Ronald C. Chaney[1] *and Gregory N. Richardson*[2]

Measurement of Residual/Remolded Vane Shear Strength of Marine Sediments

REFERENCE: Chaney, R. C. and Richardson, G. N., "**Measurement of Residual-Remolded Vane Shear Strength of Marine Sediments,**" *Vane Shear Strength Testing in Soils: Field and Laboratory Studies, ASTM STP 1014*, A. F. Richards, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 166–181.

ABSTRACT: The measurement of both residual and remolded shear strength using the vane shear apparatus is discussed. Residual shear strength is defined to be measured after 90° of vane rotation. In contrast, remolded shear strength is dependent on whether it is measured by vane remolding or hand remolding. To accomplish vane remolding, a minimum of three vane revolutions are required. The relative strengths of the various remolding methods show that (1) field vane remolding gives highest strength, (2) followed by either laboratory vane remolding or hand remolding. Order of the last two appears to depend on soils plasticity. Vane remolding is shown to be influenced by a soils anisotropy while hand remolding is not. Case studies are presented for a DSDP site in the North Pacific and the Mississippi Fan in the Gulf of Mexico. Standardization and measurement procedures to obtain repeatable and comparable results are presented.

KEY WORDS: vane shear, anisotropy, remolding, shear strength, marine, North Pacific, Gulf of Mexico, Mississippi Fan, residual strength, sensitivity

Laboratories typically perform two vane shear tests at each location, one to obtain the undisturbed undrained vane shear strength S_u and another to obtain an undrained shear strength S_{ur} on the same material after destruction of the structure along the surface of sliding. A sensitivity of the soil S_t is defined as S_u/S_{ur}. The term, sensitivity, indicates the effect of remolding on the consistency of a clay, regardless of the physical nature of the causes of the change [1]. The vane shear strength test on the disturbed material is performed in the same manner as the original test. Between the two tests the sample's original structure is destroyed, either by physically removing the sample and mixing it by hand with a spatula [2] or with a mechanical mixer, or by rapidly rotating the vane within the solid through several revolutions [3]. Few comparisons of the two techniques are available, although Richards [4] indicated that soil remolding by hand, with subsequent retesting by laboratory vane, yields a somwhat lower value of shearing strength on the disturbed material. Higher sensitivity values thereby result.

The resulting vane shear strength after destruction of the soil structure has been variously called the remolded strength, residual strength, or ultimate strength. The actual term to be used is dependent upon how the soil structure was destroyed. The process of kneading or working a clay is commonly referred to as remolding. Soils that have had their natural structure modified by manipulation in this manner are called remolded soils (ASTM Terms and Symbols Relating to Soil and Rock [D 653]). The softening effect is probably

[1] Professor and director, Humboldt State University Marine Laboratory, P.O. Box 690, Trinidad, CA 95570.
[2] Consultant, Soil and Material Engineers, Raleigh, NC.

due to two different causes: (1) destruction of the orderly arrangement of the molecules in the adsorbed layers and (2) collapse of the structure that the clay acquired during the process of sedimentation. In contrast, the residual or ultimate shear strength was defined by Skempton [5] as the ultimate shearing resistance after large displacements under fully drained conditions. After a surface of sliding forms and extensive slip occurs, the bonds between the soil particles are destroyed and the particles along the surface of sliding assume an orientation favorable to a low resistance to shear along the surface.

In the following sections the variation of shear strength as effected by the following variables will be discussed: (1) remolded or residual vane strength as compared to the undisturbed vane shear strength, (2) effect of anisotropy on the variation of the measured vane shear strength values, (3) effect of the number of revolutions of the vane on the determination of vane remolded shear strength, and (4) the effect of the liquidity index on the remolded shear strength. This will be followed by case studies from the North Pacific and the Gulf of Mexico.

Vane shear strength results presented in this paper were performed using a Wykeham/Farrance device with torsional springs. Tests were conducted normally at 9°/min unless noted otherwise. A test series was conducted using various rates of vane rotation on a pelagic clay material from the North Pacific as shown in Fig. 1. A review of Fig. 1 shows that for the test conditions and material being tested there was no effect of rotation rate on the resulting vane shear strength. A similar test program showed the same effect for the other materials used in this study.

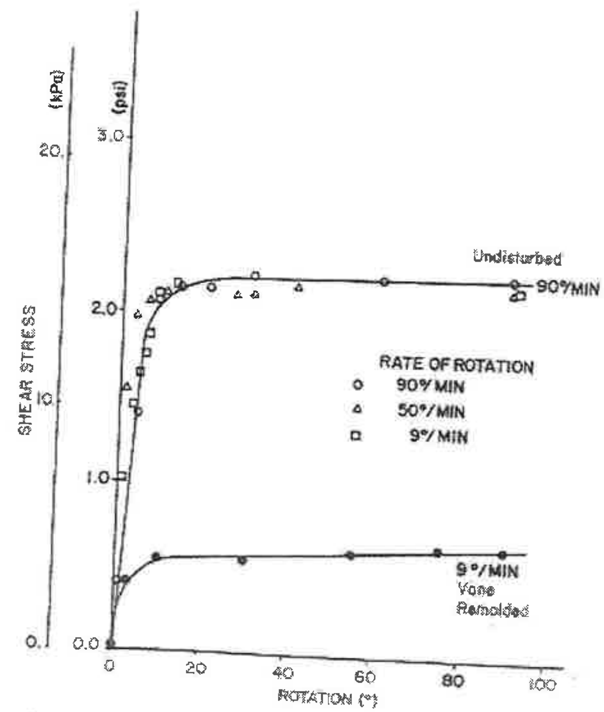
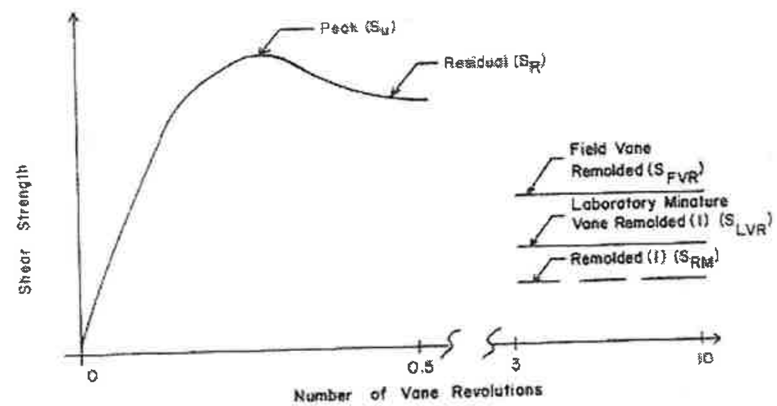


FIG. 1—*Effect of the rate of rotation on vane shear strength measurements using a torsional spring, DSDP Leg 96, Site 617A, Core 4-3A, undisturbed.*



Note: (1) Shear strength determined from either Laboratory Miniature Vane Remolded or Remolded may be reversed due apparently to soils plasticity characteristics.

FIG. 2—*Relationship between strengths measurements determined by the vane shear strengths.*

Remolded/Residual Vane Shear Strength

An idealized schematic of the various shear strengths determined using the vane shear apparatus is presented in Fig. 2. A review of Fig. 2 shows the residual strength, also called the ultimate strength as defined by Skempton [5], is the strength after a large deformation. For the purposes of this study the residual shear strength S_R will be defined as the vane strength after a rotation of 180° (0.5 revolutions of the vane). In contrast, the determination of the remolded vane shear strength depends on whether the test was conducted using an in-situ vane S_{FVR} or in the laboratory. In the laboratory, remolded vane shear strength will be shown to depend on whether the soil was remolded using either a vane S_{LVR} or by hand manipulation S_{RM}. For the purposes of this paper, vane remolding will be considered an approximation of the more thorough hand or mechanical remolding.

A comparison of relative remolded vane shear strengths as determined by these three methods is $S_{FVR} > S_{LVR}$ or S_{RM}. The reason for the observed variation between field and laboratory remolded vane shear strengths is believed due to the reduction in applied stress [6,7]. Law [8] has shown that the vane shear strength increases with increasing horizontal stress and depends to a much lesser degree on the vertical stress. In contrast, the variation between the vane shear strengths as determined from the laboratory miniature vane remolded test S_{LVR} and the hand remolded vane test S_{RM} can vary by a factor of up to 2.5 as shown in Figs. 3 through 6. Whether S_{RM} or S_{LVR} is largest, based on very limited data, appears to depend on the liquidity index of the soil (see Fig. 7).

Effect of Anisotropy

The effect of anisotropy on the determination of vane remolded and hand remolded vane shear strengths was investigated using box cores from the Eel River Fan located off

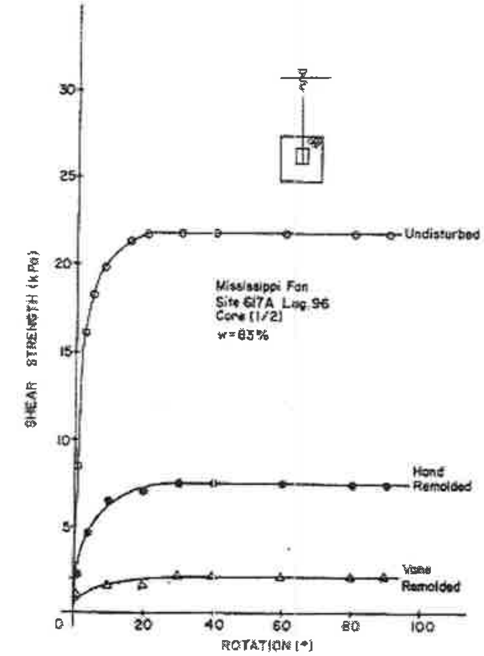


FIG. 3—*Relationship between undisturbed, hand remolded, and vane remolded laboratory miniature vane strengths, Mississippi Fan, DSDP, Leg 95, Site 617A, Core 1-2, and vertical vane orientation.*

the northern California coast near Eureka. The box cores were taken from a water depth of approximately 500 m. The soil recovered in the box core was a silty clay. Vane tests were performed in both the vertical (Fig. 4) and the horizontal (Figs. 5 and 6) directions. The horizontal tests were conducted at depths of 6 and 33 cm in the box core. A comparison between the vertical and horizontal tests indicates that the hand remolded vane tests at the top of the box core are equal (2.5 kPa). The hand remolded vane test at a depth of 33 cm is increased to a value of approximately 3.5 kPa. This behavior would be expected with increasing depth and decreasing water content.

In comparison, the shear strength as determined in the vane remolded test is dependent on the direction in which the test is performed. A review of Fig. 4 for the vertical test indicates a vane remolded shear strength of approximately 6 kPa, while in Fig. 5 for the horizontal test a remolded shear strength of approximately 3.3 kPa is determined. The undisturbed vane shear strengths presented in Figs. 4 through 6 exhibit this same behavior.

Effect of the Number of Revolutions on the Determination of the Residual Vane Shear Strength

The effect of the number of revolutions of the vane on the determination of the laboratory remolded vane shear strength for a marine clay is shown in Fig. 8. A review of Fig. 8 shows that for a case shown the shear strength decreases rapidly during the first three vane

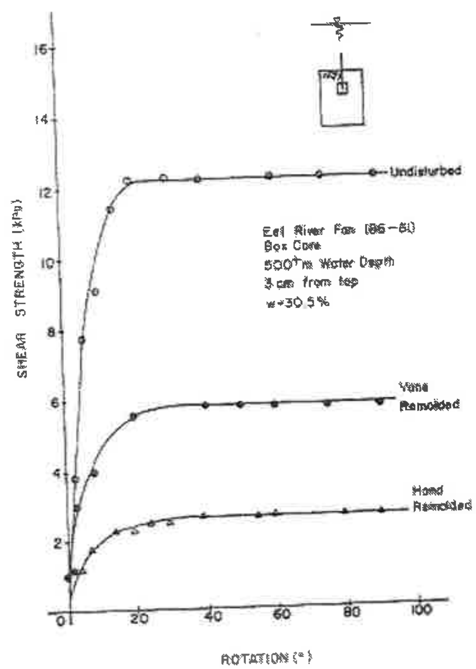


FIG. 4—*Relationship between undisturbed, hand remolded, and vane remolded laboratory miniature vane strengths, Eel River Fan (86-61), 3 cm depth, vertical vane orientation.*

revolutions. After the first three revolutions the shear strength is relatively constant over the interval from 3 to 10 vane revolutions. A summary of selected recommendations for the number of vane revolutions to determine remolded vane shear strengths is presented in Table 1. Based on the above limited information the vane remolded shear strength should be determined only after a minimum of between 3 to 5 revolutions of the vane.

Effect of the Liquidity Index on Remolded Vane Shear Strength

A number of investigators have studied the relationship between remolded shear strength and the liquidity index (LI). Pyles [*11*] showed that the ratio of vane remolded shear strength S_{LVR} to the undisturbed peak vane shear strength S_u is constant for all values of liquidity index (LI) but was dependent on whether vane strengths were determined in the field or laboratory. The vane remolded shear strength in Pyles study was determined after three revolutions. A linear relationship between LI and the logarithm of sensitivity S_t has been shown by Bjerrum [*12*] and later expanded by Eden and Hamilton [*10*]. In this work Bjerrum showed that as the liquidity index increases the sensitivity also increases. A form of this relationship can be presented as the liquidity index (LI) versus the logarithm of the remolded shear strength as shown in Fig. 14. This graph is a modified form of one previously presented by Sullivan et al. [*13*] and incorporates data from this study. The data presented in Fig. 14 were developed using different testing techniques (CU triaxial, vane, and unconfined compression tests) on remolded soil. A review of Fig. 14 shows that trends through the data from this study (dashed lines) do support the concept of a log linear relationship for each clay but not a single unique relationship as presented by Sullivan et al. [*13*]. The "uniqueness" only appears to apply for (1) a range of liquidity index, (2) a range of undrained shear strength, and (3) a specified group of clays. Various equations describing the linear relationship between LI and the logarithm of the remolded shear strength have been presented by various authors but are generally limited to the ranges in liquidity index or shear strength over which they are applicable [*13,14*].

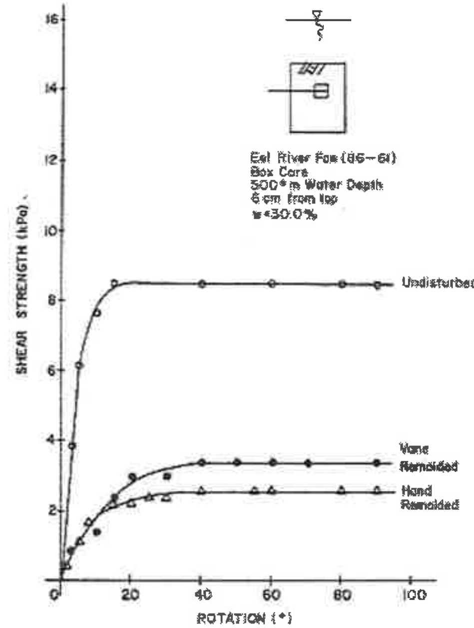


FIG. 5—*Relationship between undisturbed, hand remolded, and vane remolded laboratory miniature vane strengths, Eel River Fan (86-61), 6 cm depth, horizontal vane orientation.*

Case Studies

Test results from three sites are presented in Figs. 9 to 13. In each case, laboratory miniature vane tests were performed to determine both the undisturbed and vane remolded shear strengths. In addition, the variation of bulk density, water content, plastic limit, and liquid limit are also presented as a function of depth.

A. North Pacific, Deep Sea Drilling Project Site 576A

The site was located near the Shatsky Rise in the Northern Pacific as shown in Fig. 9. The site consisted of two units. The upper unit was subsequently divided into two subunits (1A and 1B). Subunit 1A (0 to 28 m) consisted of a yellowish brown to brown pelagic clay

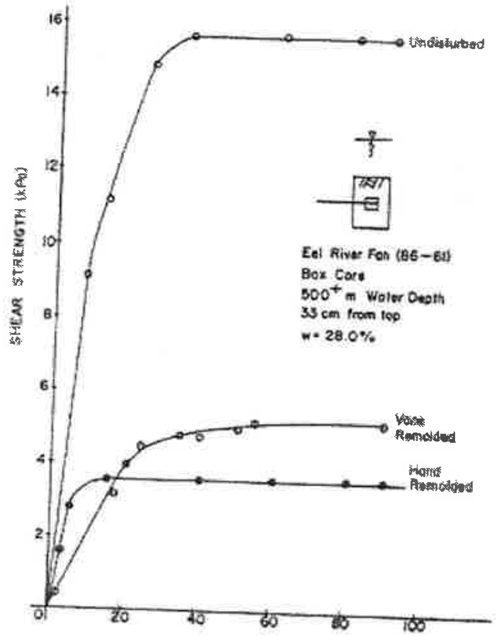


FIG. 6—*Relationship between undisturbed, hand remolded, and vane remolded laboratory miniature vane strengths, Eel River Fan (86-61), 33 cm depth, horizontal vane orientation.*

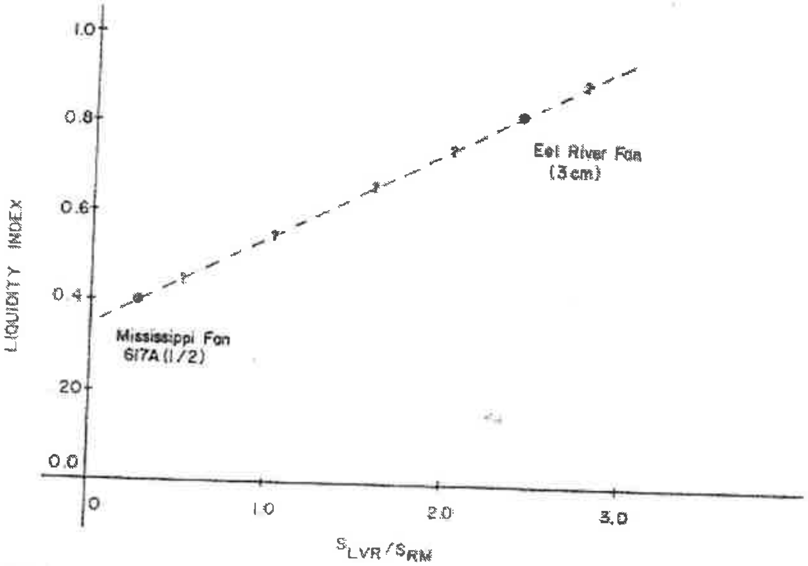


FIG. 7—*Liquidity index versus S_{LVR}/S_{RM}*

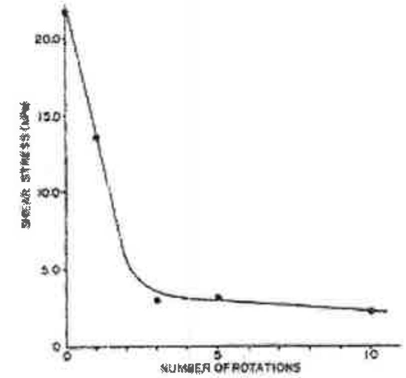


FIG. 8—*Vane remolded laboratory miniature vane strengths versus number of vane rotations, Mississippi Fan, DSDP? Leg 96, Site 617A, Core 1-2, vertical vane orientation.*

of Pleiocene and Quaternary age. Shipboard scientists estimated that this unit is largely of eloian origin. Subunit IB (28 to 55 m) consisted of a dark brown pelagic clay, which is very fine grained. Unit II extended from a depth of 55 m to the bottom of the hole and consisted of interbedded dark brown pelagic clay similar to Subunit IB and pale brown nannofossil ooze. A summary of the bulk density, water content, liquid, and plastic limits as well as the average and remolded laboratory vane shear strengths are summarized in Fig. 10. A review of Fig. 10 shows that the undisturbed vane shear strength is greater at all depths than the remolded vane shear strength and that the S_t is variable over depth ranging from approximately 3 at a depth of 10 m to 1.4 at a depth of 42 m.

B. Mississippi Fan, Deep Sea Drilling Project Site 616B

The site was located in the lower part of the Mississippi Fan alongside the fan channel as shown in Fig. 11. The site consisted of two units. The upper unit consisted of a thin (25-cm) layer of yellow brown marly foraminiferal ooze. Unit II extended below this layer to the bottom of the hole (0.24 to 370 m). This unit was subsequently divided into four sequences. Sequence 1 (0.25 to 65 m) consisted of silt laminated muds and fine grained turbidites with highly inclined laminae. Sequence 2 (65 to 146m) consisted of homogeneous very fine grained mud and clay with fewer thin silt laminae. Sequence 3 (146 to 250

TABLE 1—*Summary of selected recommendations for the number of revolutions to determine the vane remolded shear strength.*

Reference	Number of Vane Revolutions	
	Lab	Field
Arman et al. [6]	6	10
Skempton [9]	. . .	6 or more
Eden and Hamilton [10]	4	. . .
Pyles [11]	3	3

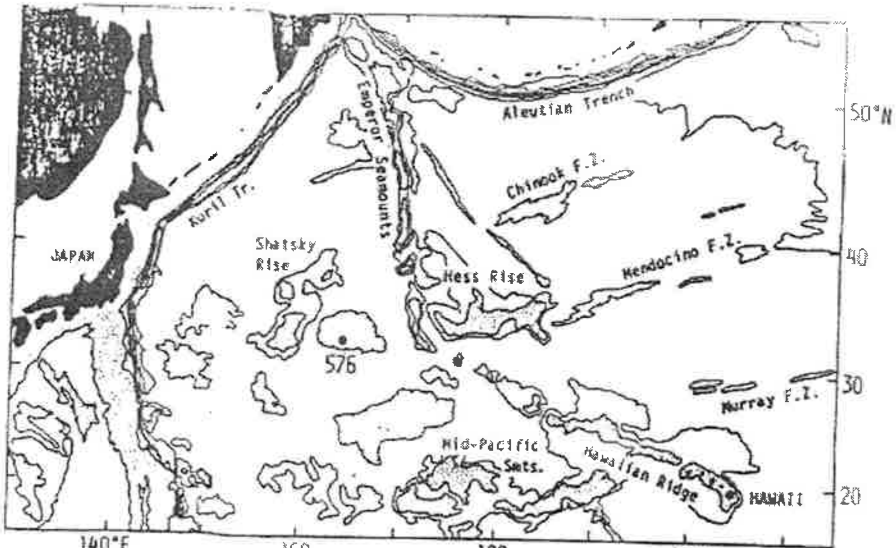


FIG. 9—*Location map of DSDP Site 576A in the Northwest Pacific.*

m) consisted of interbedded medium to fine grained sands, silty sands, lignite bearing muds and fine grained silt mud turbidites. Sequence 4 (250 to 370 m) consisted of homogeneous muds. A summary of the bulk density, water content, liquid and plastic limits, as well as the average and remolded laboratory vane shear strengths are summarized in Fig. 12. A review of Fig. 12 shows that the undisturbed laboratory vane shear strength is greater at all depths than the remolded vane shear strength and that the S_t varies from 3.5 at a depth of 70 m to 6.5 at a depth of 200m.

C. Mississippi Fan, Deep Sea Drilling Project Site 617A

The site was located near the upper portion of the Mississippi Fan in the toe area of the Massingale Slide as shown in Fig. 13. The site consisted of two units. The upper unit is thin (25 cm) consisting of an olive brown foraminifer mud. This unit overlays Unit II, which is made up of terrigenous muds and silts. Unit II is subsequently broken up into three sequences. Sequence 1 (0.25 to 46 m) consists of homogenous muds and muds with silt laminae. Sequence 2 (46 to 84 m) is composed of silt laminated mud. Sequence 3 (84 to 192 m) consists of mud with silt laminations. A summary of the bulk density, water content, liquid and plastic limits as well as the average and remolded laboratory vane shear strengths are summarized in Fig. 9. A review of Fig. 9 shows that the undisturbed laboratory vane shear strength is greater at all depths than the remolded laboratory vane shear strength and that the S_t varies from 10 at 2 m to 14 at a depth of 50 m.

A comparison of these case studies with previously published sites is presented in Table 2. A review of this table shows that for the cases presented the range of sensitivity of marine sediments varies between 2 to 14. In addition, the sensitivity is shown to increase with depth.

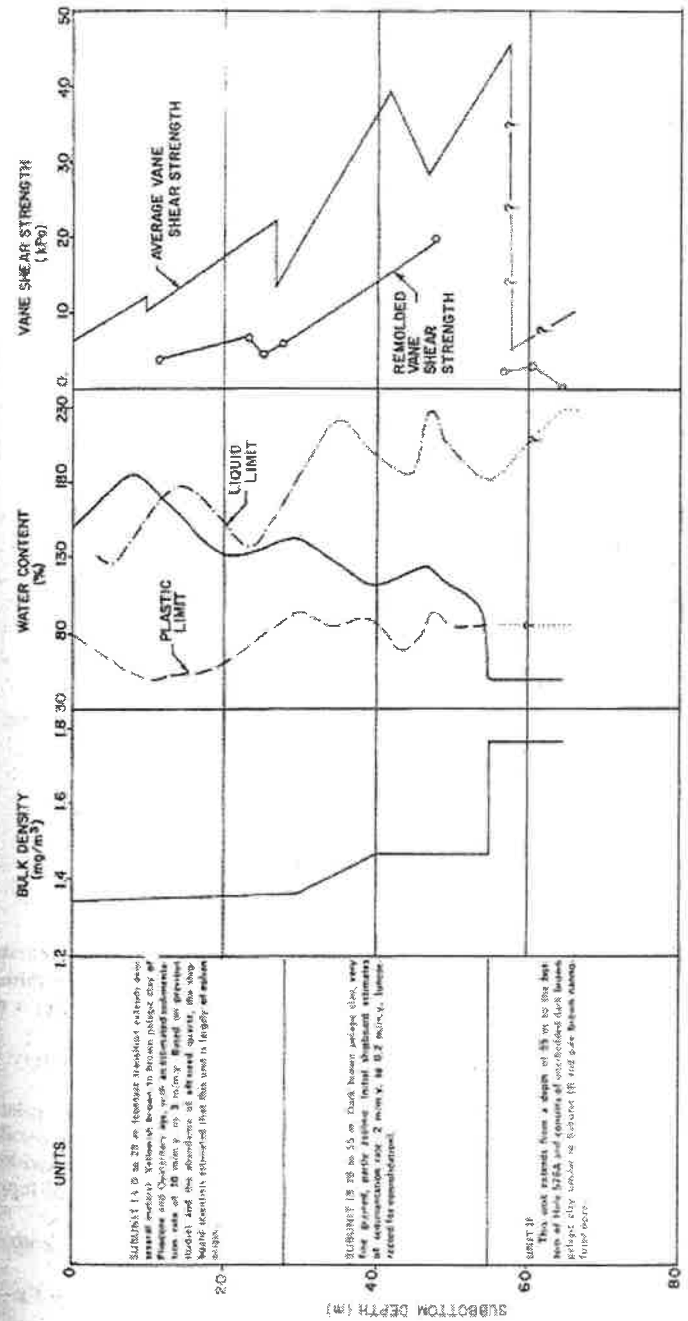


FIG. 10—*Geotechnical properties of Northwest Pacific Pelagic clays: DSDP, Leg 86, Site 576A* [15].

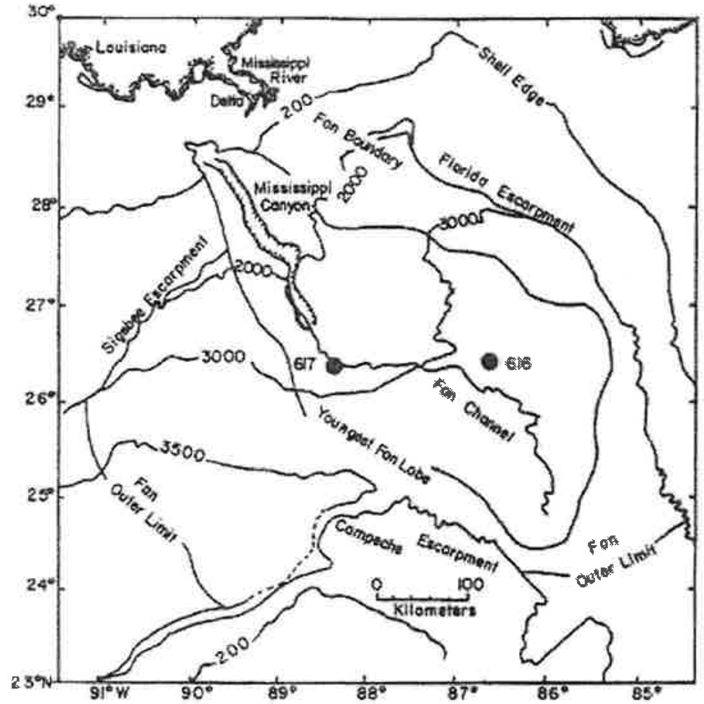


FIG. 11—*Location map of Mississippi Fan in the Gulf of Mexico showing Sites studied, DSDP Leg 96.*

Summary

In summary the following observations can be made.

1. Peak vane shear strengths vary with the orientation of the vane.
2. Hand remolded laboratory vane shear strengths do not depend on vane orientation.
3. Laboratory vane remolded shear strengths vary with the orientation of the vane.
4. Laboratory vane remolded shear strengths should be determined only after a minimum of between 3 to 5 revolutions of the vane.
5. Field vane remolded tests give higher shear strengths than either laboratory vane remolded tests or hand remolded vane shear strength tests.
6. Whether the hand remolded or laboratory vane remolded shear strength test is largest, based on very limited data, appears to be based on the liquidity index (LI) of the soil.
7. A linear relationship exists between the liquidity index (LI) and the logarithm of remolded shear strength. This relationship appears to apply for (1) a range of liquidity index, (2) a range of undrained shear strength, and (3) a specified group of clays.
8. Sensitivities for DSDP Site 576A in the Northern Pacific vary from 3 at a depth of 10 m to 1.4 at a depth of 42 m.
9. Sensitivities for DSDP Site 616B in the Gulf of Mexico on the Mississippi Fan vary from 3.5 at a depth of 70 m to 6.5 at a depth of 200 m.

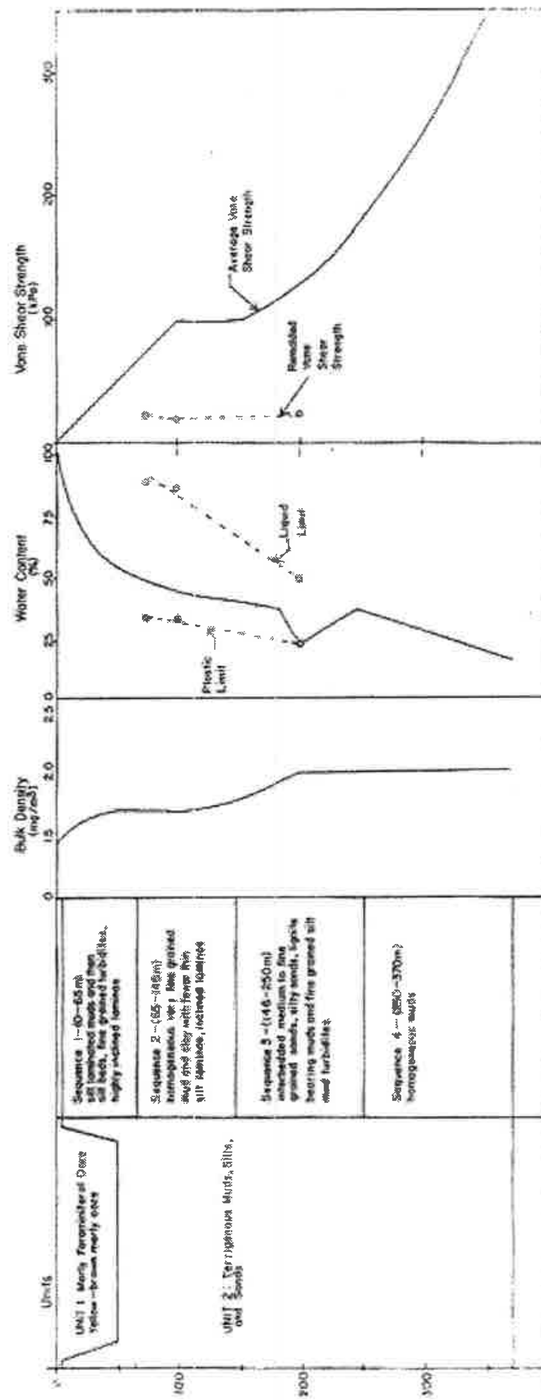


FIG. 12—*Geotechnical properties of Mississippi Fan sediments: deep sea drilling project, Leg 96, Site 616B* [16].

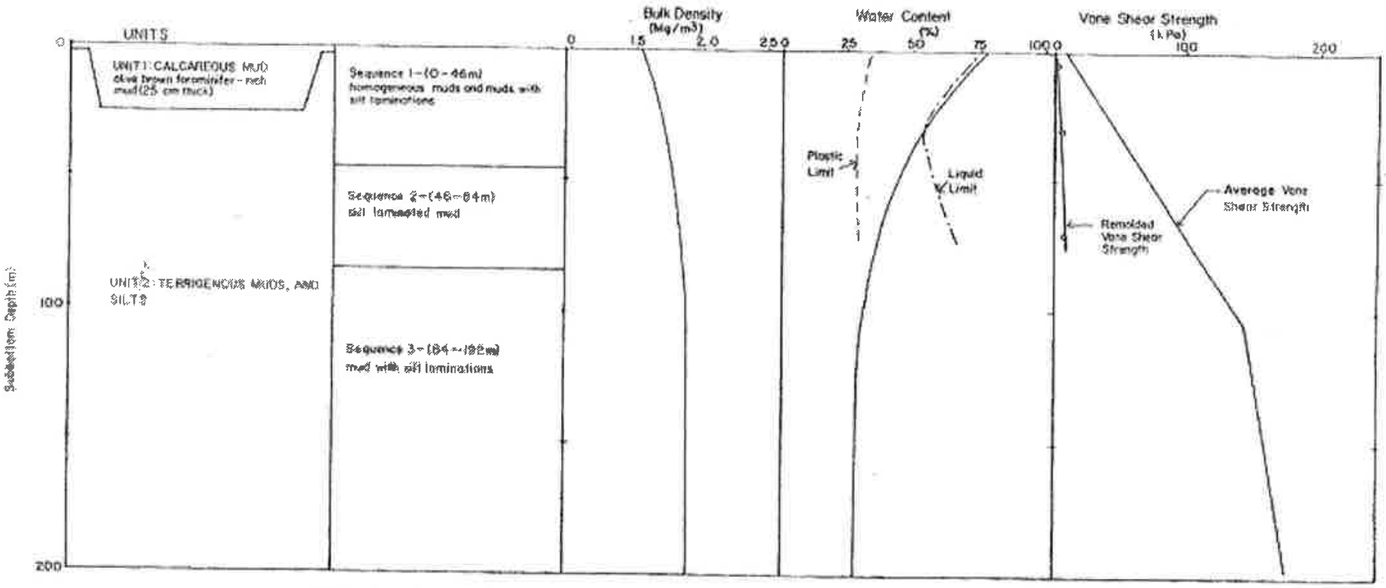


FIG. 13—*Geotechnical properties of Mississippi Fan Sediments, DSDP, Leg 96, Site 617A* [16].

TABLE 2—*Location and undrained strength properties of selected marine sediments* [17].

Sample	Water Depth, m	Location	Water Content, %	Average S_u, kPa		Sensitivity
CRUX 3	unknown	Pacific	232	12		10
CRUX 201			224	8		10
STYX 9-1C	5398	15°40'S, 172°00'W	133	13		2
STYX 9-2	5060	11°55'S, 169°32'W	284	5		4
STYX 9-3	4300	8°01'S, 166°35'W	148	6		3
STYX 9-5A	5069	8°36'N, 154°37'W	247	7		4
STYX 9-5B	5032	8°36'N, 154°18'W	388	9		4
STYX 10-1	5517	23°50'N, 143°58'W	123	4		2
STYX 10-1C	5508	23°25'N, 144°05'W	118	4		3
DSDP 576A	6217	Northern Pacific 32°0'N, 164°30'W	98 to 216	upper 10 m: S_u = 0.6 10 to 25 m: S_u = 0.28 below 25 m: S_u = 0.22	. . .	2 to 10 . . . . . .
DSDP 616B	2983	Mississippi Fan-Gulf of Mexico 26°24'N, 86°36'W	50 25	70 m: 20 200 m: 130		3.5 6.5
DSDP 617A	2467	Mississippi Fan-Gulf of Mexico 26°24'N, 88°24'W	75 42	2 m: 10 50 m: 72		10 14

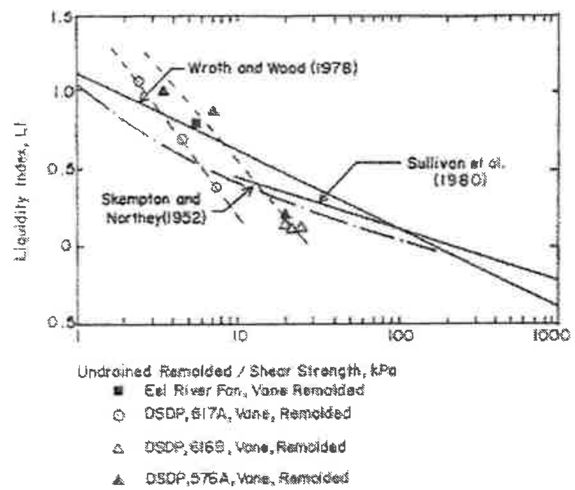


FIG. 14—*Remolded shear strength versus liquidity index.*

10. Sensitivities for DSDP Site 617A in the Gulf of Mexico on the Mississippi Fan vary from 10 at the surface to 14 at a depth of 50 m.

Acknowledgments

The data reported were derived from various studies performed by students in the Department of Environmental Resources Engineering at Humboldt State University. In particular the authors would like to acknowledge the assistance of Gretchen Rau, Brad Shipley, Michael Smith, John Steude, and Jeff Reese. In addition, the authors would also like to thank Dr. Jeff Borgeld, Department of Oceanography at Humboldt State University for box cores from the Eel River Fan. In conclusion, the authors would like to thank Dr. Adrian F. Richards for his insight into marine soil mechanics.

References

[1] Terzaghi, K. and Peck, R. B., *Soil Mechanics in Engineering Practice,* 2nd ed., John Wiley and Sons, New York, 1967.

[2] Keller, G. H., Lambert, D. N., and Bennett, R. H., Society of Economic Paleontologists and Mineralogists, Special Publication 27, 1979, pp. 131–151.

[3] Carius, T. and Richards, A. F., "San Diego Trough Geotechnical Test Area," *Marine Geotechnology,* Vol. 1, No. 4, 1976, pp. 345–370.

[4] Richards, A. F., *Deep-Sea Sediments, Physical and Mechanical Properties,* A. L. Inderbitzen, Ed., Plenum Press, New York, 1974, pp. 271–292.

[5] Skempton, A. W., "Long-Term Stability of Clay Slopes," *Geotechnique,* Vol. 14, No. 2, 1964, pp. 77–101.

[6] Arman, A., Poplin, J. K., and Ahmad, N., "Study of the Vane Shear," *Symposium on In Situ Measurement of Soil Properties,* Vol. 1, American Society of Civil Engineers, 1975, pp. 93–120.

[7] Fenske, C. W., "Deep Vane Tests in Gulf of Mexico," *Symposium on Vane Shear Testing of Soils, STP 193,* American Society for Testing and Materials, Philadelphia, 1956, pp. 165–25.

[8] Law, K. T., "Triaxial Vane Tests on a Soft Marine Clay," *Canadian Geotechnical Journal,* Vol. 16, Feb. 1979, pp. 11–18.

[9] Skempton, A. W., "Vane Tests in the Alluvial Plain of the River Forth Near Grangemouth," *Geotechnique,* Vol. 1, No. 2, 1948, p. 111.

[10] Eden, W. J. and Hamilton, J. J., "The Use of a Field Vane Apparatus," *Symposium On Vane Shear Testing of Soils, STP 193,* American Society for Testing and Materials, Philadelphia, 1956, pp. 41–53.

[11] Pyles, M. R., "Vane Shear Data on Undrained Residual Strength," *Journal of the Geotechnical Division, American Society of Civil Engineers,* Vol. 110, No. 4, Paper 18706, 1984, pp. 543–547.

[12] Bjerrum, L., "Geotechnical Properties of Norwegian Marine Clays," *Geotechnique,* Vol. 4, No. 2, 1954, pp. 49–69.

[13] Sullivan, R. A., Wright, S. J., and Senner, D. W. F., "Evaluation of Design Parameters From Laboratory Tests," *Offshore Site Investigation,* Graham and Trotman Ltd., 1980, pp. 201–216.

[14] Wroth, C. P. and Wood, D. M., "The Correlation of Index Properties with Some Basic Engineering Properties of Soils, *Canadian Geotechnical Journal,* Vol. 15, No. 2, 1978, pp. 137–145.

[15] Geotechnical Consortium, "Geotechnical Properties of DSDP Sediments from Hole 576A, Leg 86," in Initial Reports of the Deep Sea Drilling Project, Vol. 86, Scripps Institution of Oceanography.

[16] Shipboard Scientists Report, "Mississippi Fan, Sites 616B and 617A," Deep Sea Drilling Project, Leg 96, 1984.

[17] Noorany, I., "Shear Strength of Some Deep-Sea Pelagic Sediments," *Strength Testing of Marine Sediments: Laboratory and In-Situ Measurements, STP 883,* R. C. Chaney and K. R. Demars, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 251–257.