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By:

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Management Perspective

This chapter was prepared for a multidisciplinary environmental manual. Contributions are multi-national. The methodologies and research findings described in this chapter were written outside of any specific program, but the text is a contribution to an international effort for an environmental monitoring manual. The chapter contributes information on sediment physical characteristics, including in-situ and laboratory testing methods, mapping techniques, and cohesive soil erodibility and transport. The manual is intended for international use by scientific and engineering organizations.

The chapter is broken down into three main sections: Offshore Soil Mechanics, Mapping of Offshore Sediments, and Erosion and Transport of Cohesive Sediments. The basic field testing procedures for offshore sediments are described, including penetration, shear strength, pore pressure and seepage measurements. Laboratory testing methods described are moisture content, unit weight and bulk density, undrained shear strength, consolidation, viscosity, particle size, and specific surface area. Mapping techniques that have been used by NWRI are described, such as offshore sediment sampling, echo sounders and sonar devices. The section on erodibility of cohesive sediments includes river and coastal transport of sediments and the description of both in-situ and laboratory flumes.

Paramètres physiques des sédiments et techniques pour leur analyse

A. J. Zeman et T. S. Patterson

Sommaire à l'intention de la direction

On a préparé ce chapitre pour un manuel environnemental multidisciplinaire, rédigé dans le cadre d'une collaboration multinationale. Les méthodologies et les résultats des recherches décrits dans ce chapitre ne sont pas le fruit d'un programme particulier, mais d'un effort international en collaboration, destiné à la rédaction d'un manuel de surveillance environnementale. Ce chapitre présente des informations sur les caractéristiques physiques des sédiments, notamment en ce qui a trait aux méthodes d'essai *in situ* et en laboratoire, aux techniques de cartographie, ainsi qu'aux caractéristiques d'érosibilité cohésive et de transport du sol. Ce manuel est destiné à des utilisations internationales par des organisations scientifiques et par des services d'ingénierie.

Ce chapitre est divisé en trois grandes sections : la mécanique des sols extracôtiers, la cartographie des sédiments extracôtiers, et l'érosion et le transport des sédiments cohésifs. On décrit les procédures de base d'essai *in situ* pour les sédiments extracôtiers, notamment des mesures de pénétration, de résistance au cisaillement, de pression des eaux interstitielles et de suintement. Les méthodes d'essai en laboratoire décrites mesurent la teneur en humidité, le poids unitaire, la masse volumique apparente, la résistance au cisaillement (sédiments non drainés), la consolidation, la viscosité, la granulométrie et l'aire spécifique. On décrit l'utilisation de techniques cartographiques par l'INRE, par exemple l'échantillonnage de sédiments extracôtiers et les sondages à l'aide d'échosondeurs et de dispositifs sonar. La section sur l'érosibilité des sédiments cohésifs traite notamment du transport de sédiments fluviaux et côtiers, et elle présente une description de canaux expérimentaux *in situ* et en laboratoire.

Abstract

The physical parameters of sediments can be measured and mapped in several ways. Sediment strength may be tested by cone penetration, standard penetration and field vane tests. Piezometers and seepage meters may be used for obtaining porewater pressure and seepage measurements. Laboratory testing methods can be used to determine such parameters as moisture content, unit weight, bulk density, shear strength, consolidation, viscosity, particle size, and specific surface area. Offshore sediments may be mapped with sounders, multi-scan echo sounders and other devices. Erosion and transport characteristics of cohesive sediment are significantly different than for coarse grained sediments. Silt and clay particles suspended in water often have a tendency to clump together due to various factors such as particle mineralogy, electro-chemical bonds, bacteria and the hydrodynamic properties of the flow field. Processes for flow and transport for cohesive sediments vary in riverine and coastal areas. Flumes can simulate flows of cohesive sediments but are subject to limitations such as shape (straight or circular) and whether they are used in a laboratory or in-situ.

Résumé

On peut mesurer et cartographier les paramètres physiques des sédiments de plusieurs façons. On peut tester la résistance des sédiments par des essais de pénétration de cône, par des essais de pénétration normalisés et par des essais scissométriques. On peut utiliser des piézomètres et des suintomètres pour déterminer la pression des eaux interstitielles, ainsi que pour mesurer le suintement. On peut aussi utiliser des méthodes d'essai en laboratoire afin de déterminer des paramètres comme la teneur en humidité, le poids unitaire, la masse volumique apparente, la résistance au cisaillement (sédiments non drainés), la consolidation, la viscosité, la granulométrie et l'aire spécifique. Enfin, on peut cartographier les sédiments extracôtiers avec des sondes, des échosondeurs multibalayages et d'autres dispositifs. Les caractéristiques d'érosion et de transport des sédiments cohésifs sont significativement différentes de celles des sédiments grossiers. Les particules de silt et d'argile en suspension dans l'eau ont souvent tendance à s'agglomérer à cause de divers facteurs comme la minéralogie des particules, les liens électrochimiques, des bactéries et des propriétés hydrodynamiques du champ de courant. Les processus d'écoulement et de transport auxquels sont soumis les sédiments cohésifs varient selon les zones riveraines et côtières. On peut simuler à l'aide de canaux les écoulements des sédiments cohésifs, mais, pour ces simulations, on doit tenir compte de limites dues à la forme (canal droit ou circulaire) et au lieu choisi (en laboratoire ou *in situ*).

Environmental Monitoring Handbook (F. Burden, editor)
Interdisciplinary Project

Chapter 5: Sediment Physical Parameters and Techniques (A.J. Zeman and T.S. Patterson)

Contents

5.1 Introduction

From the geotechnical viewpoint, aquatic sediments can be viewed as soils deposited underwater and thus onshore geotechnical methods can be used to determine sediment physical properties. Most sediments are characterized by high water content and, in the case of cohesive sediments, by low values of shear strength and high compressiblity. Due to variable hydrodynamic conditions both in space and in time, sediments vary in texture. Usually, in normally-consolidated cohesive sediments, the shear strength increases while the compressibility decreases with the depth below the sediment-water interface.

Reliable measurements of sediment shear strength and compressibility require relatively undisturbed samples. This requirement is more severe than the one for onshore soil sampling procedures. Besides mechanical disturbances, and disturbances due to transportation, storage and preparation, aquatic sediments are disturbed by changes in hydrostatic stress, temperature, release of gases and sediment oxidation. Increased temperatures and exposure to air may result in decomposition of organic matter and a growth of bacteria. These miscellaneous disturbances can reduce or, conversely, increase the sediment strength and alter other geotechnical properties. The prevailing opinion is that all sediment samples are significantly disturbed (Monney 1971).

Coarse (granular) sediment fractions consist of rock fragments that are composed of one or more minerals either fresh or weathered. Sandy sediments typically consist of rock fragments, quartz, feldspars, mica and heavy minerals. Clay minerals predominate in fine-grained (cohesive) sediments and they are usually subdivided into three subgroups known as the kaolinites, illites and montmorillonites, Sediments usually contain a mixture of clay minerals, amorphous (iron, silicon and aluminum) oxides and organic matter. The interactions among sediment particles, pore water and dissolved constituents in pore water are primarily responsible for physical properties of fine-grained sediments. The pronounced influence of clay mineralogy on most physical properties of cohesive sediments is reflected e.g. in the Casagrande plasticity chart (Terzaghi and Peck 1968).

Offshore sediments consist of a three-phase system of solid particles, pore water and gas. Microbiological degradation of organic matter is responsible for the presence of gases. Sediment gases contain methane (CH_4) and nitrogen (N_2) in dominant amounts, and carbon dioxide (CO_2) and hydrogen (H_2) in trace quantities (Fendinger et al. 1992). Henry's law desribes the continuous balance between gas existing in the sediment as free bubbles and gas dissolved in sediment pore water. A substantial decrease in hydrostatic pressure occurs when sediment samples are brought to the surface, which produces gas ebullition and sample volume change. Changes in hydrostatic pressure and temperature and subsequent rapid gas expansion are known to produce severe disturbance of samples, particularly in sediments with high organic carbon content.

Bioturbation can change the physical properties of sediments considerably and changes in geotechnical properties due to bioturbation of sediments are related to fabric changes. A direct comparison between bioturbated and non-bioturbated deposits is difficult because sediment physical properties are also affected by conditions that prevent bioturbation, e.g. rapid sedimentation and oxygen-depleted bottom waters. It is, nevertheless, possible to evaluate the effect of bioturbation indirectly by analyzing different sediment cores and vertical trends in a single core. Bioturbation usually increases porosity and decreases compressibility. Sediment mixing and reworking further affect sediment water content, grain size and permeability. Deeper in the sediment, physical properties are more controlled by sediment composition and pore water chemistry than by fabric. For this reason, the influence of bioturbation is most pronounced in sediments close to the sediment-water interface and this influence is obliterated in more compacted sediments (Wetzel 1990).

The ASTM standard D422 uses the hydrometer method for the determination of sizes smaller than 74 μm. Geologists measure grain size of sediments using other laboratory procedures, e.g. the pipette method (Royse 1970), the sieve and sedigraph method (Duncan and LaHaie 1979) and the Coulter method (Mudroch et al. 1997). Note that in the geological literature, the boundary between the silt and clay sizes is 4 μm (8 phi) as opposed to the boundary of 2 μm used in the geotechnical literature.

For environmental concerns, sediments near the sediment-water interface are of importance. These sediments are typically of very low consistency and therefore the disturbance of these samples due to sampling should be taken into account. The issue of sample disturbance is particularly important for strength and consolidation testing. For this reason, in-situ testing is often preferred over tests on cored samples.

5.2 Offshore Soil Mechanics

5. 2.1 In-Situ Testing Methods

The difficulty in obtaining undisturbed samples for laboratory testing of very soft cohesive sediments favours the use of in-situ testing methods. However, these in-situ tests are frequently complemented by laboratory geotechnical tests as sediment samples are often collected for geologic and geochemical reasons and because in-situ tests without "ground-truth data" are frequently difficult to interpret.

5.2.1.1 Cone-Penetration Tests

Various types of cone penetrometers have been designed over the years and standard testing procedures have been developed in Europe and North America (Richards and Zuidberg 1985). The penetrometers equipped with a pore pressure measuring system are referred to as piezocones. Piezocone testing procedures should follow ASTM Standard D 344-1 and ISSF ME 1989.

The cone penetration test (CPT) can be used for both granular and cohesive sediments to obtain shear strength parameters both for drained and undrained conditions. Measured parameters are cone point resistance, friction sleeve resistance and pore pressure. Other geotechnical parameters, such as sediment geotechnical classification, relative density, undrained shear strength, drained shear strength (cohesion and friction), deformation moduli, preconsolidation pressure and coefficient of consolidation can be derived from recorded values (Senneset and Janbu 1985). Pore pressure dissipation tests may provide additional information on sediment permeability. A competent interpretation of measured values requires a solid grasp of advanced soil mechanics and a comparison of penetrometer tests with other field and laboratory measurements.

Specialized cone penetrometers can be equipped with electrodes and measuring probes to measure sediment temperature, electrical conductivity, resistivity and shear wave velocity. Research penetrometers have been designed for pore water geochemical sampling and outflow hydraulic conductivity testing (Campanella et al. 1993).

A free-fall impact penetrometer with a capability of testing the surficial ocean sediment up to a depth of 10 m was developed at Memorial University, Newfoundland with a 45 cm^2 nominal cross section (Chari 1981). The test results were compared with similar tests on a standard 10 cm^2 "Fugro" type penetrometer. The effects of the penetrometer size, cone angle, sediment/cone friction and penetration rates in cohesive and granular sediments were studied.

Two light penetrometers have been used to map the properties and thickness of contaminated freshwater sediments at the National Water Research Institute of Environment Canada (Rukavina and Trapp 2000, Zeman et al. 2000). A weighted tripod equipped with an underwater video camera and echo-sounder records the depth to refusal with a precision of about 5 cm. The second instrument is a dynamic penetrometer (Sting™), which is lowered from a boat to a predetermined depth and then allowed to fall freely and penetrate into the bottom sediment to refusal. Upon retrieval, electronically-recorded deceleration data are downloaded to a notebook computer and converted to dynamic bearing capacity values. Penetrometer measurements of soft (usually contaminated) sediments have been found more reliable than determinations using gravity coring, where the results are appreciably influenced by unavoidable shortening of sediment cores.

5.2.1.2 Standard Penetration Tests and Field-Vane Tests

The Standard Penetration Test (SPN) is used in conventional geotechnical investigations in combination with split-spoon sampling. The test consists of counting the number of blows of the drop weight required to drive the sampling spoon into the sediment for a distance of 0.3 m. This test is very rapid and it is particularly useful for investigations of stiff clays (e.g. overconsolidated till deposits), silts and sands. Offshore applications require a stable support, e.g. a drill ship or a jackup platform.

The field vane test is used for determinations of the undrained shear strength and the sensitivity of soft cohesive sediments. Offshore applications are quite analogous to onshore procedures which have been in use for at least a half century (Terzaghi and Peck 1968). The vane shear apparatus, usually consisting of a four-bladed vane fastened to the bottom of a vertical rod, is gently pushed into the sediment. The apparatus is then rotated and the relationship between torque and angular rotation is recorded. The undrained shear strength can be calculated from measured torque and vane dimensions. The sensitivity is determined from comparison of values obtained for undisturbed and fully remolded sediment conditions. In offshore applications, the field vane apparatus is usually installed on a bottom-resting platform which is controlled remotely from a supporting vessel. In shallower waters, the field vane is frequently used with standard onshore drilling rigs that operate from a fixed (spudded) platform or from a drill ship.

5.2.1.3 Porewater Pressure and Seepage Measurements

As the hydrostatic pressure increases linearly by about 10 kPa per metre of water depth, it is difficult in deeper water to measure absolute pressures close to hydrostatic values. It is, however, relatively easy to measure small differences between sediment pore pressures and the hydrostatic pressure. Differential piezometers are used to measure the extent of underconsolidation in soft fine-grained sediments. The degree of underconsolidation is expressed by the presence of the excess pore pressures (i.e. above the hydrostatic value). These instruments may be deployed at an offshore site for several months in order to monitor long-term fluctuations in excess pore pressure. Fluctuations may be produced by the passage of a large storm, or, in the case of shallow water depths, they may reflect the effect of surface waves, tides and currents. Effective shear-strength parameters can be computed from pore-pressure measurements. Results may be affected by the presence of gas and the recorded excess pore pressure may reflect pore-water pressure, pore-gas pressure, or both (Hirst and Richards 1977).

Seepage meters of different designs (tubes, inverted barrels and sample bags, pressure transducers) are installed in nearshore sediments to monitor interaction between groundwater and open water bodies. These instruments have been used to determine the horizontal and vertical sediment permeability, as well as the direction, quantity and quality of groundwater flow (Lee 1977, Cooke et al. 1993).

5.2.2 Laboratory Testing Methods

Laboratory geotechnical tests are identical in principle to those carried out with onshore soil samples. As sediments are typically of very soft consistency, appropriate testing equipment and procedures have to be selected. These departures from standard laboratory geotechnical testing will be emphasized in detail in the following paragraphs. Laboratory investigations start with a thorough inspection of sediment samples submitted to the laboratory. Apart from visual examination and sample description, examination of samples by X-rays provides information on sediment stratigraphy, sediment structure and the degree of sample disturbance prior to sample extrusion.

Information on sediment texture (particle size) and sediment plasticity is used for sediment classification. Sediment samples can be classified according to their physical properties using the well-established Unified Soil Classification System, adopted in 1952 by the U.S. Corps of Engineers and the Bureau of Reclamation (Terzaghi and Peck 1968, ASTM Standard D2487). According to this system, sediments can be divided into three major groups: coarse-grained, fine-grained, and highly organic (peaty). The boundary between coarse-grained and fine-grained sediments is taken to be the 200-mesh sieve (74 µm). The coarse-grained sediments (gravels and sands) are classified according to their grain size and size distribution. The results of plasticity tests are used for the classification of silts and clays.

Geotechnical parameters are measured according to pertinent ASTM standards. These include the natural water content (D2216), the Atterberg limits (liquid limit, plastic limit and plasticity index, D4318), grain-size distribution (D422), and various procedures to measure the shear strength (Chaney and Demars 1985) and consolidation testing (standard oedometer test, D2435). The standards for common geotechnical tests used in Germany are provided by the German Institute for Standards (DIN 1988, Kern and Westrich 1999).

5.2.2.1 Moisture (Water) Content

The natural water content is the ratio of the weight of water to the weight of sediment. In sedimentology it is common to use the weight of wet-saturated sediment (total-water content or wet-water content) while in soil mechanics the weight of dry sediment (dry-water content) is used. As weight measurements rather than volume measurements are used, this test is not very sensitive to sediment disturbance of fine-grained sediments (in contrast to free-draining coarser sediments). The loss of water is determined by drying a sample at the temperature of 105° C. If drying is carried out at a higher temperature, which is not recommended, higher water losses will be measured, particularly in samples containing swelling clay minerals and organic matter.

The natural water content can be measured directly using precise weighing and oven-drying according to a standardized procedure. Indirect measurements by methods such as time domain reflectometry and gamma ray attenuation (Mudroch et al. 1997) are seldom used in routine investigations of aquatic sediments.

5.2.2.2 Unit Weight and Bulk Density

Unit weight is the ratio of the total weight to the total volume of a sediment sample. Bulk density is the mass of a sediment sample divided by its volume, i.e. the same sediment property is measured but it is expressed in different units. Unit weight or bulk density measurements allow a conversion of water percentages by weight to water content by volume and can be used for calculating porosity and void ratio when particle density is known. Porosity is defined as the ratio of the volume of voids to the total volume. Void ratio is defined as the ratio of the volumes of voids to the volume of solids. The use of porosity is preferred in sedimentology while void ratio is commonly used in soil mechanics. Functional relationships of various sediment quantities can be found in many textbooks (e.g. Jumikis 1962, Das 1983).

ASTM Standard D2937 describes the gravimetric and volumetric determination of bulk density. A cylindrical metal sampler or a syringe is used for volume determinations. For hard sediments and rock pieces, a density balance, a pycnometer or a direct comparison with heavy liquids can be used (Mason and Berry 1968; Mudroch et al.1997). Gamma ray attenuation techniques are used for nondestructive and rapid determinations of bulk density (ASTM Standard D2922; Mudroch et al. 1997). Gamma ray attenuation techniques have been used for nondestructive bulk density measurements of sediment cores and for vertical profiles of artificially-sedimented laboratory columns used in studies of sediment deposition and consolidation (Kern and Westrich 1999).

5.2.2.3 Undrained Shear Strength

In measurements of shear strength, it is distinguished between undrained and drained testing (Terzaghi and Peck 1968). In drained tests, the changes in stress are applied slowly to allow pore pressures to dissipate and the shear stress is expressed in terms of effective stresses. Drained shear strength can be determined only in the laboratory using direct shear test and triaxial tests, which can be time-consuming for low-permeability sediments. In undrained tests, the stresses are determined so rapidly that no dissipation of pore pressures occurs and the shear stress is expressed in terms of total stresses. Relatively rapid undrained testing, in which no dissipation of pore pressures is assumed, is described in the following text.

Tests used to determine undrained shear strength include the minivane, the torsional vane, the fall cone and the pocket penetrometer. If draining of samples is possible, tests must be conducted rapidly enough so that undrained conditions prevail. All these tests are carried out only on fine-grained sediments that display clear plastic characteristics. Results obtained on sandy sediments are difficult to interpret due to dilation and partial drainage.

The miniature vane test is based on the same principle as the field vane test and testing is carried out in accordance with ASTM standard D 4648. These tests can be run quickly, require little skill and are similar to a common in-situ testing technique. In the test, a vane is inserted into a soft sediment and rotated until the sediment fails. The measured torque is then converted to the undrained shear strength. As the shear strength depends on the vane rotation rate, the vane is rotated at a recommended constant rate of 90°/min using the motorized vane shear apparatus. The lower measurement limit is about 5 kPa.

The torsional vane test (Torvane) is similar to the laboratory vane test but the vane is hand held and rotated. Poor repeatability of this test has been reported (Lee 1985).

The Swedish fall cone device (Hansbo 1957) is used for rapid measurements of the undisturbed and remolded (undrained) shear strength. The advantage of the fall cone test over the vane test is more rapid testing and better applicability to sediments with very low shear strength (0.5 kPa to 5 kPa). The fall cone test determines the depth to which a cone of given apex angle and weight penetrates the sediment under its own weight. The undrained shear strength is obtained from empirical correlations. An automated fall cone device for testing of extremely soft sediments, with shear strength values as low as 1.5 Pa, was developed at MIT (Zreik et al. 1995). A pulley and a counterweight system enables the use of very low cone weights. The new device also records cone penetration versus time throughout the test.

The pocket penetrometer (Lee 1985) is a small flat footed cylindrical probe that is pushed 6.4 mm into a sediment surface. It is particularly convenient for very firm sediments that cannot be tested by other rapid techniques. The penetration is related to the unconfined compressive strength and the value must be divided by two to obtain the shear strength.

In general, there is little correlation between the strengths of comparable samples using different testing methods. Therefore the testing method used should always be clearly stated. Rapid determinations, particularly using the Torvane and the pocket penetrometer, do not provide more than a rough comparative index of the shear strength.

5.2.2.4 Consolidation Measurements

When freshly deposited on the bed of a water body, fine-grained sediments have very high water content, void ratio and porosity values. As sedimentation continues, the overburden weight will cause the sediments to consolidate. It has been clearly recognized by Terzaghi (1923) that compaction is a function of the effective pressure, i.e. the total pressure minus the pore pressure.

A sediment deposit is normally-consolidated if it has never been under a pressure greater then the existing effective overburden load. In many offshore sediments, especially where sedimentation is rapid and sediment permeability is low, excess pore pressures causes sediments to be underconsolidated. Sediments are regarded as overconsolidated if the present effective overburden pressure is less than the maximum to which the sediment was subjected in its depositional history. The two most common reasons for overconsolidation are the removal of overburden due to erosion and the subaerial exposure and consequent desiccation of the sediment.

Consolidation problems involving very soft and highly compressible sediments are encountered in predicting behaviour of hydraulically placed fills in mine tailings and dredged material disposal. A further application is in predicting sediment behaviour due to dredged material capping and in-situ capping of contaminated sediments (Zeman and Patterson 1995, Rollings 2000).

The standard one-dimensional consolidation test (ASTM Standard D 2435) is carried out on saturated samples. The rate and magnitude of consolidation of the sediment is determined under the conditions of lateral restraint, axial loading and axial drainage in a consolidometer. The load on the sample is usually applied through a lever arm, and the compression is measured by a micrometer dial gauge or an electronic deformation gauge. The load is usually doubled every 24 hours. For each load increment, the sample deformation and the corresponding time is recorded to obtain void ratio vs. effective pressure relationships. Prescribed procedures are used to obtain 0 and 100 % consolidation as well as the coefficient of consolidation for each load.

Laboratory consolidation testing of soft sediments often requires a lighter loading sequence or a self-weight test to provide information on sediment compressibility at higher void ratios (Rollings 2000). Self-weight consolidation can be studied in laboratory settling columns where density profiles are obtained using an X-ray apparatus and pore pressures are measured by transducers or standpipes (Been and Sills 1981). Slurry consolidation consolidometers were built for measurements of sediment consolidation under very low stresses (Monte and Krizek 1976). Large oedometer tests with pore pressure measurements using the Rowe Cell (Rowe and Barden 1966) were found suitable for primary and secondary consolidation under low stresses as well as for creep tests under sustained low loads (Zeman and Patterson 1997).

The classical one-dimensional theory of consolidation (Terzaghi 1943) is restricted to problems for which vertical strains are small. In the classical theory, strain is assumed to be infinitesimal, and the hydraulic conductivity and the coefficient of compressibility are assumed constant for a given load increment. However, soft, fine-grained sediments may undergo vertical strain on the order of 50 % during the consolidation process (Rollings 2000). Recognition of the limitation of the classical theory for highly compressible sediments led to the development of finite strain theories of consolidation (Gibson et al. 1967, Gibson et al. 1981, Schiffman et al. 1984). In addition to treating large strains, variations of sediment compressibility and hydraulic conductivity during consolidation are taken into account as is self-weight in some cases.

In general, finite strain theories of consolidation result in a highly non-linear partial differential equation problem that can only be solved by a numerical technique (finite differences of finite elements) or analytical solutions can be used that use some linear-form approximations. Although comparative studies are available, a single formulation has not gained universal acceptance (Fox 1999).

5.2.2.5 Viscosity

Rheological properties of cohesive sediments are sometimes measured to determine sediment behaviour under hydrodynamic action and the results can be used for the prediction of sediment erodibility under applied shear stresses. So far, no standardized measurement of sediment viscosity has been developed and therefore comparisons of existing data are difficult (Kern and Westrich 1999).

Freshwater, marine, estuarine and man-made cohesive sediments were investigated by Migniot (1968) who used a viscometer to measure the dynamic viscosity and the initial rigidity of the sediments. In this comprehensive study, the hydraulic shear velocity was empirically related to the mean particle concentration and the initial rigidity of the sediments using tests in a 12-m long tilting flume. Comparison of viscometer measurements with any conventional geotechnical tests were not attempted in this study. Migniot's experimental results clearly showed that the water content is not a sufficient parameter to characterize hydrodynamic behaviour of a cohesive sediment. At the same water content the values of initial rigidity were found to range over several degrees of magnitude. The data showed significant influence of mineralogical composition on the initial rigidity values. Viscosity measurements were used by Robertson et al. (1965) to make a rough determination of sediment mineralogical composition.

Faas (1981) measured viscosity behaviour of sediment samples taken from the upper, middle and lower reaches of an estuary. Viscosity measurements were carried out with a conventional rotational viscometer. Significant differences in apparent viscosity between each of the estuarine segments were reported. Apparent viscosity was found to decrease down-estuary with increasing salinity in bottom sediments. Viscosity measurements with a vane-viscometer were used in a study by Kelly et al. (1982) who correlated the critical shear stress (obtained from water tunnel tests) and the Bingham yield stress (obtained from viscometer measurements) with sediment solids concentration and water salinity. More recent experience with various viscometers has been reviewed by Jones (1997).

Recently developed methods using the Nautisonde probe (Kern and Westrich 1999) allow in situ determinations of viscosity of the water column and soft sediment. Four rheologic regions are subsequently measured: a) the water column, b) suspended sediment layer, c) very soft mud, usually removed during maintenance dredging, and d) consolidated sediment that is usually not reached during maintenance dredging. From several viscosity profiles, cross-sections with "isoviscs" (lines of equal viscosity) can be constructed in the region of interest. This in situ technique is very useful for optimisation of maintenance dredging operations in marine and estuarine areas.

5.2.2.6 Particle Size Distribution

Particle size distribution has been used for the classification of sediments for sediment transport, geotechnical investigations, as well as for geological and geochemical interpretations. The particle sizes range from less than 1 μm to greater than 1 m in diameter. A geometric scale is used to separate sediments into size classes, in which class limits increase from a base of 1 mm by a factor of 2, or decrease from this base by a factor of ½. The standard classification of sediments into Wentworth size classes, phi scale classes and sieve numbers is commonly used (Royse 1970). The MIT classification has been commonly used in geotechnical literature in which particles finer than 2 μm are classified as clay-sized particles (Terzaghi and Peck 1968) while in sedimentology the boundary between silt and clay is 4 μm. It has to be emphasized that particles defined as clay on the basis of their size are not necessarily clay minerals.

Pretreatment of samples for particle size analysis is commonly required to avoid interference from flocculation and binding of individual particles by salts, Mn- and Fe-oxides and carbonates. Freeze-drying is recommended for fine-grained sediments. In the classical analysis, dry sieving is used for segregating particles coarser than silt-sized (0.063 mm). Wet sieving is used to separate fine particles from surfaces of coarser particles or to recover the fine-fractions (<0.063 mm) for analysis. If the sample contains significant amounts of silt-sized and clay-sized particles, it is necessary to perform pipette or hydrometer analysis in conjunction with the sieving. The standard testing method as outlined in ASTM method D422-63 utilizes the hydrometer for the determination of the silt- and clay-sized fractions. Both the pipette method and the hydrometer method are considered inaccurate and time-consuming and have been replaced by automated methods (Mudroch et al. 1997).

The Coulter method of sizing and counting particles (Coulter Counter™ , the electrical sensing zone technique) measures the volume of electrolyte displaced by sediment particles which pass between electrodes. Volume displaced is measured as a voltage pulse and the height of each pulse is proportional to the volume of the particle. Several thousand particles per second are individually counted and sized. The method is independent of particle shape, colour and density. The automatic data processing provides number, volume, and surface area distributions in one measurement. Particles in the range of 0.4 µm (fine clay) to 1.2 mm (very coarse sand) can be measured.

The Sedigraph™ (X-ray sedimentation technique, Micromeritics Instrument Corporation) measures the velocity of a particle falling through a viscous medium. This technique is used for measurements of particle size distributions of fine-grained sediments (0.1 µm to 0.3 mm). The sample is mixed with a viscosity specific fluid which allows the particles to go into suspension while being stirred with a magnetic stirrer or a peristalting pump. X-ray intensity is then related to the settling rate and the particle size distribution using Stokes' Law.

Commercially available laser instruments which measure the particle size distribution are based on the "time of transition theory" (Bringman Particle Size Analyzer™) and laser diffraction spectrometry (Malvern Instruments Ltd.) where the size distribution is computed using the Frauenhofer diffraction theory. A submersible laser particle-size analyzer (Krishnappan 2000) can be used for in-situ measurements of flocculated sediment particles in a riverine environment.

Electron microprobes and scanning electron microscopes are used for detailed image analysis (physical properties and chemical composition) of individual particles of extremely fine-grained sediments (Mudroch et al. 1997).

5.2.2.7 Specific Surface Area

The specific surface of a sediment particle is defined as the surface area per unit mass of sediment and is expressed in m^2/g. Differences in surface area result from particle size, clay mineral type and organic matter content. The surface area is highly correlated with cation exchange capacity and inversely proportional to particle size. Clay-sized particles contribute the most to the specific surface of an inorganic sediment. Some clay minerals have extensive internal surfaces. The specific surface for clay minerals varies from 5-20 m^2/g for kaolinite to 700-800 m^2/g for smectite group minerals with expandable internal surfaces.

Methods used to determine specific surface area of sediment particles include gas adsorption (the BET method), the ethylene glycol monoethyl ether method, and the methylene blue method. When sediment samples do not contain expandable clay minerals each of these methods should yield comparable results. The BET method, which is time-consuming and requires highly specialized equipment, should not be used for analyzing sediments containing expandable clay minerals, as only external surface areas are measured (Mudroch et al. 1997).

5.3 Mapping of Offshore Sediments

Mapping the distribution and thickness of offshore sediments is carried out by offshore coring and grab sampling using a variety of sediment sampling devices (Mudroch and MacKnight 1994). Divers are sometimes used for collecting samples where access to the sediment would otherwise be difficult, or where a high priority is put on retrieving undisturbed samples. Diver-retrieved samples are more costly and time-consuming than regular core or grab samples.

In recent years, novel mapping techniques have been used for the mapping of contaminated, mostly fine-grained sediments. Since contaminated sediments are typically of very similar grain size as clean sediments, it is often difficult to determine the volume of contaminated sediments from sedimentological or geotechnical properties.

Due to the complex pattern of contamination occurring in sediments, the use of geophysical techniques is helpful to complement the information obtained from isolated cores and samples.

Echosounder systems provide information on water depth and morphology of a sediment surface. There are three main groups of echosounders currently in use: single channel echosounder, multiple channel echosounder and multibeam echosounder (Kern and Westrich 1999). The multibeam echosounder can be used in shallow waters and its surveys produce accurate and continuous maps of the sediment surface. Very often echo sounding is combined with sub-bottom profiling (see below).

Side-scan sonar surveys (Rukavina and Versteeg 1996, Kern and Westrich 1999) are useful for mapping bottom disturbance due to shipping, dredging and dumping, which would not be detected by an underwater camera or television due to poor visibility at the bottom of a water body. The vertical resolution is in the order of several cm, while the horizontal resolution is not substantially better than 1 m.

Marine high-resolution seismic profiling has been used extensively in the last 20 to 30 years for Quaternary mapping, seabed process investigation, engineering applications, exploration for aggregates and placers, and habitat studies. There are four broad categories of marine seismic sources for high-resolution studies in common use today (Mosher and Simpkin 2000). These are: a) controlled waveform (sonar, e.g., 3.5 KHz sounder, parasound, chirp), b) accelerating water mass (e.g., boomer, airgun), c) explosive (e.g., sparker), and d) implosive (e.g., watergun).

a) Sonar transducers, which have been in common use for nearly four decades, range from high frequency bathymetric echo sounders to the modern chirp profiler. The 3.5 KHz subbottom profiler has been used in marine high resolution reflection profiling for decades. The chirp sonar is the latest advance for sub-bottom profiling, sweeping through a range of frequencies anywhere between about 400 Hz and 20 kHz.

b) Electro-dynamic sources known as "boomers" usually operate in the 1 to 5 kHz range. They provide higher penetration (between 50 and 100 m) than the chirp sonar, but are of lower vertical resolution (between 0.5 and 1.0 m). Compressed-air sources (airguns, sleeve guns) explosively release compressed air into the surrounding water. The airguns used in high-resolution profiling are smaller in size, but otherwise similar to those used in conventional exploration seismic reflection surveys.

c) The most common explosive for high-resolution marine surveying is the sparker, which generates a steam bubble by discharging electrical energy through a point electrode. Other explosive sources include dynamite, blasting caps and gas exploders.

d) Implosive sources are those which utilize the implosion of a bubble or vacuum to create an impulsive pressure wave. A more recent development is the water gun, which projects a slug of water at high speed into the surrounding water mass. The cavity produced in the wake of this slug is near vacuum, which implodes and produces a measurable signal.

Each of the above-listed basic categories of seismic sources for high-resolution profiling has their advantages and limitations. In a seismic survey, the geometric configuration of the source and receiver and the receiver design are also important considerations (Mosher and Simpkin 2000).

Another geophysical tool that has proven to be very useful in mapping contaminated sediments is an acoustic bottom-classification system called RoxAnn™, which uses the character of bottom echoes to identify the bottom-sediment type. This can be viewed in real time on a computer monitor as the information is being saved. The procedure is combined with ground-truth data from sediment samples and underwater-television observations (Rukavina and Caddel 1997).

The acoustic system DSLP (Detection of Sediment Layers and Properties) is based on a special multiple-frequency echo sounding combined with a differentiated complex numerical signal analysis (Eden et al.1999, Kern and Westrich 1999). The DSLP method is independent of utilized acoustic frequencies and provides high-resolution analysis of the stratification of suspended sediments and individual sediment layers of unknown physical and sedimentological properties. The depth of interfaces can be estimated with a vertical resolution of 3 to 5 cm. The DSLP method can be also used for accurate determinations of volumes of sediments to be dredged, which is of great importance for maintenance dredging and for sediment remediation projects.

Positioning instrumentation for mapping of offshore sediments has become much more accurate in the last decade. Whereby reference to more than one shore station through line of sight was once necessary, Global Positioning Systems (GPS) Technology now allows for more precise positioning with greater ease. This is especially true where a fixed antenna of known coordinates is used in conjunction with a GPS unit to produce Differential GPS (DGPS). Under optimum conditions, positioning with DGPS results in a horizontal accuracy of +/- 10 cm, and a vertical accuracy of +/- 1 cm (Zeman and Patterson 1997). Positioning readouts of the vessel's antenna can be displayed on a computer monitor and automatically updated every second.

5.4 Erosion and Transport of Cohesive Sediments

5.4.1 Introduction

Cohesive sediments are made up of the finest eroded particles, which are usually classified as silt and/or clay. They have physical, erosive and transport characteristics that are not only different from those of coarse sediments, but are also much more complex. To understand erosion and transport processes in both freshwater and marine environments, it is important to understand the distinction between cohesive and coarse sediments.

With coarse sediments (primarily sand and gravel), the erodibility and transport processes, in addition to flow conditions are primarily a function of particle shape and weight. The number of particles deposited per unit area, per unit time equals the number of particles eroded. The concentration of the coarse suspended bed material in the water column thus depends solely on flow conditions. Cohesive sediments, in contrast, can remain in suspension in little or no flow conditions for hours and even days. It is thus much easier to calculate or model erosion and deposition tendencies of coarse sediments in both river and coastal environments.

The boundary between cohesive and granular sediments is not clearly defined and often varies with the type of sediment. Generally, silts and especially clays are cohesive. Coarse sediments will often erode into finer sediments over time which in turn will usually become cohesive.

Particles of finer sediments tend to form flocs, rather than act independent of each other (i.e. there are interparticle forces of both attraction and repulsion). This fact can cause the clumped particles of cohesive sediments to fall into size category of coarse sediment, and to take on coarse sediment transport characteristics until particle breakup re-occurs.

There are several different forces involved in the interaction of cohesive sediment particles. The attraction between molecules and atoms (van der Waals forces) consists of short-range forces inversely proportional to the seventh power of the distance between atoms. The forces thus decrease very rapidly as distance between the particles increases. The magnitude of the force is dependent upon sediment surface properties. In some circumstances, there are forces that act between clays that are inversely proportional to the square of the distance (Coulomb forces). Kaolinite clay, for example, develops positive charges under acidic conditions. There are also bonds due to non-clay (e.g. silt) material bonding to surfaces of more than one clay particle. Iron oxide, aluminum oxide and carbonates are examples of bonding materials. Organic matter in surface soils forms interparticle bonds. Organic molecules are held at the clay surface by hydrogen bonding or electrical bonds, and aid in the bonding of clays to coarse sediments (Yong 1966).

Knowledge of the erodibility and transport processes of cohesive sediment is important from both the engineering and environmental perspectives. Annual erosion rates of land adjacent to rivers and coastlines under various flow conditions must be determined in dealing with erosion control measures. Determining the stability of shoreline structures such as hydro towers or nearby buildings relies on knowing sediment type, erodibility and flow patterns. The bulk of contaminants within soil or sediment usually bind to the finer, or cohesive particles and will thus be transported with these particles.

Numerous experiments on cohesive sediments have been conducted both in the field and in laboratories where flows and wave action are carefully measured. Despite these experiments, there is still much information that is unknown regarding relationships between chemical bonds, flow patterns and erosion rates. The following sub-sections draw from the information gleaned from such studies involved with cohesive sediment research. Flume designs commonly used for simulating flow conditions in this field of research are also briefly described.

5.4.2 Erodibility of Cohesive Sediments

Cohesive sediment can only be eroded when the electro-chemical bond existing between the sediment particles is broken. This means that the force required to break or shear the sediment (critical shear stress) must be exceeded before erosion can occur. There are two forms of erosion that exceed the critical shear stress of cohesive sediments, namely, surface erosion and bulk erosion (Mehta, 1994). Surface erosion (i.e. fluid shear stress) is the entrainment of particles at the bed surface through the breaking up of the electro-chemical bonds due to shearing under turbulent bed shear stresses. Bulk erosion is the undercutting of sediment masses, causing the eventual fall and collapse of these masses into smaller clumps. These smaller clumps are more readily eroded though surface erosion. Typical values for critical shear stress of soft estuarine sediments measured in laboratory tests are around 0.1-2 Pa (Berlamont et al. 1993).

Silt and clay particles suspended in water often have a tendency to clump together due to various factors such as particle mineralogy, electro-chemical bonds, bacteria and the hydrodynamic properties of the flow field (Krishnappan, 1996). This clumping or coalescing of the particles forms larger aggregates or clumps of sediment called flocs, which then settle out of suspension. This process, known as flocculation, causes an effective increase in particle size and increases the rate of sediment settlement. Hunt (1980) identified three prominent processes that result in the collision of particles: Brownian motion, velocity gradients (laminar and turbulent), and differential settling of particles (i.e. fast settling particles colliding with slower settling particles). Four processes result in cohesion, namely, electro-chemical bonds induced by salt, chemical coatings affecting charge characteristics of the particles, bioflocculation due to polymers secreted by bacteria and other microorganisms, and pelletization after sediment has been ingested by filter feeders and other animals (Krishnappan 1996).

For most cohesive soils, the particle-floc contact is considered to be the only significant area between particles where normal stresses and shear stresses can be transmitted (Mitchell et al. 1969). Fluid shear stress imposed on a soil surface can be related to the velocity of flow (Partheniades and Paaswell, 1970). For cohesive sediments however, correlations between the erosive force of fluid shear stress and sediment shear strength have been hard to obtain in laboratory measurements. Previous attempts to relate erosion resistance to undrained shear strength have met with only limited success (Kelly and Gularte, 1981). On average, there is a slight increase in the resistance to erosion with increasing soil density and shear strength for medium to high strength clays. Despite this fact, however, critical fluid shear stresses for cohesive soils of similar shear strength may differ by several orders of magnitude. In addition, cohesive soils with low shear strength may resist fluid shear stresses that are much higher than what other cohesive soils of higher shear strength can withstand. It is thus concluded that the mechanism of failure of a cohesive soil by fluid shear stress is different than the mechanism of mass shear stress failure form external forces (Partheniades 1972). Research has been ongoing in trying to explain this phenomenon.

The swelling of cohesive sediment particles by saturation in water causes a weakening of the electo-chemical bonds and thus increases the sediment erodibility. The amount of swelling depends on factors such as the shape of the particles, salinity of the water, sediment load, and the sodium adsorption ratio, or SAR (Grimshaw 1971). The SAR is expressed as:

$$\frac{0.043 \text{ X Sodium Concentration}}{((0.025 \text{ Calcium Concentration} + (0.04) \text{ Magnesium Concentration}))^{0.5}}$$

Swelling decreases with a lower SAR and also decreases with greater salinity (Sargunam et al. 1973). The spacing between particles in the sediment will increase with greater water content, thus increasing erodibility of the sediment.

Measurement of the erodibility of a cohesive sediment bed depends first on defining or delineating the bed. Often, there is a gradual transition from muddy water, with a high concentration of suspended cohesive sediment, to watery mud, to firm mud. This transition varies in thickness, and provides a challenge in determining the plane of the bed. For measurement of erodibility of the bed, the plane is considered to be where resistance to fluid shear stress occurs below the water flow. This is called the hydrodynamic bed, and its depth is called the hydrodynamic depth. The resistance that defines the hydrodynamic bed is dependent on bed density (Mehta et al. 1989).

Erodibility of a cohesive bed is dependent on how consolidated the bed is. Consolidation can be ongoing as cohesive sediments gradually settle into the hydrodynamic bed. Typically, the susceptibility to erosion of a bed is reduced the more consolidated it is. The more consolidated the bed, the more dense it is, which means a greater fluid shear stress is required to erode the same volume of sediment than a less consolidated bed of equal volume.

Organisms, or benthos can affect the erodibility of a cohesive sediment bed by either increasing or decreasing the potential for erosion. Organisms decompose organic matter and consequently alter sediment pH, redox potential, and pore water chemistry (Montague 1986). The production of organic coatings, or extracellular polymeric substances (EPS) by organisms has been known to hold sediment together (Decho 1990). Decreased erodibility by organisms have been measured in subtidal mats of algae in marine environments, where the mats have been measured to be five times more resistant to erosion than bare sediment (Neumann et al. 1970).

Bioturbation, or the burrowing action of benthos in the sediment bed is the most common way benthos increases erodibility (Meadows and Tait 1989). The aerating and loosening of the sediment by benthos weakens the sediment. The concentration of benthos in the sediment is in turn largely affected by the redox or oxygen-reduction potential. The redox potential is dependant on the electro-chemical properties and depth of sediment as well as oxygen levels in the water column.

Seasonal fluctuations must be considered when attempting to determine erosion rates of any specific site. The environmental conditions that affect the mortality or population of benthos, such as oxygen content in the water (i.e. redox conditions) will affect their impact on eroding the sediment. Water temperature has a very significant influence on the erosive characteristics of cohesive sediments. Erosion rates in water at 35° C are about twice as much than in water at 20° C (Partheniades 1971). Higher pH values in water also increase erodibility and will destroy positive charges in the electro-chemical bonds of the sediment (Nielson 1973). The growth of aquatic plants and their root structures in warmer seasons may create more stability within the sediment while slowing down flows. Ice scouring may occur during colder seasons.

5.4.3 Transport of Cohesive Sediments

Understanding of sediment transport requires a knowledge of various hydromechanical parameters, such as grain size, flocculation, turbidity (concentration of suspended sediment), bedforms, wave action and littoral transport. There are so many variables in nature however, that it is virtually impossible to have an understanding of flows and sediment transport that is completely accurate for all natural flow conditions. Research into sediment transport patterns has been ongoing for decades. Basic principles known at present are discussed in this subsection.

The grain size of particles will obviously be a factor of their movement in varying flow velocities. Likewise, but to a lesser extent, the size of particles in aquatic environments directly affect flow conditions. While the transport tendencies of coarse sediment are generally well known, the movement of finer particles is more complex since the finest suspended sediments can remain in suspension in little or no flow, creating turbid conditions. The velocity at which cohesive sediment settles cannot be predicted because particle size and densities change with flocculation (Krishnappan 1996), which also affects their erodibility and transport. Settling velocities of cohesive sediments in a natural suspension are considered to be around 0.01 to 10 mm/s. The value will increase with concentration due to flocculation to reach a maximum concentration of 2-10 g/l. At higher concentrations, flocs are broken and the settling velocity decreases rapidly (Berlamont et al. 1993).

Turbidity is a factor for deposition of eroded cohesive sediments. The amount of sediment that can be maintained in suspension at steady-state depends not on the flow condition, but on the available initial quantity of suspended sediment. This fact contrasts with the transport process for coarse cohesionless sediments, where the bed material transport is governed by an exchange of the sediment particles between the bed and suspension (Mehta and Partheniades 1975).

5.4.3.1 Rivers

Transport processes in rivers, with the absence of significant waves, rely mainly on flow mechanics. The varying shapes of riverbeds, the type of sediment, and the drag on flows in the river channel have a large influence on flow velocities and sediment transport.

For cohesive sediments, flow conditions have an effect on sediment suspension which is not a linear relationship. There appears to be a critical flow limit above which sediment can be maintained in suspension at high concentrations, but just below this limit all of the suspended sediment deposits rapidly (Partheniades 1972).

For steady uniform flow in regularly shaped river channels, total flow resistance may be divided into grain resistance and form resistance. Grain resistance is the result of shear and pressure forces acting on the grains comprising the boundary of the watercourse, whereas form resistance is due to the drag of larger obstructions that protrude from the boundary into the flow (Yen 1992). Total shear stress may likewise be separated into grain shear stress and form shear stress. Partitioning shear stress in this manner is significant because it is widely believed that in river flows, the transport capacity of bed sediments is controlled by grain shear stress rather than by total shear stress (Atkinson et al., 2000).

Cohesive sediments can erode by their gradual deterioration and flaking off into thin flakes. This process is known as slacking, and is significant in river flow erosion. Slacking is not a completely understood phenomenon, but it is known that one of the causes of slacking is air entrapment in the sediment voids if the sediment becomes compacted.

Where fast fluid velocities overflow an irregular shaped river bed, severe erosion or scouring of the bed can occur. Cohesive sediments are more scour resistant than coarse sediments, therefore a cohesive river bed is more stable than a bed of coarse material. Scouring of a river bed tends to lessen with time. It has been found in open flume testing (Abdel-Rahman 1962) that the maximum depth of erosion increases as both bed shear stress and bed roughness increases and as the shear strength of the bed decreases.

Cohesive river beds under steady uniform flow have been shown by Parker and Izumi (2000) to produce a series of raised bedforms, or steps that slowly migrate upstream and create hydraulic jumps. The upstream region of each step has subcritical flow, whereas the downstream region has supercritical flow ending with an hydraulic jump.

River flow mechanics vary quite a bit from flows and currents along coasts. Likewise, suspended cohesive sediments in river flows are significantly affected where rivers flow into salt water estuaries along coastlines. Salt water tends to underlie fresh water in an estuary. This produces a unique movement of sediment. The lower, denser salt water moves towards the head of the estuary and replaces the surface flowing freshwater. Some of the suspended sediments a river transports downstream are carried away as a result, which disperses them over a wider area in the estuary. If the river is polluted, the contaminants carried in the sediment will follow this pattern of deposition, where they may bioaccumulate in estuarine organisms (Oberrecht, 1997). The concentration of suspended cohesive sediments in an estuary can be as high as 100 g/l (Mehta et al. 1989).

5.4.3.2 Coastal Areas

Depths of water along coastal areas can vary to a much greater degree than in rivers. This means that much of the drag in coastal flows is induced by the upward rise to the shore, especially where onshore breezes exist. The mechanics involved in wave creation involves orbital flow patterns below the water surface that can reach down to depths of several metres. These depths are decreased towards shore with the rising lake or marine bed. Where the shallowness of the bed interferes with these orbital flows, pressure is induced on the bed by these flows in the form of normal stress.

The surface sediment often oscillates and moves in a mass as wave forces push down and release on the sediment bed. This type of movement is known as a "mud wave". The height of the mud-wave depends on the geotechnical properties of the sediment and the amplitude and wavelength of the bottom pressures. Heights of mud-waves range from a few millimetres to about a metre under storm conditions. Surface waves lose a lot of energy when mud-waves are generated. The wave height can decrease by 10% in a distance of about 20 or 30 metres (Suhayda 1986). The erosive action of the surface waves are thus decreased, since an energy transfer to the sediment bed occurs. This transfer of energy to the sediment is mainly from the normal stress induced by wave action, rather than through shear stress (Li and Mehta 1997).

Wave action has an effect on cohesive bottom sediments in shallow areas off coasts. Since surface wave action affects lower water column flow over the sediment, entrainment of cohesive sediments occurs. This dense suspension of sediments above the bed layer along coastal areas is known as fluid mud. The formation of fluid mud has been described to occur by the gradual sinking of suspended sediment as well as by wave action. Winterwerp and Kranenburg

(1997) state that fluid mud can be formed when floc particles become highly concentrated and sink so that they settle above the surface of the bed. Toorman (1992) claims that both fluidization (an increase in pore water pressure due to wave action) and liquefaction (sediment suspension resulting from shear force) produces fluid mud. Feng (1992) states that fluid mud formation occurs when the effective normal stress on the bed surface is almost non-existent.

The processes involved in the generation of fluid mud affect the reaction of a muddy bed to waves and currents, and play a major role in the transport of cohesive sediments (De Wit and Kranenburg 1997). If currents are present during wave action, the combined fluid shear stress from the two forces can be significant, causing the fluid mud to be carried away by the currents (Mehta et al. 1989). If currents are minor, or non-existent, deposition tends to take place. With continuing deposition, the mud layer moves from a loose mobile state to a grounded state, and becomes less erodible as it settles into the bed. The pore water is squeezed out and the weight of the mud layer becomes supported by electro-chemical bonds. This process is called self-weight consolidation (Teisson et al. 1993). The viscosity boundary between fluid and plastic mud was measured at 3 Pa (Migniot 1989), although there is no established theory for calculating erodibility of mud deposits (Teisson et al. 1993).

Seasonal variations in erosion along coastal areas occur. This is due to weather conditions such as seasonal wind storms, differences in water temperature affecting organism growth, water current trends and other factors. The difference in seasonal erosion affects the amount of sediment transport along coastlines for each season. The overall movement of this sediment can be measured over the course of a year or for a longer period to determine the overall trend of sediment transport.

The transport of sediments by waves and currents along a coastline is known as littoral transport. Much of the sediment that is moved by littoral transport is newly eroded, often from exposed shoreline bluffs. Where the soil around such bluffs has been contaminated, the potential exists for a fresh supply of contaminated sediments to enter the adjacent water body simply by the act of erosion. Littoral transport of contaminated sediments can cause a continuous supply of contaminants along a coastline. This is especially true where long term movement of wind and wave action transports the greater portion of eroded sediment in one direction (littoral drift). Cohesive sediments which are flocculated, will coincide with the littoral transport patterns of coarser sediments. In addition to eroded sediments, effluent from industries, sewers, streams, and agricultural runoff may add more contaminants to the littoral sediments.

The process of flocculation is largely affected by salinity levels. Consequently, flocculation characteristics can change along coastal inlets, such as estuaries. In fresh water, clay particles are kept in suspension by their molecular motion and are often negatively charged, thus decreasing flocculation. In an estuary, however, where fresh water meets and mixes with ionically charged salt water, negative charges are neutralized, and sediment particles flocculate even more so than in fresh water. More finer sediment particles, in the form of flocs, thus settle out of suspension. Variations in flocculation may occur due to tides and seasons, or due to runoff fluctuations and storm surges. Incoming tides and storm surges deposit ocean sands in many estuaries. This often produces sediment gradients ranging from coarse sand at the mouth of an estuary, to extremely fine or cohesive sediment at the head (Oberrecht, 1997).

5.4.4 Flumes

Modelling flows to test for sediment erosion and transport is usually done with a laboratory flume. Specific soil or sediment types are laid out along the base of the flume, and a continuous flow of water is induced over the sediment for varying periods of time from several minutes to several days. Measurements and observations of flocculation, settlement, etc. are taken at various intervals. There are two basic types of flumes, namely, laboratory and in-situ. Of these, flumes can be either straight or in a circular or looped pattern.

There are significant limitations to flume testing as they fail to duplicate field conditions in several ways. One notable example is the misrepresentation of induced stratification effects (Teisson et al. 1993), which are small in flume tests, but often found to be larger in field conditions. Kuijper et al. (1989) noted that erosion measurements of cohesive sediment beds in a straight flume appeared to be more severe than in a circular flume with similar sediment and velocities.

5.4.4.1 Straight Flumes

Straight flumes are typically long rectangular glass or acrylic designs that allow for straight flow simulation. They are commonly used for experimental research on noncohesive sediments such as sand and gravel, but are not considered to be suitable for cohesive sediments such as silt and clay. This is due to the tendency of the silt and clay particles to floc together. Straight flumes tend to disrupt the flocs when the flocs pass through the return pipe and diffusers which are common on straight flumes (Mehta and Partheniades, 1975). The flocs are usually fragile and are susceptible to breakage by the forced flows of the recirculating pumps. Cohesive sediment transport processes are also time dependent, ranging from hours to days for completion, creating the need for excessively long flumes (Krishnappan, 1993). Volume flows in straight flumes tend to be large. Because of this, it is more difficult to determine erosion rates from the concentration of suspended sediment due to the length of time required for complete mixing of the sediment and the subsequent changes in the overall suspended concentration (Berlamont et al. 1993).

5.4.4.2 Circular Flumes

Circular flumes generate a flow that is theoretically uniform at every section, and is free from any floc-disrupting elements. Circular flumes are thus commonly used for fine sediments. A disadvantage of circular flumes is the centrifugal force created by their rotation which tends to push the flowing water and suspended sediments towards the outer section within the flume. Natural straight flows are thus virtually impossible to simulate. It has been noted by Berlamont et al. (1993) however, that circular flumes give a good general idea for the erosion and deposition properties of cohesive sediments.

A common circular flume design (for indoor use) rests on a rotatable circular platform, and houses an annular cover plate (ring) inside the flume which makes contact with the surface water in the flume. A "king post" configuration may be used to support the flume, where the weight of the entire structure is supported by two tapered roller bearings housed within the king post. The two bearings are held in a rotating hollow shaft that supports the lower rotating platform on which the flume is mounted. The hollow shaft also supports an inner solid shaft connected to the upper turntable for the ring assembly. The two shafts are fixed axially and are independently driven by two separate drive systems (Krishnappan, 1993). The flume and the ring can thus be rotated in opposite directions as is usually done. This counter rotation is important in offsetting the centrifugal force that would otherwise produce uneven flow patterns within the circular flume.

5.4.4.3 In-Situ Flumes

Where laboratory conditions are deemed to be insufficient or inaccurate for calculating field conditions, in-situ flumes are sometimes used. An in-situ flume is designed to be lowered underwater and embedded into the sediment. The flume consists of a bottom-open channel which sinks into the sediment, and has paddles that push and circulate water around the channel. A roof isolates the inside of the channel from external disturbances. Sampling ports are incorporated into the design to allow for water sampling or measuring devices such as sensors. Flumes can vary in shape, e.g. being circular (Amos et al. 1992) or race-way shaped (Black and Cramp 1995).

5.5 Conclusions

Laboratory testing of aquatic sediments can be conducted more easily than in-situ testing. The collection of samples for laboratory analysis however, often disturbs the sample if even in a minor way, creating a disadvantage to in-situ testing. Various sampling techniques have their own distinctive limitations, and these should be considered when determining the type of information sought.

The present state of technology for locating and mapping offshore sampling sites is more than adequate for scientific research. Moreover, advancements made to sounders, multi-scan echo sounders and other devices provide basic information for sediment properties such as texture and density, although there is still room for improvement in obtaining rapid, more extensive and reliable identification of in-situ sediments.

The physical parameters of coarse-grained sediments are easily measurable to a reasonable degree of accuracy for most properties, such as moisture content and grain size. For cohesive sediments, however, measurements of grain size, erosion, and transport capabilities are hard to determine. Sediment erosion and transport is largely understood for coarse-grained sediment. For cohesive sediment, however, ongoing research has continued for decades with conflicting conclusions and remaining unknown mechanisms involved in shear strength and transport processes. While standard flume designs exist (e.g. straight, circular) for flow and transport research into cohesive sediments, variations are still common and are often designed in-house for specific research institutes.

References

Abdel-Rahman, N.M. (1962): The effect of flowing water on cohesive beds. Dr. of Science Thesis, Laboratory for Hydraulic Research and Soil Mechanics, Swiss Federal Institute of Technology, Zurich Switzerland. 114 pp.

Amos, C.L., Grant, J., Daborn, G., Black, K. (1992): Sea Carousel - a benthic annular flume. Estuarine, Coastal and Shelf Science 34: 557-577

Atkinson, J.F., Abrahams, A.D., Krishnan, C., Li, G. (2000): Shear stress partitioning and sediment transport by overland flow. J. of Hydraulic Research. 38(1): 37-40

Been, K., Sills, G.C. (1981): Self-weight consolidation of soft soils: an experimental and theoretical study. **Géotechnique, 31** (4): 519-535

Berlamont, J., Ockenden, M., Toorman, E., Winterwerp, J. (1993): The characterisation of cohesive sediment properties. Coastal Engineering 21: 105-128

Black, K.S., Cramp, A.C. (1995): A device to examine the *in situ* response of intertidal cohesive sediment deposits to fluid shear. Continental Shelf Research 15(15): 1945-1954

Buddington, E. (1996): Bedload sediment transport processes. http://www.con.wesleyan.edu/~eric/sparrow/earth.science/Bedload.sediment.transport.html

Campanella, R.G., Davies, M.P., Boyd, T. (1993): Characterizing contaminated soil and groundwater systems with in-situ testing. Proc.1993 Joint ASCE-CSCE National Conf. on Envir. Eng., July 12-14, Queen Elizabeth Hotel, Montreal

Chaney, R.C., Demars, K.R. (Eds.) (1985): Strength Testing of Marine Sediments: Laboratory and In-Situ Measurements, ASTM STP 883, Philadelphia

Chari, T.R. (1981): Static penetration resistance of soils. Proc. 6th Int. Conf. on Port and Ocean Engineering Under Arctic Conditions, **Québec, Canada,** v II: 717-725

Cooke, G.D., Welch, E.B., Peterson, S.A., Newroth, P.R. (1993): Restoration and Management of Lakes and Reservoirs, Second Edition, Lewis Publishers, Boca Raton, Florida

Das, B.M. (1983): Advanced Soil Mechanics, McGraw-Hill Book Company, New York

De Wit, P.J., Kranenburg, C. (1997): On the liquefaction and erosion of mud due to waves and current. In: Burt, N., Parker, R., Watts, J. (eds.) Cohesive Sediments. pp 331-340. John Wiley & Sons Ltd. Chichester

Decho, A.W. (1990). Microbial expolymer secretions in ocean environments: Their role(s) in food webs and marine processes. Oceanography and Marine Biology Annual Review 28:73-153

Duncan, G.A., LaHaie, G.G. (1979): Size analysis procedures used in the Sedimentology Laboratory. Hydraulics Division Manual, National Water Research Institute, Burlington, Ontario

Eden, H., Müller, V., Vorrath, D. (1999): DSLP method, a new surveying technology. In: DVW-Schriftenreihe Band 37, "Gewässermessung und Hydrographische Informationssysteme", pp. 106-115, Konrad Wittwer Verlag, Stuttgart

Faas, R.W. (1981): Rheological characteristics of Rhappanock Estuary muds, Southeastern Virginia, U.S.A., Spec. Publ. Int. Ass. Sediment. 5: 505-515

Fendinger, N.J., Adams, D.D., Glotfelty, D.E. (1992): The role of gas ebullition in the transport of organic contaminants from sediments. The Science of the Total Environment, 112: 189-201

Feng, J. (1992): Laboratory experiments on cohesive soil bed fluidization by water waves. M.S. Thesis, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville

Fox, P.J. (1999): Solution charts for finite strain consolidation of normally consolidated clays. J. Geotechnical and Geoenvironmental Eng., ASCE, 125(10):847-867

Gibson, R.E., England, G.L., Hussey, M.J.L. (1967): The theory of one-dimensional consolidation of saturated clays. 1. Finite non-linear consolidation of thin homogeneous layers. Géotechnique, 17: 261-273

Gibson, R.E., Schiffman, R.L., Cargill, K.W. (1981): The theory of one-dimensional consolidation of saturated clays. 2. Finite non-linear consolidation of thick homogeneous layers. Can. Geotech. J., 18: 280-293

Grimshaw, R.W. (1971): The Chemistry and Physics of Clays. Wiley-Interscience, New York

Hansbo, S. (1957): A new approach to the determination of the shear strength of clay by the fall-cone test. Proc. Royal Swedish Geotechnical Inst., No. 14, 46 p.

Hirst, T.J., Richards, A.F. (1977): In situ pore-pressure measurement in Mississippi delta front sediments. Marine Geotechnology, 2: 191-204

Hunt, J. R. (1980): Prediction of oceanic particle size distributions from coagulation and sedimentation mechanisms. Advances in Chemistry Series1 89: 243-257

Jones, T.E.R. (1997): A review of rheometric methods for use with fine sediments. In: Burt N., Parker, R., Watts, J. (Eds.), Cohesive Sediments, pp. 317-329, John Wiley & Sons Ltd., Chichester

Jumikis, A.R. (1962): Soil Mechanics, Von Nostrand Company, Inc., Princeton, New Jersey

Kelly, W.E., Gularte, R.C. (1981): Erosion resistance of cohesive soils. J.Hydr. Div., ASCE, 107(10): 1211-1224

Kelly, W.E., Heavers, R.M., Gardner, G. (1982): Relations between erosion resistance and shear strength of weak cohesive sediments. Preprints, 2nd Canadian Conf. on Marine Geotech. Eng., Halifax, N.S.

Kern, U., Westrich, E. (1999): Methoden zur Erkundung, Untersuchung und Bewertung von Sedimentablagerungen und Schwebstoffen in Gewässern (Methods for mapping, investigation and assessment of sediment deposits and suspended sediment in water bodies), Schriften, Deutsche Vereinigung für Wasserwitschaft (DVWK), No. 128, Bonn

Kuijper, C. (1989). Research on erosive properties of cohesive sediments. J. Geophys. Res. 94(C10): 14,341-14,350

Krishnappan, B.G. (1993): Rotating circular flume. ASCE Journal of Hydraulic Engineering 119: 758-767

Krishnappan, B.G. (1996): Cohesive sediment transport. In: Nakato & Ettema (eds.) Proceedings of an Iowa Hydraulics Colloquium, Iowa City, Iowa USA, May 22-24, 1995. Issues and Directions in Hydraulics pp. 41-53. Balkema, Rotterdam

Krishnappan, B.G. (2000): In situ size distribution of suspended particles in the Fraser River. ASCE Journal of Hydraulic Engineering, 126 (8): 561-569

Lee, D.R. (1977): A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanogr., 22: 140-147

Lee, H.J. (1985): State of the art: laboratory determination of the strength of marine soils. In: Chaney, R.C., Demars, K.R. (Eds.): Strength Testing of Marine Sediments: Laboratory and In-Situ Measurements, ASTM STP 883, Philadelphia, 181-250

Li, Y., Mehta, A.J. (1997): Mud fluidization by water waves. In: Burt, N., Parker, R., Watts, J. (eds.) Cohesive Sediments. pp 341-351. John Wiley & Sons Ltd. Chichester

Mason, B., Berry, L.G. (1968): Elements of Mineralogy, W.H. Freeman and Company, San Francisco

Meadows, P.S., Tait, J. (1989): Modification of sediment permeability and shear strength by two burrowing invertebrates. Marine Biology 101: 75-82

Mehta, A.J., Hayter, E.J., Parker, W.R., Krone, R.B., Teeter, A.M. (1989): Cohesive sediment transport. I: Process description. J. Hydraulic Engineering 115(8):1076-1093

Mehta, A.J., Partheniades, E. (1975): An investigation of the depositional properties of flocculated fine sediments. J. Hydr. Res., Delft, The Netherlands 12(4): 361-381.

Migniot, C. (1968): Etude de propriétés physiques de différents sédiments très fins et de leur comportement sous des actions hydrodynamiques (A study of the physical properties of various forms of very fine sediment and their behaviour under hydrodynamic action). La Houille Blanche, 7: 591-620

Migniot, C. (1989): Tassement et rhéologie des vases (part 2). (Settlement and rheological properties of muds). La Houille Blanche 2: 95-111

Mitchell, J.K., Singh, A., Campanella, R.G. (1969): Bonding effective stresses and strength of soils. J. of the Soil Mechanics and Foundation Division, ASCE, 95(SM5): 1219-1246

Monney, N.T. (1971): The engineering properties of marine sediments, Marine Technology Society Journal, 5,2: 21-30

Mosher, D.C., Simpkin, P.G. (2000): Status and trends of marine high-resolution seismic reflection profiling: data acquisition, http://www.pgc.emr.ca/marine/seisrefl.htm

Montague, C.L. (1986): Influence of biota on erodibility of sediments. In: Barber, R.T., Mooers, C.N.K., Bowman, M.J. (eds.) Lecture Notes on Coastal and Estaurine Studies Vol. 14: Estuarine Cohesive Sediment Dynamics. Proceedings of a Workshop on Cohesive Sediment Dynamics with Special Reference to Physical Processes in Estuaries. Tampa, Florida, November 12-14, 1984. pp. 251-269. Springer-Verlag Berlin

Monte, J.L., Krizek, R.J. (1976): One-dimensional mathematical model for large-strain consolidation. **Géotechnique,** 26,3: 495-510

Mudroch, A., MacKnight, S.D. (1994): Handbook of Techniques for Aquatic Sediments Sampling, Second Edition, Lewis Publishers

Mudroch, A., Azcue, J.M., Mudroch, P. (Eds.) (1997): Manual of Physico-Chemical Analysis of Aquatic Sediments, CRC Press, Inc., Boca Raton, Florida

Neumann, A.C., Gebelein, C.D., Mehta, A.J. (1970): The composition, structure and erodibility of sub-tidal mats, Abaco, Bahamas. J. of Sedimentary Petrology 40: 274-297

Nielson, F.D. (1973): Behavior of cohesive material from a soil engineer's viewpoint. In: Shen, H.W (ed.) Environmental Impact on Rivers (River Mechanics III). pp. 14-1 to 14-28. Hsieh Wen Shen, Colorado State University

Oberrecht, K. (1997): South Slough National Estuarine Research, Reserve Estuaries Feature Series. http://www.harborside.com/~ssnerr/artindx.htm

Parker, G., Izumi, N. (2000): Purely erosional cyclic and solitary steps created by flow over a cohesive bed. J. Fluid Mech. 419: 203-238

Partheniades, E. (1971): Erosion and deposition of cohesive materials. In Shen, H.W. (ed.) River Mechanics, Volume II pp.25-1 to 25-91. Hsieh Wen Shen, Colorado State University

Partheniades, E. (1972): Results of recent investigations on erosion and deposition of cohesive sediments. In Shen, H.W. (ed.) Sedimentation Symposium to Honor Professor H.A.Einstein. pp. 20-1 to 20-39. Hsieh Wen Shen, Colorado State University

Partheniades, E., Paaswell, R.E. (1970): Erodibility of channels with cohesive boundary. J. Hydr. Div, ASCE 96(3): 755-711

Richards, A.F., Zuidberg, H.M. (1985): In-situ determination of the strength of marine soils. In: Chaney, R.C., Demars, K.R. (Eds.): Strength Testing of

Marine Sediments: Laboratory and In-Situ Measurements, ASTM STP 883, Philadelphia, 11-40

Robertson, J.O., Rieke, H.H., Chilingar, G.V. (1965): Viscosity measurements of aqueous clay suspensions as a tool for determining mineralogic type of clays. Sedimentology, 4:181-187

Rollings, M.P. (2000): Geotechnical considerations in contained aquatic disposal design. DOER Technical Notes Collection (ERDC TN-DOER-N5), U.S. Army Engineer Research and Development Center, Vicksburg, MS. www.wes.army.mil/el/dots/doer

Rowe, , P.W., Barden, L. (1966): A new consolidation cell. Géotechnique, 16, 2: 162-170

Royse, C.F. (1970): An Introduction to Sediment Analysis, First Printing, Arizona State University, Tempe, Arizona

Rukavina, N.A., Versteeg, J.K. (1996): Surficial sediments of Hamilton Harbour: physical properties and basin morphology. Water Qual. Res. J. Canada, 31(3): 529-551

Rukavina, N.A., Caddel, S. (1997): Applications of an acoustic sea-bed classification system to freshwater environmental research and remediation in Canada. In Proceeedings of the Forth Conf. on Remote Sensing for Marine and Coastal Environments, pp. I-317-I-329, Orlando, Florida

Rukavina, N.A., Trapp, B. (2000): Mapping sediment properties with NWRI's undrewater video-acoustic tripod. Abstracts, 43rd Conf. Great Lakes and St. Lawrence River Research, Cornwall, Ontario

Sargunam, A., Riley, P., Arulanandan, I., Krone R.B. (1973): Effect of physico-chemical factors on the erosion of cohesive soils. J. of the Hydraulics Division, ASCE 99(HY3): pp. 553-558

Schiffman, R.L., Pane, V., Gibson, R.E. (1984): The theory of consolidation of saturated clays. IV. An overview of nonlinear finite strain sedimentation and consolidation. Proc. Symp. on Sedimentation/Consolidation Models: Prediction and Validation, R.N. Young and F.C. Townsend, eds., ASCE, New York, 1-29

Senneset, K., Janbu, N. (1985): Shear strength parameters obtained from static cone penetration tests. In: "Shear Strength Testing of Marine Sediments: Laboratory and In-Situ Measurements", Chaney, R.C., Demars, K.R. (Eds.), ASTM STP 883, 41-54

Suhayda, J.N. (1986): Interaction between surface waves and muddy bottom sediments. In: Barber, R.T., Mooers, C.N.K., Bowman, M.J. (eds.) Lecture Notes on Coastal and Estaurine Studies Vol. 14: Estuarine Cohesive Sediment Dynamics. Proceedings of a Workshop on Cohesive Sediment Dynamics with Special Reference to Physical Processes in Estuaries. Tampa, Florida, November 12-14, 1984. pp 401-428. Springer-Verlag Berlin

Teisson,C., Ockenden, M., Le Hir, P., Kranenburg, C., Hamm, L. (1993): Cohesive sediment transport processes. Coastal Engineering 21: 129-162

Terzaghi, K. (1923): Die Berechnung der Durchlässigkeitziffer des Tones aus dem Verlauf der hydrodynamischen Spannungserscheinungen. Sitz. Akad. Wissen. Wien, Math-naturw. Kl. 132, 105-124.

Terzaghi, K. (1943): Theoretical Soil Mechanics. Wiley, New York.

Terzaghi, K., Peck, R. B. (1968): Soil Mechanics in Engineering Practice, 2nd Ed., First Corrected Printing, Wiley, New York.

Toorman, E. (1992): Modelling of fluid mud flow and consolidation. Ph.D. Thesis: Katholieke Universiteit Leuven

Wetzel, A. (1990): Interrelationships between porosity and other geotechnical properties of slowly deposited, fine-grained marine surface sediments. Marine Geology, 92, 105-113

Winterwerp, J.C., Kranenburg, C. (1997): Erosion of fluid mud by entrainment. In: Burt, N., Parker, R., Watts, J. (eds.) Cohesive Sediments. pp 263-278. John Wiley & Sons Ltd. Chichester

Yen, B.C. (1992): Hydraulic resistance in open channels. In: Yen, B.C. (ed.), Channel Flow Resistance: Centennial of Mannings's Formula, Water Resources Publications, Littleton, CO, 1-135

Yong, B.N. (1966): Introduction to Soil Behavior. Macmillan Company, New York

Zeman, A.J., Patterson, T.S. (1995): Evaluation of primary and secondary consolidation of Hamilton Harbour sediments due to in-situ capping. National Water Resaerch Institute, Environment Canada, Contribution No. 95-02

Zeman, A.J., Patterson, T.S. (1997): Results of in-situ capping project in Hamilton Harbour, Lake Ontario, Canada. In Proceeding of the Int. Symp. Eng. Geology and the Environment, pp. 2289-2295, Athens, Greece

Zeman, A.J., Rukavina, N.A., Patterson, T.S. (2000): Research on the properties of contaminated sediments at the Randle Reef remediation site, Hamilton Harbour. Abstracts, 43rd Conf. Great Lakes and St. Lawrence River Research, Cornwall, Ontario

Zreik, D.A., Ladd, C.C., Germaine, J.T. (1995): A new fall cone device for measuring the undrained strength of very weak cohesive soils. Geotechnical Testing Journal, 18(4): 472-482

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