(d) Many areas along the Great Lakes shores that once had sufficient sand cover to protect an underlying cohesive substratum from downcutting are now coming under attack as the sediment supply has been reduced through human influences. Reductions to the sediment supply occur through entrapment of sediment at structures which protrude into the lake (including harbor jetties and land reclamation projects that have been created for many purposes, such as power plants, marinas, and docking facilities) as well as through protection of previously eroding sections of shoreline. Shabica and Pranschke (1994) describe one such area north of Chicago on Lake Michigan where the sand cover has decreased from 560 m^3/m in 1975 to 190 m^3/m in 1989. If the depletion of sediment cover continues at this site, the previously very low rates of shoreline recession (less than 0.2 m/year, or 8 in./year) may accelerate.

(4) Local wave and water level conditions. The characteristics of the local wave and water level conditions represent the fourth controlling factor on the geomorphology of consolidated cohesive coasts. Both the intensity and the directionality of the waves can influence the rate of erosion at a particular shore site. Other factors being equal, greater wave energy translates to higher downcutting rates and more rapid shoreline erosion. Directionality of the waves can have a secondary influence on downcutting rates by affecting the mobility of the sand cover over the underlying till. Large swings in wave direction can result in a more dynamic system with respect to the sediment cover. Fluctuations in water level also have an important role in cohesive shore erosion processes as explained by Stewart and Pope (1993) and Fuller (1995). While direct erosion at the bluff toe may be accelerated during high-water conditions, low water leads to acceleration of the nearshore downcutting process (which in turn allows more waves to reach the bluff toe).

b. Profile types. Boyd (1981, 1992) completed an extensive review of nearshore profile shapes for consolidated cohesive shores on the Great Lakes. These essentially fall into two categories: concave profiles and convex profiles. Figure III-5-15 provides a schematic description of these two profile types.

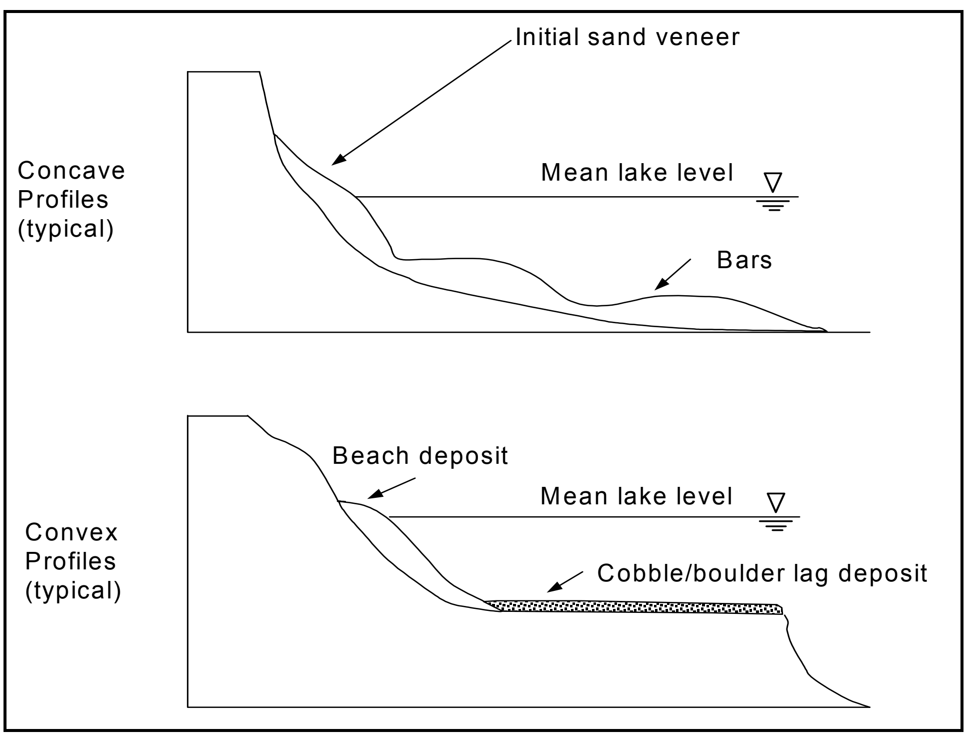

Figure III-5-15. Distinctions between concave and convex consolidated cohesive profiles

(1) Concave profiles. Concave profiles develop in fine-grained sediment with a relatively uniform erosion resistance from the closure point up to the top of the bluff or cliff. These profiles have an exponential form similar to sandy shore profiles described by Dean (1977). Sand cover over these cohesive profiles can range from perhaps as little as 25 to over 200 m^3/m measured between the bluff toe and the 4-m depth contour. The sand cover can be in the form of bars, and, in areas with a sand cover in the high end of the range, a substantial beach at the shore. Stewart and Pope (1993) found that a reduction in the range of water level fluctuations would not reduce the long-term erosion rates for cohesive shores with concave profiles. As explained above, lower water levels result in accelerated lowering of the nearshore profile, which essentially has the same effect as high water levels — allowing waves to reach the bluff toe.

(2) Convex profiles. As noted above, convex profiles develop at locations where potential lag deposits exist within the eroding material. These profiles are characterized by a nearshore shelf, which on the Great Lakes has a depth approximately 2 m below low water datum. At other locations, this depth will be determined by the median grain size of the lag deposit, the wave climate, and the range of water level fluctuations. Long-term erosion rates along these shores are less than rates for concave cohesive shores (having limited sand cover) with the same wave exposure. With the exception of high-water periods, the erosion-resistant nearshore shelf acts to dissipate wave energy before it reaches the shoreline. However, during high water periods, these shorelines are more vulnerable to erosion when waves are able to attack the bluff toe. Therefore, in contrast to cohesive shores with concave profiles, shores with convex profiles would benefit from a reduction in the range of water level fluctuations (Stewart and Pope 1993). Finally, the fish habitat function of cohesive shores with a convex profile shape is much more important owing to the surficial substrate (cobbles and boulders with limited sand cover) and the proximity to a deepwater drop-off at the edge of the shelf.

III-5-6. Sediment Properties and Measurement Techniques

a. Introduction.

(1) In the case of noncohesive sand and gravel, sediment mobility can be estimated just by knowing the grain size and shape, specific gravities of the sediment and water, and the viscosity or temperature of the water (i.e., physical properties). The mobility of cohesive sediment is a more complex phenomenon. Cohesion (particle attraction) is governed by the electrochemistry of the sediment mineral and water; its state of consolidation; and in many cases, by the presence of organisms like diatoms, which can bind the sediment particles together with mucus.

(2) The extent of data requirements will vary depending on the nature of the coastal engineering problem and the nature of the shore. This section presents an overview of the range of possible field and laboratory investigations that can be used to characterize the conditions associated with erosion, transport, deposition, and consolidation on a cohesive shore. This discussion focuses on a characterization of the specific geologic conditions related to the cohesive shore. For the measurement of environmental conditions (e.g., waves and water levels), refer to Part II-3.

b. Consolidated shore erosion. Developing an understanding of consolidated shore erosion requires information on profile shape (beach and nearshore profile techniques are summarized in Part III-3-2), presence or absence of lag deposits, bluff and nearshore stratigraphy, erodibility of the one or more cohesive units in the active nearshore erosion zone (i.e., between high water and the depth of closure), and the sand cover thickness and stability. Available techniques to assess the characteristics listed above are as follows:

(1) Field sampling and geotechnical analyses.

(a) Testing may be performed in situ or in a laboratory on samples extracted from the field. Extraction techniques for seabed or lake bed cohesive sediments include: dredging; coring; box coring; and cutting samples (the latter using a chainsaw with a trenching chain). As noted in Part III-5-6, it is important to retrieve intact samples that, to the extent possible, preserve the natural structure of the cohesive sediment.

(b) None of the available standard geotechnical test procedures provide a direct measure of the erosion resistance of a cohesive sediment in the coastal environment. Nevertheless, the more important characteristics that provide an indirect assessment of erodibility include: grain size analysis (including clay content); liquid and plastic limits; water content; undrained shear strength; bulk density; and consolidation pressure. Techniques for establishing these parameters are presented in the USACE Engineering Manual "Laboratory Soils Testing" (EM 1110-2-1906). Undrained shear strength can be determined in the field using a cone penetrometer or a vane shear apparatus.

(c) Borehole information can be valuable for assessing variations in stratigraphy both above and below the water level.

(2) Laboratory erodibility experiments.

(a) There are no standard and accepted approaches for establishing the erodibility of cohesive sediment in the coastal environment based on geotechnical properties. Therefore, to quantify the relationship between erodibility and shear stress applied under a given flow condition, it is usually necessary to perform laboratory experiments. Experiments may not be required where direct techniques have been applied to determine the erodibility of similar sediment. It is advisable that these experiments be performed with intact, and to the extent possible, undisturbed samples of cohesive sediment in order to preserve the natural structure of the soil.

(b) Four laboratory techniques for assessing erodibility are briefly reviewed in this section. These provide an example of the range of techniques that are available.

(c) Arulanandan, Loganatham, and Krone (1975), and more recently Zeman (1986), describe the use of a rotating cylinder apparatus to assess the erodibility of intact and undisturbed samples of cohesive sediment. This technique is also mentioned for testing the erodibility of mud. In this approach, a long cylindrical sample is mounted inside a larger transparent cell. The cell is then filled with water and rotated. During rotation, the torque transmitted to the inside stationary cylinder is measured to quantify the shear stress applied to the sample. At the end of the test, erosion rates are determined by the loss in mass of the sample. A disadvantage of this approach is the inability to introduce sand to the flow to assess the important influence of sand abrasion.

(d) Another small-scale laboratory technique for testing intact and undisturbed samples is described by Rohan et al. (1986). This procedure is based on an adaptation of the standard pinhole test. Water is circulated through a hole drilled through the axis of a cylindrical sample. The head loss caused by friction in the sample is measured using differential manometers in order to assess the shear stress applied to the soil by the flow. Depending on the size of the hole bored in the sample, it is possible that this technique could be adapted to assess the influence on erosion of sand in the flow.

(e) At a larger scale, intact and undisturbed cohesive sediment samples can be placed in a drop section in the floor of a unidirectional flow flume or tunnel. The sample is then exposed to different flow conditions with and without the presence of sand, and the erosion of the sample surface is surveyed intermittently to determine erosion rates for the different conditions. This technique is also frequently used for mud. Kamphuis (1990) describes the use of a tilting tunnel in which Pitot tubes were used to determine a velocity profile upstream and downstream of the sample in order to determine the shear stress applied to the sample by the flow. Cornett, Sigouin, and Davies (1994) describe a similar approach using a tilting flume for the analysis of samples extracted from the bed of Lake Michigan near St. Joseph Harbor (Parson, Morang, and Nairn 1996). In this case, a laser doppler velocimeter measured the velocity profile near the bed in order to establish the shear stress applied to the sample by the flow (Figure III-5-16). This figure shows a sand veneer migrating over the till sample in the unidirectional flow flume. In both the Kamphuis (1990) and the Cornett, Sigouin, and Davies (1994) tests, the maximum flows generated were in the range of 3 to 3.5 m/sec (10 to 12 ft/sec). Results from experiments using this technique to estimate erodibility are presented in Part III-5-7b.

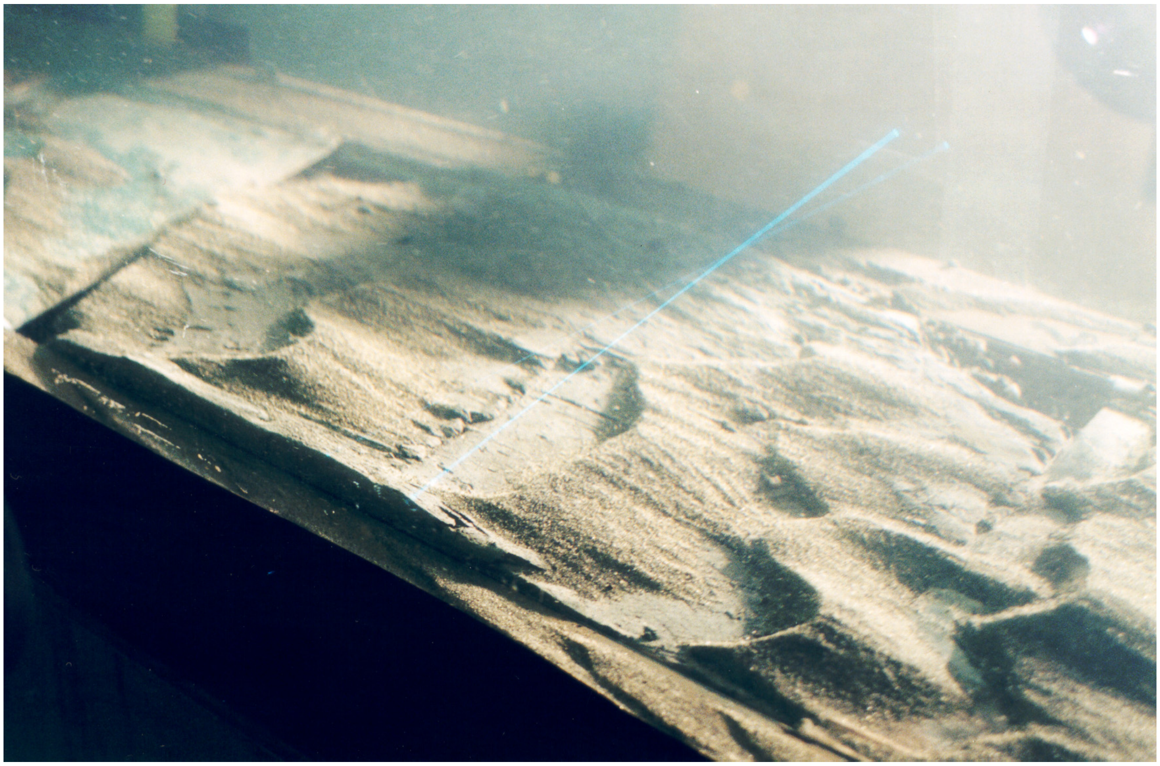

Figure III-5-16. Laser doppler velocimeter (LDV) used to determine shear stress exerted on the till bed in a unidirectional flow flume test. This test features sand in the flow acting as an abrasive

(f) The most realistic approach that can be taken to assess erodibility in a laboratory setting is to create a nearshore profile with intact and undisturbed cohesive sediment samples in a wave flume or basin. This approach was used by Skafel and Bishop (1994) to complete important research into the erosion processes on cohesive shores. Intact samples, measuring 1 m by 0.35 m by 0.45 m, encased in an open-ended steel box were extracted from the top of a bluff on Lake Erie and placed directly in a wave flume. The open-ended steel box was pushed slowly into the till by a 20-ton hydraulic ram and the till at the inner end of the box was cut away using a chainsaw with a trenching chain. The box was then removed with a crane. The till boxes were installed in the flume to create the desired profile shape. In these tests, the effects of sand cover in the form of migrating bars or a patchy veneer were tested. Also, the influence of breaking waves on the erosion of the cohesive sediment was assessed.

(3) Field techniques for assessing surface and subsurface conditions.

(a) One of the most important pieces of information in characterizing a cohesive shore profile is the sand cover thickness across the underlying cohesive profile (i.e., measured from the bluff toe out to a depth of at least 4 m). In addition, where the cohesive profile is exposed, it is also important to determine whether or not a protective lag deposit exists. As with any coastal engineering site investigation, beach and nearshore profiles are essential information. In this section, a variety of techniques for characterizing the surface and subsurface conditions, with particular focus on the sand cover thickness, are presented, ranging from the simplest to the most sophisticated.

(b) The simplest technique of estimating the thickness of the sand cover across the profile involves the following tasks:

- Complete a beach and nearshore profile from the toe of the bluff out to the depth of closure (between the 5- and 10-m water depth).

- Through the use of a steel probe or test pits, attempt to determine the thickness of sand cover near the waterline.

- Estimate the shape of the underlying cohesive profile (as a smooth exponential form) joining points between the toe of the bluff, the position of the till at the waterline (if determinable), and the troughs between the bars on the profile. Typically, the till will be exposed or only thinly covered in the troughs. If repeated profiles are available at a site, these may provide additional information on the position of the underlying till if the position of the troughs between bars shifts between surveys.

(c) In order to complement the simple technique described above, a diving inspection could be completed across the profile. The diver could use an underwater video to document conditions, and a steel probe to estimate sand cover thickness at different locations. Depending on the extent of sand cover, the till may be exposed in some areas. Alternatively, a frame-mounted video camera lowered from a boat or a remotely operated vehicle with video could be used. Video is also valuable in assessing whether or not a lag deposit exists where the cohesive layer is exposed.

(d) In place of a simple steel probe, a jet probe could be used to survey the thickness of the sand cover on the land and underwater. A jet of either water or air can be used to penetrate the sand cover (the latter is only applicable underwater). Shabica and Pranschke (1994) describe the use of a hydraulic probe consisting of an extendible 20 mm diameter pipe through which water is pumped at 2.8 kg/cm^2 (40 psi).

(e) A technique based on electrical resistivity has been used to establish the sand thickness across the subaerial section of beach for sections of the Holderness shoreline. This method is particularly useful at locations with large tidal ranges that allow for significant sections of the profile to be surveyed at low tide.

(f) Ground-penetrating radar was used to survey the thickness of the sand cover for several profiles downdrift of St. Joseph Harbor (Parson, Morang, and Nairn 1996). The limitation of this technique is that it can only be used in a freshwater environment.

(g) Sub-bottom profiling, or high-frequency seismic imaging, is another geophysical technique that is capable of establishing the thickness of sand cover over an underlying cohesive profile. Side-scan sonar is an acoustic technique that provides an image of the seabed or lake bed surficial conditions. While this procedure would not be capable of determining the thickness of sand cover, it could provide useful surficial information such as the extent of exposed gravel and cobble lag deposits. These methods are described in Part IV-5 in greater detail.

c. Erosion, transport, and deposition of mud. In the case of mud, it is useful first to examine the following hydrodynamic sediment properties that will be required by the equations presented later:

(1) Cohesion. The cohesive bond is predominantly electrochemical, increasing with the electrical conductivity of the ambient water and proximity of the particles. Conductivity increases with salinity. The bond between particles may be enhanced, particularly at rest on the bed, by biological 'glues' such as the mucus excreted by diatoms, worm tubes, and feces (Paterson 1994).

(2) Critical shear for erosion.

(a) As water flows over the mud bed, as either steady flow or oscillatory flow under tides and waves, it exerts a shear stress τ on the bed due to viscosity and turbulence (described in greater detail in Part III-6). Not only is shear a real physical stress on the bed sediment, but it also serves as empirical shorthand for the level of turbulence in the flow. Thus, it is a useful parameter in describing suspended load sediment transport; as well as fluid mud (bed load), erosion, and deposition.

(b) At the level of a stationary particle on the bed, shear forces are balanced by the forces of gravity, interparticle friction, and cohesion. Shear is augmented by lift and drag, making the force balance

$$\text{SHEAR} + \text{LIFT} + \text{DRAG} < \text{GRAVITY} + \text{FRICTION} + \text{COHESION}$$

a vector sum, the same as that for noncohesive sand and gravel, but with the addition of cohesion. As flow increases, the left-hand side of this balance increases approximately as the square of velocity, until

$$\text{SHEAR} + \text{LIFT} + \text{DRAG} = \text{GRAVITY} + \text{FRICTION} + \text{COHESION}$$

and the formerly stationary particle leaves the bed and begins to move. The shear stress at which this occurs is known as the *critical shear for erosion* or *erosion threshold* τ_c. τ_c is still shorthand for the entire left-hand side of the balance, not shear alone.

(c) The sediment 'particle' may be an individual grain; but more likely a floc, made up of several grains held together by cohesion. Cohesion plays the major role in the right-hand side of the force balance, and failure (erosion) will occur where cohesion is weakest.

(d) Critical shear τ_c is not a particularly useful concept in fluid mud. At the water/fluid mud interface, the applied shear stress is balanced by a shear strain (flow) of the fluid mud, rather than GRAVITY + FRICTION + COHESION. Also, the fluid mud is essentially a thick, viscous, laminar, boundary layer, protecting the stationary bed from any SHEAR + LIFT + DRAG approaching τ_c. Erosion of fluid mud is better described by densimetric Froude Number entrainment between two fluids (Part III-5-7e).

(3) Erosion rate at twice critical shear. Both the Parthenaides and Krone Equations (Parts III-5-7d and III-5-9c) are 'excess shear' fits to observed erosion and deposition, respectively. For example, the Parthenaides Equation (Part III-5-7d) correlates observed erosion rates with

$$\text{Dimensionless Excess Shear} = (\tau_c - \tau) / \tau_c\text{; negative } (\tau_c < \tau) \text{ for erosion}$$

The Parthenaides coefficient M_p (in units of kg/m^2/sec) (see Equation III-5-1), is the correlation coefficient between erosion rate and excess shear, when dimensionless excess shear = -1; that is, when $\tau = 2\tau_c$.

(4) Critical shear for deposition.

(a) A critical shear stress for deposition τ_s *Pa* (lbf/ft^2) is not obvious at first glance. In noncohesive sediment, the critical shear for deposition is only slightly less than that for erosion: a noncohesive particle will come to rest almost as soon as the shear is too small to move it. But the process of deposition of cohesive sediment flocs is quite different; τ_s is generally on the order of one fourth of τ_c.

(b) High shear near the bed breaks up large flocs before they can settle. Then, the resulting smaller flocs and individual particles are resuspended. The critical shear for deposition τ_s is that through which large flocs can pass without being broken up. Note that τ_s is not shorthand for something more; τ_s really is the shear stress in the bottom boundary layer which cannot overcome cohesion in the settling flocs.

(5) Sediment, fluid mud, and water densities.

(a) Important densities and specific gravities:

ρ_w = specific gravity (mass density) of water — 1,000 kg/m^3 (62.4 lb/ft^3) in fresh water, up to 1,030 kg/m^3 (64.3 lb/ft^3) in seawater

ρ_s = specific gravity (mass density) of sediment mineral (no voids): generally 2,000 kg/m^3 (125 lb/ft^3) to 2,700 kg/m^3 (170 lb/ft^3) depending on mineral

(b) Bulk sediment density voids filled with ambient water:

- Of freshly deposited flocs (may be fluid mud if < 1,100 to 1,200 kg/m^3 (70 to 75 lb/ft^3), corresponding to a mass concentration in excess of about 20 kg/m^3 (20 ppt)).

- Of existing bed surface, and layers, e.g., 1,400 kg/m^3 (90 lb/ft^3).

- Of fully consolidated sediment, generally < 2,000 kg/m^3 (125 lb/ft^3).

(6) Grain size and settling velocity.

(a) Settling velocity is a more important hydrodynamic property of cohesive sediment than grain size. Settling velocity is a measure of the sediment's behavior in suspension; grain size only allows us to guess the settling velocity.

(b) The first thing to know about cohesive sediment grain size is that it is *not* a measurable physical constant. True, the size of individual dispersed grains may be inferred from measurements of their settling velocities in distilled (free of dissolved chemicals) water: generally on the order of 10-μ or less. The settling velocity of a 10-μ sphere, 2,500 kg/m^3 (156 lb/ft^3), in water of 20 °C (68 °F) is 0.06 mm/sec (0.002 in./sec).

(c) But cohesive sediment of this size in natural, often salt, water does not stay dispersed for long. Grains stick together when they come close enough for the cohesive forces to overcome the fluid shear and gravity keeping them apart. Aggregations of cohesive sediment grains are called 'flocs.' Flocs are larger than individual grains, of course, but because of water trapped within the floc, they are also less dense than the pure mineral. Depending on the relationships among floc size, shape, and density, the result is a *floc settling velocity* that may be more or less than that of individual grains. The settling velocity must be determined with the natural sediment in the natural water.

(d) Mud may also be biologically cohesive (Paterson 1994), for example, due to mucus excreted by diatoms. Biological cohesion is even more difficult to predict than electrochemical, providing yet another reason for using natural sediment and natural water in determining floc size and settling velocities.

(7) Degree of consolidation.

(a) The degree of consolidation u is defined as the ratio of the bulk density of the sediment to the bulk density of the 'fully consolidated' sediment, measured under Part III-5-6b(5). Consolidation of cohesive sediment is the compaction of the soil mass accompanied by drainage of the interstitial water, just as with noncohesive sediment. The principal difference is the length and cross-sectional area of the drainage path. In cohesive sediments, the path length is long and the area is small (i.e., low permeability); slowing down drainage and consolidation. Drainage is through the bed surface, into the ambient water, so that a good relative measure of the length of the drainage path P is the depth of burial below the surface. Cross-sectional area of the drainage path must be inferred from measurements of permeability.

(b) Overburden speeds up consolidation but increases the length of the drainage path, especially when the overburden is also cohesive. Nevertheless, consolidation starts at the bottom of a sediment layer and follows the draining water upward, giving even a freshly deposited layer a density gradient, denser at the bottom to less dense at the surface, until the entire layer is fully consolidated. The strength of the sediment represented by the critical shear for erosion τ_c increases with density and consolidation.

(8) Field measurement techniques. Many of the cohesive sediment field and laboratory measurement techniques are the same as those for noncohesive sediment (Part III-1). Nevertheless, some accommodation must be made for mud:

(a) Bed sampling. Much depends on knowledge of the composition and density of surficial sediments, which can be gained from laboratory analysis of surface samples obtained in the field. It is unreasonable to expect that undisturbed mud samples can be collected. In fact, it is difficult to contain most surficial mud in the commonly used Shipek or Ponar grab samplers because the samples leak out. Underwater samples may have to be obtained by divers, and all samples that include entrapped water should be transported in sealed jars and stored at 4 °C (39 °F).

(b) Boreholes and cores. The techniques give information on subsurface sediment layers. Blow counts and cone penetration tests give a relative measure of the strength and density of the layers (but not of the critical shears for erosion and deposition of mud, see below), and cores taken from the layers are as close to undisturbed samples as is possible in cohesive sediment. Boreholes should extend to bedrock or similar hard, impenetrable layers, with cores and cone penetration tests in each major layer.

(c) Suspended sediment sampling. This type of testing is needed to determine composition and quantity of sediment in suspension. Generally, the technique is to pump and filter 4 L of suspension and transport the filter and contents to the laboratory for subsequent analysis. Alternatively, 1 L of suspension may be sealed in jars and transported to the laboratory for filtering and analysis there; this liter may be obtained by pumping or from any of the proprietary suspension samplers. Filters should be no larger than 10 microns. Sampling should be carried out at a minimum of four elevations over the depth, with special attention to the near-bed or fluid mud layer.

(d) Settling tube. Field settling tubes, e.g., the 'Owen Tube' (Eisma, Dyer, and van Leussen 1994) measure the settling velocity of cohesive sediment flocs in 'live' natural water, even in a natural level of turbulence. Typically an undisturbed sample of sediment-water suspension is captured in a horizontal tube. The tube is immediately turned into the vertical position, and the settling velocity of the flocs is determined from density changes that occur in the suspension at various depths in the tube and over various times.

(e) Piezometers. These instruments measure rate of drainage of excess pore pressure from natural muds, and thus permeability and rates of consolidation. Lancelot (Christian, Heffler, and Davis 1993) is a piezometer that first creates excess pore pressure on its insertion in the mud bed, and then measures the rate of decay or drainage.

(f) Optical techniques. These techniques are primarily used as a substitute for suspended sediment sampling. Two basic techniques are used: measuring light transmitted through a known illuminated volume of suspension in a turbidity meter or transmissometer (e.g. Bartz, Zaneveld, and Pak 1978); or measuring light reflected from the suspension by an 'Optical Backscatterance (sic) Sensor' or OBS (e.g. Sternberg, Shi, and Downing 1989). Both require calibration against natural sediment in known concentrations in natural water.

(g) Acoustic techniques. Many novel applications are still under development, mostly in the high-frequency (MHz) range, where for example, suspended sediment concentration and grain size profiles can be measured (e.g. Hay and Sheng 1992). At lower frequencies, echo sounding detects the elevation of the bed and of the surface of fluid mud; and in the side-scan mode, detects bed forms such as ripples and dunes, and their orientation (Hay and Wilson 1994). At still lower (seismic) frequencies, sound penetrates the bed and detects the interfaces between sediment layers of different densities, creating sub-bottom profiles.

(h) Radioactivity techniques. In these techniques, Gamma rays or X-rays are passed through a sediment/water suspension or bed layer (e.g. Sills 1994). The energy passing can be related by calibration to the mass density of the suspension or layer. These techniques are particularly useful in characterizing fluid mud layers, as and where they occur. Radioactivity techniques are also used in laboratory consolidation columns.

(i) Direct shear techniques. There are several field devices that apply a variable shear stress to the surface of a cohesive sediment bed (Gust 1994), and measure the variable rate of erosion (increase in suspended sediment in the water column) and deposition (decrease in suspended sediment in the water column). Results can be used directly in the Parthenaides and Krone equations (Equations 5-1 and 5-4) respectively. The prototype for all such devices is the annular flume, described under Part III-5-6b(9) "Laboratory Measurement Techniques," and sketched in Figure III-5-17. The Sea Carousel described by Amos et al. (1992) is an example of field adaptation of the annular flume.

(j) Correlation with shear strength. Although the critical shear for erosion τ_c would seem to be a function of the shear strength of soft cohesive soil (measured by vane, cone, or penetrometer), the form of that function is not yet known and certainly not linear. Even measuring mechanical surface shear directly on tidal mud flats (Faas et al. 1992) produces mechanical yield stress an order of magnitude larger than the hydrodynamic τ_c.

(9) Laboratory measurement techniques.

(a) Grain size analysis. Standard ASTM D422 laboratory techniques should be applied to determine the physical size of individual grains in bed, core, and suspended sediment samples. Although no ASTM standard has been published, the pipette technique (removing a known volume of suspension from a known

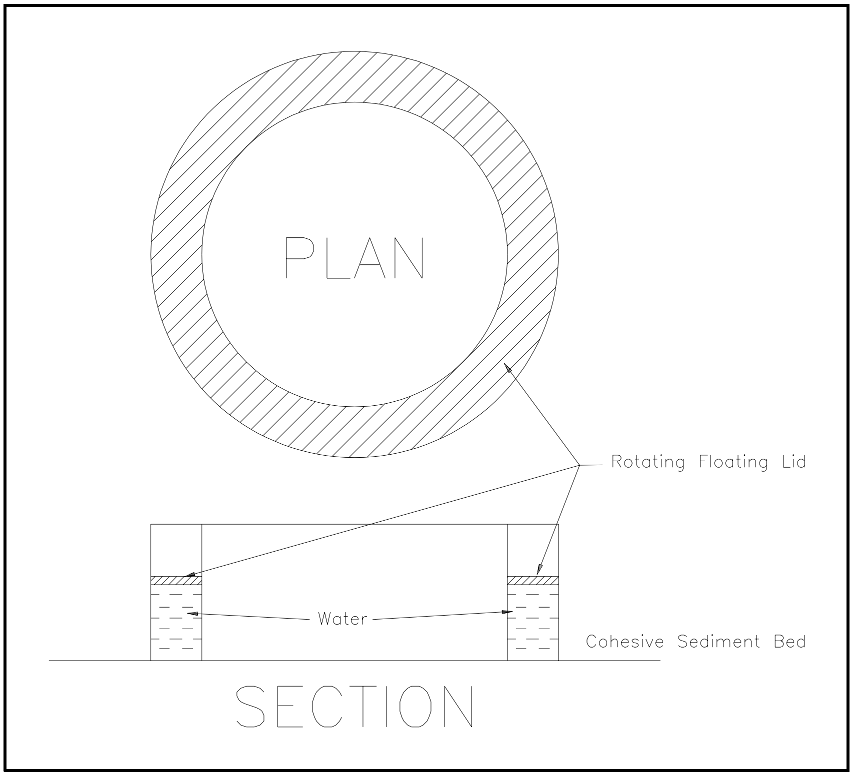

Figure III-5-17. Prototype direct shear device, the annular flume

elevation in the settling column, and filtering or drying to determine sediment concentration), is an alternative to the hydrometer technique. Total dry weight of suspended samples is also required to give field concentration in mg/l (ppm). Both hydrometer and pipette techniques measure settling velocity, and infer grain size from it. The settling column also measures settling velocity in the manner of a large-scale (typically greater than 1 m (40 in.) deep, 0.3 m (12 in.) diameter) hydrometer or pipette test (Gibbs 1972). Sensitive differential pressure transducers record the variations in suspended sediment concentration with depth and time, from which settling velocity distribution in the sample can be computed. Like the consolidation column below, settling columns need to be well-isolated from vibration and temperature changes to prevent artificial flocculation of the settling particles. For clay particules (<4 m), it will be necessary to use a nonstandard particle counter, e.g., Coulter counter. Nonstandard (natural water) hydrometer, pipette, or settling column tests should be used to estimate settling velocity of the flocs and bulk density of deposited sediment.

(b) Consolidation column. A consolidation column is a cylinder containing 2 to 3 m of natural sediment and natural water in a vibration-free environment to ensure natural rates of consolidation (Sills 1994). Variations in pore pressure with time and depth (overburden) are measured with piezometers, and in density, with gamma ray or observed volume. Estimates of permeability (length and diameter of drainage paths, and variation with bulk density) come out of the same measurements, using Equation 5-6, for example.

(c) Direct shear techniques. There are several laboratory devices that apply a variable shear stress to the surface of a cohesive sediment bed and measure the variable rate of erosion (increase in suspended sediment in the water column) and deposition (decrease in suspended sediment in the water column). Results can be used directly in the Parthenaides and Krone Equations of Parts III-5-7d and III-5-9c, respectively. The prototype for all such devices is the annular flume (e.g., Krishnappan 1993), sketched in Figure III-5-17. An annular flume is simply an endless channel in which the shear or velocity of rotation of the lid can be varied