Engineering Design in Loess Soils of Southeastern Washington

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16. ABSTRACT

Part I of this report focuses on the comparison of strength parameters of the loess soils of southeastern Washington obtained by laboratory triaxial shear testing and in situ testing using the Iowa Borehole Shear Test (IBST). Also, the disturbance of samples due to sampling technique is addressed. Loess samples tested with the IBST generally produce a lower cohesion but higher friction angle than if the same soils were tested by a UCU triaxial test. Also, the IBST produces a higher cohesion and a lower friction angle than a CU test. The failure envelopes tend to merge at higher normal stresses.

Part II of this report suggests drainage schemes to protect cut slopes in loess from rapid deterioration by erosion. This part of the report is a continuation of work completed under an earlier contract (WA-RD-69.1). Specific drainage schemes to divert surface water around or over cut slopes in loess are discussed.

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ENGINEERING DESIGN IN LOESS SOILS OF SOUTHEASTERN WASHINGTON

by

Dr. Jerry D. Higgins, Principal Investigator*
Dr. Richard J. Fragaszy, Co-investigator**
Mr. Timothy L. Martin, Research Assistant**

***Department of Geological Engineering**
Colorado School of Mines
Golden, CO 80401

Washington State Transportation Center
**Department of Civil Engineering
Washington State University
Pullman, WA 99164-2902

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IBST Mohr Envelope in Moist Clayey Loess

CU Triaxial q vs. p plot in Moist Clayey Loess

IBST Mohr Envelope in Silty Loess
CU Triaxial q vs. p in Silty Loess
CU Triaxial Mohr Envelope in Silty Loess
UCU Triaxial q vs. p Plot in Silty Loess
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Comparison Graph of CF1 by Test Type

IBST Mohr Envelope in Silty Loess

UCU Triaxial q vs. p Plot in Silty Loess

UCU Triaxial q vs. p Plot in Silty Loess

UCU Triaxial Mohr Envelope in Silty Loess

UCU Triaxial Mohr Envelope in Silty Loess

Comparison Graph of CF2 by Test Type

IBST Mohr Envelope in Clayey Loess

UCU Triaxial q vs. p Plot in Clayey Loess

UCU Triaxial q vs. p Plot in Silty Loess

UCU Triaxial Mohr Envelope in Clayey Loess

UCU Triaxial Mohr Envelope in Silty Loess

Comparison Graph of CF3 by Test Type

ABSTRACT

This study is in two parts. Part I focuses on the comparison of strength parameters of loess soils obtained by laboratory triaxial shear testing and in situ testing using the Iowa Borehole Shear Test (IBST). Much of the unique character of loess is due to its undisturbed structure and as a result, sample disturbance can greatly affect the results of laboratory tests.

Soil samples were obtained from eight sites which represented a cross-section of southeastern Washington loess ranging in texture from silty to clayey loess. Samples were taken using Shelby tubes and hand-cut methods in order to determine possible sample disturbance. Shelby tube samples had a higher dry density than hand-cut samples at all sites. In situ IBST were conducted at each of the eight sites to provide strength data which could be compared to the laboratory derived strength data. The laboratory tests were performed on both Shelby tube samples and undisturbed hand-cut samples. Unsaturated-consolidated-undrained (UCU) triaxial tests were conducted to provide total stress strength parameters for comparison with the in-situ IBST. Loess tested with the IBST generally produces a lower cohesion but higher friction angle than if the same soil was tested by a UCU triaxial test. Effective stress strength parameters were measured in the laboratory using saturated-

consolidated-undrained (CU) triaxial tests with pore water pressure measurements and were also compared with the IBST strength parameters. The IBST failure envelope tends to have a higher cohesion and a lower friction angle than the CU test results. The failure envelopes tend to merge at higher normal stresses. This appears to be due to the magnitude of the apparent cohesion.

Part II of the study focuses on the engineering properties of loess related to surface water runoff around cut slopes in the loess soils of southeastern Washington. For slope cuts in silty loess surface water diversion is required if drainage is toward the cut face. The drainageway should consist of a ditch or earth berm protected from erosion by vegetation or a filter fabric and rock cover. The area between the drainage structure and slope face should be vegetated and fenced. Cut slopes in silty loess where the natural drainage is away from the slope face do not require drainage structures; however, a fenced ROW is recommended to protect the slope crest from damage due to farming activity. Flatter cuts in clayey loess do not require drainage structures unless flow is concentrated onto the face by channels, gullies, swales, etc. General design concepts are presented for drainage systems around and over cut slopes faces.

SUMMARY

The unique engineering behavior of loess is based on its undisturbed structure. If the structure is disturbed when a test specimen is obtained and prepared, the strength parameters produced by the test may not reflect the true in situ values. The Shelby tube sampling method is often considered to yield "undisturbed" test specimens; however, in loess this is questionable.

Part I of this study compared the results of laboratory triaxial tests on Shelby tube samples and hand cut samples. Also, strength parameters obtained by laboratory triaxial shear testing was compared with insitu tests (Iowa Borehole Shear Test, IBST) to determine the effect of testing method on shear strength parameters in loess. The results of these comparisons indicate that Shelby tube samples consistently had greater dry densities than hand-cut samples. Therefore, the sampling technique does cause sample disturbance. The study also shows that total strength parameters can be determined by either an unsaturated-consolidated-undrained (UCU) triaxial test or an IBST. The IBST can produce a complete Mohr failure envelope in about an hour as compared to two days using triaxial tests. The IBST tends to produce a lower shear strength at lower normal stresses and a higher shear strength at higher normal stresses relative to UCU triaxial tests.

The second part of this report examined drainage design schemes to protect cut slopes in loess from damage by erosion. General drainage designs were formulated based on field observations of slope performance and erosion problems in southeastern Washington loess and successful designs in other states. Drainage ditches or berms should be constructed 10 to 15 ft. behind the top of a cut slope to intersect runoff and route the water around the cut face to the toe of the slope. Drainageways should be lined to protect them from erosion damage and the gradient should be maintained to assure that slope forming soils are not saturated and weakened by standing water. Water should not be allowed to flow over a cut slope unless it is contained in a lined channel or pipe. Design concepts are presented for specific cases.

CONCLUSIONS

Part I

The following conclusions are based on laboratory and in situ strength testing in the loessial soils of southeastern Washington. These conclusions may be applicable to other loessial soils due to the similar nature of loess in other parts of the world.

1. The Iowa Borehole Shear Test (IBST) generally produces a higher total friction angle (0-10 deg) and a lower total apparent cohesion (0 to 7.3 psi or 0 to 50 kPA) than the total friction angle and apparen cohesion produced by an unsaturated-consolidated-undrained (UCU) triaxial shear test.
2. Shelby tube sampling consistently produces test specimens with a greater dry density than undisturbed hand-cut test specimens obtained from the same site; however, the percent change in dry density is not predictable.
3. Hand-cut test specimens yielded the highest cohesion, followed by the Shelby tube specimens, with the lowest cohesions produced by the IBST.
4. The IBST does not produce effective strength parameters in loessial soils due to the affect of capillary induced apparent cohesion. In unsaturated loess soil the IBST may produce a friction angle close to an effective friction

angle, however, the IBST cohesion will be much greater than the true effective cohesion. An unsaturated loess can develop considerable negative pore-water pressure and as a result the IBST under-estimates the effective friction angle and over-estimates the cohesion.

The results of this study are applicable to both foundation engineering and slope stability analysis in loessial soils. As long as loess remains unsaturated, the total strength parameters can be used for design and stability analysis. The total strength parameters can be determined by either an UCU triaxial test or an IBST. If the loess becomes saturated then effective strength parameters should be used as derived by a CU triaxial test.

The IBST can produce a complete Mohr failure envelope in about an hour as compared to two days using triaxial tests. The time savings and ability to test several sites per day make the IBST an attractive alternative to triaxial testing as long as total strength parameters are required. The IBST tends to produce a lower shear strength at lower normal stresses and a higher shear strength at higher normal stresses relative to UCU triaxial tests.

Part II

Much of the damage to cut slopes in loess in southeastern Washington is due to inadequate surface drainage. In silty loess soils, cuts are generally made near vertical (1/4:1 H:V). Any flow of surface water over the face of this type of cut can cause severe erosion damage. Therefore, surface water diversion structures are required if the natural drainage above the cut slope is toward the cut. If the natural drainage above the cut diverts surface water away from the slope face, no drainage structure is recommended. However, 10 to 15 ft of fenced and vegetated ROW is recommended to protect the slope crest from damage by farming activities and as a safety measure for farm equipment operators.

Cut slopes in clayey loess are generally made flatter (2.5:1 H:V) than cuts in silty loess and stabilized with a cover of vegetation. These cuts generally are not susceptible to minor damage by sheetwash over the cut face; therefore, surface water diversion above the slope cut is not always required. Concentrated flows such as from channels, gullies, etc., can cause severe erosion damage to the cut face and a drainage diversion is recommended.

If the natural drainage is toward a cut slope in silty loess, drainageways formed by ditches or berms should be constructed 10 to 15 ft behind the top of a cut slope, preferably before the cut is opened. The channel should be flat bottomed and lined with vegetation (if low gradient i.e., less than 5%) or a filter fabric protected by a layer of aggregate for higher gradients. The gradient of the drainageway should be maintained to prevent standing water and saturation of the soil. Drainageways around the sides of cut slopes tend to have moderate (5 to 10%) to steep (greater than 10%) gradients and may require lining with a filter fabric covered by coarse rock or gabion mats, or possibly an asphalt or concrete liner. As an alternative a half-round pipe may be used. The maximum gradient that vegetation will provide adequate erosion protection is unknown for these deposits, although a 5% gradient is probably near the upper bound. WSDOT should experiment with this design. The ROW between the ditch/berm and slope crest should be seeded or the natural vegetation should be preserved, and the area should be fenced to protect the drainage structure and slope crest from damage due to farming activities.

When small drainages are truncated by a slope cut in either silty or clayey loess, water must be routed over or around the face of the slope. On 2.5:1 (H:V) or flatter slopes a shallow drainageway lined with a filter fabric and gabion mat or coarse crushed rock is recommended. Pipe half-rounds and asphalt or concrete lined ditches can also be used. If water must be routed over a near vertical cut slope, the problem becomes more difficult. Water can be routed over a vertical slope face in a pipe that is connected to a collection area and sediment trap above the head of a cut slope.

RECOMMENDATIONS FOR FUTURE STUDY

The behavior of loessial soils during triaxial and borehole shear testing is not completely understood. Recommendations for future research include studies to:

1. Measure the capillary induced negative pore-water pressure using a tensiometer built into an Iowa Borehole shear head and compare the shear strength relative to that derived by CU triaxial testing.
2. Measure the volume change of undisturbed specimens during saturation in both clayey and silty loess to determine the degree of immediate settlement (collapse) in Washington loessial soils. This information should be useful for design of shallow foundations.
3. Conduct finite element modeling of the IBST to determine the state of stress before, during, and between stages of a borehole shear test.

Most of the suggested drainage design schemes have not been used in Washington. It is recommended that the drainage designs be constructed as test sections on new projects. A record should be kept of construction problems, costs, etc., and the test sections should be monitored to evaluate the performance of each. The results of this evaluation should incorporated into a design manual.

INTRODUCTION

Loess is composed of predominantly silt-sized particles with lesser amounts of clay and/or very fine sand. Loess is a homogeneous, unconsolidated, non-stratified, eolian deposit generally considered to have a glacio-fluvial origin. Loessial soils are found worldwide; however, this study is limited to the loessial deposits of southeastern Washington.

Loess distinguishes itself from other soils of similar composition by its unique undisturbed structure. Larionov (1965) observed that the silt-sized particles are not in contact with each other, but are separated by clay coatings or clay aggregates. The undisturbed structure has a high porosity and, in the unsaturated state, develops an apparent cohesion due to capillary tension in the clay coating. The development of capillary induced cohesion in the undisturbed structure allows vertical cuts exceeding 50 ft (15 m) in height to remain stable, providing the water content remains low. However, if the water content increases and the clay binder becomes saturated, the loess becomes relatively weak and sliding failures can occur in slopes as flat as 2:1 (H:V).

An initial study of eastern Washington loess was done by Higgins and others (1985). That study identified some of the engineering problems experienced as a result of highway construction in Washington loess deposits. This study examines the evaluation of shear strength parameters, the effect of sampling method on shear strength, and suggests generalized drainage designs for cut slopes in loess.

PURPOSE OF THE STUDY

The unique behavior of loess is based on its undisturbed structure. If the structure is disturbed when a test specimen is obtained and prepared, the strength parameters produced by the test may not reflect the true in-situ values. The Shelby tube sampling method is often considered to yield "undisturbed" test specimens. Shelby tube sampling often does produce relatively undisturbed test specimens in saturated clay; however, in unsaturated friable loess, test specimens produced from Shelby tubes can become densified and/or fractured. There is also some evidence that the shear strength parameters (cohesion and friction angle) can be influenced by the type of test used to determine the parameters.

One of the objectives of this study is to determine the influence of Shelby tube sampling on the total stress shear strength produced by laboratory triaxial testing. Undisturbed hand-cut samples were tested and the results compared with the Shelby tube samples. A second objective of the study is to compare the strength parameters obtained by laboratory triaxial shear testing with in-situ testing using the Iowa Borehole Shear Test (IBST) to determine the effect of testing method on the shear strength parameters of loess.

The triaxial testing program consisted of total stress triaxial tests on unsaturated field specimens. Both Shelby tube and hand-cut specimens were tested using unsaturated-consolidated-undrained (UCU) triaxial tests. Saturated-consolidated-undrained (CU) triaxial tests were conducted on hand-cut specimens to determine effective stress strength parameters. The triaxial strength parameters, both total and effective, were compared to the in-situ strength parameters obtained from the IBST.

A third objective of this study is to present drainage design concepts for cut slopes in loess. These designs are recommended for experimentation by the Washington State Department of Transportation (WSDOT) in future construction projects. This objective is discussed at length in Part II of this report.

EASTERN WASHINGTON LOESS

An initial study (Higgins et al., 1985) conducted for the Washington State Department of Transportation (WSDOT) characterized the general trends of index properties (grain size distribution, Atterberg limits, etc.) and evaluated the cut slope performance for southeastern Washington loess deposits. These properties were found to compare favorably with deposits in the midwestern United States. The study found a varied grain size distribution within the Washington loess deposits that ranged from a clayey loess along the Idaho border which grades into a silty loess to the west. Clayey loess and silty loess are defined arbitrarily by figure 1.

THE FIELD SAMPLING PROGRAM

General Description and Objectives

The primary objectives of the field sampling program were to collect Shelby tube samples for subsequent laboratory tests, to obtain undisturbed hand-cut samples adjacent to the Shelby tube boreholes for later laboratory testing, and to conduct Iowa Borehole Shear tests in the boreholes from which the Shelby tube samples were obtained. The Shelby and hand-cut samples were tested using unsaturated consolidated undrained (UCU) triaxial tests in the laboratory to determine the total stress shear strength of each sample. The shear strengths of the soil samples were compared to determine the influence of sampling technique and testing method on total stress shear strength.

Eight field sites were located throughout the eastern Washington loessial deposits which ranged from silty loess

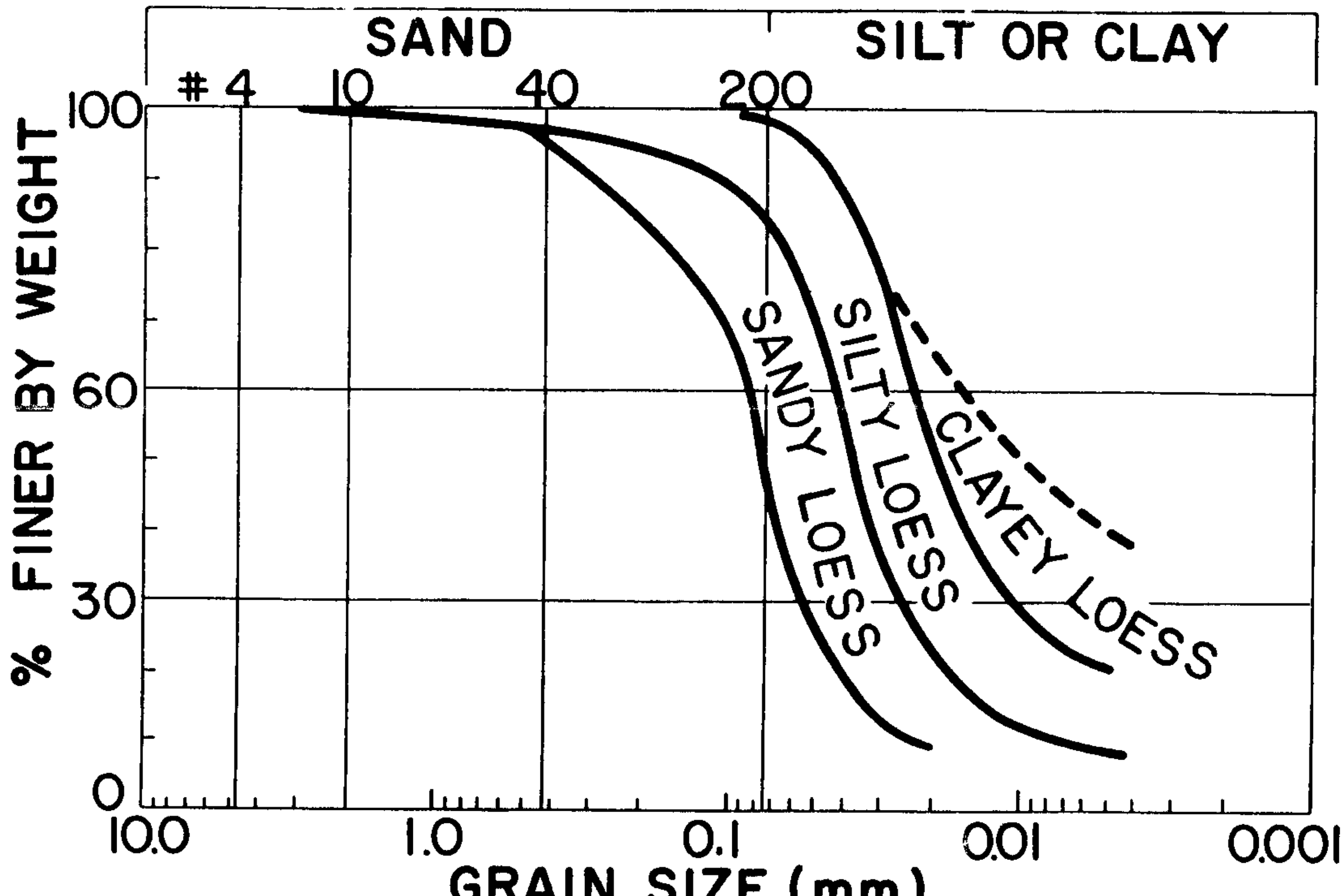


Figure 1. Definition of Clayey and Silty Loess.

near Walla Walla to clayey loess near Colfax (Figure 2). Average soil properties from the eight field sites are listed in Table 1.

Sample Pit Description

A typical field site consisted of a pit excavated to well below the root zone (8 to 10 ft or 2.5 to 3 m deep) by means of a backhoe. The plan pit dimensions were approximately 10 by 13 ft (3 by 4 m). A 2.5 ft (.75 m) high by 3 ft (1.0 m) wide bench of soil was cut in the bottom of the excavation to expedite the collection of the hand-cut samples (Figure 3).

Shelby Tube Sample Collection

The Shelby tube samples were obtained by pushing the sampling tubes into the bottom of the excavations with a backhoe. The Shelby tubes were located so that the backhoe operator could steady the bucket against the excavation wall during the pushing and pulling of a tube to ensure that the Shelby tubes moved vertically, not laterally. The tubes had to be withdrawn slowly, especially in wet soil, to minimize the effects of borehole vacuum which can create tensile fractures within the sample. Care was also taken not to "over-push" the tubes which would result in additional compression of the soil sample.

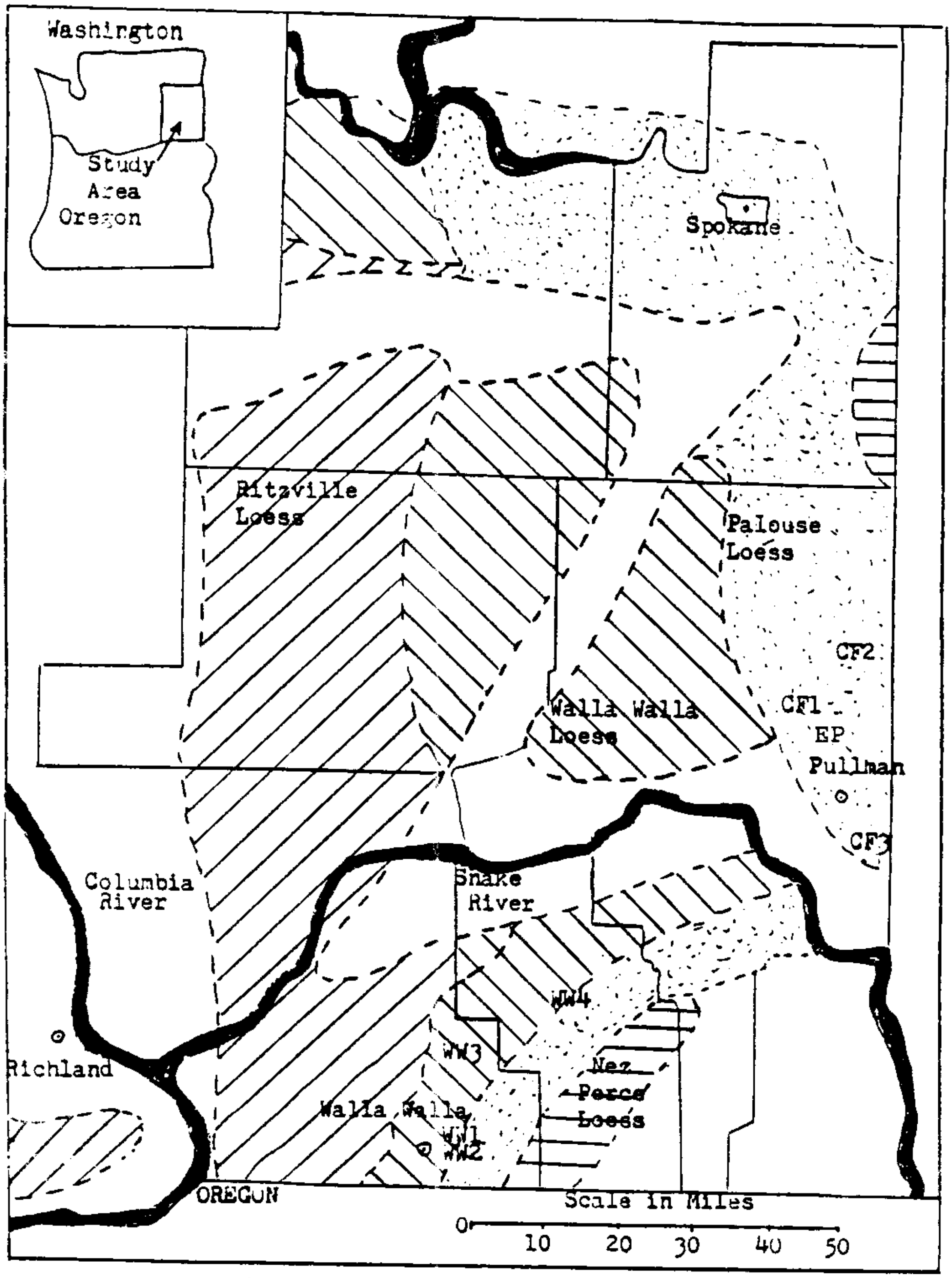


Figure 2. Map of the Study Area
(After Eske, 1959)

TABLE 1

Average Soil Properties

Soil	Dry Density	W.C. (%)	Specific Gravity	Clay (%)
WW1	1.22 g/cm^3	14.66	2.72	7
WW1H	1.19	14.66	2.72	7
WW2	1.29	13.81	2.73	8
WW2H	1.22	13.81	2.73	8
WW3	1.47	22.21	2.70	8
WW3H	1.31	22.21	2.70	8
WW4	1.21	18.85	2.67	9
WW4H	1.13	18.85	2.67	9
CF1	1.44	19.06	2.73	21
CF1H	1.36	19.06	2.73	21
CF2	1.57	23.40	2.72	12
CF2H	1.38	23.40	2.72	12
CF3	1.40	31.39	2.71	18
CF3H	1.33	31.39	2.71	18
EPH	1.37	19.48	2.74	28

Note: H in sample designation denotes a second sample at a site i.e., WW1H is a sample from site WW1, EPH is a sample from site EP.

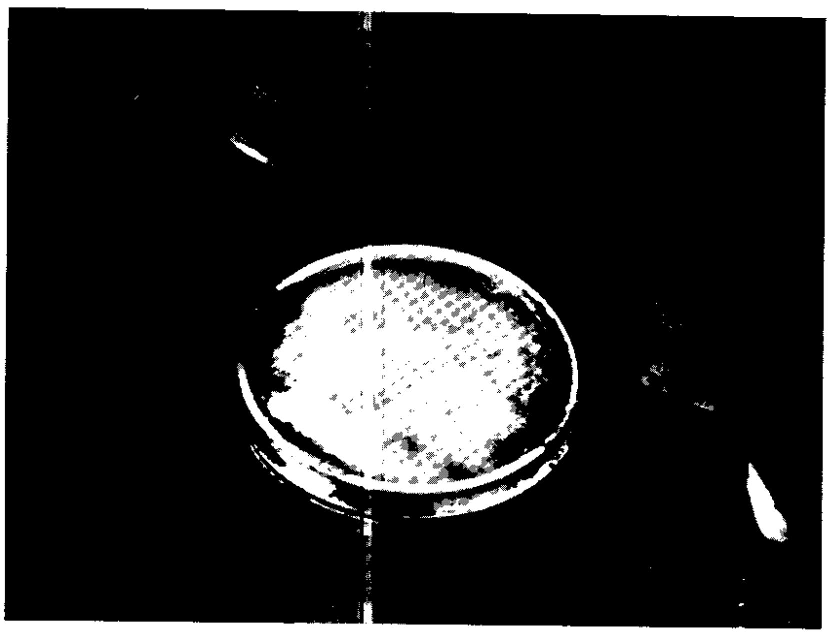


Figure 3. Sampling Excavations.

Upon extraction, the Shelby tubes were immediately labeled and sealed. The two step sealing process consisted of first covering the exposed soil in the tube ends by at least 1.3 cm of melted paraffin and secondly, by the addition of a plastic sealing cap securely taped into place. The tubes were then gently secured so they would not be jarred by movement during transport.

Hand-cut Sample Collection

The hand-cut samples were acquired from the bench of soil cut into the bottom of the sampling pit. Two methods were employed to secure undisturbed samples for laboratory testing.

The first method consisted of trimming samples into large blocks which were then subdivided in the laboratory to produce individual test specimens. The blocks were cut into shape with a machete so that a container could be inserted over the sample allowing 1.3 to 2.5 cm of space between the sample and container wall. The space was then filled with melted paraffin encasing the top and sides of the sample. After the paraffin hardened, the sample was cut off at the base, and sealed with paraffin (Figure 4). The samples were then carefully transported in the containers to the laboratory. A block sample is generally large enough to produce three to four triaxial test specimens which can be cut to size in the laboratory.

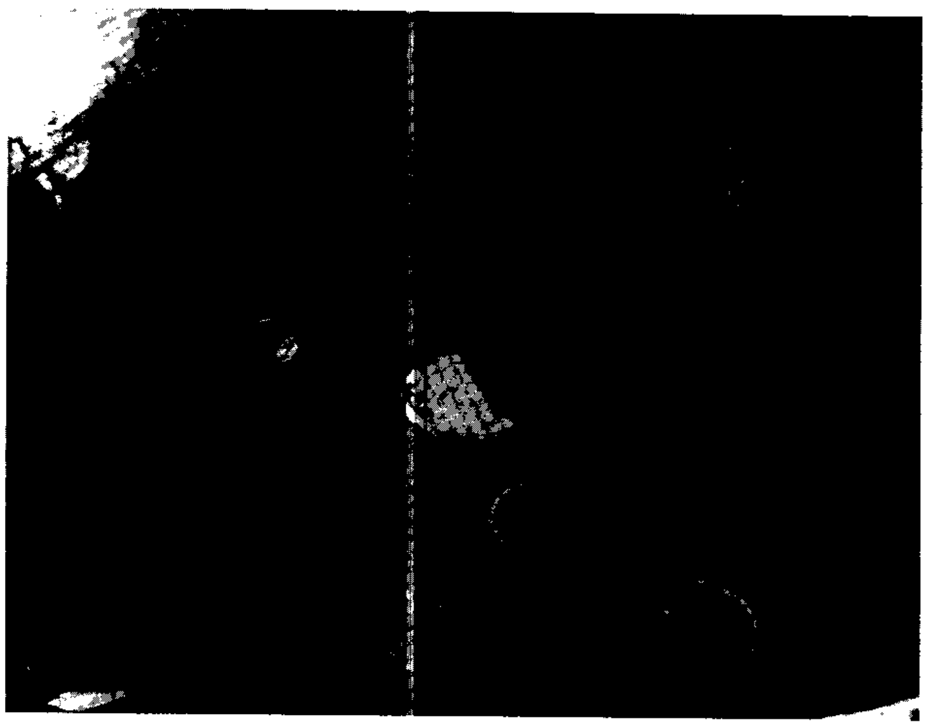


Figure 4. Obtaining Hand-cut Block Samples. (Sample is sealed in a plastic container with paraffin.)

Based on the investigators' early experience with cutting of block samples, a second method of acquiring hand-cut samples was tried which involved trimming the test specimens in the field. The samples were cut and trimmed with a knife and a portable sample trimmer and then encased in a triaxial membrane. The specimen ends were sealed with moisture content cans (in lieu of end plattens) and O-rings, and then the specimens were carefully encased with packing material to prevent damage to the test specimens during transport to the laboratory.

Of the two methods, the trimming of the triaxial test specimen in the field is the recommended method. The large block specimens are very difficult to isolate without fracturing, and melting the large amount of paraffin requires a considerable amount of time. When the paraffin is poured into the form, it often fills available worm-holes and seeps around the base of the form. Also, the blocks are heavy which may cause some difficulty extracting them from a 10 ft (3 m) deep pit. Finally, when the blocks arrive at the laboratory they must be divided into triaxial test specimens. Trimming the block into test specimens should be done at one sitting and as quickly as possible so that the soil will not change appreciably from its natural moisture content.

Trimming the triaxial test specimens in the field reduces the uncertainty of having a viable number of specimens to test in the laboratory. If a sample being trimmed in the field fractures during the cutting process, another one can be quickly obtained. Conversely, if a block specimen fractures in the laboratory during the cutting process (which is common) several test specimens may be lost. Trimming a sample directly in the field removes a major step in the sampling/testing process as well as all the concern and expense of paraffin, stoves, and forms. Also the field trimmed test specimen can be tested the next day, thereby ensuring minimal change in the natural moisture content because of less time in storage. Preparation for triaxial testing is simply a matter of removing the moisture content cans and replacing them with filter paper and end plattens.

IOWA BOREHOLE SHEAR TEST

General Description

The Iowa Borehole Shear Device (IBSD) is a portable testing instrument designed to perform a series of direct shear tests within a borehole . Since the IBST is a direct shear test it probably incorporates the non-uniform stress and strain conditions inherent in the laboratory direct shear test (Handy and Fox, 1967; Schmertmann, 1976; Saada and Townsend, 1981). The main components of the IBSD are the shear head, pulling device, and console. The components are shown in Figure 5.

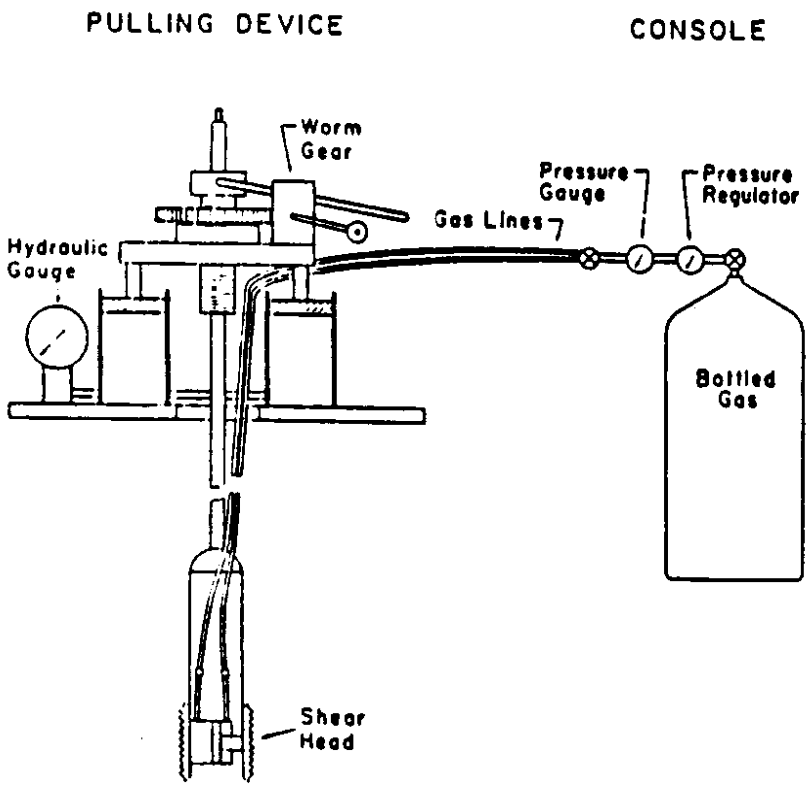


Figure 5. Components of the Iowa Borehole Shear Device (After Wineland, 1975)

The shear head is composed of two curved serrated plates connected to a gas operated piston. The plates are forced against the sides of the borehole by the piston creating a normal stress (Q_n). The shear head is then slowly drawn up vertically by the pulling device producing a shear stress (T). A series of tests are performed with increasing normal stresses (Q_n) while measuring the corresponding shear stresses (T). The shear and normal stresses can then be plotted to yield a Mohr-Coulomb failure envelope with internal friction angle (O) and cohesion intercept (c).

Conventional shear plates are designed to be used in soft-to-medium dense soils. A conventional plate has a contact area of 32.3 cm^2. There are 25 teeth composed of 60 degree wedges spaced at 2.5 mm with a tooth spacing to depth ratio of 1.15 (Lutenegger and Hallberg, 1981).

IBST - Test Type

The IBST is essentially a stage test on a single "sample" of soil. It is assumed in a stage test that the accumulated stresses and strains of all of the previous stages do not significantly affect the results of the next stage (Schmertman, 1976). After the initial shearing of the soil, the normal stress is increased and the soil is allowed to reconsolidate before the next stage of shearing is continued. The succeeding stage test does not reshear the initial shear zone but, as Schmertman points out, "The reconsolidation of disturbed zones from the previous stage, by consolidation from the next stage, forces the next failure surface deeper into less disturbed soil...".

The Mohr-Coulomb failure envelope produced by the IBST usually has a higher cohesion intercept and phi angle (angle of internal friction) than a triaxial failure envelope. Handy and Fox attribute the well-defined IBST failure envelope to the removal of the sampling variable, i.e., "Since all tests in a series are conducted at essentially the same depth in the same hole, they are in essentially the same soil."

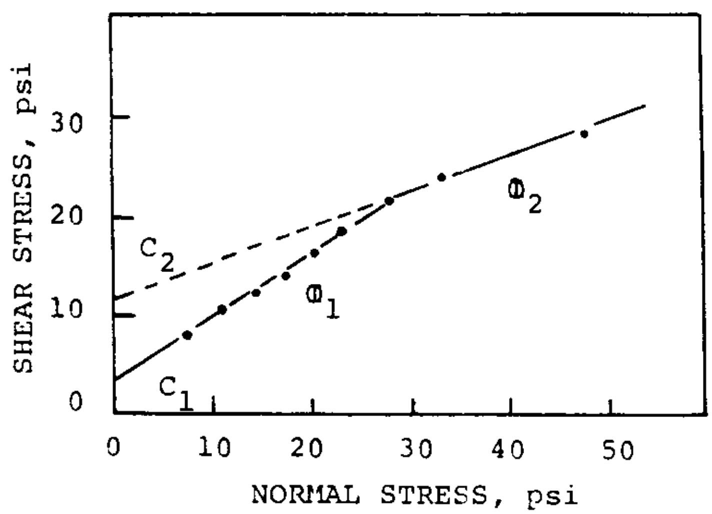
The IBST can be considered to approximate a consolidated-drained (CD) test in sands or partially saturated soils and a consolidated-undrained (CU) test in saturated clays (Schmertman, 1976; Handy, 1976,1986; Wineland, 1975; Lutenegger and Hallberg, 1981). A CD test is characterized by the absence of excess pore-water pressure during the shearing phase of the test. Until recently, the pore-water pressures present during an IBST have largely been conjecture. Lutenegger and Tierney (1986) conducted a study in which they incorporated pore-water pressure transducers into a modified shear head to monitor excess pore pressures during an IBST. The study examined the pore-water pressure behavior during the consolidation, shearing, and post-shearing phases of an IBST in saturated clay. It was suggested that pore-water pressures during each phase are a function of soil type, stress history, permeability, location of pore-water pressure measurement, and type of IBST (stage or fresh shear). In another study, Lutenegger and Hallberg (1981) proposed that "in some cases, the initial portion of a test may give data which could be considered drained, with the latter portion indicating undrained conditions" (Figure 6). The explanation for the drained-undrained behavior is attributed to unsaturated conditions at the lower stress levels in the initial portion of the test and saturated conditions at the higher stress levels in the latter portion of the test. The drained-undrained behavior was inferred from the friction angles since pore-water pressures were not measured in the test. The potential presence of excess pore-water pressure should be considered when interpreting the results of a series of IBST. Currently, some Iowa Borehole Shear Devices are being modified to incorporate pore-water pressure transducers into the shear heads.

Questionable Results

Occasionally, the operator of the IBST may want to retest a given soil if the test produces questionable results i.e., suggesting the presence of negative cohesion or a flattening of the failure envelope. Handy and Ferguson, 1975 suggest three reasons for unrealistic results:

1. Poor seating of the shear plate teeth in hard soils. The seating of the shear plate can be

γ = 115.4 pcf (1.85 g/cm^3)
w = 15.3%
S = 100%



Φ_1 = 31.7 deg.
C_1 = 3.9 psi (26.9 kPa)
Φ_2 = 20.5 deg.
C_2 = 10.9 psi (75 kPa)

Figure 6. Drained-Undrained IBST Results
(After Lutenegger and Hallberg, 1981)

improved by repeating the test with larger increments of normal pressure.

2. The existence of excess pore-water pressure which can be remedied by repeating the test with longer consolidation times.
3. Sometimes in soft soils the shear plates can cause bearing failure resulting in maximum extension of the gas operated piston. The test should be repeated with smaller increments of normal stress.

TEST PROCEDURE

The IBST was integrated into the sample collection program involving Shelby tube and hand-cut samples to provide a measurement of insitu total stress shear strength. The Iowa Borehole Shear Test procedure is listed in the following steps:

1. A sample pit is excavated to a depth of 8 to 10 ft (2.5 to 3 m) and several Shelby tube soil samples were obtained.
2. A IBST is then performed in a Shelby tube borehole.
3. The shear head is lowered into the borehole to a depth of approximately 1.5 ft (0.5 m) and secured vertically by the pulling device.
4. A normal stress (Q_n) is then applied to the sides of the borehole by the gas operated piston and the soil is allowed to consolidate for 10 to 15

minutes. The longer consolidation time may be necessary for clayey loess.

5. The pulling device is activated by turning a crank-gear arrangement to create a shearing stress on the soil immediately adjacent to the shear head. The rate of vertical displacement should be about 0.05 mm/sec, which translates to approximately 30 crank rev/min. When the shear stress peaks, the value is recorded as the maximum shear stress for the corresponding normal stress. The shearing rate should not be faster than 0.05 mm/sec. Rapid shearing is undesirable because the development of positive pore-water pressures will decrease shearing strength and viscous effects which increase it (Handy, 1976). Handy also suggests "coaxing" the highest value of shear strength by slowing down (never speeding up) the shear rate.
6. The IBST is repeated at least 3 to 4 times with increasing normal stresses ranging from 6 to 75 psi (40 to 500 kPa). The orientation of the shear head is not changed with increasing normal stress, but the test is conducted as a stage test.
7. The normal and shear stresses are then plotted, resulting in a Mohr-Coulomb failure envelope.

TRIAXIAL TESTING PROGRAM

General Description and Objectives

The triaxial testing program for loessial soil was designed to achieve two objectives. The first objective was to simulate the conditions of an IBST so that a comparison could be made between the total strength parameters of the IBST and the total strength parameters of the triaxial tests on eastern Washington loess. An unsaturated-consolidated-undrained (UCU) triaxial test is considered the best simulation of the IBST. The UCU triaxial tests yielded total strength envelopes which were compared directly with the total strength envelopes produced by the IBST. The second objective of the triaxial testing program was to determine the effective strength parameters of the loess using a saturated-consolidated-undrained (CU) triaxial test.

Comparison of Saturated vs. Unsaturated Behavior in Loess

The unique character of loess depends primarily on its undisturbed structure. When this structure is destroyed, loess behaves as other soils with the same constituents (Kane, 1968). Unsaturated loessial soil is characterized by the presence of capillary induced negative pore-water pressure. The negative pore-water pressure is responsible for the apparent cohesion in loess and is largely a function of water and clay content. As loessial soil becomes saturated, the negative pore-water pressure dissipates causing a corresponding decrease in the apparent cohesion. When 100 percent saturation is reached, the apparent cohesion is reduced to zero and any remaining cohesion can be construed as true Horslev cohesion. However, the conventional cohesion in loess is very small (0 to 0.75 psi or 0 to 5 kPa). The effective friction angle of a loessial soil remains relatively constant with an increase in saturation (Holtz and Gibbs, 1951).

Comparison of the CU and UCU Triaxial Test

In a standard CU triaxial test the saturated specimen is allowed to compress as the confining pressure is applied. When the specimen reaches equilibrium, the drainage valve is closed and the shear phase commences by applying deviator stresses to failure. Since the specimen is saturated and undrained, there is no volume change during shear in a CU triaxial test. The pore-water pressure can be measured during shear and both the total and effective stresses may be calculated during the entire test. The test can be used to produce either total or effective strength parameters (Holtz and Kovacs, 1981).

The UCU test is similar to the CU test in that a confining pressure is applied and the drainage valve is opened to allow the specimen to compress to an equilibrium volume. After the specimen reaches volume equilibrium, the drainage valve is closed, and the specimen is loaded to failure. Since the specimen is unsaturated and, depending on its initial degree of saturation, most of what drains during the consolidation phase may be air. During the shearing phase, the remaining air in the soil pores may compress resulting in some volume change even though the drainage valve is closed. The pore-water pressure cannot be accurately measured and only total stresses can be calculated.

Compression of Unsaturated Loess

The process of compressing an unsaturated loess specimen influences the shear strength of loess in two ways. The first effect of compression is to change the initial structure of the loess. Secondly, compression tends to increase the degree of saturation of the test specimen. The degree of saturation is defined as the volume of water in a soil divided by the volume of the voids. As an unsaturated specimen decreases its bulk volume, the volume of the voids decreases as air escapes and the water content remains essentially the same, thus the degree of saturation increases. Both the IBST and the UCU triaxial test compress the soil being tested, but in two different ways. Consolidation involving the IBST takes place when a normal stress (Q_n) is applied to the soil and the soil is allowed to drain 10 to 15 minutes before shearing begins. In the IBST, the minor principal stress (Q_3) and the intermediate principal stress (Q_2) are not equal during the consolidation phase. However, in a triaxial test, the minor and intermediate principal stresses are equal throughout the test, in fact the stresses are usually isotropic.

UCU Testing Apparatus

The triaxial shear test machine used in the UCU tests was a modified Karol-Warner device. The axial load was applied by a transformer controlled electric drive at a constant strain rate of approximately .7 percent per minute. The magnitude of the axial load was measured by a calibrated electronic load cell. The vertical deflection of the specimen during the test was measured by a LVDT. Both the load cell and the LVDT were attached to a voltmeter (digital read-out) which measured the LVDT displacement in millimeters and the axial load in volts. The axial load output was recorded manually at every millimeter of vertical deflection. The axial load measurements (volts) and the LVDT displacements (mm) were processed by a program written for an IBM PC to produce stress-strain data.

UCU Test Procedure

The UCU testing procedure was performed in the following manner:

1. A test specimen was obtained from a Shelby tube or from a hand-cut sample. The test specimens averaged 73 mm in diameter and 175 mm in height. Moisture contents of the test specimens were determined from the soil trimmings.

2. A test specimen was enclosed in a rubber membrane and placed in a triaxial cell.
3. The test confining pressure was applied, using water as the confining fluid, and the drainage valve opened so that the specimen could achieve an equilibrium volume. The specimen was allowed to compress from 15 to 20 minutes. The confining pressures used in a typical series of tests were 7.25, 14.5, 29.0, and 43.5 psi (50, 100, 200, and 300 KPa).
4. The drainage valve was closed and the shear phase was started and continued to failure or until 30 mm of vertical displacement. The axial load was applied at about 1.2 mm per minute. During the compression phase the axial load output was recorded at 1 mm displacement intervals.

CU Testing Apparatus

The triaxial shear test machine used in the CU triaxial tests was developed at the University of California, Berkeley. The test is controlled by a Radio Shack TRS-80 micro-computer which also records the test data in graphical and tabular form. The axial load during the test was recorded by a calibrated load cell. A LVDT recorded the vertical displacement during the test. The TRS-80 converted the loads into kPa and the vertical displacement into percent strain. Pore pressure measurements in kPa were also monitored by the computer throughout the test.

CU Test Procedure

The CU triaxial testing procedure was as follows:

1. A test specimen was obtained from a hand-cut sample.
2. The specimen was placed in a rubber membrane and placed in a triaxial cell.
3. A slight vacuum was applied to the top of the specimen and water was allowed entry through the bottom of the specimen. The vacuum drew the water through the soil and displaced the air from the voids. The saturation process required about 8 to 10 hours.
4. After saturation, a confining pressure was applied to consolidate the specimen. The drainage valve was opened and the specimen was allowed to consolidate for an arbitrary period of 3 to 5 hours. The confining pressures used in the test series ranged from 14.5 to 43.5 psi (100 to 300 kPa).
5. The specimen was subjected to 101.5 psi (700 kPa) back-pressure to assure saturation.
6. The B value was then checked with a confining pressure increment of 2.9 psi (20 kPa). The specimen was considered sufficiently saturated if the B value was at least 0.95.

7. The specimen was loaded to failure with a strain rate of 0.033 percent per minute. The pore pressure was monitored by the TRS-80 computer throughout the compression phase.

DISCUSSION OF RESULTS

This discussion compares the in-situ strength parameters obtained by the IBST with the strength parameters obtained by: UCU triaxial tests on Shelby tube specimens, UCU triaxial tests on hand-cut specimens, and CU triaxial tests on saturated hand-cut specimens. A summary of the total stress strength parameters is given in Table 2. The discussion includes the influence of water content, density, test type, and sampling method on the loessial strength parameters.

Comparison of Shelby and Hand-cut Dry Densities

The Shelby tube test specimens had a greater dry density than the undisturbed hand-cut specimens at every sampling site (Figure 7). Apparently the increase in dry density of the loess samples was caused by pushing and extracting the collection tube. The densifying potential of a soil sample is controlled by factors such as initial relative density, stress history, structure, amount of clay, water content, and sampling technique. However, no specific correlations between these factors and dry density were obvious in this study.

TABLE 2

SUMMARY OF TOTAL SHEAR STRENGTH PARAMETERS
(UCU TESTS)

Sample Number	Hand-cut Triaxial		Shelby Triaxial		Iowa Borehole Shear Test	
	(c in kPA, phi in degrees)					
	c	phi	c	phi	c	phi
WW1	58.3,	19.9	----		31.1,	29.4
WW2	62.4,	20.9	51.7,	20.3	46.9,	20.1
WW3	----		19.5,	27.7	19.9,	26.2
WW4	69.3,	19.0	46.5,	21.9	24.4,	27.6
CF1	65.7,	20.3	35.2,	18.6	23.9,	22.5
CF2	58.0,	19.2	58.6,	16.8	21.0,	22.6
CF3	25.0,	8.6	36.9,	9.9	29.2,	21.6
	(c in psi, phi in degrees)					
WW1	8.5,	19.9	----		4.5,	29.4
WW2	9.1,	20.9	7.5,	20.3	6.8,	20.1
WW3	----		2.8,	27.7	2.9,	26.2
WW4	10.1,	19.0	6.7,	21.9	3.5,	27.6
CF1	9.5,	20.3	5.1,	18.6	3.5,	22.5
CF2	8.4,	19.2	8.5,	16.8	3.1,	22.6
CF3	3.6,	8.6	5.4,	9.9	4.2,	21.6

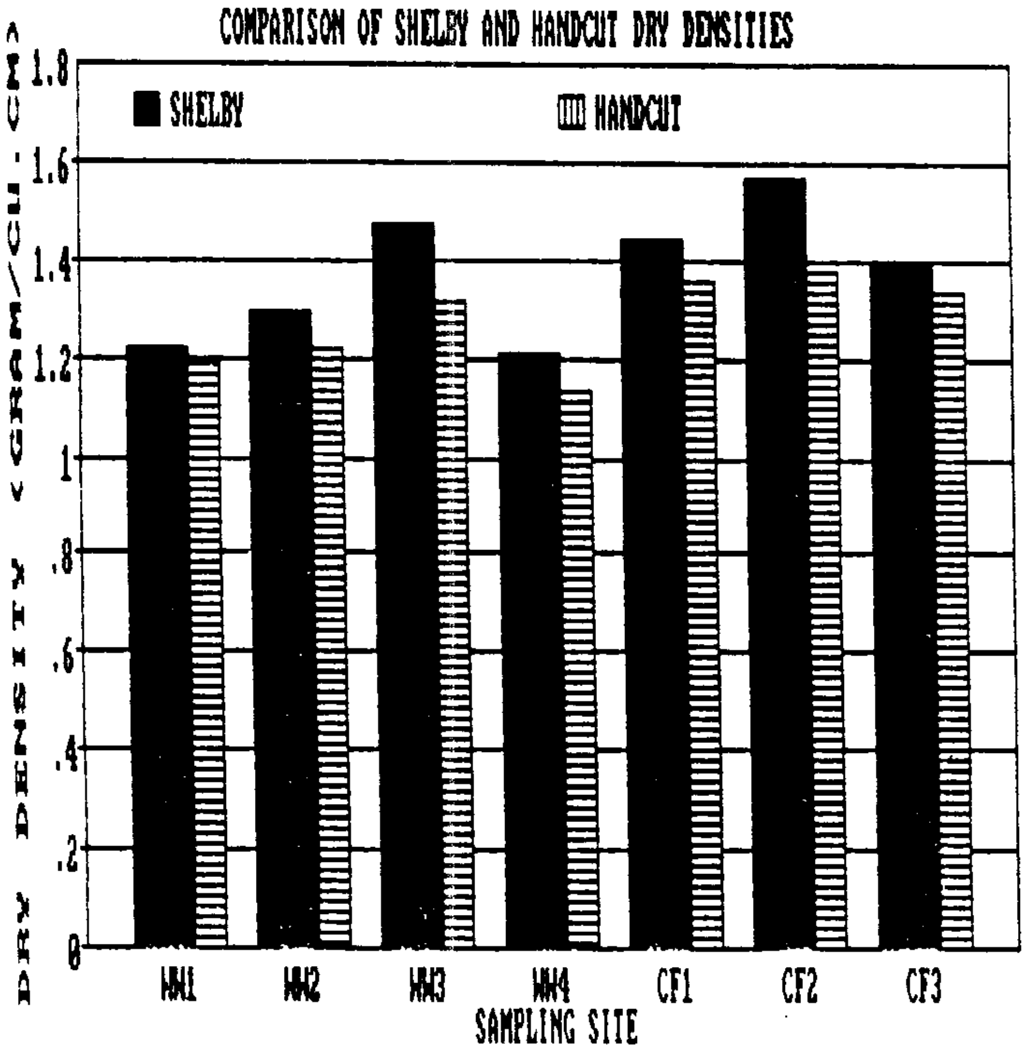


Figure 7. Bar-Graph of Dry Density vs. Sampling Method

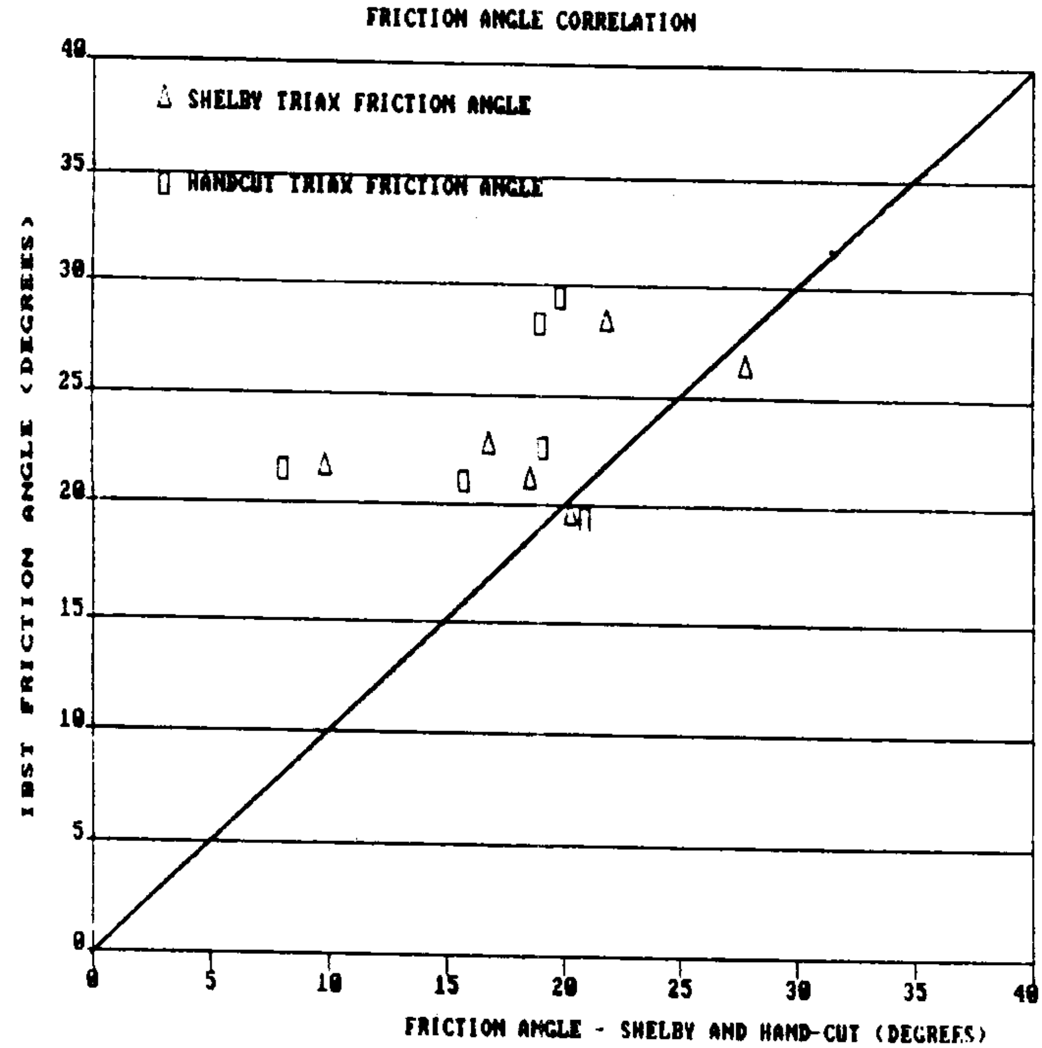


Figure 3· Friction Angle Comparison: IBST, Shelby, Handcut

Shelby and hand-cut friction angle for each site. For example, if the IBST friction angle for site X happened to be the same as the hand-cut friction angle for site X the point would plot on the 45 degree diagonal line on the graph. If the IBST friction angle was greater (less) than the hand-cut friction angle the point would plot above (below) the 45 degree diagonal.

A hypothesis is that the generally larger friction angle (from 1 to 10 degrees) of the IBST is a result of the anisotropic consolidation during the compression phase of the test. The UCU triaxial test differs from the IBST in that the test specimen is subjected to isotropic consolidation and triaxial shear. The structure of loess is probably very sensitive to the method of consolidation. The loose nature of the structure, bound together by strong capillary induced cohesion is more resistant to particle rearrangement under isotropic consolidation than under anisotropic consolidation. The anisotropic consolidation inherent in the IBST allows the silt grains to break down the particle bond creating more grain-to-grain contact during shear resulting in a higher friction angle than the conventional triaxial UCU test.

Some of the ways in which the above mentioned factors control densification are listed as follows:

1. Relative density and structure are related factors in that a loessial soil with a low relative density will likely have an extremely loose open structure. The same soil could attain a higher relative density if it was saturated at some time in its past, which may result in either collapse or subsidence (Larionov, 1965, Kane, 1968). A soil with a high relative density will exhibit less volume change during Shelby tube sampling than a low relative density sample if all other conditions remain equal.
2. A high clay content in a "dryer" soil will enable the soil to resist densification because of the high capillary induced negative pore-water pressures. A high clay content in a near-saturated loessial soil also enables a soil to resist densification. In a clayey loess soil the low permeability causes the Shelby tube induced stress to be transferred to pore-water pressure resulting in minimal changes in effective stress and hence, minimal volume change.
3. Silty loess in an arid climate is often partially cemented with calcite which strengthens the soil structure thereby increasing resistance to Shelby tube induced volume change.

4. Experience shows that poor sampling technique can cause significant densifying of a test specimen. Shelby tubes should be sharpened prior to being pushed. A Shelby tube should be steadily pushed in without oscillation. Special care should be taken so as not to "over-push" the tube. When the soil is near saturation the Shelby tube should be withdrawn very slowly to minimize borehole vacuum which can create tensile fractures in the test specimens.
5. The Shelby tube should be cut in lengths approximately three inches longer than the triaxial specimen so that the ends of the specimen can be trimmed. After a Shelby tube is cut (usually with a pipe cutter) the resulting burr should be ground off to lessen damage to the specimen during extraction. The membrane should be placed over the outside of the Shelby tube so that it can feed off as the specimen is extracted. This method causes much less sample disturbance than securing one end of the membrane to the Shelby tube and forcing the specimen through the entire length of the membrane.

Friction Angle Correlation - IBST and UCU Triaxial Test

The IBST consistently exhibits a higher friction angle than either the Shelby tube or hand-cut friction angles as shown in Figure 8. In Figure 8, the IBST friction angle for each sampling site is plotted against the corresponding UCU

The break-down of the particle bonds during strength tests is necessary before the peak effective friction angle can be reached (Holtz and Gibbs, 1951, Akiyama, 1964).

Another possible factor contributing to the larger friction angle in the IBST results from the increasing length of the shear plane with each successive stage of the IBST. As the normal stress increases the previous shear plane "heals" (Schmertman, 1976) and failure occurs in the soil along a new slightly longer shear plane. In addition to the longer shear planes at higher normal stresses, the end of the shear head tends to produce bearing failure in the soil above it as it moves upward.

Cohesion Correlation - IBST vs. UCU Triaxial Test

A loessial soil tested with the IBST generally produces a lower cohesion than if the same soil was tested with a UCU triaxial test (Figure 9). The lower cohesion is possibly a result of the anisotropic consolidation as was the higher friction angle. The disturbance of the unique loess structure by anisotropic consolidation may destroy some of the natural cohesion (Schmertman, 1976) and perhaps even reduce the apparent cohesion by altering the position of the clay-coated silt grains such that the capillary tension is reduced.

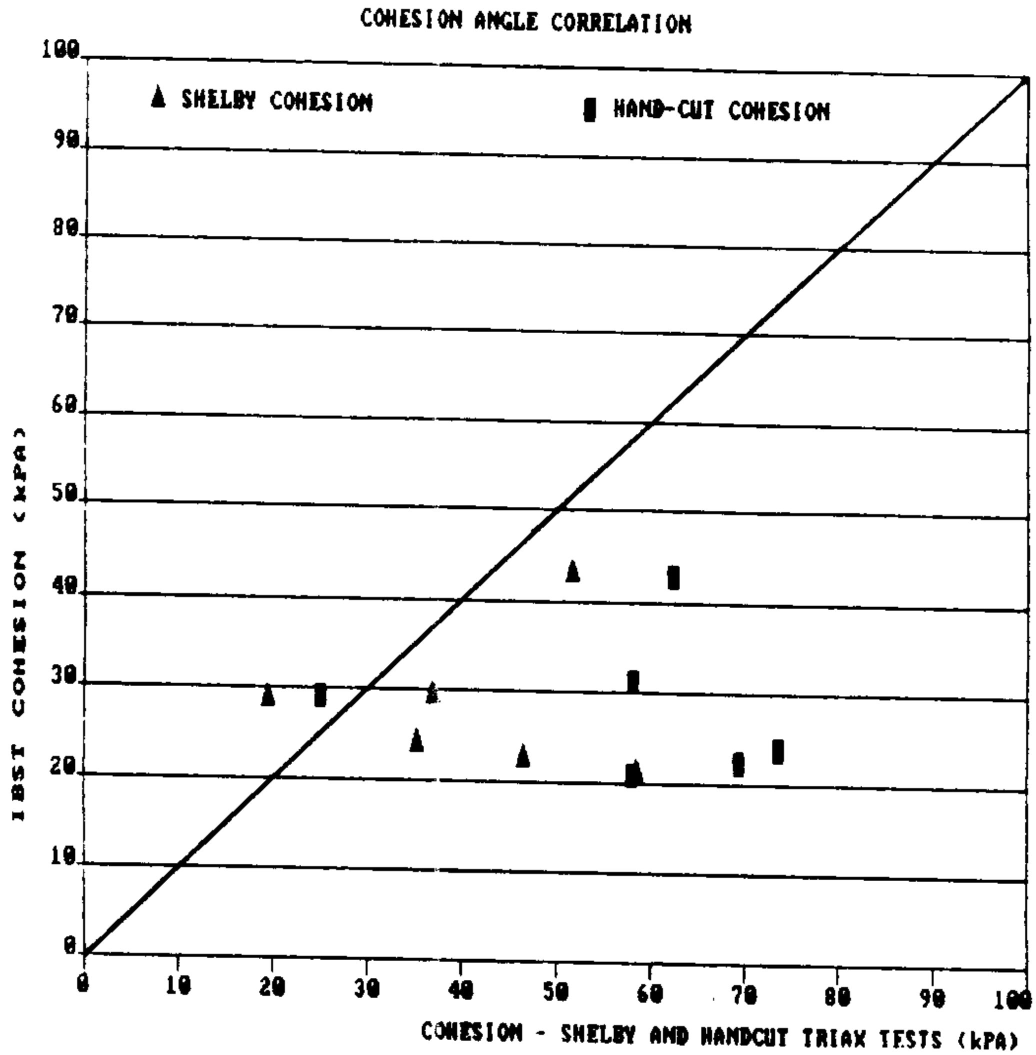


Figure 9. Cohesion Comparison: IBST, Shelby, Handcut

Interpretation of IBST in Partially Saturated Loess

Previous research using the IBST on unsaturated loess considered the tests to be consolidated-drained tests (Lohnes and Handy, 1968). A consolidated-drained test is characterized by the absence of shear strain induced excess pore pressure during the shearing phase of the test. The consolidated-drained (CD) test is usually considered to produce effective strength parameters; however, in unsaturated fine-grained soils such as loess this may not be the case. The existence of capillary induced negative pore-water pressure causes an over-estimation of the true cohesion and an under-estimation of the effective friction angle. An explanation of the effect of negative pore-water pressure is presented in the following example.

The example involves an unsaturated loessial soil which is being tested with an Iowa Borehole Shear Device (IBSD) to determine its strength properties. Since the soil is unsaturated, it has negative pore-water pressures which tend to bind the soil particles together with an apparent cohesion in addition to any conventional cohesion. The shear head is lowered into the borehole and a normal stress is applied to the soil. After consolidation, the soil is sheared to failure. The peak shear stress can be considered to be the effective shear stress at failure. The recorded applied normal stress at failure cannot, however, be considered the effective normal stress at failure. The effective normal stress at failure can be divided into two components, the normal stress applied by the IBSD and the normal stress applied by the negative pore-water pressure. The negative pore-water pressure is unknown and varies with clay and water content. A low water content in conjunction with a high clay content can produce extremely large negative pore-water pressures. Gibbs and Holland (1960) reported that the cohesive strength of low water content loess may be as high as 14.9 psi (103 kPa). The effect of the negative pore-water induced normal stress becomes less as the IBST normal stress is increased in the stage testing.

The lessening of the negative pore-water induced normal stress effect occurs with increasing normal stress because of two factors: first, it becomes proportionally smaller in comparison with the IBSD normal stress and secondly, as the soil is consolidated the degree of saturation increases thereby lowering the negative pore-water pressure. The failure envelope produced by the IBST will exhibit a cohesion consisting of any conventional cohesion and the apparent cohesion. The resulting IBST failure envelope will have a higher cohesion and a lower friction angle than the CU triaxial effective friction angle. The failure envelope will tend to merge with the true effective failure envelope at higher normal stresses and as a result, the IBST friction angle will be smaller than the true effective friction angle.

The relative difference in the IBST and CU triaxial effective friction angles measured on saturated soil is due to the magnitude of the apparent cohesion. Apparent cohesion is a result of both clay and moisture content. A soil which develops a high apparent cohesion will produce a significant difference between the IBST and the CU triaxial test effective friction angle. Conversely, a soil which generates a lower apparent cohesion will produce a smaller difference between the IBST total friction angle and the CU triaxial effective friction angle (Table 3).

Figure 10 presents results for a clayey loess (Site EP) with an IBST apparent cohesion of 3.1 psi (21.5 kPa) and a water and clay content of 19 and 28 percent, respectively. The difference between the IBST and CU triaxial friction angles is relatively small, approximately one degree. Figure 11 presents results for a silty loess (Site WW1) with an IBST apparent cohesion of 4.5 psi (31.1 kPa) and a water and clay content of 14.5 and 7 percent, respectively. The difference between the IBST and CU triaxial friction angles is about five degrees, which is somewhat larger than the more moist, clayey loess and is thought to be due to the larger apparent cohesion developed in the silty loess.

TABLE 3

Comparison - IBST and Effective Triaxial Stresses

Site No.	Test	Effective Normal Stress*		Shear Stress	
		(KPa)	(PSI)	(KPa)	(PSI)
EP	IBST	92	13.3	47	6.8
EP	Triax	50	7.3	47	6.8
EP	IBST	134	19.4	73	10.6
EP	Triax	100	14.5	73	10.6
WW1	IBST	80	11.6	60	8.7
WW1	Triax	50	7.3	60	8.7
WW1	IBST	122	17.7	88	12.8
WW1	Triax	100	14.5	88	12.8

* Note: The difference between the IBST normal stress and the Triax normal stress is caused by negative pore water pressure which results in an additional "unseen" normal stress to the IBST applied normal stress.

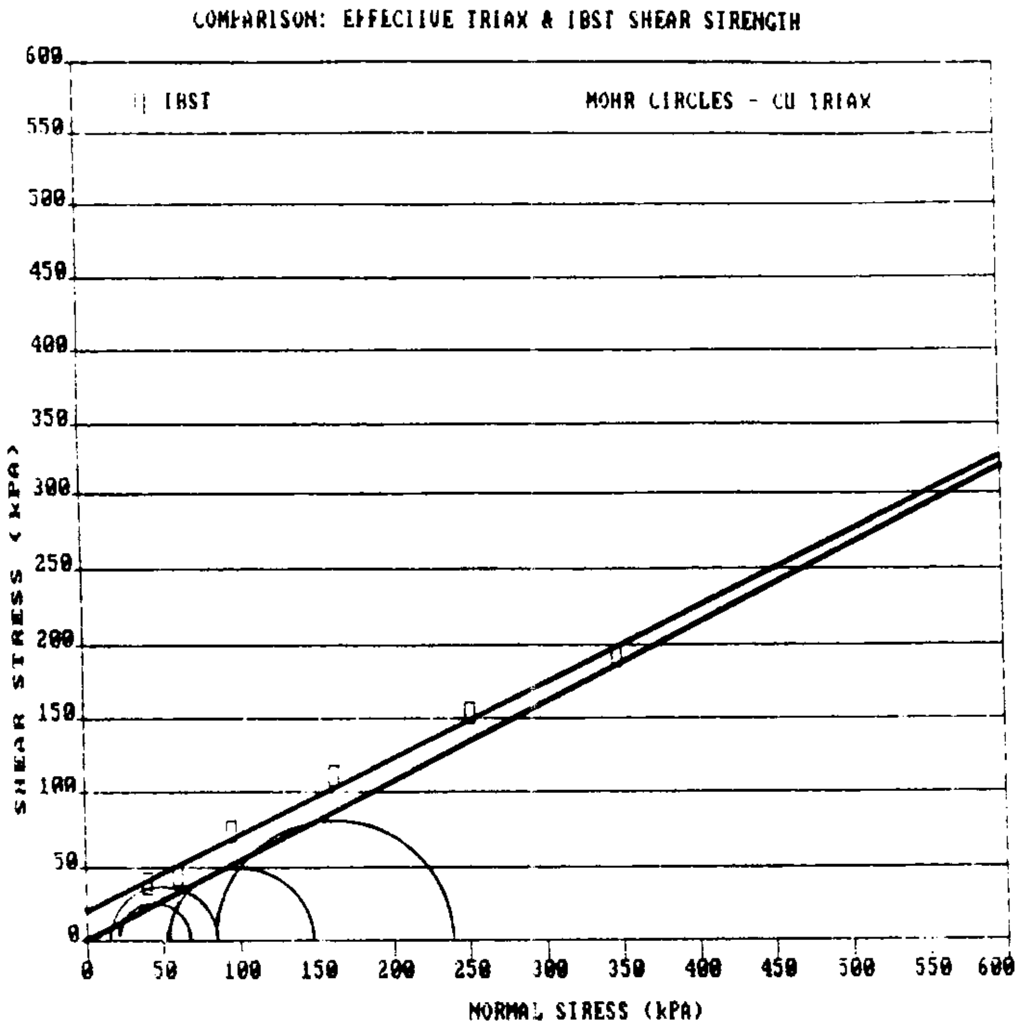


Figure 10. IBST and CU Triaxial Mohr Envelopes in Moist Clayey Loess

SITE NUMBER:	EP		
DRY DENSITY:	1.37 g/cm³		
WATER CONTENT:	19.5 %		
SPECIFIC GRAVITY:	2.74		
CLAY CONTENT:	28 %		
CU TRIAXIAL:	HAND-CUT SPECIMEN		
	COHESION:	0.5 kPA	
	FRICTION ANGLE:	28°	
IBST:	COHESION:	21.5 kPA	
	FRICTION ANGLE:	26.9°	

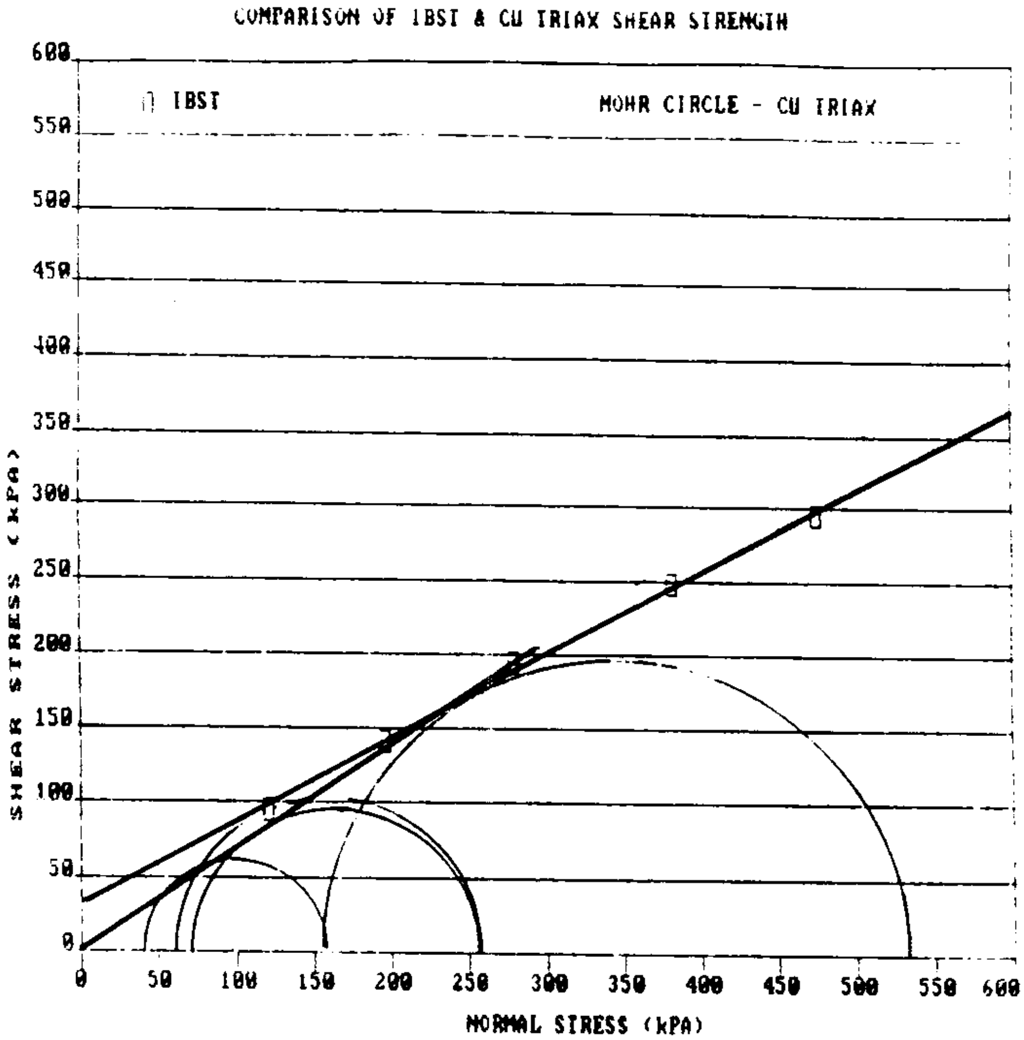


Figure 11. IBST and CU Triaxial Mohr Envelopes in Dry Silty Loess

SITE NUMBER:	WW1	
DRY DENSITY:	1.19 g/cm³	
WATER CONTENT:	14.7 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTEN+T:	7 %	
CU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	2 kPA
	FRICTION ANGLE:	34.5°
IBST:	COHESION:	31 kPA
	FRICTION ANGLE:	29.4°

The orientation of the IBST in homogeneous loessial soils does not appear to be a critical factor. "Horizontal and vertical cuts in loess have shown the same average c and phi values, but considerably more variability in the horizontal direction as would be expected if the material is somewhat stratified" (Lohnes and Handy, 1968).

Apparent Cohesion - Hand-cut vs. Shelby Tube Sampling

Hand-cut specimens yielded higher apparent cohesion relative to the Shelby tube specimens (Figure 12). The hand-cut method produces test specimens which are the less structurally disturbed of the two sampling methods. Obtaining "undisturbed" test specimens is most critical if the loess has a low natural water content. Loessial soils tend to become more friable as the natural water content is lowered. Also at low water contents loessial soils are often accompanied by calcite cementation which helps to bind the soil particles together. Friable calcite cemented loess is especially susceptible to fracturing during the sampling process. Shelby tube sampling compresses the test specimens (Figure 7) during the pushing and extraction process which tends to produce fracturing of the test specimen. If a test specimen becomes fractured it will invariably yield a lower cohesion when tested.

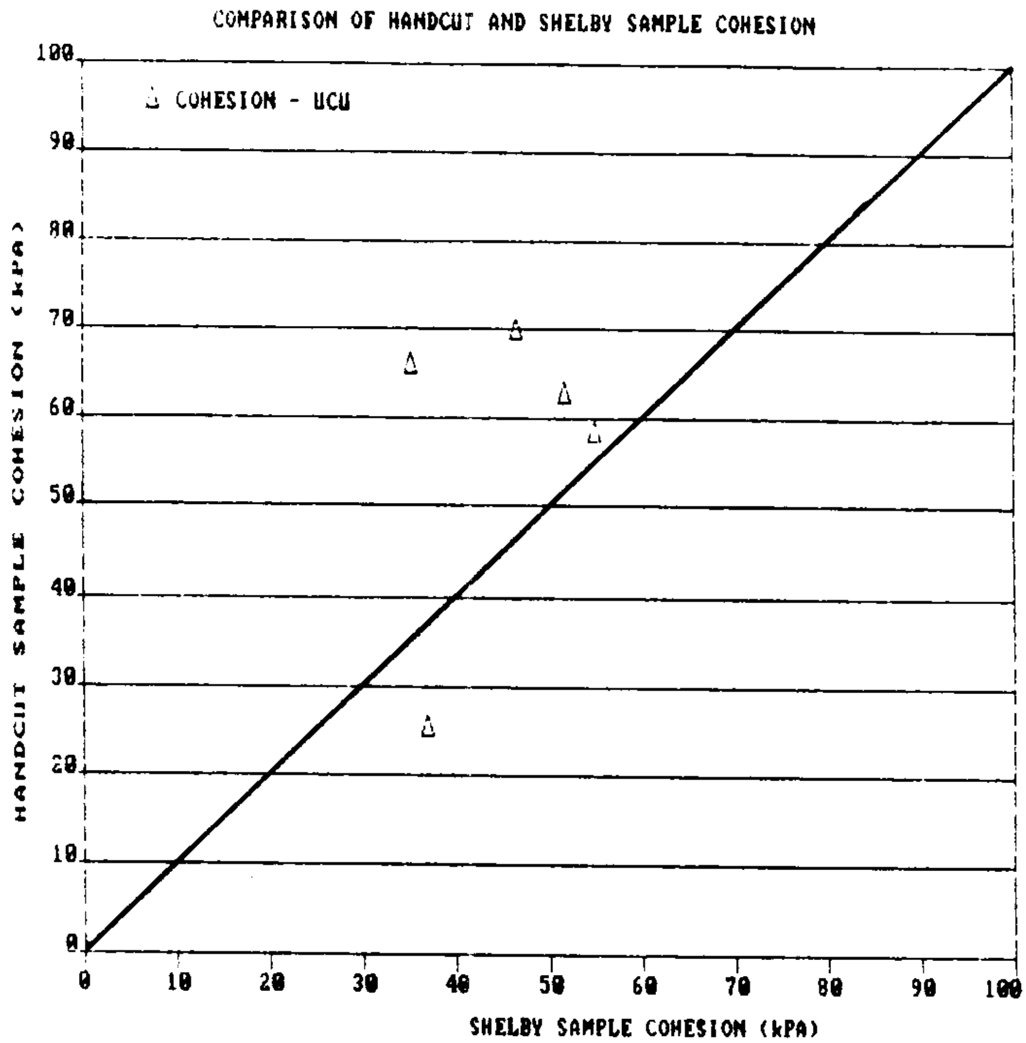


Figure 12. Comparison: Cohesion in Handcut and Shelby Specimens

Cohesion vs. Water Content

Apparent cohesion tends to decrease with increasing water content. An increase in the water content increases the degree of saturation which reduces the capillary suction in the clay and silt particles. An increasing water content also tends to dissolve the natural cementing materials which reduces the cementation component of cohesion. The hand-cut test specimens tend to be the most sensitive to differences in the natural water content (Figure 13). The Shelby and the IBST samples have much of their original conventional cohesion destroyed during the sampling and/or compression phases, and as a result they do not appear to be as sensitive to changes in the natural water content as the hand-cut samples.

Friction Angle vs. Density

As was shown earlier in Figure 7, the Shelby tube test specimens have a higher dry density than the hand-cut specimens due to sample compression during the pushing and extracting process. Figure 14 is a scatter-graph of friction angle vs. dry density. The graph can be divided into silty and clayey loess. The circled group consists of silty loess. In both groups the Shelby test specimens exhibit a higher dry density than the hand-cut specimens for any given friction angle. The silty loess exhibits a lower dry density, a lower water content, and a generally higher friction angle than the clayey loess.

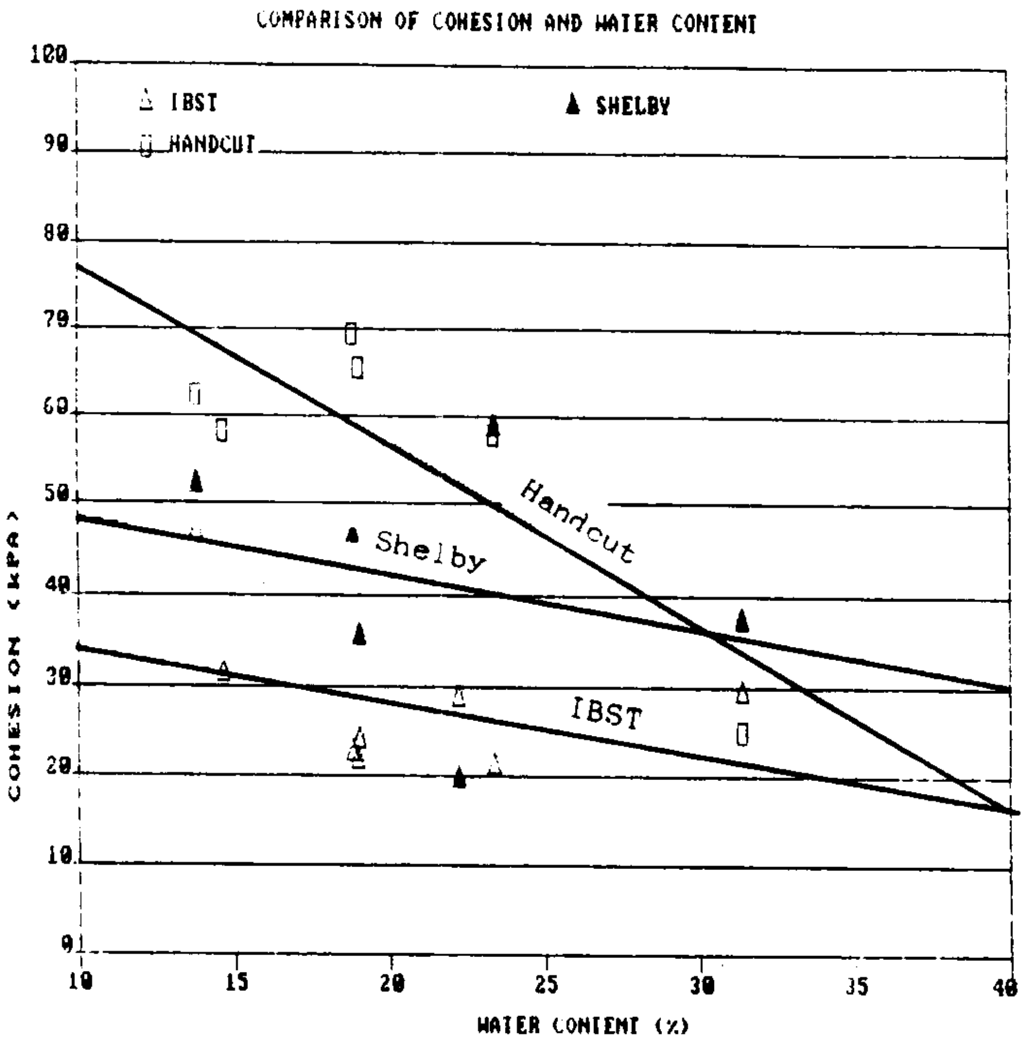


Figure 13. Comparison of Cohesion and Water Content

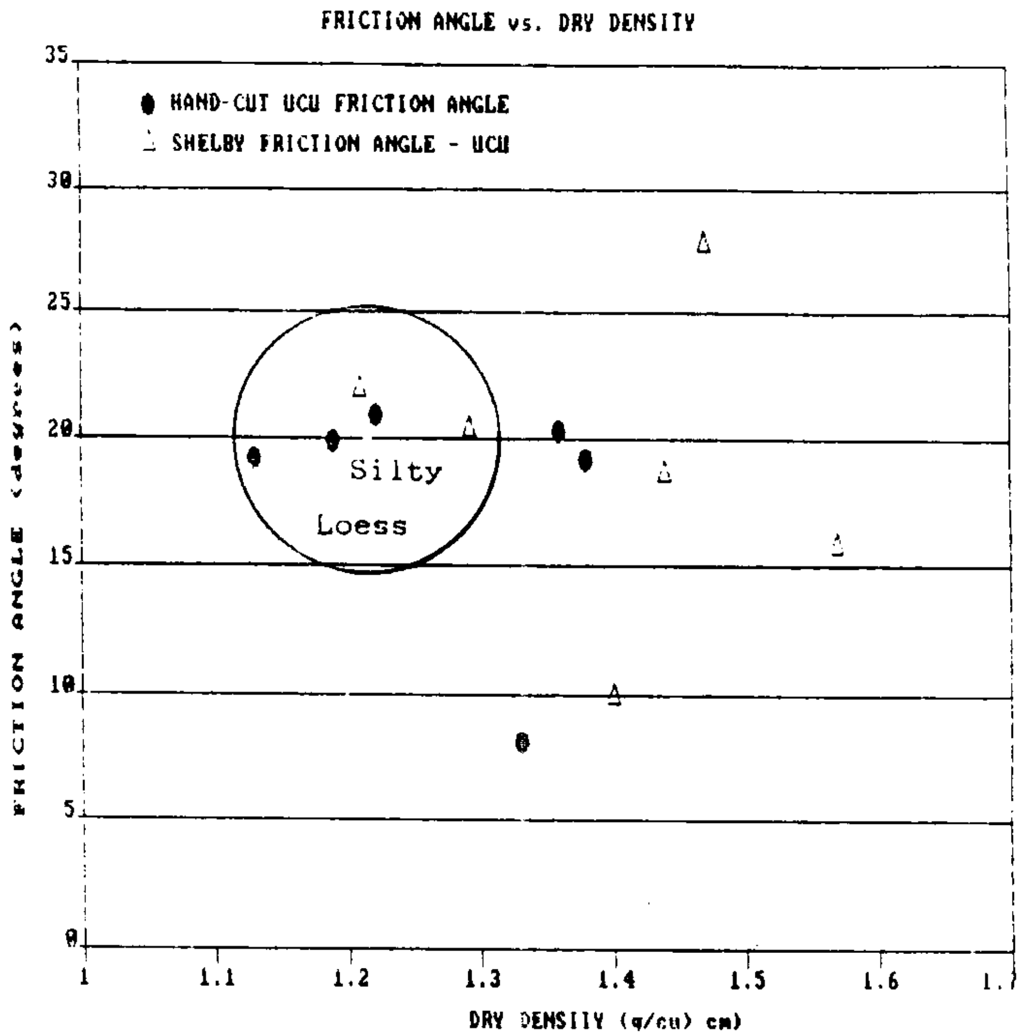


Figure 14. Comparison of Dry Density vs. Total Stress Friction Angle

Advantages of Using the IBST in Loess

The IBST has several definite advantages over other in-situ strength testing methods in loess:

1. The IBST yields a separate determination of cohesion and friction angle in one series of tests.
2. The time required to obtain a failure envelope is approximately one hour, depending on the consolidation time between tests. A series of equivalent laboratory tests would take at least two days when sample collection time is included.
3. The test results can be analyzed and plotted in the field to determine if the test is producing realistic results.
4. The IBST tests a small zone of soil which eliminates the variability which sometimes accompanies laboratory tests where samples are from different boreholes or different locations within a single borehole.
5. The equipment is portable, simple to operate, and the test can be performed by one person.
6. The IBST works well with friable soil such as loess where obtaining undisturbed specimens for the laboratory may be difficult.

Disadvantages of Using the IBST in Loessial Soils

1. Interpretation of the test results may be difficult because of unknown drainage conditions and the presence of capillary induced negative pore-water pressures in unsaturated loess.
2. The IBSD piston, which provides the normal stress to the shear plates may reach maximum expansion before the test is completed. This occurrence is most common in the softer silty loess and in the wetter clayey loess. The test should be repeated at smaller increments of normal stress so that 4 to 5 data points can be achieved before total expansion of the piston is achieved.

PART II

DRAINAGE CONTROL AROUND CUT SLOPES IN LOESS

Introduction

The evaluation of cut slope performance (Higgins et al., 1985) found that water content and grain size distribution have a primary influence on stability, provided adequate drainage is supplied. The study indicates the dry silty loess soils in eastern Washington should perform well in near vertical cuts (1/4:1, H:V) if they are protected by surface drainage structures and low natural moisture contents are maintained. Cuts in clayey loess should perform well if they do not exceed approximately 2.5 to 1 (H:V), are protected by a cover of vegetation, and if concentrated flows from gullies, swallows, etc., are not directed onto the slope face. The examination of failed slopes in Washington indicated that the major performance problems are due to poor or inadequate surface drainage systems for cuts in silty loess (and in a few cases for cuts in clayey loess) and oversteepened slopes for cuts in clayey loess. Therefore, it appears that seemingly minor design elements (such as drainage above the cut) can cause serious problems in loess. This part of the report concentrates on drainage around slope cuts.

Objectives

Originally, one of the objectives of the present study was to plan test sections for WSDOT projects using design criteria suggested in the 1985 report. The test sections would have been constructed by WSDOT on existing projects and would have included experimentation with slope drainage design in order to optimize performance versus cost. However, schedules of new construction in loess did not coincide with the research project. Therefore, this study presents general concepts of drainage design for cut slopes in loess which are recommended for experimentation in future construction projects. These concepts will be incorporated into a design manual to be published soon.

Slope Degradation from Erosion

Observations of slope performance during the 1985 study and the present study suggest that much of the degradation of slopes in road cuts in southeastern Washington loess is due to inadequate surface drainage. Field observations show that when the natural drainage diverts surface runoff around a slope cut, there is little if any damage; however, if the land surface slopes toward the cut slope and surface drainage flows over the face of the cut, significant damage occurs. In some cases, especially in silty loess, if water is concentrated near the top of a cut slope, piping is likely. Piping is a phenomenon where seeping water progressively erodes or washes away soil particles, leaving large voids (pipes) in the soil. As the piping process continues the voids enlarge and work their way backwards from the face of the cut. Eventually the pipes collapse to form erosion gullies which are enlarged by ensuing surface erosion. Animal burrows intersected by the cut slopes have also contributed to this problem. A detailed discussion of the evidence from which these conclusions are made is included in Higgins and others (1985).

As a part of the present study selected slope cuts were periodically observed along SR 195 and SR 12 in eastern Washington. The continued observation verified the conclusions stated in the earlier report. This information is incorporated in the following suggestions.

Special Engineering Problems with Loessial Soils Related to Surface Water Drainage

The designer of structures in eastern Washington loess should be fully aware of the following soil properties and should design drainage structures to avoid these problems.

1. Loess is highly erodible. The flow of water, even at low to moderate volumes and gradients (less than 5%, 5 to 10% respectively) can cause severe erosion.
2. Disturbance of the natural soil structure by grading, heavy equipment operation, farming

activities, etc., makes the soil more susceptible to erosion.

3. Saturation of the soil softens the clay binder and greatly decreases the strength. This can lead to slope failure or accelerated erosion.
4. Silty loess soils are highly susceptible to failure by piping.

Objectives of Drainage Design

Designers of surface water drainage systems around cut slopes in loess should use the following objectives as a basis for design.

1. Prevent water (sheet wash) from flowing over the face of a cut if in silty loess. Prevent concentrate flows from flowing over a cut face in silty and clayey loess.
2. Do not allow water to collect and/or saturate the soil within 10 to 15 ft of the top of the cut face in silty loess. This has been observed as a potential cause of piping.
3. Do not allow water to collect against the toe of the cut in silty or clayey loess. Saturation of the soils in the toe can cause sloughing of the slope.
4. Do not direct flow into unprotected channels (line with vegetation, artificial, or natural materials) in silty or clayey loess. Deep gullies will appear

within a short period of time i.e., 1 to 4 years.

5. Avoid disturbance of soil structure and natural vegetation at the crest of the slope cut as much as possible during and after construction to maintain soil strength and erosion resistance.

Recommended Drainage for Cut Slopes

Based on observations of erosion problems around slope cuts during the 1985 study and the present study, the following suggestions are made concerning the drainage required for cut slopes in loess.

Damage from sheetwash over the face of flattened slopes (2 1/2:1 H:V) in clayey loess has been minor if a vegetation cover is maintained. Therefore, surface water diversion above the cut is not necessary unless gullies, swales, channels, and etc., will concentrate flow onto the slope face. For cuts in silty loess (1/4:1 H:V), drainage ditches or berms are recommended to be placed 10 to 15 ft. behind the top of a cut slope, if the drainage area above the cut is inclined toward the cut. This drainageway should be u-shaped or flat bottomed and be lined by some means to protect it from erosion (figure 15). Also, a gradient must be maintained so that water does not stand and saturate the slope.

The ditch or berm should be constructed prior to opening the cut with as little disturbance to the surrounding vegetation and soil as possible i.e.,

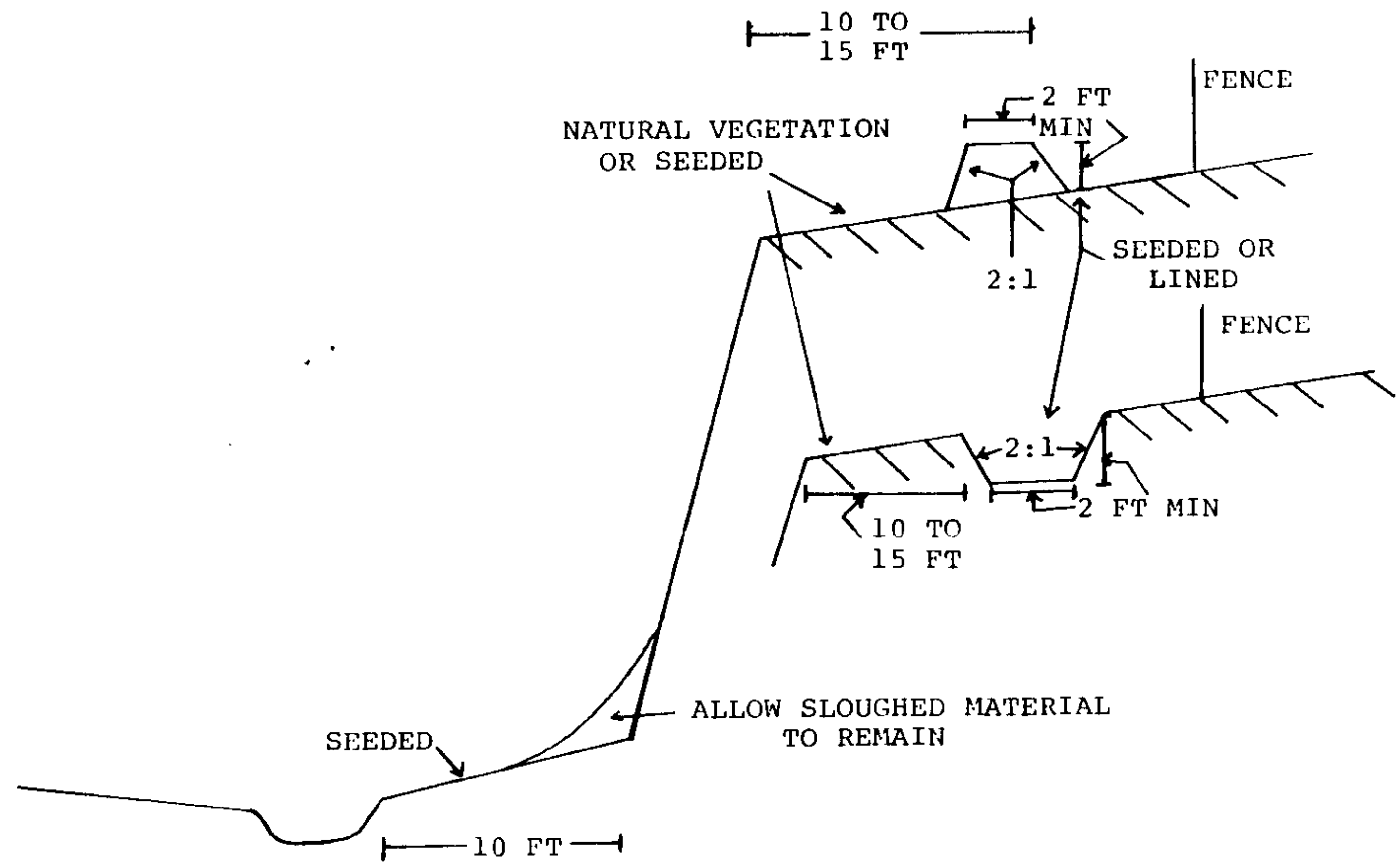


Figure 15. Drainage Above a Cut Slope in Silty Loess.

construction during dry periods. Once the cut is made, construction equipment should be kept away from the crest of the cut.

Drainageways that convey surface water around the sides of cut slopes will often have moderate (5 to 10%) to steep (greater than 10%) gradients. In many cases the required erosion protection in these channels will be more substantial than those at the head of cuts.

If natural drainage channels are truncated by a cut, the drainage system should be adequate to transmit the flow around (may require considerable ROW) or over the cut face in lined channels or structures. Direct flow over the cut face must be avoided. All of the drainage structures should be located in a fenced ROW for protection, and the area should be seeded or have the natural vegetation preserved to maintain the soil stucture and strength. Access by farm equipment would soon damage or distroy the drainage system and protective cover.

Toe drainage should be accomplished with ditches (u-shaped or flat bottomed) located approximately 10 ft. away from the toe of the slope. The ground slope between the toe of the slope and ditch should be gently inclined toward the ditch (recommended slopes between 4:1 and 5:1 H:V). Any material that spalls downslope between the toe and the ditch should be left in place to protect the toe.

General Design Schemes for Surface Drainage

Presented below are drainage design concepts that have been formulated based on the information presented above and the knowledge of the special engineering properties of loess. The authors suggest that these concepts be considered when formulating drainage designs for new construction in loess.

Drainageway Above Head of Cut Slope in Silty Loess

Generally, a ditch or berm above the head of a cut slope will have a low (0 to 5%) gradient and flows could be expected to be low in volume and velocity unless a drainage channel or gully is intersected. In this case, a flat bottomed, seeded drainageway should be adequate (assuming that climatic conditions allow a fairly thick vegetative cover to be developed). A mulch or geotextile mat or mesh should be applied to protect the seed. In areas of low rainfall where it is doubtful that a vegetative cover can be maintained, a filter fabric covered with crushed rock or coarse sand can be used. The vegetation and/or filter fabric hold the soil particles in place and protect against channel scour and piping. The sizing of the material used to cover the fabric should be chosen on the basis of expected flow velocities and should adequately cover the fabric to protect it from damaging ultra violet rays. The sizing of the filter fabric should follow ASTM filter sizing standards to prevent scour and piping erosion problems in the underlying loess and be strong enough to survive placement of the rock cover. The maximum gradient at which vegetation (grasses) will provide adequate erosion protection is unknown for these deposits, although a 5% gradient is probably near the upper bound (depending on flow velocities and volumes). WSDOT should experiment in order to optimize this design.

Drainageway Above Cut Slopes in Clayey Loess

Based on observation of performance of the clayey loess slopes, erosion damage by sheetwash over the cut slope is minor if a good vegetation cover is maintained. A drainage structure is necessary only when concentrated flows (gullies, channels, etc.) are directed over the cut face. In this case the drainage design for cuts in silty loess (above) should be followed. Drainage structures over the cut face are discussed below.

Drainageway Around the Sides of Cut Slopes

Drainageways around the sides of cut slopes tend to have moderate (5 to 10%) to high (greater than 10%) gradients, steeper than drainageways above the cut slope. Therefore, these structures may require more erosion protection than for drainageways with low gradients. Cases such as this have caused very deep erosion gullies to be formed in only a few years (Higgins et al., 1985). Four general design schemes are suggested.

a) The drainageway can be lined with filter fabric covered with coarse crushed rock (size dependent on expected flow velocities). This is probably the simplest and cheapest design.

b) The drainage channel can be lined with filter fabric under a gabion blanket. This would accomplish the same task as (a) above, except the gabion structure will allow anchoring of the mat on steep slopes and will hold the individual rocks in place. However, construction of the mat is time consuming.

c) The drainageway can be constructed of a half-round pipe. The pipe would have to be keyed into the upper reaches of the channel to prevent erosion failure. Too, the pipe would have to be placed so that a good seal (compaction) is made between the pipe and soil to prevent erosion along the soil/pipe interface. The compaction activities would tend to disturb (and weaken) the surrounding soil structure. Pipe joints would require a tight seal and seepage collars would be required to prevent leakage and possible piping.

d) Drainage channels can be lined with asphalt or concrete. This approach has been used successfully in Missouri and Illinois; however, it is expensive. Leakage along joints can allow water to seep along the concrete or asphalt/soil interface forming pipes and eventual collapse.

Drainageway Over the Face of a Cut Slope

If a cut slope truncates a drainage basin, it is difficult to channel the surface water around the cut unless enough right-of-way is acquired to intersect the water substantially up-gradient of the cut. In many cases, this could be 100 to 200 ft or more. Therefore, sometimes a drainage structure is required over the face of the cut.

In the clayey loess area of the state where cuts are 2:1 or flatter (new cuts are recommended to be constructed at 2.5:1 H:V), road cuts often truncate small drainages. Along SR 195 between Colfax and Rosalia many small drainages are truncated by slope cuts, and gully erosion is common during large runoff events (generally in the spring). Some are 2 to 3 ft deep after only one runoff event. Two types of drainage structures can be observed along this section of highway. One appears to be old and the other type has been installed for only a short period of time. The older structure is a rock and mortar lined ditch over the face of a cut slope. The structure has partially collapsed into a void eroded underneath. This is the type of failure (piping) that an asphalt or concrete structure would be susceptible to in loess. Any leakage could allow flow along the interface of the structure and soil which ultimately could result in piping and collapse of the structure.

The newer drainage structure consists of a gabion blanket or mat placed in a shallow u-shaped drainage ditch. The mat has prevented deep gullies from being formed by what appears to be some substantial flows during the spring of 1986. However, after just one spring of service many of the gabion mats showed signs of erosion of fines from underneath. Over several years it is thought that gullies will form under the mats and they will become much less effective.

Three possible design schemes for drainage over the face of a 2.5:1 or flatter cut slope in clayey loess are suggested.

a) One of the easiest designs to install would be a variation of WSDOT's gabion mat lined ditch. The ditch over the cut slope face should be flat bottomed and lined with a filter fabric, covered with a gabion mat or coarse rock. The filter fabric should be selected according to the grain size of the underlying soil to prevent erosion or piping under the mat or rock. The mat or rock cover will provide protection for the filter fabric from UV light and will anchor it in place during high flows. Also, the rock and mat blend with the surrounding soil and vegetation.

b) Drainage over a slope face can be accomplished with a half-round pipe. The pipe would need to be keyed into the drainageway above the cut slope to prevent washout of the pipe. The same requirements and disadvantages for placement of the half-round listed above apply in this case.

c) An asphalt or concrete lined drainageway is feasible, but the problems listed above must be considered.

Slope cuts in silty loessial soils of eastern Washington are usually cut near vertical (1/4:1 H:V). Also, silty loess is more susceptable to damage by erosion (scour and piping) than the clayey loess. Therefore, truncation of a drainage by a near vertical cut in silty loess presents some special design problems.

Two drainage schemes are suggested in this case.

a) Intercept the drainage high enough above the cut so that it can be channeled around the side of the cut face. In some cases the natural slope (above the cut slope) may be gentle enough that little right-of-way is required to accomplish this design; however, more often this is not the case and 100 to 200 ft or more of ROW may be required.

b) Water can be routed over the slope face in a pipe which is connected to a collection area and sediment trap above the head of the slope cut. A similar pipe drain has been installed on a vertical cut east of Dayton, Washington on SR 12. The head of the slope was excavated to install the pipe. Water has seeped along the pipe/soil interface and eroded a gully in the slope face. Therefore, if this type of drainage structure is installed, the pipe should be mounted above the ground surface, where possible, to avoid seepage along the outside of the pipe. Where the pipe is placed in an excavation, it should be fitted with seepage collars and the soil should be compacted around the pipe. Notching of the slope face should be avoided. Also, a splash plate should be installed at the toe of the slope to prevent undercutting and the pipe should be slotted to prevent clogging by ice. This design would be best suited for low to moderate volumes of flow. To avoid some of the above problems, this design scheme is best suited to be combined with a berm drainage system above the cut slope rather than a ditch (figure 16).

Protection of Right-of-Way (ROW)

The drainage structures should be located in a fenced ROW. A vegetation cover should be maintained in the ROW to protect the soil structure (and strength) near the slope crest. Continuation of the present policy, which allows farming activity up to the edge of a cut slope, would rapidly damage or distroy the drainage structures resulting in erosion damage. Also, movement of heavy farm equipment near the crest of a cut tends to disturb the natural soil structure which results in a lower strength, a lower resistance to erosion, and could lead to sudden slope failure along the edge of a near vertical cut. This could present a safety problem for farming activities very near the slope crest. Hence, a fenced ROW serves as a protective device for the drainage system as well as a safety measure. For near vertical cuts where drainage structures are not needed, a fenced ROW is also recommended. This will act as a buffer zone to protect the soils and vegetation from disturbance and help maintain the strength of the slope crest for the same reasons as stated above. Cuts in clayey

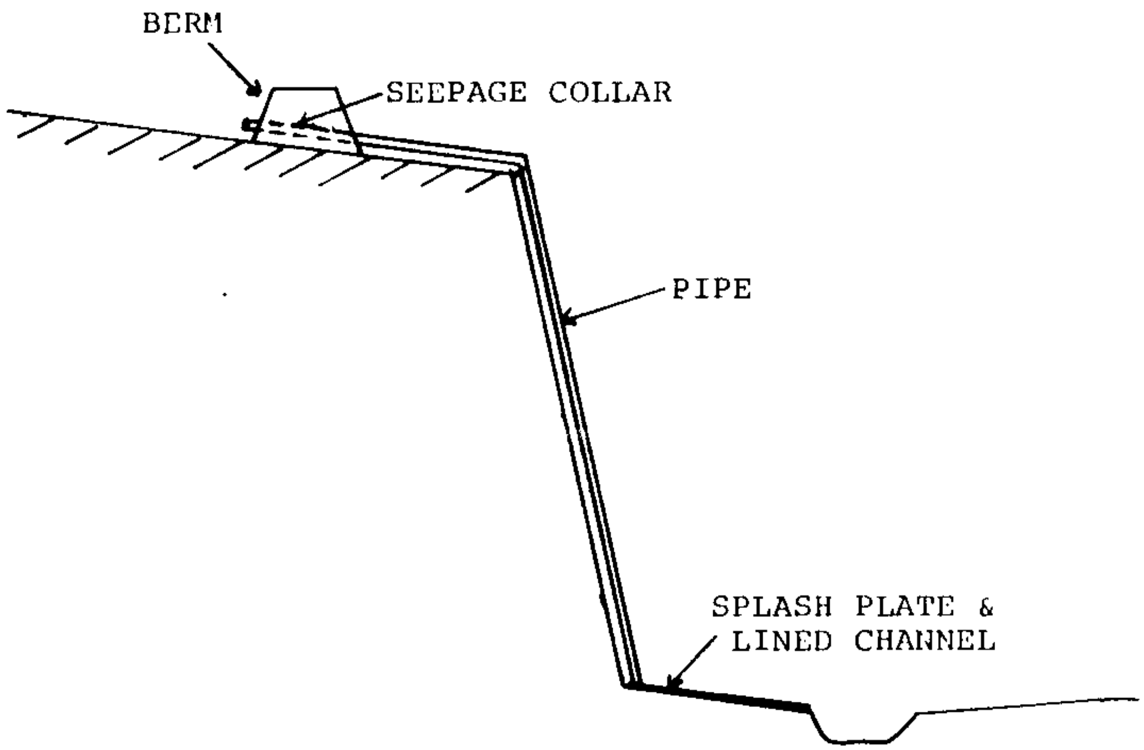


Figure 16. Drainage Over a Cut Face.

loess (2.5:1 H:V) not requiring a drainage structure may not require a protected ROW; although, some minor damage has been observed because of plowing along the slope crest.

Summary Part II

The designer of cut slopes in southeastern Washington loess should be aware of the unique properties of loess soils. Loess is highly erodible by scour and piping. Disturbance of the natural soil structure by construction activities (grading, heavy equipment operation, etc.) makes the soil more susceptible to erosion. Also, an increase in the natural moisture content of the soil softens the clay binder and greatly decreases the strength.

Observations of cut slope performance in southeastern Washington have led to recommendations for drainage structures. If the natural drainage of surface water is away from the top of a cut slope, no drainage system is recommended. For cuts in clayey loess (2.5:1 H:V) with a good cover of vegetation, sheetwash has not caused significant erosion damage on the cut face. Therefore, surface water diversion above the cut is not required unless flow is concentrated in channels, gullies, etc.

For cuts in silty loess (1/4:1 H:V) drainage ditches or berms are recommended to be placed 10 to 15 ft behind the top of a cut slope, if the land area above the cut is inclined toward it. This drainageway should be u-shaped or flat bottomed and be seeded or lined to protect it from erosion. Also, a gradient must be maintained so that water does not pond and saturate the slope.

The ditch or berm should be constructed prior to opening the cut. Once the cut is made, construction equipment should be kept away from the crest of the cut. All drainage structures should be placed within fenced ROW to protect the drainage structures , vegetation cover, and for the safety of equipment operators above the cut slopes.

If natural drainage channels are truncated by a cut slope, the drainage system should be constructed to divert the flow around or over the cut face. These structures may be seeded or lined ditches or berms, half rounds, or pipes.

Toe drainage should be accomplished with ditches (flat bottomed) located approximately 10 ft away from the toe of the slope. Any material that spalls downslope between the toe and ditch should be left in place to protect the toe of the slope.

A fenced and vegetated ROW is recommended above all cut slopes with drainage structures on the crest of the slope. This is also recommended for all near vertical cuts in order to protect the soil structure from disturbance i.e., reduce the potential for damage of the crest of the slope and as a safety measure for farm equipment operators.

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APPENDIX

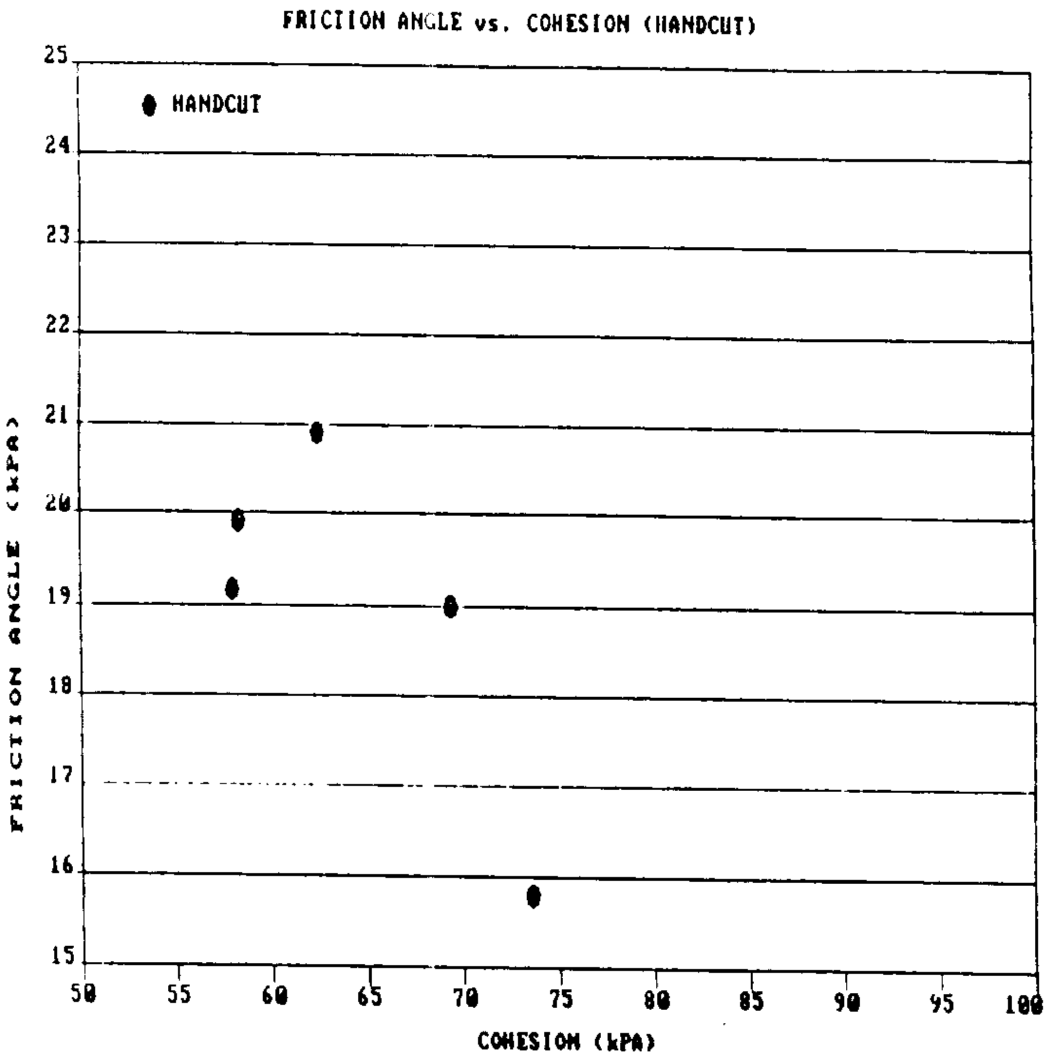

Figure 17. Plot of Friction Angle vs. Cohesion derived from UCU triaxial Hand-cut specimens

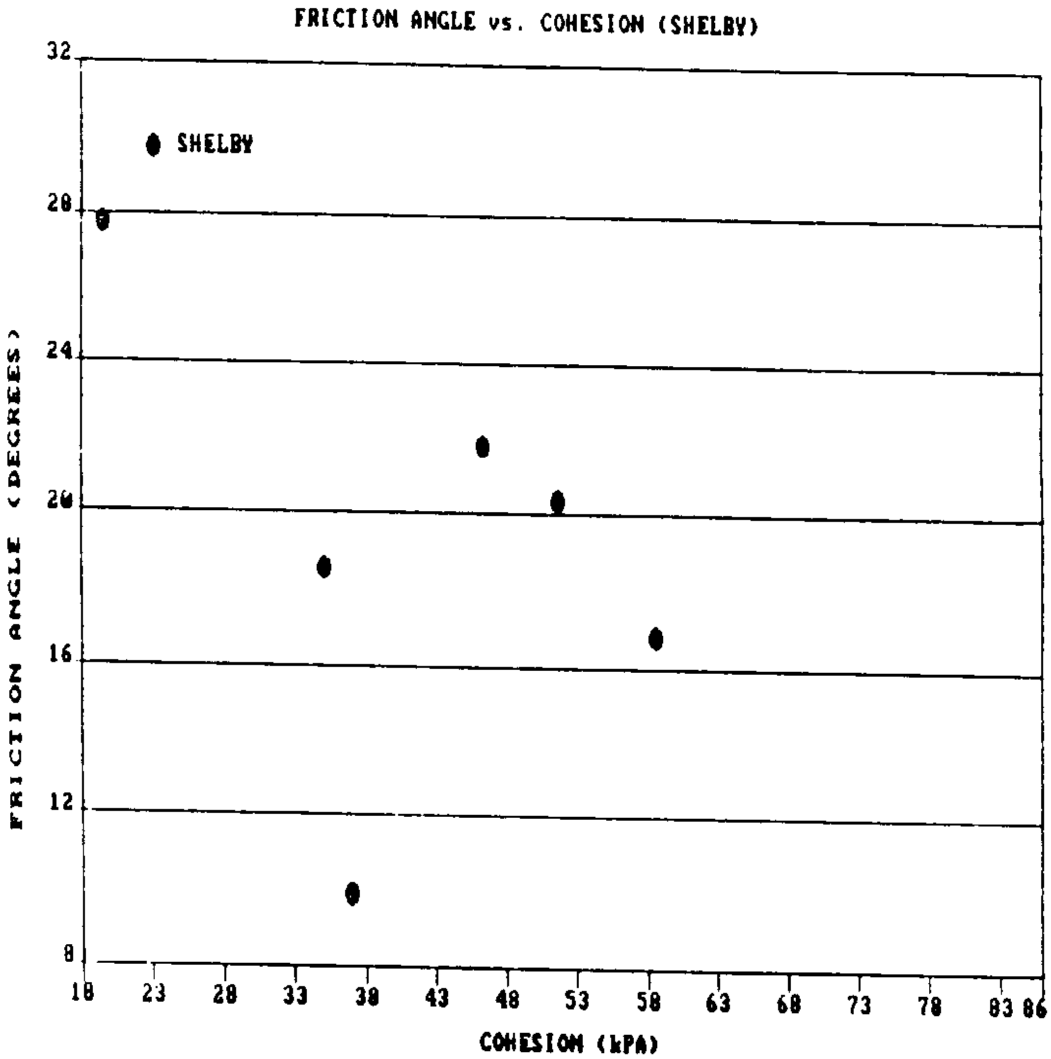

Figure 18. Plot of Friction Angle vs. Cohesion derived from UCU triaxial Shelby specimens

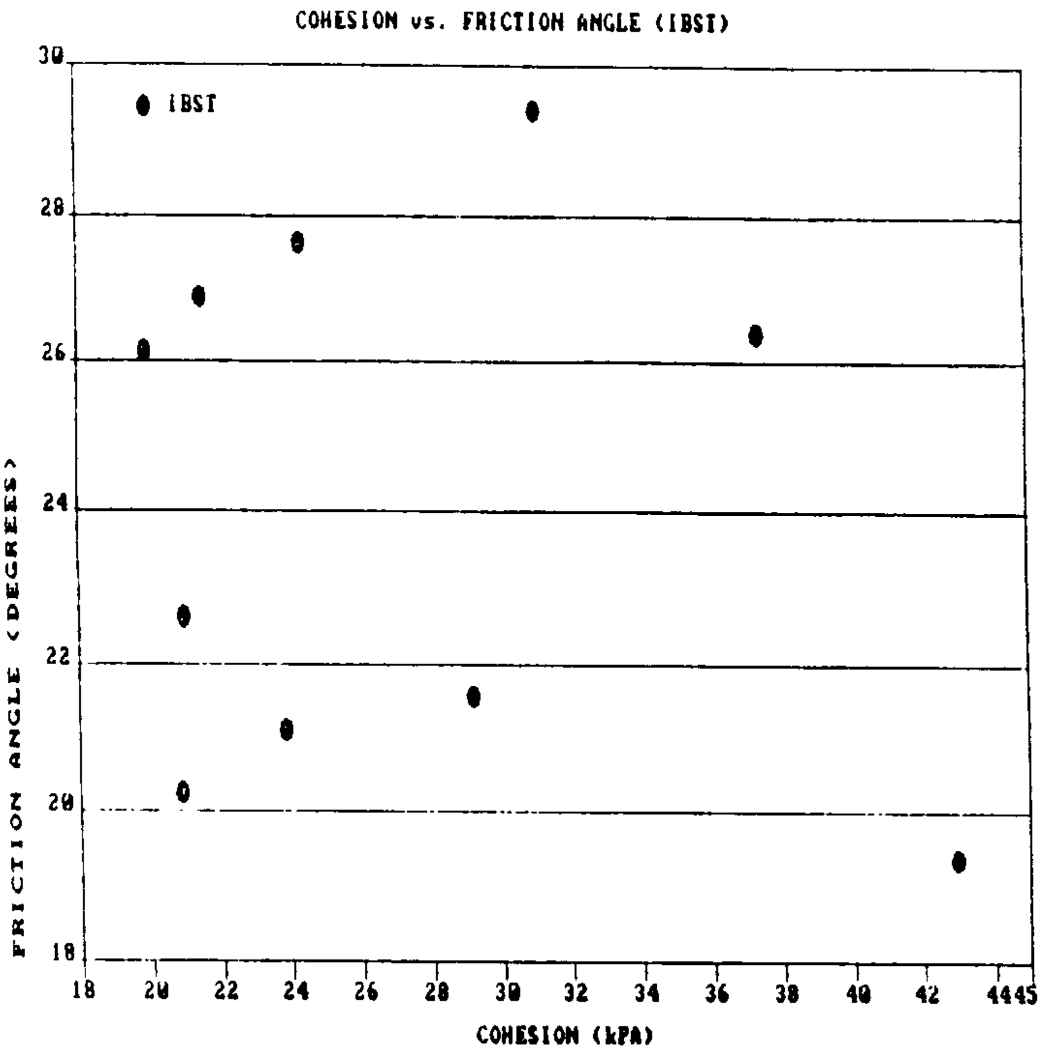

Figure 19. Plot of Friction Angle vs. Cohesion derived from the IBST

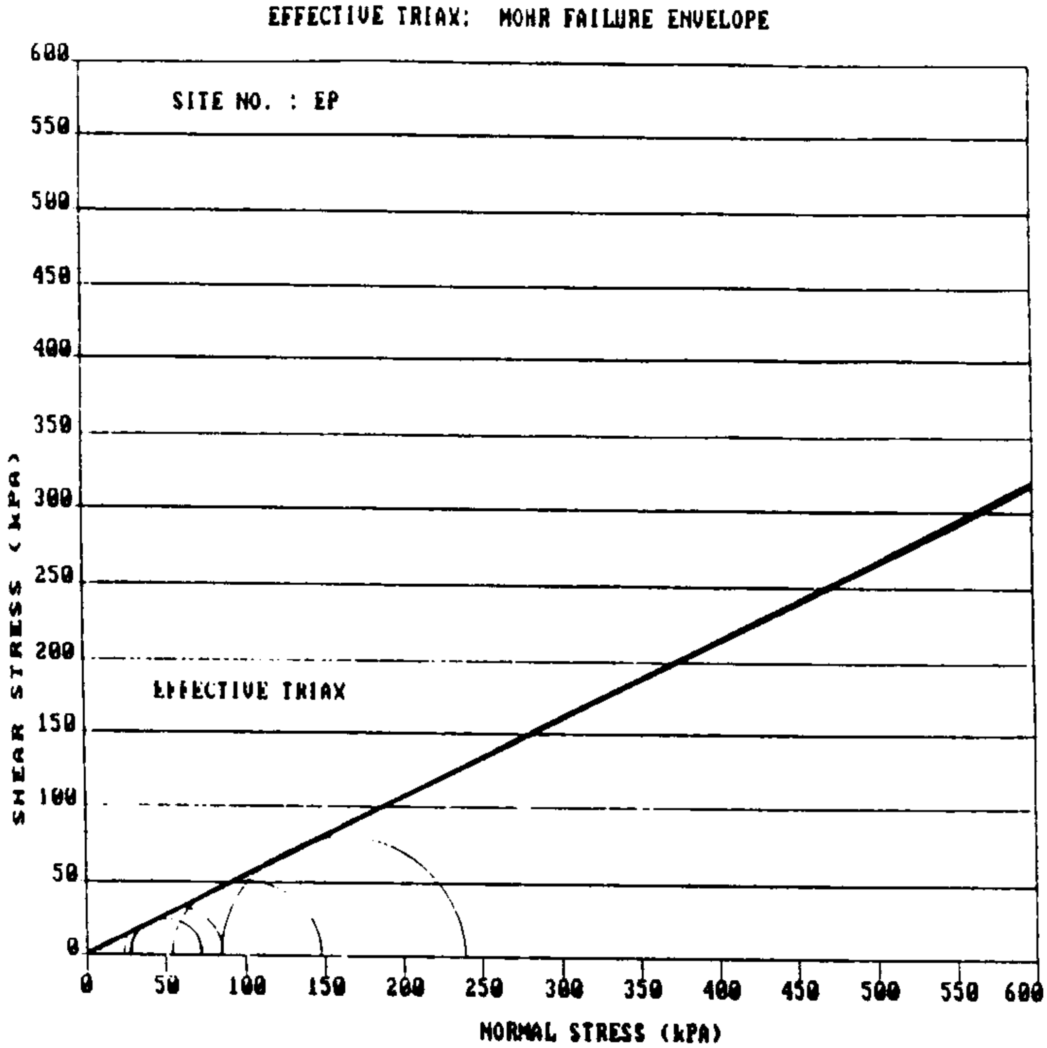

Figure 20. CU Triaxial Mohr Envelope in Moist Clayey Loess

SITE NUMBER:	EP	
DRY DENSITY:	1.37 g/cm³	
WATER CONTENT:	19.5 %	
SPECIFIC GRAVITY:	2.74	
CLAY CONTENT:	28 %	
CU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	0.0 kPA
	FRICTION ANGLE:	28°

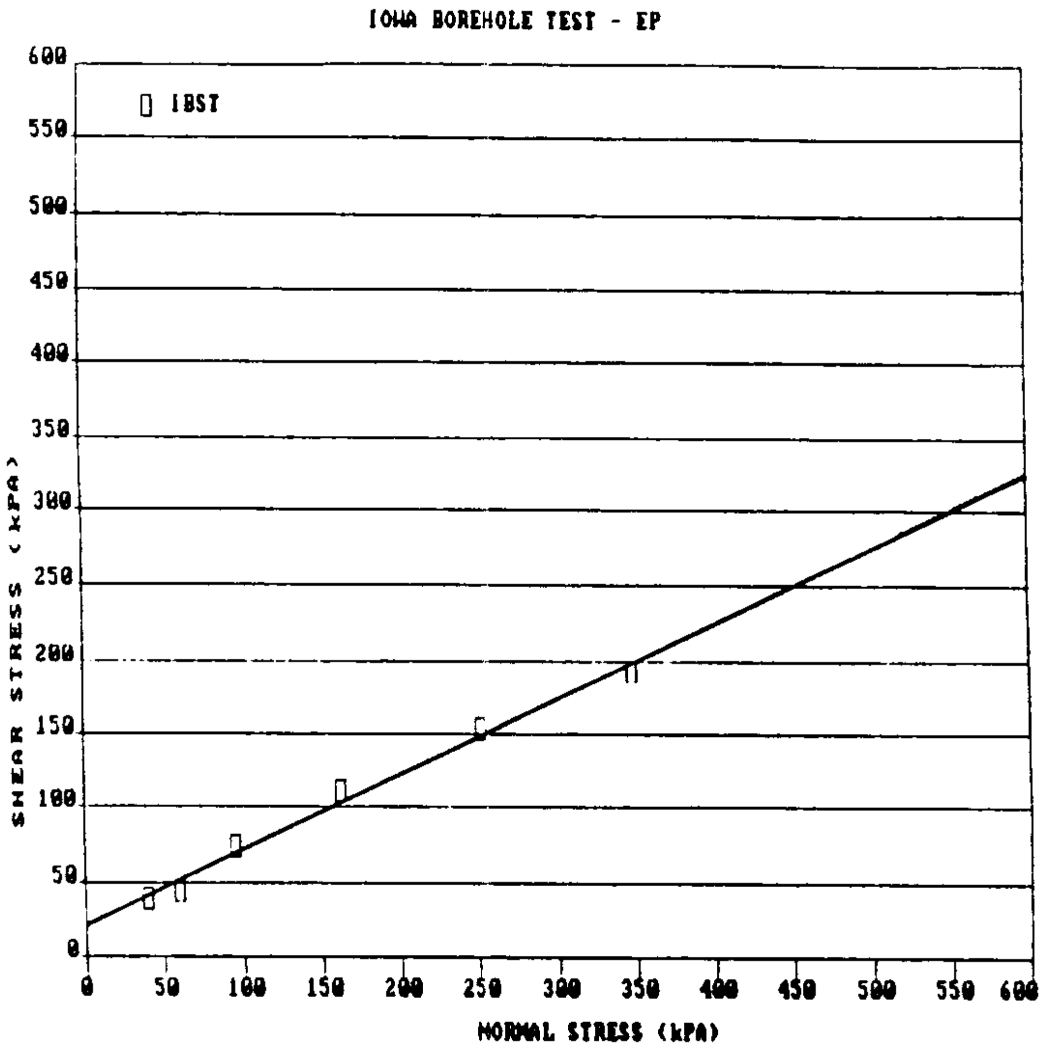

Figure 21. IBST Mohr Envelope in Moist Clayey Loess

SITE NUMBER:	EP	
DRY DENSITY:	1.37 g/cm³	
WATER CONTENT:	19.5 %	
SPECIFIC GRAVITY:	2.74	
CLAY CONTENT:	28 %	
IBST:	COHESION:	21.5 kPA
	FRICTION ANGLE:	26.9°

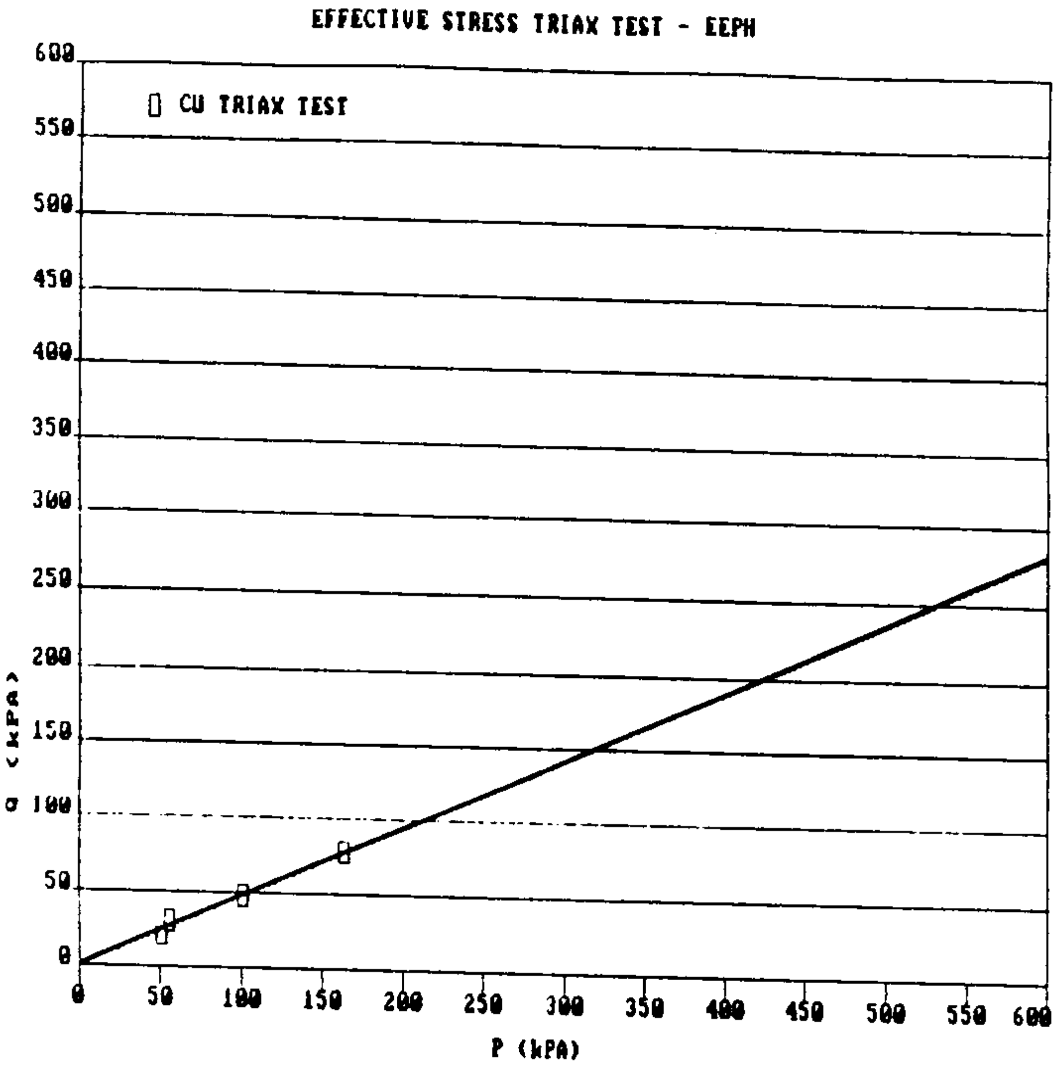

Figure 22. CU Triaxial q vs. p plot in Moist Clayey Loess

SITE NUMBER:	EP	
DRY DENSITY:	1.37 g/cm³	
WATER CONTENT:	19.5 %	
SPECIFIC GRAVITY:	2.74	
CLAY CONTENT:	28 %	
CU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	0.0 kPA
	FRICTION ANGLE:	28°

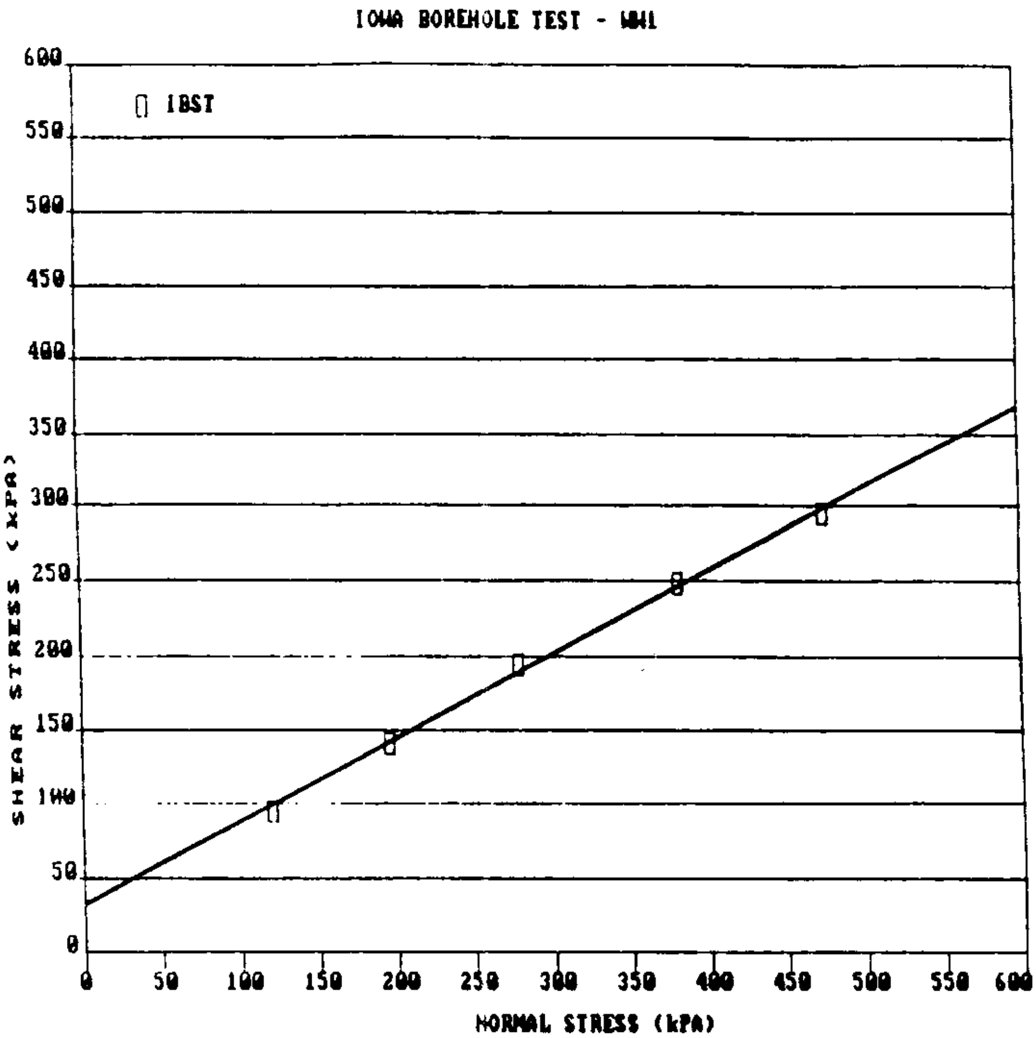

Figure 23. IBST Mohr Envelope in Silty Loess

SITE NUMBER:	WW1	
DRY DENSITY:	1.19 g/cm³	
WATER CONTENT:	14.7 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTENT:	7 %	
IBST:	COHESION:	31.1 kPA
	FRICTION ANGLE:	29.4°

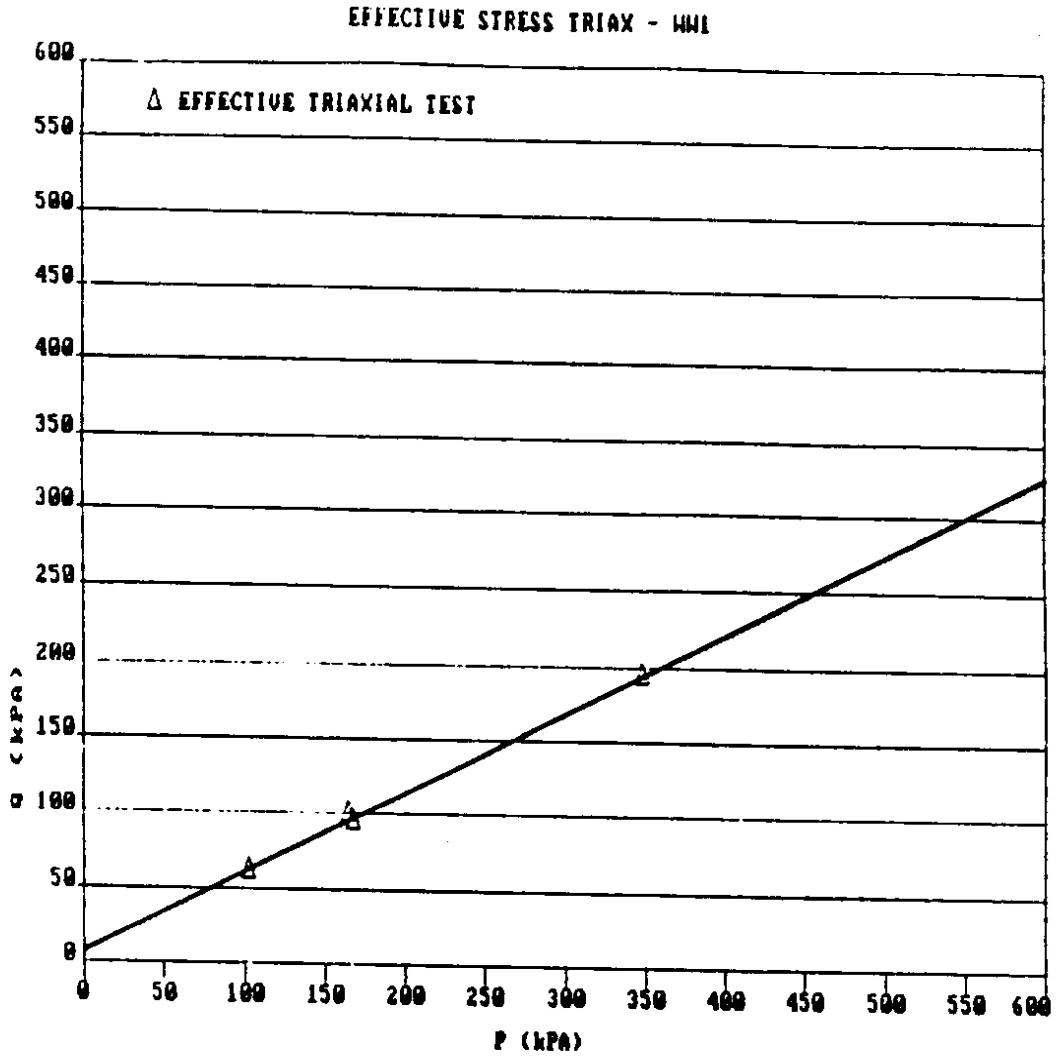

Figure 24. CU Triaxial q vs. p in Silty Loess

SITE NUMBER:	WW1	
DRY DENSITY:	1.19 g/cm³	
WATER CONTENT:	14.7 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTENT:	7 %	
CU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	2.2 kPA
	FRICTION ANGLE:	34.5°

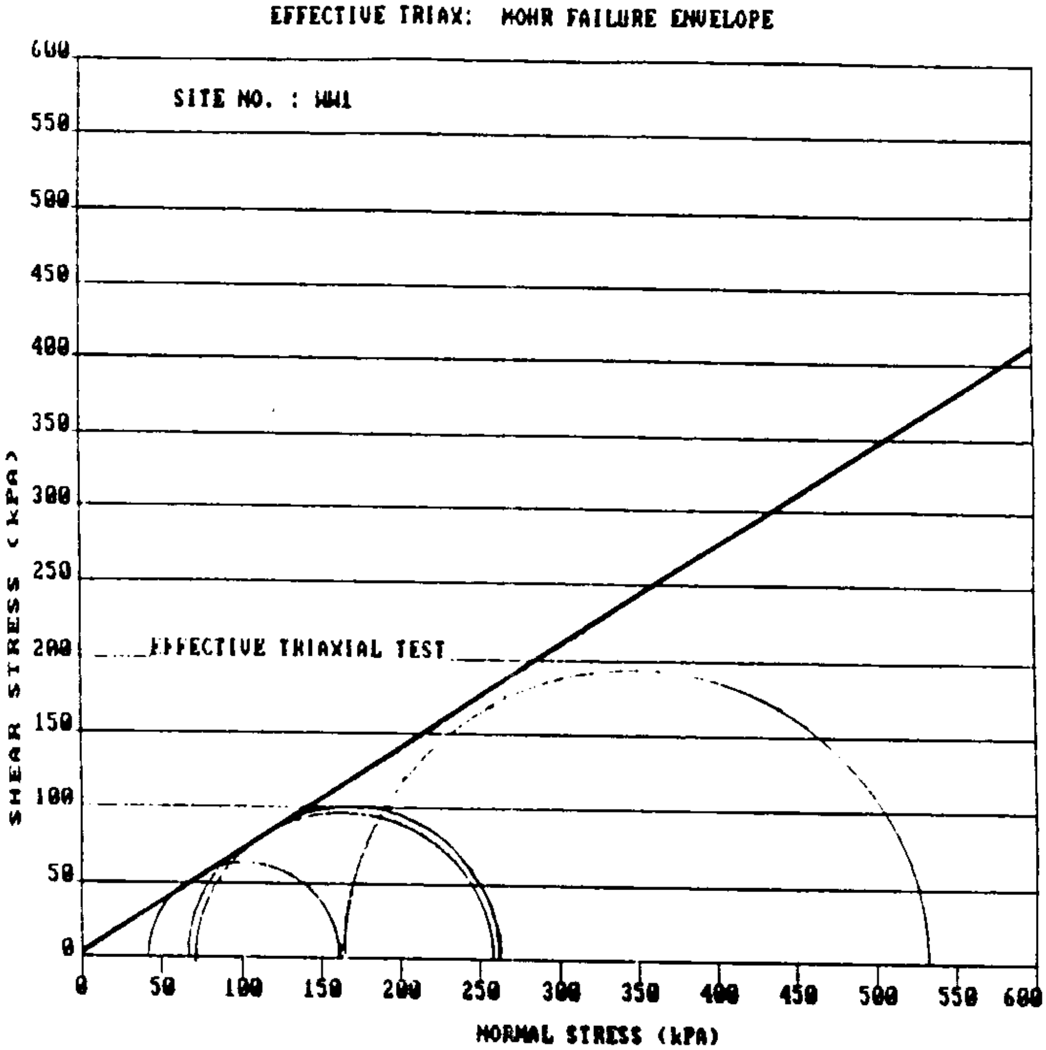

Figure 25. CU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER:	WW1	
DRY DENSITY:	1.19 g/cm^3	
WATER CONTENT:	14.7 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTENT:	7 %	
CU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	2.2 kPA
	FRICTION ANGLE:	34.5°

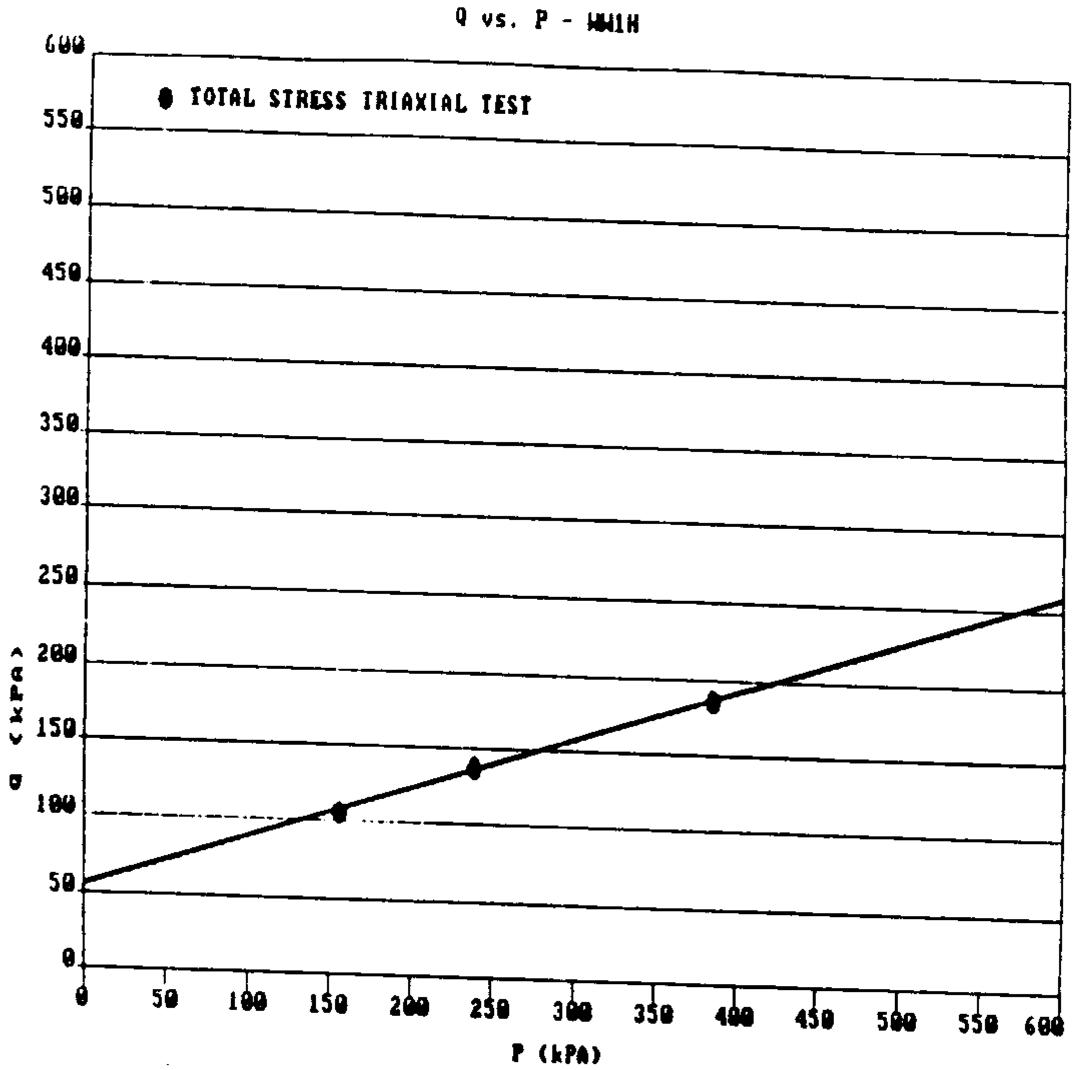

Figure 26. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER:	WW1	
DRY DENSITY:	1.19 g/cm³	
WATER CONTENT:	14.7 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTENT:	7 %	
CU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	58.3 kPA
	FRICTION ANGLE:	19.9°

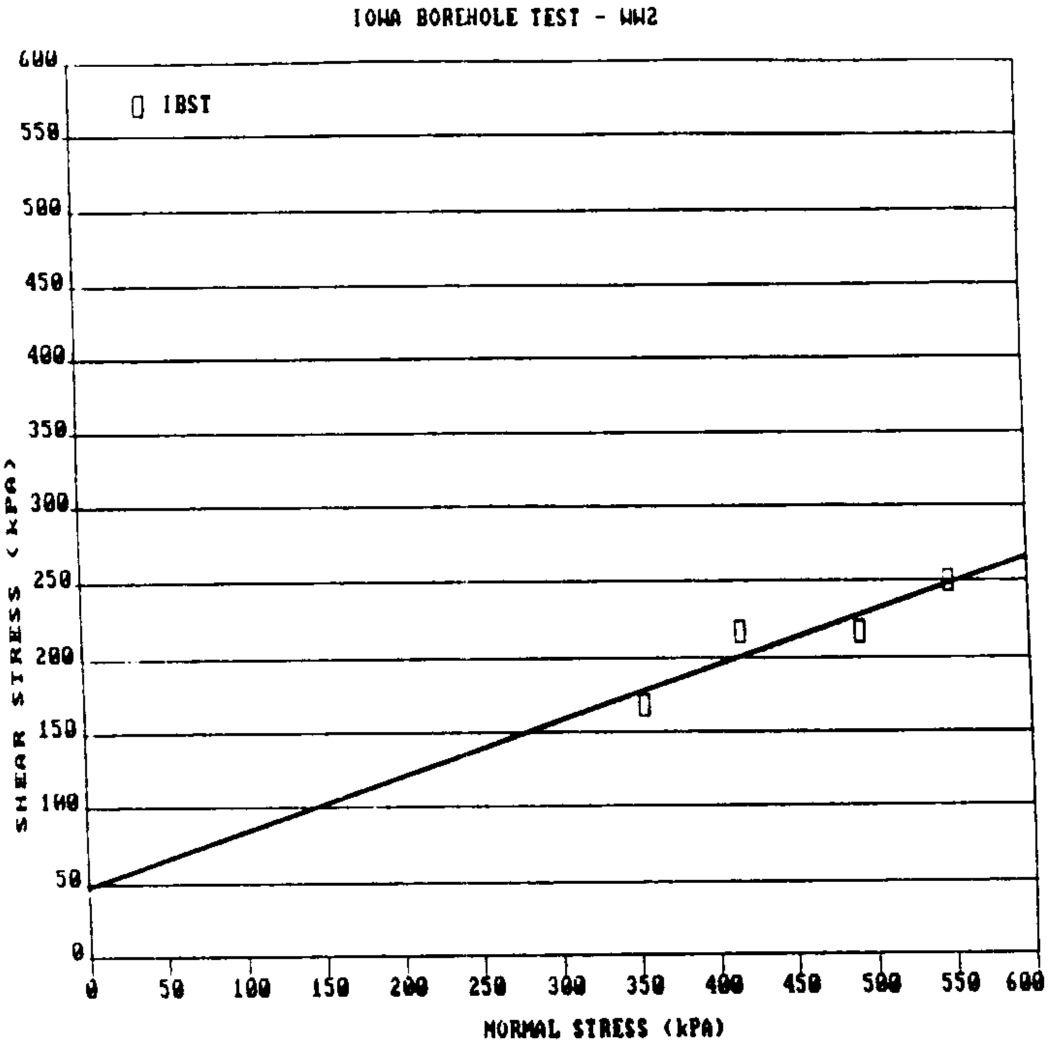

Figure 27. IBST Mohr Envelope in Silty Loess

SITE NUMBER:	WW2	
DRY DENSITY:	1.22 g/cm³	
WATER CONTENT:	13.8 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	8 %	
IBST:	COHESION:	42.9 kPA
	FRICTION ANGLE:	19.4°

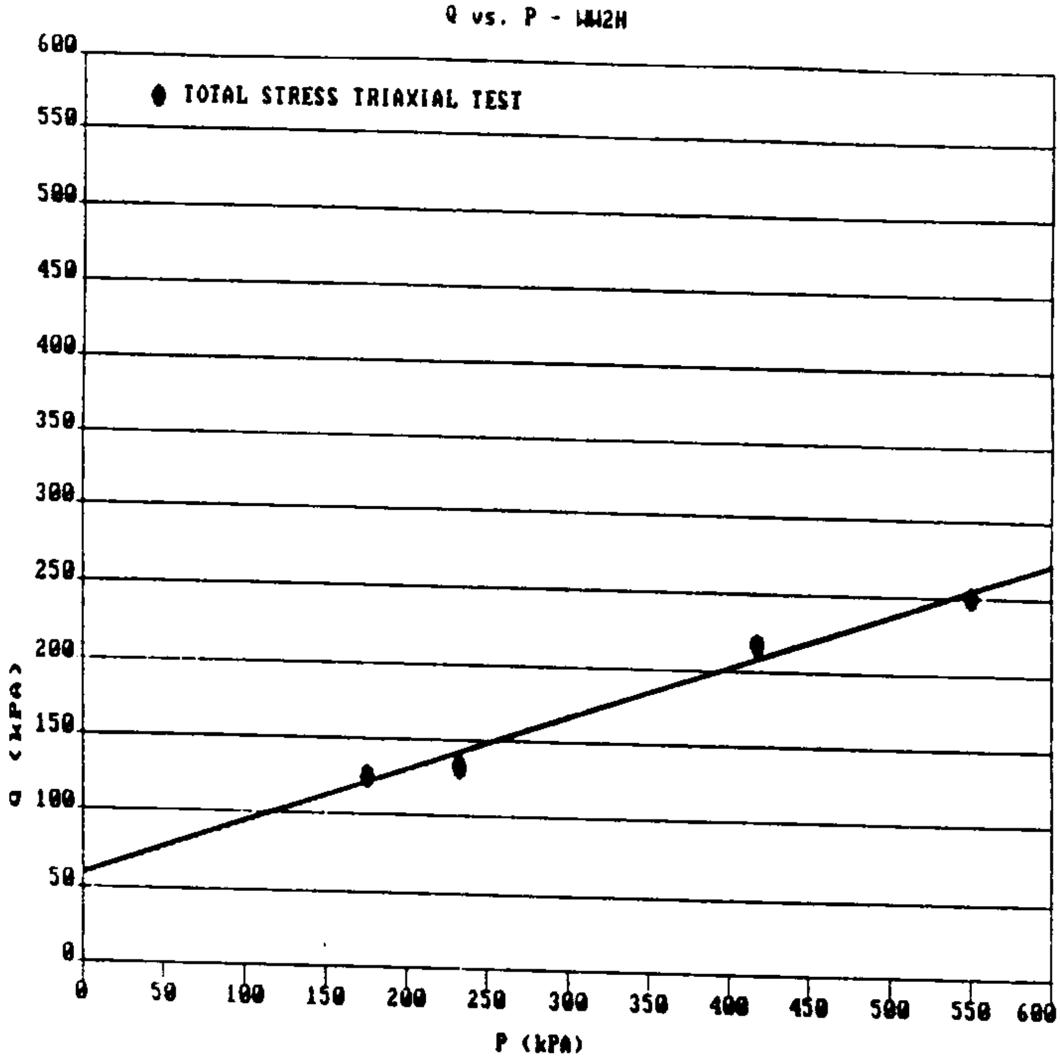

Figure 28. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER:	WW2	
DRY DENSITY:	1.22 g/cm³	
WATER CONTENT:	13.8 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	8 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	62.4 kPA
	FRICTION ANGLE:	20.9°

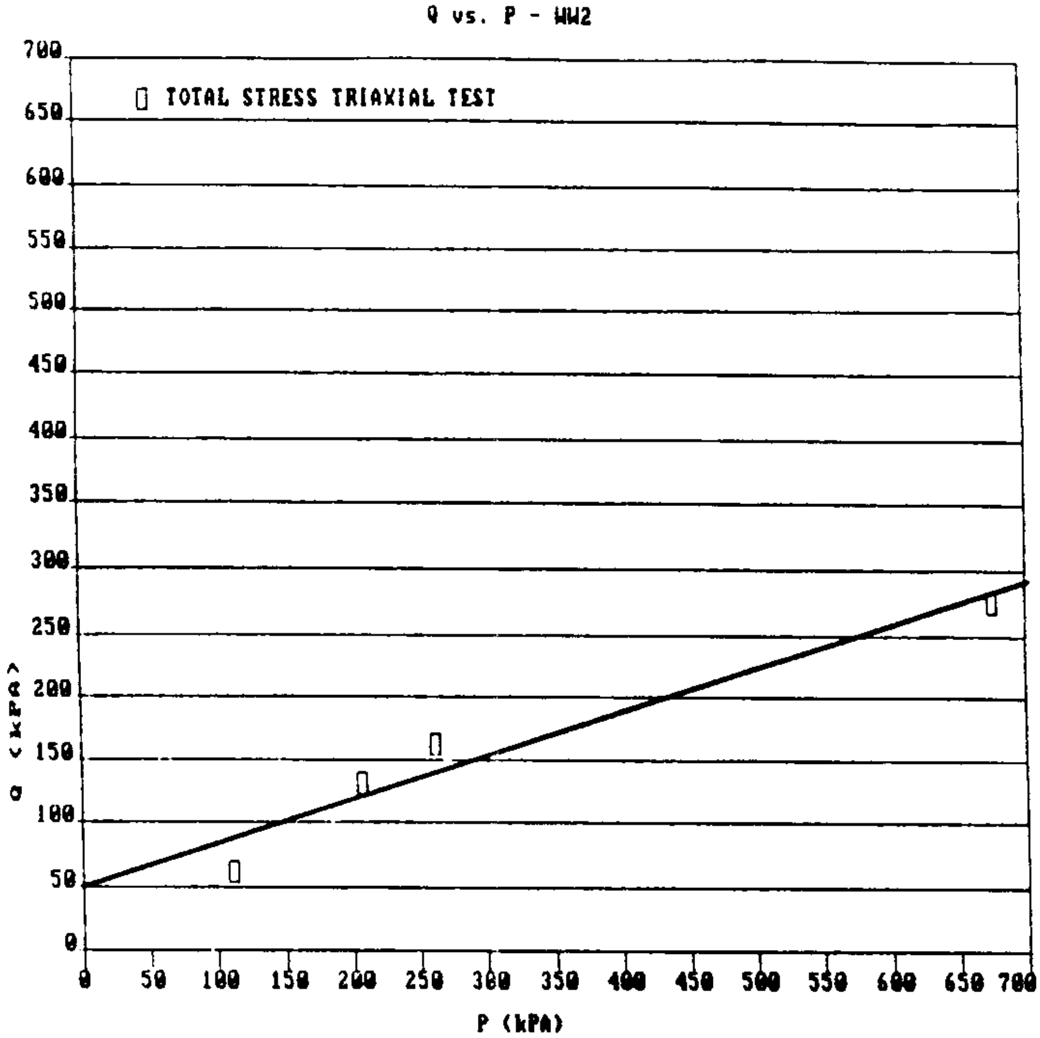

Figure 29. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER: WW2
DRY DENSITY: 1.29 g/cm³
WATER CONTENT: 13.8 %
SPECIFIC GRAVITY: 2.73
CLAY CONTENT: 8 %
UCU TRIAXIAL: SHELBY SPECIMEN
COHESION: 51.7 kPA
FRICTION ANGLE: 20.3°

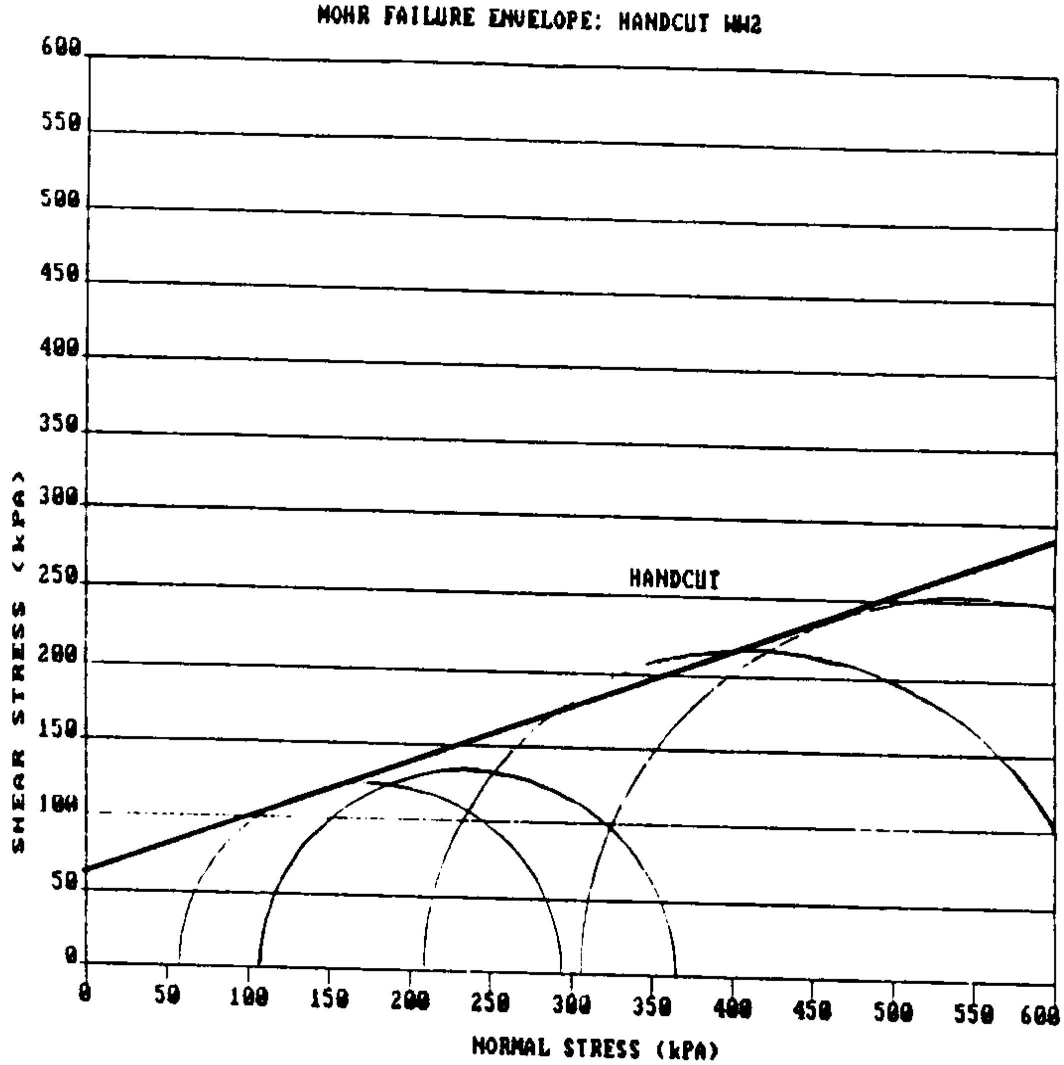

Figure 30. UCU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER:	WW2	
DRY DENSITY:	1.22 g/cm³	
WATER CONTENT:	13.8 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	8 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	62.4 kPA
	FRICTION ANGLE:	20.9°

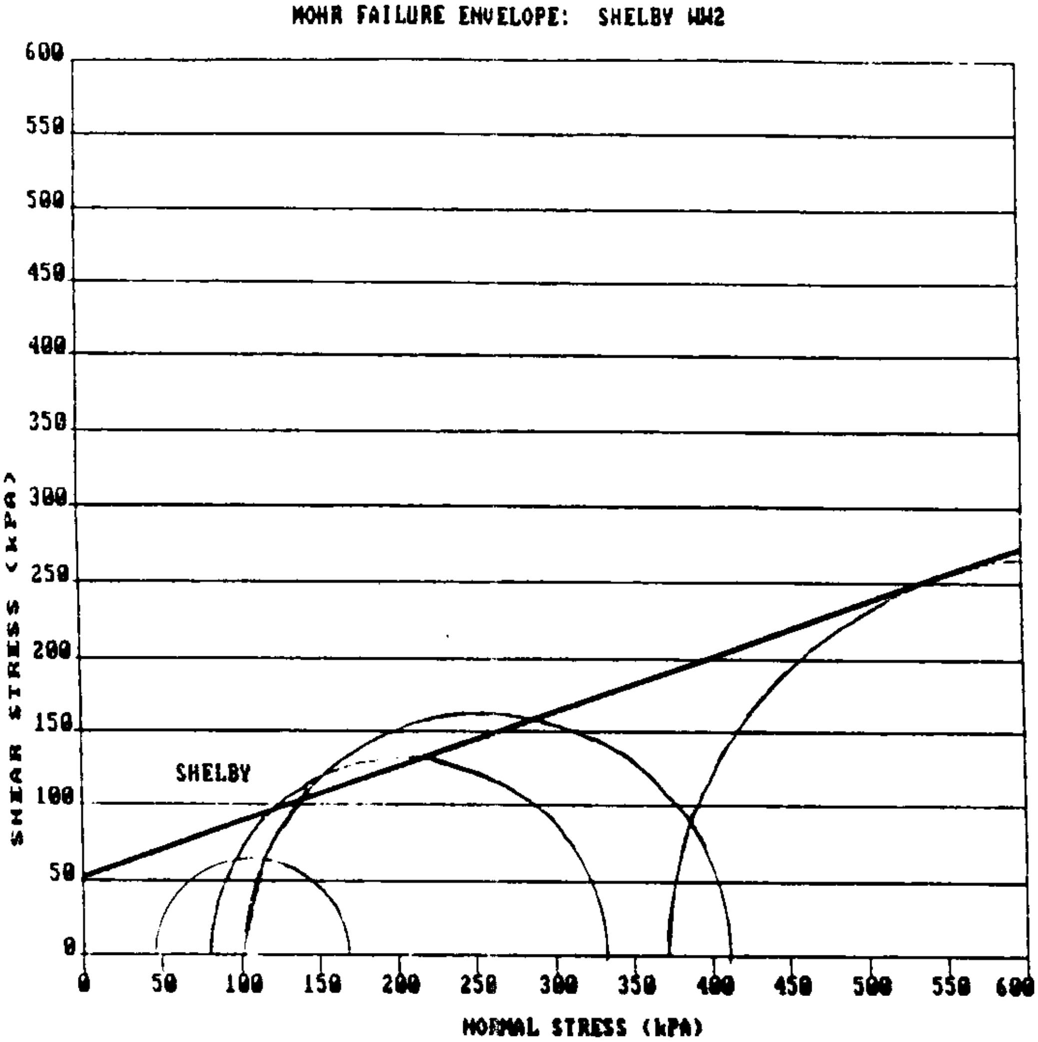

Figure 31. UCU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER:	WW2	
DRY DENSITY:	1.29 g/cm³	
WATER CONTENT:	13.8 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	8 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	51.7 kPA
	FRICTION ANGLE:	20.3°

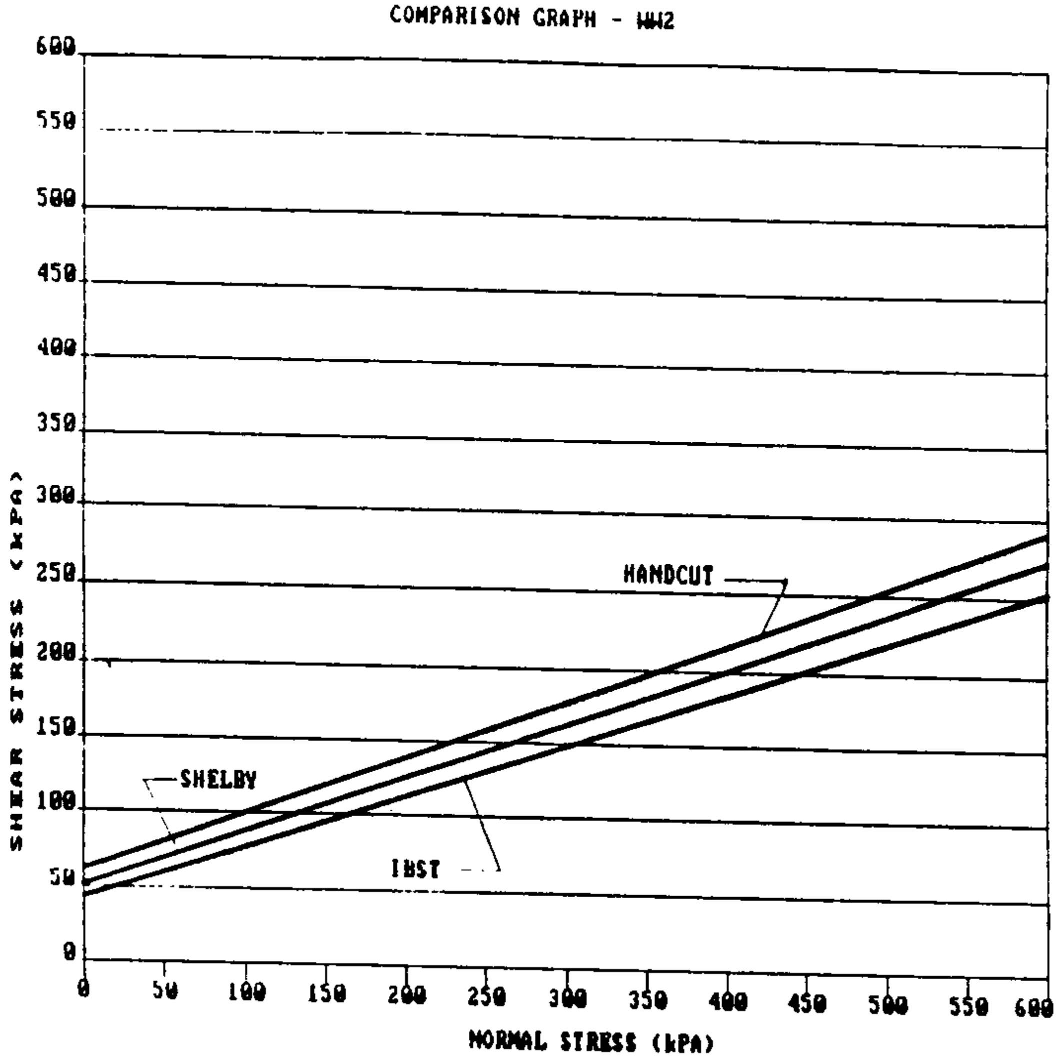

Figure 32. Comparison Graph of Site WW2 by Test Type

SITE NUMBER:	WW2	
DRY DENSITY:	1.22 g/cm³ (Handcut), 1.29 g/cm³ (Shelby)	
WATER CONTENT:	13.8 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	8 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	62.4 kPA
	FRICTION ANGLE:	20.9°
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	51.7 kPA
	FRICTION ANGLE:	20.3°
IBST:	COHESION:	42.9 kPA
	FRICTION ANGLE:	19.4°

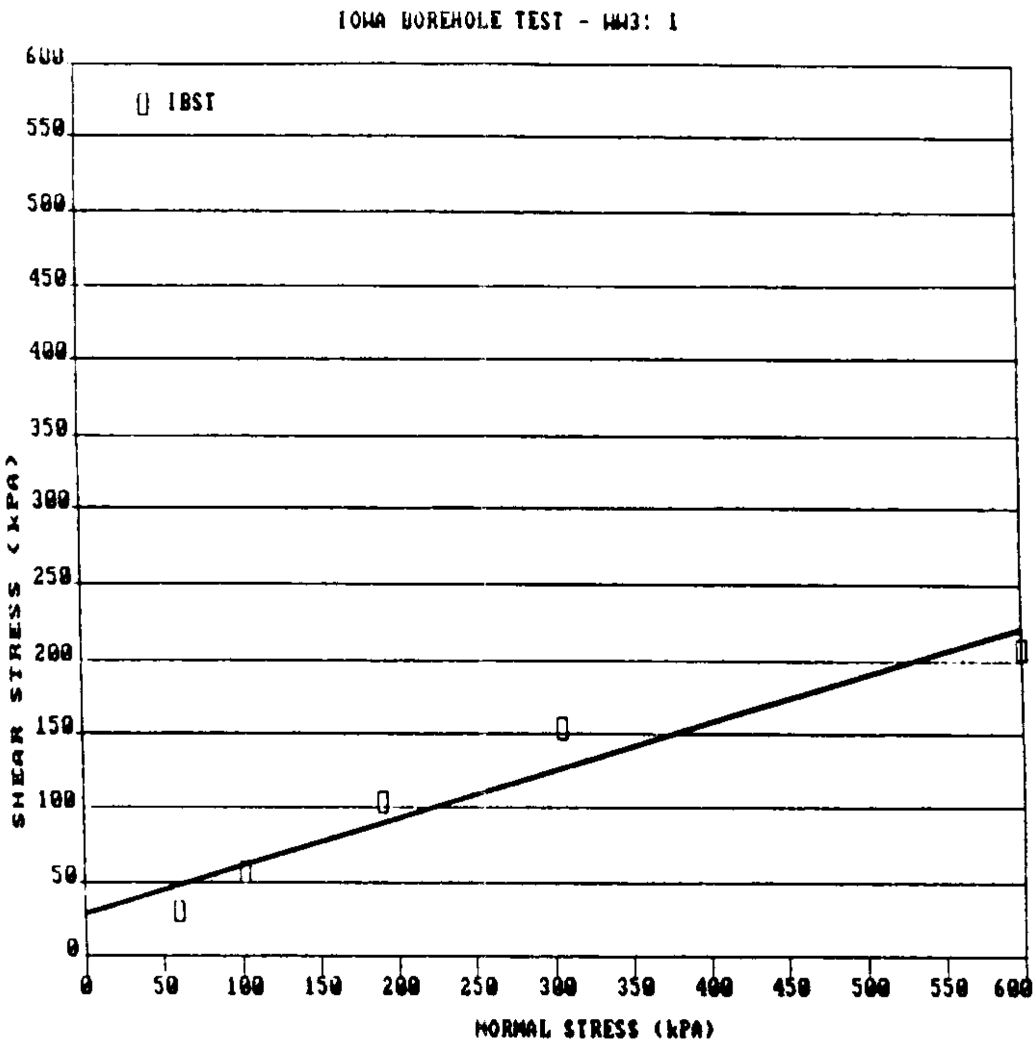

Figure 33. IBST Mohr Envelope in Silty Loess

SITE NUMBER:	WW3		
DRY DENSITY:	1.31 g/cm³		
WATER CONTENT:	22.2 %		
SPECIFIC GRAVITY:	2.70		
CLAY CONTENT:	8 %		
IBST: 1	COHESION:	28.9 kPA	
	FRICTION ANGLE:	17.9°	

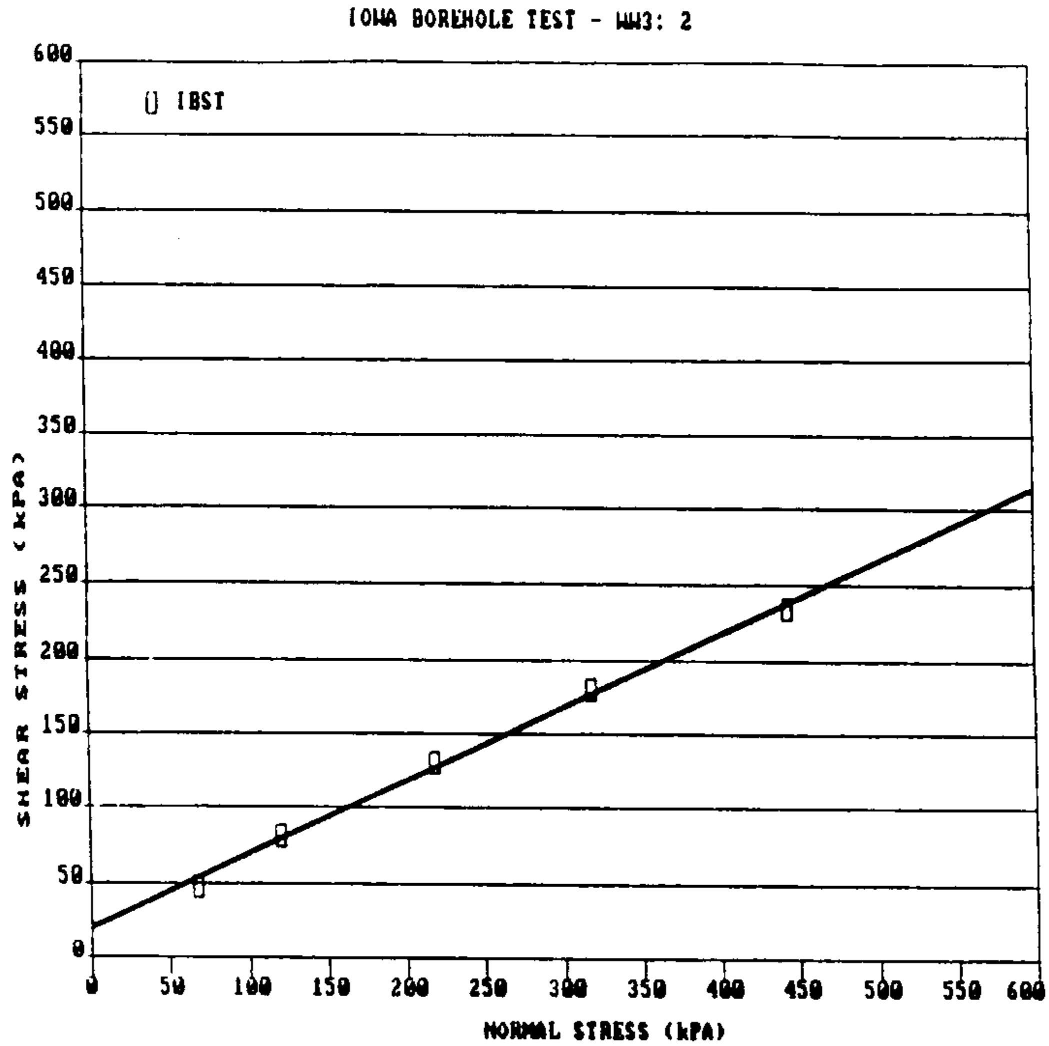

Figure 34. IBST Mohr Envelope in Silty Loess

SITE NUMBER:	WW3		
DRY DENSITY:	1.31 g/cm³		
WATER CONTENT:	22.2 %		
SPECIFIC GRAVITY:	2.70		
CLAY CONTENT:	8 %		
IBST: 2	COHESION:	19.9 kPA	
	FRICTION ANGLE:	26.2°	

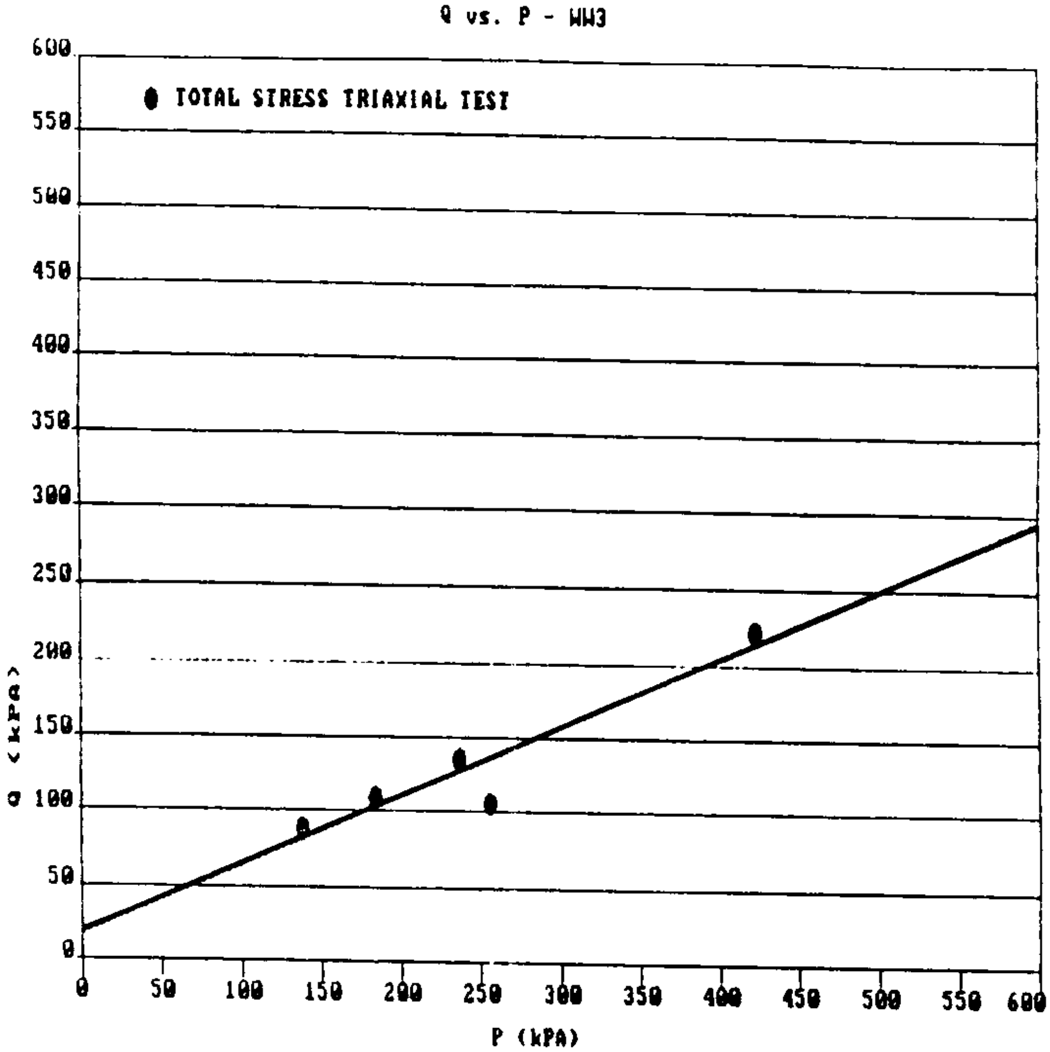

Figure 35. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER:	WW3	
DRY DENSITY:	1.47 g/cm^3	
WATER CONTENT:	22.2 %	
SPECIFIC GRAVITY:	2.70	
CLAY CONTENT:	8 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	19.5 kPA
	FRICTION ANGLE:	27.7°

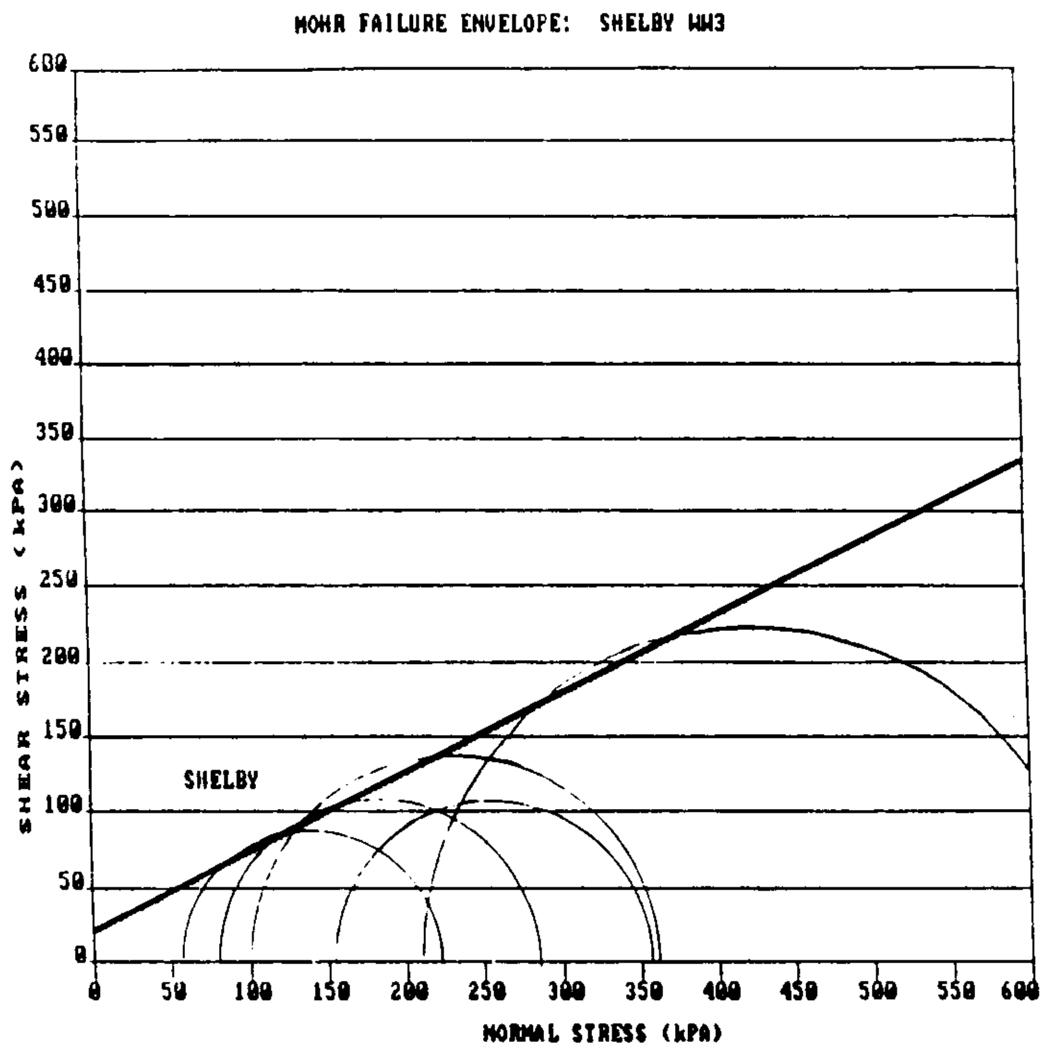

Figure 36. UCU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER:	WW3	
DRY DENSITY:	1.47 g/cm³	
WATER CONTENT:	22.2 %	
SPECIFIC GRAVITY:	2.70	
CLAY CONTENT:	8 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	19.5 kPA
	FRICTION ANGLE:	27.7°

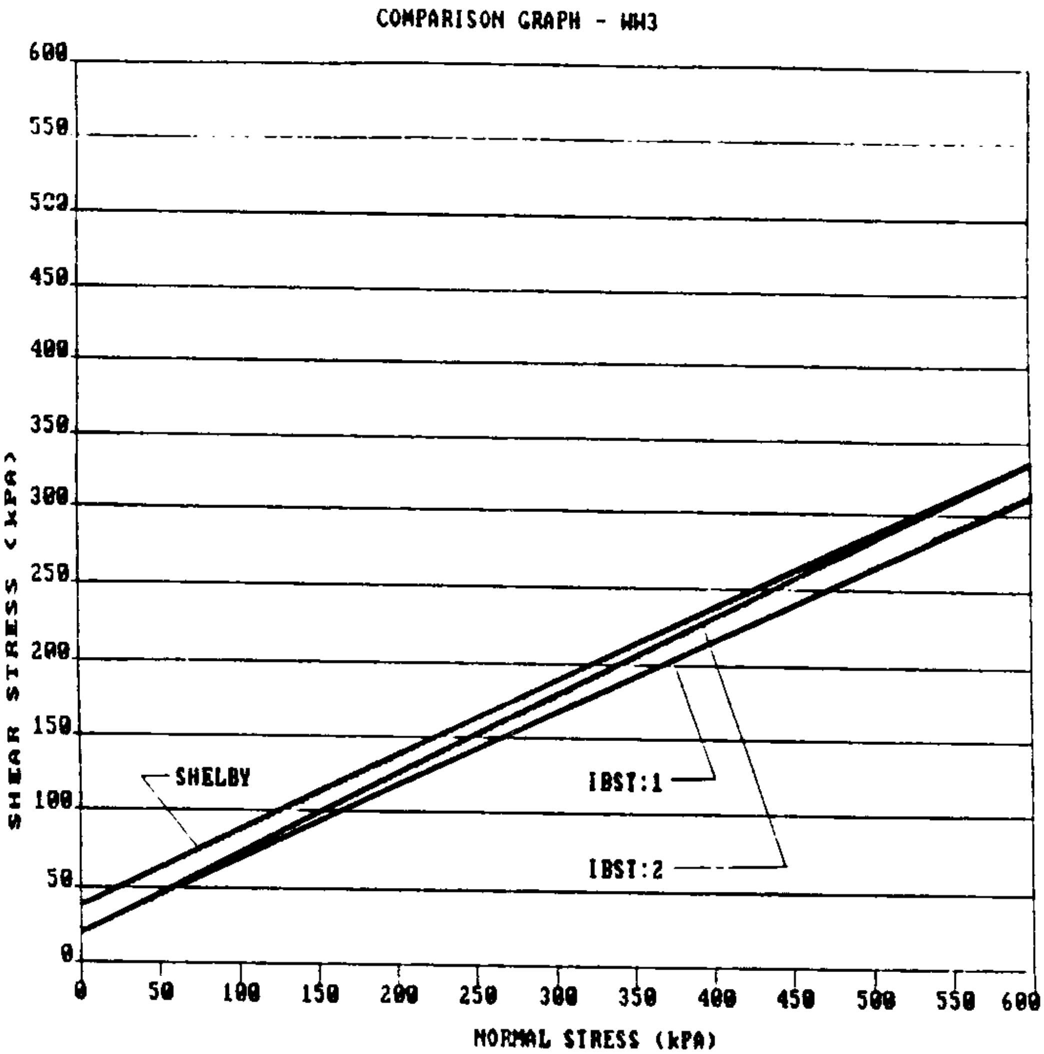

Figure 37. Comparison Graph of WW3 by Test Type

SITE NUMBER:	WW3	
DRY DENSITY:	1.47 g/cm^3	
WATER CONTENT:	22.2 %	
SPECIFIC GRAVITY:	2.70	
CLAY CONTENT:	8 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	19.5 kPA
	FRICTION ANGLE:	27.7°
IBST: 1	COHESION:	28.9 kPA
	FRICTION ANGLE:	17.9°
IBST: 2	COHESION:	19.9 kPA
	FRICTION ANGLE:	26.2°

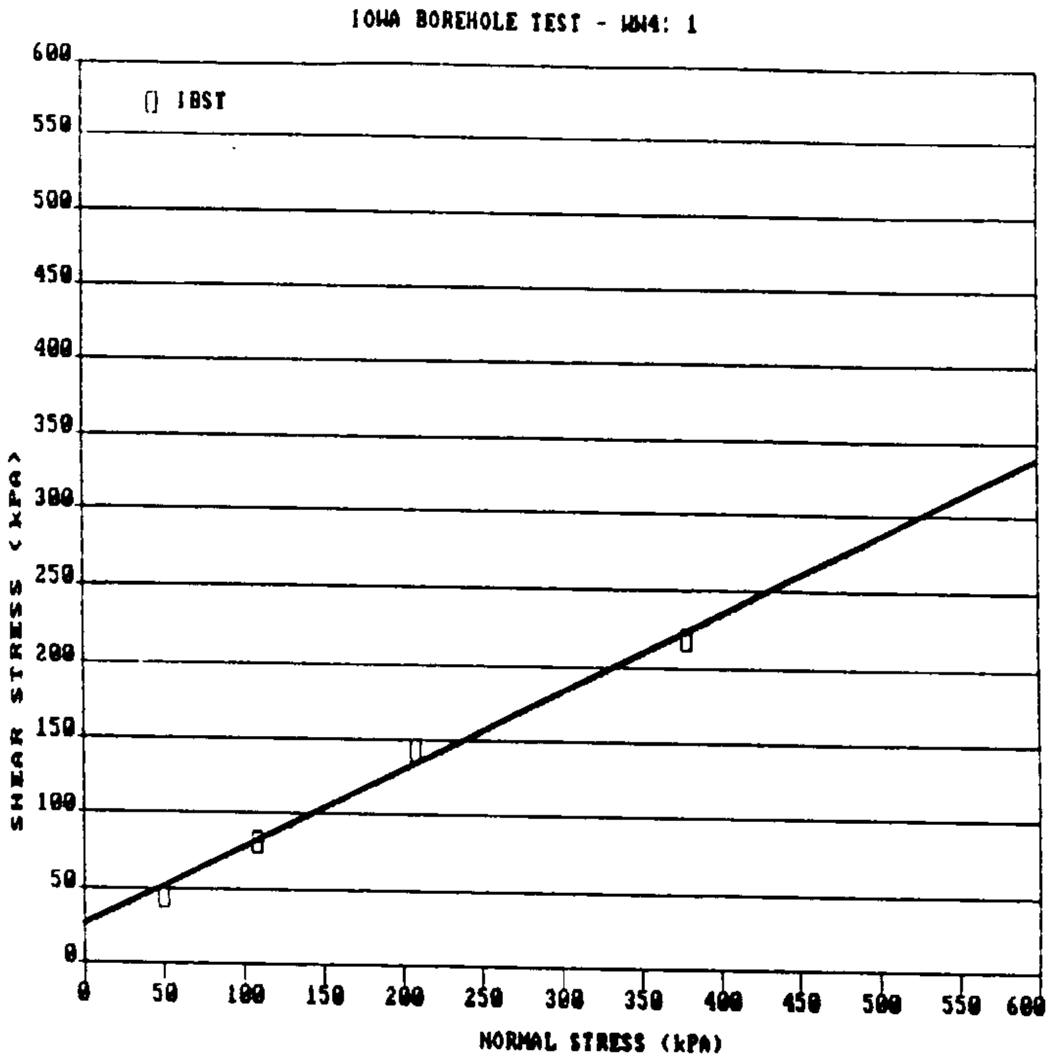

Figure 38. IBST Mohr Envelope in Silty Loess

SITE NUMBER:	WW4		
DRY DENSITY:	1.13 g/cm³		
WATER CONTENT:	18.9 %		
SPECIFIC GRAVITY:	2.67		
CLAY CONTENT:	9 %		
IBST: 1	COHESION:	24.4 kPA	
	FRICTION ANGLE:	27.6°	

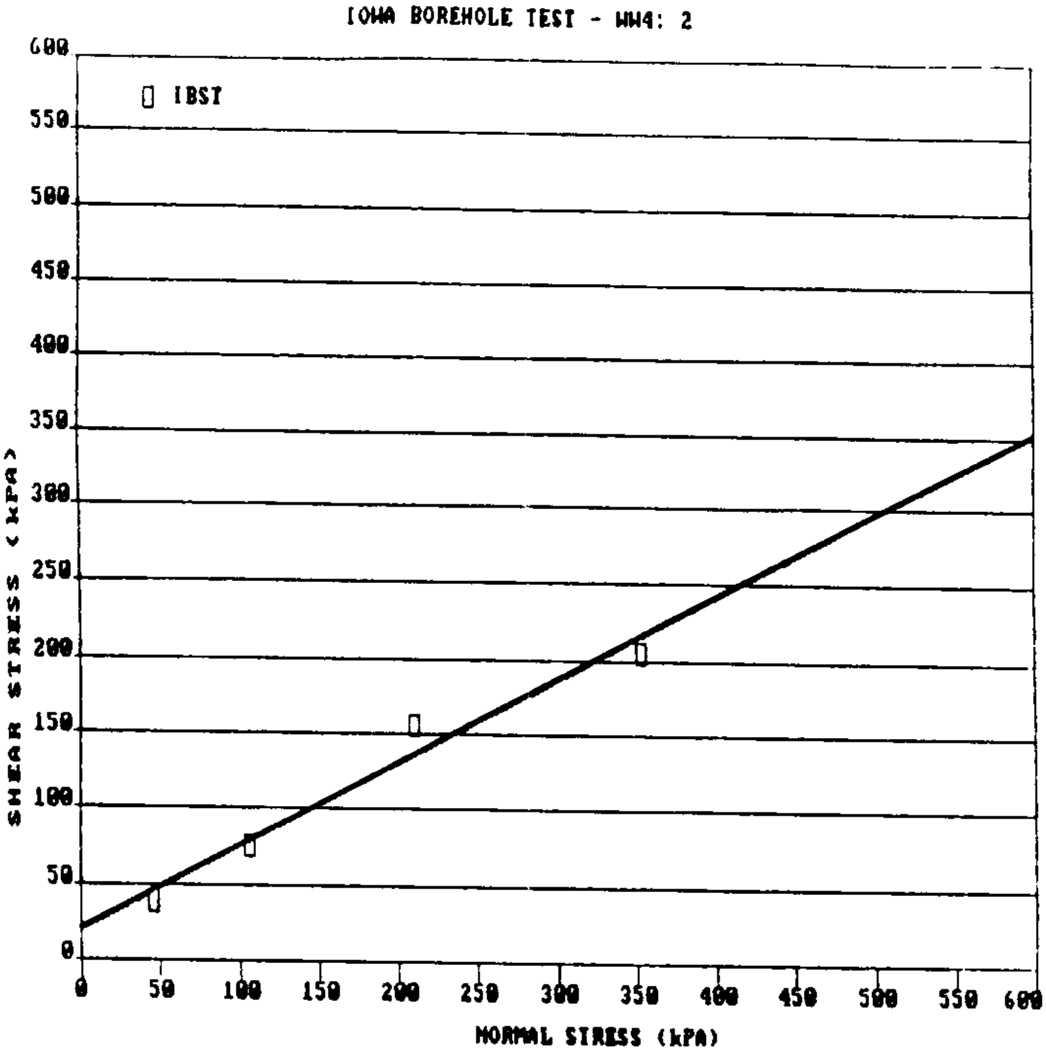

Figure 39. IBST Mohr Envelope in Silty Loess

SITE NUMBER:	WW4		
DRY DENSITY:	1.13 g/cm³		
WATER CONTENT:	18.9 %		
SPECIFIC GRAVITY:	2.67		
CLAY CONTENT:	9 %		
IBST: 2	COHESION:	20.3 kPA	
	FRICTION ANGLE:	28.9°	

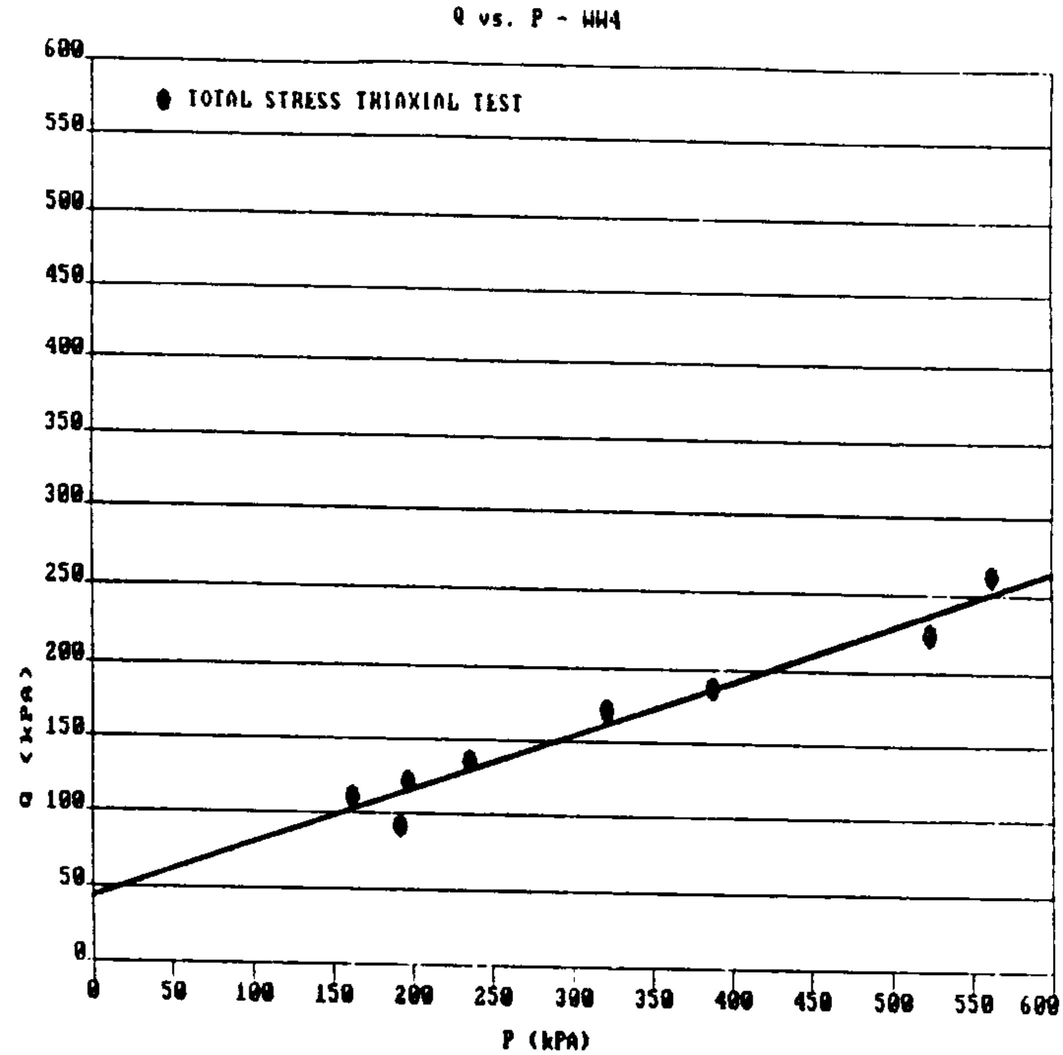

Figure 40. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER:	WW4	
DRY DENSITY:	1.21 g/cm³	
WATER CONTENT:	18.9 %	
SPECIFIC GRAVITY:	2.67	
CLAY CONTENT:	9 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	46.5 kPA
	FRICTION ANGLE:	21.9°

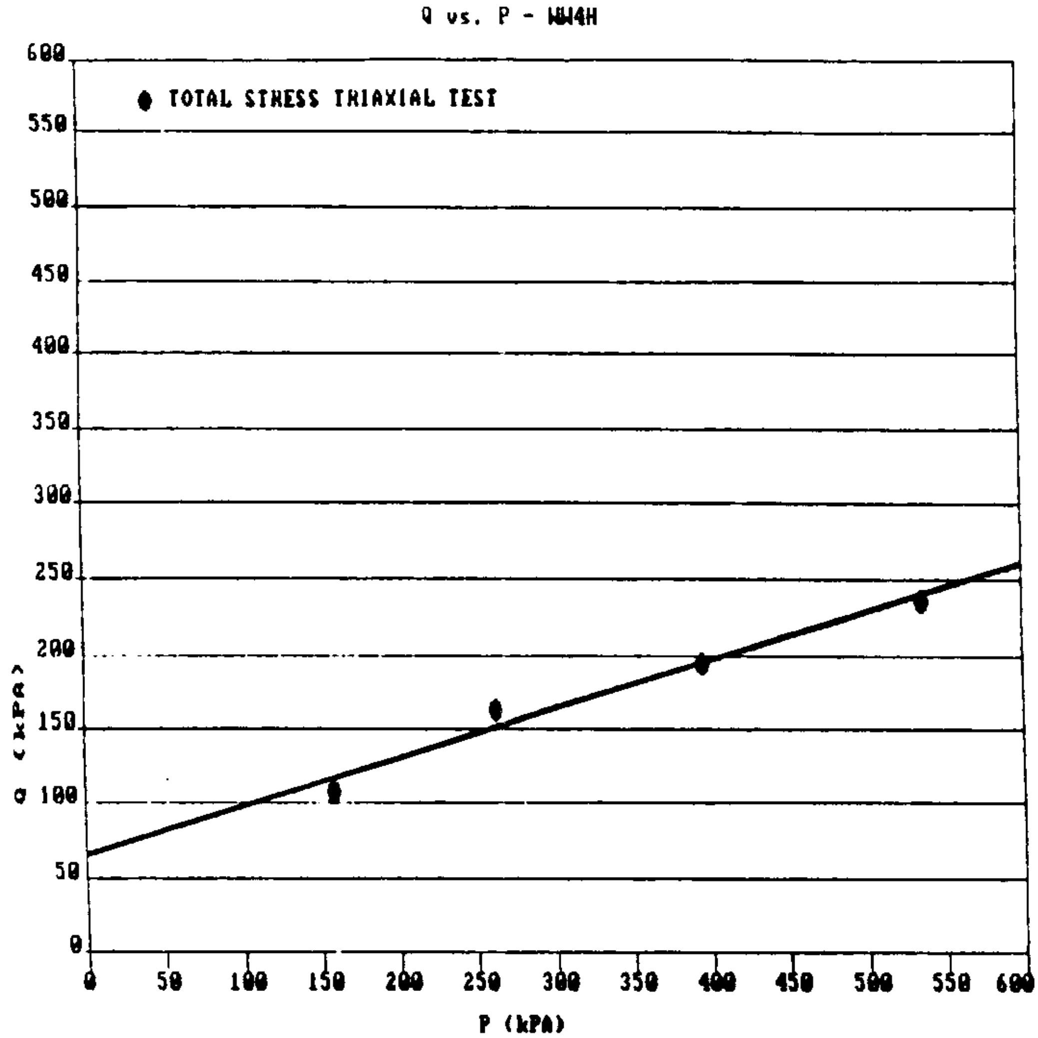

Figure 41. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER:	WW4	
DRY DENSITY:	1.13 g/cm³	
WATER CONTENT:	18.9 %	
SPECIFIC GRAVITY:	2.67	
CLAY CONTENT:	9 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	69.3 kPA
	FRICTION ANGLE:	19.0°

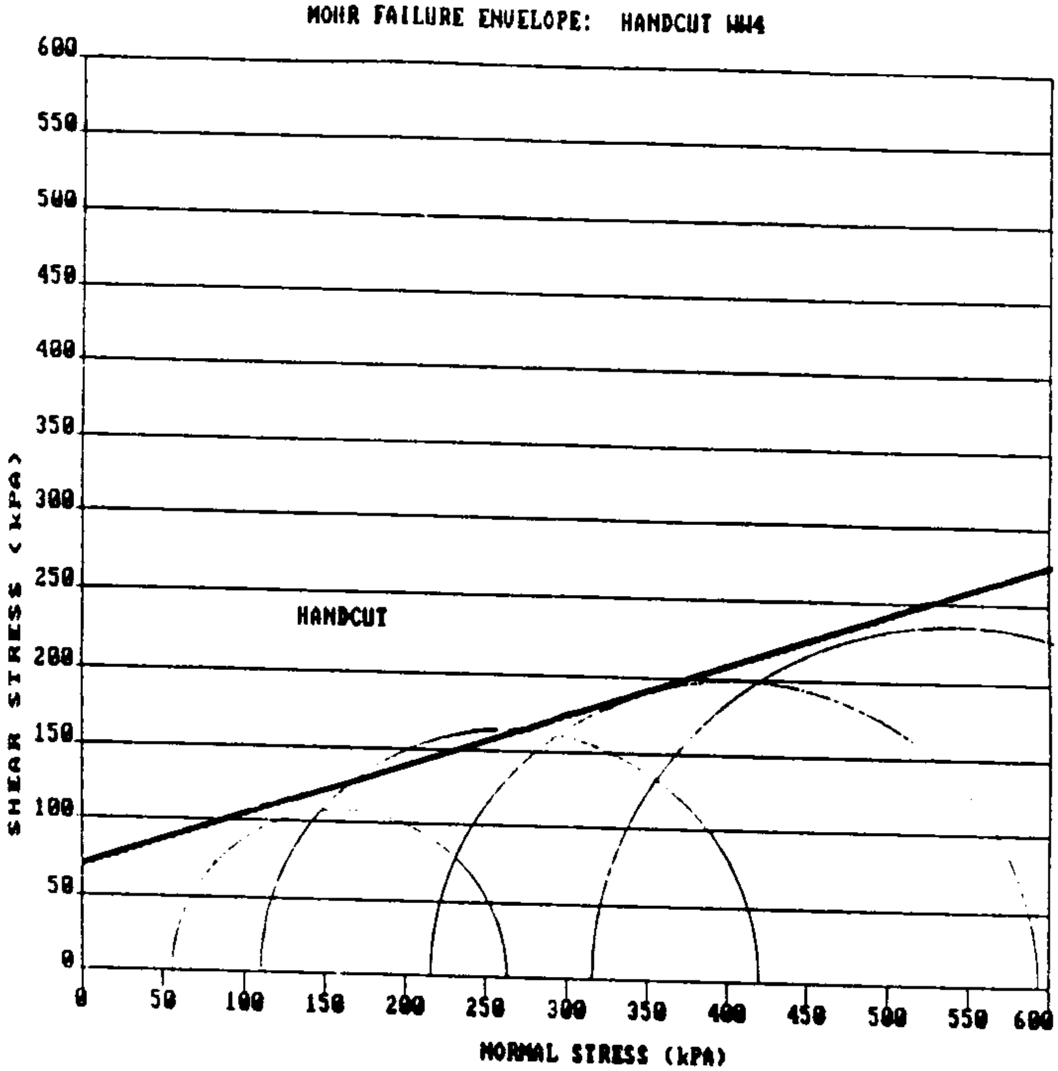

Figure 42. UCU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER:	WW4	
DRY DENSITY:	1.13 g/cm^3	
WATER CONTENT:	18.9 %	
SPECIFIC GRAVITY:	2.67	
CLAY CONTENT:	9 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	69.3 kPA
	FRICTION ANGLE:	19.0°

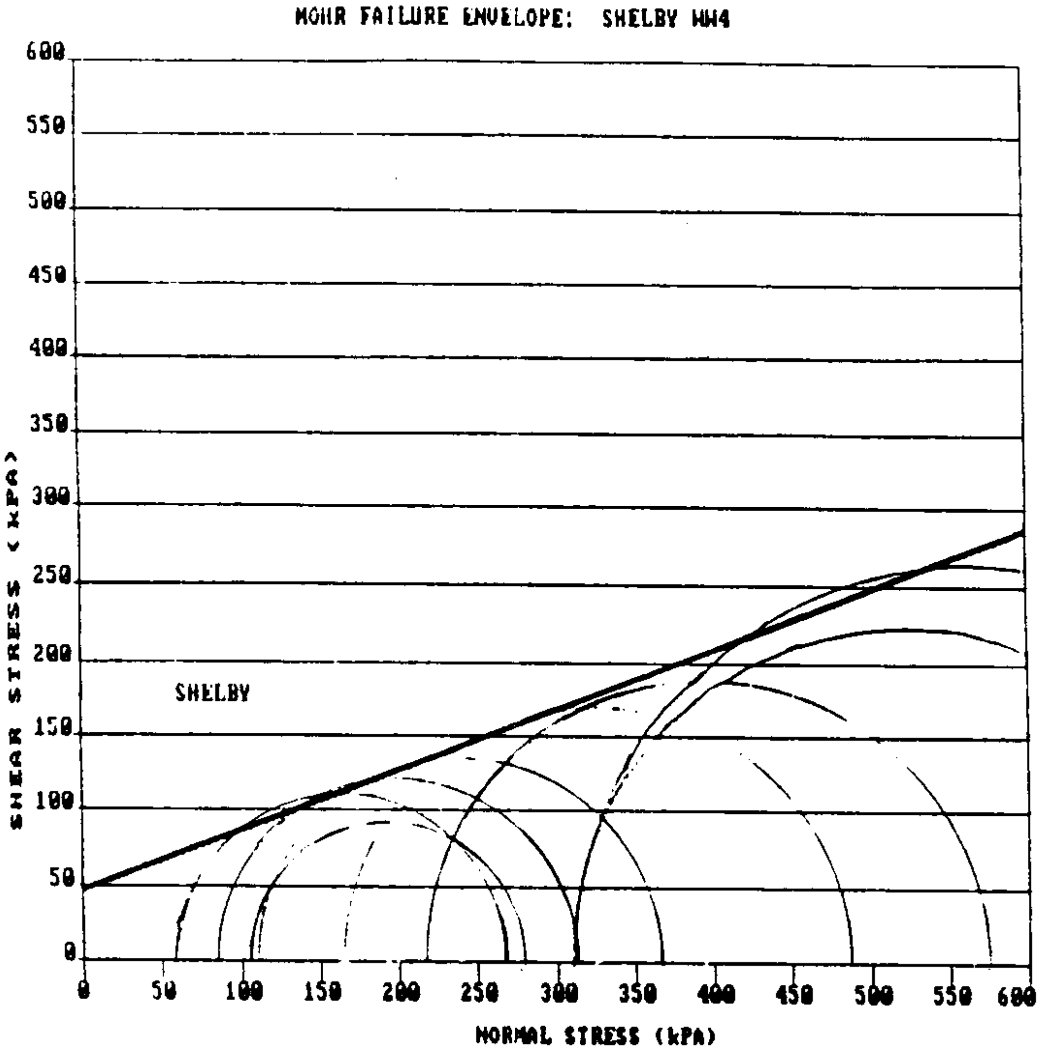

Figure 43. UCU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER: WW4
DRY DENSITY: 1.21 g/cm³
WATER CONTENT: 18.9 %
SPECIFIC GRAVITY: 2.67
CLAY CONTENT: 9 %
UCU TRIAXIAL: SHELBY SPECIMEN
COHESION: 46.5 kPA
FRICTION ANGLE: 21.9°

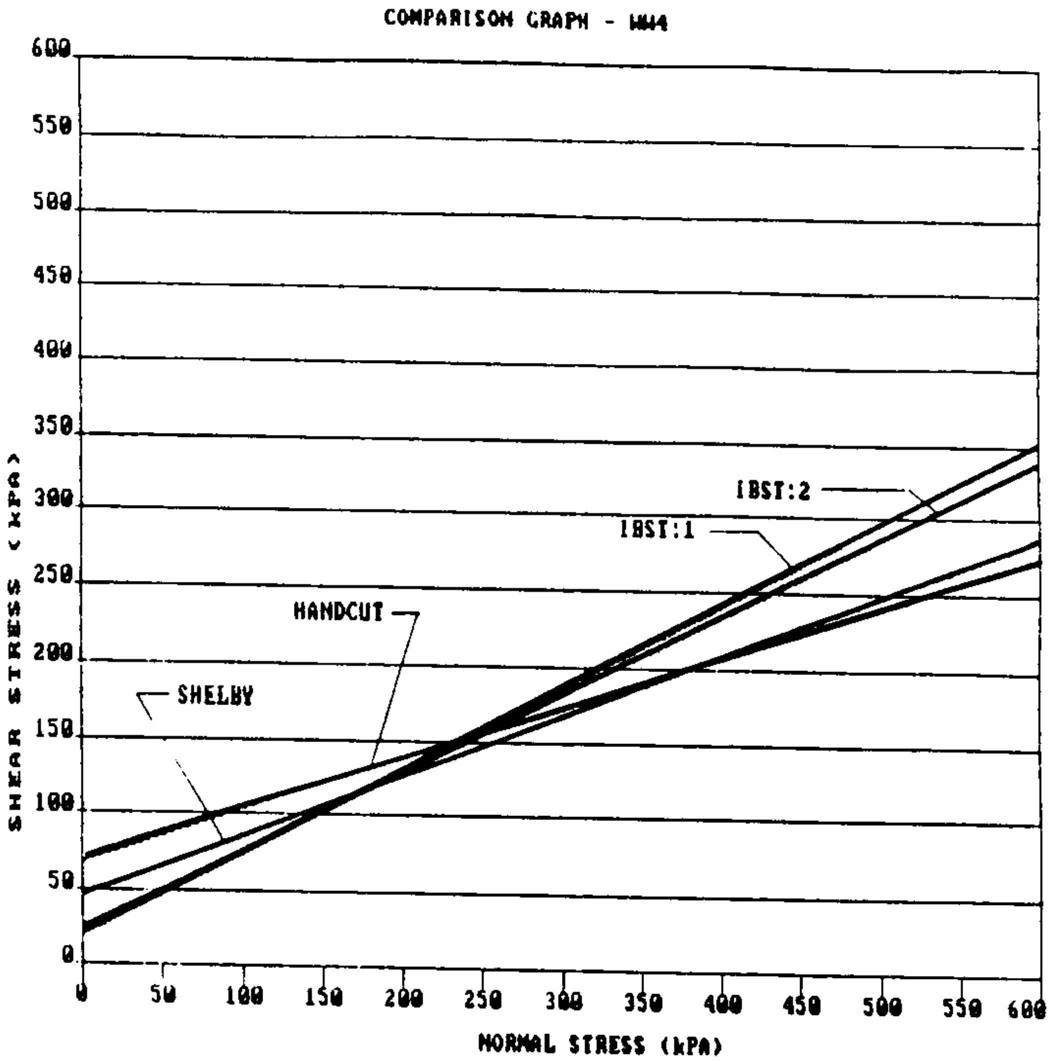

Figure 44. Comparison Graph of WW4 by Test Type

SITE NUMBER:	WW4	
DRY DENSITY:	1.13 g/cm³	
WATER CONTENT:	18.9 %	
SPECIFIC GRAVITY:	2.67	
CLAY CONTENT:	9 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	69.3 kPA
	FRICTION ANGLE:	19.0°
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	46.5 kPA
	FRICTION ANGLE:	21.9°
IBST: 1	COHESION:	24.4 kPA
	FRICTION ANGLE:	27.6°
IBST: 2	COHESION:	20.3 kPA
	FRICTION ANGLE:	28.9°

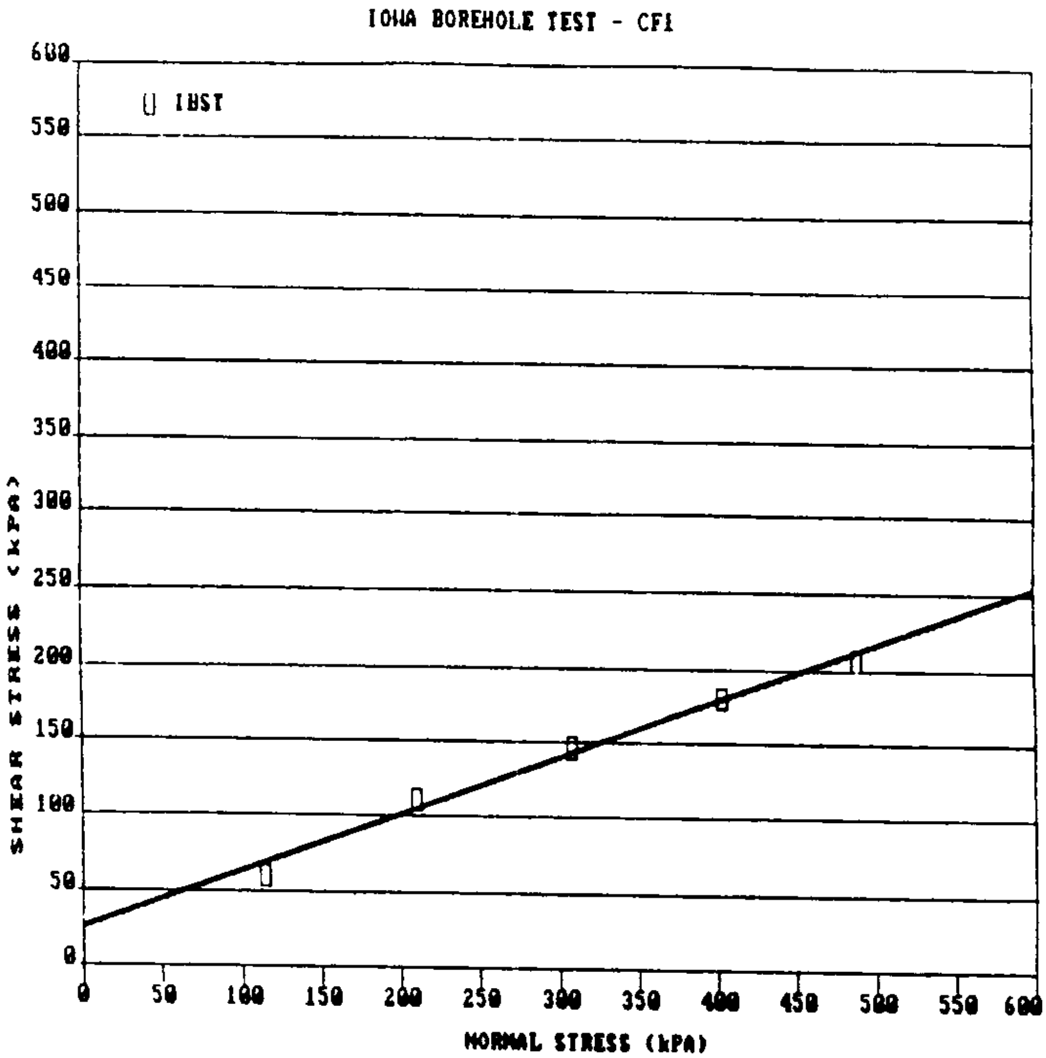

Figure 45. IBST Mohr Envelopes in Clayey Loess

SITE NUMBER:	CF1	
DRY DENSITY:	1.36 g/cm³	
WATER CONTENT:	19.1 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	21 %	
IBST:	COHESION:	23.9 kPA
	FRICTION ANGLE:	22.5°

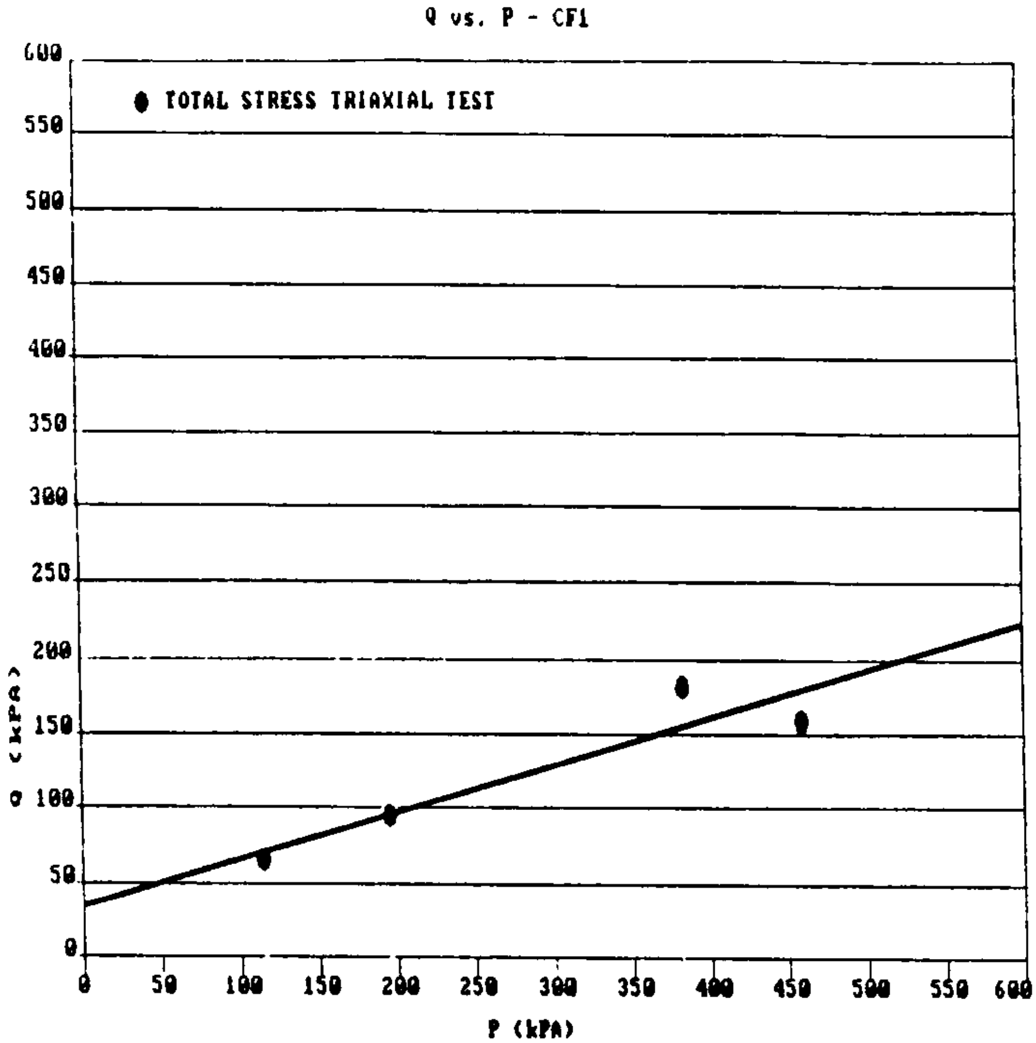

Figure 46. UCU Triaxial q vs. p Plot in Clayey Loess

SITE NUMBER:	CF1	
DRY DENSITY:	1.44 g/cm³	
WATER CONTENT:	19.1 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	21 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	35.2 kPA
	FRICTION ANGLE:	18.6°

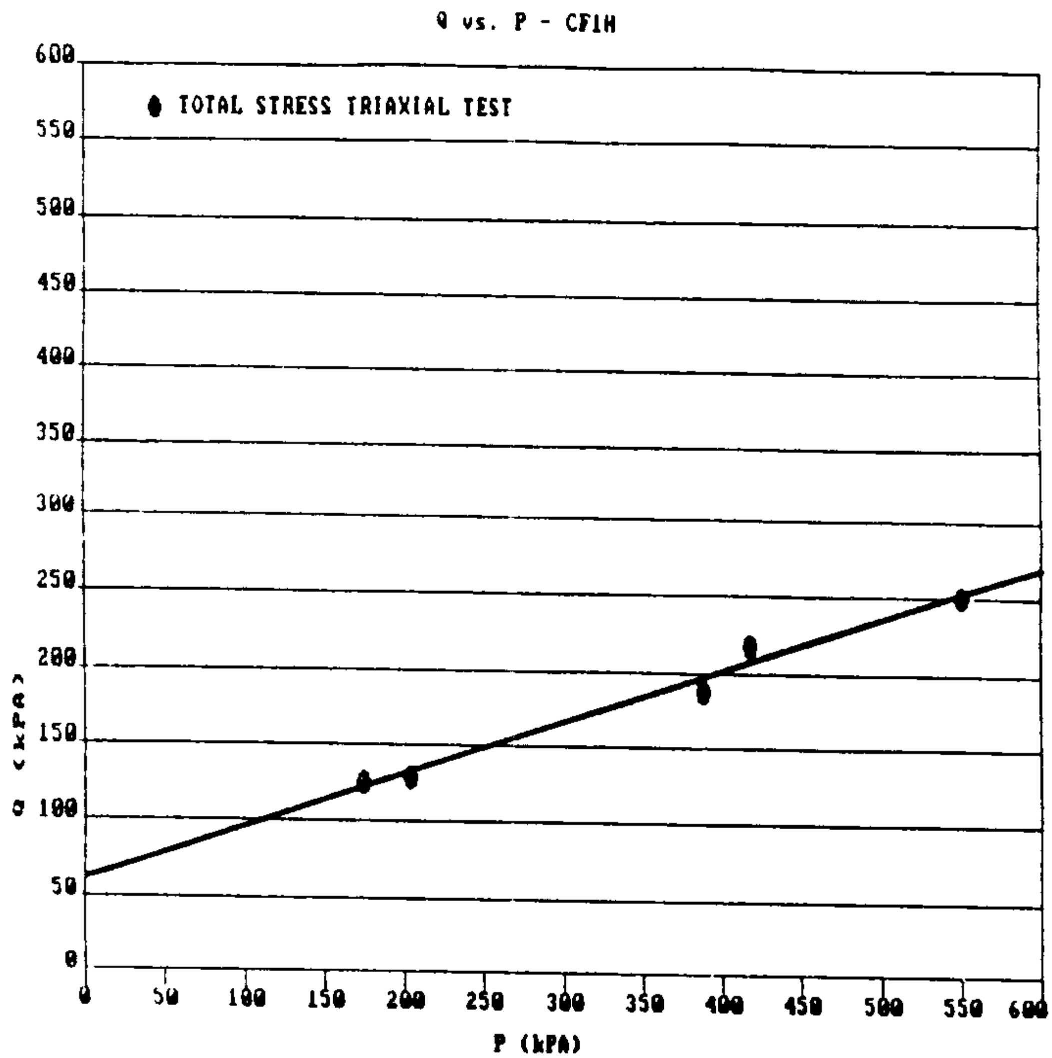

Figure 47. UCU Triaxial q vs. p Plot in Clayey Loess

SITE NUMBER:	CF1	
DRY DENSITY:	1.36 g/cm³	
WATER CONTENT:	19.1 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	21 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	65.7 kPA
	FRICTION ANGLE:	20.3°

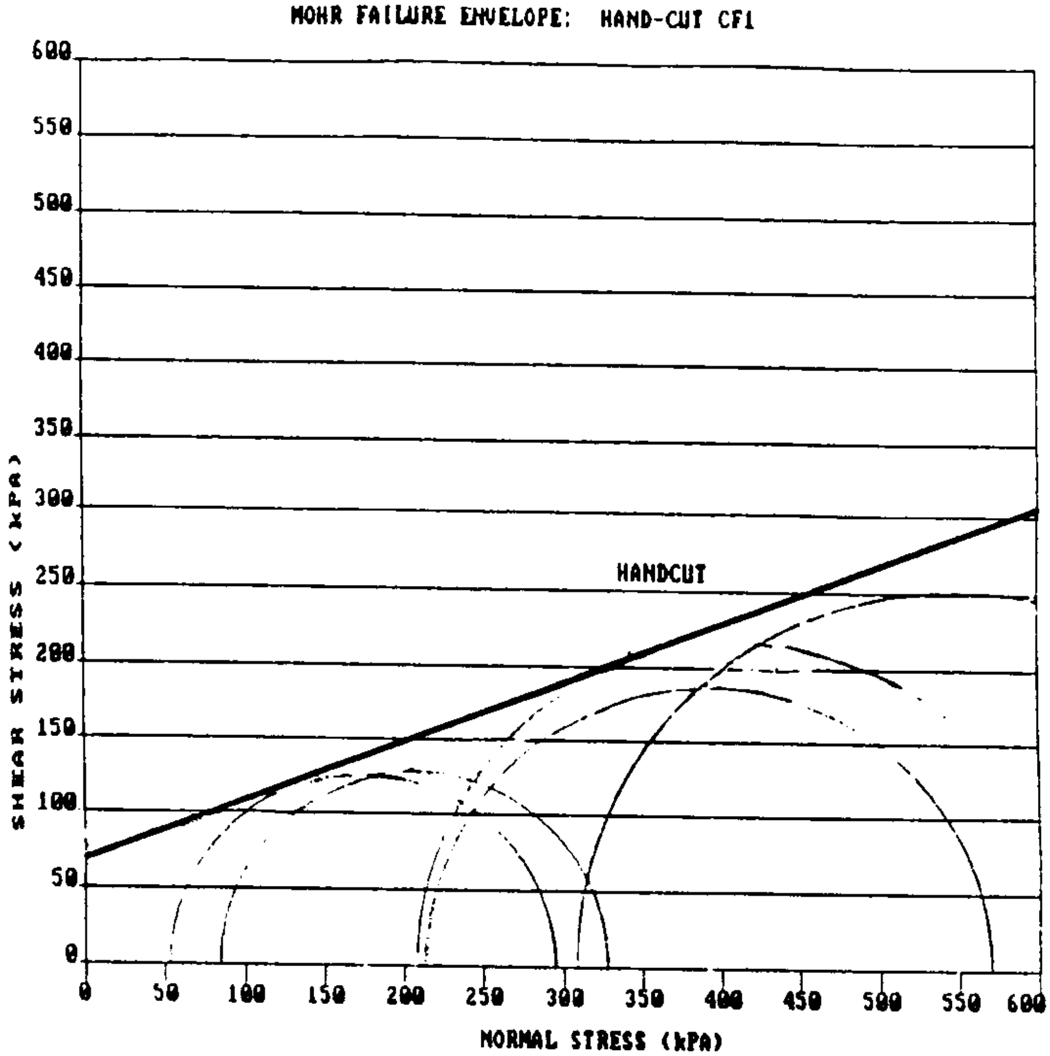

Figure 48. UCU Triaxial Mohr Envelope in Clayey Loess

SITE NUMBER:	CF1		
DRY DENSITY:	1.36 g/cm³		
WATER CONTENT:	19.1 %		
SPECIFIC GRAVITY:	2.73		
CLAY CONTENT:	21 %		
UCU TRIAXIAL:	HAND-CUT SPECIMEN		
	COHESION:	65.7 kPA	
	FRICTION ANGLE:	20.3°	

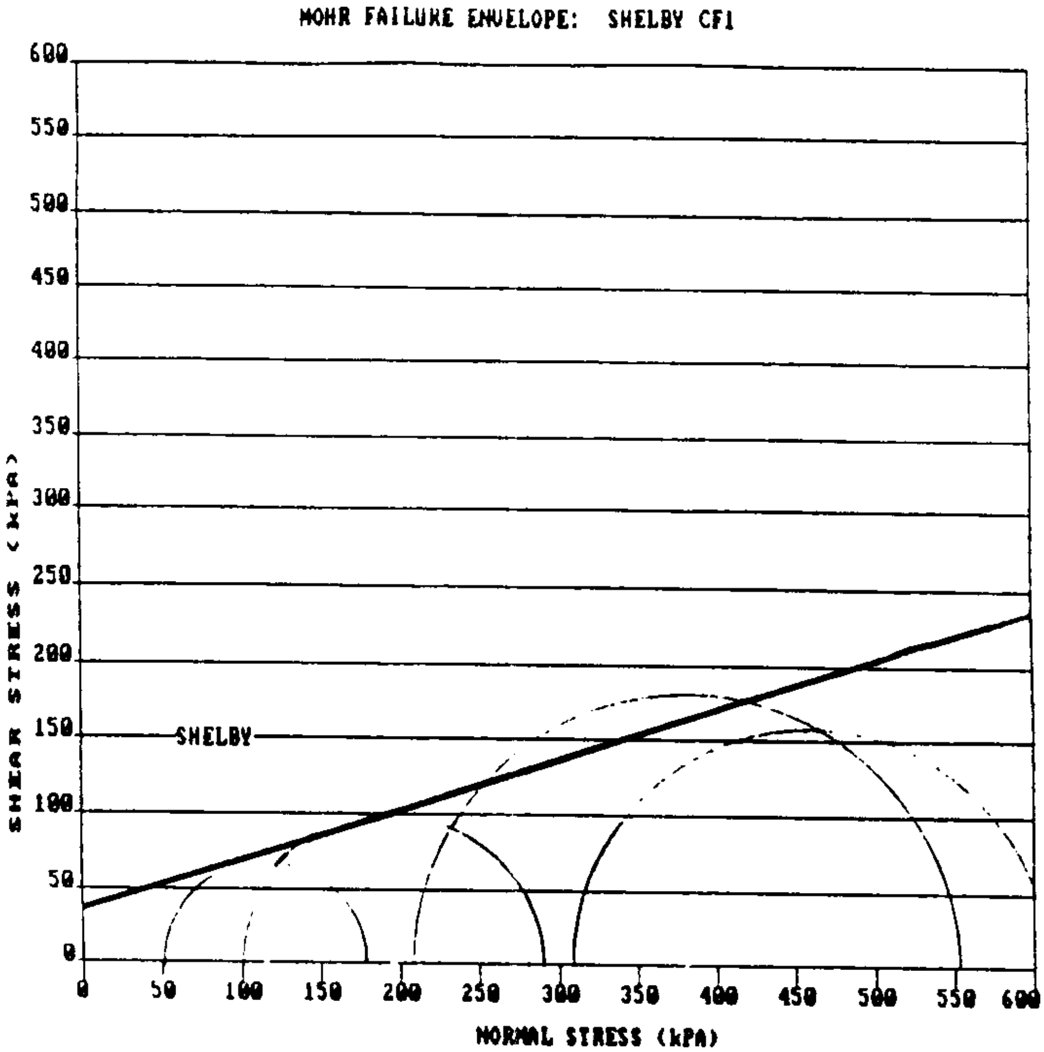

Figure 49. UCU Triaxial Mohr Envelope in Clayey Loess

SITE NUMBER:	CF1	
DRY DENSITY:	1.44 g/cm³	
WATER CONTENT:	19.1 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	21 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	35.2 kPA
	FRICTION ANGLE:	18.6°

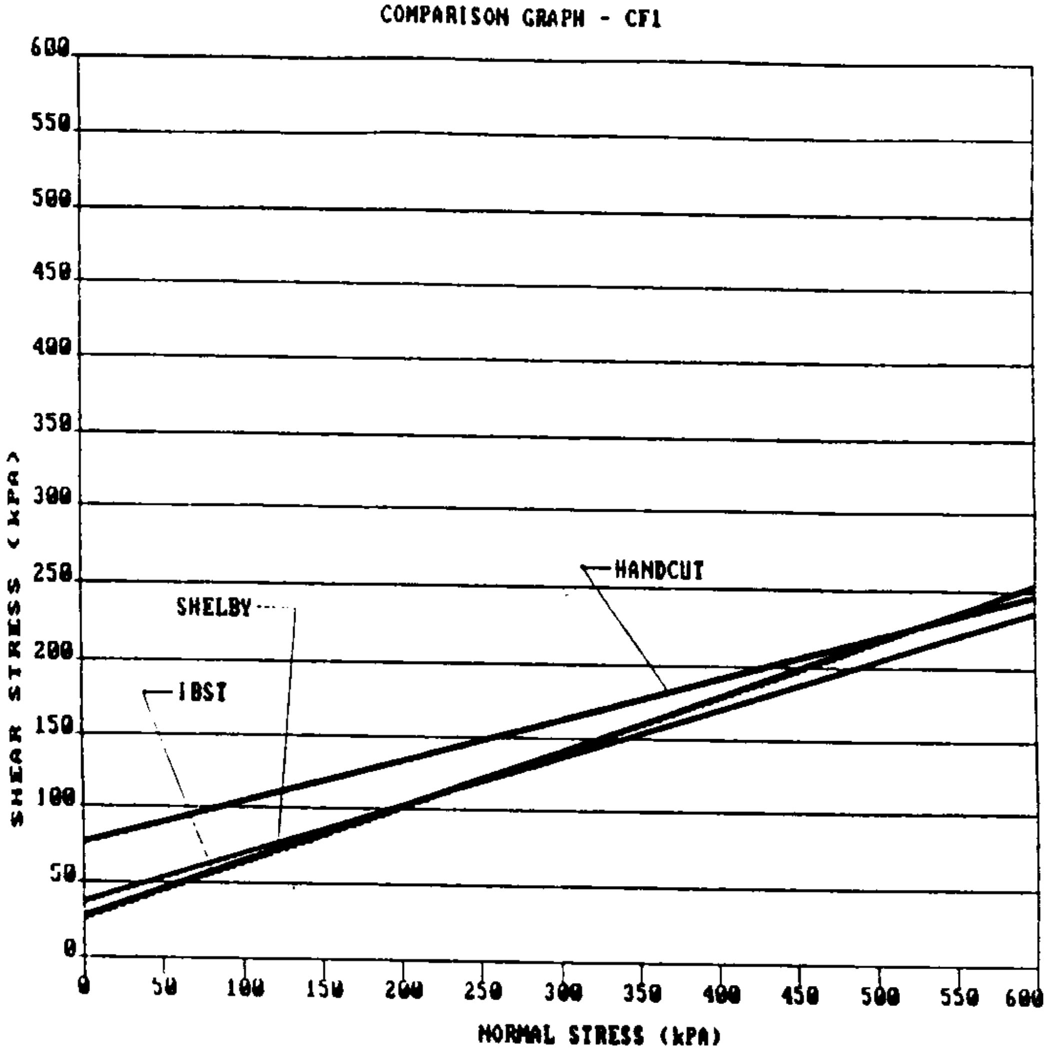

Figure 50. Comparison Graph of CF1 by Test Type

SITE NUMBER:	CF1	
DRY DENSITY:	1.36 g/cm³ (Handcut), 1.44 g/cm³ (Shelby)	
WATER CONTENT:	19.1 %	
SPECIFIC GRAVITY:	2.73	
CLAY CONTENT:	21 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	65.7 kPA
	FRICTION ANGLE:	20.3°
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	35.2 kPA
	FRICTION ANGLE:	18.6°
IBST: 1	COHESION:	23.9 kPA
	FRICTION ANGLE:	22.5

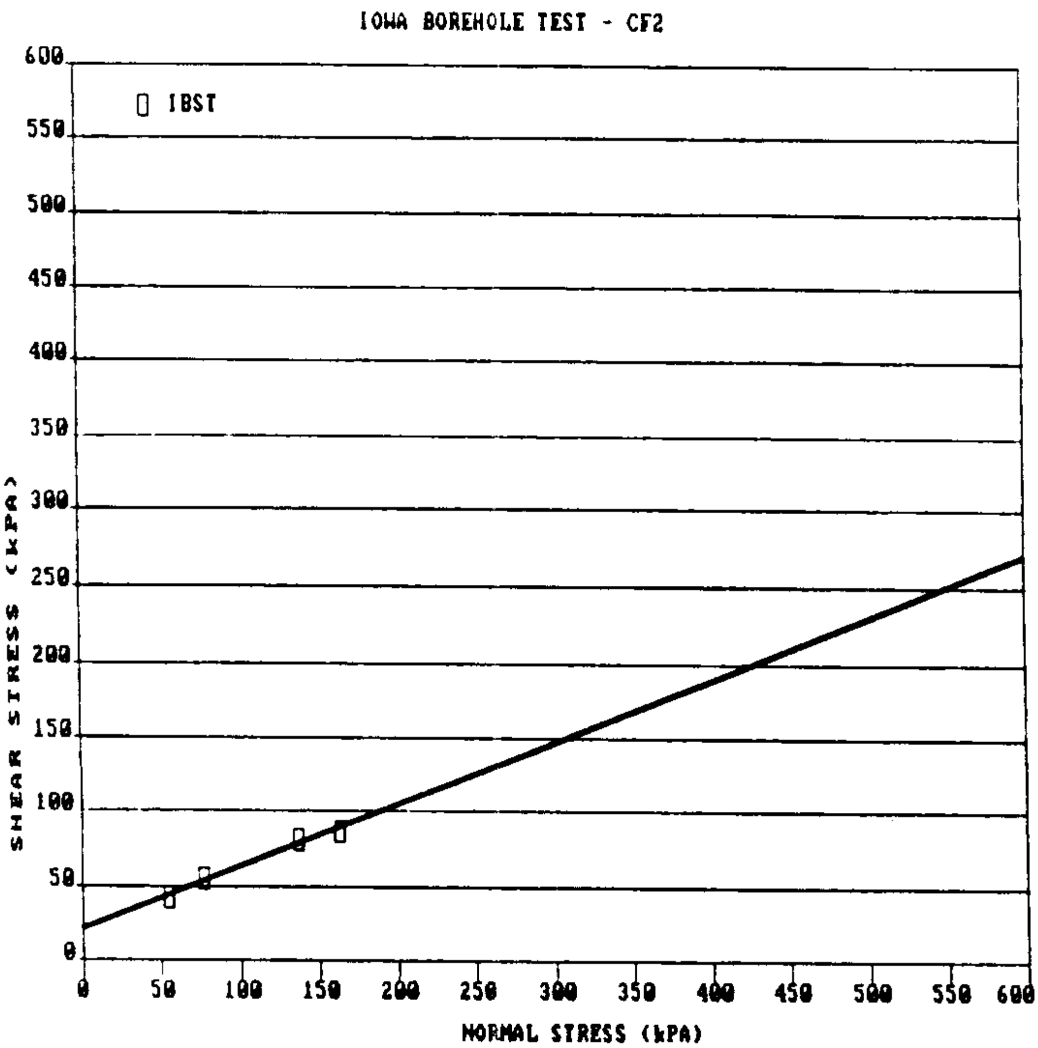

Figure 51. IBST Mohr Envelope in Silty Loess

SITE NUMBER:	CF2		
DRY DENSITY:	1.38 g/cm^3		
WATER CONTENT:	23.4 %		
SPECIFIC GRAVITY:	2.72		
CLAY CONTENT:	12 %		
IBST: 1	COHESION:	21.0 kPA	
	FRICTION ANGLE:	22.6°	

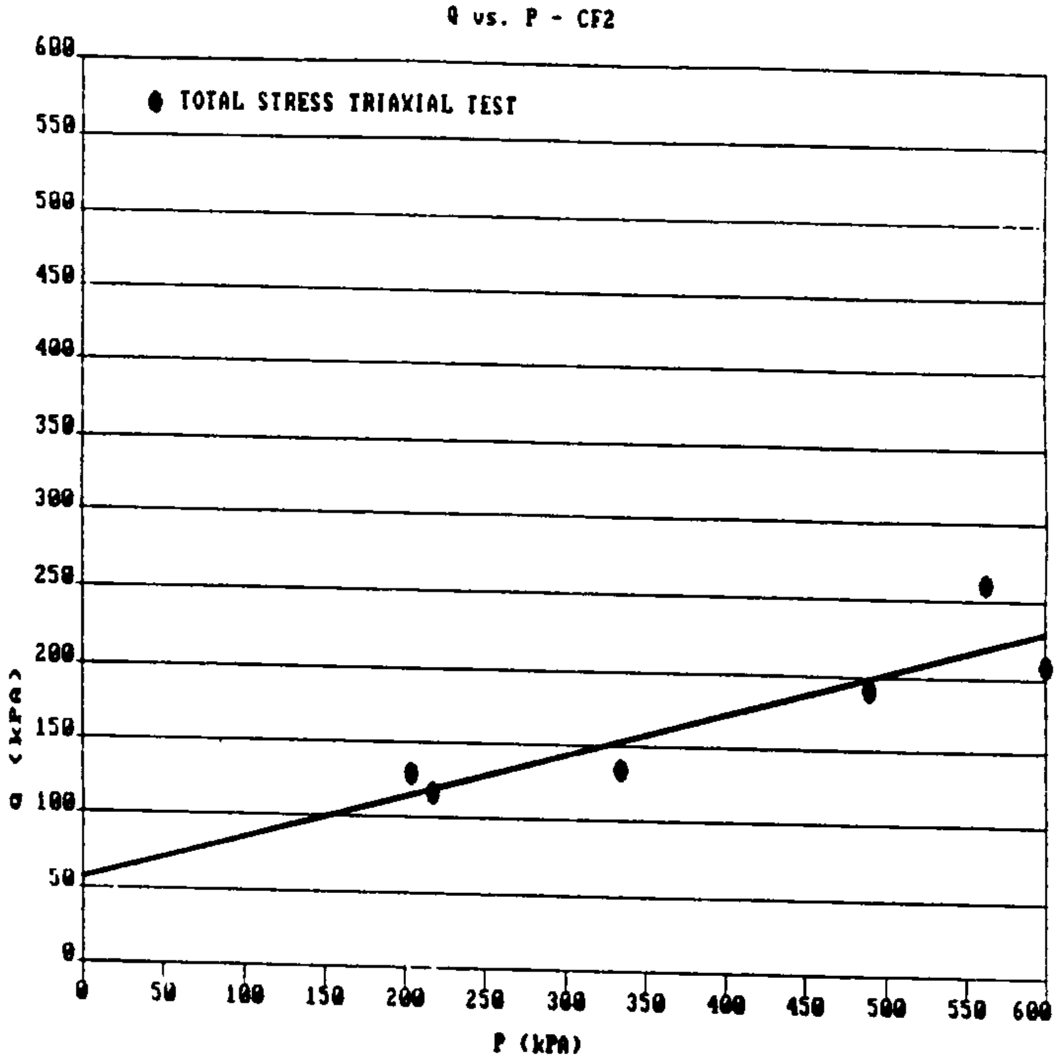

Figure 52. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER:	CF2	
DRY DENSITY:	1.57 g/cm³	
WATER CONTENT:	23.4 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTENT:	12 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	55.0 kPA
	FRICTION ANGLE:	15.8°

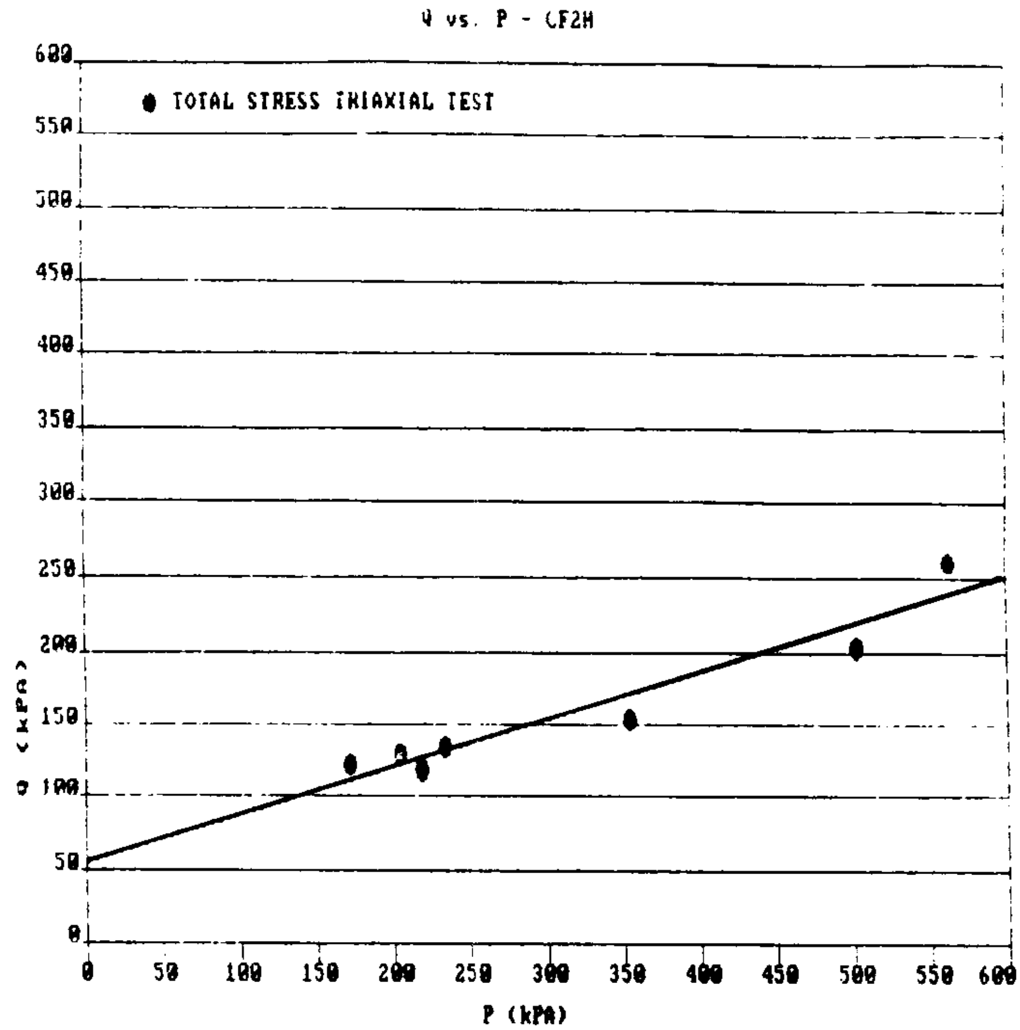

Figure 53. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER:	CF2	
DRY DENSITY:	1.38 g/cm³	
WATER CONTENT:	23.4 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTENT:	12 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	58.0 kPA
	FRICTION ANGLE:	19.2°

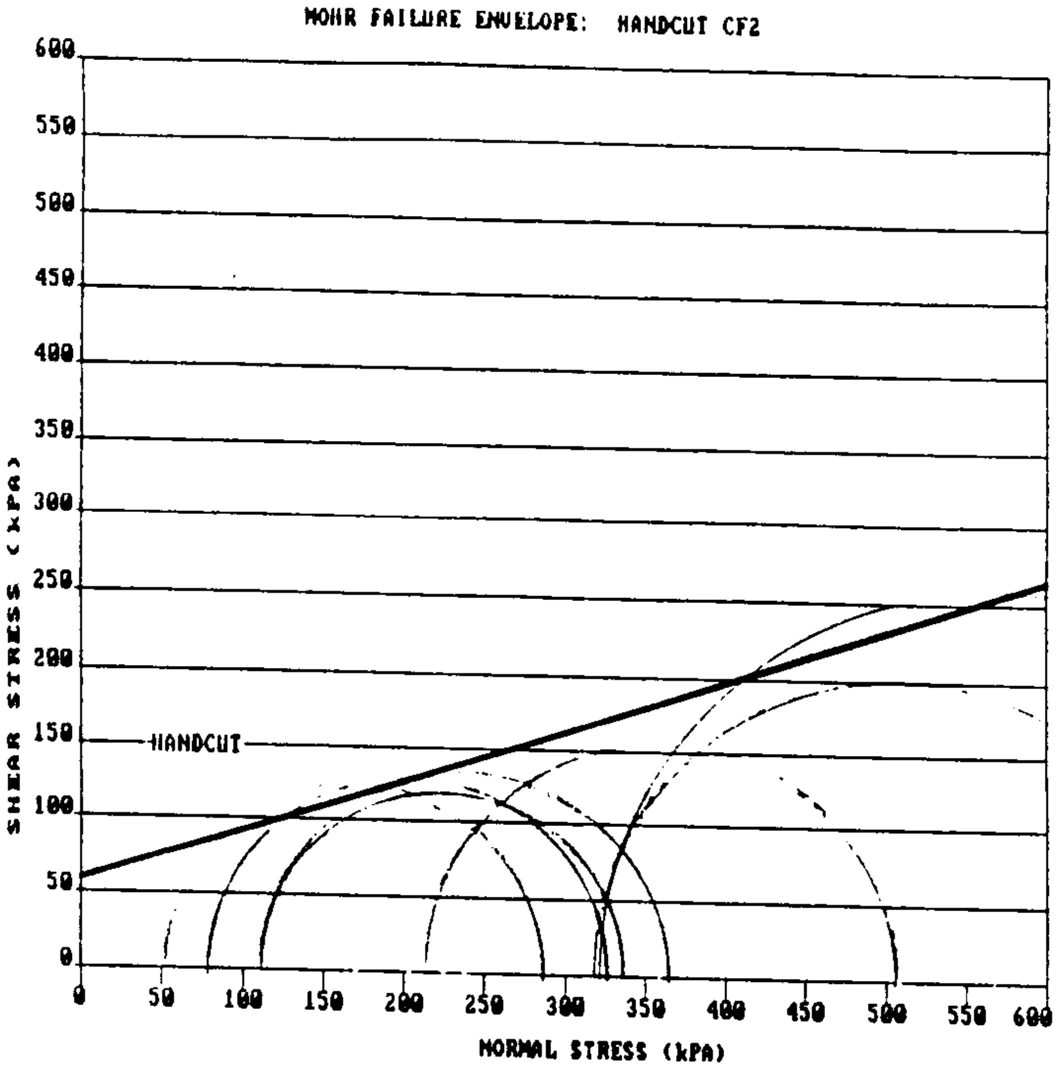

Figure 54. UCU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER:	CF2	
DRY DENSITY:	1.38 g/cm³	
WATER CONTENT:	23.4 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTENT:	12 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	58.0 kPA
	FRICTION ANGLE:	19.2°

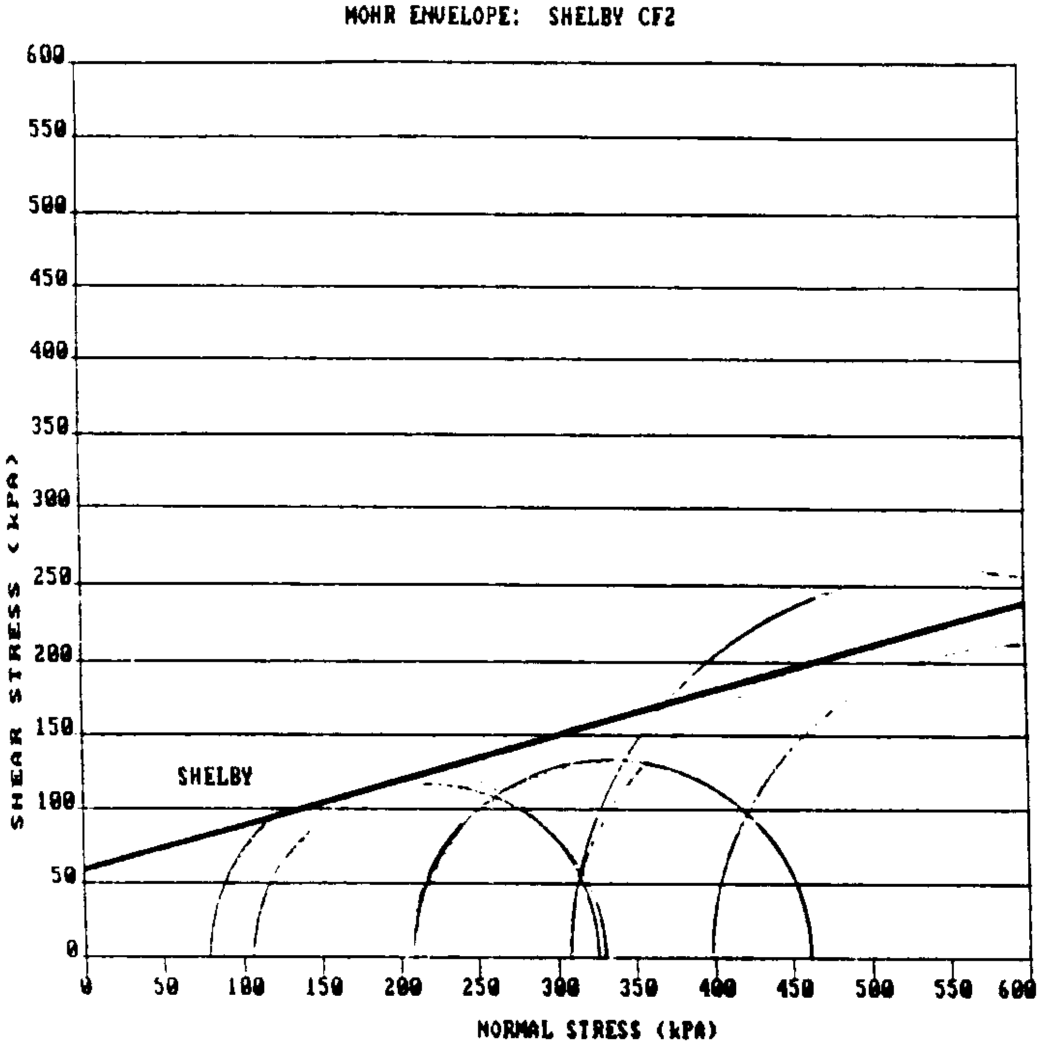

Figure 55. UCU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER:	CF2	
DRY DENSITY:	1.57 g/cm^3	
WATER CONTENT:	23.4 %	
SPECIFIC GRAVITY:	2.72	
CLAY CONTENT:	12 %	
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	55.0 kPA
	FRICTION ANGLE:	15.8°

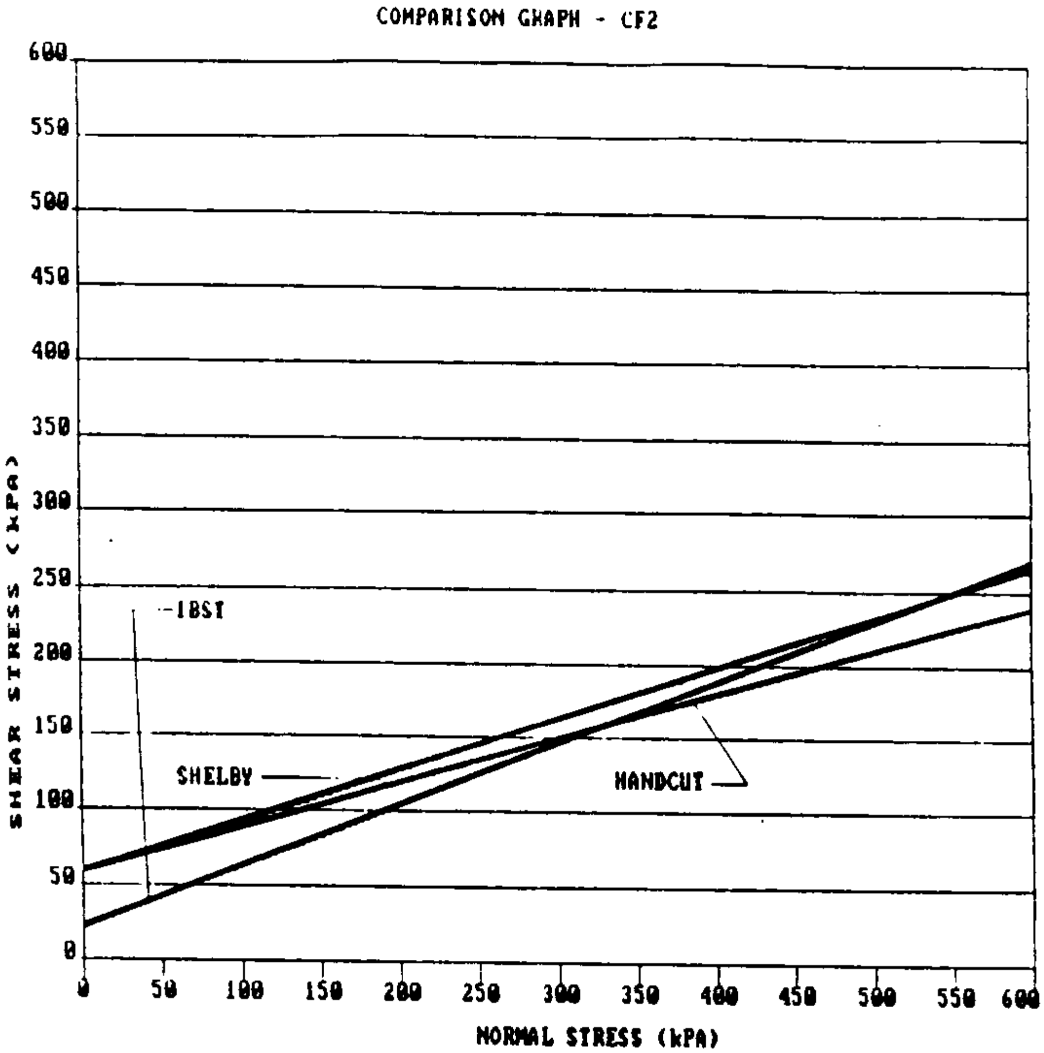

Figure 56. Comparison Graph of CF2 by Test Type

SITE NUMBER:	CF2		
DRY DENSITY:	1.38 g/cm³ (Handcut), 1.57 g/cm³ (Shelby)		
WATER CONTENT:	23.4 %		
SPECIFIC GRAVITY:	2.72		
CLAY CONTENT:	12 %		
UCU TRIAXIAL:	HAND-CUT SPECIMEN		
	COHESION:	58.0 kPA	
	FRICTION ANGLE:	19.2°	
UCU TRIAXIAL:	SHELBY SPECIMEN		
	COHESION:	55.0 kPA	
	FRICTION ANGLE:	15.8°	
IBST: 1	COHESION:	21.0 kPA	
	FRICTION ANGLE:	22.6°	

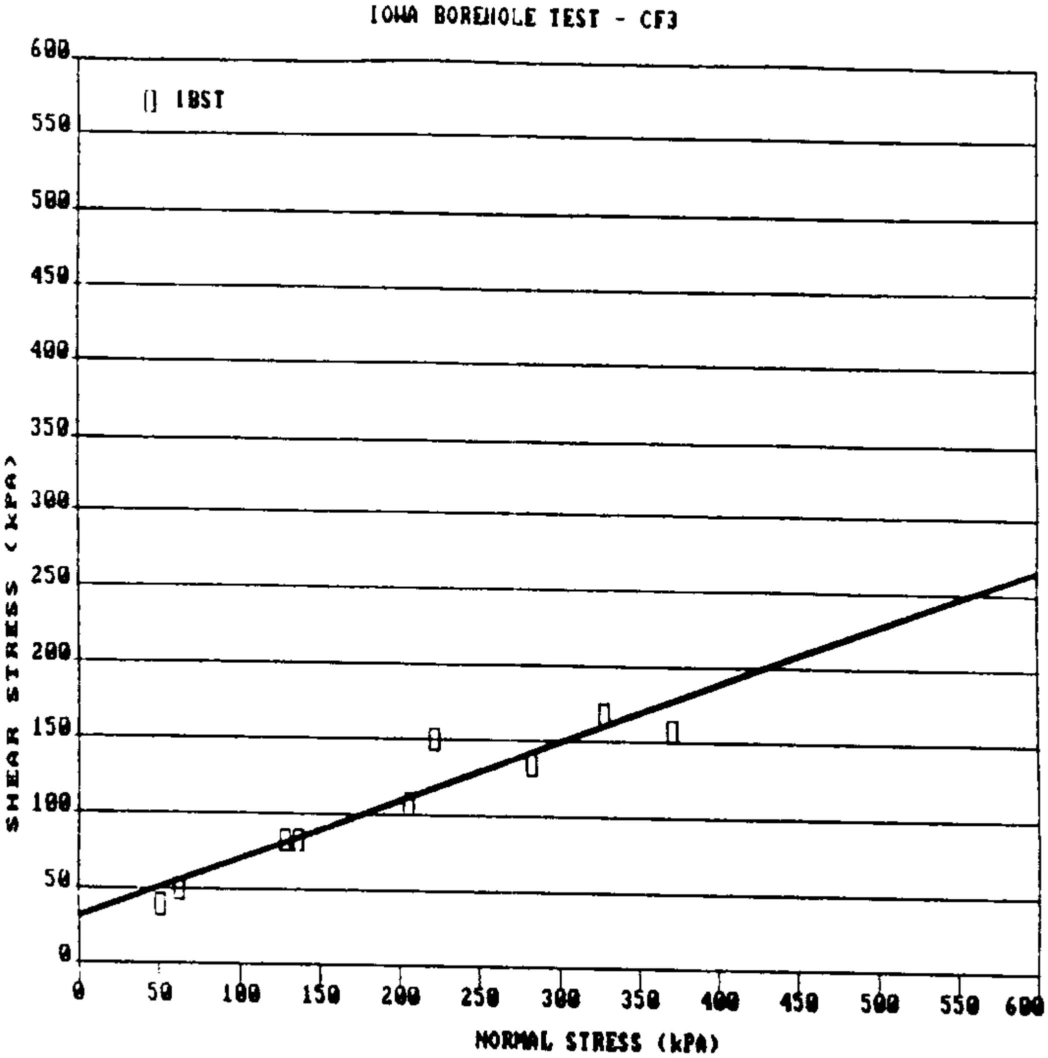

Figure 57. IBST Mohr Envelope in Clayey Loess

SITE NUMBER:	CF3	
DRY DENSITY:	1.33 g/cm³	
WATER CONTENT:	31.4 %	
SPECIFIC GRAVITY:	2.71	
CLAY CONTENT:	18 %	
IBST: 1	COHESION:	29.2 kPA
	FRICTION ANGLE:	21.6°

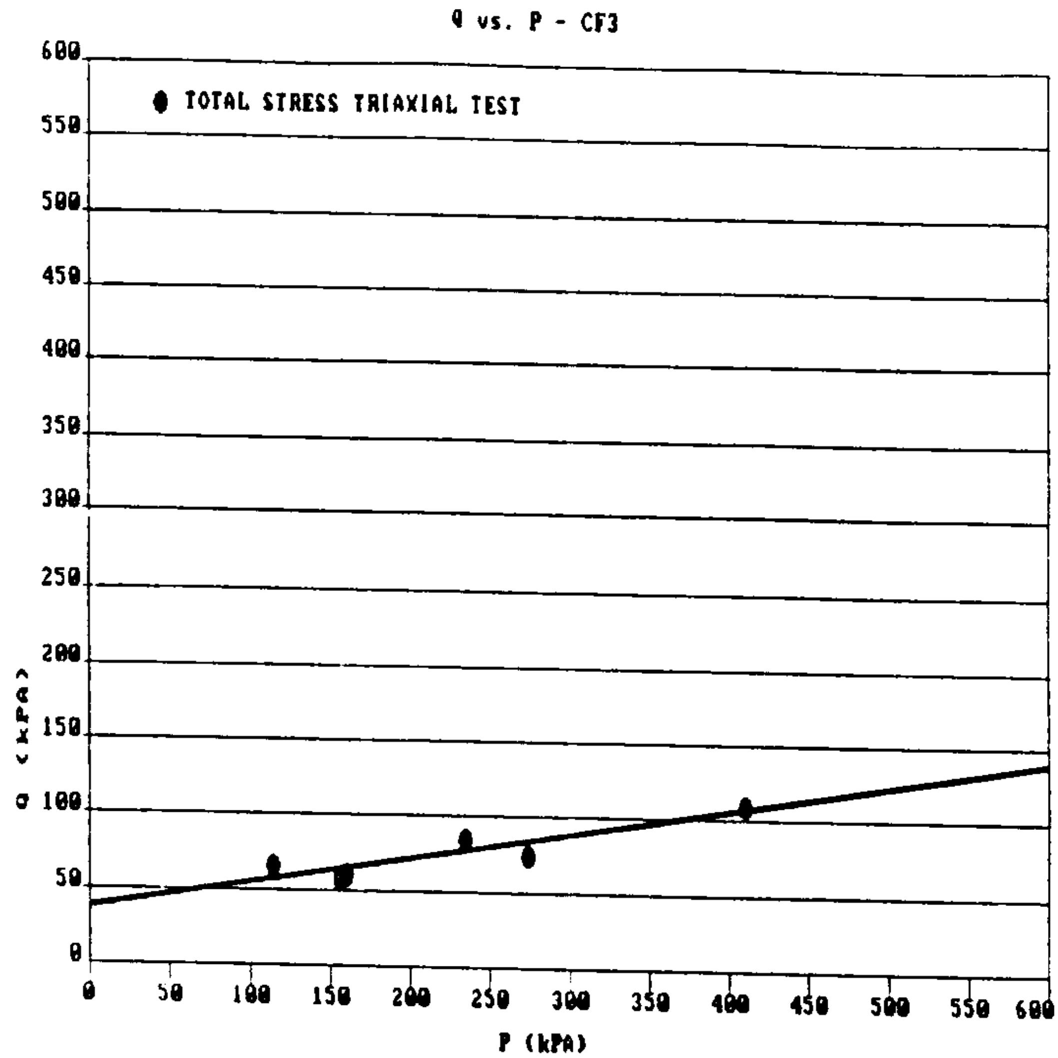

Figure 58. UCU Triaxial q vs. p Plot in Clayey Loess

SITE NUMBER:	CF3		
DRY DENSITY:	1.40 g/cm³		
WATER CONTENT:	31.4 %		
SPECIFIC GRAVITY:	2.71		
CLAY CONTENT:	18 %		
UCU TRIAXIAL:	SHELBY SPECIMEN		
	COHESION:	36.9 kPA	
	FRICTION ANGLE:	9.9°	

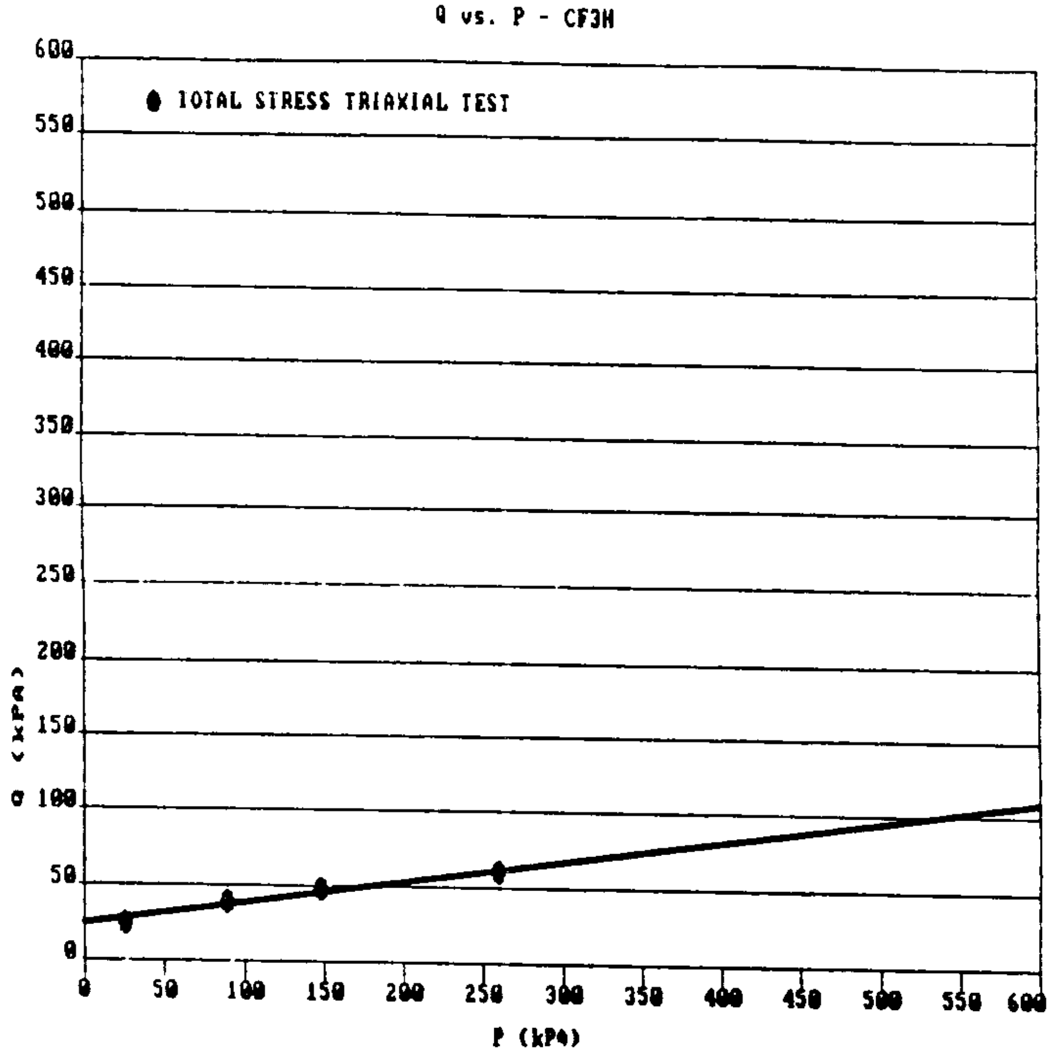

Figure 59. UCU Triaxial q vs. p Plot in Silty Loess

SITE NUMBER:	CF3
DRY DENSITY:	1.33 g/cm³
WATER CONTENT:	31.4 %
SPECIFIC GRAVITY:	2.71
CLAY CONTENT:	18 %
UCU TRIAXIAL:	HAND-CUT SPECIMEN
	COHESION: 25.0 kPA
	FRICTION ANGLE: 8.6°

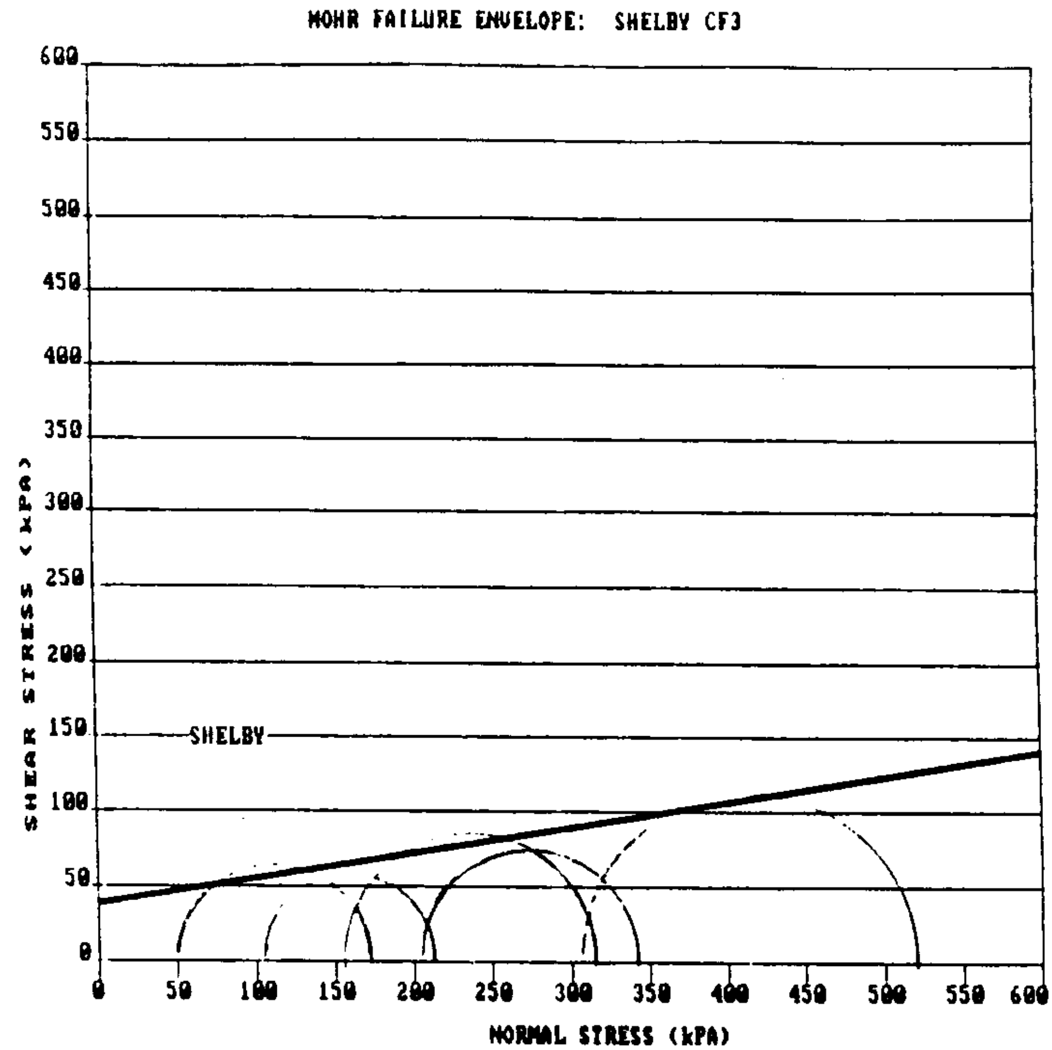

Figure 60. UCU Triaxial Mohr Envelope in Clayey Loess

SITE NUMBER: CF3
DRY DENSITY: 1.40 g/cm^3
WATER CONTENT: 31.4 %
SPECIFIC GRAVITY: 2.71
CLAY CONTENT: 18 %
UCU TRIAXIAL: SHELBY SPECIMEN
COHESION: 36.9 kPA
FRICTION ANGLE: 9.9°

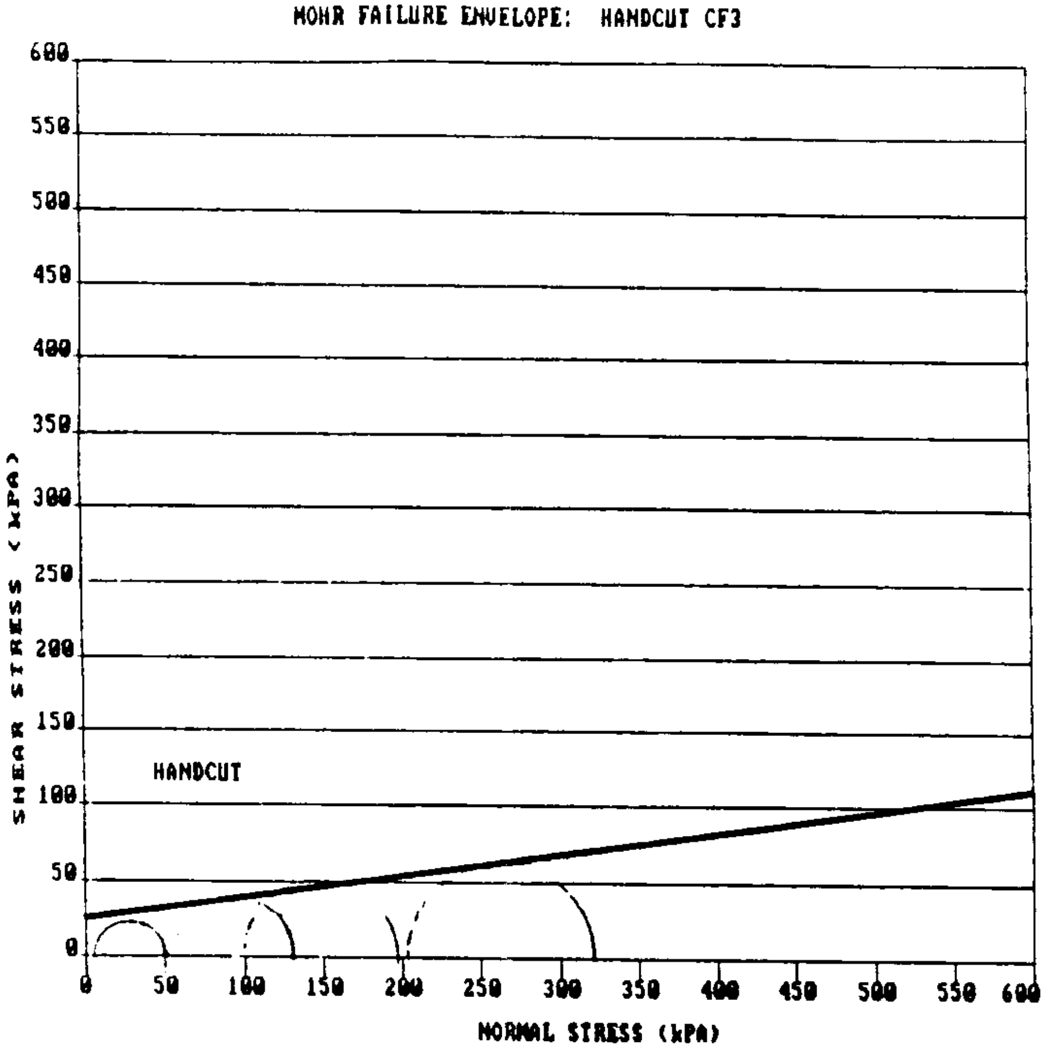

Figure 61. UCU Triaxial Mohr Envelope in Silty Loess

SITE NUMBER:	CF3	
DRY DENSITY:	1.33 g/cm³	
WATER CONTENT:	31.4 %	
SPECIFIC GRAVITY:	2.71	
CLAY CONTENT:	18 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	25.0 kPA
	FRICTION ANGLE:	8.6°

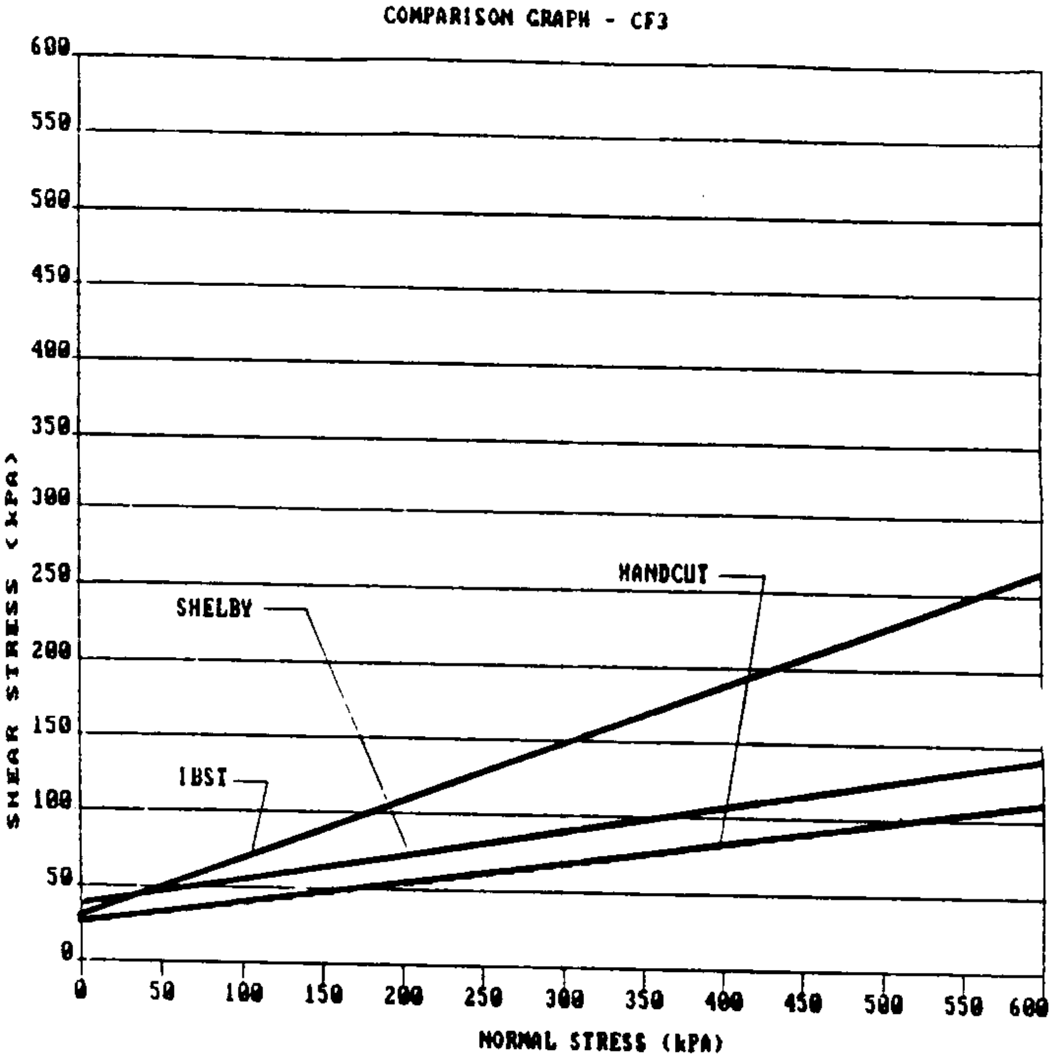

Figure 62. Comparison Graph of CF3 by Test Type

SITE NUMBER:	CF3	
DRY DENSITY:	1.33 g/cm³ (Handcut), 1.40 g/cm³ (Shelby)	
WATER CONTENT:	31.4 %	
SPECIFIC GRAVITY:	2.71	
CLAY CONTENT:	18 %	
UCU TRIAXIAL:	HAND-CUT SPECIMEN	
	COHESION:	25.0 kPA
	FRICTION ANGLE:	8.6°
UCU TRIAXIAL:	SHELBY SPECIMEN	
	COHESION:	36.9 kPA
	FRICTION ANGLE:	9.9°
IBST: 1	COHESION:	29.2 kPA
	FRICTION ANGLE:	21.6°