TU Delft
Technische Universiteit Delft

Faculteit Civiele Techniek en Geowetenschappen
Afdeling Waterbouwkunde en Geotechniek
Sectie Vloeistofmechanica

THE INTRUSION OF FINE SUSPENDED SEDIMENT INTO A SANDY SEDIMENT BED
A LITERATURE REVIEW

P.J.T. Dankers

Report no. 01-05
2005

TU Delft

Section of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA, Delft, The Netherlands. Tel. +31 (0)15 278 4070; Fax +31 (0)15 27 85975; E-mail: p.j.t.dankers@citg.tudelft.nl

Contents

List of Figures

List of Tables

Abstract

In 2001 a DIOC-project was started at Delft University of Technology on the behaviour of mud in the water column. In this project the behaviour, spreading and settling velocity of fines is studied. After an introductional literature review on the behaviour of fines released due to dredging, the focus was placed on the behaviour of the fines on the sea bed. According to our hypothesis, the fines that settle on the sediment bed can be transported into the bed, thereby changing the sediment properties. This intrusion can take place due to pressure gradients underneath waves, pressure gradients over bedforms, ripple migration, bioturbation, anthropogenic influences or combinations of these. A literature review has taken place to determine the possibility and probability of this fine sediment intrusion into the bed. The results of this literature review are presented herein.

Chapter 1

Introduction

Increasing needs for construction sand and offshore space will result in increased dredging activities in offshore areas in the coming years. This increase in dredging in turn results in an increase of sediment, merely fine sediment,that is mobilised by the dredgers and spread in the watercolumn. The fine sediment dispersed in the water column has several effects on the biotic and abiotic system depending on the type of dispersion in the water (Dankers, 2002).

In general, the North Sea bed exists of fine to coarse grained sand with small and large patches and layers of mud. In the sandy parts of the North Sea only a small percentage of the bed material consists of fines (sediment <63 μm). A small part of this fine sediment consists of clay and organic material, which can form flocs when their presence in the watercolumn is long enough. These very small particles, the mud and mud flocs, are important for the ecosystem as the organic material is a source of food for many organisms. Next to this the mud can affect the system due to light attenuation effects and low settling velocities of the sediment. These effects however only occur when the small particles are ubiquitous.

The influence of the mud on the ecosystem merely depends on their behaviour after release in the water. The fines that are released during dredging activities may settle fast as density currents (dynamic plume) or, when their settling velocity is small, spread over a large area (passive plume). Either way the environment is affected. The dynamic plumes leave a layer of fine material on the sand bed in the near vicinity of the dredged area which can cause the burial of benthos and a change in bed properties. The settled material can be resuspended again rapidly during storms or when high current velocities are prevailing (e.g. during springtide). In the case of resuspension the particles are dispersed over a large area. This would lead to large passive plumes which behave in a similar way as the passive plumes that can develop during the dredging activities. The passive plumes affect the environment by changing the light climate, which affects primary production and the growth of plants, and by increasing the organic content and thus food availability in the water. Furthermore the high amount of suspended sediment in the water column can affect sight feeders and filter feeders (filter clogging).

In a previous literature review the behaviour of the fines in the water column was discussed. The present literature review focusses on the fines that settle on the bed and possibly alter the bed properties. It is thought that some of the fines that settle on the bed after dredging may be transported into the sediment bed, thereby changing its structure, erodibility and permeability. This hypothesis of fines travelling into the bed is supported by the seasonal change in fine sediment content in the North Sea bed. In general the suspended matter concentration in the water column is higher in winter (storm season) than in summer (Suijlen & Duin, 2001). As the concentration along the coast increases instantly during storms, this increase is probably not a result of advective transport but of resuspension. This would mean that the concentration of fine sediment in the bed is decreased. The bed is however not depleted totally after the storm season which would advocate the existence of a mechanism that transports fine sediment back into the bed. The mechanisms that may cause this infiltration and mixing of fine sediment in a sandy bed are:

- Pressure gradients underneath waves
- Pressure gradients over ripples
- Ripple migration
- Bioturbation
- Anthropogenic influences

In this literature review the physics of these processes, their ability to transport or mix fine sediment into a sandy bed and the result of this transport or mixing shall be described.

Chapter 2

Bed diagenesis

The North Sea is a wave- and storm- dominated system with micro- to macro-tidal shorelines. The bed material in the North Sea consists of fine to medium (100-400 μm) sand (in some parts coarser, towards gravel), often alternating with clay layers which differ in thickness from a few cm to tens of metres. The thick mud layers are relics from the pre- and early holocene river deltas and estuaries. The upper layer of the North Sea bed shows a stratigraphical sequence which is common for storm dominated shallow shelf seas (Johnson & Baldwin, 1996). According to Johnson & Baldwin (1996) the nature of modern shelf storm deposits is controlled by: the energy level of the hydraulic regime; the type of sediment available; the direction of the storm generated currents; the amount of subsequent post storm physical and/or biological reworking; the distance from the shoreline; and the water depth. An idealised storm sequence can be divided into four stages (Johnson & Baldwin, 1996):

1. Storm erosion: a basal erosion surface, cut by combined oscillatory and unidirectional flows, which may be flat to undulatory (up to 0.4 m), with gutter casts, sole marks and intra clasts of pebbles, shells or mud stone.

2. Main storm deposition (sand): main Hummocky cross stratified interval, possibly with a parallel (horizontal to sub-horizontal) laminated layer with parting lineation directly overlying the basal erosion surface, and deposited under continuing combined flow conditions. Hummocky cross stratification has been defined as a form of medium- to large-scale cross stratification, in which the undulating and gently dipping laminae preserve a three dimensional bed form comprising large amplitude (1-5 m), low relief (0.1-0.5 m) mounds and troughs (Johnson & Baldwin, 1996).

3. Waning storm deposition (sand): wave ripples indicating a return to lower flow regime oscillatory currents, although occasionally unidirectional current ripple cross lamination is present.

4. Post storm/fair weather mud deposition: reflects either the final suspension outfall of storm derived sediment (i.e. post storm mud) or the return to normal, background sedimentation (i.e. fair weather mud).

This idealised sequence may be disrupted to varying degrees by bioturbation, which in extreme cases can obliterate physical evidence of storm deposition and mix the sand and mud fractions.

Chapter 3

Flow and transport through sediments

Total suspended matter concentrations (TSM) in the upper layer of the water column in the Dutch coastal zone change with the seasons (Suijlen & Duin, 2001). Suijlen & Duin (2001) distinguished a winter and a summer season based on the wave climate. In these seasons the mean near-surface concentrations in the Hook of Holland-Terschelling area 15 km offshore are 3.7 mg/l in summer and 4.6 mg/l in winter. Closer to the coast the mean near surface concentrations are 12 mg/l and 30 mg/l in summer and winter, respectively. The higher suspended sediment concentrations in winter can partly result from advective transport. For the other part resuspension of the bed material probably plays an important role. This can be deduced from the information that the concentration in winter increases at an instant along the whole coast of the Netherlands. After the winter season the suspended sediment settles on the bed as a thin layer of fine sediment on top of the sandy North Sea material. In this literature review we propose that due to mechanisms as advective transport through the bed, bioturbation, ripple migration and fisheries, this fine sediment layer and the fine sediment still in suspension is mixed with the sandy bed material. The mechanisms of mixing by advective transport and ripple migration will be discussed in this chapter.

The North Sea bed is covered with ripples, dunes and sand waves created by waves and currents and mounds and hollows created through biological activity. These undulations, even when they are small, cause alterations in the flow field and therefore the pressure distribution. These pressure differences can cause a flow through the sediment. Solutes and maybe even small particles can be transported into the sediment bed due to this process.

The flow around bedforms is quite similar to the flow around cylinders with the difference that flow through the object and the underlying bed can take place in the first case. The analogy between turbulent flow over cylinders and over waveforms is presented in Figure 3.1. In both cases there is a stagnation point (in the case of permeable beds the water infiltrates at this point) and boundary layer separation takes place, thereby creating vortices and a wake zone. Because of the analogy between flow over impermeable cylinders and permeable bedforms we shall first start to analyse the flow around cylinders and take it from there towards flow over and through permeable bedforms.

3.1 Flow around impermeable objects

Flow around cylinders is described and analysed in many fluid mechanics handbooks and scientific papers (Mutly Sumer & Fredsøe, 1997; Battjes, 1991; Schlichting, 1968; Battjes,

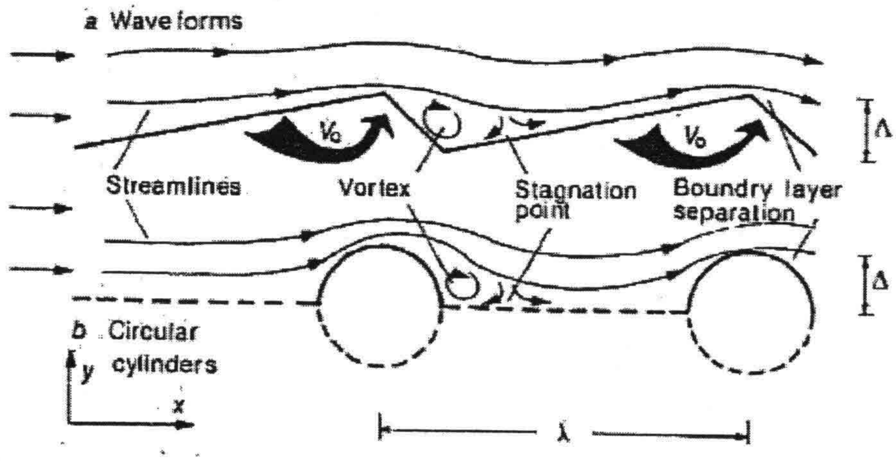

Figure 3.1: Analogies of flow conditions around objects in a flow field. a) Over-bed and in-bed flow for a sandwave bedform. b) Flow across cylinders. (Thibodeaux & Boyle, 1987)

1999). We follow Battjes (1991) to describe flow around and determine pressure on cylindrical objects. It is easiest to start with a case of ideal flow where shear doesn't play a role. For stationery flow under the influence of gravity and pressure, the energy head (H) according to Bernoulli (Equation 3.1) is constant along streamlines (ψ) and has for every streamline the same value,

$$\frac{\partial}{\partial s}\left(h + \frac{u_s^2}{2g}\right) = \frac{\partial H}{\partial s} = 0 \tag{3.1}$$

in which h is the piezometric level, s is the distance along a streamline and u_s the velocity along a streamline. These flows with uniform energy head are potential flows, they are rotation free and incompressible. Due to incompressibility:

$$\nabla \cdot \vec{u} = 0 \tag{3.2}$$

and due to rotation free

$$\nabla x \vec{u} = 0 \tag{3.3}$$

or

$$\vec{u} = \nabla \phi \tag{3.4}$$

with $\vec{u}$ is the local velocity, x is the distance in x-direction and ϕ is the flow potential. Substitution of Equation 3.4 in Equation 3.2 gives:

$$\nabla^2 \phi = 0 \tag{3.5}$$

or

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \tag{3.6}$$

which is the equation of Laplace. In the case of non-stationery flow Equation 3.1 is adjusted to:

$$\frac{\partial \phi}{\partial t} + \frac{P}{\rho} + gz + \frac{1}{2}\rho u^2 = constant \tag{3.7}$$

with t is time, P is pressure, ρ is density and u is velocity. This equation can be used to calculate the pressure field after the potential field is calculated from Equation 3.6. This can be done with numerical methods or with the method of conformal mapping. With the last method an orthogonal network is formed in the area in which the velocity and pressure field are required. The network is formed with potential lines (ϕ) and streamlines (ψ) perpendicular to each other to fulfill $\Delta\phi = \Delta\psi = \Delta q$ where q is the discharge per unit width.

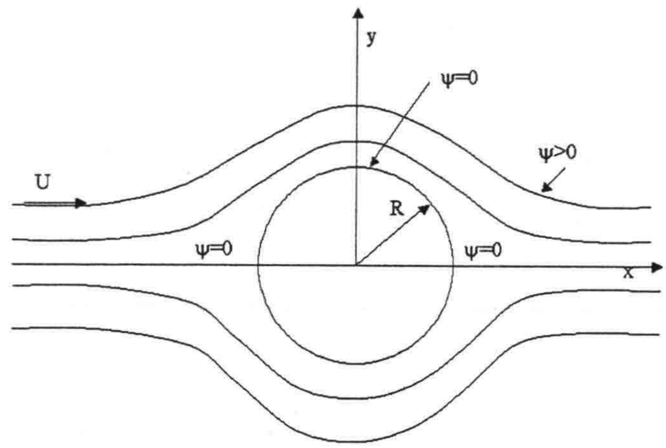

Figure 3.2: Streamlines of ideal flow around an impermeable circle

The solution with the method of conformal mapping for flow around a cylinder, following (Battjes, 1991), is given here. The uniform unperturbed flow has a velocity U in the x-direction. The flow goes around a circle with radius $r = R$. Figure 3.2 shows streamlines $\psi = 0$ for the cylindrical polar coordinates $\theta = 0$ and $\theta = \pi$ and for $r = R$. The radial velocity (velocity at specific radius u_r) is given by:

$$u_r = U\left(1 - \frac{R^2}{r^2}\right) cos\theta \tag{3.8}$$

and the tangential velocity (velocity at specific angle u_ϕ) is given by:

$$u_\theta = -U\left(1 + \frac{R^2}{r^2}\right) sin\theta \tag{3.9}$$

On the surface of the cylinder the velocity thus varies according to:

$$u_\theta|_{r=R} = -2U sin\theta \tag{3.10}$$

This gives a velocity of u=0 in the stagnation points and a velocity $u = 2U$ at the top of the cylinder. The pressure according to Bernoulli ($\Delta P = P - P_\infty = \frac{1}{2}\rho(U^2 - u^2)$) around the cylinder ($r = R$) is:

$$\Delta p|_{r=R} = \frac{1}{2}\rho U^2(1 - 4sin^2\theta) \tag{3.11}$$

The pressure thus varies from $\frac{1}{2} + \rho U^2$ at the stagnation points to $-\frac{3}{2}\rho U^2$ at the top of the cylinder. This pressure distribution is symmetrical in both the flow direction and perpendicular to the flow direction. When the cylinder is permeable the pressure in the stagnation point will be less because some flow through the object is possible. Equation 3.11 is valid for non-viscous flow or ideal flow around impermeable objects only, but it gives an indication of the pressure differences around permeable objects.

In the case we are dealing with flow in rivers or at sea viscosity should be incorporated. This changes the velocity distribution around the cylinder and the possibilities for advective transport. The non-dimensional Reynolds number (Re) can be used to determine the effects of viscosity on the flow.

$$Re = \frac{DU}{\nu} \tag{3.12}$$

in which D is the diameter of the cylinder, U is the unperturbed flow velocity and ν is the kinematic viscosity. In a low viscous flow ($Re >> 1$)the no slip condition is valid, which gives $u = 0$ at the wall. This gives a boundary layer around the cylinder in which the velocity changes from 0 at the wall to u at a distance from the object. This boundary layer thus exhibits a strong velocity gradient in which drag forces are important. A sketch of flow with a high Reynolds number around a cylinder is given in Figure 3.3. In this sketch 4 zones

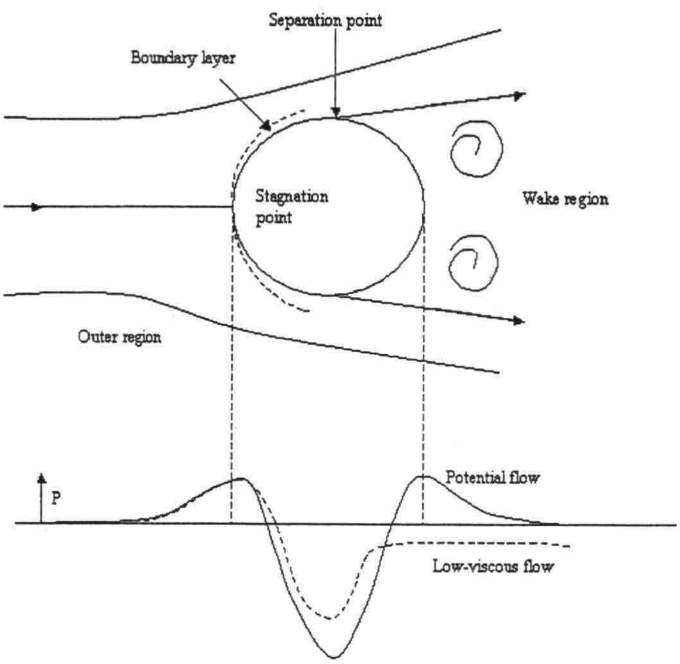

Figure 3.3: Low-viscous flow and pressure distribution around an impermeable circle.

are recognisable:

- A thin boundary layer from the stagnation point till the largest diameter
- A zone of separation of the boundary layer flow
- A wake region downstream of the cylinder, after the separation point
- An outer zone, outside the boundary layer and the wake region

In the outer zone drag forces are negligible. The pressure in this outer zone varies according to Bernoulli (Equation 3.1) just as in the case with potential flow. This pressure, which varies with $\Delta P \sim \frac{1}{2}\rho U^2$, also influences the pressure in the boundary layer because of the relative thinness of the boundary layer (Battjes, 1991). Furthermore, the pressure gradient along streamlines ($\partial p/\partial s$) influences the boundary layer. On the upstream side (between the stagnation point and the point of separation in Figure 3.3) the flow accelerates just as with potential flow and the pressure gradient is in the direction of flow ($\partial P/\partial s < 0$). This compensates (partly) the friction drag. On the downstream side, where the pressure gradient increases ($\partial P/\partial s > 0$), the pressure gradient enhances the friction drag. This results in a decrease of flow in the boundary layer, a strong increase of boundary layer thickness and a separation of the boundary layer from the object. At the point where the boundary layer separates the flow reverses its current direction. This phenomenon is always associated with the formation of vortices and with large energy losses in the wake of the body (Schlichting, 1968). After the separation point, in the wake region, the flow velocities are relatively low and the pressure is low and almost constant. According to potential flow theory the pressure distribution over a cylinder is given by Equation 3.11. However, because of viscosity effects and the resulting separation of flow from the object a measured pressure distribution differs from a distribution calculated according to potential flow. Measured distributions will always give a more or less constant under-pressure in the wake region (Mutly Sumer & Fredsøe, 1997). The pressure returns to its original value far behind the object as can be seen in Figure 3.3. In the case of streamlined shapes instead of perfectly round shapes, the pressure gradient is reduced. This causes the flow to separate at a later point and pressure to return more quickly to its original value.

3.2 Flow over impermeable bedforms

The theoretical analysis of flow around structures can also be applied to flow over and around bedforms. Huettel & Webster (2001) describe several windtunnel and flume experiments carried out by other researchers in the last three decades on flow around permeable and impermeable objects on permeable and impermeable floors.

The flow around impermeable 3D spherical obstacles is shown in 3.4. The flow behaviour

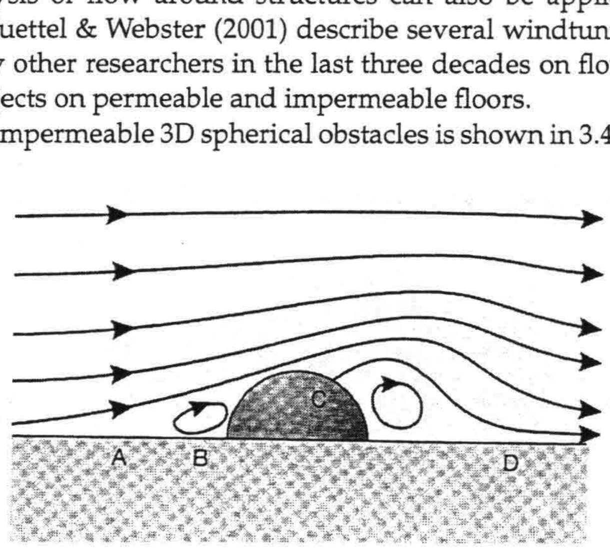

Figure 3.4: The flow around a solid obstruction according to Huettel & Webster (2001)

resembles the flow around objects as shown in the previous section with the difference that in this case only half of the picture has to be taken into account. Figure 3.4 shows a separation point (C), a vortex area and reattachment of the flow to the bed. The pressure distribution in this example will look like the one in Figure 3.3 for low viscous flow and the pressure distribution in the plane will look like Figure 3.5. The latter shows the measured pressure perturbation normalised by the free-stream dynamic pressure ($p_0 = \frac{1}{2}\rho(u_{D/2})^2$). The shade depicts areas of over pressure. In the case of permeable soils water can infiltrate in these areas due to the pressure gradient over the cylinder.

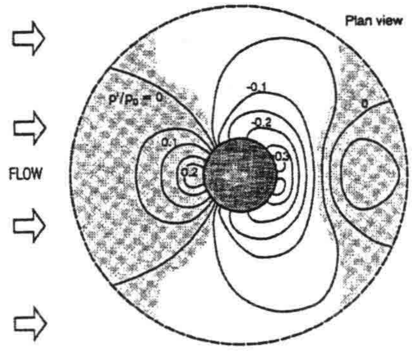

Figure 3.5: Pressure field around a hemisphere according to windtunnel measurements by Taniguchi & Sakamoto (1982) produced by Huettel & Webster (2001). Lines present isobars.

Vittal *et al.* (1977) performed measurements of shear and pressure distribution on smooth and sand coated two-dimensional triangular elements in flumes with a restricted depth. Their results were quite similar as the results expected from theory. They found a high pressure zone on the leading edge and a low pressure zone at the crest. On the lee side the pressure was more or less constant and the lowest on the element, as would be expected in the wake region. In their results they state that the pressure coefficient (C_p) depends on the depth of the flow (d) in a flume with restricted depth. This makes it not directly applicable to bedforms in the North Sea. We did however not find any data regarding pressure coefficients at $d = \infty$ and for experimental data on pressure coefficients over cylinders only the results of windtunnel experiments as given by Taniguchi & Sakamoto (1982) were found. In the latter experiments the pressure on hemispheres in a windtunnel was measured. The results of the pressure coefficient C_p versus the angle θ (angle in the x-y plane, parallel to the bed) for different angles of ϕ_a (angle in the x-z plane, z is normal to the bed) are given in Figure 3.6 for an experiment with a hemisphere of a diameter 60 mm and a free stream velocity of 16 m/s. This figure shows that the pressure coefficient becomes negative in all cases in their experiments when $\phi_a \geq 50°$. The values of C_p at different angles give an indication of what to expect around bedforms in the North Sea.

3.3 Flow over and through permeable bedforms

In the case of permeable bedforms, more or less the same pressure distribution as shown by Vittal *et al.* (1977), Taniguchi & Sakamoto (1982) and Mutly Sumer & Fredsøe (1997) can be

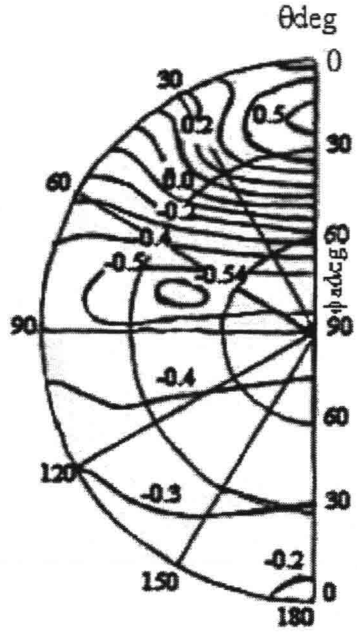

Figure 3.6: Isobars on the surface of a hemisphere. Flow direction at θ = 0 deg. (Taniguchi & Sakamoto, 1982)

expected. The difference however lies in the fact that in the case of permeable bedforms a flow through the bedform and through the bed, although small, can be initiated.

Thibodeaux & Boyle (1987) showed with laboratory experiments that porewater flow is induced by pressure gradients when dealing with flow over permeable bedforms. Convection cells developed below the bedforms and from dye experiments in porous beds they found that the dye moved in the direction of the flow. In general water entered the bedform between the trough and the crest on the windward face and left the bedform between the crest and the trough on the leeward face as is shown in Figure 3.1. These results comply with the results of Taniguchi & Sakamoto (1982) in Figure 3.6 where the pressure coefficients along a cylinder are shown.

Thibodeaux & Boyle (1987) proposed a model for estimating Peclet numbers for the effect of convection currents in porous beds. The Peclet number describes the importance of advection over molecular diffusion and is given by:

$$Pe = \frac{nud_p}{(1-n)D^0} \tag{3.13}$$

or

$$Pe = V_0 5\lambda / D^0 \tag{3.14}$$

when dealing with beds with bedforms. n is the porosity, u is the flow velocity, d_p the mean diameter of sediment particles, V_0 the porewater velocity, λ the bedform length and D^0 the molecular diffusion coefficient. Unless Pe is larger than 1, the dispersion is essentially due to the molecular diffusion. Pe can be larger than 1 when for instance u is large due to pressure gradients induced by waves or currents over bedforms.

In the theory of Thibodeaux & Boyle (1987) the pressure drop across simple shapes is described by Darcy's law, whereafter the Peclet numbers and the in-bed velocity can be predicted. This was done by dividing the total pressure on the bed into two parts. One part deals with the pressure due to the hydraulic gradient and the other one with the pressure due to the ripple form. Thibodeaux & Boyle (1987) wrote this down as follows:

$$dP/dx = dP/dx|_w + dP/dx|_h \tag{3.15}$$

with

$$-dP/dx|_w = C_P \rho U^2/\lambda \tag{3.16}$$

and

$$dP/dx|_h = \rho g S \tag{3.17}$$

U is the average stream velocity, $|_w$ is due to ripples, $|_h$ is due to the hydraulic gradient, ρ is the fluid density, λ is the ripple length, S is the slope of the water surface and C_P the pressure coefficient. For C_p Thibodeaux & Boyle (1987) used an equation by Vittal *et al.* (1977) for bedforms in shallow water ($C_p = 0.5(h_r/d)^{3/8}$). Hereafter Darcy's law is applied for the in-bed flow:

$$V_o = -\frac{k}{\mu} dP/dx \tag{3.18}$$

where V_o is the porewater velocity, k the permeability and μ the porewater viscosity. Combining all these equations leads to a prediction of the porewater velocity through a 2D element given by:

$$V_o = \frac{k}{\nu}(C_p U^2/\lambda + gS) \tag{3.19}$$

in which $\nu = \mu/\rho$ (ν is the dynamic viscosity and μ is the kinematic viscosity). Thibodeaux & Boyle (1987) compared this model to their observations and found that the model underestimated their laboratory results with a factor 2. The model gave an average porewater velocity under the crest of 0.0093 m/s while the experiments with bedforms of wavelength λ=0.55 m and height h_r=0.05 cm gave V_0=0.0024 m/s. This underestimation was partly ascribed to the simplicity of the model and the inaccurate value of C_p, which is not known for porous media (Thibodeaux & Boyle, 1987).

In Table 3.3 the porewater velocity and Peclet number are determined with the method of Thibodeaux & Boyle (1987) for different permeabilities and bedform sizes which are representative for the North Sea. The porewater velocity is determined with Equation 3.19 and the Peclet number with Equation 3.14 for beds with bedforms.

In Table 3.3 both permeability and hydraulic conductivity are used. The main difference is that the hydraulic conductivity contains properties of both the medium and the fluid while the parameter k is referred to as the intrinsic permeability, which contains properties of the medium only. The hydraulic conductivity with units of velocity characterises the capacity of a medium to transmit water, whereas the permeability with units L^2 characterises the capacity of the medium to transmit any fluid (Domenico & Schwartz, 1990). The hydraulic conductivity is given by:

$$K = \frac{k \rho_w g}{\mu} \tag{3.20}$$

where k the permeability is given by Nd_p^2, with N a dimensionless shape factor relating to the geometry of passage and d_p the mean particle diameter. The permeability can be calculated

	K [m/s]	k [m^2]	V_0 [m/s]	Peclet
Sand wave				
gravel	$3*10^{-2}$	$3*10^{-9}$	$1.33*10^{-5}$	$6.64*10^{5}$
medium sand	$3*10^{-4}$	$3*10^{-11}$	$1.33*10^{-7}$	$6.64*10^{3}$
fine sand	$3*10^{-7}$	$3*10^{-14}$	$1.33*10^{-10}$	6.64
clay	$1*10^{-11}$	$1*10^{-18}$	$4.42*10^{-15}$	$2.21*10^{-4}$
Dune				
gravel	$3*10^{-2}$	$3*10^{-9}$	$1.33*10^{-4}$	$3.32*10^{6}$
medium sand	$3*10^{-4}$	$3*10^{-11}$	$1.33*10^{-6}$	$3.32*10^{4}$
fine sand	$3*10^{-7}$	$3*10^{-14}$	$1.33*10^{-9}$	$3.32*10^{1}$
clay	$1*10^{-11}$	$1*10^{-18}$	$4.42*10^{-14}$	$1.11*10^{-3}$
Ripple				
gravel	$3*10^{-2}$	$3*10^{-9}$	$1.06*10^{-3}$	$5.31*10^{6}$
medium sand	$3*10^{-4}$	$3*10^{-11}$	$1.06*10^{-5}$	$5.31*10^{4}$
fine sand	$3*10^{-7}$	$3*10^{-14}$	$1.06*10^{-8}$	$5.31*10^{1}$
clay	$1*10^{-11}$	$1*10^{-18}$	$3.54*10^{-13}$	$1.77*10^{-3}$

Table 3.1: Hydraulic conductivity (K), permeability (k), porewater velocity (V_0) and Peclet number for several grainsizes and bedforms. Sandwave h_r=1 m, λ=20 m; dune h_r=0.5 m, λ=2 m; ripple h_r=0.1 m, λ=0.25 m. K and k from Domenico & Schwartz (1990).

using various theoretical or semi-theoretical equations, e.g. the Carman-Kozeny equation

$$k = \frac{d_p^2}{150}\left[\frac{n^3}{(1-n)^2}\right] \tag{3.21}$$

where d_p is the mean diameter of the sediment particles and n is the porosity defined as $n = \frac{\text{total of voids in sediment-water sample}}{\text{total volume of sediment-water sample}}$.

From Table 3.3 it is clear that advective flow plays an important role in North Sea sediments. The value of the Peclet number stays above 1, even for fine sand and large bedforms. Only when clay is present the permeability reduces that much that $Pe < 1$. Herein we used the minimum permeability for clay. Different clay beds might get a larger Peclet number, as well as mixtures of sand and clay. Furthermore it can be seen that the flow velocities and subsequently the Peclet number through smaller bedforms are higher than through larger bedforms.

3.4 Transport through bedforms

As flow through beds, induced by pressure gradients over bedforms, is possible; it might also be possible for solubles or even particles to be transported through the bed. Rutherford *et al.* (1995) anticipated that this induced flow through permeable sediments might play an important role in sustaining the productivity of shallow water regions by transporting organic matter and dissolved oxygen to bacteria and interstitial organisms and returning to the overlying water the nutrients that are produced. In their research they looked at the benthic oxygen uptake by pumping (the flow through beds) and developed a simple analytical model to determine how large the benthic oxygen uptake rate due to pumping would be. They found that pumping causes deoxygenation of river beds. Their model predicts that pumping makes only a small contribution (5%) to the total deoxygenation rate of a sand river but that it could make a significant contribution (50%) to deoxygenation in a gravel river, in which the bed is highly permeable and sediment microbial activity is high. This thus implies that, next to flow through the sediment, advective flow takes place.

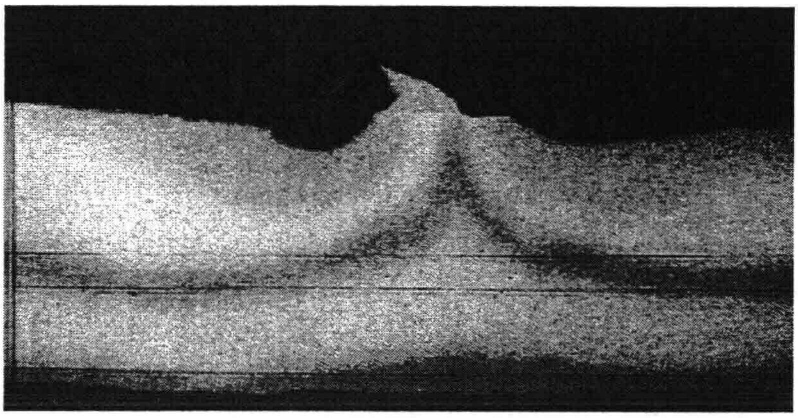

Figure 3.7: Tracer intrusion into sandy sediment at a mound 2.5 cm high. Curved lines indicate the locations of the intruding tracer fronts after 16.5 h. Straight parallel lines show the initial positions of the stained pore-water layers at 7-9 and 13-15 cm sediment depth. Flow velocity was 10 cm/s. The small dark spots indicate the intrusion of small particles. (Huettel *et al.*, 1996)

Huettel *et al.* (1996) went further. They did experiments with dyed water (Figure 3.7) and used small acrylic pigment grains of 1- and 10 μm in combination with a sand bed ($k > 2 \times 10^{-11}$ m^2) and small obstacles with a height (h_r) of 2.5 cm in a laboratory flume. The particles were found to penetrate into the sediment bed together with the water. However the intruding fluid moved much faster than the particles. Huettel *et al.* (1996) found vertical intrusion velocities of 6.9×10^{-6} m/s for the fluid in the first hour and 3.6×10^{-6} m/s for the particles. The fluid velocity agrees very well with the velocity $V_0 = 4.25 \times 10^{-6}$ m/s which we obtain when using the model of Thibodeaux & Boyle (1987). Herein we used h_r = 0.025 m, λ = 0.035 m, U = 0.1 m/s, $k = 4.5 \times 10^{-11}$ m^2, n = 0.16, C_p = 0.30, h = 0.1 m and $\mu = 9 \times 10^{-7}$ m$^2/s$. After ten hours the fluid velocity in the experiment decreased to 8.3×10^{-7} m/s and the particle velocity to 2.8×10^{-7} m/s . In contrast to the smooth front produced by the intruding water, the particle fronts were uneven. The grains funnelled through the largest interstitial spaces, producing fine particle streaks that followed the streamlines of the advective porewater flows (Huettel *et al.*, 1996). After 5 days the particle front was still progressing, however at a very low speed of 5.6×10^{-9} m/s. At the end the particles had intruded 5 cm into the sandbed, which is much further than could be done with molecular diffusion only (Huettel *et al.*, 1996). The Peclet number, Pe = 7433, which is calculated from the porewater velocity at the beginning of the experiments, also advocates the importance of advective flow and dispersion over molecular diffusion. Furthermore Huettel *et al.* (1996) found that the depth of particle intrusion increased with the height of the mound and that segregation of the 1 μm and 10 μm particles was taking place.

Although advective transport takes place and small particles can be transported, this doesn't imply that transport of cohesive sediment through these convective cells takes place. However, when it takes place the calculated porewater velocities are probably overestimated because Φ, the volumetric concentration of cohesive particles in water, is not incorporated in this model. The higher the volumetric concentration in the water column, the more sediment can be transported into the bed and the quicker the bed becomes clogged, reducing the permeability. Therefore it is probable that a maximum exists in the amount of fine sediment that can enter a sand bed before the permeability has decreased too much. In general, permeability is influenced by particle size, porosity, composition, fabric and degree of saturation. Equation **??** suggests that permeability varies with the square of the mean particle diameter. The smaller the soil particles the smaller the voids, which are the flow channels, and thus the lower the permeability. Furthermore, experimental data suggests that fine particles in a soil have the most influence on permeability (Lambe & Whitman, 1979) as can also be seen in Table 3.3.

Merckelbach (2000) performed consolidation experiments with mud in which a small amount of sand was present. He measured hydraulic conductivities up to $K = 1\times10^{-15}m/s$. In these experiments however the cohesive fraction was large enough to build the network structure of the bed and therefore this fraction mainly determined the permeability. Data on permeability in beds where sand builds the network structure and cohesive sediment is present in a small amount is not available. It is therefore not known how much fine material can infiltrate into a sand bed before the permeability is decreased too much. However, we would guess that even a small amount of cohesive sediment in a bed already decreases the permeability severely.

3.5 Transport induced by waves

Just as flow over bed forms causes pressure gradients over these bed forms, waves on top of a flat bed cause pressure gradients in the bed (Figure 3.8). Waves travelling in coastal seas (swell, wind waves and even tidal waves), may cause advective transport and possibly increase the dispersion in sediments. In this section we deal with advective transport due to swell and wind waves.

In water sufficiently shallow for the wave action to penetrate to the bed, pressure tends to be relatively high under the wave crests and relatively low under the troughs. These oscillatory pressure perturbations penetrate into the sediments, where the resulting pressure gradients induce interstitial motions (Huettel & Webster, 2001). In contrast to flow over bedforms the pressure perturbations due to standing waves do not cause a net transport of water through a flat bed because the motion caused by waves is periodic, the circulation cells are closed and the time averaged current is zero. At the sediment surface, the horizontal interstitial flows diverge under the wave crests and converge under the troughs. This diverging flow under the crests requires fluid to enter the sediment while the converging flow requires fluid to leave the sediment under the troughs (Huettel & Webster, 2001). In other words, one might say that this periodic flow of water through sediment is a kind of filtering. Riedl *et al.* (1972) introduced the term "subtidal pump" for this filtering process.

In contrast with Riedl *et al.* (1972) who only discussed the periodic movement of the water into and out of the bed, Rutgers van der Loeff (1981) and Harrison *et al.* (1983) also looked at the possible transport of solubles within the sediment itself by mechanical dispersion or

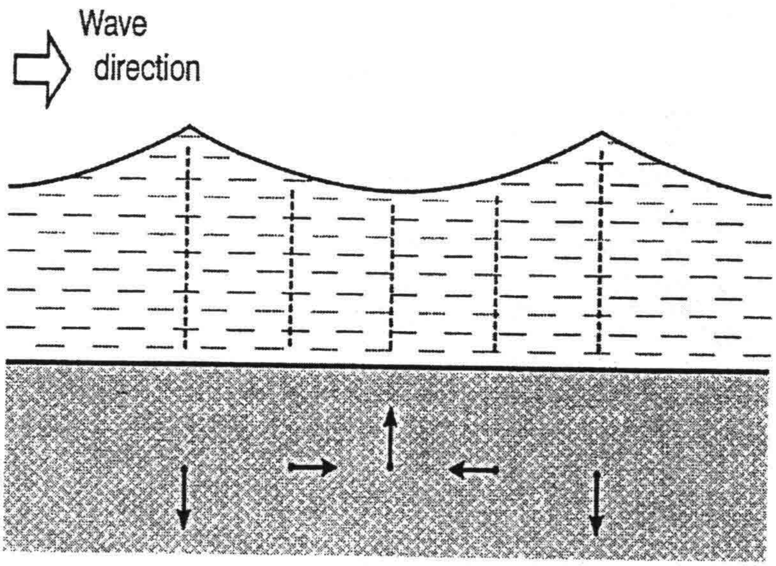

Figure 3.8: Pressure induced by waves over a flat bed

advective transport. Rutgers van der Loeff (1981) carried out field experiments in the Wadden Sea. He compared the field results with numerical simulations in order to determine whether the mobility of nutrients in the upper layer of the sediment exceeded molecular diffusion. The shallow permeable sand bottoms in the Wadden Sea, frequently subject to strong wave action, were expected to be particularly favourable for a considerable wave induced percolation of the sediment. According to Rutgers van der Loeff (1981) the percolation of water into and out of the bottom would cause a turbulent mixing of the porewater. Because of the low Reynolds number, laminar flow is however more probable. Instead of a turbulent diffusion coefficient which Rutgers van der Loeff (1981) associated to the wave parameters, we propose to refer to the effective diffusion coefficient given by Rutgers van der Loeff (1981):

$$D_w = D_{t,o} e^{-2Kz} \tag{3.22}$$

with

$$D_{t,o} = \frac{\pi k^2 \tau_w H_w^2}{2\lambda_w^2 cosh^2(n_w d)} \tag{3.23}$$

is the diffusion coefficient at the sediment surface, in which n_w is the wave number, z is the vertical distance from the bed, d the depth, K the hydraulic conductivity, τ_w the wave period, λ_w the wave length and H_w the wave height.

From his experiments in the Wadden Sea Rutgers van der Loeff (1981) obtained a diffusion coefficient in the upper layer of around 10^-9 m^2/s for water. This value was found during low to moderate wave action. In contrast, with his model he found that during a storm (T = 3.6 s, λ_w = 13 m, $H_w/cosh(n_w d)$ = 0.50 m and K = 2.10^{-4} m/s), in which one would expect a larger diffusion coefficient than during moderate wave action, $D_{t,0}$ was only $\leq 3 * 10^{-10}$ m^2/s and thus smaller than the experimental value during moderate wave action. Rutgers van der Loeff (1981) explained this difference with the fact that next to the influence of waves also ripples might be important and the existence of circulation cells under combined waves and ripples, as described by Webb & Theodor (1972) might be the reason for increased diffusivity in the field. This is discussed in Section 3.6.

Harrison *et al.* (1983) also tried to determine whether wave action increases dispersion. They developed a mathematical formalism for wave driven mechanical dispersion whereby wave-enhanced transport is simulated with an empirical diffusion coefficient. They used the Peclet number to determine whether the effective diffusion was larger than molecular diffusion. However in the case of orbital motion a large Peclet number does not necessarily mean that much effective diffusion takes place. If the scale of motion of a pore water parcel during a wave period does not exceed the pore size, it is unlikely that much effective diffusion will occur. Therefore they incorporated the orbit to grain size ratio (Or), given by:

$$Or = \frac{2v}{\omega d_p} e^{-n_w z} \tag{3.24}$$

in which n_w is the wave number, ω the angular frequency of the surface wave, d_p the grain size, z the depth below the seabed and v a velocity amplitude given by:

$$v = \frac{\kappa n_w a}{cosh n_w d} \tag{3.25}$$

in which a is the wave amplitude, κ the quotient of hydraulic conductivity and porosity and d the depth of flow. They found for an extreme case with coarse sand (2 mm) and shallow rough water (d = 5 m), which should favour wave-induced transport, a Peclet number of $Pe = 5.1 \times 10^3$ and Or = 9. The value of Or is probably large enough for the dispersion implied by the large value of the Peclet number to occur. Hereafter they calculated the penetration and flux ratio with:

$$(\frac{\alpha}{\kappa_p})^{\frac{1}{2}} \tag{3.26}$$

where α is the mean dispersion coefficient or the effective diffusivity and κ_p the porous medium molecular diffusivity. In the purely molecular case $\alpha = \kappa_p$. For the example mentioned above, Harrison *et al.* (1983) used $\kappa_p = 1.01*10^{-9} m^2/s$. They found $\alpha = 7.6*10^{-6}$ m^2/s and a penetration and flux ratio of 87. This means that due to the wave-induced motion the effective diffusivity α is increased almost 4 orders of magnitude over its molecular value κ. This shows that in a very favourable environment extra dispersion by waves is possible. Harrison *et al.* (1983) also calculated the dispersion for a shelf area on the east coast of the U.S. (d_p = 0.16 mm, T_w = 7 s, λ_w = 60 m, d = 10 m). They found Pe = 2.5 and Or = 0.32 which already implies that extra diffusivity due to waves is not well developed because Or <1. When we follow the same procedure for waves in the North Sea with medium waves and medium sand (λ_w = 20 m, $d_p = 300 \times 10^{-6}$ m, T_w = 15 s, d = 20 m, n = 0.4, $K = 5 \times 10^{-4}$ m/s and wave amplitude a = 0.3 m) we would get an Orbit number of ≈ 0.09. This shows that also in this case the Orbit number is not large enough for mechanical dispersion or extra diffusivity due to waves to be important. Larger wave amplitudes do not seem to change this fact. The water depth in seas is too large for waves to have a real influence on the bed. It seems that if wave induced diffusion is important it would be in nearshore (shallow), sandy areas.

The fact that extra diffusivity doesn't take place in seas doesn't directly mean that transport of small particles is not taking place. There is no data or information on this subject but possibly the transport of small particles is different under regular, irregular, standing and progressive waves. Underneath regular waves the porewater trajectories are closed and no net transport of water takes place. However, due to a random walk principle (i.e. the way in of water is not the same as the way out) it might very well be possible that when sediment is transported into the bed it stays in the bed till the upper layer of the bed becomes clogged. Underneath irregular waves the porewater trajectories are not closed, which makes the transport of sediment through the bed even easier, assuming that the pressure gradient due to waves on the bed is large enough for circulation cells to develop.

3.6 Transport induced by waves and ripples

Huettel *et al.* (1996) showed that circulation cells developed underneath a rippled bed and that particles can be transported through these cells. Rutgers van der Loeff (1981) and Harrison *et al.* (1983) showed that similar type of circulation cells can develop underneath waves when circumstances are right. A combination of both ripples and waves may therefore also promote the development of circulation cells and transport of particles. There has been done some research on the combined action of bedforms and waves, e.g. Shum (1993), Shum & Sundby (1996) and Huettel & Webster (2001) and the resulting transport of water through the sediment. Shum (1993) found that water can transport organic material and dissolved oxygen inside the bed and return the produced nutrients to the water column by means of the already mentioned mechanism of the subtidal pump. Most researchers have looked at this process in combination with oxygen exchange while the possible transport of particles is ignored as it has never been thought to be of importance to the ecosystem.

Based on an analytical model, Shum (1993) confirmed the presence of net advection which extends to a few ripple heights below the ripple surface over a wide range of wave conditions and sediment characteristics. An example of streamlines induced by waves through ripples with a slope, $S_r = 0{,}1$, and a ratio of thickness of permeable sediment layer to ripple height, $h_s/h_r = 1$, is given in Figure 3.9. It shows the mean wave-induced pore water circula-

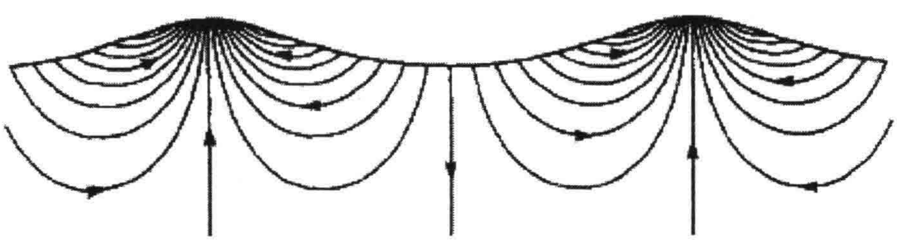

Figure 3.9: Streamlines which present the mean wave-induced pore water circulation under a rippled bed (Shum, 1993; Shum & Sundby, 1996)

tion. The flow into the ripple takes place along almost the whole ripple surface, whereas the flow out of the ripple only occurs at the crest. The magnitude of the flow is higher below the crests than below the troughs close to the top of the sediment layer, and decreases with the distance from the water-sediment interface such that at a depth of 0.4 times the ripple length it is less than 10% of the magnitude immediately below the surface of the sediment layer

(Shum, 1993). It is assumed that the phasing of waves and ripples also influences pore water velocities, thereby causing fluctuations around the mean porewater velocities. According to Shum's (1993) model, the circulation can initiate the transport of solutes in the interstitial water through the sediment. The advective flux of solutes varies along the ripple profile and within the wave period according to the magnitude of the local pore water flow normal to the surface. Hence the concentration at both the top and bottom of the laminar sub-layer just above the bed is likely to vary both temporally and along the length of the ripple (Shum, 1993).

Shum (1993) and Shum & Sundby (1996) examined the soluble oxygen concentration profiles in ripples and the transport of soluble oxygen through them with a two-dimensional model. In this model the interior of the sediment bed was assumed to have constant porosity and permeability, the flow to follow Darcy's law and to be forced by pressure fluctuations at the sediment surface created by the passage of gravity waves. Shum & Sundby (1996) grouped the physical and chemical characteristics of this system into four dimensionless numbers; the ripple slope (S_r), the ratio of the magnitude of velocity in pore water to that immediately above the sediment bed (V_0/u), the Peclet number (Pe) and Damköhler's second number ($D_a = (\frac{\alpha T}{\mu T/L^2})$), which gives an idea about the consumption rate, i.e. in the case of soluble oxygen the amount of oxygen that enters the bed, is used by organisms and processes and therefore does not leave the bed anymore. The soluble oxygen concentration field was found to vary mainly with changes in Pe and D_a. When $Pe \leq 1$, molecular diffusion is the dominant transport process and the concentration field is nearly the same as below a flat bed over the entire range of D_a (Shum, 1993). As the magnitude of advective transport increases (Pe increases), wave-induced circulation brings inflow of high concentration from the overlying water down the ripple trough. The solute concentration then decreases along the trajectory of pore water according to the rate of consumption and finally the pore water exits through the ripple crest at a lower solute concentration. This process can lead to a considerably higher soluble oxygen concentration below a trough than below a crest (Shum, 1993). Following the same reason, when consumption dominates advective and diffusive transport ($D_a >> 1$ and $D_a >> Pe$) the solute concentration decreases much more below the ripple crest than below the trough. On the other hand, when advective transport dominates both the rate of consumption and diffusive transport ($Pe >> 1$ and $Pe >> D_a$), the low consumption rate causes only a slight decrease in the solute concentration of the inflow over its trajectory through the sediment layer. This would lead to a fairly uniform concentration in the top layer of interstitial water away from the ripple crest, with a concentration value close to that of the overlying water. The significance of advective transport of solutes is demonstrated in Figure 3.10 with the variation of vertical concentration profiles with Pe. This figure shows the increase in concentration with depth for increasing Peclet numbers. The curve for a concentration profile underneath a flat bed is also given (line a). This clearly indicates the effect of the combined action of waves and ripples. The flux of solutes across a rippled sediment surface can be substantially higher than that in the absence of wave-induced pore water circulation. The ratio between the flux under wave-ripple combinations and ripples only, increases monotonously with Pe and S_r. Shum (1993) found this ratio to have a maximum value of 4 at Pe = 1000 and S_r = 0.05 and around 5 for S_r = 0.10

Of course the above mentioned is valid on beds where wave effects are significant at the bottom. To determine whether wave effects are important we can use the Keulegan-

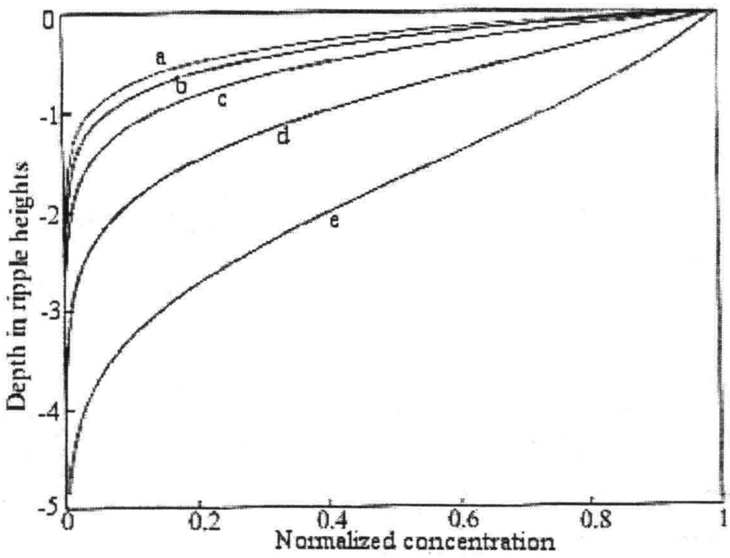

Figure 3.10: Vertical concentration profiles midway between ripple crest and trough for D_a = 1000, S_r = 0.1 and h_s/h_r = 1. Curves b to e correspond to Pe = 32, Pe = 100, Pe = 316 and Pe = 1000, respectively. Curve a is the concentration profile for the corresponding case (D_a = 1000) below a flat bed. The vertical distance is measured from the water-sediment interface. (Shum, 1993)

Carpenter number given by:

$$KC = \frac{u_{or} T_w}{\lambda} \tag{3.27}$$

where λ is the ripple length and u_{or} is the amplitude of the wave induced oscillatory velocity in the water column immediately above a flat bed according to linear potential flow theory,

$$u_{or} = \frac{\pi}{\sinh \mathrm{n_w d}} \frac{\mathrm{H_w}}{\mathrm{T_w}} \tag{3.28}$$

. The KC number is a measure of the strength of waves on the bed. In the North Sea at a depth of 20 meter the value of u_{or} will be small even at large wave heights, which implies that the combination of waves and ripples would not be important. In shallow areas such as near shore areas and intertidal areas, the wave effect can be important. Also, when dealing with long waves or tidal waves the pressure gradients can be strong enough to invoke a flow through the bed, although this would create convection cells at a larger scale than bedforms. The precise impact of a combination of waves and ripples on the development of circulation cells and the possible advective transport of cohesive particles remains a question to be answered.

3.7 Ripple migration

Next to advective transport of cohesive sediment through convection cells, bedform migration can also be a cause of cohesive sediment transport into a sediment bed. Small particles in the water column settle out of suspension and mainly deposit in the troughs and on the lee side of bedforms. During ripple migration, sediment from the upstream face of the ripple is transported over the crest and deposited in the trough. In this way fine sediment in the trough is covered with the coarser material of the ripple itself. When the next ripple passes the sediment layer in the trough is partially eroded again and deposited in the next trough. The same process works with other bedforms. As a result the sediment is mixed, but only within the bedform itself (Figure 3.11).

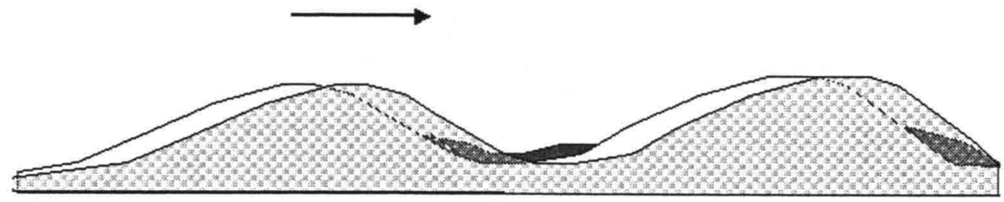

Figure 3.11: Sketch of ripple migration and the mixing of fine sediment (dark colour)

The bedform migration rate depends on factors as stream velocity, wave height, grain size and amount of cohesive sediment and organic material. Ribberink & Al-Salem (1994) report ripple migration rates in laboratory flumes of 0.1 - 0.5 mm/s and Amos *et al.* (1999) report rates of around 0.01 mm/s and 0.1 mm/s at current speeds between 0.1 and 0.3 m/s. The migration velocities of larger bedforms like sandwaves are somewhat smaller, in the order of tens of meters per year (Morelissen *et al.*, 2003).

A possible situation in which ripple migration is capable to mix substantial amounts of fines through the bedforms is after storms and when relic bedforms are present. After a storm, mud is deposited on relict storm ripples or on a more or less flat bed. The amount of deposited mud depends on the amount that was resuspended during the storm itself. As it settles, it forms a thin layer on the bed. In the case of remigration of the bedforms or the forming of ripples (when initial condition is flat bed) and their migration, this deposited layer shall get mixed with the ripple material. There is a maximum amount of fine material that can get mixed through this process as the intrusion of cohesive sediment will decrease the erodibility and thus migration rate of the ripples. It is not precisely known at what concentration of cohesive sediment this would happen but Van Ledden & Van Kesteren (2001) describe that at a clay percentage of 5% the properties of a bed change from non-cohesive to cohesive and the erodibility decreases significantly. It is quite probable that this amount is almost never reached due to the occurrence of storms and the resuspension of the fine sediment.

The process of bedform migration probably causes mixing of cohesive sediment through the bedforms themselves but not through the whole sediment bed. However, after the fine sediment is captured within the bedforms it is available for further transport into the bed, possibly by advective flow as mentioned in the previous sections.

3.8 Conclusion

In permeable sediments interstitial water motions can be effective transport mechanisms. In this chapter it was investigated whether cohesive sediment could be transported from the water column into a sediment bed. The hypothesis was that mechanisms as pressure gradients over bedforms, pressure gradients underneath waves, a combination of ripples and waves, and ripple migration, drive interstitial flow and thus induce advective flow. There is no literature on the subject of cohesive sediment transport through sediment beds but there is on transport of water and solubles. It was shown that circulation patterns exist in and underneath bedforms with a uniform flow and similar circulation patterns develop underneath waves. The flows underneath bedforms where shown to be advective, i.e. small particles could be transported along. Underneath waves the circulation patterns were found to be closed, which implies no net transport of water was taking place. This should not necessarily be the case for irregular waves, but no data on this was found. Furthermore, underneath waves the effective diffusivity did not exceed molecular diffusivity, even in the cases that where expected to favour wave induced transport. This implies wave action alone is probably not a strong advective transporter. Still, it should be noted that although the net transport of water is zero, possible transport of particles needn't be zero due to the different pathways of fluid entering the bed and fluid leaving the bed. The combined action of waves and bedforms in theory seems to be a better mechanisms that invokes advective transport, especially in shallow waters. Regrettably, no experimental data on particle transport by this mechanism is available.

The migration of ripples can cause mixing of sediment from the water column into the bed. However, this mixing occurs in the active top layer only and the imported sediment is not transported to deeper layers. Additional mechanisms such as pressure gradients due to ripples and waves might be able to transport the imported sediment from the layer with bedforms to the more inactive sediment bed.

The amount of cohesive sediment to be imported in a bed, in both cases of sediment transport due to pressure gradients as mixing due to ripple migration, is probably limited. The intrusion of cohesive sediment in a permeable bed can lead to clogging and a strong reduction in permeability. How quick the permeability decreases and the entrance of new particles is prohibited depends on the type of clay mineral, the sand grain size, void ratio and probably other characteristics and is not known yet.

In the North Sea around the 20 m depth contour only pressure gradients over bedforms seems to be a possible mechanism of cohesive sediment transport into the sand bed. Ripples, dunes and sandwaves are present in many areas in the North sea, also at these depths. Waves are also present but probably do not have much influence anymore at the bed level.

Chapter 4

Bioturbation

Benthic organisms like worms and algae are known to have a stabilising and/or destabilising effect on sediment beds with their faecal pellets, polysaccharides and reworking (Cadée, 2001; Grant *et al.*, 1982; Paterson *et al.*, 1990). Other effects of benthic organisms are vertical displacement and sorting of sediment and the traces animals leave by their motions. Benthic animals move themselves by locomotion. This locomotion causes traces on the sea floor. Different species have different modes of locomotion (e.g. peristaltic movement, glide-crawling, bolting, pacing, drilling and chimney climbing) (Schäfer, 1962). Due to their burrowing and feeding activities and their locomotion, the sediment in the upper layer of the bed gets mixed. It is difficult to determine the amount of mixing that occurs due to bioturbation. However, it is probable that in areas with a large amount of benthic fauna the mixing by bioturbation is larger than mixing by advective flow induced by waves and ripples. On the other hand, in areas that favour advective flow through sediment (high energetic environments) the sediment transport is often too high for many benthic organisms to live, so bioturbation is not abundant (Cadée, 2001).

Lee II & Swartz (1980) did an extensive literature review on sediment reworking rates. They proposed a classification of benthic invertebrates in relation to bioturbation processes. The organisms were grouped according to three dichotomises:

- epifaunal/infaunal: Epifaunal organisms are species that feed on the surface and occasionally burrow into the sediment (e.g. flatfish), whereas infauna feed in the sediment (e.g. worms)

- mobile/stationery: The mobile fauna are separated into vagile species and excavators. Vagile fauna burrow through the sediment by displacement of particles, creating temporal gaps or burrows (e.g. shrimp) and excavators move through the sediment by digging semipermanent or permanent burrows (e.g. some crab species)(Lee II & Swartz, 1980). Stationery species stay more or less at the same place (e.g. some crab species)

- deposit/suspension feeders: A large difference between deposit feeders (e.g. *macoma baltica*) and suspension or filter feeders (e.g. worms (*lanicce*), cockle, mussel, razorclam) is the fact that the faecal pellet production by deposit feeders changes the sediment characteristics and microbial activity without adding new material to the sediment. Filter feeders filter sediment out of the water column and thus add new material to the sediment bed (Lee II & Swartz, 1980).

In this way 12 guilds of organisms are recognised. The main classification is on deposit and suspension feeders, whereafter a subdivision can be made into epifaunal/infaunal and mobile/stationery.

Deposit-feeding animals often mix the upper layer of the bed intensively. Both particles on and in the bed are ingested and later deposited as faeces. For these species it doesn't matter whether a small layer of mud lays on a sand bed or whether the mud forms a layer in the bed or is mixed in the bed. Deposit feeders are always able to detect and consume the organic material in the mud. However, specific species do have preferences for material on or in the bed and also for larger or smaller mud particles. Conveyor-belt species (head down deposit feeders) and funnel-feeders, who are part of the deposit feeders have preferences for particular small particle sizes, leaving the very coarse sand fraction and larger particles concentrated in layers and bringing the fine sediment towards the surface as faecal pellets, thus causing segregation (Lee II & Swartz, 1980; Meadows, 1991).

In Table 4 the classification of Lee II & Swartz (1980) is presented. The table shows that most species feed and burrow in the upper centimetres of the bed, except the conveyor-belt species that have a feeding zone till 30 cm deep. The depth of bioturbation is thought to depend on the species and the environmental properties. Deposit feeders are thought to be the main bioturbators, transporting sediment in a vertical direction. The importance of large herbivores and predators however should also be mentioned. Examples are crater-like holes of 4-5 metre wide and 2-3 metre deep, created by large tile-fish and communal burrow systems of crustaceans, formed in a horizontal plane 3-5 metre below the surface with long shafts towards the surface. Both can be found on the ocean floor (Cadée, 2001) and in both cases a lot of sediment is mixed and replaced. For the different guilds of bioturbators Lee II & Swartz (1980) reviewed the rate and depth of particle transport and the differences in transport among guilds as shown in Table 4.2. This Table shows that reworking rates and depths differ extensively for different species. However most reworking seems to take place in the upper 10 cm with some exceptions of 20 and even 76 cm.

Where Cadée (2001) and Lee II & Swartz (1980) give different values of bioturbation rates and bioturbation depths for benthic animals, Boudreau (1998) tried to determine a mean mixed depth of organic material in sediments. He found a mean mixed depth of 9.8 ± 4.5 cm caused by bioturbation and mechanical dispersion. This value, found as a worldwide mean for the mixed depth, however, is only applicable for decaying material (organic material). At a depth of 9.8 cm the material would have been so long on its way that decomposition would have taken place.

Classification (guilds)	Guild abbreviation	Representative Taxa	Type	Feeding zone	Particle Reworking from:			Biodeposition	Pelletization	Tubes	Fluid transport
					Feeding	Burrowing	Excavation				
I Suspension Feeders											
IA Filter Feeders	FF										
Mobile infaunal	MIFF	*Mya, Mercenaria*	Bivalvia (shellfish)	Bottom few cm of water column	0	+	0	+	+	0	++
Stationary infaunal	SIFF	***sabellids, phoronids***	Polychaeta (worm), Phoronidae (worm)	Bottom few cm of water column	0	( )	0	+	+	+	+
Stationary epifaunal	SEFF	***Mytilus, Crassostrea***	Bivalvia (mussel, oyster)	Bottom to several metres into water column	0	0	0	++	++	0	0
IB Raptorial feeders	RF	***cerianthids***, corals	Anthozoa (seeanenomy)	Bottom to several metres into water column	0	0	0	+	0	0(+)	0(+)
II Deposit Feeders											
IIA Surface deposit feeder	SDF										
Mobile infaunal SDF-vagile	MISDF-V	***Tellina, Macoma, cirratulids, nereids***	Bivalvia, Polychaeta	0-1 cm of sediment	+	=	0	0(+)	+	0(+)	+
Mobile infaunal SDF-excavator	MISDF-E	*Uca*	crab	0-1 cm of sediment	++	0	++	0	++	0	++
Stationary infaunal SDF	SISDF	***spionids, onuphids, Amphitrite***	Polychaeta	0-1 cm of sediment	+	0	0	0(+)	+	+	+
Mobile epifaunal SDF	MESDF	***Hydrobia, holothurians***	Gastropoda (snail), seecucumber	0-3? cm of sediment	+(++)	+	0	0	++	0	0
IIB Subsurface Deposit-feeder	SSDF										
Mobile infaunal SSDF-vagile	MISSDF-V	***Yoldia, Nucula, Scoloplos, Nephtys***	Bivalvia, Polychaeta	0-≥20 cm of sediment	+	++	0	0	++	0	++
Mobile infaunal SSDF-excavator	MISSDF-E	***Callianassa, Upogebia***	Crab, lobster	0->1 m of sediment	++	0	++	0(+)	+(++)	0	++
Funnel Feeders	FUN	***Leptosynapta, Arenicola***	seecucumber, Polychaeta	Predominantly upper 0-1 cm, down 10 cm	++	+	0	0	0	0	++
Conveyor-belt species (=stationary SSDF)	CB	***Pectinaria, Clymenella***	Polychaeta	Deeper sediment 3-30 cm	+(++)	0	0	0	+?	+	+(++)

Table 4.1: Feeding mobility classification and sediment modifying processes for each guild, after Lee II & Swartz (1980). 0 indicates process absent or normally of minor importance in modifying sediment, + indicates process present in at least some species and moderately to highly significant in modifying sediment, ++ indicates process present in at least some species and of major significance in modifying sediment, ( )indicates occasional importance or importance for subset of species within guild. Boldfaced types are species present in the North Sea and/or Wadden Sea.

Species	Guild	Individual Reworking Rate (mg/ind/day)	Total Reworking Rate (g/m^2/yr or as specified)	Depth of Reworking	Comments	Source
Annelids (worms)						
Abarenicola pacifica	FUN	10900			Average high and low tide, 1-3.5 g/ind.	O
Amphitrite ornata	SISDF	5100		Surface	17 °	O
Clymenella torqquata	CB	1650	73,062	20 cm	annual rate adjusted for Temp	C
Pectinaria gouldii	CB	6000	6,000	6 cm	All sediment, annual rate adjusted for Temp	O
Pectinaria gouldii	CB	2000			just faeces	O
Scoloplos robustus	MISSDF-V	99	1212-10742	2-13 cm	Ingestion, April-October	C
Scoloplos robustus	MISSDF-V	512	6237-56133		Burrowing, April-October	C
Freshwater oligochaetes, 3 species	CB, MISSDF-V	1-250	18-230 kg/year	4.6 cm	Just faeces, annual rate adjusted for Temp	O
Bivalves (shellfish)						
Macoma balthica	MISDF-V	1.7	415	Surface	Just Faeces, 10 °C, annual rate not adjusted for T	O
		370	90500		Faeces and pseudofaeces, 10 °C	O
Macoma balthica	MISDF-V	520		Surface	Faeces and pseudofaeces, 15 °C	O
Yoldia linatula	MISSDF-V	282	2262	2 cm	Faeces and pseudofaeces	O
Gastropods (snails)						
Hydrobia minuta	MESDF	1	26-8871	2 mm	Annual rate not adjusted for Temp	O
Crustaceans						
Callianassa californiensis	MISSDF-E	33000-82500		<76 cm	Amount deposited per entrance, excavation and feeding?	C
Callianassa major	MISDFF-E	3472	126-633 kg/year		Amount deposited per entrance, just faeces	O
Paraphoxus spinosus	MISDF-V	8910	544-2159 kg/year	0-1 cm	Burrowing	C
Echinoderms						
Leptosynapta tenuis	FUN	10400-18430		0.5-10 cm	Faeces and below surface reworking	O

Table 4.2: Individual particle reworking rates, after Lee II & Swartz (1980). O=original data C=calculated from data

Bioturbation traces of benthic animals are found in both sandy and muddy environments. The amount of bioturbation is thought to depend on mud content, amount of oxygen and energy level. With aerobic environments having the highest amount of bioturbation (Johnson & Baldwin, 1996). Cadée (2001) and Schäfer (1962) state the importance of hydrodynamic energy and the clear correlation between the amount of energy and the amount of reworking. Bioturbation is mainly active at low and intermediate energy levels where walking, crawling and burrowing animals and growing plants disturb the sediment bed. In high energetic environments bioturbators are not as abundant as in environments with less energy and as a result there is less bioturbation.

Chapter 5

Anthropogenic influences

Fishing, dredging and other human activities take place in the North Sea. Fishing is probably the most extensive, occurring throughout the North Sea, while dredging only takes place at specific locations. During these activities fine sediment can become mobilised and their properties can be altered.

In the case of fishing the impact merely depends on the method applied. Here we shall discuss only two methods, beam trawls and scallop dredges; both demersal trawls. Demersal trawls have two major effects on the environment. First, the net removes, destroys and damages a number of organisms per unit area. Secondly, the trawl gear (wires, doors, sweeps and net) disturbs the sediment surface (Smith *et al.*, 2000). The latter effect can have a number of secondary sub-effects like mixing of the sediment surface, oxygenation of deeper sediment layers, the release of buried organic matter and nutrients, but also destruction and removal of habitats. Smith *et al.* (2000) conducted research on the effects of trawling on sediment chemistry and macrofaunal community structure. They found that large marks were left by the trawlers, especially the trawl doors. The lifetime of these marks strongly depended upon grain size, current strength, and biological activity, but a lifetime of 5 years was not extraordinary. An example of the tracks left by fishers is given in Figure 5.1. In addition, different parts of the trawling gear have a different impact on and especially a different penetration depth of the bed. Churchill (1989) measured a penetration depth of the trawling doors from a few cm up to 30 cm. In contrast, the net and rope are designed to only cut through the upper centimetre of the sediment bed (Smith *et al.*, 2000).

Either way, the passage of the trawl can be responsible for resuspension, layering and mixing of the sediment. Layering occurs when due to resuspension of the sediment and the succeeding segregation during settling a layered bed is produced with a thin layer of fines on top of a sandy bed. Mixing can occur when a layer of fine material is already present on the bed whereafter the passage of a trawl can mix the top layer with the underlying sand.

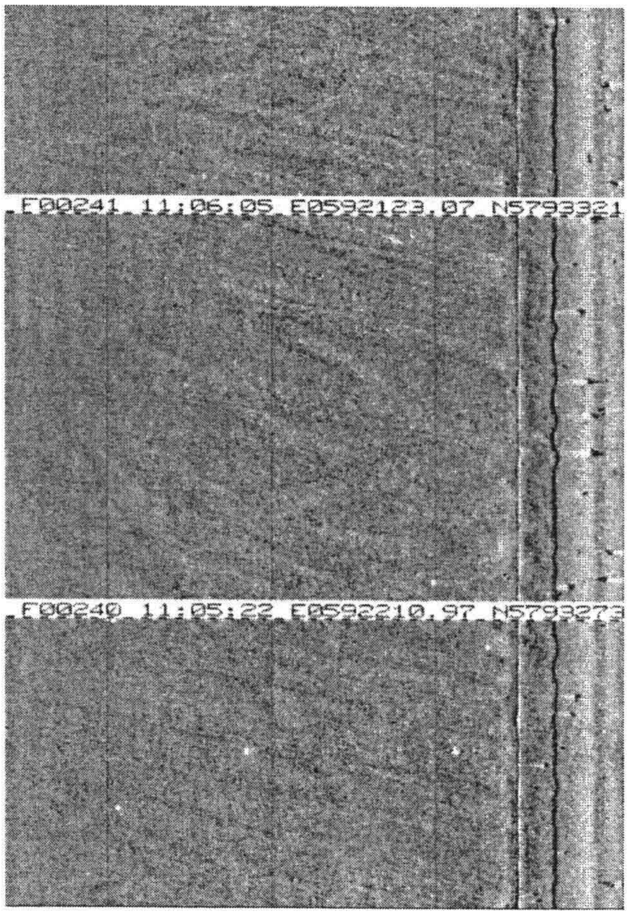

Figure 5.1: Trawling tracks on the North Sea bed. Horizontal scale 100 m between lines, vertical scale 25 m between lines.(Pers. comm. M. Kleinhans)

Chapter 6

Conclusions and recommendations

The concentration of suspended matter in the North Sea may increase during large scale sand extractions and land reclamation. Part of this suspended matter will eventually settle on the sea bed. The impact of such additional sedimentation of mostly fine sediment has never been studied. Also in natural environments, where increased sedimentation of cohesive sediment can take place, the fate of the settled material and the consequences for the bed (e.g. erodibility, permeability, grain size distribution, bedform development) are poorly known. A clear understanding of the interaction between this fine cohesive sediment that settles on the bed and the autochthon sediment (sand) in natural environments is needed before conclusions can be drawn on the impact of large scale dredging in the North Sea.

In this literature review we concluded that mixing of the setting sediment with the autochthon sediment is probable to take place. Several processes are described by which fine, cohesive sediment might infiltrate into the bed. These processes are:

- pressure gradients over bedforms
- pressure gradients underneath waves
- pressure gradients due to waves and ripples
- ripple migration
- bioturbation
- anthropogenic influences

Circulation cells within the bed are shown to develop due to pressure gradients over bedforms. Furthermore experiments show that in these circulation cells advective transport of solubles and even small particles takes place. Whether transport of cohesive particles takes place has however never been studied.

Circulation cells in the bed also develop underneath waves. Due to the periodic motion of the waves the net transport of water into the bed is zero. However, as the pathway of the intruding water is not the same as the outflowing water, solubles and small particles can get stuck on their way through the sediment. Furthermore, the development of closed circulation cells was only shown to occur underneath regular standing waves. Not much is known of the development of these circulation cells underneath propagating and/or irregular waves. The latter case may favour advective transport through the sediment bed but this should first be tested with experiments.

The combination of waves and bedforms, as present in many parts of the North Sea, appears to yield larger advective transport rates than waves only. However, the transport rate is not known. Neither is it known whether cohesive sediment can infiltrate the bed by this mechanism.

In the case of migrating ripples, fine sediment in the ripple troughs can get mixed with the bed sediment. This mixing can happen quite fast, at the same rate as the migration velocity of the ripples and dunes itself. However, due to ongoing reworking and migration a lot of fine sediment gets resuspended again. Furthermore, the more mixing of cohesive sediment into the sand bed occurs, the more impermeable the bed gets and the less probable the migration or development of bedforms becomes. In the North Sea this may lead to a flat or relic rippled bed in which circulation cells, either underneath waves or ripples, do not form due to the almost impermeability of the sediment bed. At which amount of cohesive sediment in the bed this might happen is not known.

The influence of bioturbation on mixing showed to be bipartite: bioturbation can both mix and sort the sediment, although mixing prevails. The amount and rate of reworking for many species in the North Sea is more or less known. Information on the quantity and seasonality of presence of different species is however not known. This makes it difficult to estimate the influence of bioturbation on the mixing process.

Finally, anthropogenic influences, like fishing, can disturb and alter the sediment bed in such a way that neither advective transport through ripples nor ripple migration and bioturbation takes place as the bed is flattened and deprived of organisms by the trawling system. This might be the case in large parts of the North Sea, where extensive fishing takes place. Fishing itself (especially the trawling gear) can on the other hand mix or relayer sediment in the bed as the upper part of the sea bed is agitated.

This literature review has shown that many questions still remain in the field of sea-bed interaction. Neither the possible transport of cohesive sediment through convection cells, nor the consequences for the bed characteristics are understood. Also the importance of bioturbation, ripple migration and fishing on the mixing of sediment is not clear. The main questions to be addressed in order to understand the importance of advective flow, bioturbation, ripple migration and fishing on mixing are:

- The pressure gradients around obstacles in the North Sea and the quantity and timescales of advective flow through these obstacles, such as around ripples and dunes, but also around sandwaves, which are typical for certain areas in the North Sea.

- Do the pressure gradients around obstacles and underneath waves cause advective transport and if so, where does the flow infiltrate and where does it leave the bed?

- What is the amount of fine material that infiltrates in a sand bed for different D_{50} sand?

- How does the permeability change with increasing concentration of fines in the bed? Does clogging play a role?

- Does the infiltration of fines in a sand bed change the behaviour (e.g. erodibility) of the sand bed?

- In the case of standing waves: does the advective flow bring and keep fines in the sediment bed despite the fact that the flow is periodic and the mean flow is zero?

- In the case of progressing waves: do these waves cause circulation cells with an advective flow and can this flow transport cohesive sediment?
- To what extent do different processes as bioturbation, advective flow, ripple migration and fisheries contribute to the mixing of fines into a sand bed? For instance, is advective flow still important when extensive bioturbation is present and vice versa.
- What are the rates of mixing due to bioturbation in the North Sea when seasonality and species abundance is taken into account?
- What are the rates of mixing due to fishing in the North Sea?

These question can be addressed by first doing some simple experiments. Thereafter verification can take place by doing laboratory experiments in a flume and/or a wave tank. Simple experiments for example can be:

- Measure the permeability for a typical North Sea sand bed with various amounts of fines in it.
- Create an underpressure in a sand layer and measure whether dyed water infiltrates. After that do the same test with several sizes of dyed fines instead of dyed water and measure the filtration rates.
- Continue these tests with oscillating underpressures and overpressures in order to mimic the periodic behaviour due to waves. With this test also the pathway of the particles can be studied.
- Measure the pressure distribution around permeable obstacles.
- Determine the amount of advective flow on a solitary mound with a flow over it. Injection of dye in the mount or the presence of coloured fines (dyed or fluorized) in the water can show the presence and propagation velocity of advective flow in a permeable object.

Acknowledgements

This work is funded by the DIOC-Water Project (Transient processes in Hydraulic Engineering and Geohydrology) of Delft University of Technology. The writer would like to express her appreciation to dr. ir. Han Winterwerp, prof. dr. ir. Marcel Stive, and ir. Walther van Kesteren for their valuable advice and suggestions.

List of symbols

Roman symbols

A	Area
C_p	Pressure coefficient
c_d	Drag coefficient
D	Diameter of cylinder
D_a	Damköhler's second number
D^o	Molecular diffusion coefficient
D_t	Turbulent diffusion coefficient
$D_{t,0}$	Apparent diffusion coefficient
d	Depth of flow
d_p	Mean particle diameter
g	Acceleration of gravity
H	Energy head
H_w	Wave height
h	Piezometric level
h_r	Height of element
KC	Keulegan-Carpenter number
K	Hydraulic conductivity
k	Permeability
L	Length of element
L_1	Length upstream face of element
N	Shape factor
n	Porosity
n_w	Wave number
Or	Orbit to grain size ratio
P	Pressure
P_d	Pressure downstream of element
P_u	Pressure upstream of element
Pe	Peclet number
R	Radius of cylinder
Re	Reynolds number
r	Radius
S	Slope of water surface
S_r	Ripple slope
s	Distance along streamline

T_w	Wave period
t	Time
U	Unperturbed flow velocity
U_c	Central average velocity
u	Velocity
u_r	Velocity at radius r
u_s	Velocity along streamline
$\vec{u}$	Local velocity
V_0	Porewater velocity
x_L	Distance along upstream face of element
z	Height
z_b	Depth below seabed
$\|_w$	Due to ripples
$\|_h$	Due to hydraulic gradient

Greek symbols

α	Mean dispersion coefficient
κ	Porous medium molecular diffusivity
λ	Ripple length
λ_w	Wave length
μ	Porewater viscosity
ν	Viscosity
ρ	Density
θ	Angle in radians
Φ	Volumetric concentration of cohesive particles
ϕ	Velocity potential
ϕ_a	Angle in x-z plane
ψ	Streamline
ω	Angular frequency of surface wave

References

AMOS, C.L., BOWEN, A.J., HUNTLEY, D.A., JUDGE, J.T., & LI, M.Z. 1999. Ripple migration and sand transport under quasi-orthogonal combined flows on the Scotian shelf. *Journal of Coastal Research*, **15**(1), 1–14.

BATTJES, J.A. 1991. *Vloeistofmechanica*. Lecture Notes.

BATTJES, J.A. 1999. *Vloeistofmechanica*. Lecture Notes.

BOUDREAU, B.P. 1998. Mean mixed depth of sediments: The wherefore and the why. *Limnology Oceanography*, **43**(3), 524–526.

CADÉE, G.C. 2001. Sediment dynamics by bioturbating organisms. *In:* REISE, K. (ed), *Ecological comparison of sedimentary shores*, vol. 151. Verlag Berlin Heidelberg.

CHURCHILL, J.H. 1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. *Continental Shelf Research*, **9**, 841–864.

DANKERS, P.J.T. 2002. *The behaviour of fines released due to dredging: A literature review*. Tech. rept. Delft University of Technology.

DOMENICO, P.A., & SCHWARTZ, F.W. 1990. *Physical and Chemical Hydrogeology*. John Wiley & Sons, Inc.

GRANT, W.D., BOYER, L.F., & SANFORD, L.P. 1982. The effects of bioturbation on the initiation of motion of intertidal sands. *Journal of Marine Research*, **40**(3), 659–677.

HARRISON, W.D., MUSGRAVE, D., & REEBURGH, W.S. 1983. A wave-induced transport process in Marine Sediments. *Journal of Geophysical Research*, **88**(C12), 7617–7622.

HUETTEL, M., & WEBSTER, I.T. 2001. *Porewater flow in permeable sediments*. Oxford University Press. Chap. 7, pages 144–179.

HUETTEL, M., ZIEBIS, W., & FORSTER, S. 1996. Flow-induced uptake of particulate matter in permeable sediments. *Limnology and Oceanography*, **41**(2), 309–322.

JOHNSON, H.D., & BALDWIN, C.T. 1996. *Shallow clastic seas*. 3 edn. Blackwell Science. Chap. 7, pages 232–280.

LAMBE, T.W., & WHITMAN, R.V. 1979. *Soil Mechanics, SI Version*. Series in Soil Engineering. John Wiley & Sons, New York.

LEE II, H., & SWARTZ, R.C. 1980. *Biological Processes Affecting the Distribution of Pollutants in Marine Sediments. Part II. Biodeposition and Bioturbation.* Vol. 2. Ann Arbor Science. Chap. 29, pages 555–606.

MEADOWS, A. 1991. Burrows and burrowing animals: an overview. *Chap. 1, pages 1–13 of:* MEADOWS, P.S., & MEADOWS, A. (eds), *The environmental impact of burrowing animals and animal burrows.* Clarendon Press.

MERCKELBACH, L. 2000. *Consolidation and strength evolution of soft mud layers.* Ph.D. thesis, Delft University of Technology.

MORELISSEN, R., HULSCHER, S.J.M.H., KNAAPEN, M.A.F., NÉMETH, A.A., & BIJKER, R. 2003. Mathematical modelling of sand wave migration and the interaction with pipelines. *Coastal Engineering*, **48**, 197–209.

MUTLY SUMER, B., & FREDSØE, J. 1997. *Hydrodynamics around cylindrical structures.* Advanced Series on Ocean Engineering, vol. 12. World Scientific.

PATERSON, D.M., CRAWFORD, R.M., & LITTLE, C. 1990. Subaerial exposure and changes in the stability of intertidal estuarine sediments. *Estuarine, Coastal and Shelf science*, **30**, 541–556.

RIBBERINK, J.S., & AL-SALEM, A.A. 1994. Sediment transport in oscillatory boundary layers in cases of rippled beds and sheet flow. *Journal of Geophysical Research*, **99**(C6), 12,707–12,727.

RIEDL, R., HUANG, N., & MACHAN, R. 1972. The subtidal pump: a mechanism of intertidal water exchange by wave action. *Marine Biology*, **13**, 210–221.

RUTGERS VAN DER LOEFF, M.M. 1981. Wave effects on sediment water exchange in a submerged sand bed. *Netherlands Journal of Sea Research*, **15**, 100–112.

RUTHERFORD, J.C., BOYLE, J.D., ELLIOTT, A.H., HATHERELL, T.V.J., & CHIU, T.W. 1995. Modelling benthic oxygen uptake by pumping. *Journal of Environmental Engineering*, **121**(1), 84–95.

SCHäFER. 1962. *Aktuo-paläontologie nach Studien in der Nordsee.* Oliver and Boyd. Translated from German as: Ecology and Palaeoecology of marine environments (1972), G.Y. Craig (ed.).

SCHLICHTING, H. 1968. *Boundary-Layer Theory.* 6 edn. Series in Mechanical Engineering. McGraw-Hill.

SHUM, K.T. 1993. The effects of wave-induced pore water circulation on the transport of ractive solutes below a rippled sediment bed. *Journal of Geophysical Research*, **98**, 10289–10301.

SHUM, K.T., & SUNDBY, B. 1996. Organic matter processing in continental shelf sediment - the subtidal pump revisited. *Marine Chemistry*, **53**, 81–87.

SMITH, C.J., PAPADOPOULOU, K.N., & DILIBERTO, S. 2000. Impact of otter trawling on an eastern Mediterranean commercial trawl fishing ground. *ICES Journal of Marine Science*, **57**, 1340–1351.

SUIJLEN, J.M., & DUIN, R.N.M. 2001. *Variability of near-surface total suspended matter concentrations in the Dutch coastal zone of the North Sea*. Tech. rept. 2001.150x. RIKZ.

TANIGUCHI, S., & SAKAMOTO, H. 1982. Time-averaged aerodynamic forces acting on a hemisphere immersed in a turbulent boundary. *Journal of Wind Engineering and Industrial Aerodynamics*, **9**, 257–273.

THIBODEAUX, L.J., & BOYLE, J.D. 1987. Bedform-generated convective transport in bottom sediment. *Nature*, **325**, 341–343.

VAN LEDDEN, M., & VAN KESTEREN, W. 2001. *Erosion model for sand-mud mixtures*. Delft University of Technology.

VITTAL, N., RANGA RAJU, K.G., & GARDE, R.J. 1977. Resistance of two dimensional triangular roughness. *Journal of Hydraulic Research*, **15**(1), 19–36.

WEBB, J.E., & THEODOR, J.L. 1972. Wave-induced circulation in submerged sands. *Journal Marine Biology Association, U.K.*, **52**, 903–914.