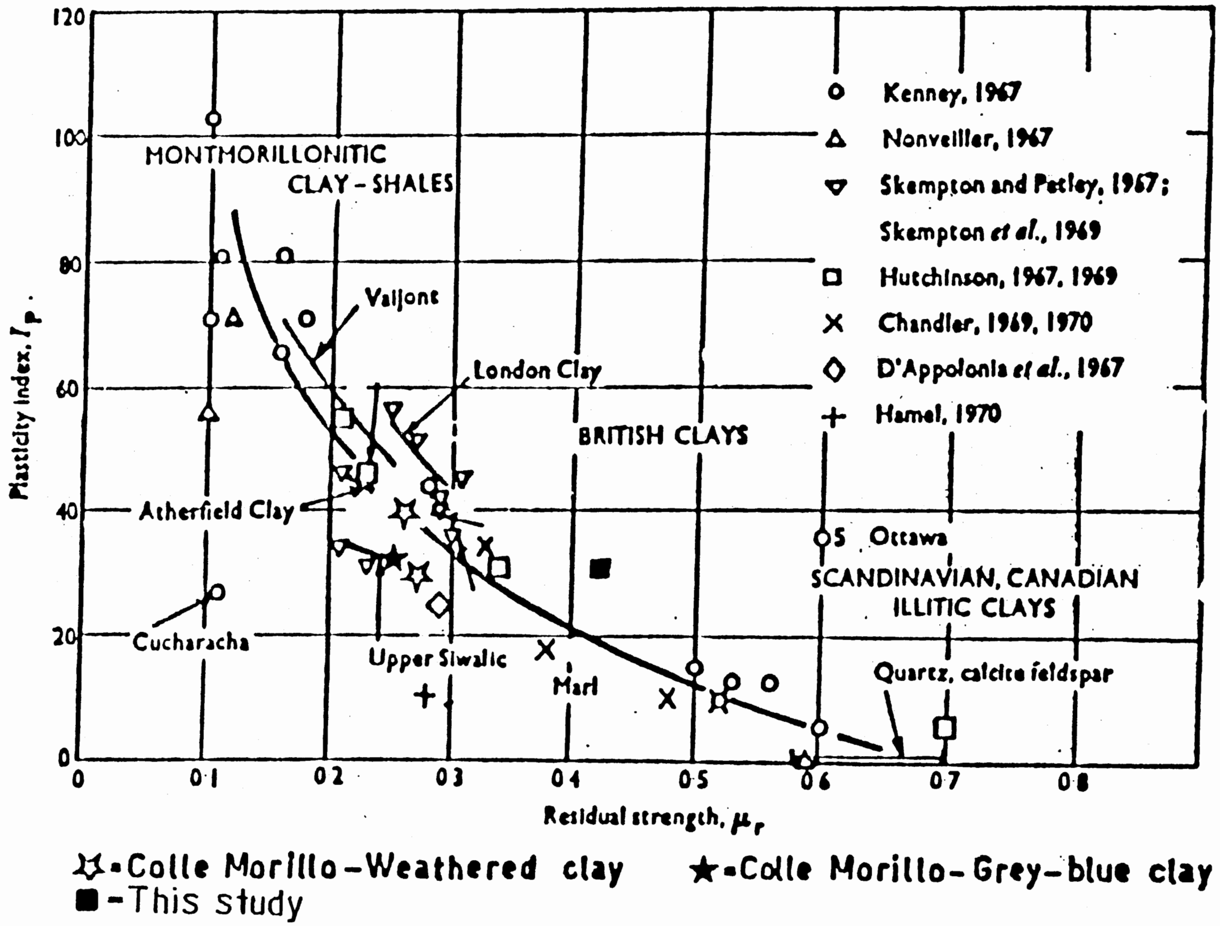


Figure 11. Correlation Between Residual Friction Angle with Plasticity Index (5).

straight line, curved failure envelope were found in many laboratory test results[3,4,7]. Hawkins[7] suggested that while correlating the residual shear strength with other soil properties, the normalized factor (residual shear strength/effective normal stress) should be used. Townsend[21] explained that the curved strength envelope was caused by the clustered clay particle effect. At low effective normal stress, the failure zone is wider and particles are still in clusters. Therefore, the measured residual strength is higher than the plate-to-plate friction of clay particles. As a compromise when testing data is not sufficient to construct a complete failure envelope, straight line approaches over the in-situ stress range could be used as the design approximation.

Slope Stability and Residual Shear Strength

In 1964, Skempton[17] presented his studies on the long-term stability of clay slopes in which he proposed that residual shear strength of clay was the controlling factor in the stability analysis of slopes. He stated that any subsequent movement on an existing slope failure surface was resisted only by the residual strength of the soil. In the following years, numerous landslide cases were studied by researchers throughout the world in which they all reached a similar conclusion that the strength parameters from slope stability analyses on existing failure surfaces using a safety factor of unity coincides with the residual shear strength of the soil[2,3,5,8,9,13]. Therefore, instead of the conventional peak shear strength, the residual strength should be considered in the design and analysis of slopes where a failure surface existed or was suspected to exist.

Considering the design of new slopes, the use of residual shear strength tends to be too conservative since no pre-existing failure surface is expected. The peak strength, in this case, appears to be the dominant strength within the soil mass. For some over-consolidated clays and shales, creep or progressive failure inside the soil mass are common[2,5,6,9]. Therefore, the engineer must choose the correct strength parameter as well as the safety factor in designing slopes. If the failure surface is present or suspected the lowest limit of strength, i.e. the residual shear strength, should be employed in slope stability designs.

Due to the fact that the residual shear strength is the primary resistance for slopes with pre-existing slip surface, back analysis from such a slope with safety factor of one is used for calculating the residual shear strength. Slope stability analysis procedures are generally based on the assumption of limit equilibrium within the soil mass. Detailed descriptions of the theory and methods of analysis are given in Chapter IV. The main short-coming of back analysis is that it treats the residual shear strength in an average sense along the slip surface. Skempton[18] pointed out that stability analysis and laboratory tests cannot be expected to yield results within an accuracy limit better than about 10%. Even with this limitation, residual shear strengths from the back stability analysis were used in comparison with the results from laboratory tests for this study.

CHAPTER III

LABORATORY TESTING PROGRAM

Introduction

The laboratory testing program for this research was conducted in two stages. The first stage was the development of a data acquisition and analysis system. The second stage involved the application of the developed system to measure the residual shear strength of samples from a highway backslope slide failure in Eastern Oklahoma.

Data Acquisition and Analysis System

Generally, a data acquisition and analysis system is made up of both hardware and software portions. The hardware part of the system is divided into four components; the target instruments, the data logger, the computer (CPU and mass storage) and the interface between the data logger and the computer. For the software part, there are four functions to be fulfilled. They are: control and configuration of the data logger, communication between the computer and the data logger, storage and retrieval of data to and from the mass storage, and reduction of the logger data and its presentation in a useful format. In this each part of the system will be discussed.

Hardware

The triaxial test machine and direct shear test machine are the two target instruments to be modified. In order to configure the instruments to be monitored by the data logger, conventional proving ring dial gauges, pressure gauges, and displacement dial gauges were replaced by sensors that output electronic signals. Detail descriptions of the basic units and the modifications made are as follows.

Triaxial Test Machine

Basic Triaxial Test Unit. The basic components of a triaxial compression test apparatus are the test chamber, the motor and gear box for providing necessary displacement and the pressure source for both back saturation and confining pressure. The triaxial machine used in this research consists of three separated test chambers with common pressure source and driving motor. Therefore, each set of three samples with different confining pressure could be tested at the same time.

Sensors and Logger. The main modification made to the triaxial machine was replacement of conventional gauges by electronic sensors. The block diagram of the modified triaxial test machine and corresponding sensors is shown in Figure 12. The sensors (DCDT, pressure transducer and

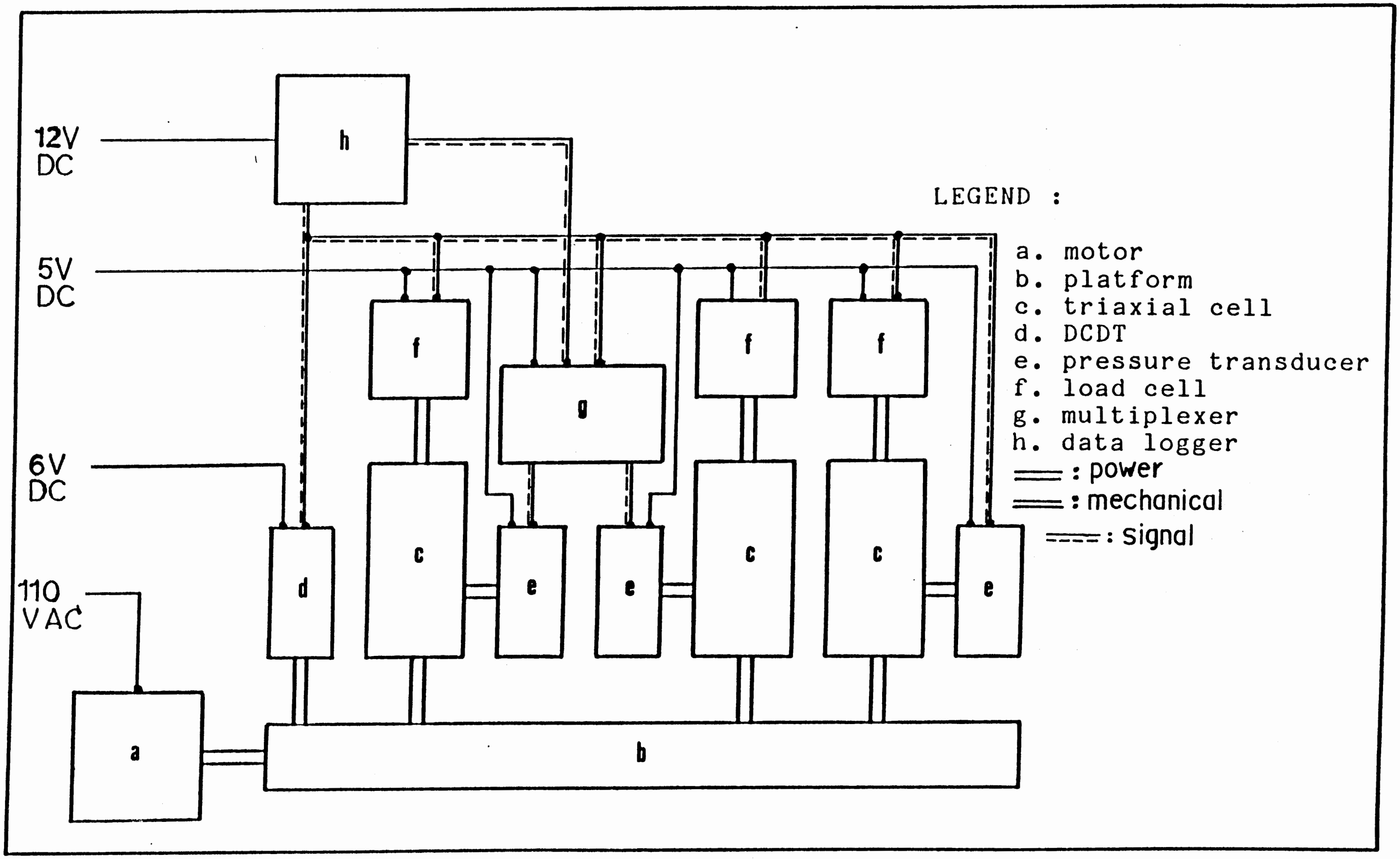


Figure 12. Block Diagram for the Triaxial Test Apparatus.

load cell) are common to both the triaxial test machine and direct shear test machine. They will be discussed together in a separate section.

Repetitive Direct Shear Test Machine

Basic Direct Shear Test Unit. The direct shear machine contains three main parts. The split shear box provides the pre-determined failure plane for the sample placed inside, the motor and gear box are the source for shearing force and horizontal displacement. The loading frame applies normal stress on the sample.

Sensors and Logger. Similar to the triaxial compression machine, the horizontal and vertical displacements are measured by DCDT instead of dial gauges, and the shearing force is detected by a load cell attached on the machine axis. The block diagram of the direct shear machine as well as the sensors and logger are shown in Figure 13.

Repetitive Motion Controller. In addition to the sensors and logger, a repetitive motion controller was designed to change the direction of the shearing motion automatically. With this controller, whenever the horizontal displacement reaches the pre-set margins the motor was reversed and the direction of motion was reversed. The circuit diagram of the controller is shown in Figure 14.

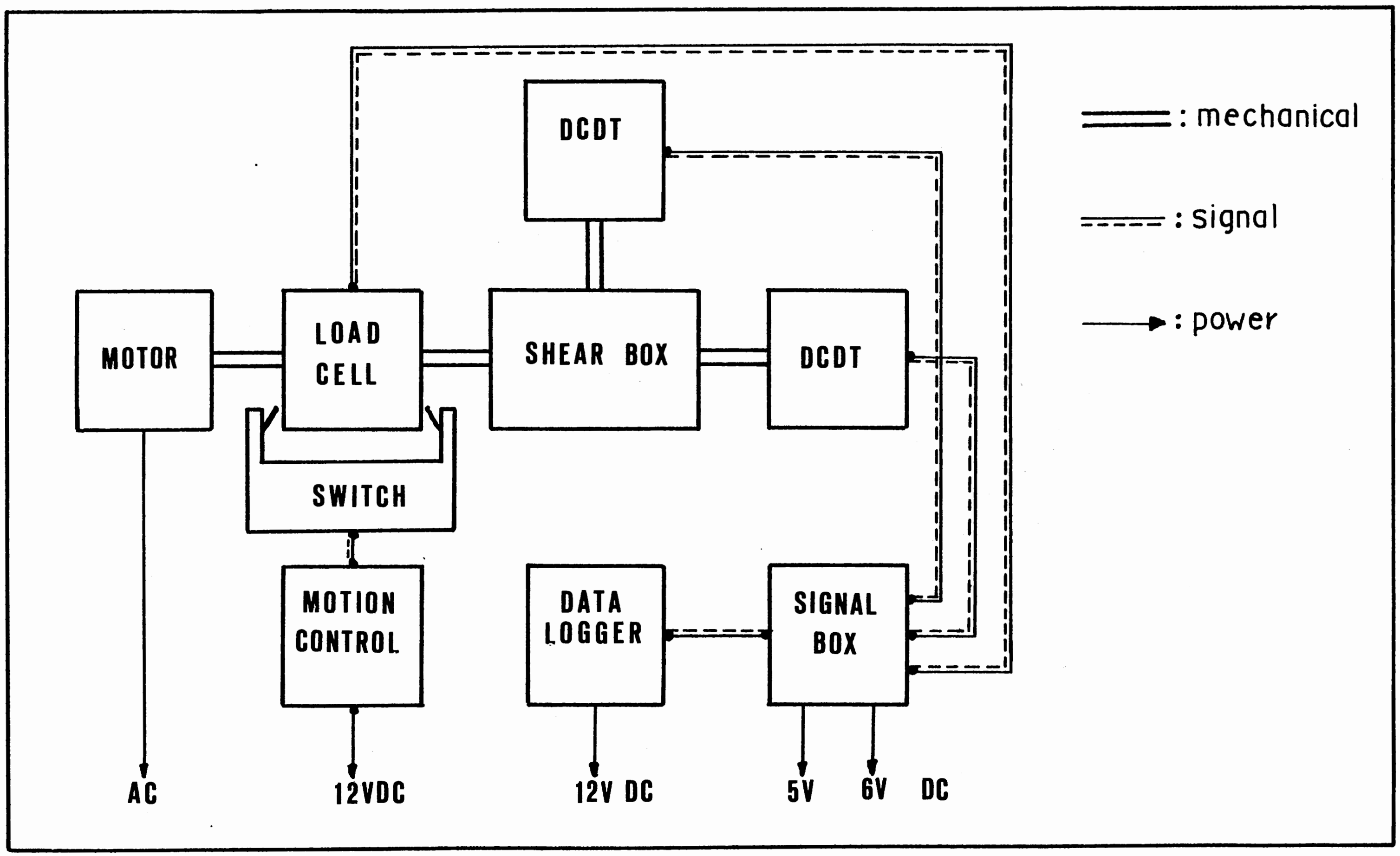


Figure 13. Block Diagram of the Repetitive Direct Shear Test Machine.

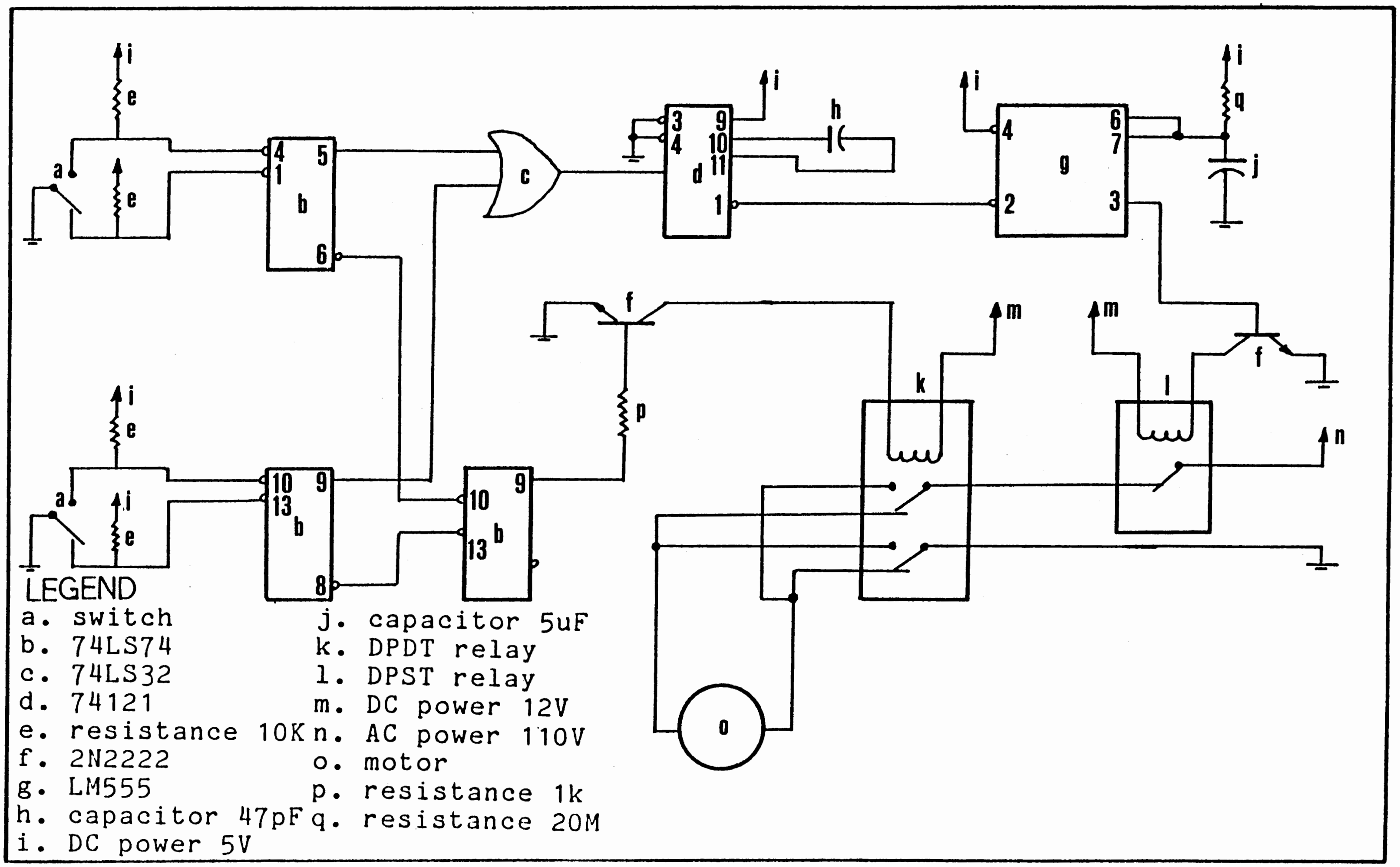


Figure 14. Circuit Diagram of the Repetitive Motion Controller.

Sensors

DCDT. The direct current displacement transducers (DCDT) used in this research were manufactured by Hewlett Packard, model no. DCDT250 (Fig. 15a). The DCDT converted measured displacements to differential voltage changes. For this model, every 6.6 voltage change corresponded to one inch of the displacement.

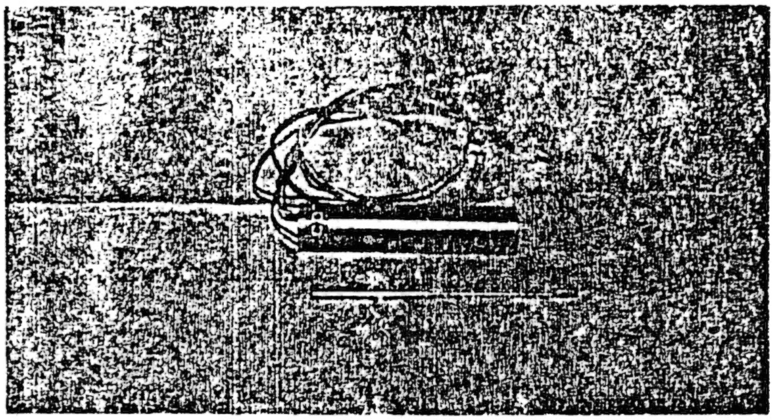
Load Cell. The same type of load cell (BLH Model U2 with 1000 pound capacity), shown in Figure 15b, was used in both the triaxial test machine and direct shear machine. For this model, 200 pounds of load difference results in 1 mv of voltage change.

Pressure Transducer. The pressure transducers (CEC Type 4-325 with 100 psi range) used to measure pore water pressure in the triaxial test, shown in Figure 15c, were mounted in a plexiglass housing. Every 0.2 mv of voltage difference from the pressure transducer represented 1 psi pressure change.

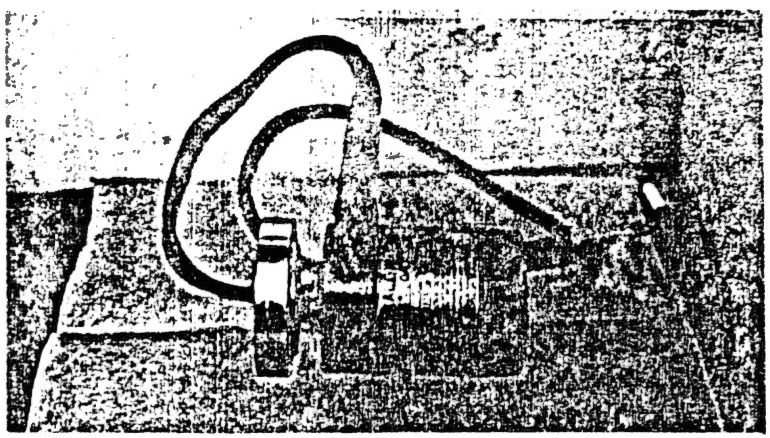
Data Logger

A data logger is a device that converts analogue signals to digital signals. The major considerations for selecting a data logger are its resolution and signal converting speed. In this research program, the time interval between two data points is ten minutes. For such a

a. DCDT



b. LOAD CELL



c. PRESSURE TRANSDUCER

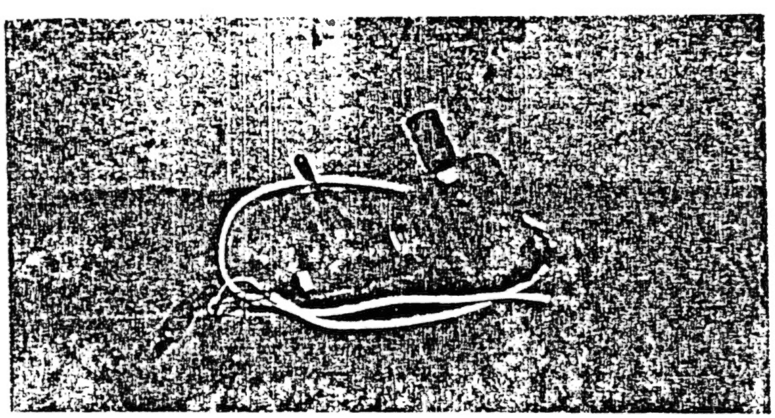


Figure 15. Sensors.

concern. On the other hand, the accuracy of the displacements, loads, and pore water pressures to be measured are very important in both the triaxial test and direct shear test. Therefore, it requires good data logger resolution to acquire data from the sensors.

In order to fulfill the above requirements, the EASY LOGGER, a self-contained portable data logger, manufactured by the Omni Data Company was purchased for use in the OSU Soil Mechanics Laboratory. The EASY LOGGER consists of three components; a 12 bit 6 channel analogue to digital signal converter, a handheld terminal, and an EPROM pack for temporary data storage. Because there are only six channels for receiving data, it is insufficient for the seven sensors (1 DCDT, 3 load cells and 3 pressure transducers) in the modified triaxial test machine. To expand the logger, a multiplexer was built to send signals from two sensors for the same channel. The circuit diagram of the multiplexer is shown in Figure 16.

Computer

The computer is the main control mechanism of the data acquisition and analysis system. In this system, an IBM Personal Computer provides communication through a serial port to receive data from the data logger. In addition, the computer was equipped with two floppy disk drives to serve as mass storage devices for storing the data.

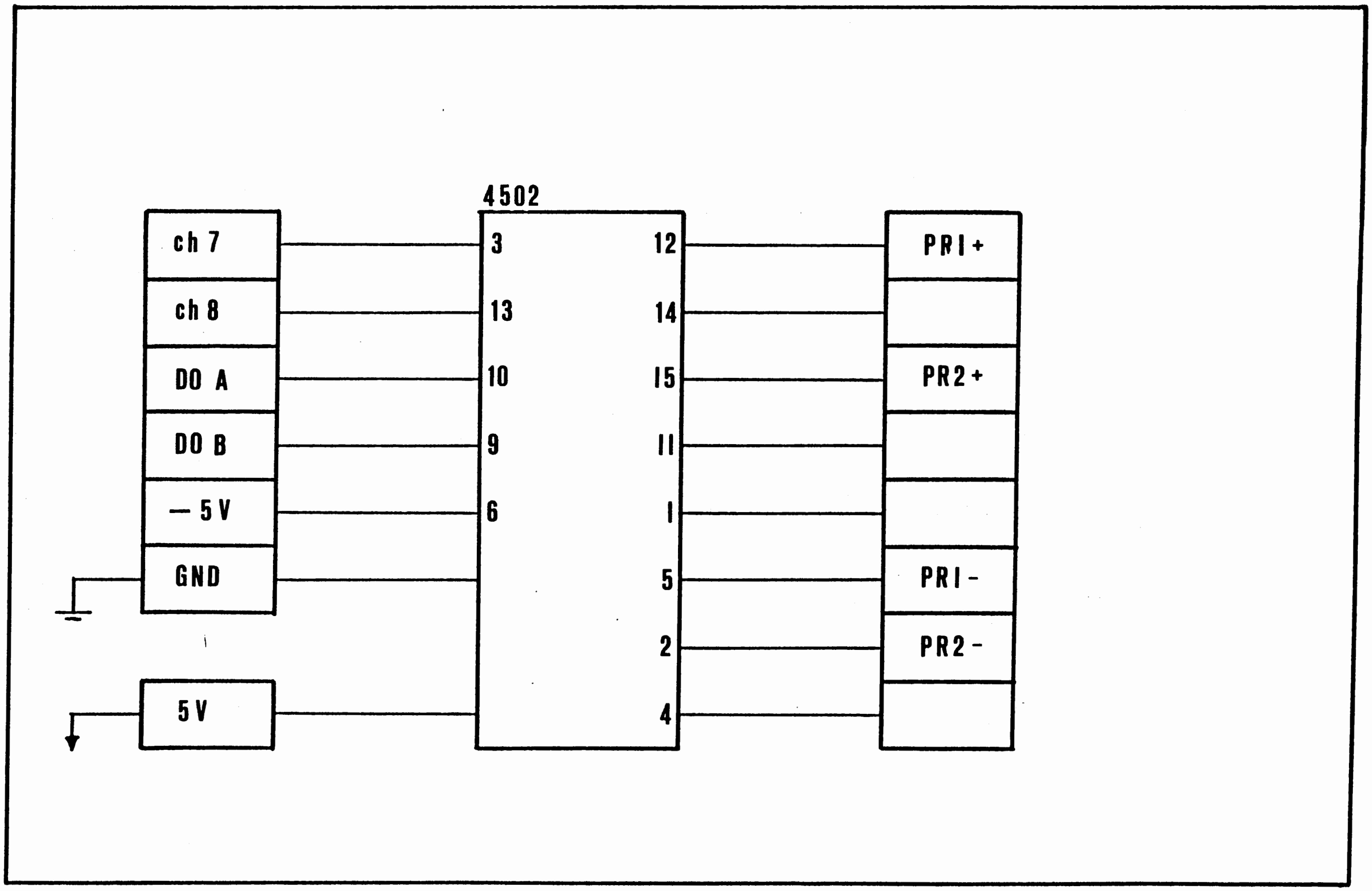


Figure 16. Circuit Diagram of the Multiplexer.

Software

There are two sets of programs included in the data acquisition and analysis system. One is for the triaxial test and the other is for the repetitive direct shear test. Each program set provides two main functions. The first function is to configurate the data logger and to communicate with the data logger to receive data and store it. The second function is to analyze the data and present the results. A detailed discussion along with a user's manuals for the two program sets are included in Appendix A.

CONNECT, RRBAR AND RESULT

The program set for the triaxial test consists of three programs, CONNECT, RRBAR and RESULT. The program CONNECT serves the first function as described previously. The program RRBAR analyzes the raw data stored in the disk and reduces it to an intermediate data set. Finally, RESULT analyzes the intermediate data set and presents the completed results in both tabulated and graphic formats.

SETUP AND DIRECT

There are two programs, SETUP AND DIRECT, included for the repetitive direct shear test. The communication is accomplished through the program SETUP. The data reduction and result presentation are done with the DIRECT program.

Residual Shear Strength Testings

The R/R-Bar triaxial test and repetitive direct shear test were used in this research. Besides the two strength tests, supporting tests were required for determining the basic soil mechanics properties of the soil samples used in the research. These properties were useful for indicating the general behavior of the soil. The supporting tests were; Atterberg Limits, grain size distribution, specific gravity, hydrometer analysis to determine the percentage of clay particles and consolidation test for measuring the preconsolidation pressure of the soil.

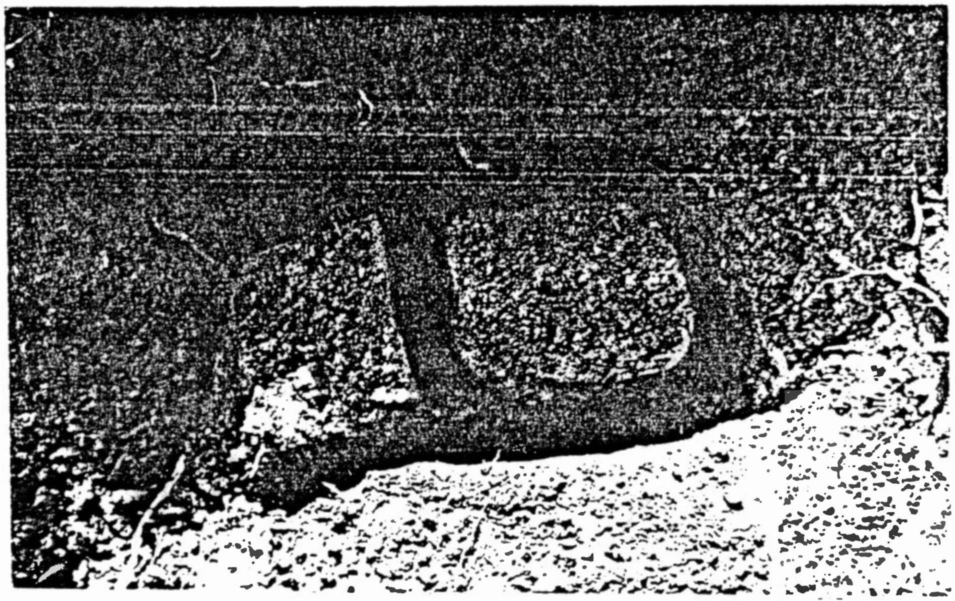
Sample Preparation Methods

Sample preparation methods affect the results of the tests. In this research program, three different sample preparation methods were used. Undisturbed samples were used to represent the natural conditions of the soil. Fully remolded samples represented the total disturbed condition of the soil. Partially remolded samples were used to simulate the soil conditions at the landslide failure zone.

Undisturbed Samples. In most practical applications, samples obtained using Shelby tubes are considered to be undisturbed. The Oklahoma Department of Transportation attempted to obtain undisturbed samples using Shelby tubes but were not successful due to the natural fissures, fractures along with weathered nodules encountered at the landslide site. In an attempt to obtain better quality undisturbed samples, a trench was dug down to the depth on top of the estimated failure zone. Blocks of soil samples with dimensions of approximately 1/2 x 1 x 1 feet were carefully carved out and sealed in aluminum foil and coated with wax (Fig. 17). Undisturbed samples were then trimmed out from the soil blocks in the laboratory using a sharp edged mold of the desired diameter. Because of the loose structure of the soil samples, the mold was advanced in small increments into the soil block. After the designated shape was trimmed by a sharp knife, samples were then cut to its proper length and extracted from the mold.

Partially Remolded Samples. The principle behind the partially remolded sample was to remove the natural soil structure but still preserve the gradation and compositions of the soil samples. The steps taken for preparing partially remolded samples were as follows.

1. Trim out undisturbed samples as described above so the natural soil conditions were preserved.
2. The sample was broken down to pass U. S. No. 40 sieve. At this stage, most of the natural soil structure that would affect the strength parameters was eliminated.
3. The loose soil was divided into three equal parts and statically compacted in the mold of desired dimensions in three layers.



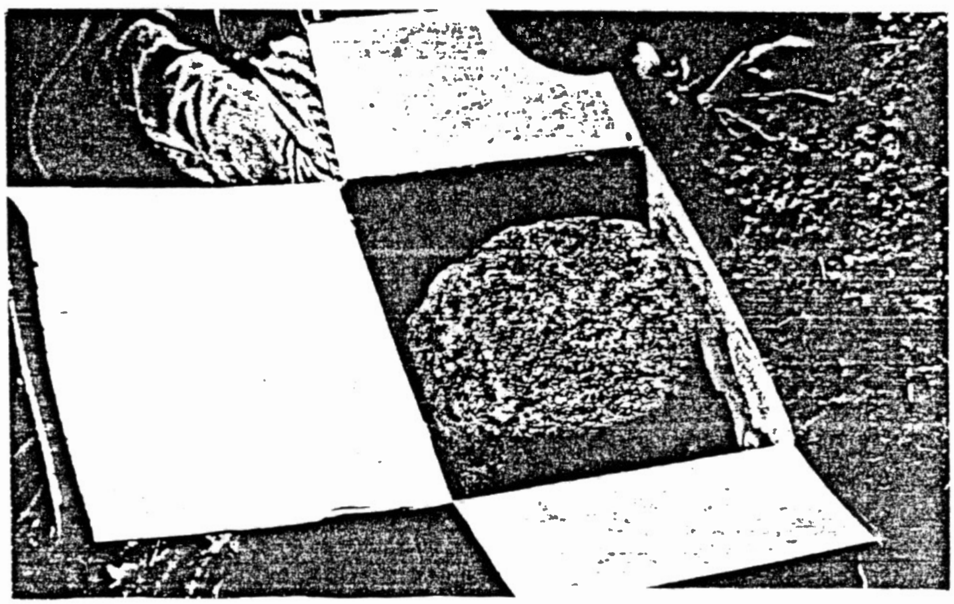


Figure 17. Sampling of the Undisturbed Samples.

4. Samples were then extruded from the mold for testing.

<u>Fully Remolded Samples.</u> As was discussed in the previous chapter, it is generally believed that the clay particles in a soil influence the residual shear strength of the soil. In addition, when undisturbed samples and partially remolded samples were tested, those particles with sizes larger than U. S. No. 40 sieve influenced the test results. Thus, fully remolded samples were prepared to reduce these effects and to focus on the strength of the fine grain portion of the soil. Seven steps were used to prepare the fully remolded samples. They are described as follows.

1. The soil samples were soaked in distilled water for 24 hours.
2. The saturated soils were placed in a mixer and blended for 3 minutes, until the soil structure was broken down to form a soil slurry.
3. The slurry was washed through U.S. No. 40 sieve and the fine portion was dried in a 110^{o} C oven for 24 hours.
4. The dried soil was broken down to pass a U. S. No. 40 sieve using are electric grinder.
5. The required amount of distilled water was added to the dried soil to obtain the density and water content of the undisturbed sample.

6. The soil was statically compacted in the mold in three layers.
7. The sample was extruded from the mold and tested.

Testing Procedures for R/R-Bar Triaxial Test

The R/R-Bar Triaxial Test, also known as the consolidated undrained (CU) triaxial test with pore water pressure measurement, was the most effective shear strength test. The pore pressure measurements allowed the effective stress conditions to be calculated from the undrained test results. The testing procedures are described as follows.

Setting Up the Samples. After the samples were prepared using the procedures previously described, the tests were set up using the following steps (Fig. 18).

a. The sample was placed on the top of the pedestal inside the triaxial cell with filter papers on both ends.
b. The sample was wrapped with striped filter paper and carefully sealed inside a rubber membrane.
c. The triaxial cells were then clamped and sealed.
d. The triaxial test chamber was filled with dilute antifreeze until every part of the membrane was submerged in the water/antifreeze mixture.
e. The test chamber was placed on the platform of the triaxial machine.
f. A bearing ball was placed on the top of the piston

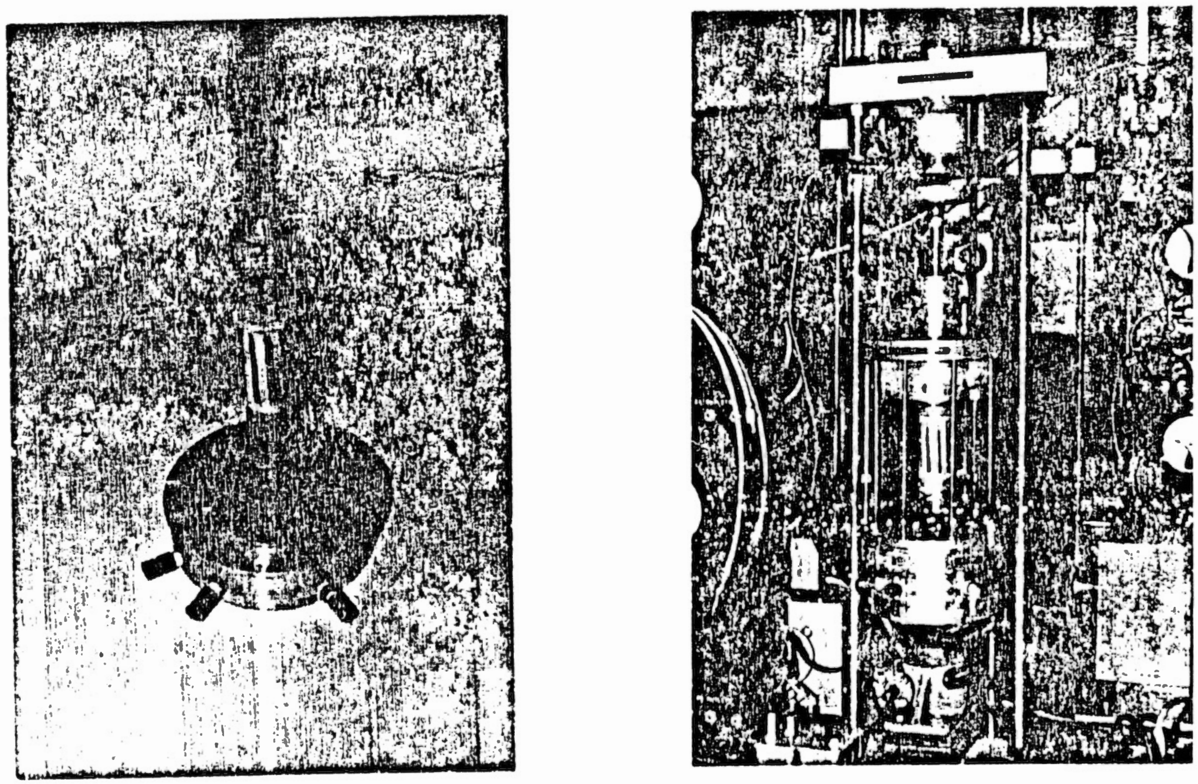


Figure 18. Setup the Triaxial Test Samples.

and the load frame holding the load cell was lowered to contact the bearing ball.

Back Pressure Saturation Stage. A back pressure of 30 psi was applied to the cell and to both burettes which were connected to the top and bottom pedestals inside the cell. The pressure was maintained for at least 24 hours so all the trapped air inside the sample was dissolved in the de-aired water. At this stage, the soil samples were considered to be in fully saturated state.

Setting Up the Data Logger. The program CONNECT was used to setup the Easy Logger. The user's manual presented in Appendix A explains detailed procedures.

Setting Up and Testing the Sensors. The require setup procedures and circuit diagrams are listed in appendix B.

Consolidation Stage. Before starting the consolidation stage of the triaxial test, the Bishop's B coefficients for each sample was measured to estimate the degree of saturation of the samples. The procedures used were described as follows.

a. The Easy Logger was set to option "00" using the handheld terminal and started to record the initial pore water pressure readings for about 5 minutes.
b. The "B" pressure regulator for each triaxial chamber was set to the required all around pressure plus 30 psi with the pore pressure transducer to water

burette valve closed.

c. The data logger continued recording pore pressure data for another 5 to 10 minutes.

d. The pore pressure transducer to water burette valves were opened. Water column rises in the burette were measured with time. This step marks the starting point of the consolidation stage.

e. The Easy Logger was set to option "00" to stop the data logging. The program CONNECT was used to transfer logged data to the diskette.

f. The program RRBAR was used to analyze the Bishop "B" coefficients for the test samples. At the same time, the Eprom Eraser was used to clear the Data Pack.

Shearing Stage. The procedure used for starting the shearing stage of the triaxial test was as follows.

a. The program CONNECT was used to setup the Easy Logger for the shearing stage.

b. The Easy Logger was set to option "00" from the handheld terminal to start recording the initial values for more than 20 minutes.

c. The motor was turned on with the gear box set to the designated strain rate.

d. After the shearing test was completed, the motor was turned off and the data was transferred from the Easy Logger to a diskette using the program CONNECT.

e. The programs RRBAR and RESULT were used to analyze the shear test results.

Testing Procedures for Repetitive Direct Shear Test

The repetitive direct shear test was a modified direct shear test in which the direction of the shear box travel was changed back and forth automatically. Shear testing procedure used was as follows.

Setting Up the Samples. The sample was prepared following the procedures previously described and then placed into the direct shear box with porous stones and filter papers on both the top and bottom of the sample (Fig. 19).

Saturation Stage. The shear box was filled with distilled water and 0.1 tsf pressure was applied on top of the sample for 24 hours.

Consolidation Stage. Instead of the displacement transducer, a dial gauge was used for the consolidation measurements. The procedures are described below.

a. The dial gauge was zeroed and the designated load was placed on the loading frame. The time the load was applied was taken as time "0".
b. Vertical displacement was recorded with time.
c. The data was recorded until the sample completed primary consolidation.

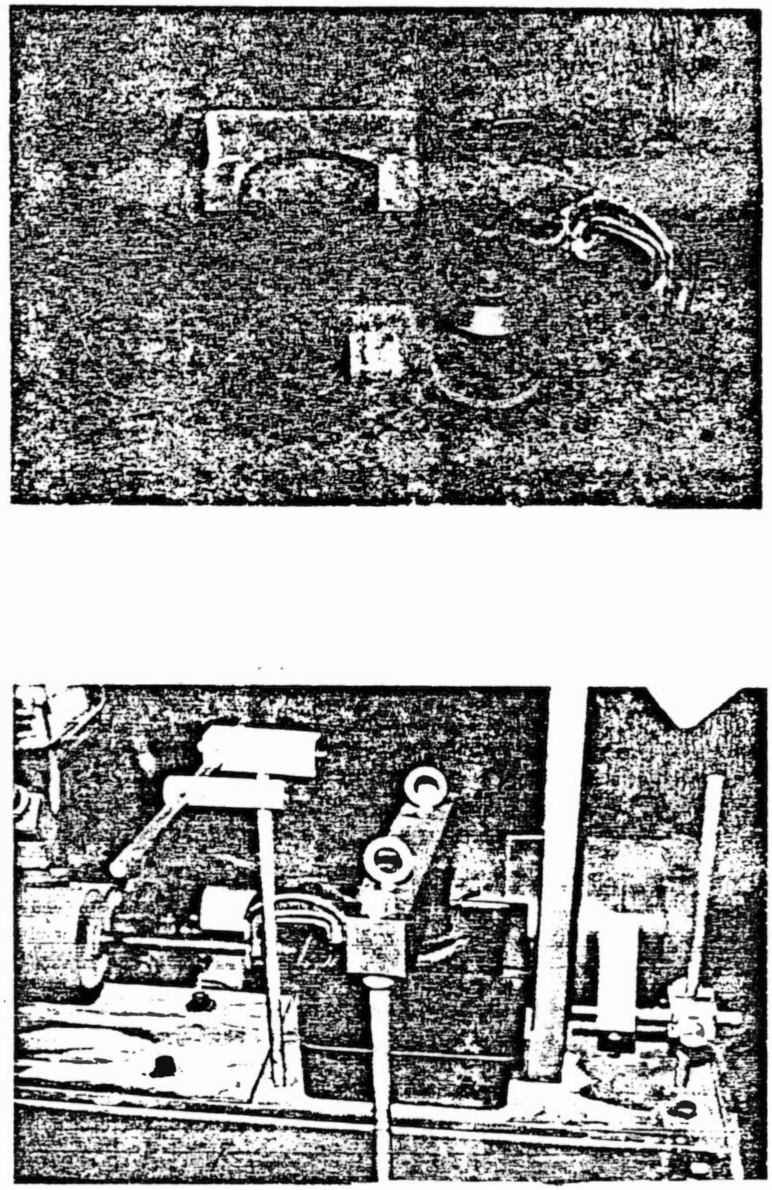


Figure 19. Setup the Repetitive Direct Shear Test Samples.

Setting Up the Data Logger. The Easy Logger was set up according to the procedures described in the user's manual for the program SETUP in Appendix A.

Setting Up and Testing the Sensors. The required setup procedures and circuit diagrams are listed in the appendix B.

Shearing Stage. The procedures used for starting the shearing stage for the repetitive direct shear test was as follows.

a. The Easy Logger was set to option "00" from the handheld terminal to start recording the initial values for more than 20 minutes.

b. The motion controller switches were placed below the load cell, making sure that the backward switch was in contact.

c. The motor was turned on with the speed set to the designated strain rate.

d. After the shearing test are completed, the motor was turned off and the data was transferred from the Easy Logger to a diskette using the program DIRECT.

e. The program DIRECT was used to analyze the shear test results.

Testing Procedures for Supporting Laboratory Tests

Atterberg Limits Test. Samples were air dried and ground to passing U. S. No. 40 sieve. Appropriate quantities of distilled water were mixed with the dry samples and allowed to equilibrate for 24 hours. ASTM procedures D423-60 for liquid limit and D424-59 for plastic limit were used to run the tests.

Grain Size Distribution Test. Particle size distribution was determined by means of the sieve analysis. Standard U.S. sieves (No. 10, 20, 40, 100 and 200) were used for the sieve analysis. The appropriate amount of sample was soaked in distilled water for at least 24 hours and then washed over the sieves. The procedure of grain size analysis followed the ASTM D422-63 specification. The portion of the sample passing the No. 200 sieve was collected and oven dried for use in the hydrometer analysis.

Hydrometer Analysis. ASTM D422-63 procedure with a control cylinder were used for the hydrometer analysis.

Consolidation Test. TAH consolidometers in the OSU Soil Mechanics Laboratory were used for the consolidation test following the ASTM D2435-70 procedure.

Specific Gravity Samples were soaked in distilled water for at least 24 hours then tested using the ASTM D854-58 procedure.

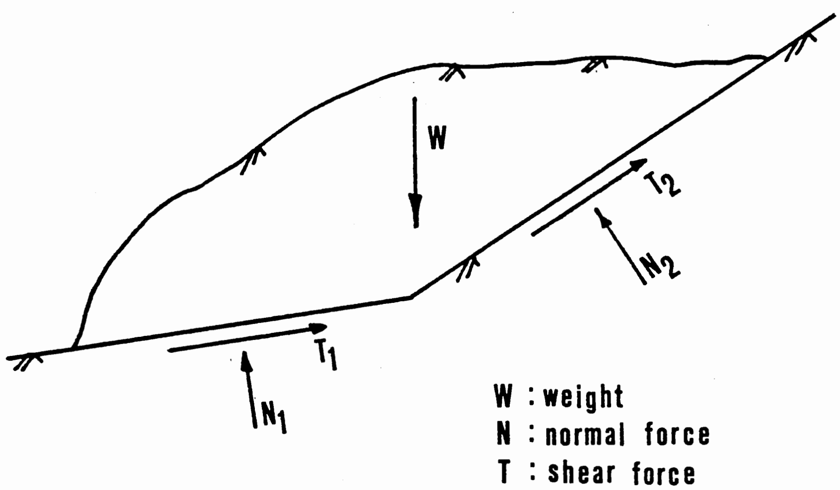
CHAPTER IV

SLOPE STABILITY ANALYSIS

Introduction

Slope instability occurs when the equilibrium of the soil mass is disturbed. Sources of disturbance may be natural or manmade. Examples of natural sources are, long duration intensive rainfall, severe flooding, erosion and liquefaction. Manmade causes are excavation, rapid drawdown of reservoir water level and excess loadings from embankment constructions. For most highway backslope landslide cases, excavation of the slope toes together with the rising of groundwater level due to intensive rainfall are the common causes for the slope instabilities.

The primary driving force for the stability of an earth slope is gravity. The soil mass on a slope, as shown in Figure 20, is by itself a statically indeterminant system. That is, the number of equilibrium equations available is less than the number of unknowns in the system. The statically indeterminant system together with the plastic characteristics of soil require that assumptions be made to solve the problem.



No. Equations	No. Unknowns
$\Sigma H = 0$	T_1 T_2
$\Sigma V = 0$	N_1 N_2
$\Sigma M = 0$	
3	4

Figure 20. Force Diagram for Soil Mass on a Slope.

Generally the stability analyses of earth slopes are accomplished using a method of plastic limit equilibrium. The first assumption made is the location of a potential failure surface. This is not a problem for soil masses with pre-existing failure surfaces. For soils with no distinct failure surfaces, additional geotechnical and geological information are required to make proper engineering judgments. The next assumption is the relationships for the inter-slice forces. By doing this, extra equations are introduced and the system becomes statically determinant. Among the methods based on the assumptions of plastic limit equilibrium, Methods of Slices have been used the most. The general formulation of the Method of Slices is discussed in the following section.

Generalized Method of Slices

There are several different methods within the Generalized Method of Slices. They differ from each other according to their assumptions about the inter-slice forces. The general procedures for the methods of slices, as described by Perloff[24], is cited as follows.

Referring to Figure 21a, the soil mass of a earth slope can be divided into slices after the presumed failure surface is located. All the forces acting on the n-th slice are shown in Figure 21b. For the number of n slices, we have 6n-3 unknowns as listed in Table II. There are three equilibrium equations for each slice; horizontal force

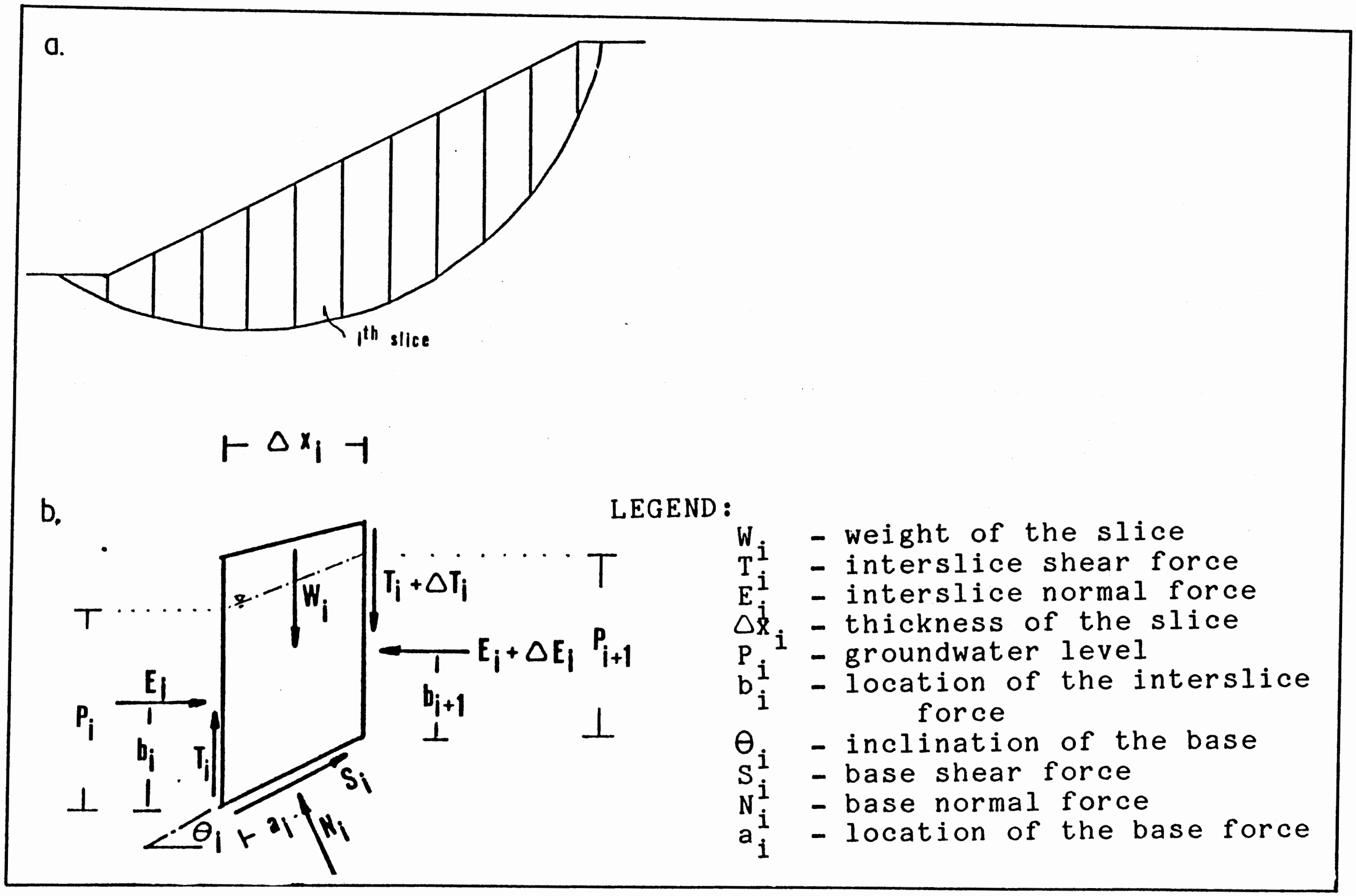


Figure 21. Force Diagram for the General Method of Slices.

TABLE II

FACTORS IN EQUILIBRIUM FORMULATION OF SLOPE STABILITY FOR N SLICES

Unknown	Number
E_i	n-1
T_i	n-1
b_i	n-1
N_i	n
S_i	n
a_i	n
Total	6n-3

equilibrium, vertical force equilibrium and moment equilibrium. Thus, there are 3n equations for the 6n-3 unknowns in the system.

The safety factor is assumed to remain constant along the failure surface. The safety factor, defined as the ratio of the total resisting force over the total driving force, can be viewed as the ratio of the shearing forces calculated from the Mohr-Coulomb-Terzaghi failure criteria over the resisting shear forces at the bottom of each slice, that is,

$$s = (c \Delta x_i / \cos \theta_i + \sigma' \tan \phi')/S.F. \quad . \quad . \quad . \quad (3)$$

For the n-slices in the system this adds n extra equations from the above relationship. Therefore, the total number of equations available for the system becomes 4n. The safety factor is, at the same time, a new unknown so that the total number of unknowns is increased to 6n-2.

Representation of the relationships between the inter-slice normal and shear forces as a function of the x coordinates is,

$$T_x / E_x = \alpha f(x) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

in which α is a constant and f(x) is a assumed function of x. For the n slices in the system, there are now n-1 new equations corresponding to the n-1 slice-to-slice contact surfaces and the total number of equations becomes 5n-1. Consequently, the additional variable α increases the total number of unknowns to 6n-1.

An assumption is made about the location of the normal reaction forces on the bases of the slices, which are fixed at the center of the width assuming the thickness of the slices are very small. This eliminates the n unknowns of a_i from the system and brings the total number of unknowns down to 5n-1.

The system now becomes statically determinant with 5n-1 unknowns and 5n-1 equations. It is unnecessary to solve the 5n-1 simultaneous equations since the safety factor is the only variable to be determined in the stability analysis of slopes. Iteration schemes are used to search for the safety factor of the system. Janbu's method was used in this research and will be discussed in detail.

Janbu's Method

The basic assumption about α and f(x) for Janbu's Method is done implicitly by assuming the line of thrust for each slice. The line of thrust is the line connecting the points of application for the resultant forces at both sides of a slice. Instead of the extra n-1 equations introduced from the relationship of α and f(x), $b_i(x)$'s which indicate the point of application are assumed for each slice to slice interface. That is, the total number of unknowns decreases by n-1 and the resulting system is statically determinant with 4n equations for the 4n unknowns.

The iteration scheme for the Janbu's Method includes two cycles of searching. The first cycle is embedded inside the second cycle. Refer to Appendix C for the derivations of the working equations used. The step by step discussion is described as follows.

1. The initial $\Delta T(x_i)$'s are assumed zero for the whole system.
2. An initial safety factor is assumed and the corresponding S_i for each slice are computed.

$$N_i' = N_i - U_i \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

$$U_i = \frac{(P_{i+1} + P_i)}{2\cos\theta_i} \gamma_w \Delta x_i \quad . \; . \; . \; . \; . \; . \; . \quad (6)$$

$$S_i = \frac{\dfrac{c \cdot \Delta x_i}{\cos\theta_i} + N_i' \cdot \tan\phi'}{S.F.} \quad . \; . \; . \; . \; . \; . \; . \quad (7)$$

3. The S_i's are substituted into equation (8) and a new safety factor is calculated.

$$S.F. = \frac{\Sigma((S_i\cos\theta_i - U_i\sin\theta_i)\tan\phi' + c\,\Delta x_i\tan\theta_i)}{\Sigma(S_i \sin\theta_i)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (8)$$

4. Steps 2 and 3 are repeated until the difference between the two successive safety factors is within tolerable range. This is the inner search cycle for the whole search scheme.

5. The resulting S_i's are substituted into equation (9) to determine ΔE_i's and thus the E_i's for the whole system.

$$\Delta E_i = \frac{S_i}{\cos\theta_i} - (W_i + \Delta T_i) \tan\theta_i \quad \ldots\ldots\ldots\ldots\ldots \quad (9)$$

6. Reasonable b_i's are assumed which represent the line of thrust for each slice and the T_i's are calculated at the inter-slice interface form equation (10).

$$T_i = E_i \tan\delta_i + \Delta E_i \left(\frac{b_{i+1}}{\Delta x_i} + \frac{\tan\theta_i}{2} \right) - \frac{\Delta T_i}{2} \quad \ldots\ldots\ldots\ldots\ldots \quad (10)$$

7. From the T_i's obtained in step 6 calculate the ΔT_i's for each slice.

8. Using the ΔT_i's obtained in step 7 to repeat the inner search cycle starting from step 4. The final convergence is done when the difference between the two safety factors from two successive outer cycles

approaches tolerable range.

There are three precautions to be considered in the search scheme. First, the assumptions about the line of thrust affect the results as well as the rate of convergence for the whole iteration process. Therefore, special care must be taken when making the assumptions. Unreasonable assumptions will in fact result in unpredictable answers. Second, because of roundoff errors from the computer, along with the assumptions of plastic limit equilibrium, this iteration scheme does not necessarily satisfy the patch test for numerical stability. That is, using finer slices for the same system does not guarantee better results. Third, the safety factor may not converge fast enough or may never converge. In this case, different slope stability analysis methods should be used to replace the Janbu's method.

Back Analysis of Janbu's Method

The goal for slope stability back-analysis is to derive the strength parameters of soils from the presumed safety factor along the failure surface. The problem encountered here is that there are two new unknowns, the cohesion "c" and the internal friction angle "ϕ". On the other hand, there is only one new condition, the safety factor. Consequently, new searching strategies are needed to modify the original Janbu's method for back analysis.

In order to overcome the shortage of one condition for solving the system, a value for either of the strength parameters is assumed and the corresponding parameter is calculated for the pre-defined safety factor. A new problem arises, when the Janbu's method is used to calculate the safety factor according to the given strength parameters and not the other way around. The solution for this problem is to fix one strength parameter and then apply the Janbu's method for the safety factors corresponding to different values of the other parameter. At this stage, strength parameters for a specific safety factor of interest can then be interpolated from the results. By repeating the same process for different values of the first parameter, a curve can be drawn to represent the possible strength parameters for the desired safety factor.

In this research, the safety factor in the back-analysis was assumed to be unity to obtain the residual strength parameters for comparison with laboratory tests results.

Case History

The landslide studied was located in Eastern Oklahoma, about 15 miles east of Tulsa. It was along the right-of-way of a new highway project under construction by the Oklahoma Department of Transportation. In the middle of the construction, the landslide occurred after excavation of the toe of the slope. The cause of the landslide was believed to be the combined effect of excavation of the slope toe and variation of the groundwater level. Figure 22 shows the

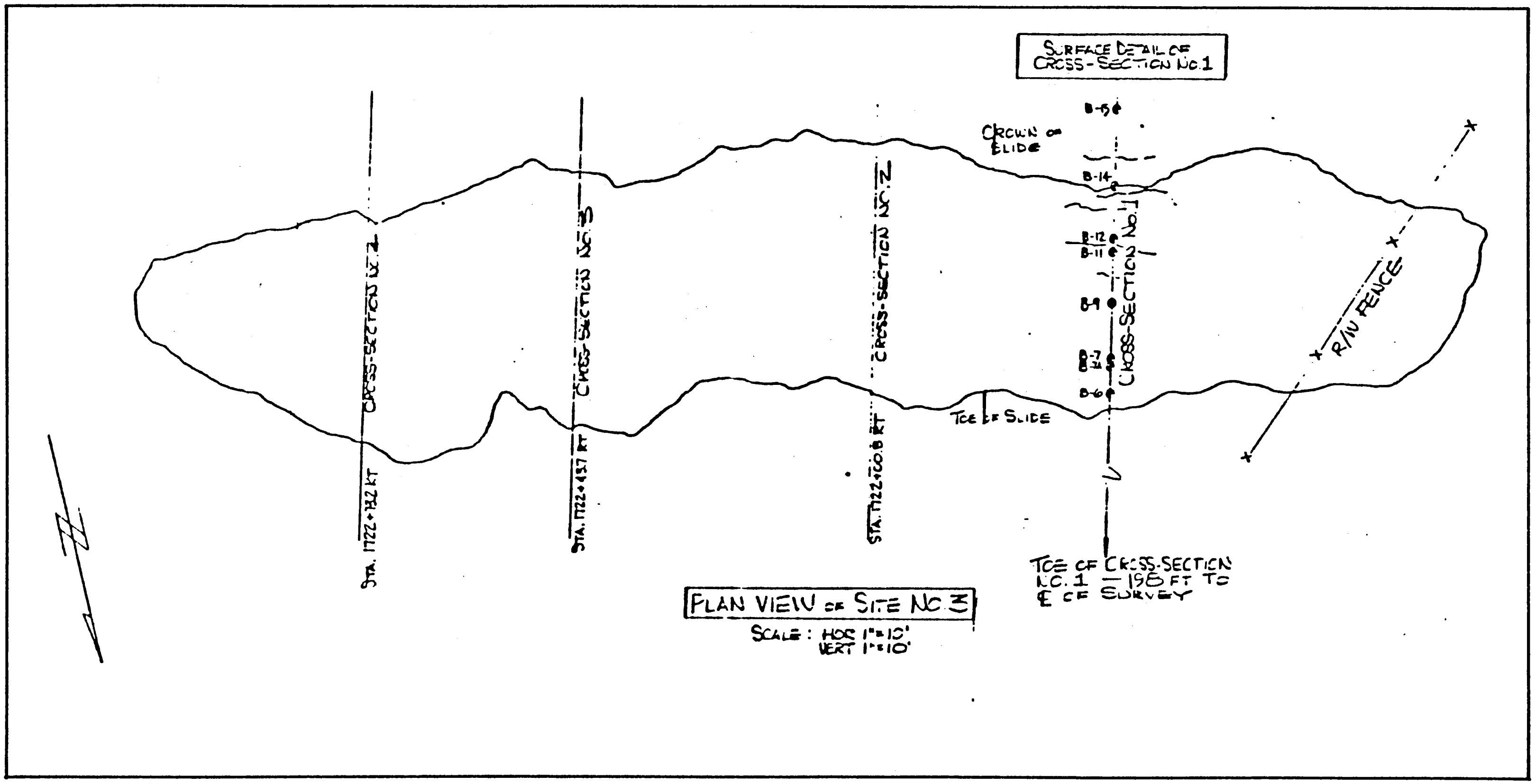


Figure 22a. Plane View of the Landslide

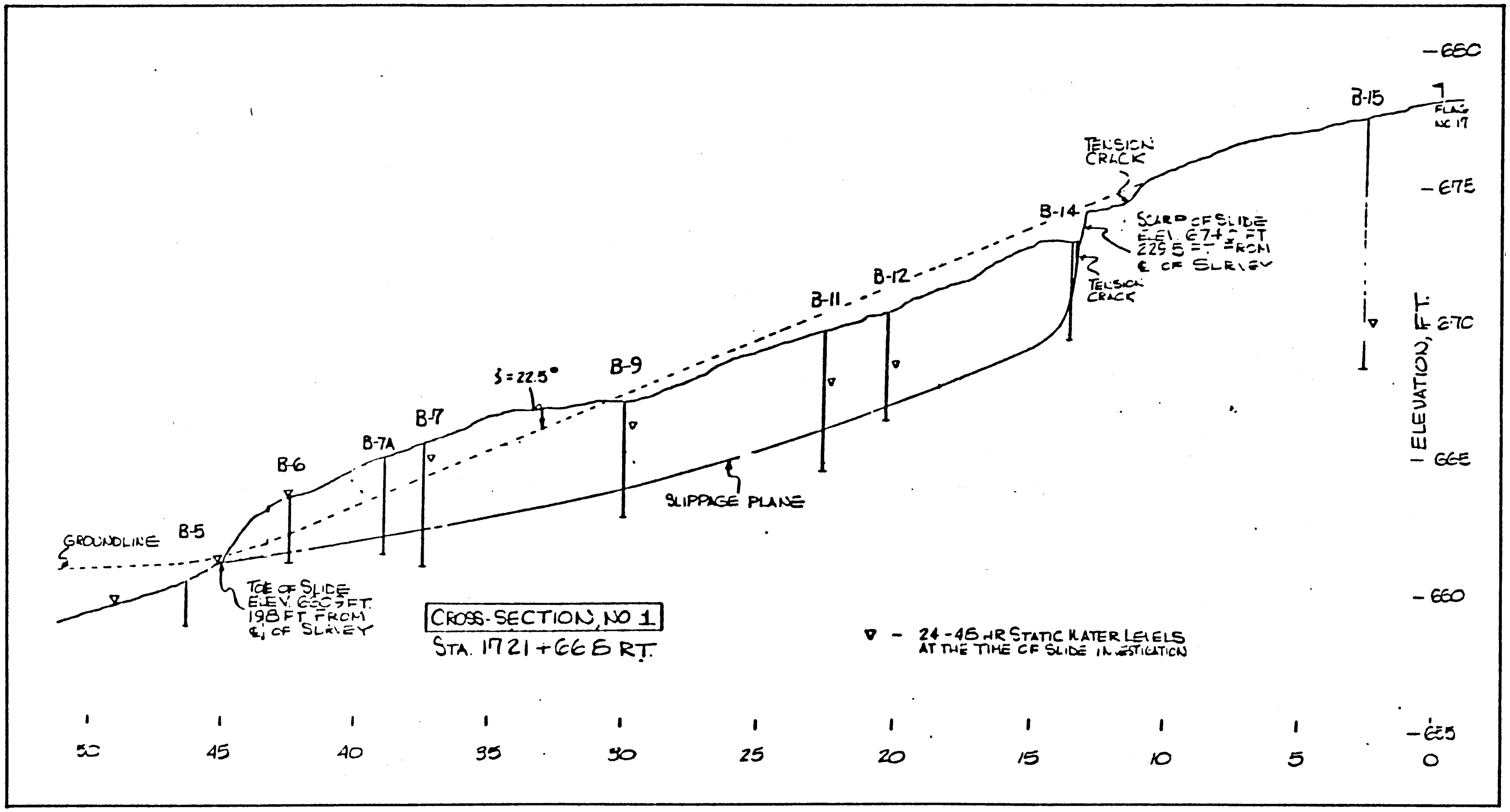


Figure 22b. Profile of the Landslide

plain view and profile of the landslide.

After the slope failure, a detailed investigation was conducted on the failure site. Efforts were made to extract undisturbed samples using Shelby tubes but failed due to the fractures and fissures in the sample. Testing samples for this study was obtained from the bottom of a trench dug on top of the approximated failure surface. In addition, the profile of the slope failure along with the groundwater level is used in the back analysis.

CHAPTER V

ANALYSES AND DISCUSSIONS OF RESULTS

Introduction

The objective of this research was to develop a data acquisition and analysis system for determining the residual shear strength of clays. Through the modification of the existing testing apparatus as previously discussed, the data acquisition and analysis system was completed. The further task to be fulfilled was the validation of the results from the tests.

The data collected throughout this research were reduced and summarized in Appendix F. The reduced data are discussed in this chapter. They are divided into four categories; basic engineering properties of the soil samples, results from the repetitive direct shear tests, results from the triaxial tests and back-analysis of the landslide.

The analyses and discussions are presented in the following sequence. First of all, basic engineering and index properties were correlated with residual shear strength. Results from the back analysis of the slope failure are discussed and serve as the basis for the comparisons with the laboratory test results. Finally, the effects of different sample preparation methods and different data reduction schemes for the two shear strength testings are discussed.

Basic Engineering properties

Results of the basic engineering and index properties are summarized in Table III. The grain size distribution curves from both mechanical sieve analysis and hydrometer analysis are shown in Figure 23. Results of the consolidation test and Casagrande's graphic construction for the pre-consolidation pressure are presented in Figure 24.

From the above supporting tests, the soil is classified as a CH according to the Unified Soil Classification System. In addition, the soil is an overconsolidated clay with OCR (Overconsolidation Ratio) of approximately 3.0.

The index properties used for the correlation with the residual shear strength were, percent clay size particles, liquid limit and plasticity index. Results from this study were plotted in the correlation curves (Fig. 9,10 and 11) presented in Chapter II. The plasticity index and percent clay size particles showed that the residual friction angle obtained from this study was higher than the average correlation curves. On the other hand, the liquid limit appeared to give lower values than the correlation curve. One possible explanation for this deviation is that the liquid limit test in this study was conducted using the

TABLE III

BASIC ENGINEERING PROPERTIES FROM THE SUPPORTING TESTS

Natural Water Content (%)	19.8
Liquid Limit (%)	58.7
Plastic Limit (%)	27.5
Plasticity Index (%)	31.2
USCS Classification	CH
% < 2 μ	45
Preconsolidation Pressure (psf)	1560
OCR	3.0

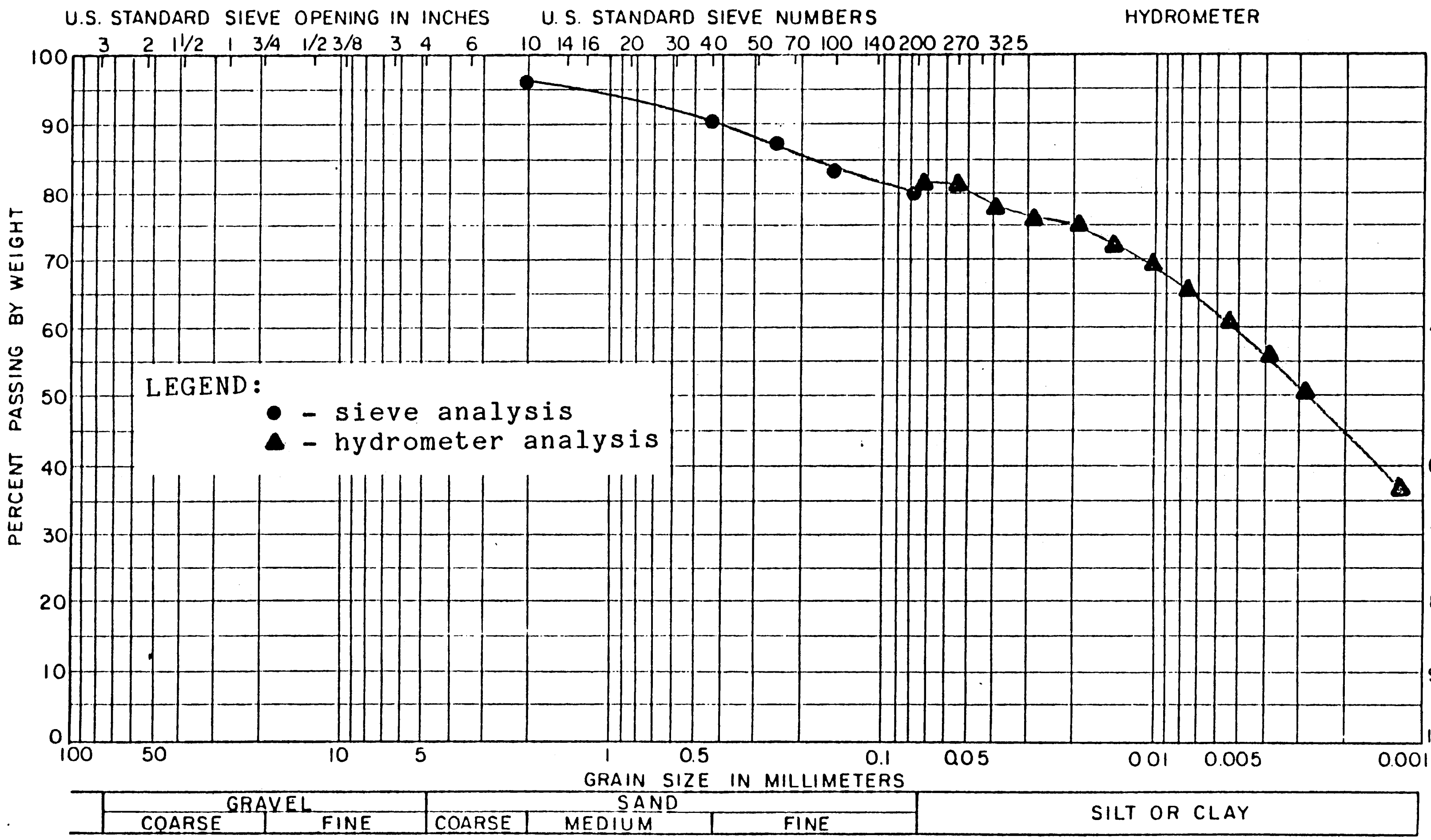


Figure 23. Grain Size Distribution Curve.

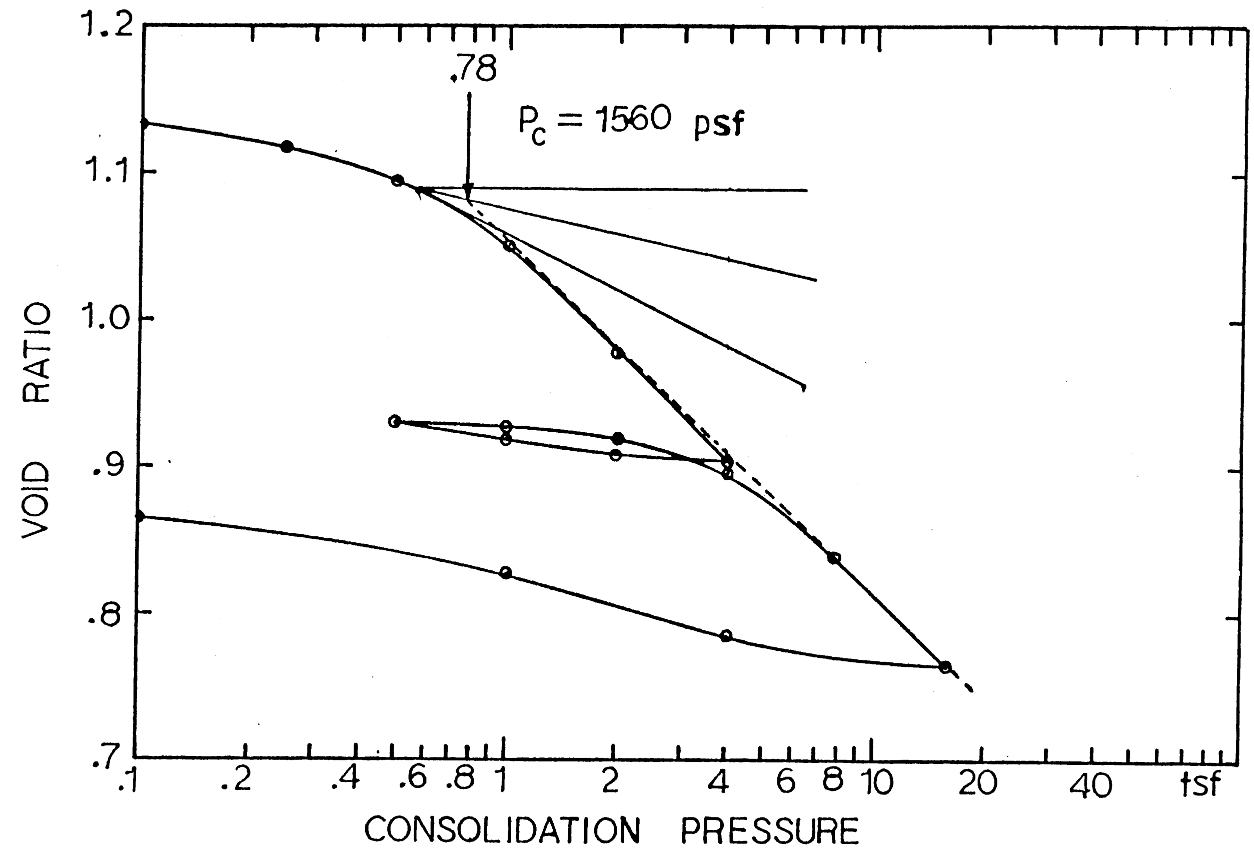


Figure 24. Consolidation Curve.

natural soil sample. Therefore, some soil particles may still in their natural cluster and thus reduce the measured liquid limit.

As was pointed out in the previous chapter, the laboratory testing procedures for the indexes are not standardized and prone to human errors. Thus, the above correlation should be considered as more qualitative than quantitative indications.

Back Analysis of the Slope Stability

In this study, the back analysis of the slope failure with a safety factor of one was conducted using Janbu's Method. Soil profiles before and after the slope failure were used along with different groundwater levels (Fig. 25). Three groundwater levels; below the slip surface, at the ground surface, and at the middle level between the above two levels were used for both soil profiles before and after the slope failure. In addition, natural groundwater levels obtained from the geotechnical survey after the landslide were used for the soil profile after the slope failure. Furthermore, a patch test with different number of slices (4, 8, 16, 32 slices) was included for testing the numerical stability of the Janbu's method.

Numerical Stability of Janbu's Method

There were two situations where the safety factor was numerically unstable. First, when the friction angle

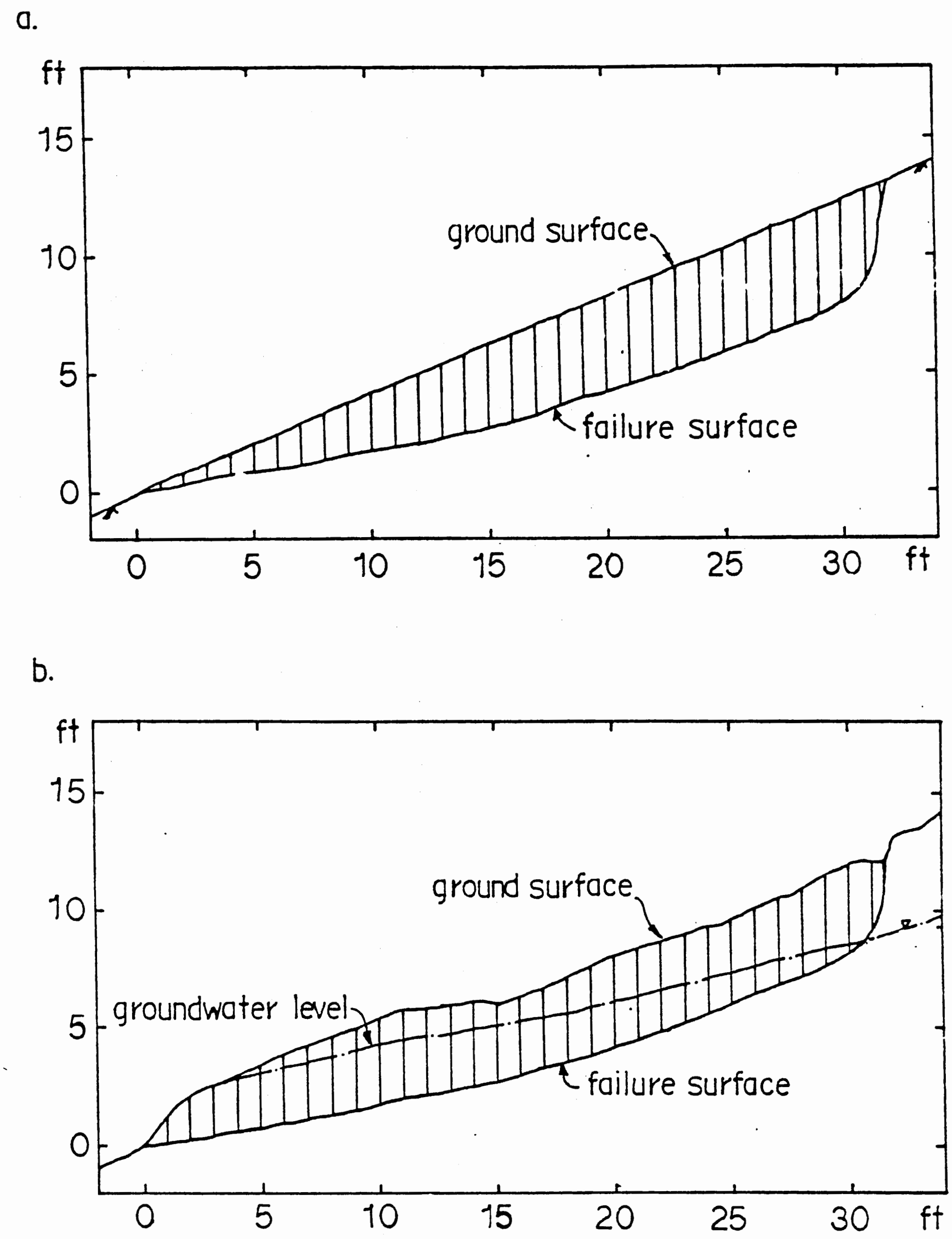


Figure 25a. Slope Profile Before Lanslide.
25b. Slope Profile After Lanslide.

approaches zero, cohesion can not yield a safety factor of one. From Figure 26, there is a clear discontinuity in the curve for safety factors. Proper interpolation can not be drawn from this curve. Second, the safety factor did not converge in several cases when the cohesion was close to zero.

These two numerical instability problems become more serious when the number of slices increases. One source of error is due to the accumulation of roundoff errors involved in the computer calculations. When more slices were used in the analysis the number of calculations required also increased and thus induced more roundoff errors. Another source of instability was from the original assumptions of the Janbu's Method. The assumption in doubt is that the safety factor was assumed to be the same along the failure surface. When the slices were refined, the actual safety factors corresponding to each slice becomes more specific for the stress conditions on each slice. Generally, there will be stress concentration near the toe of the slope and thus the corresponding safety factor is lower. This defies the original assumption and therefore resulted in the numerical instability.

Furthermore, the iterative searching scheme used in the Janbu's method was a source of numerical instability. The search scheme was basically a root finding procedure for non-linear simultaneous equations. The convergence of such a system depends on the starting search point and the system

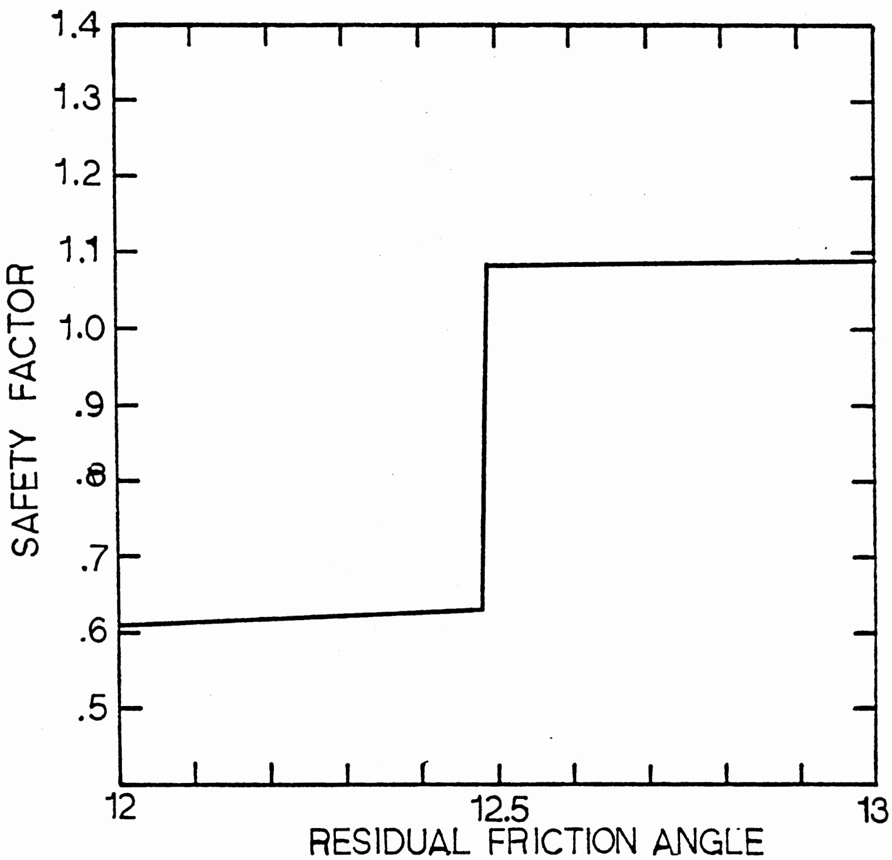


Figure 26. Discontinuity in Safety Factor Interpolation.

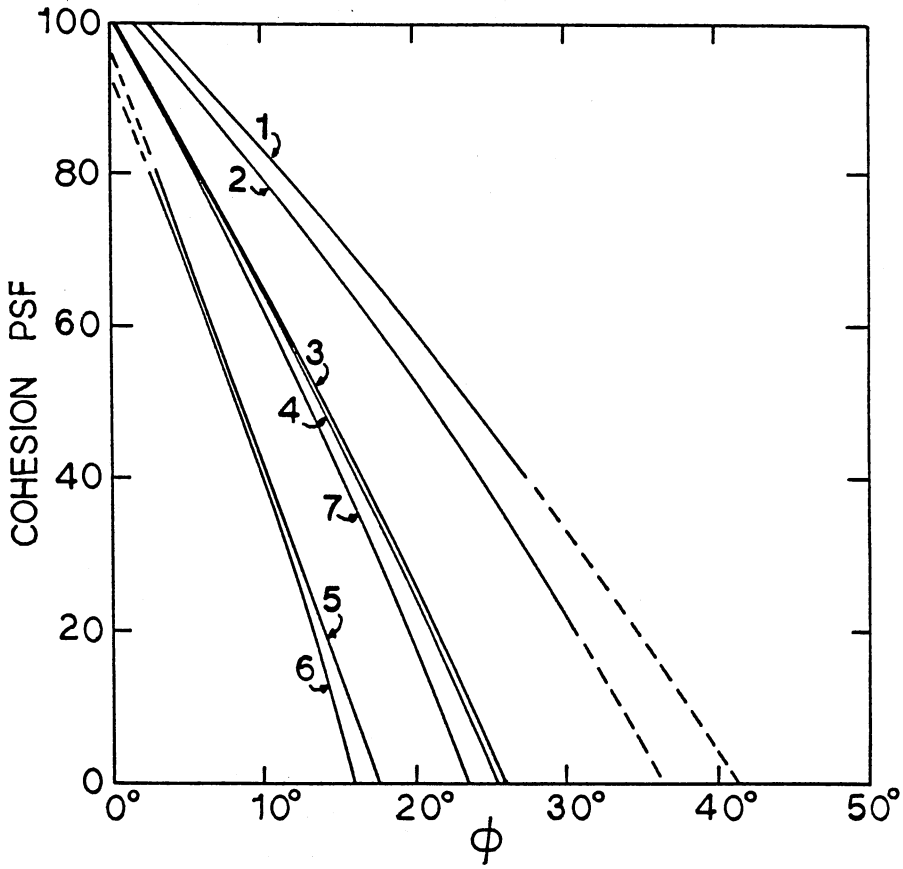
equations themselves. There is no single method that will guarantee convergence for all non-linear simultaneous equations. In Janbu's method, the formulation of the simultaneous equations was determined by the soil profile and the assumption regarding the line of thrust for the inter-slice forces. The formulated simultaneous equations for the slope profile with high groundwater level in this study were found sensitive when the cohesion was close to zero.

Result from the patch test showed that the calculated safety factor became stablized when 16 slices were used. But, when the number of slices increased to 32, the numerical instability discussed previously became more profound. Therefore, safety factors calculated using 16 slices were used in the following discussions.

The numerical instability of Janbu's method is embedded in its original assumptions, formulations, and searching scheme used. Until more accurate and reliable methods are developed, it is still widely accepted for slope stability analysis.

Effects of the Soil Profile

There are two sets of curves, each representing the back analysis results from soil profile before and after the slope failure, see Figure 27. Within each set of curves, the four lines represent the four different groundwater conditions. They are, GWT=0 for no groundwater present,



LEGEND:

1 - GWT=1.0 before failure
2 - GWT=1.0 after failure
3 - GWT=0.5 before failure
4 - GWT=0.5 after failure
5 - GWT=0.0 before failure
6 - GWT=0.0 after failure
7 - natural GWT after failure

Figure 27. Shear Strength Parameter Curves for Safety Factor of Unity Analysis.

GWT=0.5 for groundwater level at the middle between the slip surface and the ground surface, GWT=1.0 representing the worst case where the groundwater surface coincides with the ground surface, and the ground water level indicated during the field investigation.

From the curves two distinct trends indicate that the results are in good coordination with the facts. First, the curves show that the safety factor for the stability of a slope would decrease with increasing groundwater level. Second, the safety factors of the soil profile after landslide are higher than before. For any combination of shear strength parameters that falls inside a curve, the corresponding safety factor is less than one, i.e. landslides are expected to occur.

Results from Laboratory Tests

Laboratory test results for different shear strength tests as well as different data reduction schemes and sample preparation methods are summarized in Table IV. Detail discussions are presented in the following sections.

Results from Repetitive Direct Shear Tests

The repetitive direct shear test results for the partially remolded samples showed irregular readings, Figure 28. In fact, the readings were so random that no meaningful stress-strain curve could be drawn. This phenomenon was not noted in the triaxial tests. The cause

TABLE IV

SUMMARY OF SHEAR STRENGTH PARAMETERS FROM LABORATORY TESTS

Test	Friction Angle
R/R-Bar Triaxial Test	
Undisturbed Sample	
Peak Strength	
from Mohr' Circle	32.0
from Webb's Correction	28.0
Residual Strength	
from Mohr' Circle	23.0
from Webb's Correction	23.0
Remolded Sample	
Peak Strength	
from Mohr' Circle	29.0
from Webb's Correction	26.0
Residual Strength	
from Mohr' Circle	26.5
from Webb's Correction	23.0
Repetitive Direct Shear Test	
Undisturbed Sample	
Peak Stregth	21.0
Residual Strength	14.0
Remolded Sample	
Peak Strength	12.0*
Residual Strength	12.0+

* cohesion = 600 psf.
\+ cohesion = 173 psf.

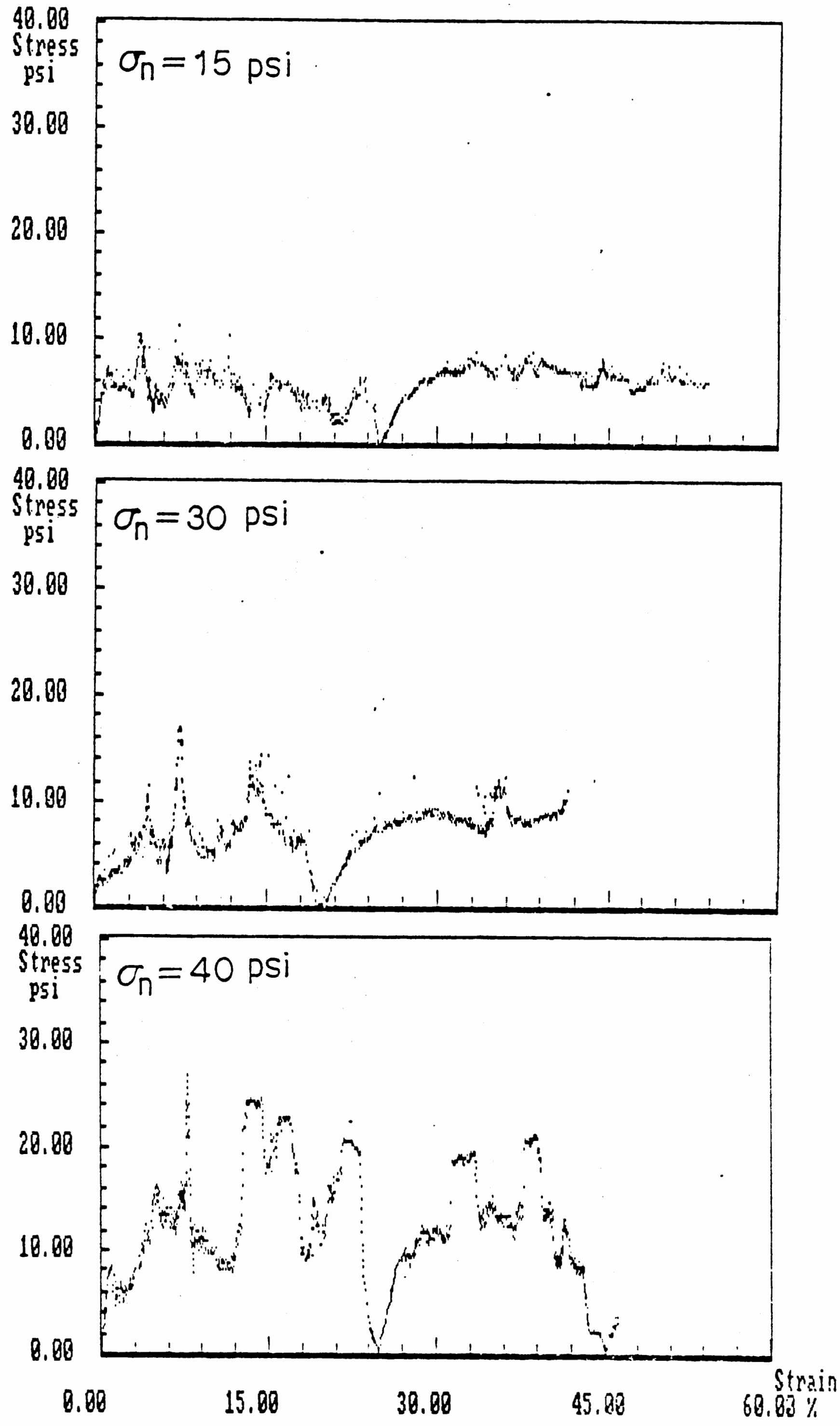
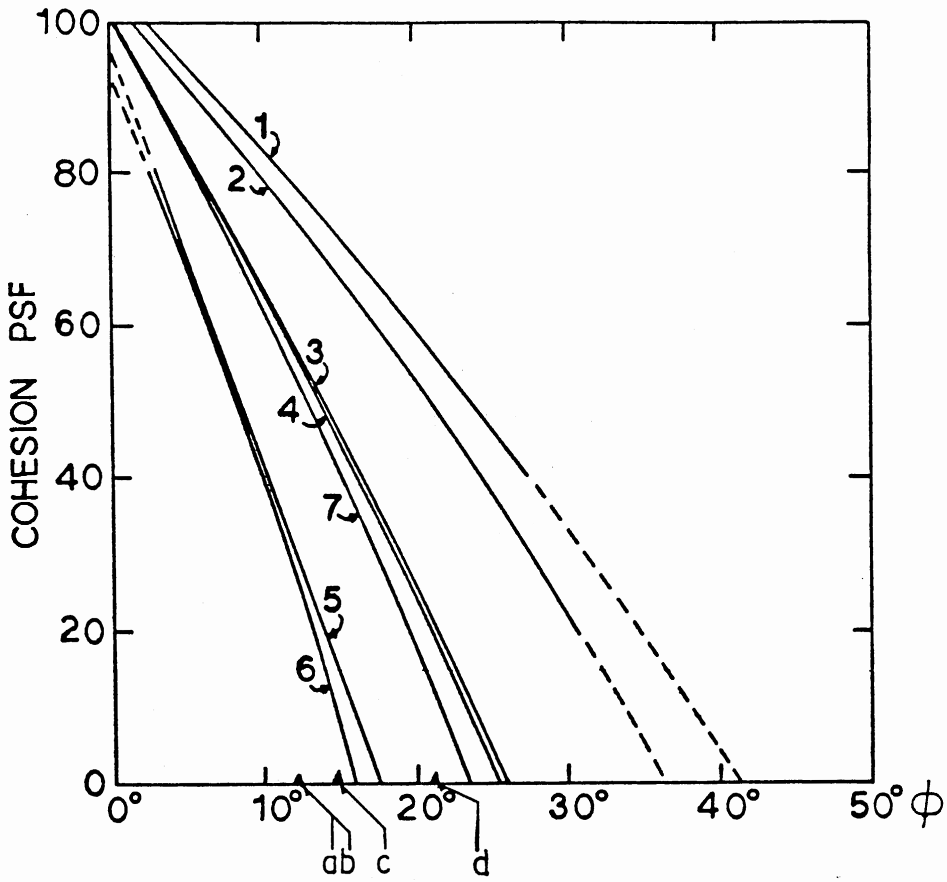


Figure 28. Irregular Stress Reading for Partially Remolded Samples in Direct Shear Test.

of the irregular readings was the presence of the coarse grain nodules in the natural soil and which remained left in the partially remolded soil samples. For the undisturbed samples in the direct shear tests, existing fissures and fractures enable the nodules to translate without significant influence. That is, the nodules behaved as "anchors" between the two parts of the direct shear test specimen which caused the random peak shear stresses. The peak stresses then dropped off quickly when the nodules "rolled over" and failed surrounding soils. The fact that peaks shear stresses increased with increasing normal stresses also indicates the "anchoring" effect from the coarse grain nodules. This "anchoring" effect can be eliminated by removing the nodules from the soil samples as in the fully remolded samples.

The residual shear strength obtained from the repetitive direct shear tests were low compared to the slope stability back analysis, see Figure 29. The corresponding safety factors are presented in Table V. One possible explanation is that the strain rate used (10% per 24 hours) was not slow enough. In this case, pore water pressure may have built up inside the sample. Therefore, the actual effective normal stresses would be less than what was used in the data analysis.

The pore water pressure effect can be explained by comparing the results from the refined samples with the undisturbed samples. Because the refined samples were



LEGEND:

1 - GWT=1.0 before failure
2 - GWT=1.0 after failure
3 - GWT=0.5 before failure
4 - GWT=0.5 after failure
5 - GWT=0.0 before failure
6 - GWT=0.0 after failure
7 - natural GWT after failure
a - residual for refined samples with cohesion
b - peak for refined samples with cohesion
c - residual for undisturbed samples
d - peak for undisturbed samples

Figure 29. Results from Direct Shear Tests Compared with Back Analysis Curves.

TABLE V

SAFETY FACTOR CALCULATED CORRESPONDING TO THE RESIDUAL SHEAR STRENGTH FROM REPETITIVE DIRECT SHEAR TESTS

Test	Soil Profile			
	GWt= 0.0	0.5	1.0	natural
Undisturbed Sample				
Peak (21.0)				
before failure	1.21	0.81	-	
after failure	1.25	0.82	-	0.85
Residual (14.0)				
before failure	0.78	0.52	-	
after failure	0.81	0.53	-	0.55
Remolded Sample				
Peak (12.0)				
before failure	0.67	0.45	-	
	* 4.41	4.00	3.66	
after failure	0.69	0.46	-	0.47
	* 4.44	4.01	3.76	4.10
Residual (12.0)				
before failure	0.67	0.45	-	
	+ 1.74	1.47	1.23	
after failure	0.69	0.46	-	0.47
	+ 1.77	1.47	1.28	1.51

* : with cohesion = 600 psf
+ : with cohesion = 173 psf
- : did not converge

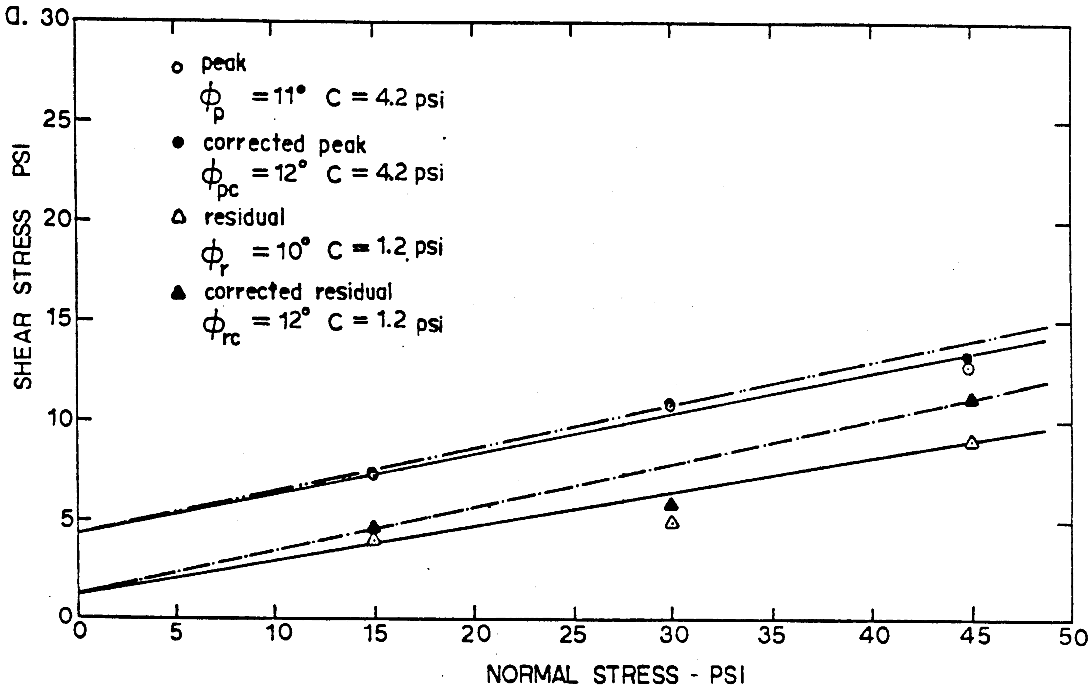
composed of only the fine grain portions and were remolded without the natural fissures, the permeabilities were expected to be lower than the undisturbed samples. The pore water pressure effect should be greater for the refined samples, see Figure 30. This is true since the failure envelopes for the refined samples exhibit higher cohesion than the undisturbed samples. For remolded samples without natural bonding, cohesion is most likely the result of pore water pressure effects.

Finally, the cross section area correction was very important in the repetitive direct shear test when the corresponding strain was very large. From Figure 31, the percent error for cross section area is plotted with respect to percent strain. For the strain used for residual strength (about 30%), the corresponding error was as high as 37.6%. Therefore, equation for area correction which discussed in Chapter II was used for calculation of the shear stress.

Results from R/R-Bar Triaxial Tests

Unlike the repetitive direct shear test, partially remolded samples gave similar results to the undisturbed samples. The results are plotted with the slope stability back analysis results in Figure 32. The calculated safety factors are also presented in Table VI.

Two data reduction schemes were used in obtaining the shear strength parameters for the triaxial tests. The first



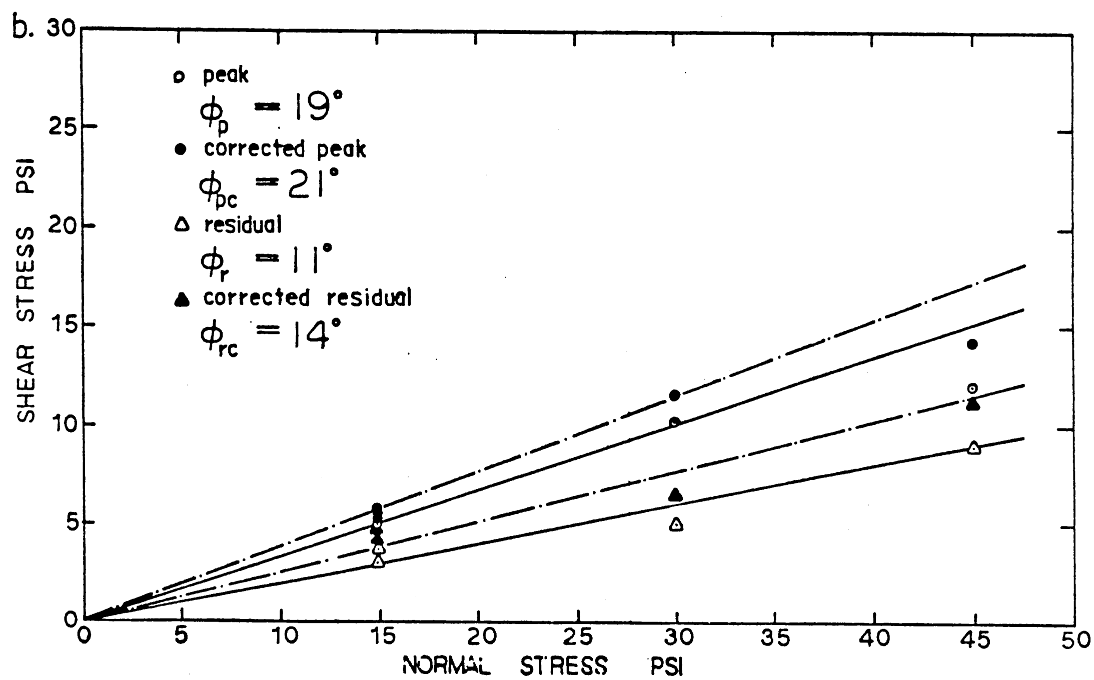


Figure 30a. Failure Envelopes for Refined Samples in Direct Shear Tests.
30b. Failure Envelopes for Undisturbed Samples in Direct Shear Tests.

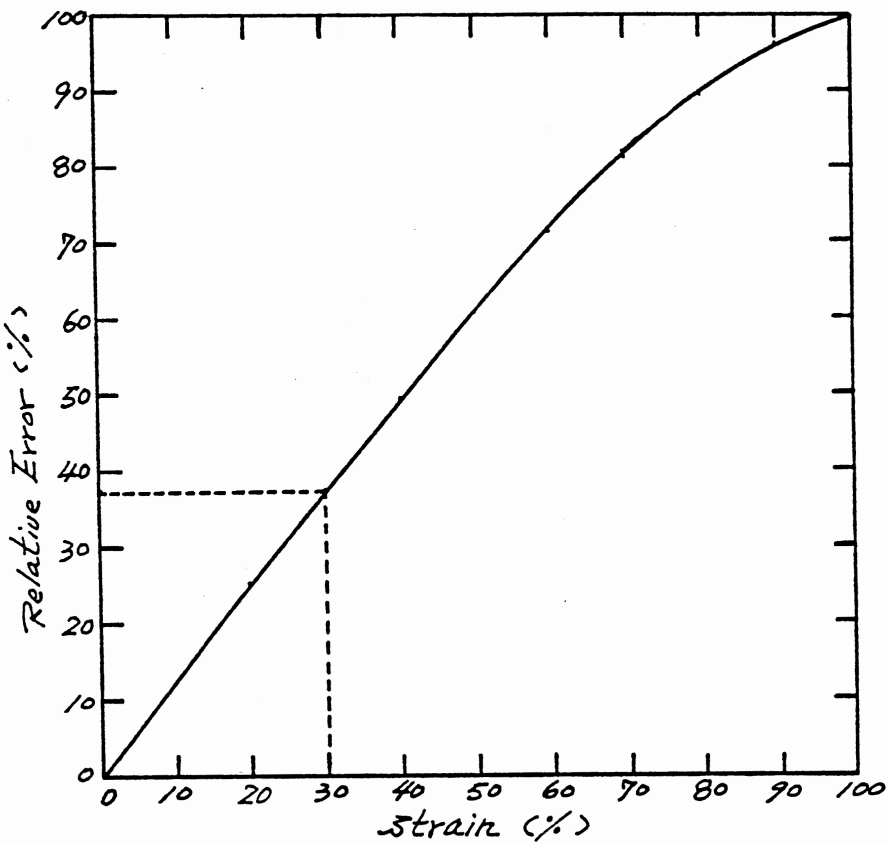
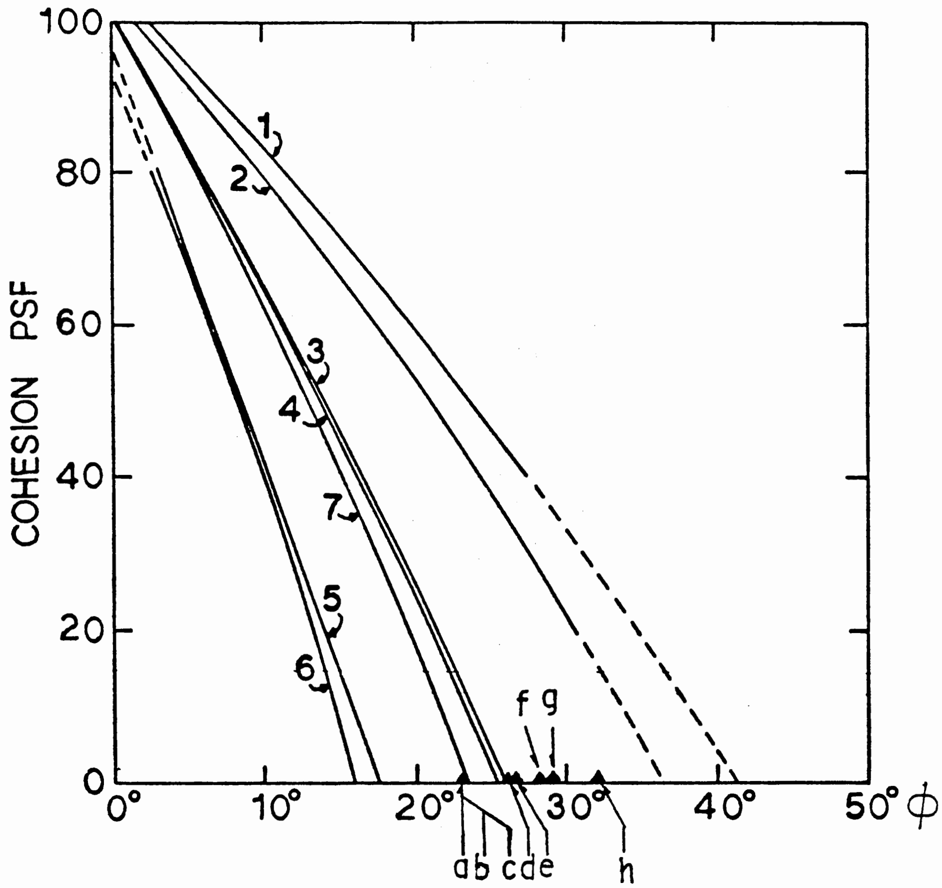


Figure 31. Percent Error Curve for Area Correction.



1 - GWT=1.0 before failure 2 - GWT=1.0 after failure
3 - GWT=0.5 before failure 4 - GWT=0.5 after failure
5 - GWT=0.0 before failure 6 - GWT=0.0 after failure
7 - natural GWT after failure
a - residual for undisturbed samples - Mohr's circle
b - residual for undisturbed samples - Webb's correction
c - residual for remolded samples - Webb's correction
d - peak for remolded samples - Webb's correction
e - residual for remolded samples - Mohr's circle
f - peak for undisturbed samples - Webb's correction
g - peak for remolded samples - Mohr's circle
h - peak for undisturbed samples - Mohr's circle

Figure 32. Results from R/R-Bar Triaxial Tests Compared with Back Analysis Curves.

TABLE VI

SAFETY FACTOR CALCULATED CORRESPONDING TO THE RESIDUAL SHEAR STRENGTH FROM R/R-BAR TRIAXIAL TESTS

Test	Soil Profile GWt= 0.0	0.5	1.0	natural
Undisturbed Sample				
Peak				
a. (32.0°)				
before failure	1.97	1.31	-	
after failure	2.03	1.34	-	1.39
b. (28.0°)				
before failure	1.67	1.12	-	
after failure	1.73	1.13	-	1.18
Residual				
a. (23.0°)				
before failure	1.34	0.89	-	
after failure	1.38	0.91	-	0.94
b. (23.0°)				
before failure	1.34	0.89	-	
after failure	1.38	0.91	-	0.94
Remolded Sample				
Peak				
a. (29.0°)				
before failure	1.74	1.17	-	
after failure	1.80	1.19	-	1.23
b. (26.0°)				
before failure	1.53	1.03	-	
after failure	1.58	1.04	-	1.18
Residual				
a. (26.5°)				
before failure	1.57	1.05	-	
after failure	1.62	1.07	-	1.11
b. (23.0°)				
before failure	1.34	0.89	-	
after failure	1.38	0.91	-	0.94

a : Mohr's circle
b : Webb's correction
- : did not converge

was construction of Mohr's circles. Peak strengths is taken at 20% strain if no peak values were reached. Mohr's circles at the end of the tests were used for residual shear strength. The second method was Webb's correction method as described in Appendix E.

From the results shown in the back analysis curves, the strength parameters agreed well with the slope stability back analysis. The safety factors from peak strengths fall below one when the groundwater level rises close to ground surface. This indicates the occurrence of the slope failure. For the residual shear strength parameters, the corresponding safety factors is close to the back analysis curve for natural groundwater level with soil profile after landslide. This confirms the validity of the results from R/R-Bar triaxial test for residual shear strength testing.

Judging from the results, the slope may slide further if the groundwater level rises to above the middle between the ground surface and the existing failure surface. Therefore, a remedial design based on residual strength should be considered.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

One of the purposes of this research was to develop the data acquisition and analysis system discussed above. Additionally, the residual strength measurements were made by a series of laboratory tests and compared to back analyses of a landslide failure case history. Several conclusions may be drawn from the discussions, along with recommendations for further research.

Conclusions

The results of the research program described herein indicate the following conclusions:

1. Through the comparison between results from laboratory test and slope stability back-analysis, the developed data analysis system has shown its validity for both peak and residual shear strength measurements.

2. About 70%-80% engineer efforts can be saved through the use of the developed data acquisition and analysis system.

3. Peak strength as well as the residual strength determined from R/R-Bar triaxial tests on undisturbed samples are both acceptable.

4. In the repetitive direct shear test, errors induced by omitting the cross section area correction are negligible for peak strength but were profound for the residual strength with large strain.

5. The strain rate (10% per 24 hour) used in the repetitive direct shear tests with refined samples was too high for proper pore water pressure dissipation.

6. The test period required for repetitive direct shear tests is three times longer than that of the R/R-Bar triaxial tests. Thus, the R/R-Bar triaxial test is more suitable for both peak and residual shear strength testing.

7. Index properties appear to be generally in good correlation with results from other researchers. But, they should be treated as a qualitative rather than quantitative indication.

Recommendations for Further Research

1. Real time control of the testing apparatus can be done by applying the computer for monitoring the progress of laboratory tests. With the application of feedback mechanisms and computer control, soil samples can be tested under designed stress paths and thus better resemble the actual underground conditions.

2. An iterative finite element scheme which accounts for the non-linear stress/strain relationship could be used for slope stability analysis. In this case, stress/strain curves from laboratory tests which ranging from peak to

residual strength should be used.

3. Larger samples could be used for reducing the effects of the coarse grain nodules in the direct shear tests.

4. A slow strain rate should be used for repetitive direct shear tests on samples with low permeability.

5. The laboratory data analysis system developed can be expanded to all other soil mechanics laboratory tests. In addition, a laboratory project management system can be developed based on the expanded data analysis system.

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APPENDIX A

USER'S MANUAL FOR COMPUTER PROGRAMS

The hardware requirements for using the computer programs are an IBM PC/XT/AT or compatibles with at least 480Kb of memory, one floppy disk drive, an IBM CGA or Hercules graphic adaptor and a RS-232C serial communication port. The Hercules version of the program will run only through HBASIC. Programs for the CGA version are "EXE" files and may be executed directly. The procedures to invoke the programs are described as follows.

1. Put the program diskette in drive "A" (left drive) and turn on the computer. The diskette is equipped with DOS and can boot on by itself. If the computer is already turned on, put the program diskette into drive "A" and then re-boot the computer. At the same time, put the data diskette into drive "B".
2. Under the "A" prompt (A>) type "SETCGA" for computers equipped with IBM CGA or type "SETHGC" for Hercules graphic card.
3. Under the "A" prompt (A>), type "HBASIC Program-name.HGC/C:1000/F:6" for Hercules Graphics. If the IBM CGA is used, type "Program-name". The "Program-name" is the assigned name for each program.
4. After seeing the greeting messages on screen, follow the instructions for data input.

Basic Data Input Formats

The data input formats for the programs are separated by different screens. There are two kinds of screens for data input, random position screens and selection screens.

Within a screen, there are three types of fields, string fields, numeric fields and yes/no fields. The method to input data for different screens and fields are different.

The fields are the basic unit for data input. Within the boundaries of each field indicated by "[]", characters or numbers can be typed. If the user attempts to exceed the boundary, there will be a beep sound and the last typed characters will overlap on the last position of the field. The names of the fields denote the valid type of data accepted for the field. String fields will accept any printable characters. Numeric fields will accept only numbers and decimal point. Yes/no fields will accept only "Y" for yes or "N" for no. If an invalid character is typed in a field, a beep will sound and the character will not be accepted. In addition, there are also several special keys accepted while editing a field. They are list as follows.

1. Del key, deletes the character under the cursor.
2. Left/right arrow key, moves the cursor left/right one character.
3. Gray left arrow key, deletes the character left of the cursor.
4. Ins key, toggles the insert mode on and off. If the insert mode is on, all the characters under and right of the cursor will be pushed right one position.

The screens are used to group data for a specific purpose. Within different screen types there are different ways to move through the fields in the screen. Selection screens are indicated by "Select from the following ...", while the random positioned screens show irregular positions for the fields.

In a selection screen, only the number keys, the "Q" key and up/down arrow keys are valid. The number keys are used for making selections directly from the listed options. The up/down arrow keys will move the selection through the table. The "Quit" selection can only be selected by pressing the "Q" key. When the intended selection is made, which is indicated by the " " sign, press the carriage return key to complete the selection.

For random positioned screens, the up/down arrow keys along with the carriage return key are used to move through the fields. The up arrow key moves the cursor to the last field. The down arrow key and carriage return key move the cursor to the next field. After data for all the fields are properly typed in, F10 is pressed to complete the input for the screen. If there is no error detected, a message asking for confirmation will appear on the bottom of the screen. Press "Y" for affirmative and then leave the screen. If there are errors detected or a "N" is pressed, a beep will sound and an error message will be shown at the bottom of the screen. At this time press any key and program will return to the screen mode for necessary corrections of the data.

Basic Data Output Formats

There are two formats for result presentation: tabulated printout and graphic screen output. The graphic screen can be viewed on the monitor. The tabulated printout can only be obtained through a printer. In order to obtain a hardcopy (printouts) of the results, an IBM printer should be connected to the computer and turned on.

To obtain the tabulated printout results choose the tabulated printout option on the selection table. As for the graphic screen, there are several steps to follow for the screen dump. The first step is to press the carriage return key clearing the extra message on the screen. Then, press the Shift key and the PrtSc key at the same time. For Hercules graphics, an additional "0" should be pressed to start the screen copy process. Before sending data to the printer precautions should be taken; namely, 1)check if the printer is on, 2)check if there is enough printout paper, 3)adjust the margins of the printer paper.

Immediately after the program starts, a greeting message (Fig. 33) will be shown on the screen. This is common for all the programs. Press any key to proceed with the program execution.

User's Guide For Program CONNECT

This program serves the functions of communicating with the data logger. Before executing this program be sure that the RS-232 port is connected to the Easy Logger and the handheld terminal for the Easy Logger is turned off. The flow chart for this program is shown in Figure 34. The program consists of several screens which are discussed in the following paragraphs.

SOIL MECHANICS LABORATORY
SCHOOL OF CIVIL ENGINEERING
OKLAHOMA STATE UNIVERSITY
Stillwater, Oklahoma

LABORATORY DATA ANALYSIS SYSTEM
Version 1.0
by
Y. C. You
SPRING, 1987, Stillwater

R/R Bar Triaxial Test Data Analysis
Connection With the Data Logger

<Press Any Key to Continue>

Figure 33. Greeting Screen.

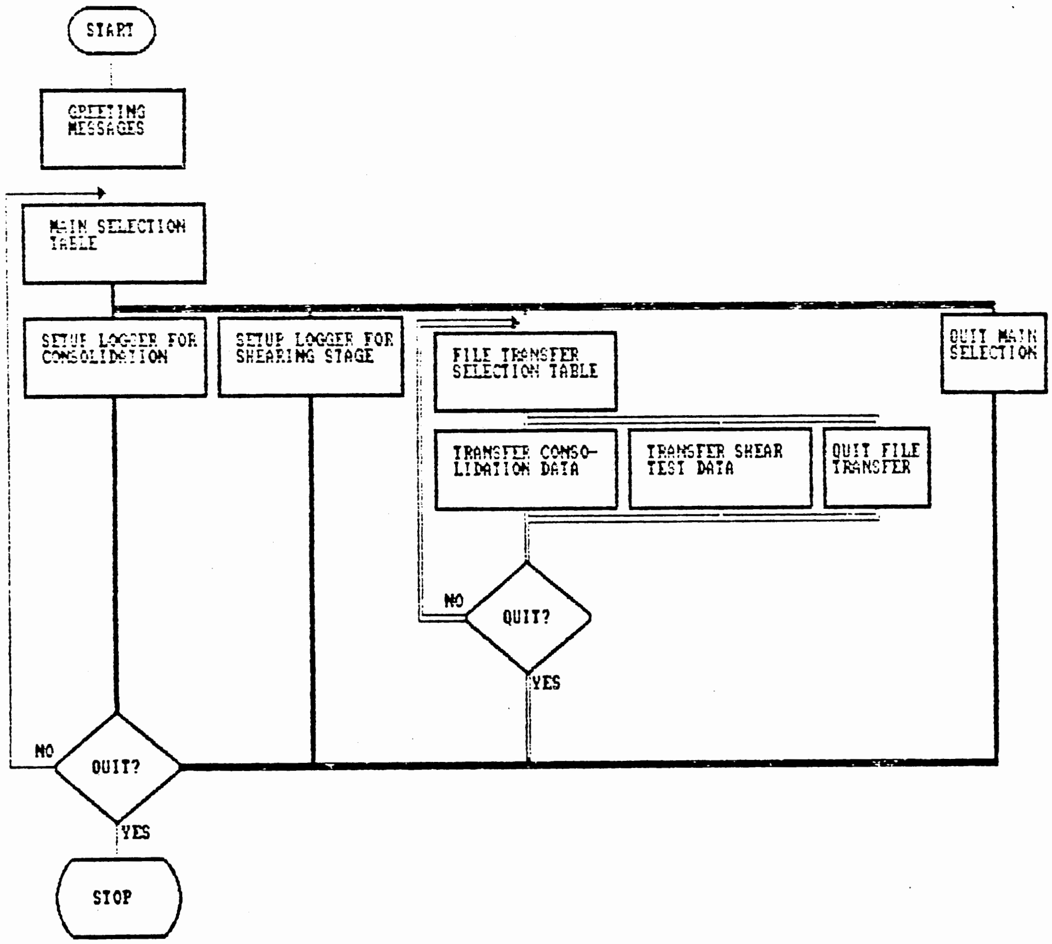


Figure 34. Flow Chart for Program CONNECT.

Main Selection Screen

The screen, shown in Figure 35, is the main selection screen with four options. They are listed below.

Option #1: setup the Easy Logger for the consolidation stage of the triaxial test.
Option #2: setup the Easy Logger for the shearing stage of the triaxial test.
Option #3: transfer data form the Easy Logger to diskette.
Option #4: quit the program CONNECT.

Instruction Screens

The instruction screen, as shown in Figures 36, which instruct the user how to activate the communication with the Easy Logger through the RS-232 port. The Ring Button Box is located between the RS-232 port and the Easy Logger. The yellow lights on the box indicate signals transmitted out from the computer. The red lights flash when the Easy Logger is sending out data. If the lights are still off after the ring button is pressed, check the ends of the serial communication cable for proper connection. Be sure that the connectors on each end of the cable are attached properly. If the red light is on but not flashing for more than 1 minute, the system inside the Easy Logger is suspended. In this case, turn off the power supply of the Easy Logger and stop the program execution. Wait for 10 seconds, turn on the power for the logger again and re-start the program execution.

```
Select stage for Easy Logger Setting : [1]

√ 1. Setting up the Easy Logger for consolidation.
  2. Setting up the Easy Logger for shearing.
  3. Receive Data From the Data Logger.
  Q. Quit.
```

Figure 35. Main Selection Screen for CONNECT.

```
Connect the Series Cable to the Easy Logger.
The Cable is located beside the monitor.
The ring button is on the Cable box.
Press ring button once.
```

Figure 36. Instruction Screen.

Project ID Screen

There is one field on this screen for the input of the project ID (Fig. 37). The project ID is the name of the laboratory testing project provided by the user. It is a character string with eight characters. This name should be the same as the corresponding testing project name in the project initialization screen in the RRBAR program.

File Transfer Selection Screen

This selection screen, shown in Figure 38, consists of three options. The options are described as follows.

Option #1: transfer the consolidation stage data from the Easy Logger to the diskette for the Bishop's "B" coefficient calculation.
Option #2: transfer the shearing stage data form the Easy Logger to the diskette.
Option #3: quit this screen.

The CONNECT program does not produce any output data, therefore, the RRBAR program must be used to analyze the raw data from the Easy Logger for intermediate results.

User's Guide For Program RRBAR

This program analyzes the data previously transferred form the Easy Logger. Be sure that the corresponding data is on a data diskette in disk drive "B" before this program is activated. The flow chart showing the algorithm for this program is in Figure 39. RRBAR consists of 5 screens which are described in the following paragraphs.

```
Input Program ID : [TTRSDL1 ]
```

Figure 37. Project ID Screen.

```
Select Stage for File Transferring : [1]

√ 1. Transferring Consolidation Stage Data.
  2. Transferring Shearing Stage Data.
  Q. Quit File Transferring.
WARNING: Transfer file will destory the file which
  transfer previously under the same project name.
```

Figure 38. File Transfer Selection Screen.

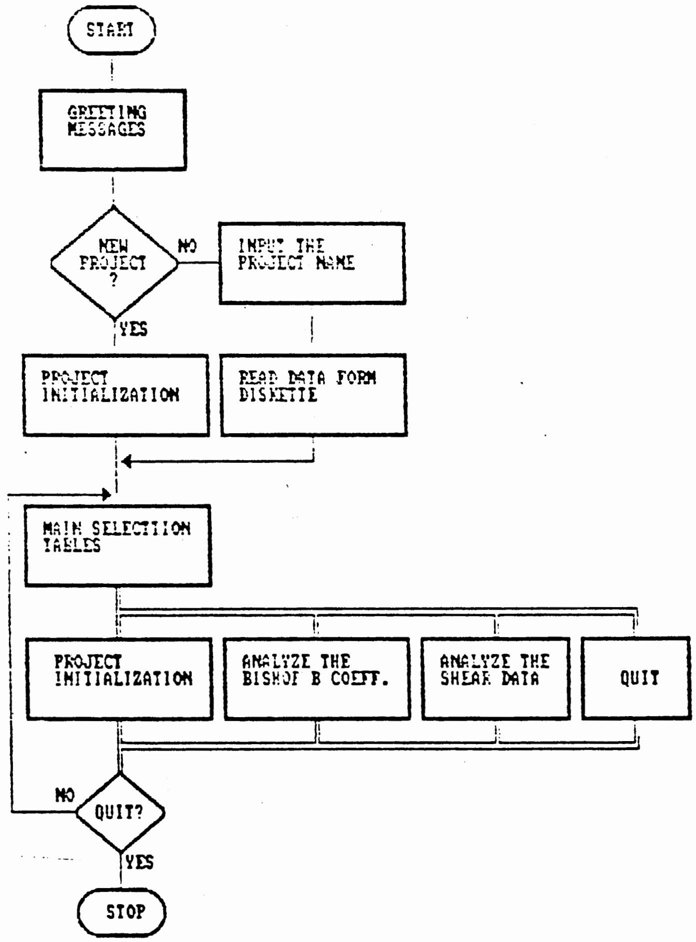


Figure 39. Flow Chart for RRBAR.

Project ID Screens

Following the greeting screen, the program prompts a message asking if this is a new testing project. If the user responds with a "Y" then the program will proceed to project initialization. If "N" is keyed in, the program will show the Project ID Screen for the project name to be used. This project name is the same as the one discussed previously in the CONNECT program. Make sure that the project initialization data corresponding to the project name is on the disk in drive "B".

Project Initialization Screen

The project initialization screen for the RRBAR program, shown in Figure 40, consists of 22 fields. The detail discussions of these fields are listed as follows.

Field # 1: the name of the project, a string field with 8 characters. This project name is unique and should be used for all corresponding data files concerning the project.
Field # 2: the test number, a numeric field with 2 spaces.
Field # 3: brief description of the test project, a string field with 50 characters.
Field # 4: month in numbers, a numeric field with 2 spaces.
Field # 5: date in numbers, a numeric field with 2 spaces.
Field # 6: year in numbers, a numeric field with 2 spaces.
Field # 7: the names of the persons conducting the test, a string field with 50 characters.
Field # 8: the height of the sample in inches, a numeric field.
Field # 9: the diameter of the sample in inches, a numeric field.
Field #10: the specific gravity of the sample, a numeric field.

```
═══════════════════════ Testing Program initialization ═══════════════════════
 Test Program : [TTRSDL1 ]                                 Test No.  : [1 ]
 Test for : [THESIS                                   ]   Date :[3 ]/[1 ]/[87]
 Tested by: [YET-CHENG YOU                            ]

 Sample Description :
   Height : [2.8      ] in.     Diameter : [1.3303  ] in.      Gs : [2.8    ]
 [UNDISTURBED SAMPLE FROM SLOP FAILURE SURFACE                               ]
 [BROWN CLAY WITH SMALL NODULES                                              ]

 Triaxial Cell No. :               1                 2                  3
 Regulator A (psi)           [30      ]        [30      ]         [30      ]
 Regulator B (psi)           [45      ]        [60      ]         [90      ]
 Consolidation pressure      [        ]        [        ]         [        ]

 Strain rate : [0.000196  ] in./min
═════════════════════════════<F10 to complete the input>══════════════════════

  Are you sure of the above data? (Y/N) [ ]
```

Figure 40. Project Initialization Screen for RRBAR.

Field #11&12: description of the sample, two string fields each has 78 characters.
Field #13: back pressure saturation pressure for test unit No. 1 in psi, a numeric field.
Field #14: cell pressure for test unit No. 1 in psi, a numeric field.
Field #15: the calculated consolidation pressure for test unit No. 1 in psi, a derived data.
Field #16: back pressure saturation pressure for test unit No. 2 in psi, a numeric field.
Field #17: cell pressure for test unit No. 2 in psi, a numeric field.
Field #18: the calculated consolidation pressure for test unit No. 2 in psi, a derived data.
Field #19: back pressure saturation pressure for test unit No. 3 in psi, a numeric field.
Field #20: cell pressure for test unit No. 3 in psi, a numeric field.
Field #21: the calculated consolidation pressure for test unit No. 3 in psi, a derived data.
Field #22: the strain rate used, a numeric field.

Main Selection Screen

The main selection screen, shown in Figure 41, has 4 options. They are described in the following.

Option #1: modify the test project initialization.
Option #2: analyze the Bishop "B" coefficient.
Option #3: analyze the shearing test data.
Option #4: quit this program.

All the output data from the RRBAR program are automatically stored on the diskete in drive "B" with the project name as the file name. No final results are available at this stage. Use the program RESULT to reduce the final results.

User's Guide For Program RESULT

This program analyzes the intermediate data produced by RRBAR and then presents the final results. Before starting

```
 Select from the following options :  [1]
√ 1.  Testing program initialization.
  2.  Get Bishop B data from file and analyze.
  3.  Get Shearing Data from file and analyze.
  Q.  Quit.
```

Figure 41. Main Selection Screen for RRBAR.

this program, be sure that the corresponding data is on the data diskette in drive "B". The flow chart for RESULT is shown in Figure 42. This program consists of 6 screens which are described in the following paragraphs.

Project ID Screen

The project name is the same as discussed in the previous programs. Refer to the previous sections for this input screen.

Main Selection Screen

The main selection screen for RESULT, shown in Figure 43, has 8 options. They are listed as follows.

Option #1: show total stress vs strain curves.
Option #2: show effective stress vs strain curves.
Option #3: show pore water pressure vs strain curves.
Option #4: show principal stress ratio vs strain curves.
Option #5: show total stress paths.
Option #6: show effective stress paths.
Option #7: tabulated print out the results.
Option #8: quit this program.

Stress vs Strain Curve Specification

When any of the first three options on the main selection table is selected, the program shows this screen for the curve specifications (Fig. 44). This screen contains two fields, both are for input of numeric data.

Field #1: the range of the strain, in %.
Field #2: the range of the stress, in psi.

Noted that both input numbers should be multiples of 4 so that the coordinates can be properly scaled.

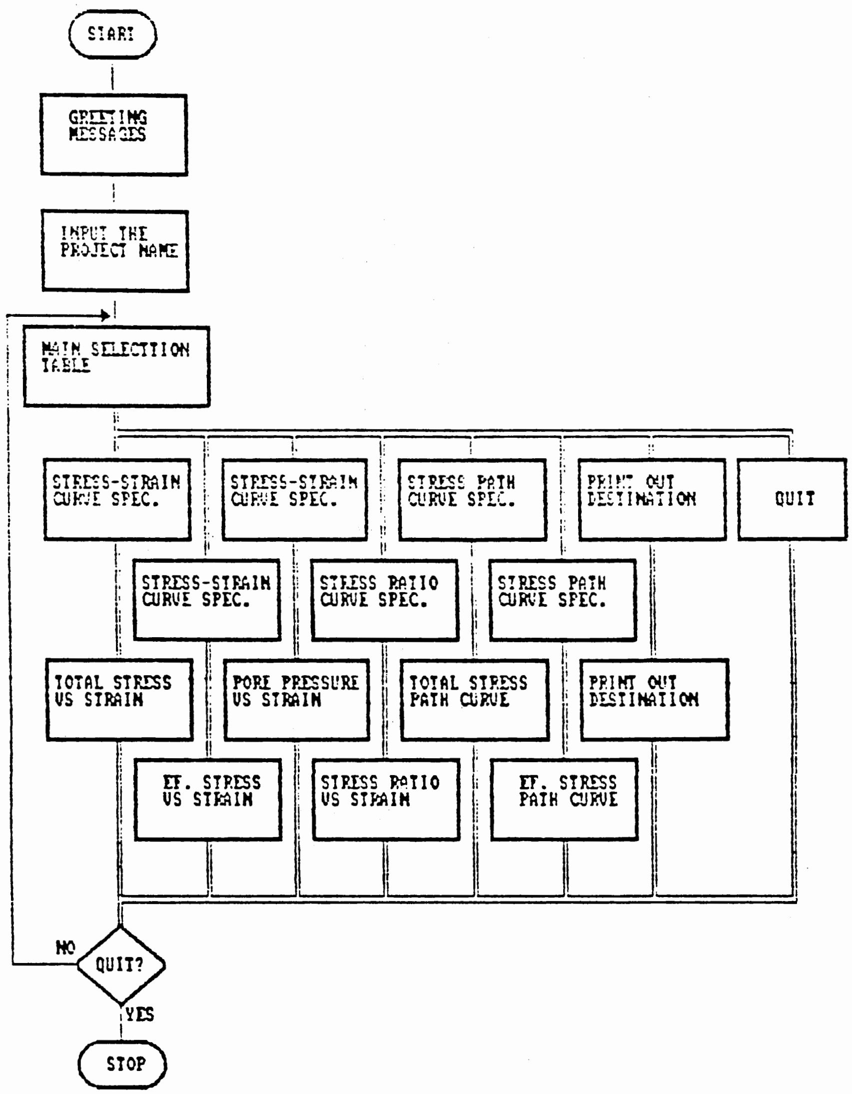


Figure 42. Flow Chart for RESULT.

```
Select from the following options : [1]
√1. Total Vertical Stress vs Strain curve.
 2. Effective Vertical Stress vs Strain curve.
 3. Pore Pressure vs Strain curve.
 4. Principal Stress Ratio vs Strain curve.
 5. Total Stress Path.
 6. Effective Stress Path.
 7. Print out the Test Result Summary.
 Q. Quit
```

Figure 43. Main Selection Screen for RESULT.

```
═══════ Stress vs Strain Curve Specification ═══════
 Input range for strain: [40    ] %
 Input range for stress: [160   ] PSI
 Note: the ranges should be muliples of 4.
═══════════<F10 to complete the input>═══════════
```

Figure 44. Stress-Strain Curve Specification Screen.

```
══ Stress Ratio vs Strain Curve Specification ═══
 Input range for strain: [40    ] %
 Input range for ratio : [ 8    ]
 Note: the ranges should be muliples of 4.
═══════════<F10 to complete the input>═══════════
```

Figure 45. Stress Ratio vs Strain Curve Specification Screen.

Stress Ratio vs Strain Curve Specification

If the fourth option is selected, the program shows this screen for the corresponding curve specifications (Fig. 45). This screen contains two numeric fields as described in the following.

Field #1: the range of the strain, in %.
Field #2: the range of the stress ratio.

Noted that in order to scale the curve properly, both input numbers should be multiples of 4.

Stress Path Curve Specification

If the fifth or sixth option is selected, the program shows this screen for the curve specifications (Fig. 46). This screen has two numeric fields as described in the following.

Field #1: the range of the average of the principal stresses, in psi.
Field #2: the range of the deviator stresses, in psi.

Noted that both input number should be multiples of 4 for proper scaling of the coordinates.

Print Out Specification

If the seventh option is selected from the main selection screen, the program shows this screen for directions (Fig. 47). The screen has two fields which are described in the following.

Field #1: the destination of the print out, "P" - to the printer, "S" - to the screen and "F" - to the disk file.
Field #2: the time interval to select data for

```
═══════ Stress Path Curve Specification ═══════
Horizontal stress- p  : [120  ] PSI  (S1+S3)/2
Vertical stress   - q  : [80   ] PSI  (S1-S3)/2
Note: the ranges should be muliples of 4.
══════════<F10 to complete the input>══════════
```

Figure 46. Stress Path Curve Specification Screen.

```
══════════════ Print out Specification ══════════════
Where to print:[P]-(S)creen, (F)ile, (P)rinter.
Time interval to print: [ 20  ] min.
Note: time interval must be multiples of 10.
════════════<F10 to complete the input>════════════
```

Figure 47. Print Out Specification Screen.

printout.

Noted that the minimum time interval limit is 10 minutes.

Sample Results

The sample results from this program are shown as follows in Figures 48a-h respectively.

User's Guide For Program SETUP

This program communicates with the Easy Logger for the repetitive direct shear test. Before this program starts, make sure that the RS-232 port is connected to the Easy Logger and the handheld terminal for the Easy Logger is turned off. The flow chart for this program is shown in Figure 49. It consists of five screens which are discussed as follows.

Main Selection Screen

The screen, shown in Figure 50, is the main selection for SETUP. The selections are listed below.

Option #1: setup the Easy Logger for the repetitive reversal direct shear test.
Option #2: transfer data form the Easy Logger to diskette.
Option #3: quit this program.

Instruction Screens

The instruction screens are the same as those discussed in the program CONNECT. Refer to the Instruction Screen

SOIL MECHANICS LABORATORY
SCHOOL OF CIVIL ENGINEERING
OKLAHOMA STATE UNIVERSITY
Stillwater, Oklahoma

R/R bar Triaxial Test Data Analysis
Testing Program Initialization Data

Test Program : [TTRSDL1]   Test No. : [1]
Test for : [THESIS   ] Date :[3]/[1]/[87]
Tested by: [YET-CHENG YOU   ]

Sample Description :
Height : [2.8   ] in.   Diameter : [1.3303] in.
[UNDISTURBED SAMPLE FROM SLOP FAILURE SURFACE   ]
[BROWN CLAY WITH SMALL NODULES   ]

Triaxial Cell No. :	1	2	3
Regulator A (psi)	[30.00]	[30.00]	[30.00]
Regulator B (psi)	[45.00]	[60.00]	[90.00]
Consolidation pressure	[15.00]	[30.00]	[60.00]

Strain rate : [0.000196] in./min.

Figure 48. Sample Results Produced by RESULT.

R/R̄ Triaxial Shearing Data Summary

Test Program : [TTRSDL1] Page No. : [1]
Test for : [THESIS] Date :[3]/[1]/[87]
Tested by: [YET-CHENG YOU]
Cell No. : [1] Cell Pressure S3 : [15.00] psi

Strain %	Deviator Stress psi	Pore Press. psi	Total V. Stress S1	Effect. Stress S1'	(S1+S3) / 2	(S1-S3) / 2	S1'+S2' / 2	S1' / S3'
0.00	0.00	-0.15	15.00	15.15	15.00	0.00	15.15	1.00
0.24	11.00	0.65	26.00	25.35	20.50	5.50	19.85	1.77
0.32	17.40	1.70	32.40	30.70	23.70	8.70	22.00	2.31
0.42	24.00	2.95	39.00	36.05	27.00	12.00	24.05	2.99
0.63	30.80	3.90	45.80	41.90	30.40	15.40	26.50	3.77
0.87	35.40	4.65	50.40	45.75	32.70	17.70	28.05	4.42
1.04	38.60	5.35	53.60	48.25	34.30	19.30	28.95	5.00
1.23	40.80	6.00	55.80	49.80	35.40	20.40	29.40	5.53
1.50	42.80	6.45	57.80	51.35	36.40	21.40	29.95	6.01
1.73	45.60	6.50	60.60	54.10	37.80	22.80	31.30	6.36
1.93	47.20	6.70	62.20	55.50	38.60	23.60	31.90	6.69
2.15	47.80	6.45	62.80	56.35	38.90	23.90	32.45	6.59
2.41	49.20	6.65	64.20	57.55	39.60	24.60	32.95	6.89
2.71	50.60	6.75	65.60	58.85	40.30	25.30	33.55	7.13
2.88	52.20	7.05	67.20	60.15	41.10	26.10	34.05	7.57
3.05	52.40	6.90	67.40	60.50	41.20	26.20	34.30	7.47
3.26	53.40	7.10	68.40	61.30	41.70	26.70	34.60	7.76
3.56	54.40	7.05	69.40	62.35	42.20	27.20	35.15	7.84
3.78	55.40	7.20	70.40	63.20	42.70	27.70	35.50	8.10
3.90	55.60	7.05	70.60	63.55	42.80	27.80	35.75	7.99
4.12	55.80	6.95	70.80	63.85	42.90	27.90	35.95	7.93

Figure 48. Sample Results Produced by RESULT (Cont.).

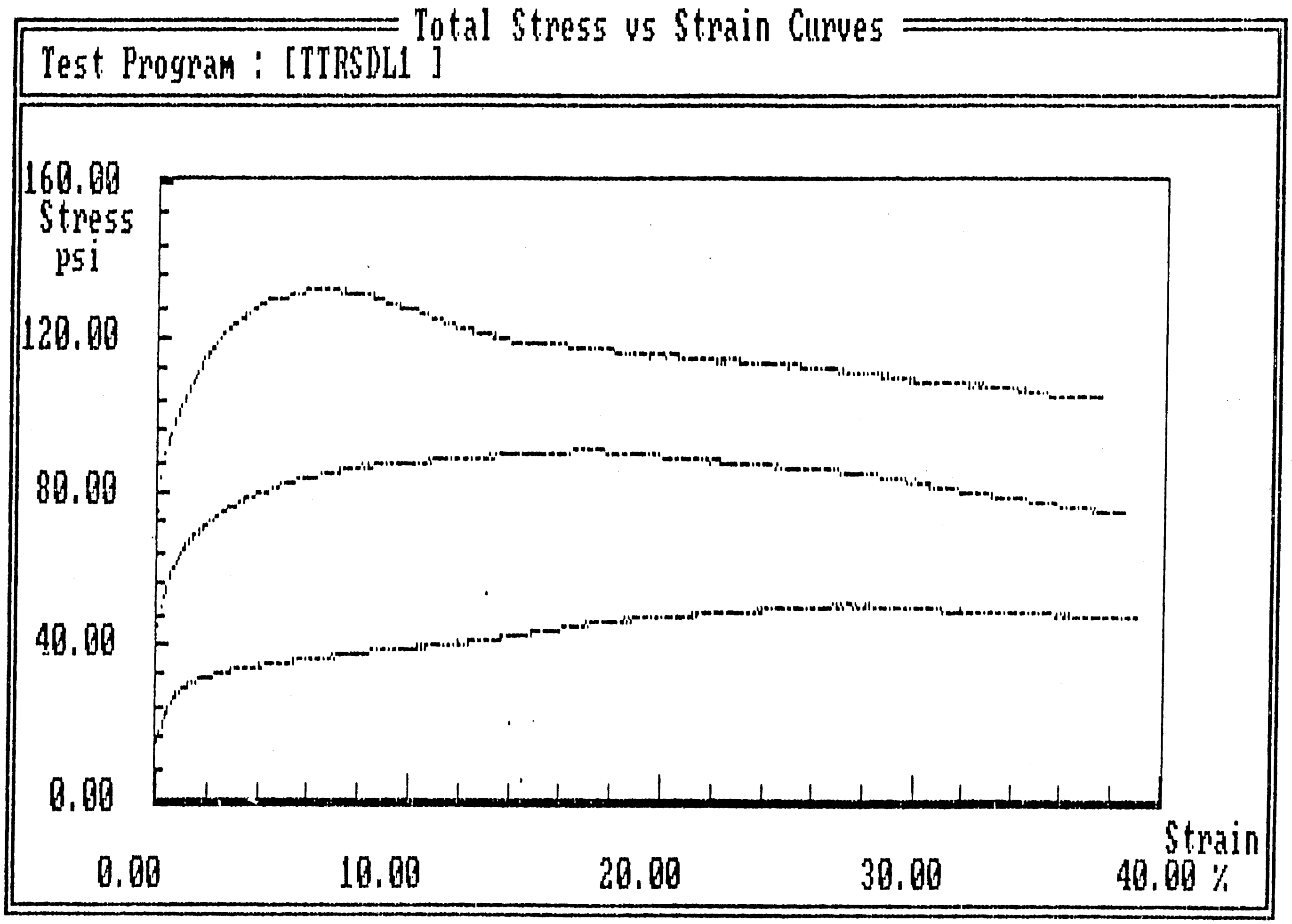


Figure 48. Sample Results Produced by RESULT (Cont.).

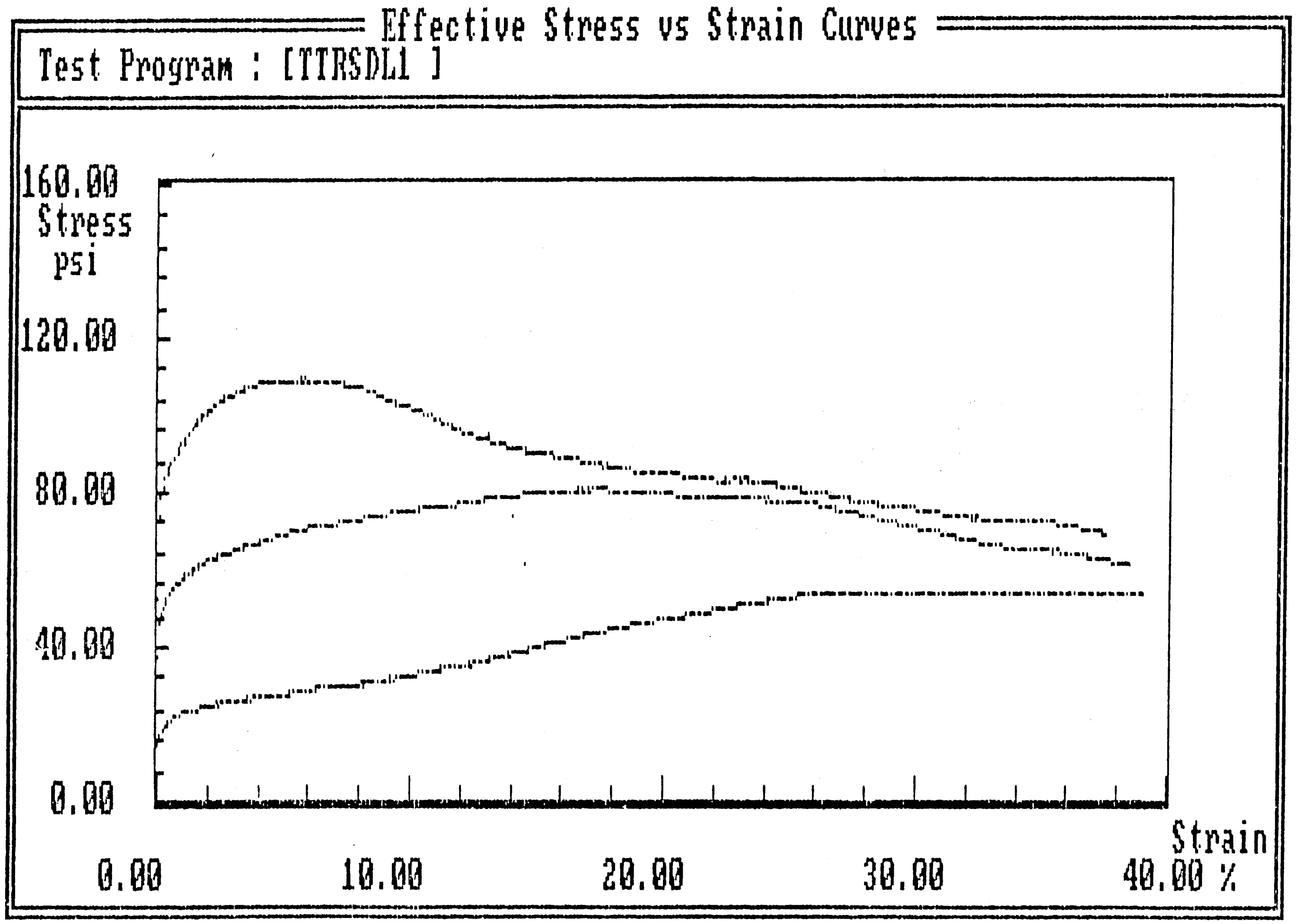


Figure 48. Sample Results Produced by RESULT (Cont.).

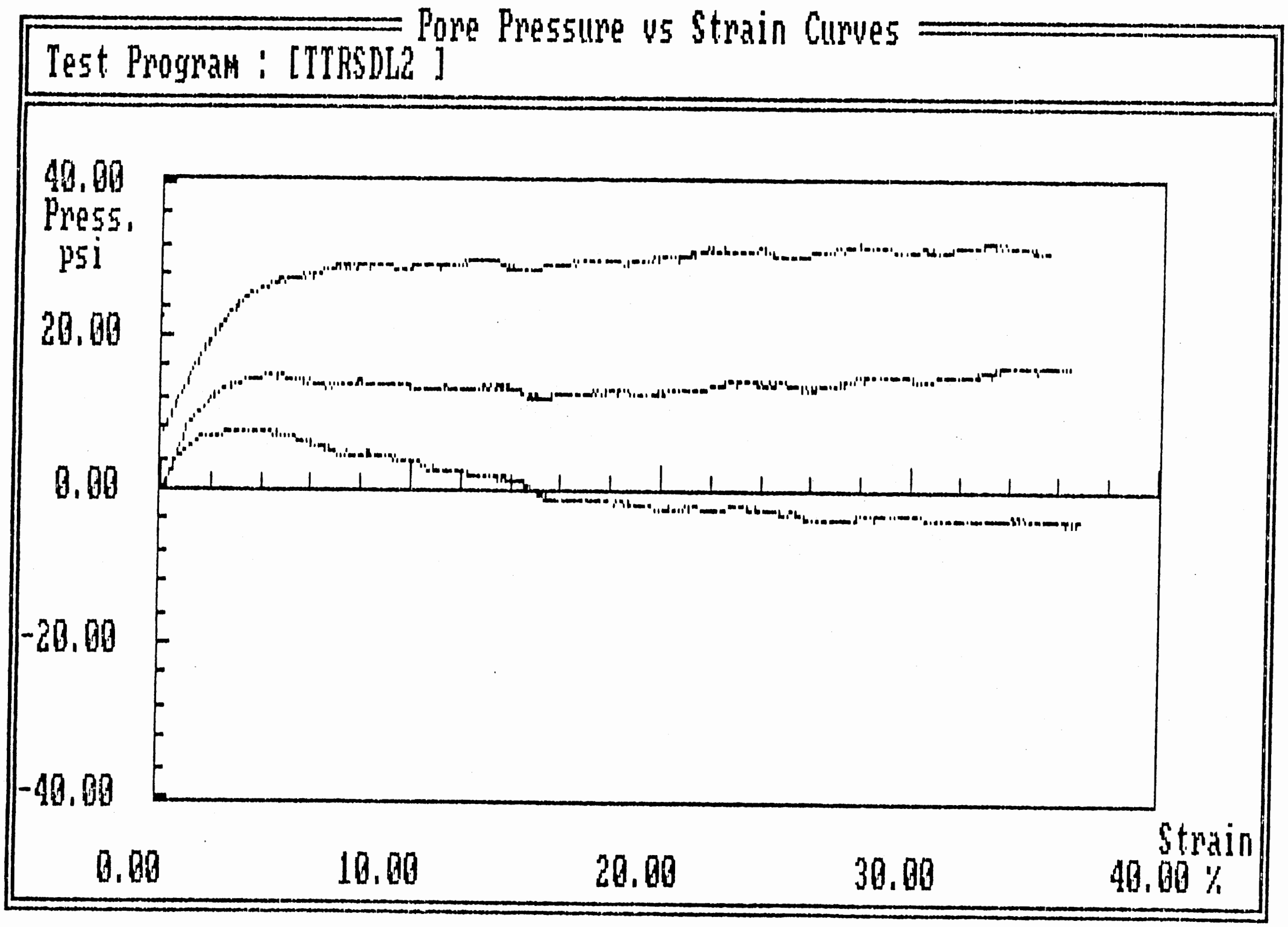


Figure 48. Sample Results Produced by RESULT (Cont.).

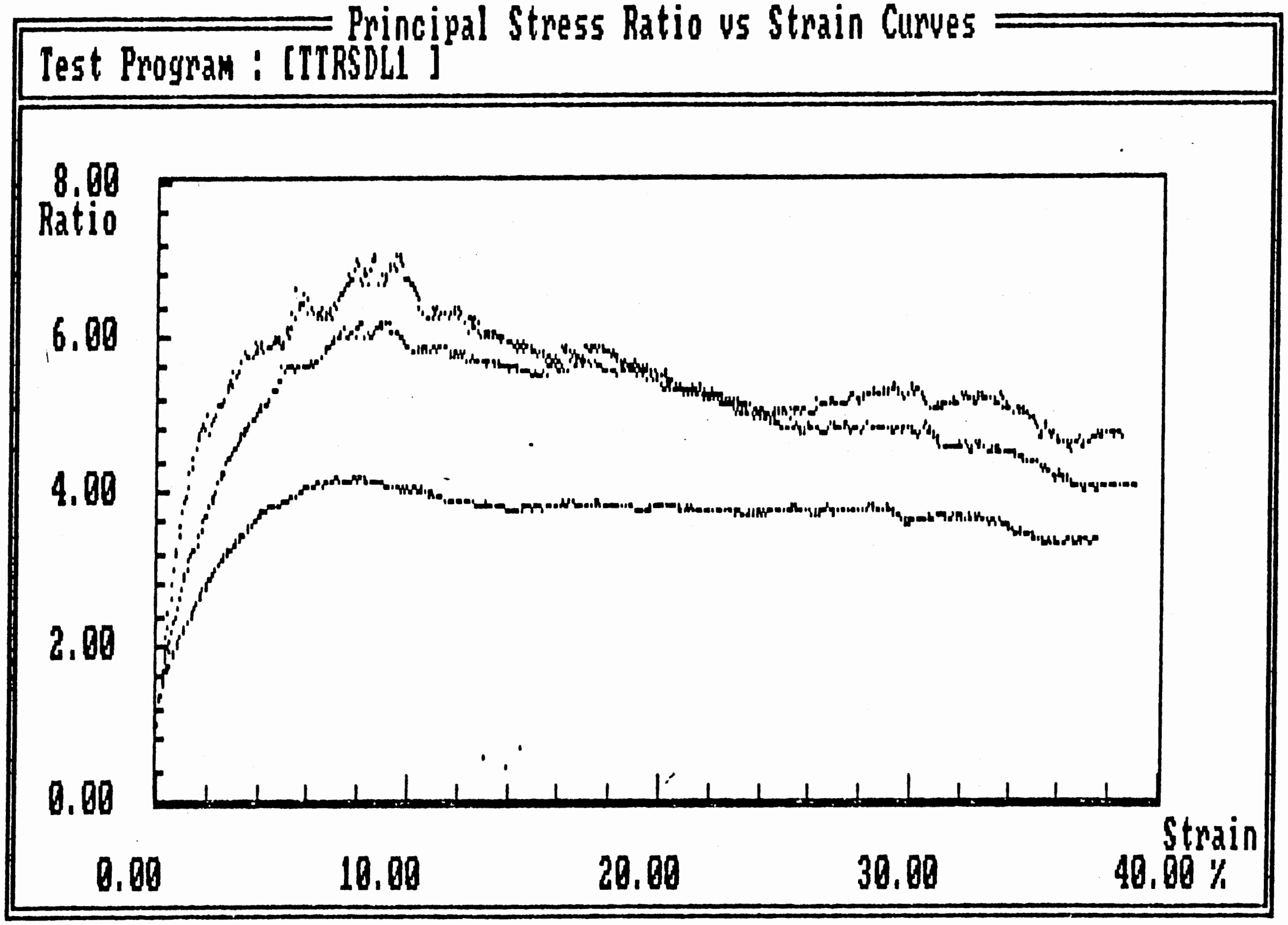


Figure 48. Sample Results Produced by RESULT (Cont.).

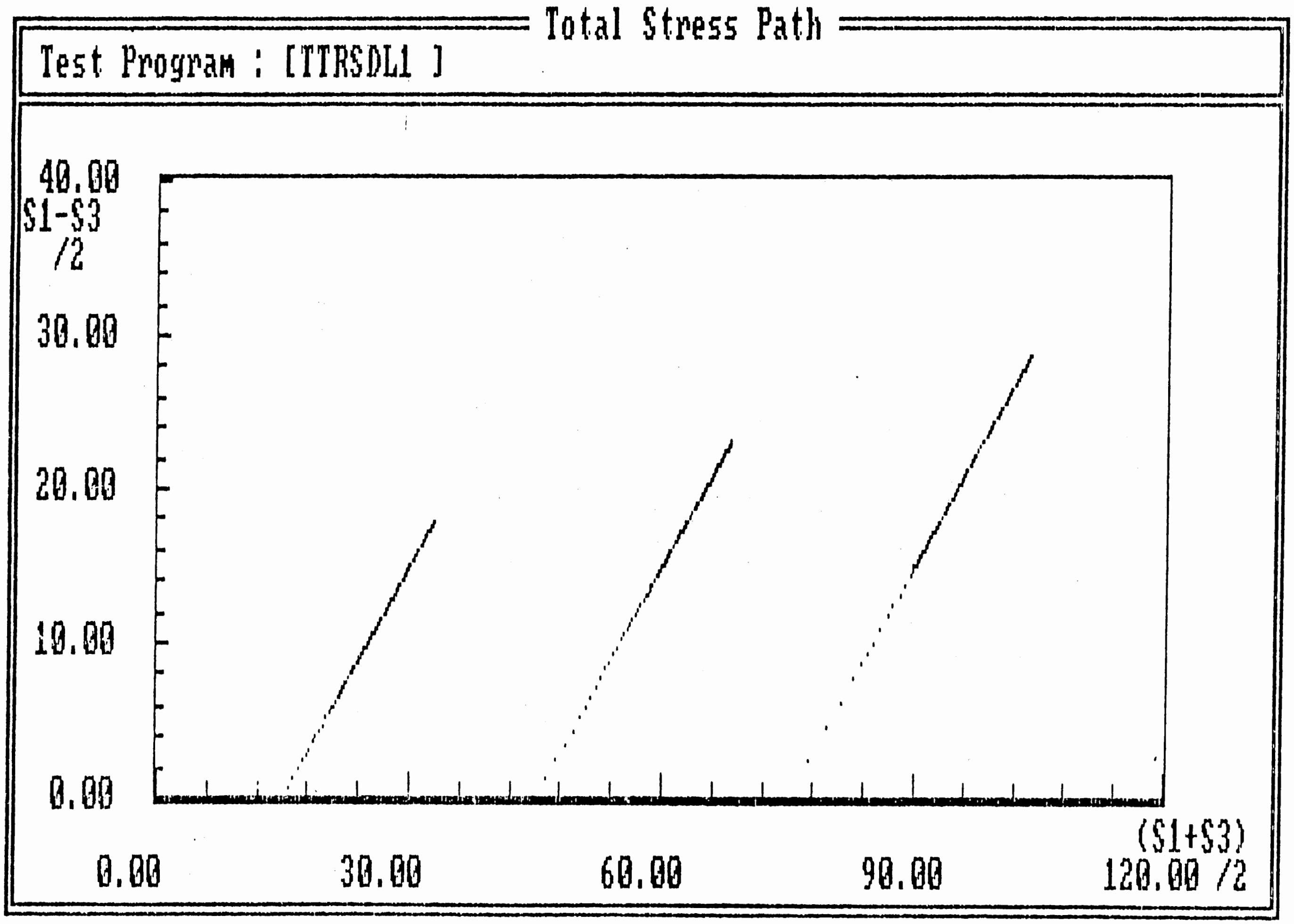


Figure 48. Sample Results Produced by RESULT (Cont.).

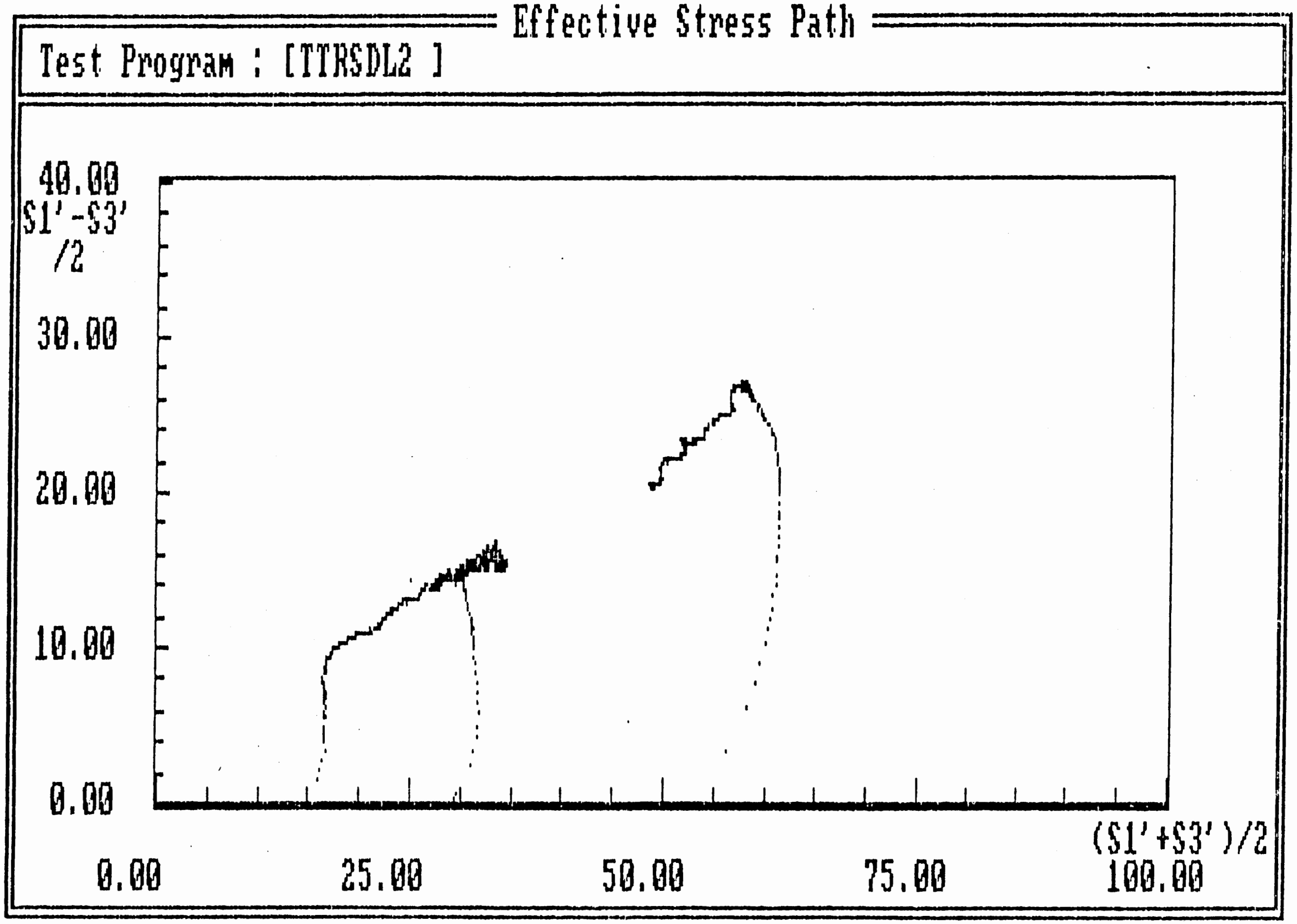


Figure 48. Sample Results Produced by RESULT (Cont.).

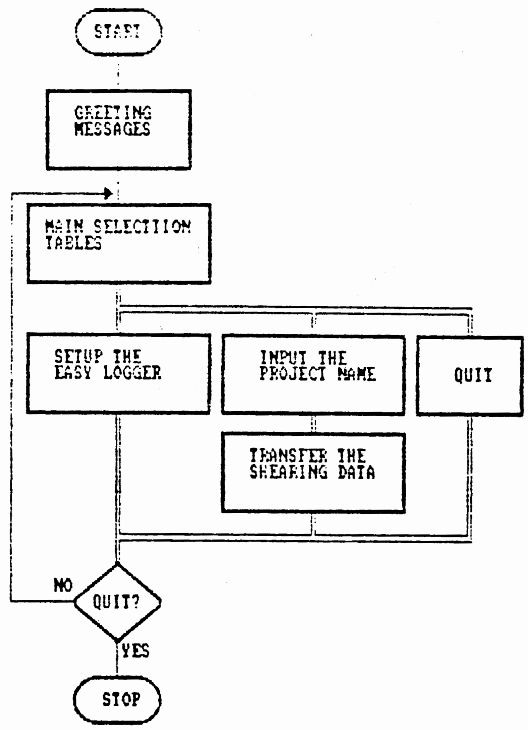


Figure 49. Flow Chart for SETUP.

```
Select stage for Easy Logger Setting : [1]

√ 1. Setting up the Easy Logger.
  2. Receive Data From the Data Logger.
  Q. Quit.
```

Figure 50. Main Selection Screen for SETUP.

section in the user's manual for program CONNECT.

Project ID Screen

The project ID screen is the same as those discussed previously. Refer to the sections for detail discussions.

The SETUP program does not produce any output data, use the DIRECT program to analyze the data and print out the reduced results.

User's Guide For Program DIRECT

This program analyzes the data previously transferred form the Easy Logger and presents the results. Be sure that the raw data has already been transferred to the data diskette before the execution of this program . The flow chart for DIRECT is shown in Figure 51.

Project ID Screens

The procedures for the project ID inputs are the same as those in the RRBAR program. Refer to that section for detailed discussions.

Project Initialization Screen

The project initialization screen for DIRECT, shown in Figure 52, consists of 13 fields, which are described in the following.

Field # 1: the name of the project, a string field with 8 characters. The project name is unique and should be used for all corresponding data files.

Field # 2: the test number, a numeric field with 2 spaces.

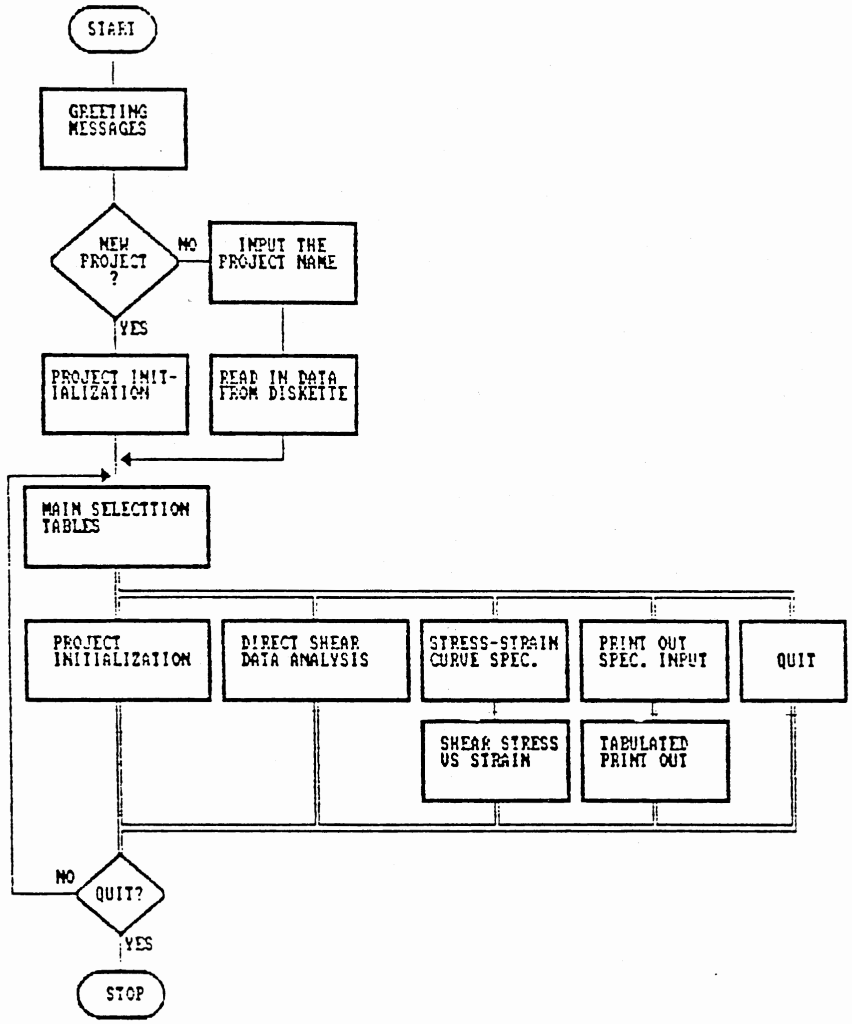


Figure 51. Flow Chart for DIRECT.

```
═══════════════════════ Testing Program initialization ══════════════
Test Program : [REFINE1 ]                                Test No.  : [1 ]
Test for : [THESIS                                    ]  Date :[3 ]/[10]/[87]
Tested by: [Y. C. YOU                                 ]

Sample Description :
  Height : [0.75     ] in.       Diameter : [2.5     ] in.
[REFINED SAMPLE                                                          ]
[1 TSF NORMAL LOAD                                                       ]

Normal Load : [ 74     ] lb.
Strain Rate : [0.000174  ] in./min
═══════════════════════════<F10 to complete the input>═══════════════
```

Figure 52. Project Initialization Screen for DIRECT.

Field # 3: brief description of the test project, a string field with 50 characters.
Field # 4: month in numbers, a numeric field with 2 spaces.
Field # 5: date in numbers, a numeric field with 2 spaces.
Field # 6: year in numbers, a numeric field with 2 spaces.
Field # 7: the names of the persons conduct the test, a string field with 50 characters.
Field # 8: the height of the sample in inches, a numeric field.
Field # 9: the diameter of the sample in inches, a numeric field.
Field #10&11: description of the sample, two string fields each has 78 characters.
Field #12: normal load on the sample, in lb.
Field #13: the strain rate used, a numeric field.

Main Selection Screen

The main selection screen for DIRECT, shown in Figure 53, has 5 options. The options are described in the following.

Option #1: modify the test project initialization.
Option #2: analyze the direct shear test data.
Option #3: show cumulative shear strain vs stress curve.
Option #4: tabulated summary of the results.
Option #5: quit this program.

Stress vs Cumulative Strain Curve Specification

When the shear stress vs strain curve option is selected, the program shows this screen for the curve specifications (Fig. 54). This screen contains two fields. Both fields are for numeric data input.

Field #1: the range of the strain, in %.
Field #2: the range of the stress, in psi.

Noted that both input numbers should be multiples of 4

```
Select from the following options : [1]
√1. Testing program initialization.
 2. Direct Shear Test Data Analysis.
 3. Cumulative Strain with Positive Shear Stress.
 4. Tabulated Summary of the Results.
 Q. Quit.
```

Figure 53. Main Selection Screen for DIRECT.

```
╔═════ Stress vs Strain Curve Specification ═════╗
║ Input range for strain: [60   ] %               ║
║ Input range for stress: [20   ] PSI             ║
║ Note: the ranges should be muliples of 4.       ║
╚═══════════<F10 to complete the input>═══════════╝
```

Figure 54. Stress vs Strain Curve Specification Screen for DIRECT.

so that the coordinates can be properly scaled.

Print Out Specification

If the print out option is selected, the program shows this screen for directions. The screen is the same with the print out specification screen discussed in program RESULT.

Sample Results

The sample result printouts from this program are shown as follows in figures 58a-c.

SOIL MECHANICS LABORATORY
SCHOOL OF CIVIL ENGINEERING
OKLAHOMA STATE UNIVERSITY
Stillwater, Oklahoma

Repetitive Direct Shear Test Data Analysis
Testing Program Initialization Data

```
Test Program : [REFINE1 ]                                        Test No. : [1 ]
Test for : [THESIS                                      ]  Date :[3 ]/[10]/[87]
Tested by: [Y. C. YOU                                   ]

Sample Description :
  Height : [0.75     ] in.       Diameter : [2.5     ] in.
[REFINED SAMPLE                                                        ]
[1 TSF NORMAL LOAD                                                     ]

Normal Load : [ 74     ] lb.
Strain Rate : [0.000174  ] in./min
```

Figure 55. Sample Results for DIRECT.

Repetitive Direct Shear Test Summary Test Program : [REFINE1] Page No. : [1] Normal Load 74 lb.			
Cumulative Strain %	Vertical Strain %	Shearing Force lb.	Shear Stress psi
0.000	0.0000	0.000	0.00
0.012	0.5489	0.200	0.04
0.109	0.5519	13.400	2.73
0.218	0.5541	17.400	3.54
0.339	0.5552	21.000	4.28
0.467	0.5558	23.000	4.69
0.600	0.5556	24.800	5.05
0.703	0.5560	27.400	5.58
0.830	0.5572	28.000	5.70
0.945	0.5586	27.200	5.54
1.079	0.5596	30.000	6.11
1.194	0.5602	28.400	5.79
1.321	0.5614	31.200	6.36
1.461	0.5632	32.000	6.52
1.582	0.5620	32.600	6.64
1.715	0.5642	32.800	6.68
1.818	0.5640	33.200	6.76
1.952	0.5648	33.600	6.84
2.091	0.5661	34.200	6.97
2.212	0.5673	34.400	7.01
2.321	0.5681	34.400	7.01
2.455	0.5683	34.400	7.01

Figure 55. Sample Results for DIRECT (Cont.).

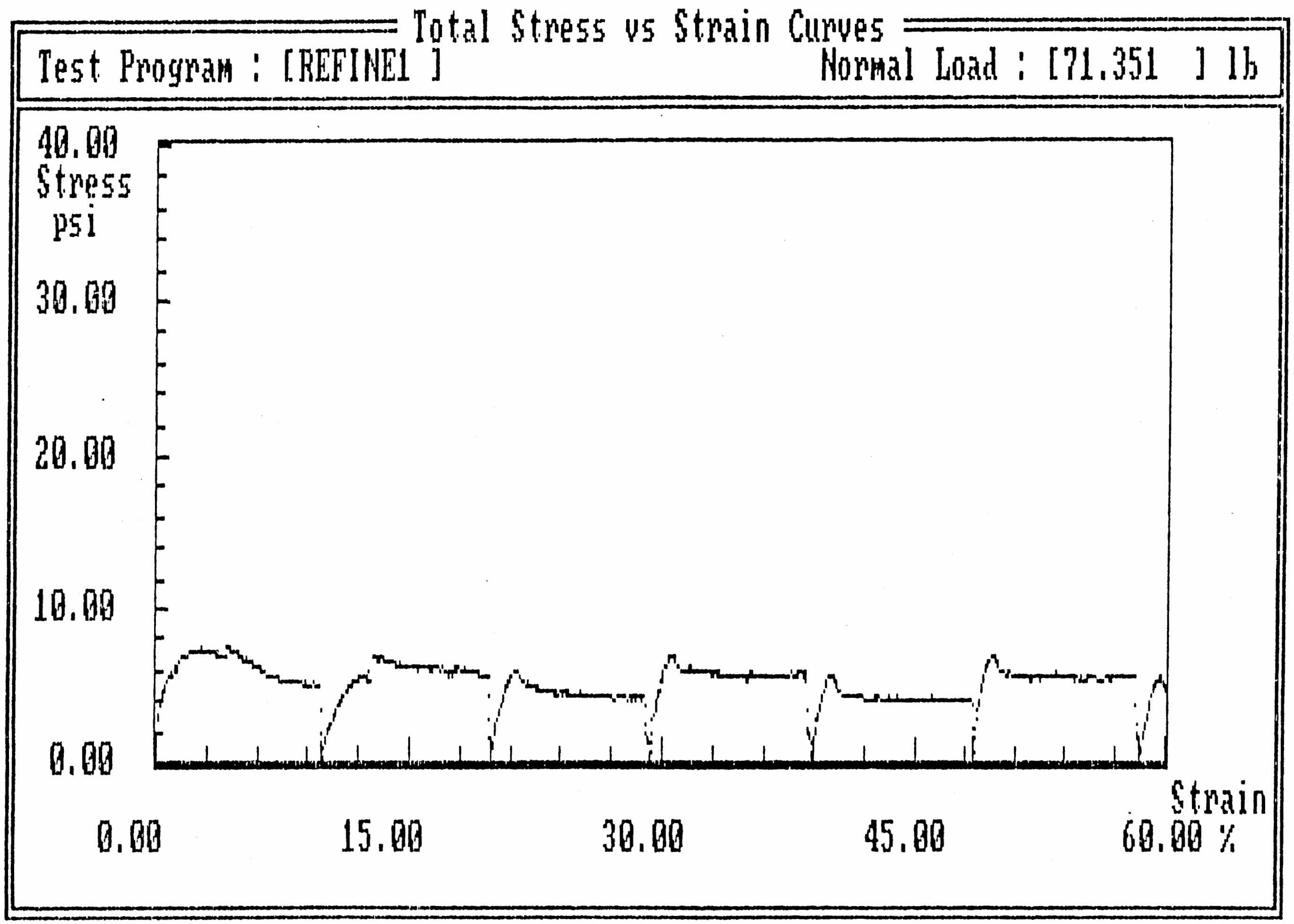


Figure 55. Sample Results for DIRECT (Cont.).

APPENDIX B

SETUP AND TESTING THE INSTRUMENTS

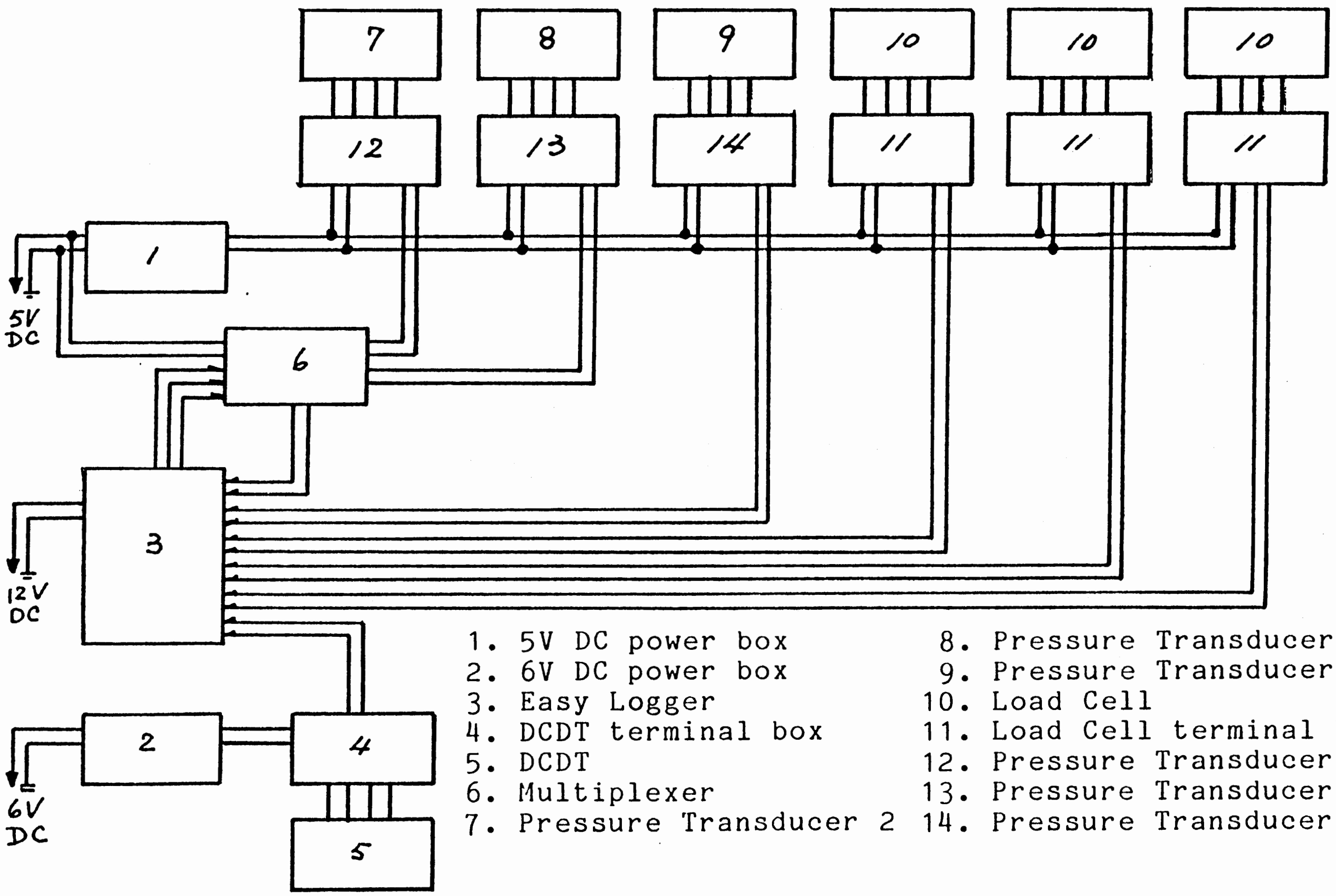
Instruments for the Triaxial Test

The instruments discussed in this chapter output electronic signals. The circuit diagram for the modified triaxial test machine is shown in Figure 56. Instruments discussed are power supplies, sensors, multiplexer and the Easy Logger.

Power Supplies

There are three separate power supplies in this system. Power supply "A" is an adjustable DC power supply. It was adjusted to output 5 V DC for the load cells, pressure cells and multiplexer. Power "B" supply outputs 6 V DC and is the power supply for the DCDT. Finally, power "C" supply produces 12 V DC for the Easy Logger.

Referring to Figure 57a and b, the lines from power supplies "A" and "B" are connected directly to the power source terminal boxes shown in the figure. As for power supply "C", the lines are connect to the DC input and DC ground sockets on the Easy Logger as shown in Figure 57c.



1. 5V DC power box
2. 6V DC power box
3. Easy Logger
4. DCDT terminal box
5. DCDT
6. Multiplexer
7. Pressure Transducer 2
8. Pressure Transducer 3
9. Pressure Transducer 1
10. Load Cell
11. Load Cell terminal box
12. Pressure Transducer box 2
13. Pressure Transducer box 3
14. Pressure Transducer box 1

Figure 56. Circuit Diagram for the Triaxial Test Machine.

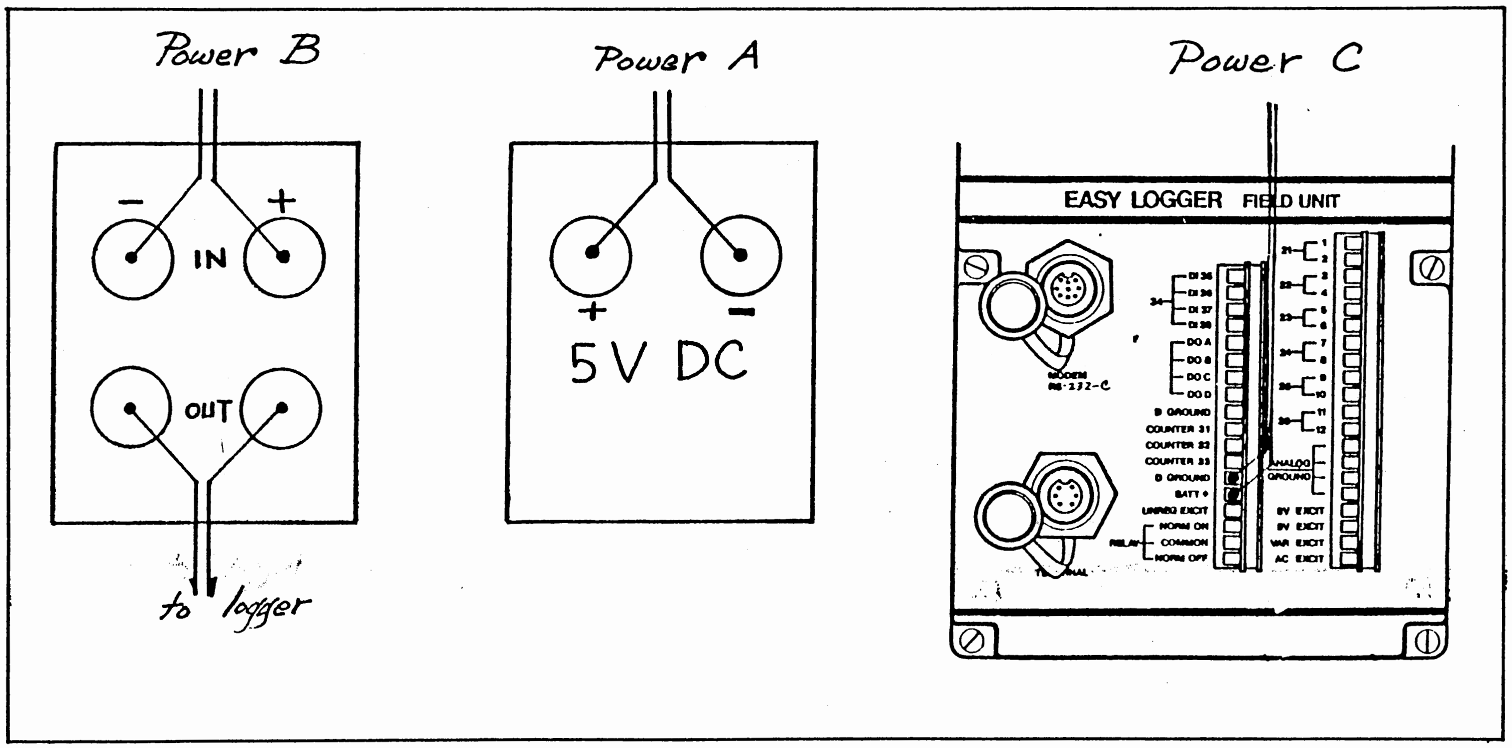


Figure 57. Power Supply Connection Boxes for the Triaxial Test Machine.

Sensors

DCDT. There is one DCDT in the system. The four input and output lines are connected to the terminal box as shown in Figure 58a.

Pressure Cell. There are three pressure cells corresponding to the three triaxial test units. The connection between the four input/output lines and the terminal box is shown in Figure 58b.

Load Cell. There are three load cells corresponding to the three triaxial cell units for measuring the axial load data. The four lines from the load cell are connected to the terminal box as shown in Figure 58c.

All the signals from the sensors are collected at the female D shaped connector shown in Figure 59. The male side of the D shaped connector distributes lines to both the multiplexer and the Easy Logger.

Multiplexer

The circuit connections for the multiplexer, shown in Figure 59, indicates the sockets for the lines from the sensors and the logger.

Easy Logger

The socket layout, shown in Figure 60, shows all the connection sockets the Easy Logger has available. Besides

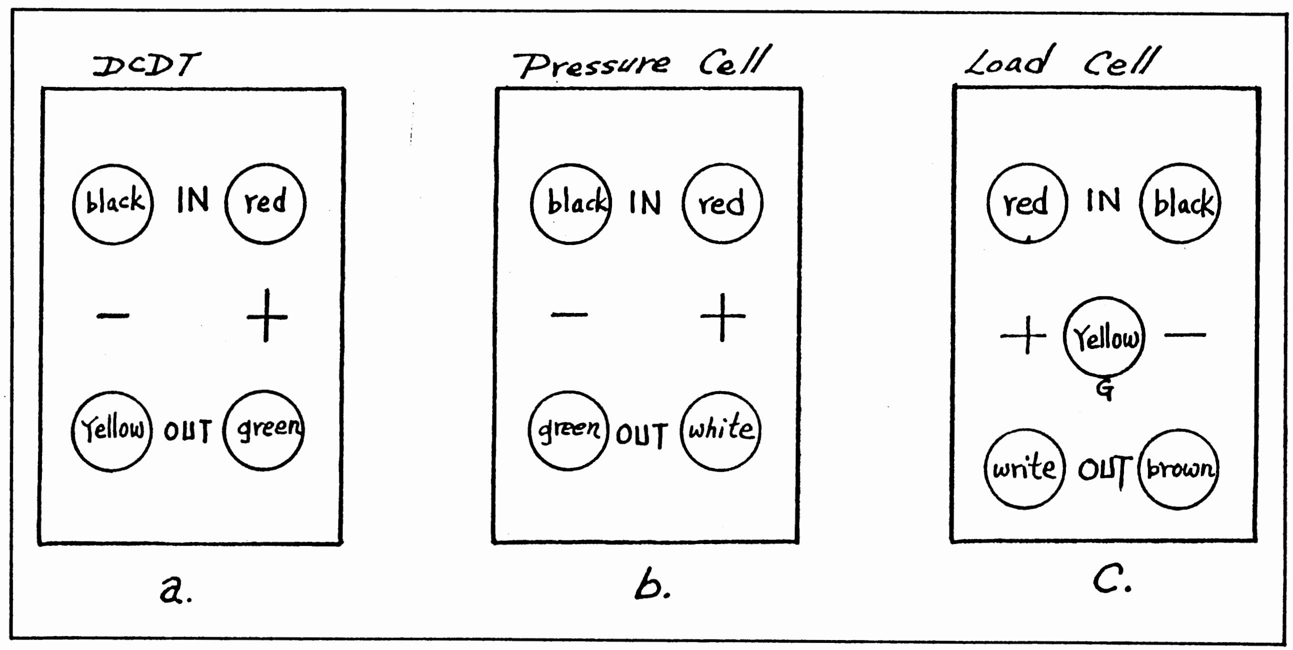


Figure 58. Terminal Boxes for Triaxial Test Machine.

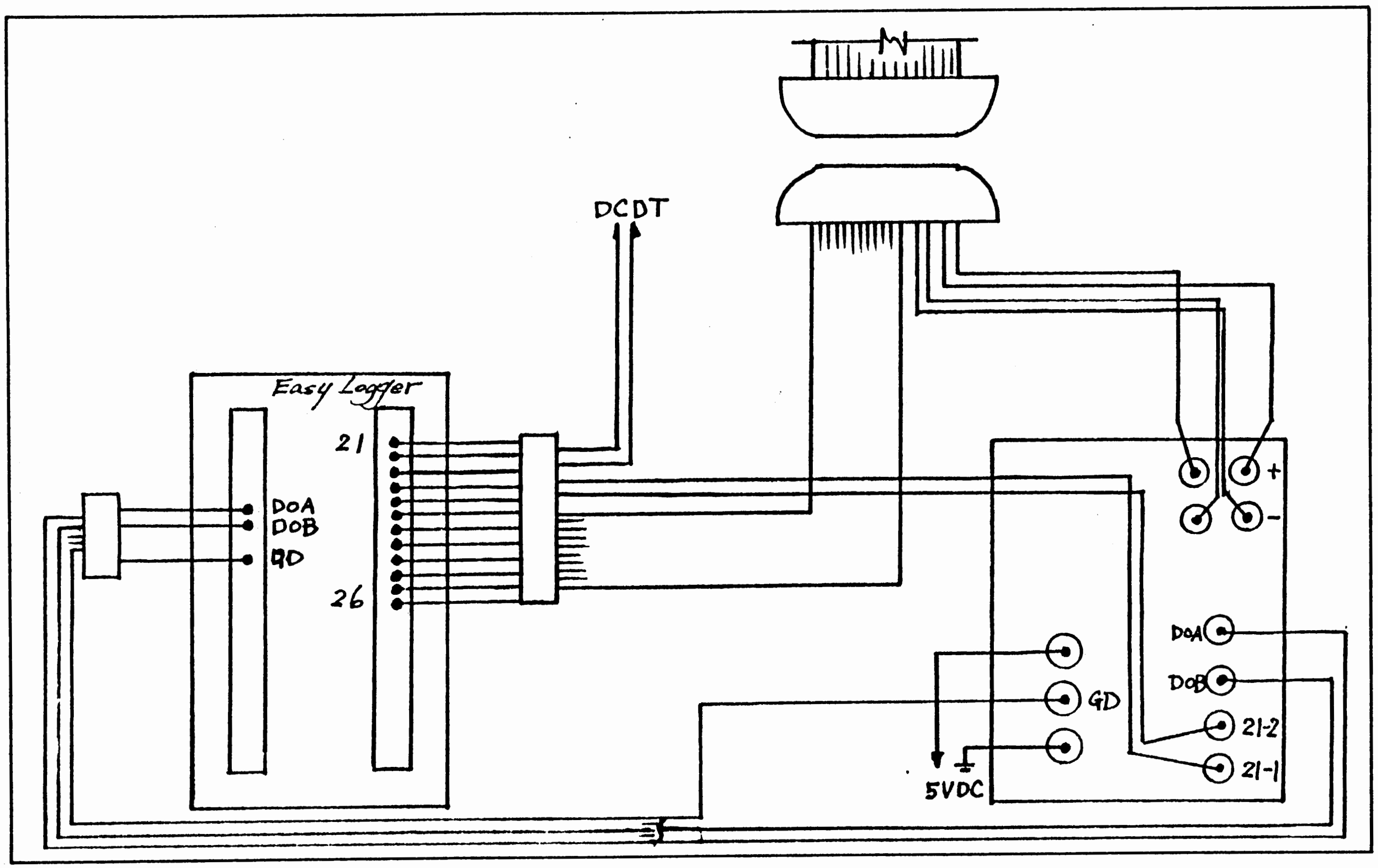


Figure 59. Circuit Between Multiplexer and Easy Logger.

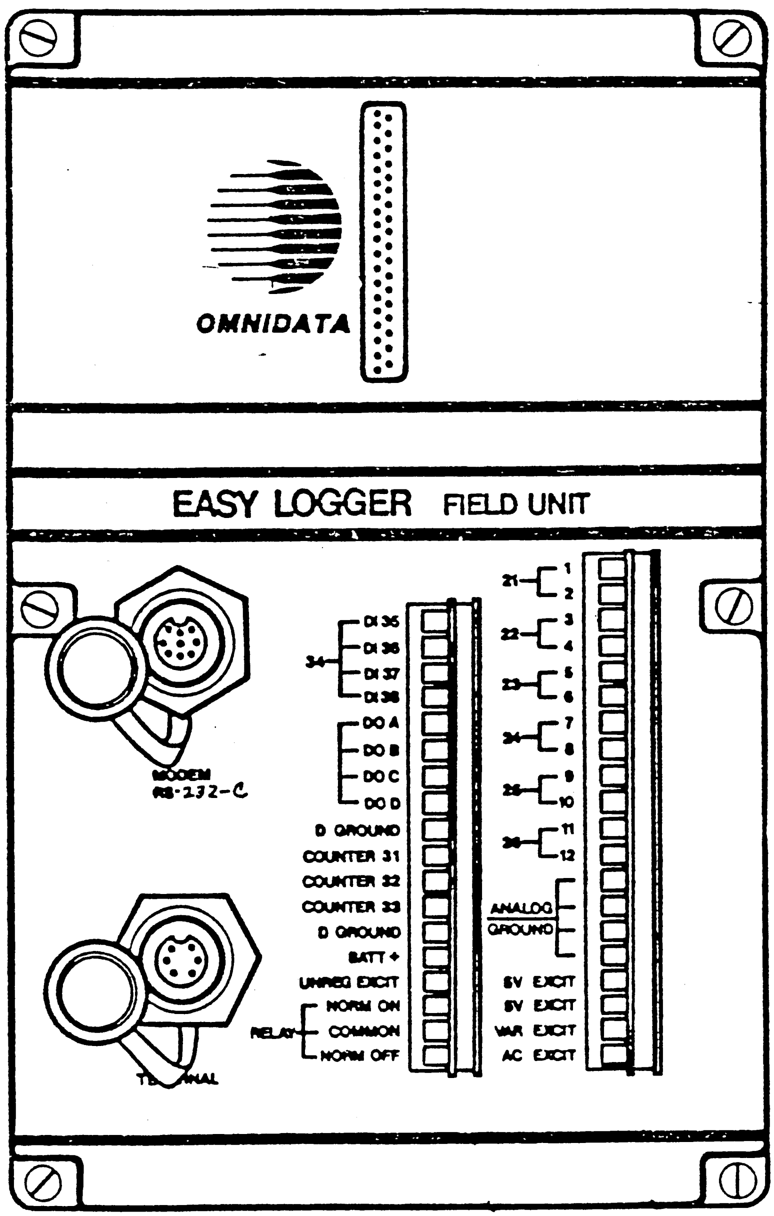


Figure 60. Easy Logger Socket Layout.

the connection from the power supply, the two strip plugs are connected to the logger at the indicated positions on the figure.

Testing the Instruments for the Triaxial Test

After all the sensors and the logger are connected as discussed above, there are several check points to be tested so that the signals are transmitted properly. The procedures for checking the system are described as follows.

Testing the Power Supplies

For power supplies "A" and "B", check points are the power input sockets at the sensor terminal box. With the sensors connected, the measured voltage has already accounted for the resistance along the wires and within the sensors. For the power supply "C", the output voltage should be checked at the Easy Logger side of the power supply lines. A voltmeter is required to check the output voltages .

Testing the Sensors and Easy Logger

After the power supplies are tested and adjusted properly, the sensors and logger should be tested together. The procedures for testing them are listed as follows.

1. Turn on the Easy Logger from the handheld terminal.
2. After seeing the message "SELECT THE OPTION", type in "24" for testing the sensors.

3. Under the message "SENSOR NAME", check the sensors by key in the name of the sensor then followed by the ENTER key. The setup sensor names are,
   DISP : for the DCDT.
   LD1 : for the load cell at unit #1.
   LD2 : for the load cell at unit #2.
   LD3 : for the load cell at unit #3.
   PR1 : for the pressure cell at unit #1.
   PR2 : for the pressure cell at unit #2.
   PR3 : for the pressure cell at unit #3.
4. Wait for about 1 minute, the logged voltage will show on the handheld terminal.
5. When the voltages is very close to zero, check the corresponding sensor and its connections.
6. Refer to the Easy Logger User's Manual for detail description of the operation for the handheld terminal. Be sure not to change the setup inside the logger. Any change will affect the data formats sent out from the logger and thus affect the operation of data reduction program.

Instruments for the Repetitive Direct Shear Test

Instruments discussed here are power supplies, sensors, Easy Logger and repetitive motion controller. The circuit diagram for the repetitive direct shear test machine is shown in Figure 61.

Power Supplies

There are four power supplies in this system. Power supplies "A", "B" and "C" are the same as those for the triaxial test machine. Power supply "D" is for the repetitive motion controller, it provides two different voltages, 12 V DC for the relays and 5 V DC for the timer-switch circuit board. Proper connection for the power supplies are shown in Figure 62.

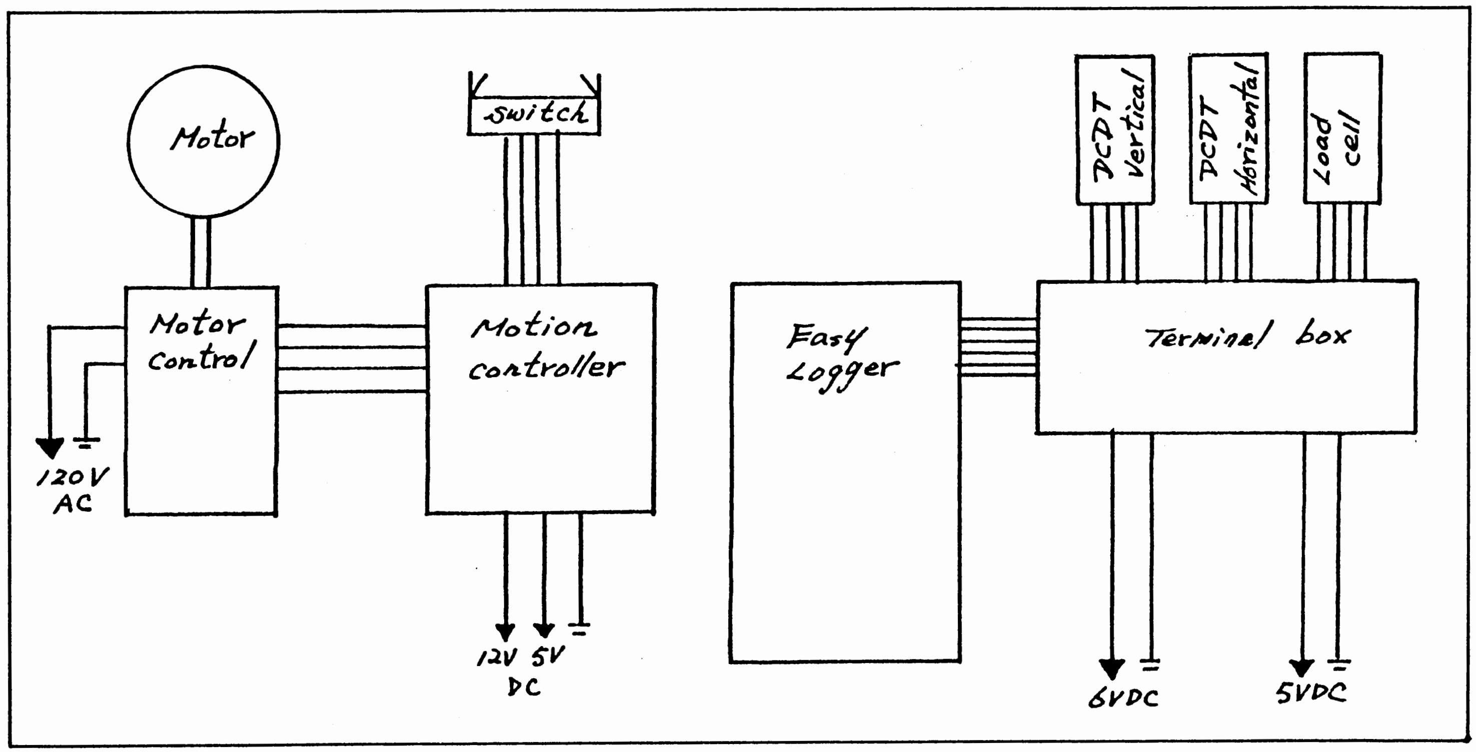


Figure 61. Circuit Diagram for the Repetitive Direct Shear Test Machine.

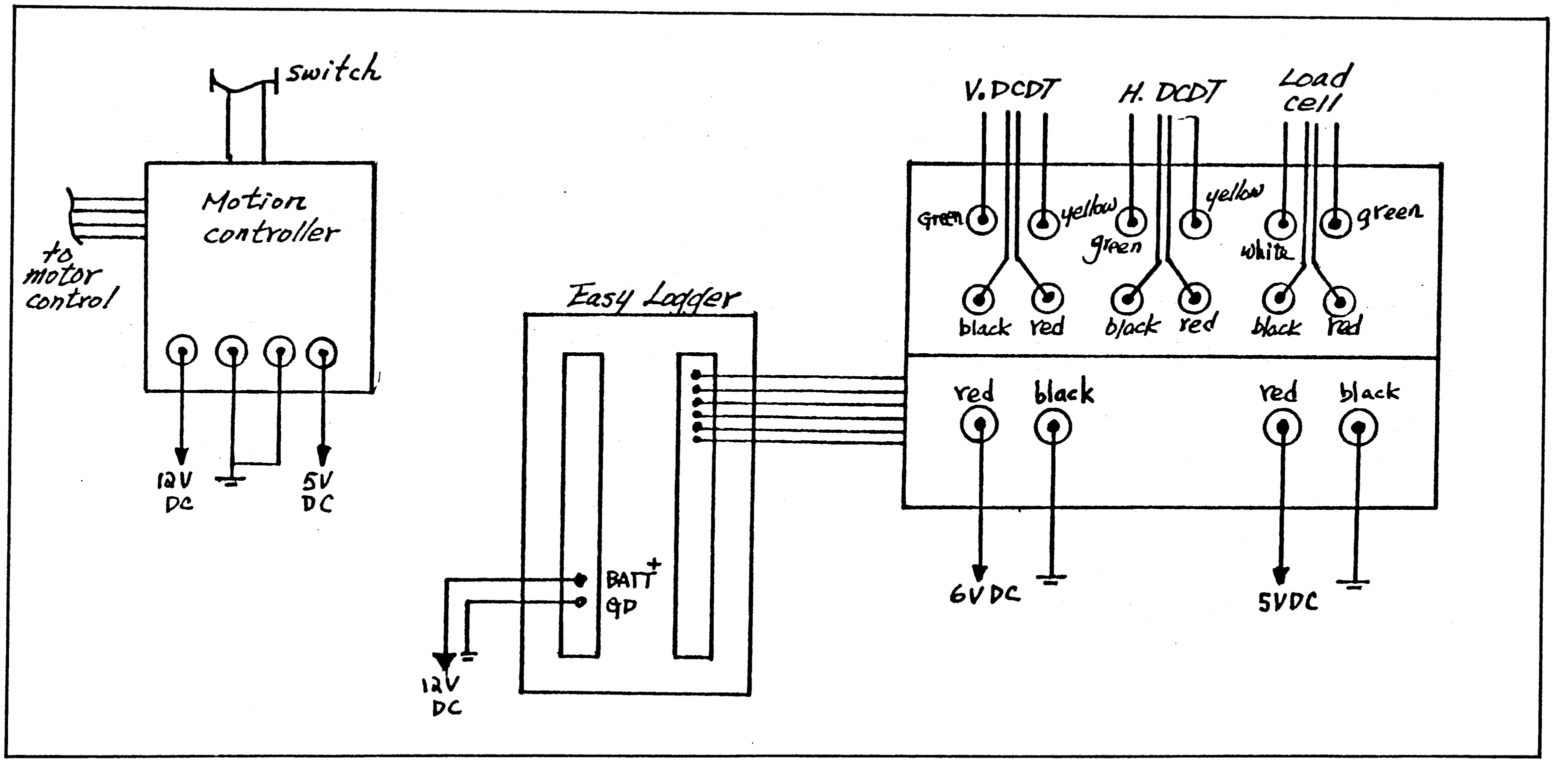


Figure 62. Terminal Boxes and Power Supply Connections for Direct Shear Test.

Sensors

There are two DCDTs and a Load Cell in the system. To setup the sensors simply plug in the connectors to the matching color sockets on the terminal box (Fig. 62).

Easy Logger

In addition to the power supply lines, the lines from the terminal box to the Easy Logger are also shown in Figure 62.

Testing the Instruments for the Repetitive Direct Shear Test

Similar to the triaxial test machine, all the testing and checking of the instruments should be done following the setups previously described.

Testing the Power Supplies

Test the "A", "B" and "C" power supply as was discussed for the triaxial test machine. The "D" power supply is checked at the connectors ends on the motion controller box.

Testing the Sensors and Easy Logger

Check the sensors and logger the same way described in the checking procedures for the triaxial test machine. The only difference is the names for the sensors, specifically;

DC1 : the vertical DCDT.
DC2 : the horizontal DCDT.

LD : the load cell.

If no output voltage is detected, check all the sensor connections.

Testing the Repetitive Motion Controller

There are four steps to check the motion controller.

1. Before putting the switches under the load cell, push each switch respectively. If the relays inside the box do not respond, check the lines and then repeat the above process.
2. Place the switches under the load cell with the switch for the reversing margin in contact.
3. Turn on the motor, if the motor turns in the forward direction then the equipment is ready.
4. If the motor direction is wrong, reverse the switches and start from step 2 again.

APPENDIX C

DERIVATION OF EQUATIONS FOR JANBU'S METHOD

Janbu's method is one of many methods of slices. This derivation is a modification of the Janbu's original method with ground water level considerations. Forces acting on the i-th slice of a system with n slices is shown in Figure 6 .

First, from vertical force equilibrium for the slice,

$$N_i \cos\Theta_i = W_i + \Delta T_i - S_i \sin\Theta_i$$

or

$$N_i = \frac{(W_i + \Delta T_i)}{\cos\Theta_i} - S_i \tan\Theta_i \quad . \; . \; . \; . \; . \; . \; . \; . \quad (11)$$

Second, from horizontal force equilibrium for the slice,

$$\Delta E_i = S_i \cos\Theta_i - N_i \sin\Theta_i \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (12)$$

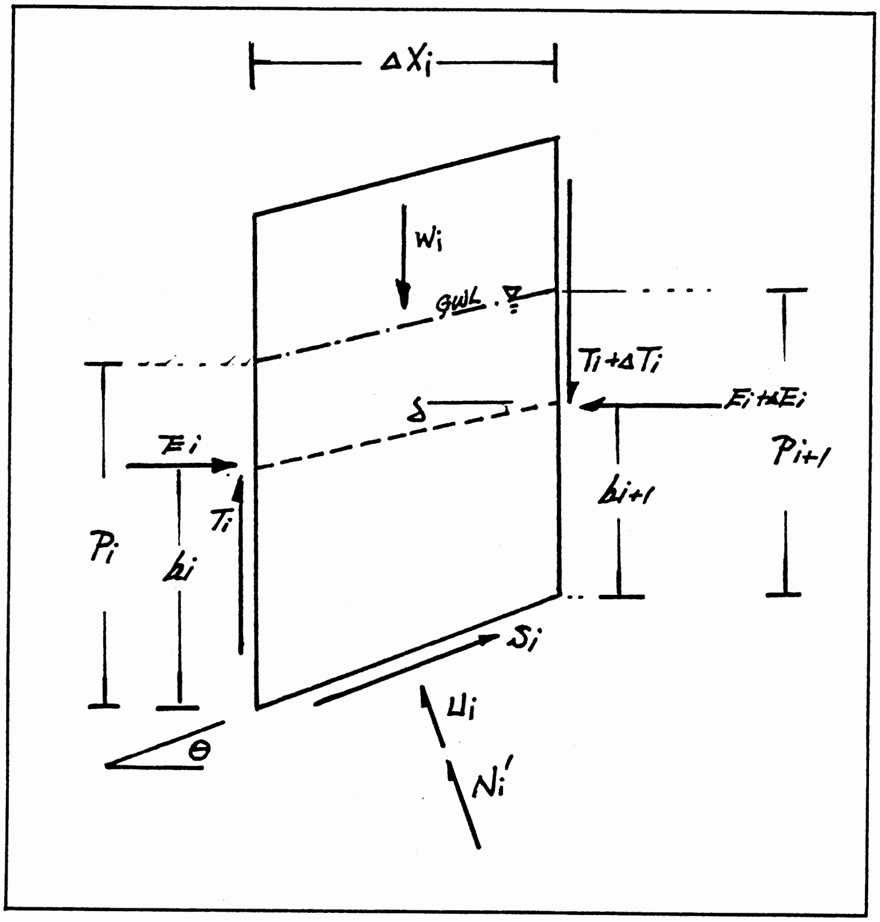


Figure 63. Forces Acting on Soil Slice for Janbu's Method.

Substituting (11) into (12)

$$\Delta E_i = \frac{S_i}{\cos\theta_i} - (W_i + \Delta T_i)\tan\theta_i \quad \ldots\ldots \quad (13)$$

Then, from moment equilibrium and the assumption of N_i acting at the center of the slice base,

$$T_i = E_i \tan\delta_i + \Delta E_i \left(\frac{b_{i+1}}{\Delta x_i} + \frac{\tan\theta_i}{2} \right) - \frac{\Delta T_i}{2} \quad \ldots\ldots \quad (14)$$

Considering the pore water pressure, the effective normal force becomes

$$N_i' = N_i - U_i \quad \ldots\ldots \quad (15)$$

where the force induced from the pore water pressure

$$U_i = \frac{(P_{i-1} + P_i)}{2\cos\theta_i} \gamma_w \Delta x_i \quad \ldots\ldots \quad (16)$$

and from the Mohr-Coulomb failure creteria,

$$\tau = c + \sigma' \tan\phi' \quad \ldots\ldots \quad (17)$$

Therefore, the shear force at the slice base becomes

$$S_i = \frac{c\Delta x_i/\cos\theta_i + N_i'\tan\phi'}{S.F.} \quad \ldots\ldots\ldots \quad (18)$$

From equation (15) and (18),

$$N_i = \frac{S_i\ S.F.}{\tan\phi'} + U_i - \frac{c\,\Delta x_i}{\cos\theta_i\ \tan\phi'} \quad \ldots \quad (19)$$

For the overall horizontal force equilibrium

$$\Sigma E_i = 0 \quad \ldots\ldots\ldots\ldots \quad (20)$$

or

$$\Sigma(S_i\cos\theta_i - N_i\sin\theta_i) = 0 \quad \ldots\ldots\ldots \quad (21)$$

Substitute (18) and (19) into (21),

$$S.F. = \frac{\Sigma((S_i\cos\theta_i - U_i\sin\theta_i)\tan\phi' + c\,\Delta x_i\tan\theta_i)}{\Sigma(S_i\sin\theta_i)} \quad \ldots\ldots\ldots\ldots \quad (22)$$

APPENDIX D

SAMPLE DATA INPUT FOR PROGRAM JANBU

The program JANBU is a slope stability analysis program using Janbu's Method. It requires the user to prepare detail soil profile information including the pre-determined failure surface, ground surface and groundwater surface. Because the program is designed specially for the purpose of back stability analysis, it interacts with the user for different shear strength parameters corresponding to given soil profile. The flow chart representing the algorithm for this program is shown in Figure 64. The procedures for using the program are discussed as follows.

The first step for preparing the soil profile data is to divide the soil block above the failure surface into vertical slices, then store the data records described below in a disk file. The first record of the data file contains five fields separated by commas.

Field #1: number of slices in the slope profile.
Field #2: moist unit weight of the soil in pcf.
Field #3: saturated unit weight of the soil in pcf.
Field #4: required accuracy for safety factor.
Field #5: allowable maximum number of iteration.

Following the first record, are the number of slices plus 1 records corresponding to each slice to slice interface as well as the two ends. Each record consists of

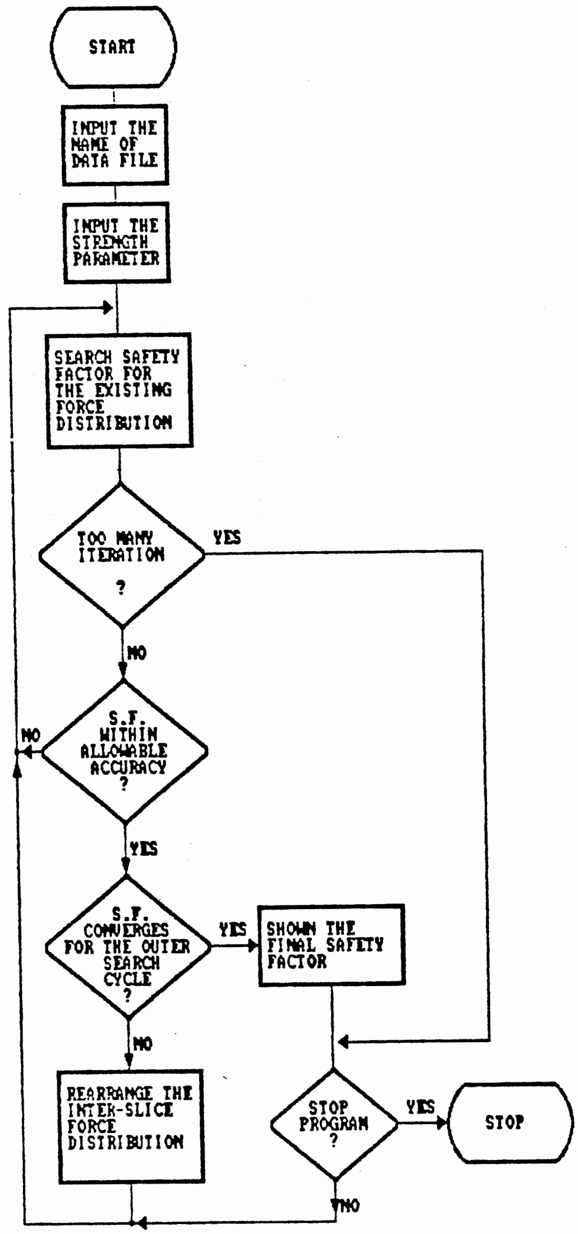


Figure 64. Flow Chart for Program Janbu.

four fields.

Field #1: the horizontal coordinate at the bottom of the slice interface in feet.
Field #2: the vertical coordinate at the bottom of the slice interface in feet.
Field #3: the vertical coordinate at the top of the slice interface in feet.
Field #4: the vertical coordinate at the top of the groundwater surface of the slice interface in feet.

If groundwater is not present in the system, input for Field #4 is the same as Field #2.

The second step is to invoke the program by typing the program name "JANBU" at the DOS prompt ">" followed by a carriage return. The program will ask for the data file name and the strength parameters of the soil. The soil strength parameters are friction angle in degree and cohesion in psf.

During program execution, the intermediate safety factor for each iteration are shown on the screen. If the safety factors converge to the required accuracy within the maximum number of iterations, the search will stop with the final safety factor shown on the screen. If the program does not converge within the limits, it will abort the search and prompt the user for different strength parameters to begin another search.

There are two ways to stop the program execution. The normal termination for the program is to answer "N" after each search for the prompt "Do you wish to continue another search?". The second way is used when the maximum number of iterations was set too high. In this case, the program can be stopped by simply pressing the Ctrl and Scroll Lock keys at the same time.

This slope stability program is a special purpose program with several limitations. The program handles only homogeneous soil profile and requires the user to prepare detail soil profile data before using it. Another limitation is that the units system used in the data file is restricted to the U.S. Customary System. The most important drawback for this program is that the safety factor is not guaranteed to converge for all the situations. Refer to the discussion in Chapter V concerning this numerical instability of the method.

APPENDIX E

WEBB'S CORRECTION METHOD FOR TRIAXIAL TEST

In 1969, Webb[12] proposed a correction method for the calculation of residual shear strength parameters from triaxial test results. The basic assumption of this method is that after the formation of the failure plane within the sample, two halves of the sample will slide relative to each other similar to the sample in the direct shear test. Because of the relative sliding motion, the two halves become eccentric and thus induce horizontal forces acting on the sample. The forces are shown in Figure 65 and the corresponding derivations are described as in the following.

From force equilibrium for the upper half of the sample, the force acting on the failure plane can be represented by its normal and tangential components,

$$H = L\cos\theta + H\sin\theta \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (23)$$

and,

$$S = L\sin\theta - H\cos\theta \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (24)$$

Hence, the normal effective stress acting on the slip

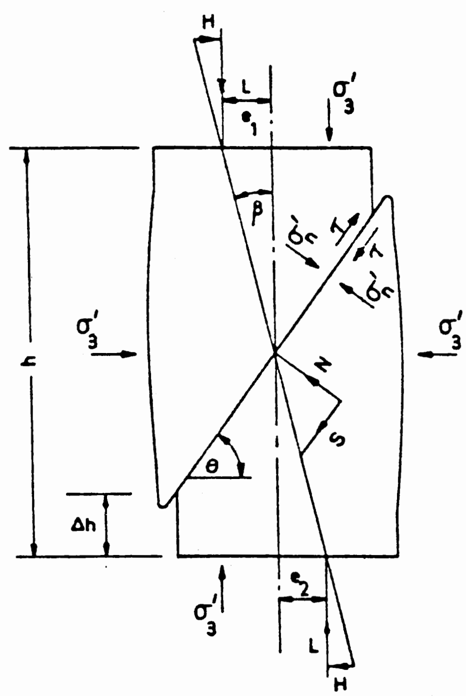


Figure 65. Force Diagram for Triaxial Test Sample with Failure Surface.

surface is,

$$\sigma_n' = N/A_s + \sigma_3' \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (25)$$

and the shear stress

$$\tau = S/A_s \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (26)$$

Since the ratio H/L = $\tan\beta$,

$$\sigma_n' = \frac{L}{A_s} (\cos\theta + \sin\theta \tan\beta) + \sigma'_3 \quad . \; . \; . \; . \; . \quad (27)$$

and,

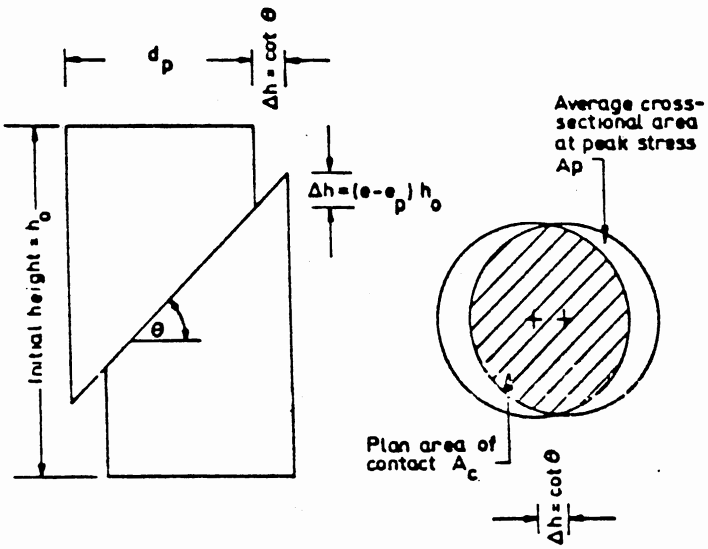
$$\tau = \frac{L}{A_s} (\sin\theta - \cos\theta \tan\beta) \quad . \; . \; . \; . \; . \quad (28)$$

Where A_s is the corrected area after sliding occurs. The area correction is similar to the area correction in the direct shear test. The only difference is that A_s is the projection of the corrected area on the inclined plane. That is,

$$A_s = A_c / \cos\theta \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (29)$$

Reference to Figure 66 for the area correction.

There are three prerequisites for using this method, the angle of inclination θ, the angle β and the strain when the slip surface occurred. In this study, the angles of slip



(a) Post-failure displacement along shear plane. (b) Plan area of shear plane.

$$\theta = \cos^{-1}\left(\frac{\Delta h}{d_p}\right)$$

$$A_c = \left(\theta d_p^2 - \Delta h \cdot \sqrt{d_p^{\,2} - \Delta h^2}\right)/2$$

Figure 66. Area Correction for Webb's Method.

surfaces are measured from the test samples after the test. The failure strains were estimated when the vertical load measured become constant.

As for the angle β , Webb concluded that by estimating $\tan\beta = 0.05$, the error in the residual friction angle is less than $\pm 1^\circ$. Therefore, $\tan\beta$ was set to 0.05 for this study.

Equations (27), (28) and (29) were used in the analysis. The calculated σ_n and τ were plotted for the peak and residual friction angles.

APPENDIX F

LABORATORY TEST DATA

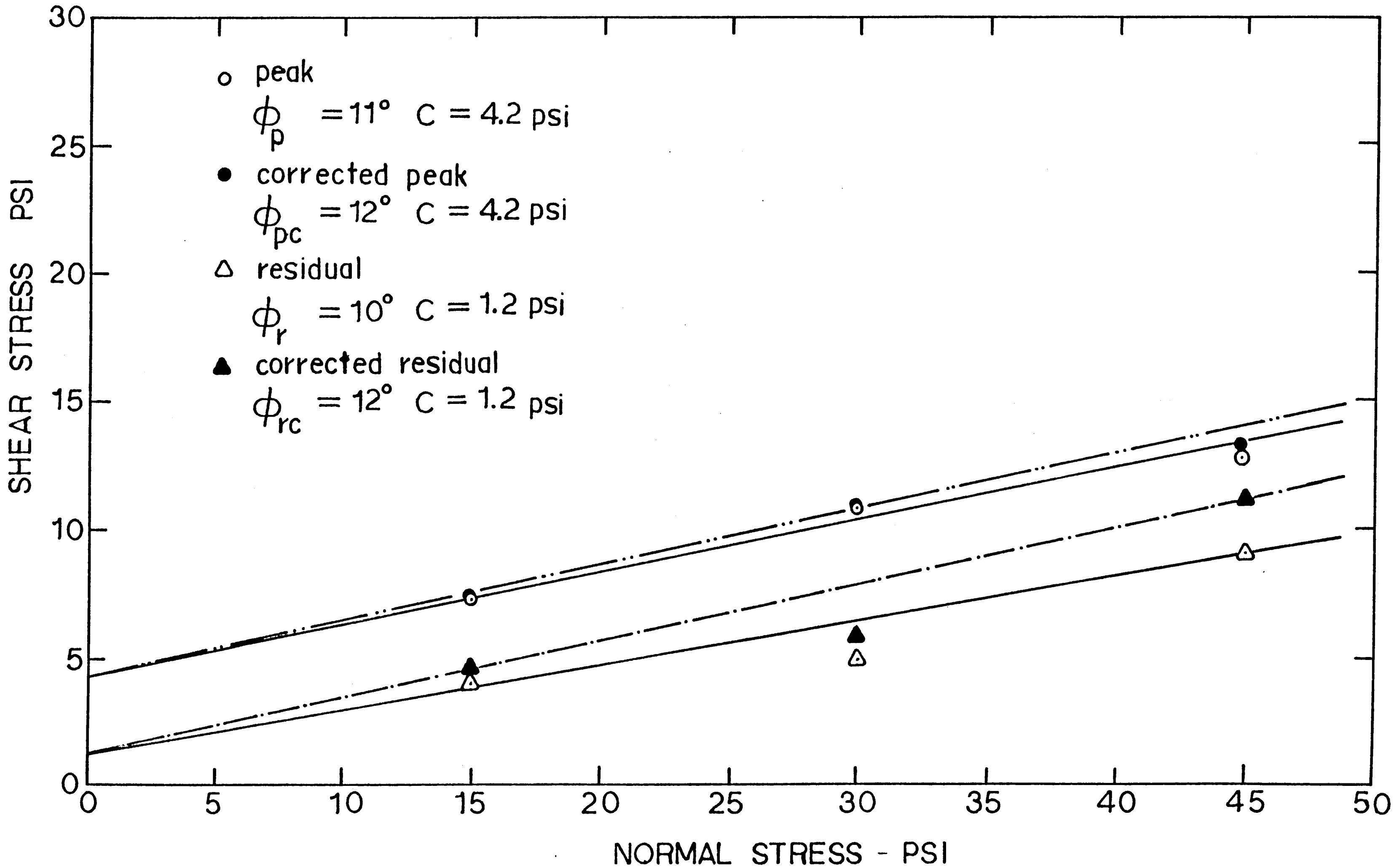


Figure 67a. Failure Envelope for Refined Sample from Direct Shear Test.

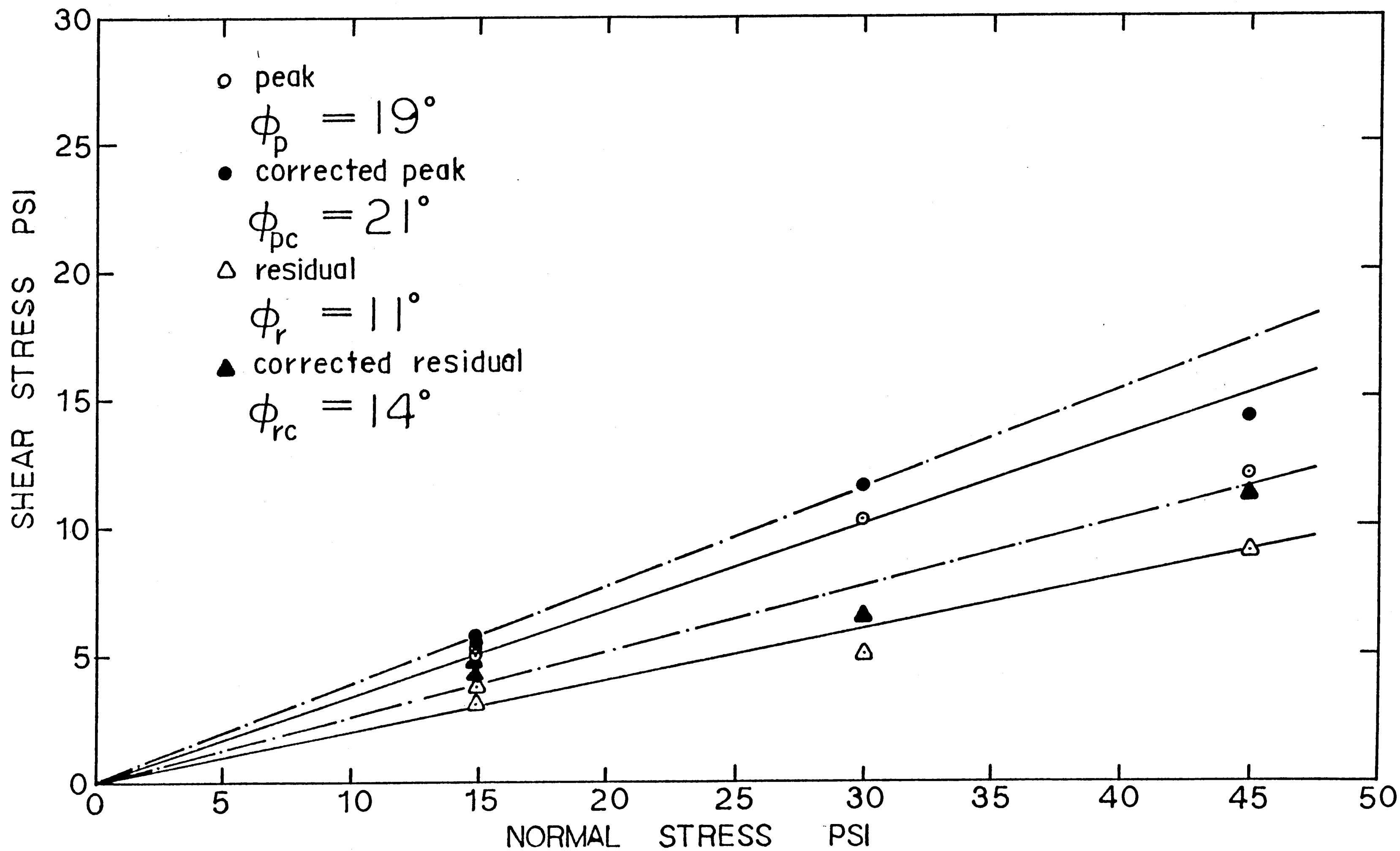


Figure 67b. Failure Envelope for Undisturbed Sample from Direct Shear Test.

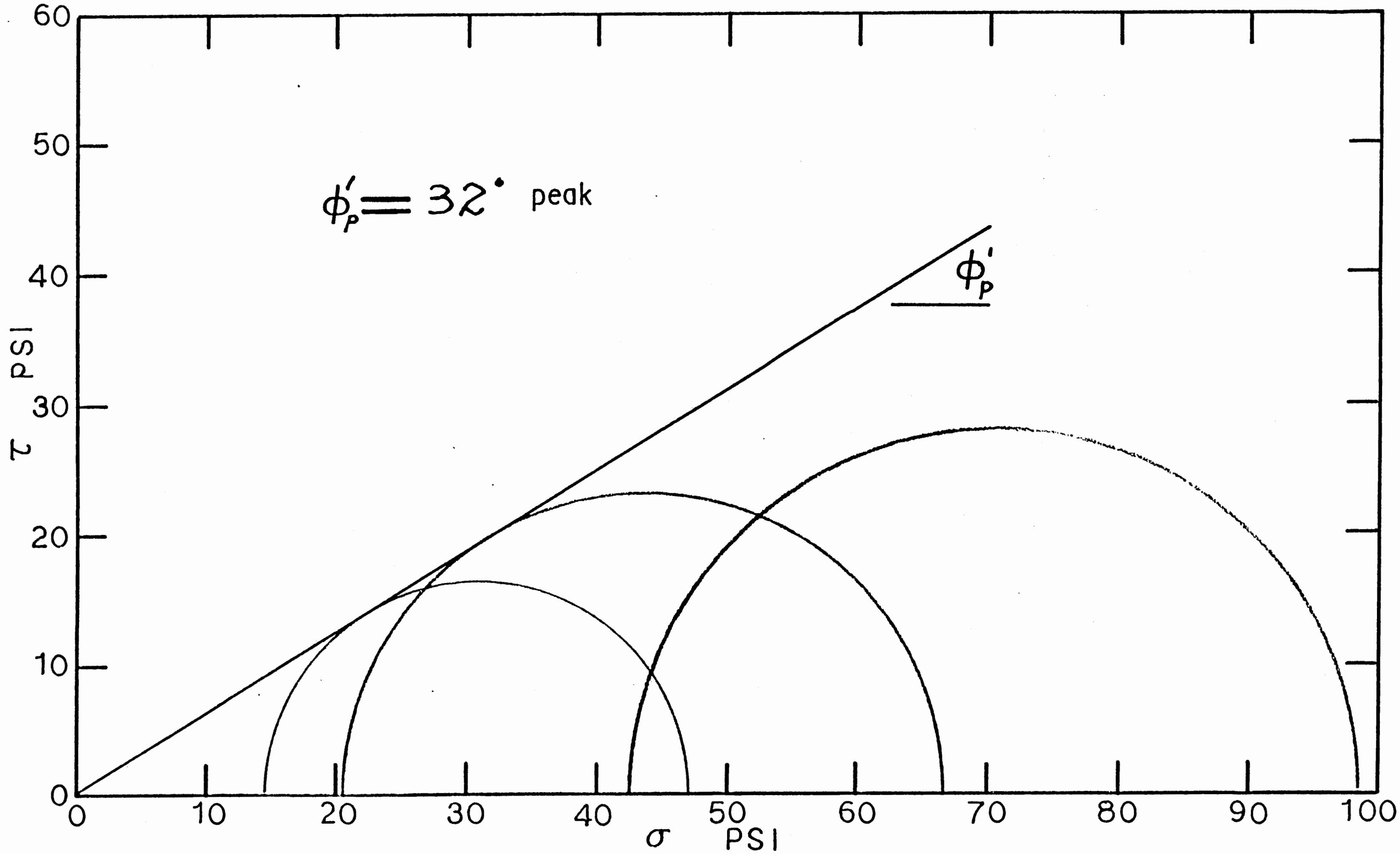


Figure 67c. Mohr-Coulomb Failure Envelope for Undisturbed Samples at Peak Stress.

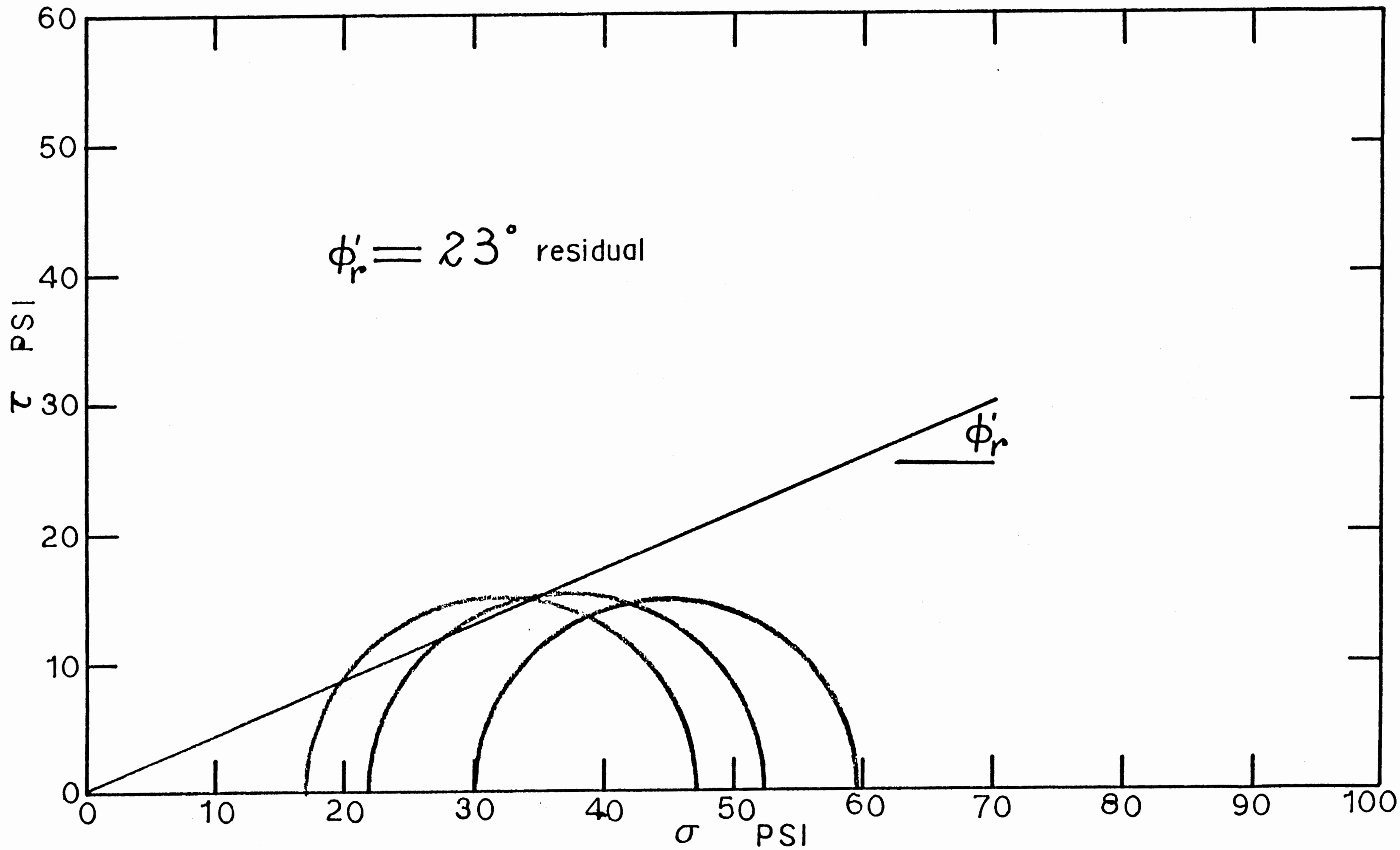


Figure 67d. Mohr-Coulomb Failure Envelope for Undisturbed Samples at Residual Stress.

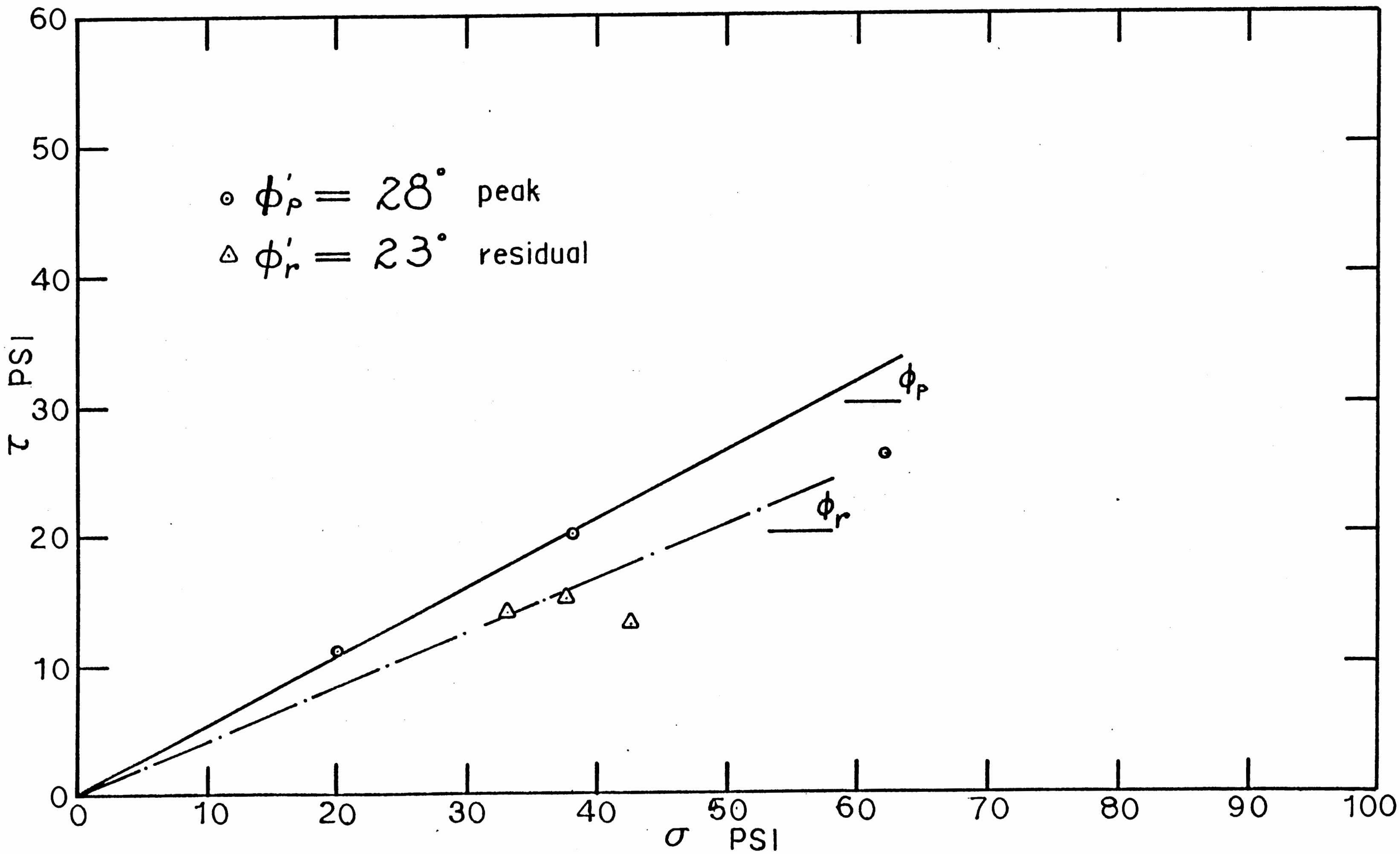


Figure 67e. Failure Envelope from Webb's Method for Undisturbed Samples.

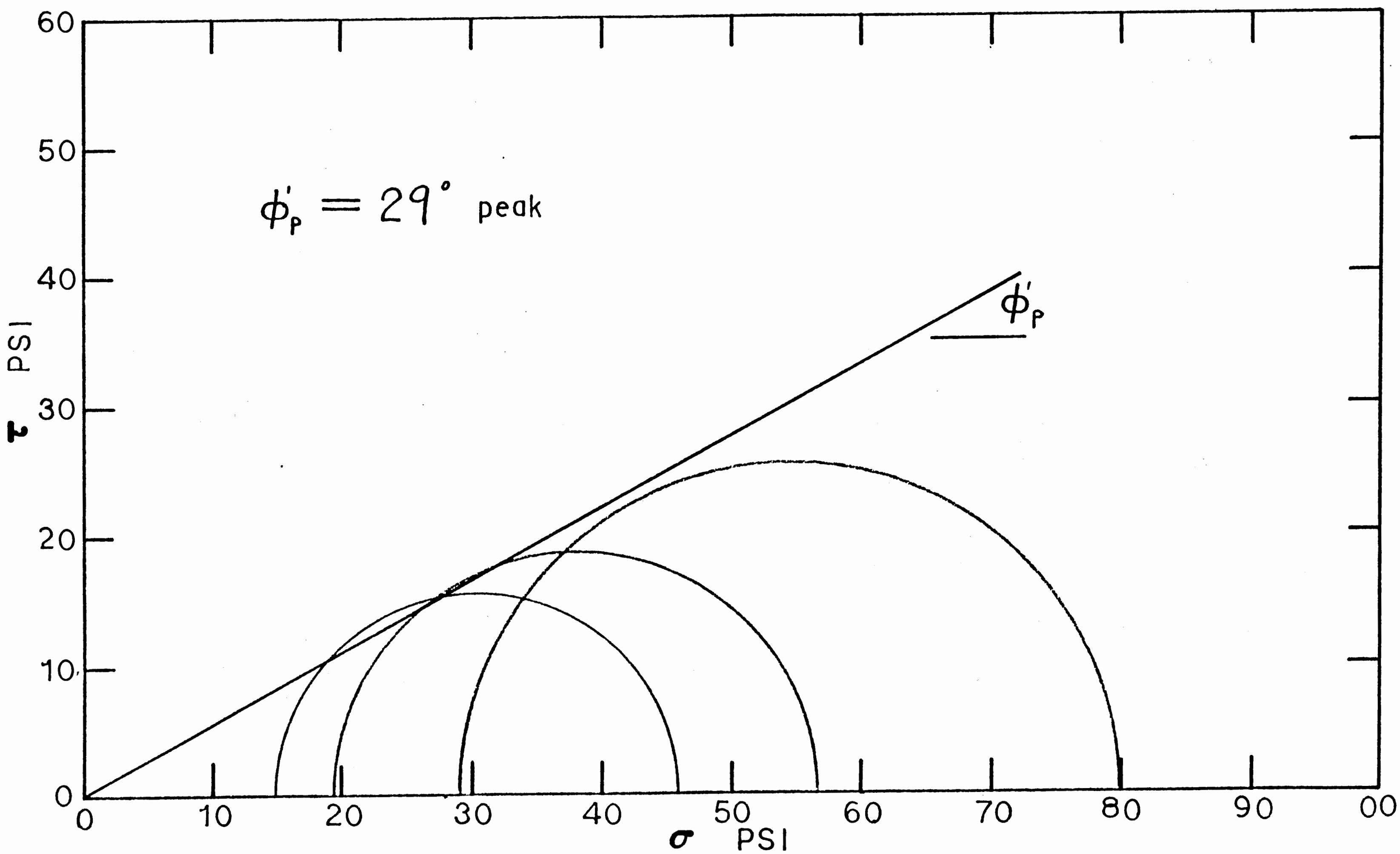


Figure 67f. Mohr-Coulomb Failure Envelope for Remolded Samples at Peak Stress.

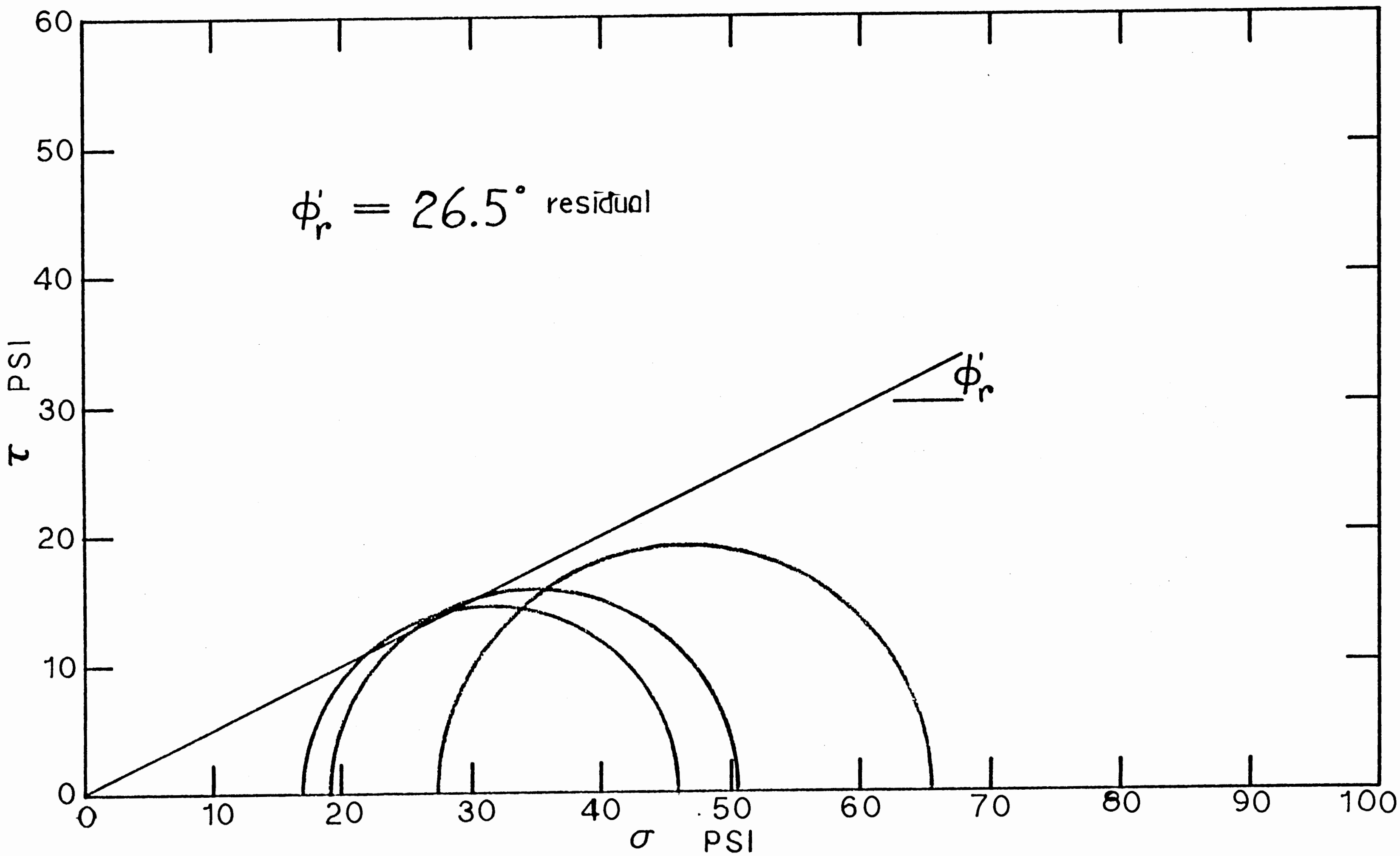


Figure 67g. Mohr-Coulomb Failure Envelope for Remolded Samples at Residual Stress.

✓

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Doctor of Philosophy

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