Summary

A symposium on "Laboratory and In-Situ Strength Testing of Marine Sediments" was held at the winter meeting of ASTM in San Diego, CA on 26 and 27 Jan. 1984. The symposium was sponsored by ASTM Committee D-18 on Soil and Rock.

About 30 papers were presented during the day and a half, three-session symposium on recent research and experiences related to the measurement of marine sediment strength. State of the art presentations were made by Adrian F. Richards on In-Situ Strength Testing and by Homa J. Lee on Laboratory Strength Testing. Approximately 90 individuals attended the symposium.

The objective of this paper is to organize and briefly summarize the findings of each symposium contributor, to augment these results with the results of nonsymposium researchers, and to incorporate comments of attendees and manuscript reviewers to provide a balanced view. It is hoped that this summary will fulfill the needs and objectives of this symposium, namely, to identify tests and procedures that require standardization by ASTM as well as to identify research areas which require further investigation. The goal of a marine geotechnical investigation is to characterize the properties and behavior of sediment in the field where loading occurs.

Sediment Disturbance/Environmental Factors

Attempts to determine the strength properties and behavior of marine sediments either by in-situ or laboratory testing are often affected by factors related to the degree of sediment disturbance or environmental factors. There are generally different factors that influence in-situ measurements than laboratory measurements.

In-situ testing appears to offer the advantage of measurements on undisturbed sediments that incorporate the existing localized temperature, pressure, and gas charged conditions. The principal limitation of this approach is that it cannot simulate or control a variety of environmental or structural loads or both. In addition, a stationary reference system for vertical positioning of the in-situ probe relative to the mudline is difficult to establish because either a ship (barge) deck or a bottom supported platform are affected by ocean waves and currents. Even during a "flat" sea state, there may be considerable error in the strength measurements. A bottom supported platform tends to be preferable to a ship's deck; however, the level of mechanical and electrical sophistication needed for such a system may be cost prohibitive for routine engineering studies, and it may require its own large support vessel (Johnson and Beard). Bottom platforms are generally heavy so as to provide the reaction necessary to press, jet, or vibrate a probe into the seabed. As a result the platform may sink slightly into a soft cohesive seabed altering its reference level and creating a breakout problem during return to the ship's deck. When used in granular soils, the state of stress may be altered directly beneath the platform and have an effect on strength measurement.

Laboratory testing offers the greatest flexibility for performing effective stress measurements, for simulating stress paths of field loading, and for minimizing costs. However, sample quality has always been a concern. Holt and Ims have evaluated the problem of tube plugging during sampling, which leads to gaps in the stratigraphic profile and low recoveries. Recovery lengths are related to soil bearing capacity at corer tip and the friction resistance force inside the sample tube. Sediment samples containing dissolved gas were studied by Chace. Expansion during pressure release was observed to progress significantly slower than during the compression sequence. Samples that were allowed to expand for periods of more than 5 h did not regain their initially pressurized density following recompression. Deep ocean samples without gas will also experience bulk water expansion from pressure release [*1*], but this affect is quite small for water depths less than 1000 m (3000 ft). Temperature changes from 0°C at the seabed to 20 to 30°C at the surface can also affect sample quality. All of these environmental/disturbance factors may necessitate special core sample handling and storage before testing. It is good practice to X-ray samples before testing to assess sample quality.

Arctic marine environments will undoubtedly impose additional environmental and sampling constraints on laboratory and field testing. Shields et al have defined some of the problems associated with warm permafrost, specially the susceptibility to creep deformations. They proposed the use of a pressuremeter to evaluate long-term creep behavior in the field. While their study was limited to laboratory testing of frozen sands, significant creep deformations were observed, but they were unable to develop a simple constitutive model.

Most marine sediments contain cementing agents in the form of calcium carbonate and silica. Rad and Clough subjected naturally cemented sands from Pacific coastal bluffs to drained and undrained triaxial testing. Cementation varied from weak to strongly cemented. They found that cementation enhances the peak strength, the brittleness index, and sample stiffness while lowering the failure axial strain. Friction angles were affected little by cementation level; however, there was a direct relationship between cementation level and the cohesion intercept. More research is needed on naturally cemented silts, clays, and coraline sands.

Sediments in water depths less than a few hundred feet are subject to storm wave induced loadings, which can alter the pore-water pressures and state of effective stress. Clukey et al performed wave loading tests on a normally consolidated silt in a laboratory wave tank. Pore water pressures were measured and observed to rise continually for steep waves until liquefaction. Liquefaction occurred at lower cyclic stress ratios than currently available data for sands would indicate. Waves of low steepness generated steady state residual pore-water pressures less than necessary for failure. Drainage and stress history affects remain to be studied.

Strength Measurements Variables

Many different test methods have been devised to determine the drained and undrained strength of sediments. While drained and undrained strengths are related through the effective stress principle, marine sediment laboratory and field measurements do not usually provide the data to develop this relationship without very extensive testing and analysis. As a result, a single test method may only provide approximate strength values or limited information on one aspect of strength behavior because of the complex material, disturbance, and loading conditions associated with that specific test [2]. A detailed testing program should combine laboratory and in-situ testing (Sonnerfeld et al, Jefferies et al, Attwooll et al, and Winters).

For drained shear strength, the objective is to determine the effective friction angle ϕ' and cohesion c' (if appropriate). During design and analysis the stress path of loading will yield the stress state and thus the drained strength. The effective strength parameters ϕ' and c' are influenced to same degree by density and disturbance conditions, the intermediate principal stress, and for clays, the rate of strain. Most drained strength testing continues to be performed in the laboratory where volume changes can be monitored during loading. The piezocone provides an in-situ capability of assessing drainage behavior during insertion in sands or partial drainage in silts. Svano et al have developed the theories for converting drained cone resistance to effective friction angle based upon a bearing capacity factor for a deep probe. While this procedure appears to offer promise, there is a need for further detailed fieldwork to verify the theory.

Undrained strength measurements are affected by the same factors as drained strength testing but to a greater extent. Factors, such as sediment disturbance, which obliterates stress history, can have a major effect on undrained strengths depending on soil sensitivity. During strength testing, it is essential to work with undisturbed sediment and to reconstruct the in-situ K_0 stress state (Jefferies et al). While laboratory testing offers the opportunity to reconstruct the in-situ stress state, to simulate most any stress path, and measure pore pressures for an effective stress based analysis, the disturbance and environmental factors discussed previously can have a major effect on strength measurements.

The normalized stress-strain (SHANSEP) analysis of Ladd and Foote is finding increased application with the marine sediments as acknowledged by Young et al, Noorany, and Lee to minimize disturbance effects. The use of normalized strength data requires performing consolidometer tests to determine the overconsolidation ratio (OCR) profile for the soil deposit. Mesri [3] has stated that the determination of the OCR from consolidation tests also involves as much uncertainty as the undrained strength itself. This is due to consolidometer tests being as sensitive to sample disturbance as triaxial tests. Therefore, SHANSEP may be of limited use in the evaluation of undrained shear strength if used with poor quality samples. In addition, research has also shown that quick clays and naturally cemented clays do not exhibit normalized behavior because the structure of these clays is significantly altered during consolidation to higher stresses.

In-situ tests with or without pore-pressure measurements appear to offer the most popular method of determining the undrained strength profile. Most marine sediments are normally consolidated so that positive excess pore pressures develop during shear, and the undrained strength profile is the basis for design. The effects of stress path for the different in-situ devices, such as the field vane, borehole shear, cone penetrometer, and pressuremeter are all different. Consequently the strength profile from each apparatus would be different if all other factors are the same.

The seabed stress state K_0 can create problems for in-situ testing when overconsolidated soils occur. OC soils exist along continental margins as a result of erosion, slumping, coastal dune migration, ice scouring, and tectonics among other conditions. They possess high "short-term" undrained strengths as a result of their lower void ratio and higher K_0 value compared to nonconsolidated (NC) soils. Highly overconsolidated soils may weaken with time because of the dissipation of negative excess pore pressures creating a problem for designers since most in-situ test programs may not adequately assess OC conditions. The addition of the piezometer to the cone penetrometer provides a method of identifying OC deposits and performing a more detailed study of sediment strength behavior.

In-Situ Testing

The remote location of the seabed and harsh, variable marine weather dictates that in-situ testing equipment be simple and quick to operate and yet provide data that are repeatable and representative of in-situ strength conditions (Richards and Zuidberg). Most of the in-situ related papers were involved with cone penetrometer testing for these very reasons. McNeilan and Bugno and Johnson and Beard used a cone with a friction sleeve and a seafloor jacking platform to press in the cone. Johnson and Beard used pumped water to minimize shaft friction successfully in stiff to dense soils without affecting cone readings in clay. For silts, partial pore pressure dissipation was observed to be the primary factor influencing measured cone resistance (McNeilan and Bugno), but this conclusion should be expected because drainage alters the effective stress path of loading from the undrained condition.

The use of a piezometer with cone penetration has been undergoing development for the last ten years [*4*] in an attempt to interpret cone penetrometer (CPT) tests on an effective stress basis. Senneset and Janbu have further developed the theories for obtaining the shear strength parameters both for drained and undrained conditions with pore-pressure measurements. This effective stress approach offers a great deal of promise, however field research is needed to check out the validity of this approach. Jefferies et al have shown, for example, that overconsolidation effects can complicate interpretation of in-situ measurements and constitute one of several unknown cone factors CPT test profiles were extremely repeatable at a site compared to in-situ vane tests, which showed considerable scatter.

Tumay and Acar, using a piezocone, have shown that the ratio of excess pore pressure at the cone tip to tip resistance provides a basis for predicting stress history of a deposit. While the scatter in their experimental results s_u/q_u is considerable, this approach may provide the means for identifying the presence of the unknown cone factors in a deposit to justify further detailed studies. Bennett et al used pore pressures from a piezometer probe in an NC clay to measure strength. Both Tumay and Acar and Bennett et al use dissipation of pore pressures with time after stopping the probe to predict the coefficient of consolidation or coefficient of permeability or both.

A number of other in-situ strength tools have been used with success but were limited to the shallow marine environment with water depths of about 30 m (100 ft) or less. The borehole shear test (BST) was used in a multistage test mode by Handy et al to measure shear strength, evaluate undrained strength parameters c and ϕ, and examine undrained soil-pile shear in a stiff marine clay. The BST test data, however, requires a good deal of interpretative skills, which are minimized to some degree by evaluating data immediately as obtained.

Pressuremeters were also used with varying levels of success by Jefferies et al, Sonnenfeld et al, and Shields et al. Jefferies et al had very consistent results with a self-boring pressuremeter in a uniform silty clay that showed the deposit to be overconsolidated with $K_0 = 2$. By comparison, Sonnenfeld et al had problems with the Menard pressuremeter test, which was explained by operational difficulties in a variable stratified soil deposit. They found that the Marchetti dilatometer provided good moduli data, compared to other lab and field tests, for this variable deposit. Shields et al used the pressuremeter as a basis for studying creep behavior in warm permafrost tests in the laboratory to study the operational problems before future field tests in the Beaufort sea. While this is not a realistic field test for even shallow marine creep testing, unless a platform is already in place, the lab results provide a basis for extrapolating to field conditions.

The cone penetration test with piezometer and friction sleeve appears to be easily adaptable to deep-water studies from a drill string, but the cost is extremely high. For lower cost deep water site survey and subbottom investigation, the expendable doppler penetrometer (Beard) is likely to be the valuable tool. It will probably undergo further development through the addition of a piezometer and other sensing tools, and lower cost penetrometers will become available commercially.

Laboratory Testing

The factors influencing laboratory strength testing have been summarized by Lee who noted that environmental and core disturbance effects are significant and often difficult to overcome. Yet, the test procedures that are used generally depend upon the sediment being sufficiently stiff to minimize handling disturbance. Sediments from the upper 0.9 to 3.0 m (3 to 10 ft) are often too soft to support their own weight and, therefore, may not be trimable for sophisticated strength testing. A previous study by Young et al [5] has shown that push sampling gives much better quality samples than the conventional wire-line percussion method.

Soft sediments continue to be tested within the core tube at a cut face using one of the several available undrained strength tools such as the lab vane, torvane, or fall core. Noorany used the lab vane on soft pelagic clays. The strengths (s_u/σ'_v) were found to be very high in the upper 10 m ($s_u/\sigma'_v = 0.6$) and decreased to $s_u/\sigma'_v = 0.22$ below 25 m. The high values in the surface sediments were attributed to aging and possible cementation effects as have also been observed by other investigators.

Noorany has also performed triaxial tests on stiffer sediments to obtain the effective stress parameters c' and ϕ'. Effective friction angles tend to coincide with expected trends for soil plasticity and gradation. However, some deep-sea sediments appear to have higher than expected friction angles, but there is no explanation for these. High friction angles may result from aging and overconsolidated behavior or possibly experimental error. Gulhati and Rao have proposed a rational procedure for performing multi-stage triaxial tests for instances where insufficient sediment is available for a rigorous testing program. Multi-stage triaxial testing, however, introduces another mechanism for disturbing the sediment and should be avoided when sufficient sediment is available. The normalized stress parameter (NSP) method of Ladd and Foote is finding increased use during strength testing for samples that are of good quality to slightly disturbed (Lee).

Drumwright and Nelson studied creep and stress relaxation behavior of deep-sea clay as the mechanism affecting hole closure following projectile implantation into the seabed. A cubical specimen was subjected to true triaxial loading. The magnitude and rate of stress relaxation increased with increasing void ratio. A finite value of octahedral shear stress existed at the completion of stress relaxation, and as long as this octahedral stress was less than the minimum value (strength), plastic deformation of the soil mass did not occur. This test method is complex and is not likely to be standardized by ASTM until a simpler version evolves, which perhaps makes use of a conventional triaxial device.

Dynamic testing provides information on wave loading effects, elastic properties, and damping of marine sediments. Cyclic triaxial testing was performed by Skotheim et al and Winters; resonant column testing followed by cyclic triaxial testing was performed by Saada and Macky and Pamucku and Suhayda; and Goulois et al used a direct cyclic simple shear test. While these tests differ little for land and marine soils, some of the empirical relationship and expected behavior established for land soils may not work well for marine soils where as others perform satisfactorily. For example, Saada and Macky show that the

Ramberg-Osgood-Masing model for representing the behavior of soils is inadequate, and Pamacku and Suhayda found that laboratory measurement of the dynamic shear modulus of soft underconsolidated marine clays may be unreliable. On the other hand, Winters found that the cone penetrometer test (CPT) and triaxial test both predicted liquefaction equally well. Most of these investigators agree that dynamic tests should simulate the effective stress state, cyclic loading, and drainage conditions. Dynamic testing remains an area where considerably more research is needed for marine soils.

A number of new strength tests have also been proposed for marine sediments. Edil and Toha have developed a new technique for measurement of the poroelasticity of marine soils. The test requires the determination of a single (but composite) poroelasticity factor from either of two testing modes on a laterally constrained soil column. A column length of 1 m or more is required for permeable soils, thus, increasing the importance of saturation and side wall friction on cyclic pore-pressure measurements. This test offers considerable promise, however, more research on the testing procedures and application of results are needed.

Amerasinghe and DeGroff have proposed the use of a rod shear test device to evaluate skin friction effects between pile and soil. During this test, a rod of pile material is bored through a triaxial compression sample with O-ring seals at the top cap and triaxial base. The soil is consolidated around the rod after which weights are hung off the bottom of the rod until pull-out. This proposed test method has some problems with friction and end effects, which can be improved, and provides an alternative to the present method of direct shear testing.

The point load test has been used by Abbs on weak carbonate cemented sediments and rocks. In this test, a cylinder of cemented materials is loaded to failure between two cone shaped plattens. The point load index is linearly related to the unconfined compressive strength although the coefficient that relates these two parameters is lower for cemented marine rocks than for land rocks. This test is quick and easy to perform because it requires no sample preparation, and it can be performed in the field with a portable hydraulic frame.

Comparison of Laboratory and In-Situ Strengths

Methodologies for correcting laboratory tests to in-situ strength were discussed by Chaney et al. These methods are (1) multiplying an estimated undisturbed lab sample strength by an empirical correction factor, (2) use of an analytical model to extrapolate strength values from tests on disturbed samples, and (3) direct computation of strength values using pore-water pressure extrapolated from lab test data.

Attwooll et al showed that the in-situ tests indicated higher shear strengths than did laboratory tests. He observed that this seemed to be due to differences in results of empirical relationships rather than variation of soil properties. Jefferies et al in turn stated that the CPT is the most repeatable in-situ test and the PMT test in turn is a prerequisite to a meaningful laboratory program. Sonnenfeld et al performed in-situ tests using SPT, PMT, and DMT methods from a barge. By combining various methods, both in-situ and laboratory, a large data base can be developed and cross checking is possible.

Winters reported a liquefaction susceptibility evaluation using both laboratory and in-situ tests on silty sediments. The in-situ test that he used was the CPT. Results indicated that cyclic triaxial laboratory tests showed a lower susceptibility to liquefaction than did the in-situ tests, perhaps because of densification during sampling, but they did yield approximately the same ranking of sites.

Attwooll et al and Jefferies et al both emphasized that investigators for major projects should involve the use of both in-situ and laboratory tests. This comprehensive approach enables evaluation of the shear strength by comparison of results for consistency and with established empirical relationships. In addition, Jefferies et al proposed that in-situ testing should be used as a guide for laboratory testing of marine soils if the strength and deformation properties of the soils are to be fully understood.

Conclusions

This symposium has shown that there is a need to modify some existing ASTM standards and to develop some new standards. Of the strength methods presented, the cone penetrometer test (CPT) deserves special attention because of its popularity and the evolution of associated tools and analyses. The following conclusions are justified from these symposium papers:

1. No one laboratory or in-situ testing method can provide all the data necessary to answer the questions posed by a large geotechnical investigation.
2. In-situ testing should be used as a guide for laboratory testing of marine soils if the strength and deformation properties of the soils are to be fully understood.
3. The CPT is the most repeatable in-situ test and can give a continuous profile of soil stratigraphy.
4. Cyclic triaxial tests show a lower susceptibility to liquefaction than results from CPT tests.
5. The normalized stress parameter method is recommended for use during laboratory strength testing of samples that are of good quality to slightly disturbed.

References

[1] Richard, A. F. and Parker, H. W., "Surface Coring for Strength Measurements," *Proceedings of the ASCE Civil Engineering in the Oceans I,* San Francisco, CA, Sept. 1967, p. 445.

[2] Lambe and Whitman, *Soil Mechanics,* Wiley and Son, New York, 1969, 553 pp.

[3] Mesri, G., "Discussion: New Design Procedures for Stability of Soft Clays," *Journal of Geotechnical Engineering Division, American Society of Civil Engineers,* Vol. 101, 1975, pp. 409–411.

[4] Janbu, N. and Senneset, K., *Proceedings,* European Symposium on Penetrating Testing, Vol. 2.2, Stockholm, Sweden, 1974, pp. 181–193.
[5] Young, A. G., Quiros, G. W., and Ehlers, C. J., "Effects of Offshore Sampling and Testing on Undrained Soil Shear Strength," *Offshore Technology Conference,* OTC 4465, Houston, TX, 1983, pp. 193–204.

Ronald C. Chaney
Talonicher Marine Laboratory
Humboldt State University
Trinidad, CA 95570; cochairman and coeditor.

Kenneth R. Demars
The University of Connecticut
Storrs, CT 06268; cochairman and coeditor.