Final Report

DETERMINING THE SHEAR STRENGTH OF VARVED CLAY USING VANE SHEAR

by

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Table of Contents

Table of Figures

Introduction

A previous project (70-3) analyzed field data from fills built over the varved clay in the Connecticut River Valley. The analysis dealt primarily with rate and amount of settlement. No information on shear strength could be determined from the field data directly since there were no failures. The study of shear strength of the varved clays under the previous project was limited to a correlation of laboratory strength results from tests included in various design reports. There remained some question as to the value of the shear strength of the varved clay in the field.

During the Spring 1978, the Joint Highway Research Advisory Council approved a research project in the Department of Civil Engineering to study the strength of varved clay using vane shear. State Project 164-161 was selected from the work schedule of the ConnDOT Soils Section. The location is Kennedy Road in Windsor. This project involved the soils investigation for replacing bridges and approaches over an existing railroad.

The Field Vane Test

1. General

Many engineers find stability analyses of embankments based on undrained strength of the foundation clay both reliable and convenient. Modern vane shear apparatus was developed about thirty years ago in Scandinavia to estimate undrained strength(3). This test was developed to eliminate some of the disturbance due to sampling and conventional testing.

Several configurations of vanes have been tried. The most common vanes used for testing are described in ASTM D2573-72(7). Four rectangular vanes are arranged in a cruciform about a vertical shaft. Each vane has a length-to-width ratio of two. The vanes are inserted into the clay deposit and rotated at a predetermined rate, usually 0.1 deg./sec. The torque can be recorded as a function of rotation or only the maximum torque noted. The maximum torque is considered a measure of undrained strength. After the maximum torque is developed by the soil, the vane assembly is sometimes rotated rapidly through ten or more revolutions. Within a minute after rapid rotation of the vane, another torque measurement is begun. Maximum torque measured after ten revolutions is considered a measure of the remolded strength. Each measured torque must be corrected for friction. Procedures for determining the torque required to overcome friction in the assembly are described in the ASTM method.(7)

The measurement of the torque takes place at the ground surface. The vane can be pushed from the bottom of a borehole into the clay sufficiently far so that disturbance caused by advancing the hole is minimal. In the case of soft deposits the vane inside a sheath is advanced by pushing to the desired depth. The vane is then pushed ahead of the sheath and the torque applied and measurement taken. At the end of the test the vane is retracted inside the sheath and the entire assembly advanced to a new depth of interest.

2. Estimating Shear Strength-Standard Method

The undrained shear strength is estimated from the measured maximum torque. The derivation of the equation for this calculation can be found in various textbooks.(9)

Assuming the distribution of strength across the ends of the vanes (top and bottom) is uniform, the relation becomes:

$$T = \frac{Su\,\pi}{2} D^2H\,[1 + (D/3H)] \quad . . . . 1$$

where: T = torque, Su = undrained shear strength, D = diameter of vane assembly and H = vane height.

Any distribution of shear strength can be assumed across the ends, making the final equation slightly different. A larger value of Su can be calculated if the distribution of mobilized strength on the ends is assumed directly proportional to the radius. However, these assumptions have little effect on the computed values (about 5%).

3. Limitations of the test

The vane shear test has been under study for some time. While there is no way to demonstrate theoretically the relation between strength from the vane shear with strength from the triaxial test, engineers have found vane shear strengths useful when tempered with experience in a given locality.(5)

In some cases, the vane test has overestimated the shear strength of the soil. Several of these difficulties were easily traced to the presence of stiff inclusions such as shells or sand pockets.

Bjerrum(3) reviewed cases of embankment failures. In each case, the stability analysis used undrained strengths from vane tests. He concluded that in these cases, the error was caused by a viscous effect and the speed of vane rotation. The magnitude of the error increased with increasing plasticity index. His study included fourteen cases. From these cases, he developed the curve shown in Fig. 1. The correction factor "μ_R" is plotted on the vertical axis against the plasticity index on the horizontal axis. The correction factor is applied to the vane shear strength thus:

$$(Su)_{field} = (Su)_{vane} \cdot \mu_R \quad \text{. . . . . 2}$$

where: $(Su_{vane}$ = undrained strength computed from vane test; μ_R = correction factor; and $(Su)_{field}$ = value of undrained strength actually exhibited by the foundation clay.

As can be seen from Fig. 1 the value of μ_R is less than 1.0 for most clays indicating that the value of undrained strength as determined from a field vane test should be reduced for an accurate stability analysis.

The anisotropic properties of clays have also been investigated using the field vane. These studies systematically changed the shape of the vanes to measure the resistance in different directions. Aas investigated strength anisotropy by varying the ratio of H to D.(11) A similar study was accomplished with diamond-shaped vanes.(10) Bjerrum addressed the importance of anisotropy but did not develop a relation similar to the one shown in Fig. 1.(3) He did, however, suggest that another coefficient could be developed with sufficient data so that the correction equation would read:

$$(Su)_{field} = (Su)_{vane} \, \mu_R \, \mu_A \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 3$$

where: μ_A = correction factor for anisotropy; other symbols as before.

Vane Tests in the Varved Clay

The strength of varved clay has been investigated in various regions outside Connecticut.(1)(2)(6) On the basis of laboratory and field tests, Ladd and Foott(8) recommended that the $(Su)_{vane}$ be corrected with a $\mu = 0.85 \pm 0.05$ for overconsolidated varved clays whose failure arc is circular. In locations requiring a berm, where the most probable failure surface is a sliding wedge whose length is 3 to 4 times its depth, they recommended a value of $\mu = 0.75 \pm 0.05$.

Research Approach

Previous laboratory tests indicated that the strength of varved clay is anisotropic. The feasibility of using diamond-shaped vanes for testing on this project was investigated.(10) However, vanes of the proper dimensions could not be passed through the available borehole casing.

It was, therefore, decided to use the standard vane and correlate vane strengths with unconsolidated-undrained tests run on samples as they were recovered in the field. In this way, disturbance due to transporting and storing the samples would be eliminated and the results using the vane could be compared to conventional tests in a triaxial apparatus.

A special device was fabricated to test the feasibility of conducting the vane test by pushing an apparatus to the desired depth. This apparatus is shown in Fig. 2. Figure 2 shows the shaft partially retracted. When fully retracted the shaft is locked on the lugs at the top of the apparatus. When the desired depth is reached, the inner shaft is rotated one-quarter turn and pushed down approximately two feet to make the test. At the end of the test the vanes are pulled up, the shaft is again locked and the apparatus pushed forward.

Field Procedure

Every effort was made to combine this testing with the normal procedures of the field crew from ConnDOT's Soil Division causing as little delay as possible. The field crew advanced the boreholes, extracted samples for triaxial testing and supplied a Sprague and Henwood field vane apparatus. UConn personnel conducted the vane and triaxial tests in the field. Several successful tests were made with the new field vane apparatus. However, the resistance to pushing the apparatus through the varved clay was considerable. It was decided to attempt driving it into the clay. However, the lugs could not stand the shock of driving and sheared off.

A Wykham-Farrance triaxial test apparatus was used for the unconsolidated-undrained tests. A sample extractor was used to remove the soil from the Shelby tubes as soon as they were recovered from the borehole. Cylindrical samples 1.5 inches in diameter by 3 inches long were trimmed and mounted on the pedestal of the triaxial cell. A rubber membrane was placed around the sample and secured to the pedestal and loading cap on top of the sample with "O" rings. The chamber was secured to the base, then filled with water and placed in the loading frame. The chamber pressure was increased by applying air pressure to the water surrounding the sample. The triaxial test was conducted by increasing the vertical stress until failure occurred.

Electrical power for the triaxial apparatus, extractor and air compressor was supplied by a Kohler portable generator.

Laboratory Tests

Two thin-walled-tube samples were sealed with paraffin in the field and transported to the laboratory for testing. Two consolidation tests and three consolidated-undrained triaxial shear-strength tests were run on these soil samples. The consolidation pressures used in the tests were 12.21 and 22.4 psi. All tests were run with back pressure.

The consolidation test was run in a brass ring, three inches in diameter and one inch thick. The triaxial tests were run in the same apparatus used in the field.

Results

The results of the tests conducted in the field are shown in Fig. 3. The measured Su is plotted with depth. As can be seen from Fig. 3, the strength of the clay first decreases with depth, then increases. This pattern is often found in clays that have been desiccated and is typical of the Connecticut Valley varved clays. The special vane fabricated for this project yields approximately the same value for Su as the standard vane, and the triaxial-test results are about the same as the field vanes. Fig. 4 shows the stress-strain curves for these tests.

Figure 5 shows the consolidation results of the sample that contained both clay and silt varves. The recompression ratio based on strain (RR) is 0.07. The virgin compression ratio based on strain is 0.19 and the apparent maximum past pressure is 3 tons/ft^2. The recompression ratio is higher than analyzed from field data.$^{(12)}$ The virgin compression ratio is lower. These differences may be the effect of disturbance.

Figure 6 shows a consolidation test on a silt varve. The recompression ratio is 0.015. Both these samples were taken from a depth of 12-14 feet.

A summary of test results is shown in Fig. 7. The ratio of undrained strength to approximate consolidation pressure is plotted against the log of the overconsolidation ratio. The ratio of undrained strength to consolidation pressure on the sample ($Su/\bar{\sigma}_c$) increases with overconsolidation ratio. The results in Fig. 7 indicate that laboratory samples should be tested consolidated-undrained. The consolidation process overcomes some of the disturbance due to transportation and handling of samples.

Observations

1. During the field work for this project one vane shear test with the standard Sprague and Henwood Apparatus required about as much time as running one triaxial unconsolidated-undrained test. The tests with the U. Conn. Apparatus were faster, when the apparatus could be pushed to the desired depth. Measuring shear strength by vane could probably be made simpler if an apparatus were fabricated that could be driven with a standard 140 lb weight, then the vanes pushed ahead, and the torque applied with readings taken automatically.

2. The shear strength values from the two types of tests compared about as well as reported tests from sites in the same varved clay in Massachusetts. (8)

Conclusions

1. Standard vane shear testing in the field yields approximately the same value of undrained strength as the unconsolidated-undrained test.

2. The testing time in the field could be shortened using an apparatus that could be pushed or driven to the desired depth.

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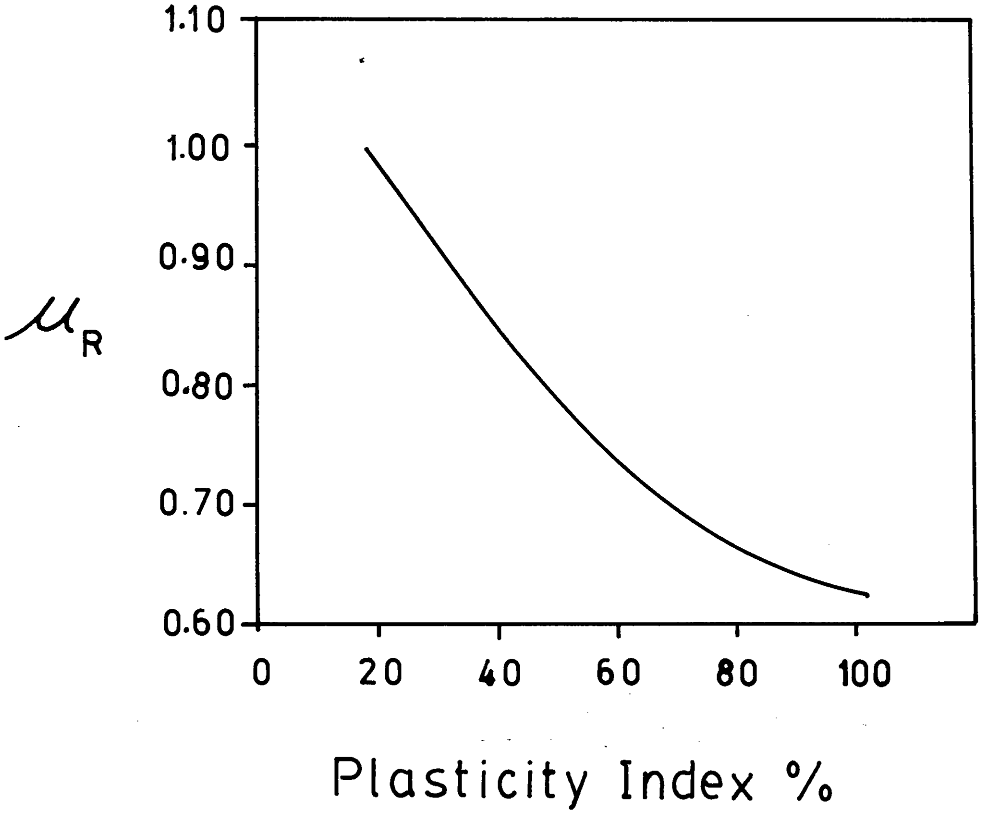
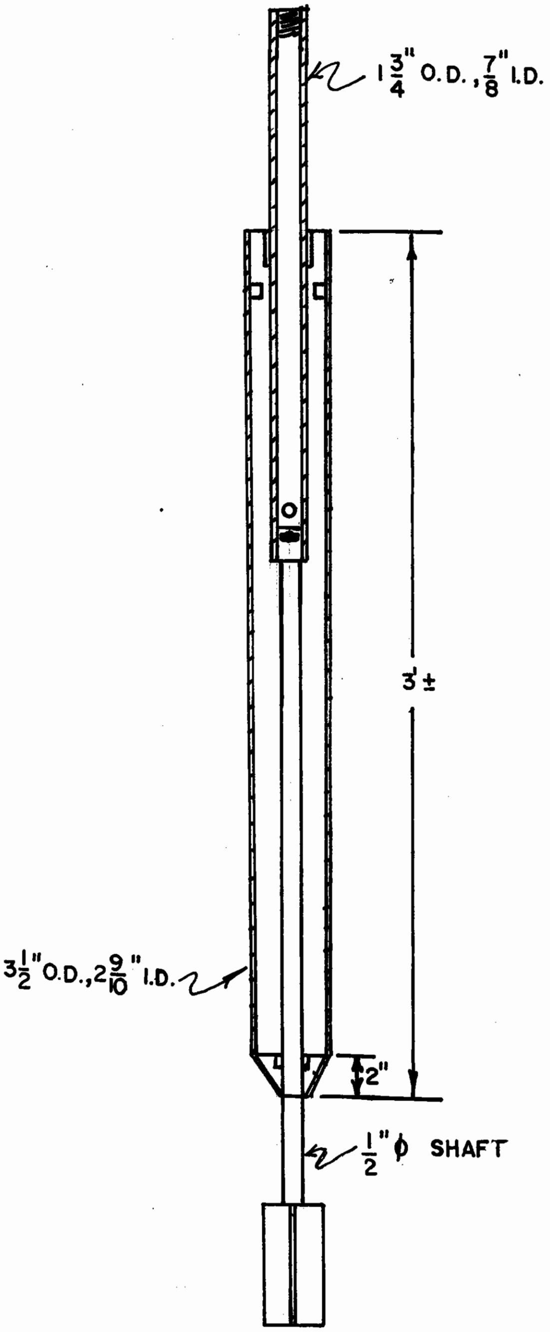


Fig. 1 Bjerrum's Correction Factor



NOT TO SCALE

Fig. 2 U. Conn. Vane

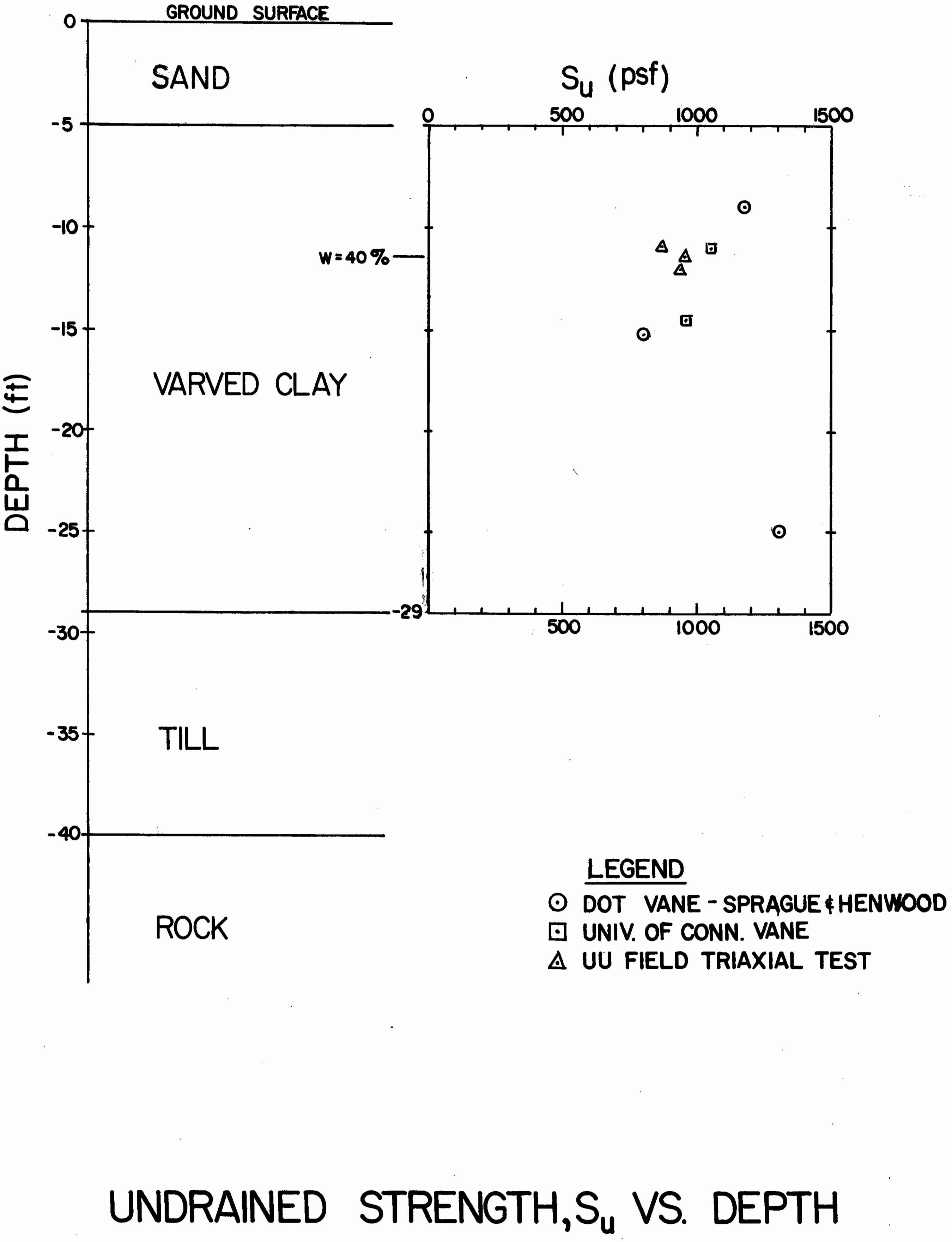


Fig. 3 Undrained Strength vs. Depth

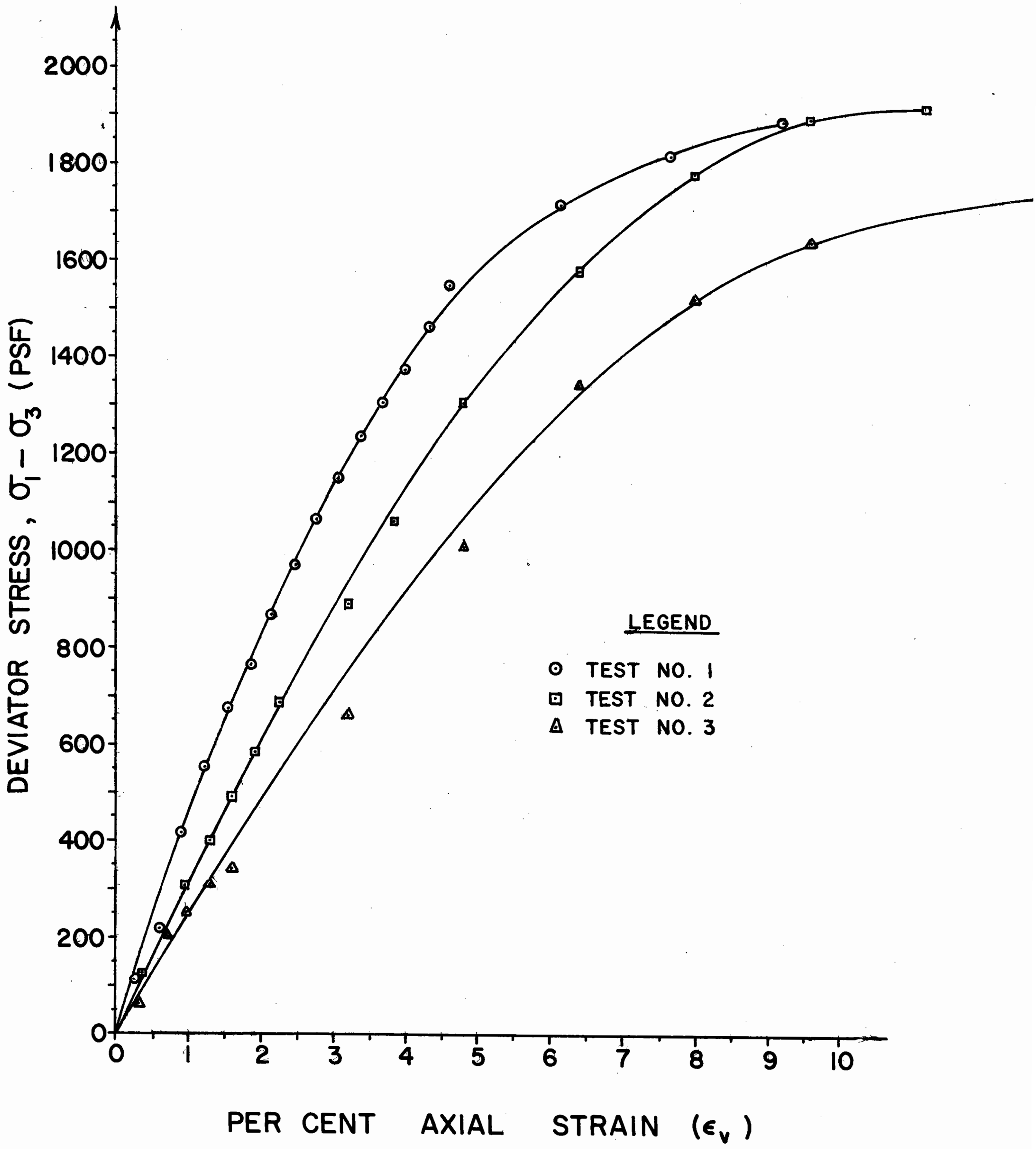


Fig. 4 UU Test Results

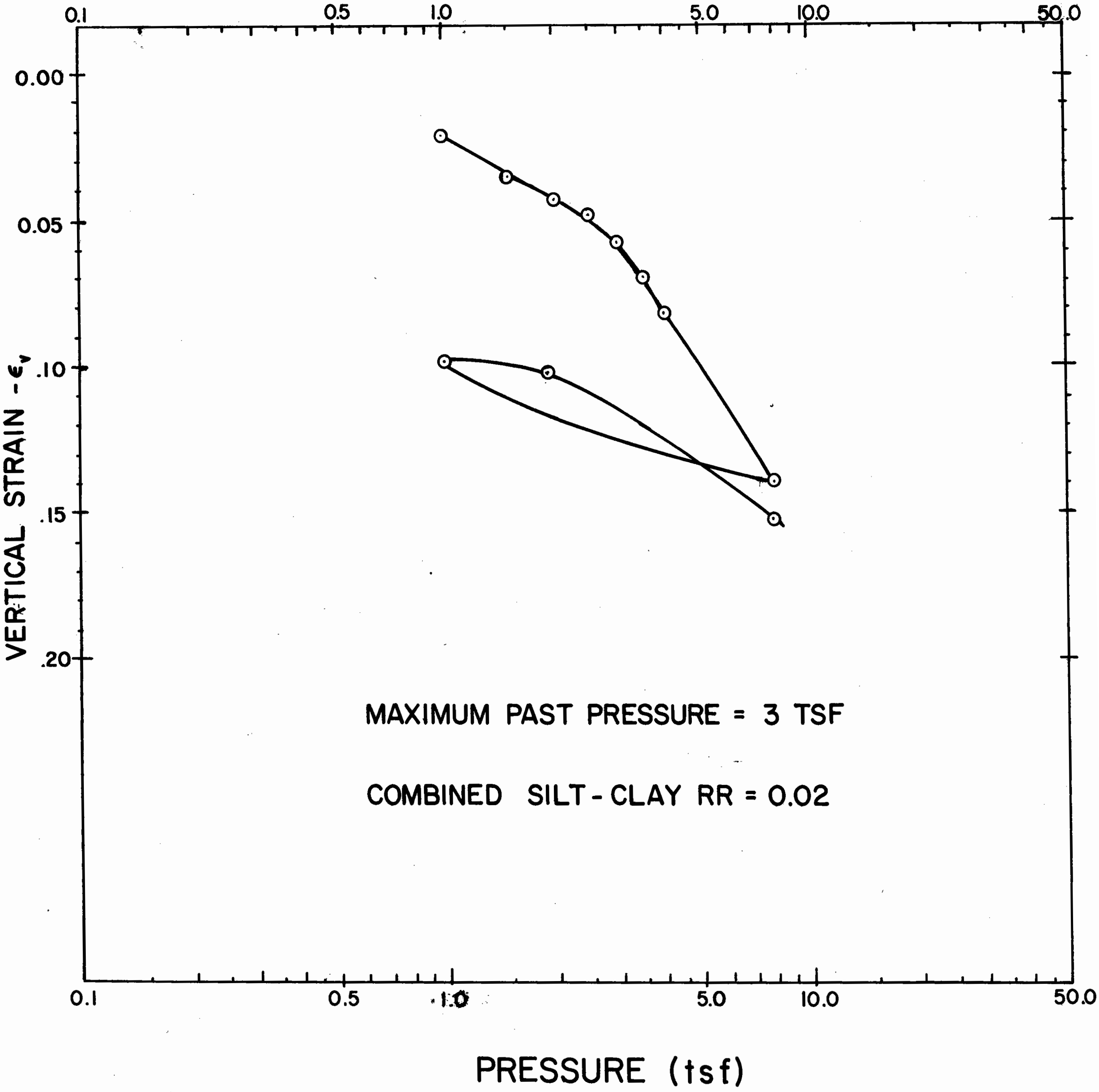


Fig. 5 Compression Curve for Clay Varve

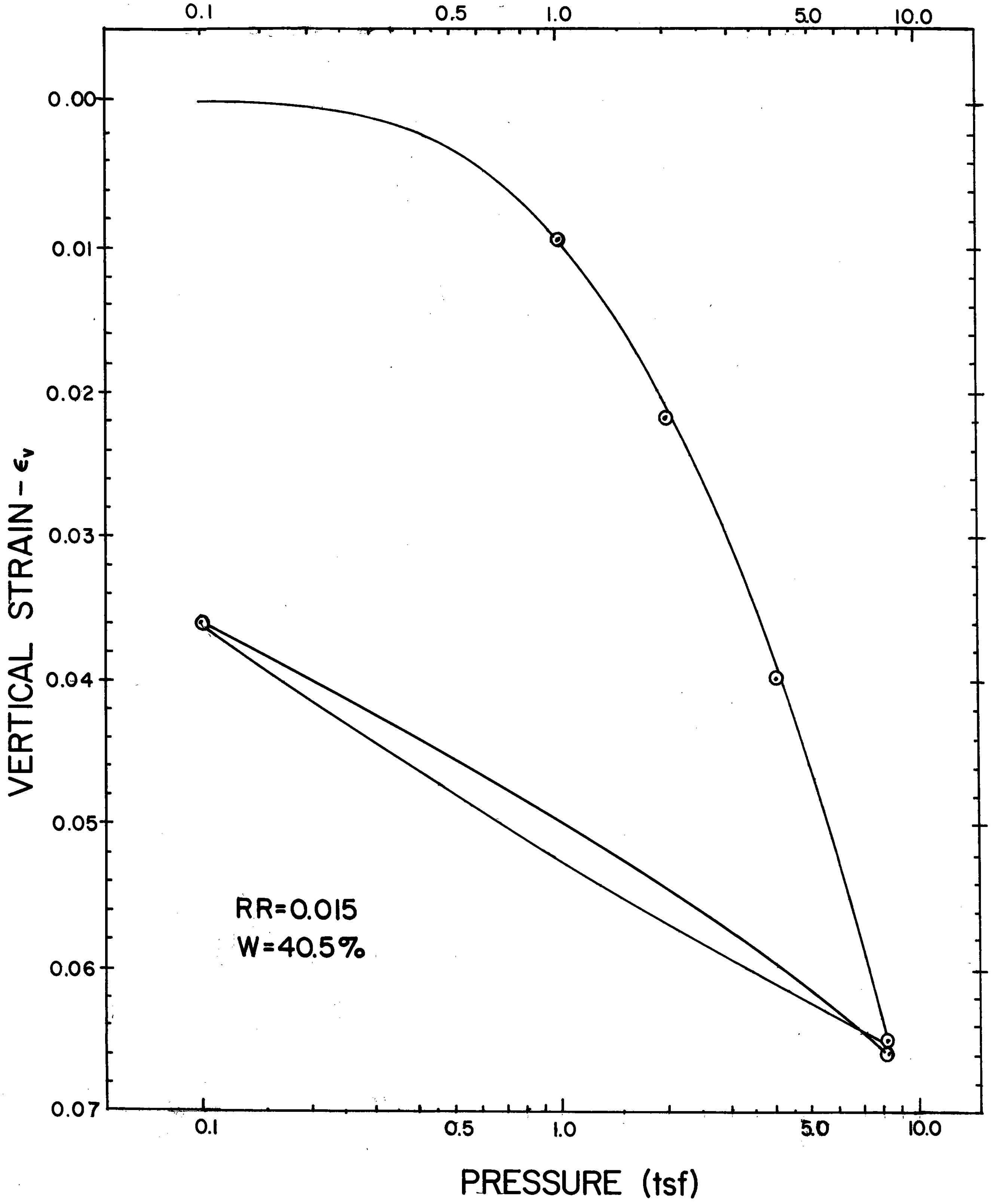


Fig. 6 Compression Curve for Silt Varve

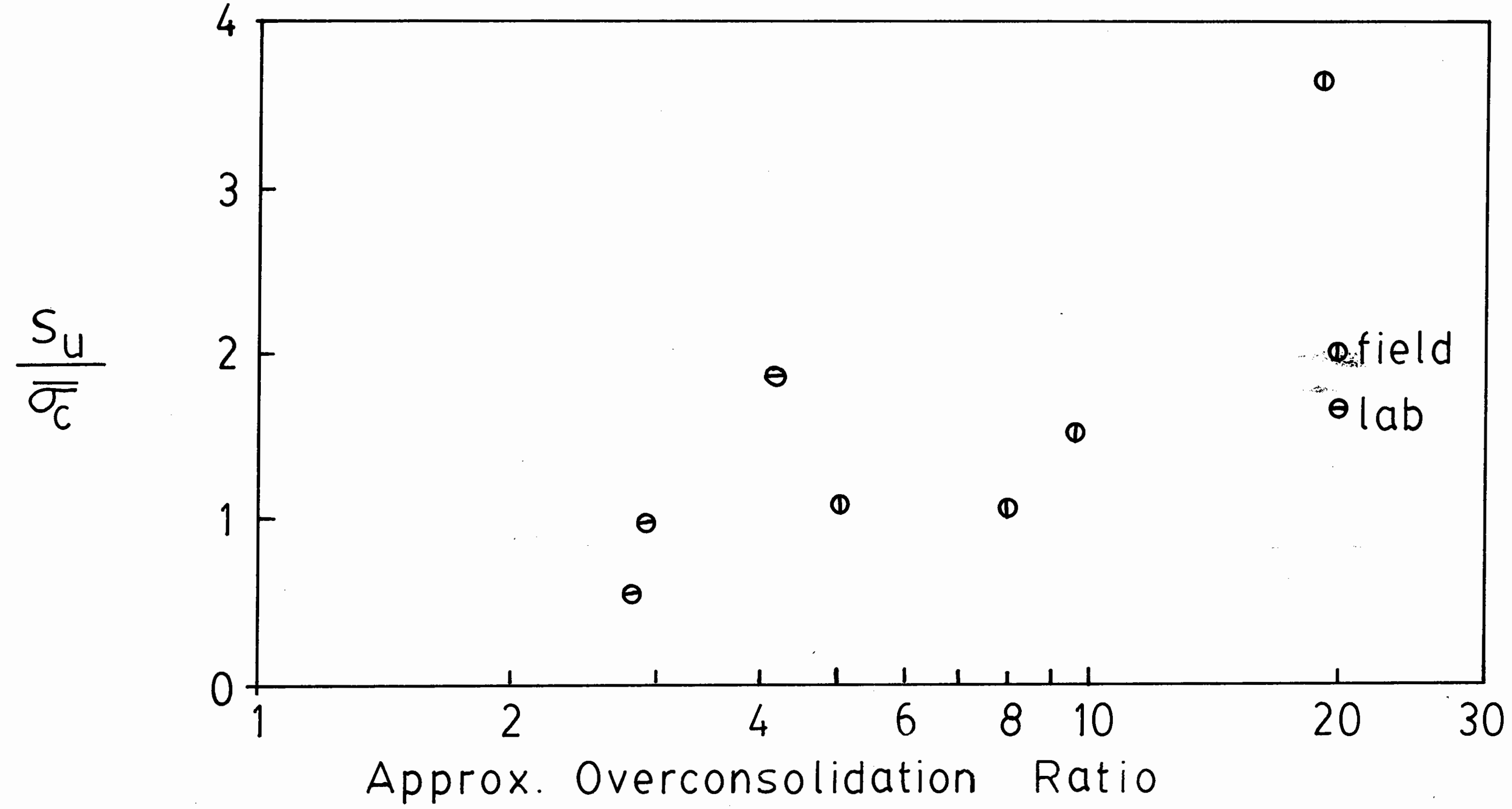


Fig. 7 Plot of Undrained Strength Data