9. STRENGTH

9.1. Principles

PHYSICAL BACKGROUND

Definition of Sediment Strength

Most soils and rocks are visco-elastic materials. Well-developed mathematical theories are available only for linear visco-elasticity, whereas soils and rocks have highly nonlinear stress-strain-time behavior. Therefore, time-independent elasto-plastic theory is often used to describe the stress-strain relationships of natural materials: the material is linearly elastic up to the yield point, and then it becomes perfectly plastic (Holtz and Kovacs, 1981). Some materials are brittle and exhibit little stress when strained (rocks); others are work-hardening (e.g., compacted clays and loose sands) or work-softening. The latter model is particularly applicable to clayey, soft, saturated, marine sediments, such as those usually measured with the instruments described in this chapter: stress decreases as the sediment is strained beyond a peak stress. The sediment yields (fails) at the peak stress, which can be defined as the sediment's strength.

Mohr-Coulomb Failure Criterion

According to Mohr, the shear stress on a failure plane at failure reaches some unique function of the normal stress on that plane, or

$$\tau_{ff} = f(\sigma_{ff}), \quad (1)$$

where τ is the shear stress and σ is the normal stress. The first subscript f refers to the failure plane and the second f means "at failure." This function can graphically be expressed by the Mohr failure envelope, the tangent to Mohr circles at different τ and σ at failure. The Mohr failure hypothesis states that the point of tangency of the Mohr failure envelope with the Mohr circle at failure determines the inclination of the failure plane.

Coulomb found that there was a stress-independent component of shear strength and a stress-dependent component. He called the latter the internal angle of friction, ϕ, and the former seems to be related to the intrinsic cohesion and is denoted by the symbol c. The Coulomb equation is then

$$\tau_f = \sigma \tan\phi + c, \quad (2)$$

where τ_f is the shear strength of the soil, σ is the applied normal stress, and ϕ and c are the strength parameters. Both parameters are not inherent properties of the material tested, but also depend on the test conditions.

The Mohr-Coulomb strength criterion is the combination Mohr failure envelope, approximated by linear intervals over certain stress ranges, and the Coulomb strength parameters:

$$\tau_{ff} = \sigma_{ff} \tan\phi + c. \quad (3)$$

This is the only failure criterion that predicts the stresses on the failure plane at failure, which is relevant to potential sliding surfaces in geotechnical applicatons.

Drained and Undrained Shear

When sediment is sheared under a load or applied stress, excess pore pressure is produced that may or may not escape depending on the permeability of the sediment and the time available. If the pore pressure can dissipate, the sediment is most likely work-hardened. Therefore, from an experimental standpoint (triaxial testing), undrained shear (total stress analysis) or drained shear (effective stress analysis) can be applied to the sediment.

In the undrained shear scenario, volume changes translate into pore pressure changes, and the assumption is made that the pore pressure and therefore the effective stress (= total stress minus pore pressure) are indentical to those in the field. The total, or the undrained shear strength, is used for the stress analysis. Tests must be conducted rapidly enough so that undrained conditions prevail if draining is possible in the experimental setup.

In the second, drained scenario, shear stress is used in terms of effective stresses. The excess hydrostatic pressure must be measured or estimated. Knowing the initial and the applied (total) stresses, the effective stress acting in the sediment can be calculated. The volume change depends on the relative density and the confining pressure. This approach is philosphically more satisfying because pore water cannot carry any shear stress; i.e., shear strength is thought to be controlled by the effective stresses (Holtz and Kovacs, 1981). Drained shear can ordinarily be determined only in the laboratory and the procedure is not popular because there are serious practical problems. Particularly in low-permeability material, the rate of loading must be sufficiently slow to avoid the development of excessive pore pressure, which can cause a test to take many days or weeks, and valve, seal, and membrane leaks may become a problem.

Testing for Shear Strength

There are three limiting conditions of consolidation (happens before shear) and drainage (happens during shear) that model real field situations: consolidated-drained (CD), consolidated-undrained (CU), and unconsolidated-undrained (UU). Unconsolidated-drained is not a meaningful condition because drainage would occur during shear and the effects of confining pressure and shear could not be separated. A special case of the UU test is the unconfined compression (labeled here informally as UUU) test, where the confining pressure equals zero (atmospheric pressure). This is by far the most common laboratory strength test used in geotechnical engineering today (Holtz and Kovacs, 1981). The effective stress at failure, and therefore the strength, is identical for the UU and UUU tests. In practical terms, the following conditions must be satisfied for this to be true:

1. 100% saturation,
2. specimen (core interval) must be intact and homogenous,
3. material must be fine-grained (clay), and
4. specimen must be sheared rapidly to failure to avoid draining and evaporation.

Direct shear test and triaxial tests are the common laboratory shear strength tests. Addiitonal special tests are for direct simple shear, ring shear, plain strain, and true triaxial test. These tests allow independent control and measurement of at least the principle stresses, σ_1 and σ_3, and changes in void ratio and pore pressure. The results can be analyzed in the σ-τ diagram (Mohr circle), *p*-*q* diagram (stress path), and other methods (e.g., Lambe and Whitman, 1979; Holtz and Kovacs, 1981). However, all these tests are too complex to be conducted in the shipboard laboratory. Instead, ODP provides two rapid and simple tests, the vane shear tests and the penetrometer test. These tests should be used as a guide only because there are many reasons why the results are only approximate (e.g., Lambe and Whitman, 1979). Particularly the influence of pore pressure changes during the undrained experiment cannot be estimated.

Vane Shear Test

Undrained shear strength can be determined using a vane that is inserted into soft sediment and rotated until the sediment fails. The torque, *T*, required to shear the sediment along the vertical and horizontal edges of the vane is a relatively direct measure of the shear strength. It must be normalized to the vane constant, *K*, which is a function of the vane size and geometry:

$$\tau_f \sim s_u = T / K, \qquad (4)$$

where s_u is a common notation for the vane shear strength (e.g., Lambe and Whitman, 1979). Shear strength has the units of pascals (= N/m^2), torque has the units of newton·meters (N·m), and *K* has the units of meters cubed (m^3). Two systems are available onboard *JOIDES Resolution* to determine vane shear strength. The automated vane shear system measures angular deflection of springs that were calibrated for torque. The hand-held Torvane directly returns a measure of shear strength from calibrated springs.

Penetrometer Test

Failure can be defined as the maximum principal stress difference, which is the same as the (unconfined) compressive strength of the specimen, $\sigma_1 - \sigma_3$. At a prescribed strain, shear strength, τ_f, is related to compressive strength, $\Delta\sigma_f$, by

$$\tau_f \sim \tau_{max} = (\sigma_1 - \sigma_3) / 2 = \Delta\sigma_f / 2. \qquad (5)$$

If $\Delta\sigma_f$ is determined in a UUU test by reading off the vertical strain, such as with the pocket penetrometer, the value must be divided by 2 to obtain the shear strength.

ENVIRONMENTAL EFFECTS

If there is visible core disturbance, measurements should not be taken. Moisture loss while the split core is being processed affects the shear strength measurements.

USE OF SHEAR STRENGTH

Shear strength, or shear resistance, of sediments is the most important aspect of slope stability. However, the shear strength values obtained onboard do not alone allow any slope stability analysis. They represent merely a relative strength profile.

For clay-rich marine sediments, the stress-strain behavior is greatly dependent on the stress history of the sample. The latter can be estimated in a semiquantitative way by the ratio of measured shear strength to in situ overburden stress, σ_{ov}:

$$h = s_u / \sigma_{ov}. \qquad (6)$$

For normally consolidated, fine-grained, cohesive soils, *h* has a value of about 0.25. Larger values indicate overconsolidaion, smaller values indicate underconsolidation. Marine sediments are typically overconsolidated in the uppermost few to several meters and slightly or strongly underconsolidated in the subjacent 100–200 m and deeper.

9.2. Automated Vane Shear (AVS) System

EQUIPMENT

Vane shear strength, S_u, of soft sediment at laboratory conditions is determined using a motorized miniature vane shear apparatus, following the ASTM D 4648-87 procedure (ASTM, 1987). A four-bladed vane is inserted into the split core and rotated at a constant rate of 90°/min to determine the torque required to cause a cylindrical surface to be sheared by the vane. The difference in rotational strain between the top and bottom of a linear spring is measured using digital shaft encoders. Maximum spring deflection at peak strength is determined by the AVS program and can easily be verified or adjusted by the user.

Undrained shear strength is

$$S_u = T / K = (\Delta / B) / K, \qquad (7)$$

where S_u is in pascals (N/m^2), T is torque (N·m), K is the vane constant (m^3), Δ is the maximum torque angle at failure (°), and B is the spring constant that relates the deflection angle to the torque (°/[Nm]). This simple relationship applies only if all the terms have been converted to SI units; otherwise, conversion factors must be used appropriately.

Potential sources of error using the motorized vane shear device are fracturing, particularly at S_u greater than 100–150 kPa, sand- and gravel-sized material (e.g., ice-rafted debris in glacial sediments), and surface drying of the core.

The moderately destructive measurements are done in the working half, with the rotation axis parallel to the bedding plane. Typical sampling rates are one per core section until the sediment becomes too firm for instrument penetration.

The motorized vane shear apparatus and springs were purchased from Wykeham Farrance Engineering, Ltd.

The vanes are usually manufactured by ODP.

CALIBRATION

No routine calibration is performed by the user. However, spring constant B and vane geometry K are important coefficients that must be verified and measured if new specimens are purchased or manufactured.

Vane Calibration

When a new AVS blade is produced or purchased, the vane blade constant K must be determined. ODP personnel are responsible for this occasional calibration. K is a geometrical factor and is calculated as

$$K = \pi D^2 H/2 \, (1 + D / 3H) \times 10^{-9}, \qquad (8)$$

where D and H are the vane diameter (maximum width of two wings) and height in millimeters and K has the units of cubic meters. The procedure is as follows:

1. Take multiple measurements of vane height and diameter, and enter them in the program utility available at the AVS station.
2. Press “Calibrate” in the calibration utility; the program calculates the mean value, standard deviation, number of measurements, and vane constant. The new constants are automatically used by the measurement program.
3. Initiate upload of the calibration statistics and vane constant into the ODP database.

Spring Calibration

The springs used to measure torque must be calibrated to the angles of rotation. ODP personnel are responsible for this occasional calibration. The spring constant, B, is defined as

$$B = \Delta/T, \qquad (9)$$

where T is the torque (provided in kg·cm by the manufacturer) and Δ is the corresponding deflection angle. ODP personnel enter the data into a calibration utility that converts the data to N·m and determines the regression slope that corresponds to B. The conversion is

$$T\,(\text{N·m}) = 0.0981 \times T\,(\text{kg·cm}). \qquad (10)$$

The calibration procedure is as follows

1. Enter the factory-supplied angle and torque data in the program utility available at the AVS station.
2. Press “Calibrate” in the calibration utility; the program calculates the regression coefficients.
3. Update the spring constant for the measurement program.
4. Initiate upload of the calibration statistics and spring constant into the ODP database.

In 1995, the following springs and constants were used (they are presumably based on regression of torque values in $kg^{-1}cm^{-1}$):

1. 0.0092109,
2. 0.018857,
3. 0.030852, and
4. 0.045146.

PERFORMANCE

Precision

Repeatability of torque measurement in the exactly same material is estimated to be better than 5%.

Accuracy

This depends on the reference method used (e.g., common triaxial test) and the material measured (e.g., sand vs. soft clay) and includes uncertainties resulting from pore pressure developed during the measurement and the lack of confining pressure. For large vane shear field tests, Lambe and Whitman (1979) estimated that results are accurate to 20% at best.

MEASUREMENT

The user is guided through the measurements by the AVS program. The position of the measurement in the core section is entered automatically in the program. Measured strain is plotted against calculated torque. The principal measurement steps are

1. Choose and mount the appropriate spring and vane and ensure that the corresponding identifiers are selected in the program.
2. Insert the vane until it is completely immersed in the sediment and start the program. It is crucially important for the relative precision and accuracy of the measurement that the vane is always inserted completely.
3. When the run has terminated, withdraw the vane and clean it.

DATA SPECIFICATIONS

Database Model

Table 9—1 AVS database model.

AVS section

avs_id [PK1]
section_id
run_num
run_date_time
system_id
spring_calibration_id
vane_calibration_id
direction
rotation_rate
raw_data_collected

AVS section data

avs_id[PK1] [FK]
pp_top_interval [PK2]
pp_bottom_interval
max_torque_angle
residual_torque_angle

AVS raw data

avs_id [PK1] [FK]
pp_top_interval [PK2] [FK]
avs_record_number [PK3]
torque_angle [PK4]
strain_angle

AVS vane calibration

vane_calibration_id [PK1]
calibration_date_time
vane_id
vane_constant
diameter_mean
diameter_sd
number_of_dia_meas
height_mean
height_sd
number_of_height_meas
comments

AVS spring calibration

spring_calibration_id [PK1]
calibration_date_time
spring_id
spring_constant_m1
spring_m0
spring_mse
comments

AVS spring calibr. data

spring_calibration_id [PK1] [FK]
torque_angle [PK2]
pp_torque

Notes: All values in the database should be in SI units (general rule). Vane and spring constants should be converted during the calibration procedure so that conversion factors do not have to be applied in standard queries.

Standard Queries

Table 9—2 AVS query A (results, measurements, and parameters) (to be implemented).

Short description	Description	Database
Sample ID	ODP standard sample designation	Link through [Sample]sample_id
Depth	User-selected depth type	Link through [Sample]sample_id
Su	Shear strength S_u	= [AVS Section Data] max_torque_angle
		/ [AVS Spring Calibration] spring_constant_m1
		/ [AVS Vane Calibration] vane_constant
Max. Angle	Maximum torque angle (at failure)	[AVS Section Data] max_torque_angle
Res. Angle	Residual torque angle	[AVS Section Data] residual_torque_angle
Run	Run number	[AVS Section] run_number
DateTime	Date and time of measurement	[AVS Section] run_date_time
Direction	Direction of measurement (usually x)	[AVS Section] direction
Raw Data	Flags if raw data were saved	[AVS Section] raw_data_collected
Vane	Vane identification	[AVS Vane Calibration] vane_id
Spring	Spring identification	[AVS Spring Calibration] spring_id

Table 9—3 AVS query B (raw data) (to be implemented).

Short description	Description	Database
Torque	Torque angle	[AVS Raw Data] torque_angle
Strain	Strain angle	[AVS Raw Data] strain_angle
Sample ID	ODP standard sample designation	Link through [Sample]sample_id

Table 9—4 AVS query C (vane calibration) (to be implemented).

Short description	Description	Database
DateTime	Calibration date/time	[AVS Vane Calibration] calibration_date_time
Vane ID	Vane identification	[AVS Vane Calibration] vane_id
Vane Const.	Vane constant	[AVS Vane Calibration] vane_constant
Dia. mean	Diameter, mean of measurements	[AVS Vane Calibration] diameter_mean
Dia. s.d.	Diameter, std. dev. of measurements	[AVS Vane Calibration] diameter_sd
Dia. n	Diameter, no. of measurements	[AVS Vane Calibration] number_of_dia_meas
Height mean	Height, mean of measurements	[AVS Vane Calibration] height_mean
Height s.d.	Height, std. dev. of measurements	[AVS Vane Calibration] height_sd
Height n	Height, no. of measurements	[AVS Vane Calibration] height_of_dia_meas
Comments	Comments	[AVS Vane Calibration] comments

Table 9—5 AVS query D (spring calibration) (to be implemented).

Short description	Description	Database
DateTime	Calibration date/time	[AVS Spring Calibration] calibration_date_time
Spring ID	Spring identification	[AVS Spring Calibration] spring_id
Spring m1	Spring m_1 (spring constant; slope)	[AVS Spring Calibration] spring_constant_m1
Spring m0	Spring m_0 (intercept)	[AVS Spring Calibration] spring _m0
R square	Mean squared error (mse)	[AVS Spring Calibration] spring _mse
Comments	Comments	[AVS Spring Calibration] comments

Table 9—6 AVS query E (spring calibration data) (to be implemented).

Short description	Description	Database
Angle	Angle	[AVS Spring Calibration] torque_angle
Torque	Calibration torque at angle	[AVS Spring Calibration] pp_torque
DateTime	Calibration date/time	[AVS Spring Calibration] calibration_date_time
Spring ID	Spring identification	[AVS Spring Calibration] spring_id

9.3. Torvane

EQUIPMENT

The Torvane is a hand-held instrument with attachments calibrated to shear strength for different ranges (stiffness of sediment; Table on page 8). It is rarely used because the automated vane shear device available has a larger range, better precision, and presumably superior accuracy.

Table 9—7 Specifications of Torvane attachments.

Diameter (mm)	Height of vanes (mm)	*Maximum* τ_f *(kPa)*
19	3	250
25	5	100
48	5	20

DATA SPECIFICATIONS

Database Model

Table 9—8 Database model.

TOR section data
tor_id [PK1]
sys_id
section_id
run_date_time
direction
core_temperature
range
comments

TOR sample data
tor_id [PK1] [FK]
pp_top_interval [PK2]
measurement_no [PK3]
pp_bottom_interval
strength_reading
comments

Standard Queries

Table 9—9 AVS query A (results and more) (to be implemented).

Short description	Description	Database
Sample ID	ODP standard sample designation	Link through [Sample]sample_id
Depth	User-selected depth type	Link through [Sample]sample_id
Strength	Strength reading (at failure)	[TOR Sample Data] strength_reading
DateTime	Date and time of measurement	[TOR Section Data] run_date_time
Direction	Direction of measurement (usually x)	[TOR Section Data] direction
Range	Sensitivity range	[TOR Section Data] range
Comments	Comments	[TOR Sample Data] comments

9.4. Pocket Penetrometer

EQUIPMENT

The penetrometer is a flat-footed, cylindrical probe that is pushed 6.4 mm deep below the split-core surface. The resulting resistance is the unconfined compressive strength or $2S_u$. The mechanical scale is in units of kilograms per square centimeter, which are converted into units of kilopascals by

$$2\tau_f \text{ (kPa)} = 98.1 \times 2\tau_f \text{ (kg/cm}^2\text{)}. \quad (11)$$

The maximum τ_f that can be measured with the pocket penetrometer is 220 kPa.

DATA SPECIFICATIONS

Database Model

Table 9—10 Database model.

PEN section data
pen_id [PK1]
sys_id
section_id
run_date_time
direction
core_temperature
adapter_used
comments

PEN sample data
pen_id [PK1] [FK]
pp_top_interval [PK2]
measurement_no [PK3]
pp_bottom_interval
strength_reading
comments

Standard Queries

Table 9—11 AVS query A (results and more) (to be implemented).

Short description	Description	Database
Sample ID	ODP standard sample designation	Link through [Sample]sample_id
Depth	User-selected depth type	Link through [Sample]sample_id
Strength	Strength reading (at failure)	[PEN Sample Data] strength_reading
DateTime	Date and time of measurement	[PEN Section Data] run_date_time
Direction	Direction of meas (usually x)	[PEN Section Data] direction
Adaptor	Adaptor used (sensitivity range)	[PEN Section Data] adapter_used
Comments	Comments	[PEN Sample Data] comments