V. DEEP SEA DRILLING PROJECT PROCEDURES FOR SHEAR STRENGTH MEASUREMENT OF CLAYEY SEDIMENT USING MODIFIED WYKEHAM FARRANCE LABORATORY VANE APPARATUS

Robert E. Boyce, Scripps Institution of Oceanography, La Jolla, California

INTRODUCTION

The purpose of this paper is to present the Deep Sea Drilling Project (DSDP) procedures pertaining to shear strength measurements on fine-grained clayey sediment, which are performed using a modified Wykeham Farrance "Laboratory Vane Apparatus." I will here define shear strength, and then briefly discuss (1) the Coulomb-Hvorslev shear strength equation, and note how the friction and cohesion components are related to the nonclay and clay sediments, respectively; (2) the relationship of shear strength to pore pressure, drainage, and grain-size distribution; and (3) the prerequisites for a proper sample for vane shear measurement. The main body of the text will provide (1) a derivation of technical formulas which apply to the vane equipment and its calibration; (2) step-by-step procedures; and (3) calculation of the original shear strength, and sensitivity. The appendices contain calibration data and descriptions of the vane equipment.

"Shear strength of a soil, or sediment mass, is the summation of the forces of friction, cohesion, and bonding which combine to resist failure by rupture along a slip surface or by excessive plastic deformation under applied stresses" (Moore, 1964). However, shear strength is a complex property which is also related to the rate of shearing, the manner and rate of stress application, mineralogy (clay type), cementation, grain-size distribution, sample disturbance, pore pressure, permeability and drainage of the pore water during shearing (Richards, 1961; Moore, 1964; Wu, 1966; Scott and Schustra, 1968; Lamb and Whitman, 1969; Kravitz, 1970; and others).

According to Richards (1961) and Kravitz (1970), the following shear failure theory is the Coulomb (1776) failure equation as modified by Hvorslev (1936; 1937). Shear strength of a sediment at failure, τf, is as follows:

$$\tau_f = c + (\sigma - \mu) \tan \phi \qquad (1)$$

where

- c = cohesion,
- σ = normal stress on the plane of failure,
- μ = excess pressure in pore water,
- ϕ = angle of internal friction,
- $(\sigma\text{-}\mu)$ = effective stress,

Equation 1 has two components: cohesion, c, friction, $(\sigma\text{-}\mu)$ tan. As summarized by Hamilton (1969), "Shear strength in sands, without significant amounts of fine silt and clay is defined by the friction component (i.e., these are 'cohesionless' sediments). Most silt-clay sediments have both cohesion and friction (under normal stress). A few clays may have no angle of internal friction, in which case the shear strength is defined by cohesion alone."

$$\tau_{f_{\text{clay}}} = c \qquad (2)$$

According to Kravitz (1970): "In studies involving completely saturated clays of low permeability, such as those found in ocean environments, shear strength is usually obtained under conditions of no change in water content. This procedure is called undrained or quick testing. During undrained (quick) testing the normal stress"..."of zero. The saturated sediment then behaves with respect to the applied stresses at failure as a purely cohesive material with an angle of shearing resistance"..."equal to zero. When these conditions are met the equation for shear strength is expressed as "τf = c..."(Fellenius, 1927 and Skempton and Golder, 1948)."

However, according to Moore (1964), Equation 1 is used mainly as a simplified relationship "...for the convenience of calculating engineering properties of soils, it is generally understood that actual isolation of the cohesional and frictional components of sediments is theoretically unrealistic (Lambe, 1961)."

The relationships of Equations 1 and 2 to undrained shear strength in saturated clayey sediments are discussed by Schmertmann and Osterberg (1960), Richards (1961), Wu (1966), Hamilton (1969), Kravitz (1970), and others. Lamb (1960) discusses the shear strength of coarse sediments with respect to the additive relationships of cohesion, friction, interference, and dilatancy.

The following are some examples of the physical changes which may occur in a sediment sample when it shears: (1) the sample may expand or contract depending on the grain size distribution and packing structure; (2) the shearing stress may be in part directed upon the pore water trapped in the sediment, if the sample is very fine-grained and impermeable (undrained sample); (3) or shearing force may be entirely directed upon the grain-to-grain structure if the sample's grain size is large and the sample is highly permeable allowing the water to drain (drained sample); (4) and if a sample is moderately permeable, then the shear strength will be in part related to (a) the rate at which the shearing stress is applied, and (b) the rate which the pore water drains out of the sample.

DSDP VANE SHEAR SAMPLE

For DSDP samples for "shear strength determination" with the vane shear technique, a fine-grained sample is selected so that permeability is low enough that the sample is assumed to be "undrained" (no water flowing through the pores) during the shear test. To enhance this relationship the vane shear speed must be very rapid (Lamb and Whitman, 1969; Scott and Schoustra, 1968) and thus the DSDP vane shear device is set at 89° of torque per minute (compared with the typical 6° per minute suggested in ASTM, 1975). These shear strength measurements are conducted under laboratory pressures and temperatures.

Relatively undisturbed clayey sediment samples are selected. A criterion for disturbance is visibly undistorted bedding, although a truly undisturbed sample does not exist.

VANE SHEAR TECHNIQUE

The vane shear technique was originally developed by the British Army (Skempton, 1949) to measure the cohesion of clay sediments, which is the shear strength in certain special cases. Basically the vane shear device (Appendix A) consists of a 4-bladed vane (each blade 90° from the others) to which a known torque is applied (DSDP torque is applied at a rate of about 89° per minute). When the vane is inserted into a clay sediment (assumed to be undrained), torque is applied to the vane axis until it shears about a surface area which approximates that of a cylinder with the diameter and height of the vane. Since the torque applied to the vane is measured (just before shear failure) by a calibrated spring stress, the shear strength can be calculated. The vane theory, spring calibration, and general calculations and procedures are described below.

Vane Shear Formulas

Formulas using the vane's geometric measurements have been discussed in detail by several investigators (Skempton, 1949; Gibbs et al., 1960; ASTM, 1975). In order to relate DSDP data to the literature we will show the development of formulas as published by Gibbs et al. (1960) and Skempton (1949) and then indicate the formulas DSDP uses.

As shown by Gibbs et al. (1960), Equations 3 through 9 below show the derivation of the torque computations as related to a vane:

$$\text{Total torque} = T = T_1 + 2T_2 \tag{3}$$

where

T_1 = torque resistance on the vertical cylindrical surface.

$2T_2$ = torque resistance on the horizontal top and bottom, assuming constant unit shear resistance.

$$T_1 = (2\pi rh)rc = 2\pi chr^2, \text{ where } h = \text{vane height, } r, \text{ vane radius} \tag{4}$$

$$T_1 = 8\pi cr^3, \text{ when the height, } h, \text{ is twice the diameter} \tag{5}$$

$$dT_2 = c(2\pi x dx)x \tag{6}$$

$$T_2 = 2\pi c \int_0^r x^2 dx = 2\pi c \frac{r^3}{3} \tag{7}$$

Thus for geometry of Biggs' vanes, where the height is twice the diameter, Equations 8 and 9 below are appropriate, which Gibbs et al. (1960) derived by substituting Equations 5 and 7 into Equation 3:

$$T = 8\pi cr^3 + \frac{4\pi cr^3}{3} = \frac{28}{3}\pi cr^3 \tag{8}$$

Therefore,

$$c = \frac{3T}{28\pi r^3} \tag{9}$$

However, the geometry of DSDP's vanes, where the height is not necessarily twice the diameter, slightly different equation forms are derived below by substituting Equations 4 and 7 into Equation 3:

$$T = 2\pi c\, hr^2 + 2\,(2\pi c \frac{r^3}{3}) \tag{10}$$

$$= 2\pi c\, r^2\,(h + \frac{2r}{3}) \tag{11}$$

$$= 2\pi c\, r^2 h\,(1 + \frac{2r}{3h}) \tag{12}$$

Equation 12 will be shown to be equivalent to Skempton's (1949) equation below. According to Skempton (1949).

$$\tau_f = c = \text{shear strength for clays}$$

$$= \frac{2T}{\pi(d)^2 h\,(1 + \frac{1d}{3h})} \tag{13}$$

where, d = diameter of the vane.

Therefore,

$$2T = c\,\pi(d)^2\,h(1 + \frac{1d}{3h}) \tag{14}$$

substituting $2r$ for d:

$$2T = c\,\pi(2r)^2\,h(1 + \frac{2r}{3h}) \tag{15}$$

$$T = 2c\,\pi\,r^2\,h(1 + \frac{2r}{3h}) \tag{16}$$

Equations 12 and 16 are identical, therefore the Skempton (1949) equation (13) is equivalent to the equations derived from Gibbs et al. (1960).

The formula that the DSDP uses is derived from Equation 13, by substituting the spring torque for T as follows:

$$\tau_f = c = \left[\frac{2t}{\pi d^2 h\,(1 + \frac{d}{3h})}\right](\text{maximum degree spring stress}) \tag{17}$$

where

t = spring torque factor in (g-cm)/degree

T = t X (maximum degree spring stress)

c = τf = cohesion and shear strength of clays at failure.

When inserting the vanes into the sediment, there is a certain length of the vane's rod in the sediment above the buried vane blades. This rod may have a certain friction or cohesion component, which the investigator may calculate using the rod diameter (in Appendix B) and the depth that the rod is buried in the sediment. Any DSDP investigator should state whether or not he applied a correction for the buried part of the rod. However, current practice among specialists is to ignore this correction.

Vane Height and Diameter

For detailed vane measurements see Appendix II. The present (March, 1975) vanes have the following average diameters and heights:

Vane 1: Diameter = 1.278 cm
Height = 1.2785 cm

Vane 2: Diameter = 1.281 cm
Height = 1.284 cm

Vane 3: Diameter = 1.273 cm
Height = 2.539 cm

Vane 4: Diameter = 1.272 cm
Height = 2.544 cm

Spring Constants

Each spring is calibrated by applying a known torque to the spring and measuring its rotation or strain to the nearest one-half degree of rotation. See Appendix C for techniques, calibration data, and constants. A summary of the Spring Factor calibrations is as follows:

Spring 1 = 9.1185 (g-cm)/degree = t

Spring 2 = 20.219 (g-cm)/degree = t

Spring 3 = 32.718 (g-cm)/degree = t

Spring 4 = 51.106 (g-cm)/degree = t

At the time of calibration, these factors were reproducible within 0.5% to 0.3%.

Example Calculations of Shear Strength

Examples of the shear strength calculations are as follows, when using Vanes 1, 2, 3, or 4. Substitute the diameter and the height of each vane into Equation 17, and then reduce Equation 17 to the following equations with constants for Vanes 1, 2, and 3 or 4, respectively:

Vane 1 equation and vane constant:

Shear strength =

$$c = (0.22858 \text{ cm}^3)\ t \text{ (maximum degree spring stress)} \quad (18)$$

Vane 2 equation and vane constant:

Shear strength =

$$c = (0.22665 \text{ cm}^3)\ t \text{ (maximum degree spring stress)} \quad (19)$$

Vanes 3 and 4 equation and vane constant:

Shear strength =

$$c = (0.13264 \text{ cm}^3)\ t \text{ (maximum degree spring stress)} \quad (20)$$

Therefore, in summary, when Vanes 1 or 2 are used during the tests, then Equations 18 or 19, respectively, are used to calculate the shear strength. When Vanes 3 or 4 are used during testing, then Equation 20 can be used in both cases to calculate the shear strength.

PROCEDURES

Two tests are run: (1) a shear strength test on the original, "relatively undisturbed" sample, and (2) a shear strength test on the same sample after it has been remolded. These tests are supplemented by collecting porosity, wet-bulk density, water content, and grain-size samples.

The shear strength measurement of the original "relatively undisturbed" sample is done as outlined below:

1) First a relatively undisturbed clay sample is selected. The sample is assumed to be relatively undisturbed if sedimentary structures are present and are not distorted.

2) It is desirable to orient the vane so that its axis is perpendicular to the bedding in the sediment, therefore if it is possible, the vane axis is oriented parallel to the core's axis and is inserted into the end of the unsplit section. If this is not practical, either because of core disturbance or coarse-grained sediment at the section ends, then the core is split along its axis and the vane axis is then oriented parallel[2] to the sedimentary bedding, which is perpendicular to the core's axis. Vanes 3 or 4,[3] which have the longer blades (about 2.54 cm), are used when the vane is inserted parallel to the core's axis, and Vanes 1 or 2, with the shorter blades (approximately 1.27 cm), are used when the core has been split along its axis and the vane is inserted perpendicular to the core's axis. The smaller vane allows for the sample's smaller size. The proper vane is selected and its identification number is recorded, and the vanes orientation relative to the core is recorded.

3) All of these samples are properly secured so that they do not rotate when the vane is rotated.

4) An appropriate spring is selected so that shearing will occur between 20° and 90° stress. The spring's identification number is recorded.

5) The stress pointer (inner dial) and strain pointer. (outer dial) are aligned at 0°. It is made certain that all the play in the system is removed. If the vane system is operated in a horizontal position, then the pointer is taped to the pointer deflector. If the vane system is operated in a vertical position, and the investigator wishes to measure stress and strain readings after failure by shearing occurs, then the pointer is taped to the pointer deflector, otherwise the stress pointer will remain on the maximum shear stress after shear failure occurs.

6) The vane is inserted into the sample until the blades are buried below the sediment surface. The

[1]See Rocker (1974) for discussion of problems relate to anisotropic sediment which result from the different vane orientations.

[2]See Rocker (1974) for discussion of problems related to anisotropic sediment which result from the different vane orientations.

[3]Prior to Leg 43 only the short vanes were available, therefore in these cases the short vanes were also used parallel to the core's axis.

blades are buried 2.0 cm[4] if the vane's axis is oriented parallel to the core's axis. If the vane's axis is oriented perpendicular to the axis of the core, and the core has been split along its axis, then the blades are buried 1.0 cm. If the sample is too small to bury the blades 1.0 cm, then the depth of burial is measured and recorded (being certain the blades are centered within the sample).

7) The motor is turned on and both the stress and strain pointers are recorded for every 5° of stress rotation (or often as possible) and for every 1° of strain rotation (or as often as possible). The rotation of the stress and strain pointers are read to the nearest half degree. In addition, a special attempt is made to record the maximum stress before failure occurs, in order to measure the maximum shear strength. If the vane shear device is run in a horizontal position, or in a vertical position with the pointer attached to the pointer deflector, then the stress and strain readings are continued after shearing failure occurs until the stress pointer decreases 5° to 10°. If the vane shear device is operated in a vertical position, and the pointer is not taped to the pointer deflector, then the inner dial will maintain the maximum stress reading at the time of shear failure.

8) After shearing has occurred, at least five consecutive strain (vane rotation) readings (and stress readings if the pointer is taped to the pointer deflector) are recorded which are increasing in similar increments. The above readings and a vane rotation (strain) of at least 20° are necessary in order to insure a valid test (Richards, 1961).

9) The temperature is recorded.

Shear strength measurement of the remolded sample is done as outlined below:

1) The spring is removed and the vane is spun until it rotates easily in the sediment (the vane is spun at least 2 times[5]). Care is taken to prevent air from entering the sample.

2) The spring is remounted (or a different weaker spring with its identification number being recorded) in the same manner as described above for the "original shear strength" test (undisturbed test), and the vane is allowed to remain stationary in the sediment for 10 min. The temperature and the time the vane is allowed to remain stationary in the sediment are recorded.

3) The vane shear remolded test is now done in the same manner as described above for the "original shear strength" test, however, the remolded test does not necessarily have a distinct maximum shearing stress as in the "original shear strength" test.

[4]As of 15 December 1975 (beginning of Leg 45) the depth that the blades are buried (from both ends of the vane) beneath the sediment surface was changed to be equal to the length of the vane, however, this will apply only when the vane axis is oriented parallel to the core axis, as this is the only case where there is enough room to do so. See Rocker (1974) for sketch of split core with a similar small vane and a brief discussion of problems with DSDP samples. The inside diameter of the core is 6.61 cm. DSDP is considering using a smaller vane which will allow the blade to be properly buried.

[5]The vane was to be spun 10 times, but this was reduced to 2 times to be certain that air would not be drawn into the sample (Homa Lee, 1974, personal communication).

DATA CALCULATIONS

Stress is plotted versus degrees vane rotation (g/cm²versus degrees vane rotation) for both the original strength and the remolded strength. The shear strength and remolded shear strength are calculated from the maximum degrees stress using Equation 18, 19, or 20, depending which vane was used, and with the appropriate spring factor corresponding to which spring was used. Sensitivity is also calculated, which is the ratio of the sample's original shear strength to its remolded shear strength.

$$S_t = \tau_o / \tau_r \qquad (21)$$

where

τo = original shear strength at failure

τr = shear strength of sample after remolding

St = sensitivity.

Units of g/cm² may be converted to pounds per square inch by a conversion factor:

$$\mathrm{g/cm^2} \times 0.01422 \frac{\mathrm{cm^2\ lb}}{\mathrm{g\ in^2}} = \mathrm{lb/in^2} = \mathrm{psi}$$

The Sedimentary Petrology and Physical Property Panel recommends the units of kilopascals (1 kilopascal = 10 g/cm²).

APPENDIX A
Vane Shear Equipment

The vane shear device used by the DSDP, upon the recommendation of Adrian F. Richards, is the Wykeham Farrance Engineering Limited Laboratory Vane Equipment Number WF2350. This equipment is described in the Wykeham Farrance Engineering Limited "WF2350 Laboratory Vane Equipment Handbook" (Wykeham Farrance Engineering Limited, Weston Road, Trading Estate, Slough, Bucks, England) printed by Mergewise Limited of Ascot. Richards (1961) and Kravits (1970) also have a brief description (and photographs) of the basic unmodified equipment.

The original Wykeham Farrance Laboratory Vane Equipment is modified as follows: (1) the pulley[6] system is modified to allow stress to be applied to the spring (by the motor) at a rate of 89° per minute[6] so that the shear test is fast enough to prevent the sample from draining; (2) the motor is remounted over a neoprene "2 mm thick gasket" to minimize vibration from the motor; and (3) DSDP's own core racks and sample-holding devices are used. The vanes used are described in Appendix B.

Briefly, the laboratory Vane Equipment has a motor which rotates (89° per minute) one end of a calibrated, coiled spring about its axis, with the other end of the spring being required to turn a vane about its axis. The other end of the vane is in the sediment sample. Mechanical devices are used which indicate the amount of rotation of the vane at the other end of the coiled spring, and in addition, the amount of rotational stress applied to the spring.

At some (maximum) torque or stress the vane will begin to rapidly rotate and the sediment will begin to fail by shearing. The shearing force is related to the maximum torque applied and the cylindrical shearing surface of the vane, which is assumed to have the height and diameter of the vane. These parameters allow the shear strength to be calculated.

[6]These modifications were suggested by Ardrian Richards (1973, personal communication).

APPENDIX B
Vane Diameters and Heights

Measurements of the vane's diameters, heights, and shaft diameters are listed in Table 1, along with their mean values. Sea Figure 1 for a sketch of the vane and identification of these parameters. Vane 1 was not absolutely straight when it was delivered from the company, but it was straightened as best as possible. The blades of Vane 2 do not join precisely in the center axis, as one blade is offset by 0.02 cm. This occurs where the blades terminate without the shaft. Vane 2 is slightly different from Vane 1, as the narrow part of the shaft of Vane 2, the 0.32-cm-diameter shaft adjacent to the blades, goes to a 0.48-cm-diameter shaft more abruptly. Vanes 3 and 4 have a shaft diameter adjacent the blades of 0.31 cm, which changes to a shaft diameter of 0.475 cm. These changes in the shaft diameters occur at a distance which is at least 2.5 cm away from the blades and therefore only the narrow parts of the shafts are buried in the sediment during the shear strength tests. All baldes have a thickness of about 0.045 cm.

APPENDIX C
Spring Calibrations

Each spring was calibrated in the vane shear device by applying a known torque to the spring and measuring its rotation or strain to the nearest one half degree of rotation. This was done by using a calibration wheel with a known radius.

The wheel has a groove around its circumference for a string which allows the string axis (single layer of string) to be flush with the circumference of the wheel. A weighing pan of known weight and a connecting string of known weight per cm was used to add precise and accurate weights (within ±0.003 g) to the calibration wheel. The radius of the wheel was multiplied by the weight suspended by the wheel to obtain g-cm moment per degree rotation of the wheel. The springs factors are in units of (g-cm)/degree. The springs were calibrated with about 10 to 20 weighings calculated to g-cm per degree. The average of these calculations above 30° rotation were used to determine the spring constants. These calibration data and charts can be found in Tables 2 through 5 and Figures 2 through 5. The calibration wheel is discussed in the Company Manual "Laboratory Vane Shear Transducer and Adapter Kit," Model LVST-015, S/N-009.

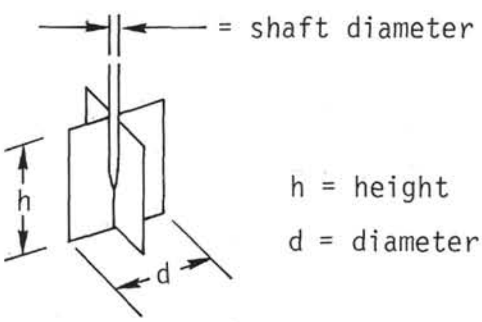

Figure 1. *Partial view of the vane blades.*

A summary of the Spring Factor calibrations are as follows:

Spring 1 = 9.1185 (g-cm)/degree = t
Spring 2 = 20.219 (g-cm)/degree = t
Spring 3 = 32.718 (g-cm)/degree = t
Spring 4 = 51.106 (g-cm)/degree = t

These factors were reproducible within 0.5% to 0.3%. The actual degree readings for a given weight were reproducible within 1° to 0.5°. During shear strength measurements the stress and strain rotations are recorded to the nearest half degree.

REFERENCES

ASTM, 1975. Standard method for field vane shear test in cohesive soil: ASTM Designation: D 2473-72. *In* 1975 Annual Book of ASTM Standards, part 19, Natural Building Stones; Soil and Rock; Peats, Mosses, and Humus. ASTM, Philadelphia, p. 221-324.

Bjerrum, L. and Lo, K. Y., 1963. Effect of aging on the shear-strength properties of a normally consolidated clay: Geotechnique, v. 13, p. 147-157.

Bjerrum, L. and Wu, T. H., 1960. Fundamental shear-strength properties of the Lilla Edet Clay: Geotechnique, v. 10, p. 101-109.

TABLE 1
Mean Blade Diameters and Heights from Six Measurements Along Each Blade Height and Diameter (Shaft Diameters are Also Listed)

Vane	Blade Height (cm) Blade 1	Blade Height (cm) Blade 2	Blade Diameter (cm) Blade 1	Blade Diameter (cm) Blade 2	Diameter Shaft (cm)	Mean Blade Height (cm)	Mean Blade Diameter (cm)
1	1.28	1.275	1.28	1.28	0.32	1.2785	1.2783
	1.28	1.28	1.275	1.28			
	1.28	1.28	1.275	1.28			
	1.275	1.28	1.28	1.28			
	1.28	1.275	1.28	1.28			
	1.28	1.28	1.275	1.275			
2	1.28	1.285	1.285	1.28	0.32	1.2785	1.281
	1.28	1.285	1.285	1.28			
	1.28	1.29	1.28	1.28			
	1.28	1.29	1.28	1.28			
	1.28	1.285	1.28	1.28			
	1.28	1.29	1.28	1.28			
3	2.54	2.53	1.27	1.27	0.310	2.539	1.273
	2.545	2.535	1.275	1.275			
	2.545	2.535	1.275	1.275			
	2.54	2.535	1.275	1.27			
	2.54	2.54	1.275	1.27			
	2.54	2.54	1.275	1.27			
4	2.54	2.545	1.265	1.27	0.310	2.544	1.272
	2.54	2.55	1.27	1.275			
	2.545	2.545	1.275	1.275			
	2.545	2.54	1.28	1.27			
	2.54	2.54	1.27	1.275			
	2.54	2.55	1.27	1.27			

TABLE 2
Spring 1: Torque Calibration

A	B	C	D	E	F	G	H	I	J	K
Wire Length (cm)	Wire Weight (g)	Pan Weight (g)	Weight (g)	(A+B+C) Total Weight (g)	Degrees Strain on Spring Trial 1	2	3	Avg.	Relative Zero°	Moment 5.753·wt (g-cm)	Torque per Degree (g-cm/degree)
0.00	0.0000	0	0	0.0000	260.	260.5	260.5	260.5	0.0		
43.00	0.5762	Pan	0	18.3907	272.5	272.5	272.5	272.5	12.	105.80	8.817
43.60	0.5842		10	28.3987	277.5	278.	278.5	278.	17.5	163.38	9.336
44.30	0.5936		20	38.4081	284.	285.	283.5	284.	23.5	220.96	9.402
44.71	0.5991		30	48.4136	290.	289.5	290.	290.	29.5	278.52	9.441
45.41	0.6085		40	58.4230	297.	297.	297.5	297.	36.5	336.11	9.208
46.11	0.6179		50	68.4324	302.5	302.	302.	302.	41.5	393.69	9.487
46.71	0.6259		60	78.4404	310.	309.5	308.5	309.	48.5	451.27	9.304
47.42	0.6354		70	88.4499	316.	317.	316.5	316.5	56.	508.85	9.087
47.92	0.6421		80	98.4566	323.	323.5	323.	323.	62.5	566.42	9.063
48.52	0.6502		90	108.4647	330.	329.5	330.	330.	69.5	625.00	8.978
49.22	0.6595		100	118.4740	335.5	336.	336.	336.	75.5	681.58	9.028
49.93	0.6691		110	128.4836	342.	342.	343.	342.6	82.	739.17	9.014
50.43	0.6758		120	138.4903	348.	348.	347.5	348.	87.5	796.73	9.105
51.03	0.6838		130	148.4983	355.	355.	354.5	355.	94.5	854.31	9.040
51.73	0.6932		140	158.5077	360.5	361.	361.	361.	100.5	911.89	9.074
52.44	0.7027		150	168.5172	367.	367.	367.	367.	106.5	969.48	9.103
52.94	0.7094		160	178.5239	373.5	373.5	373.5	373.5	113.	1027.05	9.089
53.64	0.7188		170	188.5333	379.5	380.	379.5	379.5	119.	1084.63	9.115
54.45	0.7296		180	198.5441	385.5	385.5	385.	385.5	125.	1142.22	9.138
54.95	0.7363		190	208.5508	392.	392.	392.5	392.	131.5	1199.79	9.124
55.65	0.7457		200	218.5602	399.	399.5	399.	399.	138.5	1257.38	9.079
56.36	0.7551		210	228.5696	404.	405.5	405.5	405.5	145.	1314.96	9.069
56.96	0.7633		220	238.5778	413.	413.	412.	413.	152.5	1372.54	9.000
57.76	0.7740		230	248.5885	418.	418.5	419.	418.5	158.	1430.13	9.051
58.26	0.7807		240	258.5952	425.5	424.5	423.5	424.5	164.	1487.00	9.071
58.76	0.7874		250	268.6019	430.5	430.5	430.5	430.5	170.	1545.27	9.090
59.77	0.8009		260	278.6154	436.5	436.5	437.	436.5	176.	1602.87	9.107
60.37	0.8090		270	288.6235	443.5	443.	442.5	443.	182.5	1660.45	9.098

Average spring factor for 29.5 through 182.5° = 9.1185 (g-cm)/degree.

Note: Wheel radius = 2.265 inches = 5.753 cm; weight wire per cm = 0.0134 g/cm; 4 cm of wire allowed for knot connecting pan bridle to wire; weight ofpan and bridle = 17.8145 g; all numbers listed are not rounded off, they do not indicate precision.

Coulomb, C. A., 1776. Essai sur une application des regles de maximis et minimis a quelgues problemes de statique, relatifs a l'architecture: Mem. Mathematique Phys., L'Academie Roy. Sci., Paris, p. 343-382.

Gibbs, H. J., Hilf, J. W., Holtz, W. G., and Walker, F. C., 1960. Shear-strength of cohesive soils. Am. Soc. Civil, Eng. Res. Conf. Shear-strength of cohesive soils, Boulder, Colorado, June 1960, p. 33-162.

Grim, R. E., 1962. Applied clay mineralogy: New York (McGraw-Hill).

Hamilton, E. L., 1964. Consolidation characteristics and related properties of sediments from experimental mohole (Guadalupe Site): J. Geophys. Res., v. 69, p. 4257-4269.

Hamilton, E. L., 1969. Sound velocity, elasticity, and related properties of marine sediments, North Pacific: II Elasticity and elastic constants: San Diego (Naval Undersea Research and Development Center), Tech. Paper 144.

———, 1971. Elastic properties of marine sediments: J. Geophys. Res., v. 76, p. 579-604.

Horn, D. R., Delach, M. N., and Horn, B. M., 1968. Correlation Between Acoustical and Other Physical Properties of Deep-Sea Cores, Northwest Atlantic: Columbia University (Lamont-Doherty Geological Observatory Contract No. N00024-67-C-1186) Tech. Rept 5.

Horn, D. R., Horn, B. M., and Delach, M. N., 1968a. Correlation between acoustical and other physical properties of deep-sea cores: J. Geophys. Res., v. 73, p. 1939-1957.

———, 1968b. Sonic properties of deep-sea cores from the North Pacific Basin and their bearing on the acoustic provinces of the North Pacific: Columbia University (Lamont-Doherty Geological Observatory Contract No. N00024-67-C-1186), Tech. Rept. 10.

Hvorslev, M. J., 1939. Conditions of failure for remolded cohesive soils: 1st Intern. Conf. Soil Mechanics and Foundation Eng. Proc., v. 3, p. 51-53.

———, 1937. Uber die festigkeitseignenschaften gestorter bindiger boden: Ingeniorridenskabelige Skriftor A, Danmark, Naturvid, Samfund. Copenhagen, 159 p.

———, 1960. Physical components of the shear strength of saturated clays: Am. Soc. Civil Engineers, Res. Conf. on Shear Strength of Cohesive Soils, Boulder, Colorado, June 1960, p. 169-273.

Keller, G. H. and Bennett, R. H., 1973. Sediment mass physical properties — Panama Basin and Northeastern Equatorial Pacific: *In* van Andel, T. J., Heath, G. R., et al., Initial Reports of the Deep Sea Drilling Project. Volume 16: Washington (U.S. Government Printing Office), p. 494-512.

Kravitz, F. H., 1970. Repeatability of three instruments used to determine the undrained shear strength of extremely

TABLE 3
Spring 2: Torque Calibration

	A	B	C	D	E	F	G	H	I	J	K
					Degrees Strain on Spring						
					Trial						
Wire Length (cm)	Wire Weight (g)	Pan Weight (g)	Weight (g)	(A+B+C) Total Weight (g)	1	2	3	Avg.	Relative Zero°	Moment 5.753·wt (g-cm)	Torque per Degree (g-cm / degree)
0.00	0.0000	0	0	0.0000	112.5	113.	112.5	112.5	0.0	0.00	0.000
37.00	0.4958	Pan	0	18.3103	117.5	117.5	117.	117.5	5.	105.34	21.068
37.50	0.5025		20	38.3170	123.5	123.	123.5	123.5	11.	220.44	20.040
38.10	0.5105		40	58.3251	129.	129.	128.5	129.	16.5	335.54	20.336
38.61	0.5173		60	78.3318	134.5	134.5	134.5	134.5	22	450.64	20.484
39.21	0.5254		80	98.3399	140.	140.5	140.	140.	27.5	565.75	20.573
39.81	0.5335		100	118.3480	146.5	146.5	146.	146.5	34	680.86	20.025
40.31	0.5402		120	138.3547	151.5	152.	151.5	151.5	39.	795.95	20.409
40.92	0.5483		140	158.3628	156.5	157.	157.	157.	44.5	911.05	20.473
41.52	0.5563		160	178.3708	163.	163.	163.	163.	50.5	1026.16	20.320
42.02	0.5631		180	198.3776	169.	169.	169.	169.	56.5	1141.27	20.199
42.62	0.5711		200	218.3856	174.	174.	174.	174.	61.5	1256.39	20.429
43.22	0.5792		220	238.3937	180.5	180.	185.5	180.	67.5	1371.48	20.318
43.73	0.5859		240	258.4004	185.5	185.5	185.5	185.5	73.	1486.58	20.364
44.33	0.5940		260	278.4085	191.	190.5	191.5	191.	78.5	1601.68	20.404
44.93	0.6020		280	298.4166	197.	197.	197.	197.	84.5	1716.79	20.317
45.43	0.6088		300	318.4233	202.5	202.5	202.5	202.5	90.	1831.89	20.354
46.04	0.6169		320	338.4314	208.5	208.5	208.	208.5	96.	1947.00	20.281
46.64	0.6250		340	358.4395	214.5	214.5	214.5	214.5	102.	2062.00	20.216
47.24	0.6330		360	378.4475	220.	220.	220.	220.	107.5	2177.21	20.253
47.84	0.6411		380	398.4556	225.5	226.	226.	226.	113.5	2292.32	20.197
48.35	0.6478		400	418.4623	232.	232.	231.5	232.	119.5	2407.41	20.146
48.95	0.6559		420	438.4707	237.5	237.5	237.5	237.5	125.	2522.52	20.180
49.55	0.6640		440	458.4785	243.5	242.5	243.	243.	130.5	2637.63	20.207
50.05	0.6707		460	478.4852	249.5	249.5	249.	249.5	137.	2752.73	20.093
50.65	0.6788		480	498.4933	255.5	255.	255.	255.	142.5	2867.83	20.125
51.36	0.6882		500	518.5027	261.	260.5	260.5	260.5	148.	2982.95	20.155
51.96	0.6963		520	538.5108	268.	267.	267.	267.	154.5	3098.05	20.052
52.56	0.7043		540	558.5188	273.	272.5	272.	271.5	159.5	3213.16	20.145
53.06	0.7111		560	578.5256	277.5	278.	277.5	277.5	165.	3328.26	20.171
54.27	0.7272		600	618.5417	290.5	290.	289.5	290.	177.5	3558.47	20.048
54.87	0.7353		620	638.5498	296.5	296.	296.	296.	1835	3673.58	20.020

Average Spring Factor for 34° through 184° = 20.219 (g-cm)/degree.

Note: Wheel radius = 2.265 inches = 5.753 cm; weight wire per cm = 0.0134 g/cm; 4 cm of wire allowed for knot connecting pan bridle to wire; weight of pan and bridle = 17.8145 g; all numbers listed are not rounded off, they do not indicate precision.

weak, saturated, cohesive sediments: J. Sediment. Petrol., v. 40, p. 1026-1037.

Lambe, T. W., 1960. A mechanistic picture of shear strength in clay: Am. Soc. Civil Eng., Res. Conf. on Shear Strength of Cohesive Soils, Boulder, Colorado, June 1960, p. 555-580.

Lambe, T. W. and Whitman, R. V., 1969. Soil mechanics: New York (John Wiley and Sons, Inc.).

Lee, H. J., 1973. Measurements and estimates of engineering and other physical properties, Leg 19. *In* Creager, J. S., Scholl, D. W. et al., Initial Reports of the Deep Sea Drilling Project, Volume 19: Washington (U.S. Government Printing Office), p. 701-720.

Mitchell, J. K., 1964. Shearing resistance of soils as a rate process: J. Soil Mechanics Found. Div., v. 90, SM 1, p. 29-61.

Moore, D. G., 1964. Shear strength and related properties of sediments from experimental mohole (Guadalupe Site): J. Geophys. Res., v. 69, p. 4271-4291.

Moore, D. G. and Shumway, G., 1959. Sediment thickness and physical properties, Pigeon Point Shelf Ca.: J. Geophys. Res., v. 64, p. 367.

Richards, A. F., 1961. Investigations of deep sea sediment cores, Part I, shear strength, bearing capacity, and consolidation: Washington (U.S. Navy Hydrographic Office), Tech. Rept 63.

________, 1962. Investigations of deep sea sediment cores, Part II, Mass Physical Properties: Washington (U.S. Navy Hydrographic Office), Tech. Rept 106.

Rocker, K., 1974. Vane Shear Strength Measurements on Leg 27 Sediment. *In* Veevers, J. J., Heirtzler, J. R., et al., Initial Reports of the Deep Sea Drilling Project, Volume 27: Washington (U.S. Government Printing Office), p. 425-432.

Rosenquist, I. T., 1960. Physico-chemical properties of soils: soil water systems: Norwegian Geotechnical Inst. Publ. 37.

Schmertmann, J. H. and Osterberg, J. O., 1960. An experimental study of the development of cohesion and friction with axial strain in saturated cohesive soils: Am. Soc. Civil Eng., Res. Conf. on Shear Strength of Cohesive Soils, Boulder, Colorado, June 1960, p. 643-694.

Schreiber, B. C., 1968a. Sound velocity in deep sea sediments: J. Geophys. Res., v. 73, p. 1259-1268.

________, 1968b. Cores, v. 8 in marine geophysical program 65-67-Central North Pacific Ocean, Area V: Alpine Geophysical Assoc., In., U.S. Naval Oceanographic Office Contract N62306-1688.

TABLE 4
Spring 3: Torque Calibration

	A	B	C	D	E	F	G	H	I	J	K
Wire Length (cm)	Wire Weight (g)	Pan Weight (g)	Weight (g)	(A+B+C) Total Weight (g)	Degrees Strain on Spring, Trial 1	Trial 2	Trial 3	Avg.	Relative Zero°	Moment 5.753·wt (g-cm)	Torque per Degree (g-cm/degree)
0.00	0.0000	0	0	0.0000	1.5	2.0	2.0	2.0	0.0	0.00	0.000
39.00	0.5226	Pan	0	18.3371	5.5	5.5	5.5	5.5	3.5	105.49	30.140
39.90	0.5347		50	68.3492	14.	14.5	14.5	14.5	12.5	393.21	31.459
40.81	0.5468		100	118.3613	23.	23.5	23.5	23.5	21.5	680.93	31.671
41.61	0.5576		150	168.3721	31.5	32.	31.5	31.5	29.5	968.64	32.835
42.51	0.5697		200	218.3842	40.	40.	40.	40.	38.	1257.36	33.062
43.42	0.5818		250	268.3963	49.	49.	49.	49.	47.	1544.08	32.853
44.32	0.5939		300	318.4084	58.	58.5	58.5	58.5	56.5	1831.80	32.421
45.22	0.6060		350	368.4205	66.5	67.	67.	67.	65.	2119.52	32.608
46.13	0.6181		400	418.4326	75.5	75.5	75.5	75.5	73.5	2407.24	32.752
46.93	0.6289		450	468.4434	84.	84.5	84.	84.	82.	2674.95	32.865
47.94	0.6423		500	518.4568	93.	93.	93.	93.	91.	2982.58	32.777
48.84	0.6544		550	568.4689	102.	102.	102.	102.	100.	3270.40	32.704
49.64	0.6652		600	618.4797	110.5	111.	110.5	110.5	108.5	3558.11	32.794
50.65	0.6787		650	668.4232	119.5	120.	119.5	119.5	117.5	3845.84	32.731
51.35	0.6881		700	718.5046	128.5	128.5	128.5	128.5	126.5	4133.55	32.676
52.25	0.7002		750	768.5146	137.	137.5	137.	137.	135.	4421.26	32.750
53.16	0.7123		800	818.5268	145.5	146.	146.5	146.	144.	4708.98	32.701
54.06	0.7244		850	868.5389	156.	156.5	156.	156.	154.	4996.70	32.446
54.96	0.7365		900	918.5510	163.5	164.	164.5	164.	162.	5284.42	32.620
55.77	0.7473		950	968.5618	172.5	172.5	173.	172.5	170.5	5572.14	32.681
56.77	0.7607		1000	1018.5752	181.5	181.5	181.5	181.5	179.5	5859.86	32.645

Average Spring Factor for 29.5° through 179.5° = 32.718 (g-cm)/degree.

Note: Wheel radius = 2.265 inches = 5.753 cm; weight wire per cm = 0.0134 g/cm; 4 cm of wire allowed for knot connecting pan bridle to wire; weight of pan and bridle = 17.8145 g; all numbers listed are not rounded off, they do not indicate precision.

Scott, R. F., and J. J. Schoustra, 1968. Soil mechanics and engineering: New York (McGraw-Hill).

Seed, H. B., Mitchell, J. K., and Chan, C. K., 1960. The strength of compacted cohesive soils: Am. Soc. Civil Eng., Res. Conf. on Shear Strength of Cohesive Soils, Boulder, Colorado, June 1960. p. 877-964.

Skempton, A. W., 1949. Vane tests in the alluvial plain of the River Forth Near Grangemouth: Geotechnique, v. 1, p. 111-124.

———, 1969. Effective stress in soils, concrete, and rocks. *In* Internat. Soc. Soil Mechanics and Foundation Engineering. British National Society, Pore Pressure and Suction in Soils; Conference Organized by the British National Society...at the Institution of Civil Engineers, March 30 and 31, 1960: London (Butterworths).

Warkentin, B. P., and Yong, R. N., 1962. Shear strength of montmorillonite and kaolinite related to interparticle forces. Natl. Conf. Clays and Clay Minerals, 9th, Proc: New York (Pergamon Press).

Wilson, S. D. and Dietrich, R. J., 1960. Effect of consolidation pressure on elastic and strength properties of clay: Am. Soc. Civil Eng., Res. Conf. on Shear Strength of Cohesive Soils, Boulder, Colorado, June 1960, p. 419-435.

Wu, T. H., 1966. Soil mechanics: Boston (Allyn and Bacon).

Yong, R. N. and Warkentin, B. P., 1966. Introduction to soil behavior: New York (MacMillan).

TABLE 5
Spring 4: Torque Calibration

	A	B	C	D	E	F	G	H	I	J	K
					Degrees Strain on Spring						Torque per Degree
Wire Length (cm)	Wire Weight (g)	Pan Weight (g)	Weight (g)	(A+B+C) Total Weight (g)	Trial 1	Trial 2	Trial 3	Avg.	Relative Zero°	Moment 5.753·wt (g-cm)	$\left(\frac{\text{g-cm}}{\text{degree}}\right)$
0.00	0.0000	0	0	0.0000	95.	95.5	95.	95.	0.0	0.00	0.000
35.00	0.4690	Pan	0	18.2835	97.	97.5	97.	97.	2.	105.18	52.59
36.10	0.4838		100	118.2983	108.	108.	108.	108.	13.	680.57	52.35
37.21	0.4986		200	218.3131	118.5	119.5	119.	119.	24.	1255.96	52.332
38.41	0.5147		300	318.3292	130.	130.	130.	130.	35.	1831.35	42.324
39.32	0.5296		400	418.3441	141.	141.5	141.5	141.5	46.5	2406.73	41.758
40.67	0.5450		500	518.3595	152.5	153.	152.5	152.5	57.5	2982.12	51.863
41.83	0.5605		500	618.3750	164.	164.5	164.	164.	69.	3557.51	51.558
42.93	0.5753		700	718.3898	175.5	175.5	175.5	175.5	80.5	4132.90	51.340
44.09	0.5908		800	818.4053	186.5	187.5	187.5	187.	92.	4708.29	51.177
45.24	0.6062		900	918.4207	198.5	199.5	199.5	199.	104.	5283.67	50.805
46.35	0.6210		1000	1018.4355	211.	211.5	211.	211.	116.	5859.06	50.509
47.45	0.6358		1100	1118.4503	222.5	222.5	223.	222.5	127.5	6434.44	50.466
48.55	0.6505		1200	1218.4651	233.5	233.	234.	233.5	138.5	7009.83	50.612
49.66	0.6654		1300	1318.4799	244.5	245.5	245.	245.	150.	7585.21	50.568
50.76	0.6802		1400	1418.4947	255.	256.	256.	256.	161.	8160.60	69.687
51.97	0.6964		1500	1518.5108	266.5	266.	266.5	266.5	171.5	8735.99	50.939
53.07	0.7112		1600	1618.5256	278.	277.5	278.	278.	183.	9311.38	50.882

Average Spring Factor for 35° through 183° = 51.106 (g-cm)/degree.

Note: Wheel radius = 2.265 inches = 5.753 cm; weight wire per cm = 0.0134 g/cm; 4 cm of wire allowed for knot connecting pan bridle to wire; weight of pan and bridle = 17.8145 g; all numbers listed are not rounded off; they do not indicate precision.

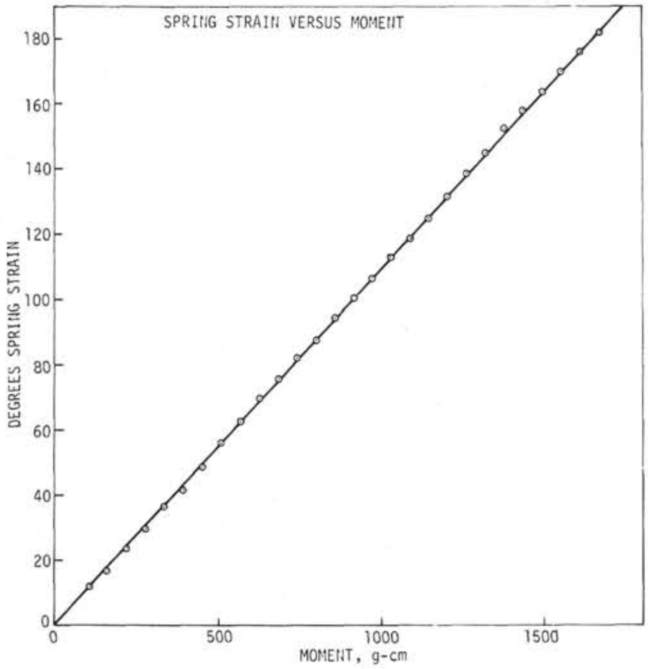

Figure 2. *Spring I: Recalibration 19 October 1973 by R. E. Boyce. Spring Factor = 9.1185 (g-cm)/degree, which is an average for the data from 29.5° through 182.5° and is the line shown in the graph.*

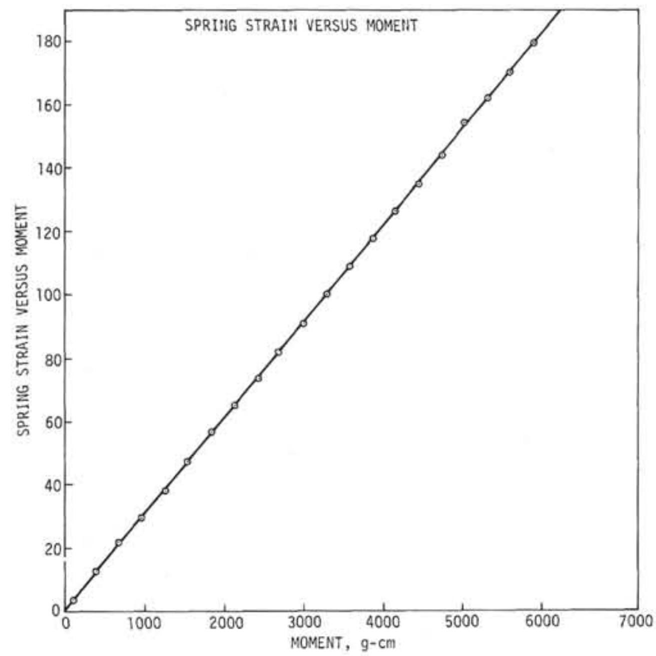

Figure 4. *Spring 4: Recalibration 19 October 1973 by R. E. Boyce. Spring Factor = 51.106 (g-cm)/degree, which is an average for the data from 35° through 183° and is the line shown in the graph.*

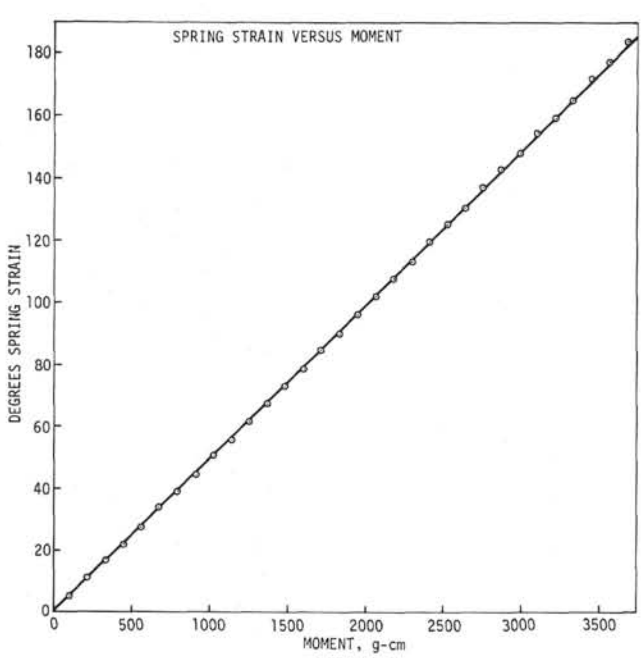

Figure 3. *Spring 2: Recalibration 19 October 1973 by R. E. Boyce. Spring Factor = 20.219 (g-cm)/degree, which is an average for the data from 34° through 184° and is the line shown in the graph.*

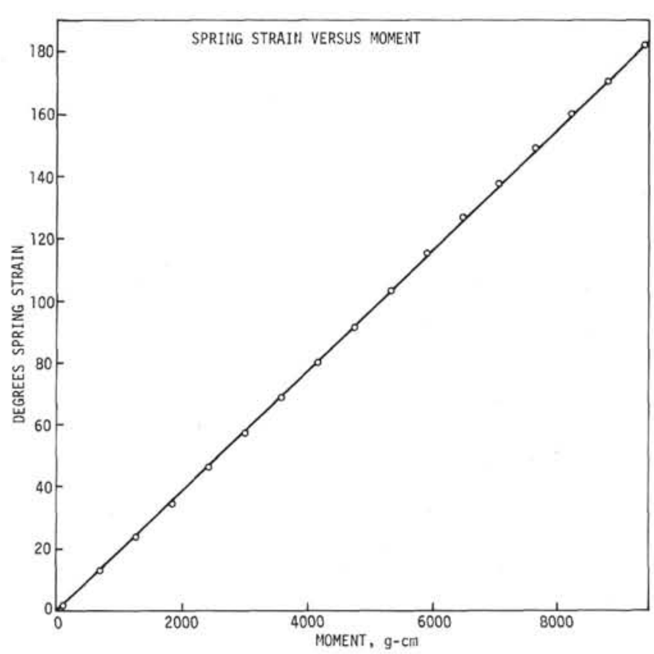

Figure 5. *Spring 3: Recalibration 19 October 1973 by R. E. Boyce. Spring Factor = 32.718 (g-cm)/degree, which is an average for the data from 29.5° through 179.5° and is the line shown in the graph.*