J. C. Winterwerp
Senior Scientist, WL | delft hydraulics,
Delft, the Netherlands and Associate
Professor, Delft University of
Technology, the Netherlands

Z. B. Wang
Senior Scientist, WL | delft hydraulics,
Delft, the Netherlands and Assistant
Professor, Delft University of
Technology, the Netherlands

J. A.Th. M. van Kester
Senior Scientist, WL | delft
hydraulics, Delft, the
Netherlands

J. F. Verweij
Project Leader, HAM
Dredging and Marine
Contractors, the
Netherlands

Far-field impact of water injection dredging in the Crouch River

J. C. Winterwerp, Z. B. Wang, J. A. Th. M. van Kester and J. F. Verweij

Water injection dredging (WID) is a dredging technique by which the sediment to be removed is fluidised through low-pressure injection of water into the bed. Upon fluidisation, the mud flows as a density current away from the dredging site. In this paper the far-field effects of WID are evaluated—that is, the large-scale dispersion and deposition patterns of the mobilised sediments are determined. This is done with numerical simulations using a two-layered fluid mud model, which takes account of the effects of supercritical fluid mud flow, and for all mud exchange processes in the vertical direction. This model is applied to simulate a dredging work carried out in the River Crouch, UK. The agreement of the numerical results with observed patterns of dispersion and deposition is satisfactory. Next it is shown how this model can be used to evaluate alternative dredging strategies. With respect to the WID operations in the River Crouch, it is concluded that the far-field effects of the work are small.

NOTATION

c	sediment concentration by mass in upper layer
c_m	sediment concentration by mass in fluid mud layer
C_s	coefficient in entrainment model
C_σ	coefficient in entrainment model
D	horizontal dispersion coefficient
D_m	deposition from upper layer: $D_m = W_s c (1 - \tau_{Z_m} / \tau_d) S (1 - \tau_{Z_m} / \tau_d)$
E_b	erosion consolidated bed, Partheniades formula: $E_b = M (\tau_{Z_b} / \tau_e - 1) S (\tau_{Z_b} / \tau_e - 1)$
E_m	entrainment parameter, see main text equation (1)
ϵ_{ijk}	permutator: $\epsilon = 1 / -1$ for cyclical/anti-cyclical i, j, k , otherwise $\epsilon = 0$
f	Coriolis parameter
g	gravity
h	thickness of upper layer ($\approx$ water depth)
M	erosion parameter
S	switch function: $S(x) = x$ for $x > 0$
t	time
u	velocity of upper layer
u_*	shear velocity of main flow
$u_{*,m}$	shear velocity at water–mud interface: $u_{*,m}^2 = \lambda (u - u_m)^2$
$u_{*,s}$	stirring term: $u_{*,s}^3 = u_*^3 + u_{*,m}^3$
u_m	velocity of fluid mud layer
V_c	consolidation velocity

W_s	settling velocity
x	longitudinal coordinate
Z_b	elevation of consolidated bed with respect to reference level
Z_m	elevation of water–mud interface with respect to reference level
Z_s	elevation of water surface with respect to reference level
$\Delta\rho$	density difference over water–mud interface
δ	thickness fluid mud layer
λ	friction coefficient
ν	kinematic viscosity
ρ	fluid density of upper layer (taking into account the effect of salinity)
ρ_m	bulk density of fluid mud layer
τ	shear stress
τ_b	bed shear stress
τ_B	Bingham strength
τ_d	critical shear stress for deposition
τ_e	critical shear stress for erosion
τ_Z	shear stress at level Z (i.e. water surface, interface and base of mud layer)

1. INTRODUCTION

Harbour authorities all over the world have to maintain their harbour basins and navigation channels through frequent dredging operations. Various dredging techniques to safeguard navigation have been developed in the past. A fairly recent technique is water injection dredging (WID), which consists of low-pressure injection of large volumes of water into the bed. As a result, the bed is fluidised and the sediment to be removed is transported in the form of a density current from the dredging site. A sketch of this technique is presented in Fig. 1. The transport paths, augmented turbidity and fate of the mobilised sediment determine whether the cost-effective WID-technique is feasible from an environmental point of view.

This paper deals with the far-field effects of WID and discusses the large-scale dispersion and deposition patterns of the mobilised mud. This is done by a numerical modelling study, simulating WID activities in the River Crouch, UK. The numerical model is compared with the results of *in situ* tracer experiments. Next, the model is used to compare various alternative dredging scenarios.

A full-scale WID experiment was carried out in the Haringvliet,¹ which is one of the closed branches of the Rhine-Meuse delta in the Netherlands. The site is characterised by a depth of about 10 m and virtually stagnant flow conditions. These experiments revealed the generation of a 0.5–0.8 m thick fluid mud layer with a concentration of 50–100 g/l, flowing at a velocity of about 0.2–0.3 m/s. Above this layer, virtually no sediment is found in the water column. Hence this WID experiment generated a distinct two-layer system.

Also theoretical studies by Kranenburg and Winterwerp² showed that subaqueous fluid mud occurrences can be treated as two-layered systems. The transport and fate of the sediments, mobilised by WID, is therefore modelled with a two-layer model (2L FLUID MUD MODEL). This model is described in the next section of this paper.

In the literature several two-layer (2L) models are presented; those describing the behaviour of saline–freshwater systems are best known. Hodgins *et al.*³ presented a 2L model with two horizontal directions (2D/2L) including interfacial shear, but without interfacial mixing. This model was deployed to simulate the salt water intrusion into the Fraser River, Canada. Kawahara *et al.*⁴ developed a similar 2D/2L model, but included interfacial mixing as well. Their model was used to study the impact of a harbour extension on the salinity distribution in the Shinano River, Japan. Brandt *et al.*⁵ developed a 1D/2L model with Boussinesq terms and interfacial shear, dedicated to simulate internal wave propagation. This model was used to study the internal flow in the Strait of Gibraltar. Another 2D/2L model was developed by Heathershaw *et al.*⁶ to simulate the internal tide in temperature-stratified flows on the shelf break in the Celtic Sea.

A few models have been developed to simulate the behaviour of turbidity currents. These studies focus on the front of these turbidity currents, and shear and interfacial mixing effects are omitted. Bonnecaze *et al.*⁷ developed a 1D/2L model, including gravity and advection effects, and compared their results with laboratory experiments. Moodie *et al.*⁸ developed a 2D/2L model and carried out a numerical study concerning the effect of deposition on the evolution of a turbidity current.

All these models have in common that the dynamics of both layers is coupled, but exchange of mass between the two layers is omitted in general. This latter effect was included in the

2D/2L model for fluid mud developed by Odd and Cooper,⁹ which was applied to study the transport and fate of natural fluid mud occurrences in the Severn estuary, UK. The present authors use this model concept as a basis for their development. However, some features are added to simulate the transport of WID-induced fluid mud. Moreover, the entrainment description developed by Kranenburg and Winterwerp² is implemented.

The next sections describe the relevant physical processes governing the transport and fate of WID-induced fluid mud and the set-up of the 2L FLUID MUD MODEL. The authors pay special attention to the modelling of supercritical fluid mud flow, as this is a new and important feature. Next, the model is validated qualitatively against *in situ* tracer experiments during a WID-work in the Crouch River, UK, and finally the model is used to assess the far-field effects of alternative dredging strategies.

2. RELEVANT PHYSICAL PROCESSES

The fluid mud, generated by WID is a dense suspension with a typical sediment concentration of the order of 50–100 g/l, a viscosity of 10 to 100 times that of water and a shear thinning, thixotropic behaviour. The latter implies that, when left alone, it can develop a certain strength. This strength, however, can be broken down again when the mud becomes subject to shear. Because its density is larger than that of water, fluid mud lies on or flows over the bed of a river or sea, underneath a layer of fresh or saline water; the latter still may contain suspended sediment.

Because of the large gradients in fluid properties over the water–fluid mud interface, the water column and fluid mud layer may be treated as two different fluid layers. In the present study the behaviour of these fluids is described with the continuity and momentum equations averaged over the layer thicknesses (see Fig. 2).

WID-generated fluid mud appearances have a thickness varying between a few centimetres to a few decimetres. In general, however, their thickness is much smaller than that of the overlying water column. The motion of the fluid mud (density current) will therefore not affect the motion of the upper water layer, which covers almost the entire depth. This allows a decoupling of the two fluid layers. The only interaction takes place through the interfacial shear stresses which may propel the fluid mud and affect the effective hydrodynamic roughness of the water movement.

It is appreciated that vertical concentration profiles in the water column and in the consolidating fluid mud layer are likely to occur. A depth-averaged approach of each layer is therefore only allowed if these gradients are not too large. This implies that the water column concentrations at which the interaction between the suspended sediment and the turbulent flow field, which are likely to occur at a few g/l, do not play a role, and that for the lower layer only freshly deposited fluid mud layers are considered.

Fluid mud appearances are always confined in space, and this is especially so for WID-induced fluid mud. Hence, large areas of the river bed are not covered with fluid mud. To enable the modelling of these very confined WID-induced fluid mud

appearances, a new so-called drying routine is implemented in the 2L FLUID MUD MODEL as part of the present study. This routine allows for the proper modelling of local supercritical fluid mud flow occurring over steep slopes, and is further elaborated upon in Section 3 and Appendix 2.

The water movement in the upper layer is described by the depth-averaged shallow water equations for continuity and momentum, taking into account the effects of Coriolis force, horizontal salinity gradients, turbulent viscosity and bed and wind-induced surface friction. The equations are presented in Appendix 1 and are solved with the so-called ADI method on a boundary fitted, orthogonal curvilinear grid. The numerical scheme for the advection terms is based on a second-order upwind approach, which has small numerical diffusion.¹⁰

The transport of the diluted suspended sediment is described with the depth-averaged advection–diffusion (mass balance) equation, which is solved on the same grid as the water movement. Within this balance equation, source and sink terms are included to account for the exchange processes drawn in Fig. 2. Note that in the present modelling, sedimentation on a rigid or consolidated bed (right-hand side of Fig. 2) always results in the (temporal) formation of fluid mud.

Also for the fluid mud layer, the mass balance and momentum equations are solved on the same grid as the flow module. These equations are basically similar to those of the upper layer. However, some important additional assumptions are being made; the most important ones are as follows.

- (a) The sediment concentration in the fluid mud layer is kept constant in space and time; its value is to be specified by the user, based on *in situ* observations or experience. As a result, the mass balance equation simplifies into an equation for the evolution of the thickness of the fluid mud layer. It is noted that this assumption implies that the parameter settings of the model are site-specific.
- (b) The fluid mud is modelled as a Bingham plastic fluid. When the stresses imposed on the fluid mud are smaller than the Bingham strength τ_b , the fluid mud layer cannot

flow; nor can it be eroded by turbulent entrainment processes.

- (c) The near-field processes around the dredging vessel of fluid mud generation by WID activities are modelled through a source term in the mass balance and momentum equation in the form of a user-specified flow rate and direction, and an initial layer thickness. These parameters are defined by the operational WID procedure mainly, and by the sediment properties to a lesser extent. Note that applying the WID technique is standardised, which implies that the thickness and density of the generated fluid mud will always have similar values.

The fluid mud layer can flow in the horizontal direction because it can be dragged by the main current, it can flow downhill over a slope due to gravity effects, and it can flow because of a gradient in the water surface (slope) or interface, exerting a horizontal pressure gradient on the mud. All these agents are explicitly accounted for in the fluid mud momentum equations (see Appendix 1). These processes can be regarded as horizontal processes.

Also in the vertical direction several processes are important. These, however, are related to the exchange of sediment between the fluid mud layer and its environment, and do not propel the fluid mud. These processes are sketched in Fig. 2, and described in Section 4.

The 2L FLUID MUD MODEL is run in three steps

- (a) The water movement in the upper layer is computed first
- (b) The resulting hydrodynamic data are stored to a file
- (c) The movement of the fluid mud layer is computed, together with the mass balance in upper and lower layers, using the water movement data from the file. This procedure is possible, as the movements of the upper and lower layer only interact through interfacial shear.

3. SUPERCRITICAL FLUID MUD FLOW

Water injection dredging is often deployed in estuaries and coastal areas, which generally contain vast intertidal areas. Therefore, numerical simulations of the flow in such systems can only be carried out with models that contain so-called flooding and drying algorithms. The behaviour of fluid mud is comparable to the drying and flooding of intertidal areas, as the mud deposits will be confined in space, and may flow under the influence of gravity and/or flow-induced drag. Contrary to the water movement on intertidal areas, however, fluid mud flow will often be internally supercritical.

This section explains how supercritical fluid mud flow and the effects of drying and flooding are accounted for in the 2L FLUID MUD MODEL. This model is embedded in the DELFT3D system of WL | delft hydraulics in which the shallow water equations are solved with a finite difference ADI method, yielding stable solutions at large Courant numbers.¹¹ The drying and flooding algorithm used in this system basically implies that the flow velocity at a specific computational point is set to zero when the total water depth at that point becomes smaller than a certain threshold value. When all flow velocities of a computational box are set to zero, this box becomes inactive—that is, it is entirely excluded from the flow

computations; its water or mud volume at that time is maintained however. When the water or mud level rises again, and the water depth around this box exceeds (twice) the threshold, the box becomes active and the water or mud volume stored in this box becomes again part of the computational domain. For details the reader is referred to Stelling *et al.*¹² and Falconer and Chen.¹³

For the (supercritical) fluid mud flow a special approach is implemented, which implies that the local bed and fluid mud level at the border of a computational box are defined as a function of the flow direction (upwind procedure), or, when the specific computational point is inactive, dependent on the local fluid mud level gradient. It can be shown¹⁴ that in this case positive definite fluid mud thicknesses are obtained if the Courant condition is met. Details of the procedure are given in Appendix 2.

It is noted that on intertidal areas the water depth can become very small, and the fluid mud thickness may not be negligible any more with respect to the water depth. However, flow velocities on intertidal areas are small in general. Hence the error introduced will be small.

Figure 3 presents a picture of the computed supercritical fluid mud flow in the River Crouch in front of Burnham Yacht Harbour, induced by WID operations. The mud is fluidised

throughout the marina basin and flows over the slope of the river bank into a large depression in the river (see next sections). Typical computed flow velocities of the fluid mud flow on the slopes of the river amount to about 0.05–0.1 m/s at a layer thickness of 0.01–0.1 m, yielding internal Froude numbers of about 0.2 to 1.4. Hence, on the steepest slopes, the flow becomes supercritical.

4. THE EROSION OF FLUID MUD LAYERS

The WID-induced fluid mud layers may be eroded in the form of entrainment processes by the turbulent water column above. These processes can be described with the integral entrainment model published by Kranenburg and Winterwerp.² Three regimes are distinguished as listed below and illustrated in Fig. 4.

- (a) $\tau_b \leq \tau_B$: no erosion.
- (b) $\tau_b > \tau_B$: entrainment (equation (1)).
- (c) $\tau_b > \tau_e$: surface erosion (see Appendix 2).

Here τ_b is the bed shear stress, τ_e the critical shear stress for erosion and τ_B the Bingham strength of the mud. The process of surface erosion is modelled with the familiar formula by Partheniades.¹⁵ As the work required to maintain the vertical profile of the dilute sediment suspension is small, the entrainment formula by Kranenburg and Winterwerp² can be simplified to

Fig. 3. Computed (supercritical) fluid mud flow in River Crouch; arrows indicate flow velocity and direction and concentrations are given in g/l

Fig. 4. The three regimes of: no erosion; surface erosion; and entrainment

$$E_m = \frac{2C_s \langle u_{*,m}^2 - \tau_B / \rho_m \rangle (\mathbf{u} - \mathbf{u}_m) + C_\sigma \langle u_{*,s}^2 - \tau_B / \rho_m \rangle \mathbf{u}_{*,s}}{g h \Delta \rho / \rho + C_s (\mathbf{u} - \mathbf{u}_m)^2} c_m$$

in which the terms between the angular brackets are relevant only if their value is positive—if not, they are zero. The coefficients C_s and C_σ have been found from empirical data and amount to: $C_s = 0.25$ and $C_\sigma = 0.42$. The Bingham strength of the fluid mud is set at $\tau_B = 0.2$ Pa, which is a reasonable value for fresh mud deposits, and which is large enough to prevent the thin deposits in the far-field to slide from the slopes of the channels to the intertidal areas.¹⁶

5. CASE STUDY: WID IN RIVER CROUCH

The Crouch River is a 25 km long estuary in the United Kingdom, flowing from west to east into the North Sea. The mouth of the River Crouch is located at about 15 km north of the mouth of the River Thames. Burnham Yacht Harbour is situated on the northern bank of the Crouch River, about 10 km

inland from the river mouth. A plan view of the river is given in Fig. 7, with more details in Figs 5 and 6 respectively.

There are no significant river discharges entering the Crouch River to the extent that freshwater inflow can be neglected. The dominant water movement is by the flooding and ebbing of the tide. The tidal range at Burnham-on-Crouch varies between 3.2 m at neap tide to 5.0 m at spring tide. Flow velocity amplitudes are typically 0.8 m/s at mean tidal conditions.

The dredging operations were carried out with the WID vessel Baldur throughout the marina, following a kind of a herring-bone pattern to promote an unhindered flow of the generated fluid mud. The work took place during the daytime for a total duration of 63 h between 19 and 26 January 1996. Note that spring tide occurs around January 21 and 22. The total volume of dredged sediment was 6200 m³. This sediment is diluted however by the WID process, increasing its volume. The solids

Fig. 5. Tracer concentrations (number of particles) in water samples taken on 22 January

Fig. 6. Tracer concentrations (number of particles) in bed samples taken 23–25 January

Fig. 7. Computed maximum suspended sediment concentration (g/l) on 22 January

concentration within the bed is estimated at about 400 g/l and in the induced fluid mud layer at 75 g/l; these estimates are mean values of detailed measurements carried out at another location.¹ The latter data are applicable because of the standardised procedure of the dredging technique. Note that the far-field results will only be slightly affected by these near-field parameters, hence their exact value is not of large importance. The production of fluid mud will therefore amount to about 0.139 m³/s.

It is illustrative to analyse these volumes a bit further. The total mass of sediment released into the River Crouch during the dredging operations amounts to about 470 t per tidal cycle (assuming non-stop work). The WID-induced fluid mud layer will be eroded rapidly, to be entrained and dispersed in the river. As the River Crouch is a highly dynamic system, the mobilised sediment that is brought in the water column by entrainment processes will be mixed rapidly over the river width and its tidal excursion. At a mean depth of about 5 m, this would locally yield an initial mean concentration of about 20 mg/l.

During half an hour around slack water, the flow velocity is so small that the suspended sediment can settle at a rate $W_s \times c$, yielding temporary deposits with a thickness of about 1 mm, at a sediment concentration of 75 kg/m³. Note that this value agrees with the thickness estimated from the tracer tests described below.

A tracer study is carried out by mixing fluorescent particles with the fluidising water that is injected in the bed during the normal dredging operations on 22 January 1996, during 10 min, that is, at 15:23–15:30 hours and at 15:32–15:35 hours. A total of 2.08×10^{16} tracer particles were injected into 16.3 m³ of dense sediment. The tracer particles adhere to the sediment and the sediment/tracer mixture and original sediment behave identically. Hence, the behaviour of the traced material can be considered representative of the dredged sediment.

The dispersion of the dredge material in the river was tracked by means of several surveys, measuring the content of the fluorescent tracer in the water column immediately after their release. Also sediment samples from intertidal areas near the river bank were collected at 13 different sites in the Crouch

River during the period 23–25 January. The results of the field measurements are summarised in Figs 5 and 6. Data collected throughout 22 January suggest that, once outside the harbour, the majority of the dredge material was transported initially in an eastward direction by the ebb tide and remained close to the north bank. The collected bed samples indicated little or no deposition of the material, suggesting that within 3 to 4 h after release the material remained either in suspension or accumulated in very soft sediment layers on the bed.

The results of these surveys indicated that mud is deposited on the intertidal mud-flats in the western part of the estuary. Measurements near Coleward, at the north shore of the confluence Roach–Crouch, show relatively high tracer concentrations in the bed samples.

6. NUMERICAL SIMULATION OF WID WORK IN BURNHAM YACHT HARBOUR

The numerical model covers the entire River Crouch from North Fambridge up to Holliwell Point near the river mouth, as depicted in Figs 10 and 11. The effects of the bifurcation upstream of Burnham Yacht Harbour are taken into account by modelling this bifurcating branch for a length of about 1500 m. This is sufficient as this branch is flooded only occasionally and has a small storage capacity. The water movement at the confluence Crouch River–Roach River is simulated by including the River Roach for a length of about 2500 m.

A curvilinear boundary-fitted grid is applied, with a grid size of about 25 m near Burnham Yacht Harbour to about 50 m near the river mouth. The time step is set at 20 s, which is sufficiently small to guarantee accurate results. The model is controlled by a prescribed variation in water level at its downstream boundary, and a zero river inflow at its upstream boundary (closed boundary).

The flow model is calibrated by comparing the computed water level along the river with data from the Admiralty Tide Tables, prescribing the astronomic components from the Tide Table at the river mouth. The agreement is excellent, but not shown here as space is limited.

The simulations are carried out with a cyclical tide with an amplitude of 2.2 m, which is slightly above mean tide. Simulation over a complete spring neap tidal cycle is not yet

Fig. 8. Computed maximum thickness of sediment deposits (m) on 24 January

Fig. 9. Model predictions of the variation of the total amount of WID-mobilised sediment in the entire Crouch River, in its water column and on the bed; $t = 0$ depicts the onset of the dredging works—that is, 19 January, 13:30 hours

possible because the intermediate data file (see section 3) would become prohibitively large. A period of about three weeks is simulated; within this period all sediment is cleansed from the water column for all simulations.

Samples of the sediment from Burnham Yacht Harbour were collected and analysed by HAM Dredging and Marine Contractors in November 1995. The analysed sediment was defined as a clayey silt. It consisted of 40% clay, 59% silt and 1% sand. The grain sizes D_{50} and D_{90} were approximately $4 \mu\text{m}$ and $40 \mu\text{m}$, respectively. The various sediment parameters used in the simulations are based on experience with similar muds and are given in Table 1.

Figure 7 presents the maximum sediment concentration in the water column, computed for 22 January at maximum flood velocity (MFV), to be compared with the measured values in Fig. 5. Fig. 8 presents the maximum thickness of the sediment deposits, computed for January 24 at low water slack (LWS), to be compared with the measured values in Fig. 6.

The results of the numerical simulations of the WID-induced sediment dispersion in the River Crouch can be compared qualitatively with the results of the tracer experiments.

- The sampling locations were limited to a river stretch of about 4 km at either side of Burnham Yacht Harbour. The numerical results show that the sediment is dispersed rapidly far beyond this area, being transported to the North Sea and accumulating in dead-end regions of the river farther away. This explains why only less than 6% of the tracer material could be retraced.
- The numerical results show a rapid entrainment of the fluid mud after leaving the harbour mouth. This results (temporarily) in a narrow plume of concentrated sediment in the water column during ebb tide just downstream of the harbour. This picture agrees well with the observations from the tracer experiments (see Figs 5 and 6).
- From the tracer experiments mud deposits on the intertidal areas along the river bank of about 1–5 mm were found. The thickness of the deposits obtained with the numerical simulations are about 1 mm (see Fig. 8), a little smaller, but still in the proper range.

We can conclude that, albeit on the basis of a limited set of data, the far-field dispersion of WID-induced fluid mud computed with the 2L FLUID MUD MODEL agrees well with the

Parameter	Value	Parameter	Value
Settling velocity	W_s 0.5 mm/s	Critical deposition stress	τ_d 0.1 Pa
Erosion parameter	M 10^{-4} kg/m^2	Critical erosion stress	τ_e 0.5 Pa
Entrainment	See equation (1)	Yield strength	τ_B 0.2 Pa
Fluid mud concentration	c_m 75 g/l	Fluid mud density	ρ_m 1066 g/l
Consolidated bed conc.	c_b 400 g/l	Bed density	ρ_b 1266 g/l
Water density	ρ 1020 g/l		

Table 1. Sediment parameters in 2L FLUID MUD MODEL

picture deduced from the *in situ* tracer experiments. This agreement is good in a qualitative sense, but also quantitatively: the computed thickness of mud deposits are of the same order of magnitude as found from the tracer experiments.

Figure 9 shows the computed variation of the total amount of mud in the water column, on the river bed and in the entire river. It is noted that the maximum amount of mud in the river is about half of the 2.5×10^6 kg generated by the WID process. This is due to a loss of mass over the downstream boundary when mud is transported during ebb into the open sea, where it is severely diluted by mixing processes, and moved away from the river mouth by large-scale circulations at sea. This process

is modelled by preventing this mud to re-enter the river during the subsequent flood. This cycle continues until an equilibrium is achieved after 350 h, that is, at 2 February.

The maximum amount of sediment is attained after about 150 h, after which it decreases when the WID work is terminated.

Figures 10 and 11 show the computed suspended sediment concentration and thickness of mud deposits around $t = 150$ h, when the maximum amount of the WID-mobilised sediment is in the water column (Fig. 10) and when the maximum amount of the WID-mobilised sediment is deposited on the bed (Fig. 11).

An inspection of the computed spatial distributions (Figs 3, 7, 8, 10 and 11) shows the following features of the far-field dispersion of the WID-induced fluid mud.

- The mud flows out of Burnham Yacht Harbour as a density current, following the local bathymetry, slightly dragged by the tidal flow, forming (temporarily) a fluid mud layer of a few decimetres at most in the depressions in front of the harbour; on the steepest slopes, the flow becomes internally supercritical.
- A major part of this fluid mud layer is entrained rapidly by the tidal flow and mixed efficiently over a major part of the river. Maximum concentrations in this phase of the dispersion process do not exceed 50 mg/l.
- More than half of the volume of sediment mobilised by the WID activities is transported to the North Sea during ebb tide, and does not re-enter the river during the next flood.
- During LWS some mud is deposited for a short time (about half an hour) on the bed of the river channel, at high water slack (HWS) hardly any sediment can settle on the channel bed.
- Deposits of a few millimetres thickness have been measured on the intertidal areas along the river bank in the vicinity of Burnham Yacht Harbour. Also the numerical simulations show that only a very small fraction of the WID-generated mud is accumulating here.
- The major part of the mud, remaining in the estuary, accumulates in the upstream part of the river and in the two branches facing south. These deposits do not exceed a few centimetres in thickness. This implies that the Crouch River is a so-called flood-dominated estuary—that is, the net transport of sediment entering from the sea is upstream. This is caused by the asymmetry of the tide: the large tidal range causes a considerable deformation of the tide, yielding a relatively short flood period with large velocities, and a longer ebb period with smaller velocities.
- The tidal flow generates an anticlockwise circulation around the shoals of Bridgemarsh Island—that is, the wide area in the western part of the estuary. During flood tide, water flows upstream along either side of the shoal, whereas during ebb tide only the deeper channel along the right bank of the river carries water. Such circulation systems mix the sediment carried in suspension very efficiently over the river.
- The suspended sediment concentration can locally acquire values up to 200 mg/l for a short period of time. These values are confined however to the very shallow areas, where little re-entrainment may already result in relatively large suspended sediment concentrations.
- About one week after the dredging activities stopped, almost no sediment was traced in the water column: all sediments mobilised by the WID process had been transported to the North Sea or accumulated on intertidal areas, mainly in the dead-end regions of the river.

7. ALTERNATIVE DREDGING STRATEGIES

Next the 2L FLUID MUD MODEL is used to evaluate two alternative dredging strategies. In the first alternative (called ebb-WID) the sediment in the harbour basin is removed by water injection dredging, but the work is carried out only between HWS and maximum ebb velocity (MEV), day and night, with the purpose to transport as much sediment to the

Fig. 12. Variation of total amount of WID-mobilised sediment in the entire Crouch River, in its water column and on the bed for alternative 1 (ebb-WID)

North Sea as possible. The patterns of suspended sediment concentrations and mud deposits are similar to those presented in Figs 10 and 11, and are not presented here.

Figure 12 presents the computed mass balance of the volume of sediment in the River Crouch, showing that the maximum amount of WID-mobilised sediment is reduced by about 20%, as compared to Fig. 9. The reduction is not larger because Burnham Yacht Harbour is located about 10 km from the river mouth, which is comparable to the tidal excursion. This maximum amount of sediment now occurs after 200 h, as the working time of this dredging alternative amounts to about nine days instead of six days.

The second alternative (called back-hoe dredging) consists of a classical dredging operation with a back-hoe crab. In this case three times more sediment has to be removed from the harbour basin because of the inaccuracy of this method to meet the required depth over the entire basin. The dredged sediment is dumped in a deep pit at the confluence north-west of Foulness Island (Fig. 5), about 4 km from the river mouth. This work will take about 16 days, yielding 50 trips with the barge to the dumping location.

The erosion of the dumped sediment (alternative 2) is modelled with the Partheniades erosion formula, as the dumped dredging

Fig. 13. Variation of total amount of mobilised sediment in the entire Crouch River, in its water column and on the bed for alternative 2 (back-hoe dredging)

specie is not fluid. Fig. 13 presents the computed mass balance of the volume of sediment in the River Crouch, showing that the maximum amount of WID-mobilised sediment is now reduced to 40% compared to Fig. 9, whereas eventually the amount of sediment accumulating in the bed of the river amounts to only 20% of that of Fig. 9. This latter reduction is caused by the proximity of the North Sea to the dumping location, compared to that of Burnham Yacht Harbour.

8. DISCUSSION AND CONCLUSIONS

The River Crouch is a highly dynamic system. As a result the WID-induced fluid mud is eroded rapidly and dispersed over the estuary. A considerable part of the dredged sediments is transported to the North Sea, as the dredging site is located about one tidal excursion from the sea. The resulting sediment concentrations in the estuary's water column appeared typically of the order of several tens of mg/l, although concentrations up to several hundreds of mg/l are predicted in the shallow intertidal areas for short periods of time. Mud deposits on the river banks and intertidal areas are a few millimetres thick, although locally in the dead-end branches deposits with a thickness of a few centimetres are computed. This implies that the far-field impact of water injection dredging is so small that it cannot be measured directly, but has to be established with, for instance, tracer experiments, as described in this paper.

The present study shows qualitatively that the far-field dispersion and deposition patterns of WID-mobilised sediment can be simulated properly with the 2L FLUID MUD MODEL described herein. The re-erodable deposits are thin, and they consolidate rapidly during quiet conditions and erode rapidly during accelerating flow. As the numerical model results will not vary much when this mud is eroded in, say, 5, 10 or 15 min, the model results are not very sensitive to the parameter settings of the consolidation and erosion formulae applied.

The 2L FLUID MUD MODEL can be used to evaluate the environmental impact of alternative dredging strategies. When the dredging operations in Burnham Yacht Harbour are carried out during ebb only, the total amount of mobilised sediment that remains within the estuary is only slightly smaller than in the case of the actual dredging work. A significant reduction in this amount of sediment can only be obtained if the dredged sediment is carried by barges and dumped closer to the sea.

Freshwater input in the River Crouch is negligible. The water movement may therefore be described with the depth-averaged shallow water equations in the upper layer of the 2L model. However, in many estuaries, freshwater input is important, resulting in a considerable gravitation circulation. In this case the upper layer is to be modelled with the three-dimensional shallow water equations. This is the subject of our ongoing research.

Another limitation of the present model occurs when thick layers of fluid mud are present in the major part of the estuary. In that case non-Newtonian effects and the interaction of high-concentrated suspensions with the water movement through the damping of vertical turbulent motions become important and have to be implemented in the model. However, this is yet

beyond the current state-of-the-art, and more basic research is required before this can be done.

9. ACKNOWLEDGEMENTS

This study was initiated by Mr Bart van der Schrieck of HAM Dredging Marine Contractors. We would like to thank HAM for financing the study and giving permission to publish the results. We acknowledge Mr Cor Flokstra and Mr Willy ter Horst for the implementation of the 2L FLUID MUD MODEL in the software environment of DELFT3D, and Mr Rinze Bruinsma for running the model and producing the various figures in this paper.

10. APPENDIX I. THE 2L FLUID MUD MODEL

The water movement and sediment transport in the upper layer, containing dilute suspensions of mud, as implemented in the 2L FLUID MUD MODEL are governed by the following.

- (a) The continuity equation for water, using Einstein's summation convention

$$2 \quad \frac{\partial h}{\partial t} + \frac{\partial h u_i}{\partial x_i} = 0$$

- (b) The momentum equation

$$3 \quad \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} - c_{ijk} f_k u_j + \frac{gh}{2\rho} \frac{\partial \rho}{\partial x_i} + g \frac{\partial Z_s}{\partial x_i} - \nu \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\tau_{zs,i}}{\rho h} + \frac{\tau_{zi,i}}{\rho h} = 0$$

where Z_i is either Z_m if fluid mud is present, or Z_b if no fluid mud is present.

- (c) The mass balance for suspended sediment

$$4 \quad \frac{\partial hc}{\partial t} + \frac{\partial h u_i c}{\partial x_i} - \frac{\partial}{\partial x_i} \left(h D \frac{\partial c}{\partial x_i} \right) = -D_m + E_m$$

The behaviour of the lower, fluid mud layer is governed by the following.

- (a) The mass balance for sediment in the lower layer, which simplifies to an equation for the layer depth

$$5 \quad \frac{\partial \delta}{\partial t} + \frac{\partial u_{m,i} \delta}{\partial x_i} = \frac{D_m - E_m + E_b - V_c}{c_m}$$

- (b) The momentum equation for the lower layer

$$6 \quad \frac{\partial u_{m,i}}{\partial t} + u_{m,j} \frac{\partial u_{m,i}}{\partial x_j} - c_{ijk} f_k u_{m,j} + g \frac{\partial Z_s}{\partial x_i} + \frac{g \Delta \rho}{\rho_m} \left(\frac{\partial Z_m}{\partial x_i} - \frac{\partial Z_s}{\partial x_i} \right) - \nu_m \frac{\partial^2 u_{m,i}}{\partial x_j^2} - \frac{\tau_{zm,i}}{\rho_m \delta} + \frac{\tau_{zb,i}}{\rho_m \delta} = 0$$

- (c) The rheological model

$$7 \quad \tau_{zb,i} = \left(\tau_B + \frac{\lambda}{8} \rho_m u_{m,j}^2 \right) \frac{u_{m,i}}{\sqrt{u_{m,j}^2}}$$

(d) The stresses at the water–mud interface

$$8 \quad \tau_{z_m, i} = \frac{\lambda}{8} \rho u_j^2 \frac{u_i}{\sqrt{u_j^2}}$$

11. APPENDIX 2. FLOODING AND DRYING AND SUPERCRITICAL FLUID MUD FLOW

The shallow water equations solved in the 2L FLUID MUD MODEL are solved with the finite difference alternating direction implicit (ADI) method¹² on the staggered grid given in Fig. 14(b). This staggering implies that the layer thickness at the velocity points has to be obtained by averaging depth and water level values from neighbouring points. The thickness of the water layer h^u for the velocity point $u_{i+\frac{1}{2}, j}$ for instance is presented in equation (9) as an example.

$$9 \quad h_{i+\frac{1}{2}}^u = \frac{Z_{s_{i,j}} + Z_{s_{i+1,j}}}{2} - \frac{Z_{b_{i+\frac{1}{2},j-\frac{1}{2}}} + Z_{b_{i+\frac{1}{2},j+\frac{1}{2}}}}{2}$$

The flooding and drying procedure implies that the flow velocity is set to zero when $h_{i+\frac{1}{2}}^u < \varepsilon_h$, where ε_h is a user-defined threshold value. Such an inactive velocity grid point becomes active again when $h_{i+\frac{1}{2}}^u > 2\varepsilon_h$.

A net flow into a computational box does not necessarily imply positive water depth in the box centre. Therefore an additional requirement has to be met: $h_{i,j}^\zeta > 0$, where superscript ζ refers to the water level point. The depth at a water level point is given by

$$10 \quad Z_{b_{i,j}}^\zeta = \max\left(Z_{b_{i+\frac{1}{2},j+\frac{1}{2}}}, Z_{b_{i+\frac{1}{2},j-\frac{1}{2}}}, Z_{b_{i-\frac{1}{2},j+\frac{1}{2}}}, Z_{b_{i-\frac{1}{2},j-\frac{1}{2}}}\right)$$

If this would result in a non-positive water volume in an active computational box, the procedure at this half-time step is repeated, but now with the computational box set dry. The flow velocity is set to zero in the four surrounding velocity points.

The upwind scheme for supercritical mud flow implies that the mud thickness is defined as a function of the mud flow direction. If $u_{i+\frac{1}{2}, j} > 0$ (Fig. 14(b)), the thickness of the fluid mud at this velocity point becomes

$$\delta_{i+\frac{1}{2}, j}^u = Z_{m_{i,j}} - Z_{b_{i,j}}^\zeta$$

whereas for $u_{i+\frac{1}{2}, j} < 0$

$$\delta_{i+\frac{1}{2}, j}^u = Z_{m_{i+1,j}} - Z_{b_{i+1,j}}^\zeta$$

At dry points the thickness of the fluid mud layer is defined as a function of its slope, that is

$$\delta_{i+\frac{1}{2}, j}^u = Z_{m_{i,j}} - Z_{b_{i,j}}^\zeta \quad \text{for } Z_{m_{i,j}} > Z_{m_{i+1,j}}$$

and

$$\delta_{i+\frac{1}{2}, j}^u = Z_{m_{i+1,j}} - Z_{b_{i+1,j}}^\zeta \quad \text{for } Z_{m_{i,j}} < Z_{m_{i+1,j}}$$

Note that mass is always conserved with this procedure.

For the time integration the ADI scheme is applied. For the one-dimensional case, the continuity equation becomes

$$11 \quad \frac{\delta_{i+\frac{1}{2}}^{l+\frac{1}{2}} - \delta_{i+\frac{1}{2}}^l}{\Delta t} + \frac{\delta_{i+\frac{1}{2}}^l u_{i+\frac{1}{2}, j} - \delta_{i-\frac{1}{2}}^l u_{i-\frac{1}{2}, j}}{\Delta x} = 0$$

It can be shown¹⁴ that, for the upwind approach, positive definite water levels are guaranteed if the Courant condition for velocity is met

$$12 \quad \frac{\Delta t u_{i+\frac{1}{2}, j}}{\Delta x} < 1$$

REFERENCES

1. RIJKSWATERSTAAT, WL | DELFT HYDRAULICS and HAM-VOW. Evaluation Report on WIB-experiment Haringvliet, 1995 (in Dutch).
2. KRANENBURG C. and WINTERWERP J. C. Erosion of fluid mud layers—I: Entrainment model. *Journal of Hydraulic Engineering*, ASCE, 1997, 123, No. 6, 504–511.
3. HODGINS D. O., OSBORN T. R. and QUICK M. C. Numerical model of stratified estuary flows. *Journal of the Waterway, Port, Coastal and Ocean Division*, ASCE, 1997, 103, No. WW1, 25–42.
4. KAWAHARA M., MORIHIRA M., KATAOKA S. and HASEGAWA K. Periodic finite element in two-layer tidal flow. *International Journal for Numerical Methods in Fluids*, 1981, 1, 45–61.

5. BRANDT P., ALPERS W. and BAKHAUS J. O. Study of the generation and propagation of internal waves in the Strait of Gibraltar using a numerical model and synthetic aperture radar images of the European ERS1 satellite. *Journal of Geophysical Research*, 1996, 101, No. C6, 14 237–14 252.
6. HEATHERSHAW A. D., NEW A. L. and EDWARDS P. D. Internal tides and sediment transport at the shelf break in the Celtic Sea. *Continental Shelf Research*, 1987, 7, No. 5, 485–517.
7. BONNECAZE R. T., HUPPERT H. E. and LISTER J. R. Particle-driven gravity currents. *Journal of Fluid Mechanics*, 1993, 250, 339–369.
8. MOODIE T. B., PASCAL J. P. and SWATERS G. E. Sediment transport and deposition from a two-layer fluid model of gravity currents on sloping bottoms. *Studies in Applied Mathematics*, 1998, 100, 215–244.
9. ODD N. V. M. and COOPER A. J. A two-dimensional model of the movement of fluid mud in a high energy turbid estuary. *Journal of Coastal Research*, 1989, No. 5, 185–194.
10. STELLING G. S. and LEENDERTSE J. J. Approximation of convective processes by cyclic ADI-methods. *Proceedings of the 2nd ASCE Conference on Estuarine and Coastal Modelling, Tampa, USA*, 1991.
11. LEENDERTSE J. J. *Aspects of a Computational Model for Long Period Water Wave Propagation*. RAND Corporation, 1967, Memorandum RM-5294-PR.
12. STELLING G. S., WIERSMA A. K. and WILLEMSE J. B. T. M. Practical aspects of accurate tidal computations. *Journal of Hydraulic Engineering, ASCE*, 1986, No. 9, 802–917.
13. FALCONER R. A. and CHEN Y. An improved representation of flooding and drying and wind stress effects in a two-dimensional tidal numerical model. *Proceedings of the Institution of Civil Engineers*, 1991, Part 2, 659–678.
14. STELLING G. S., KERKAMP H. W. J. and LAGUZZI M. M. Delft flooding system: a powerful tool for inundation assessment based upon a positive flow simulation. In: *Hydro-informatics '98* (V. Babovic and L. C. Larsen (eds)). Balkema, Rotterdam, 1998, pp. 449–456.
15. MEHTA A. J. Characterisation of cohesive sediment properties and transport processes in estuaries. In: *Lecture Notes on Coastal and Estuarine Studies*, Vol. 14, Estuarine Cohesive Sediment Dynamics. Springer-Verlag, 1984, pp. 290–325.
16. BERLAMONT J. Pumping fluid mud: theoretical and experimental considerations. *Journal of Coastal Research*, 1989, No. 5, 195–206.

Please email, fax or post your discussion contributions to the secretary by 1 June 2003: email: kathleen.hollow@ice.org.uk; fax: +44 (0)20 7799 1325; or post to Kathleen Hollow, Journals Department, Institution of Civil Engineers, 1–7 Great George Street, London SW1P 3AA.