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Open Water Disposal of Barged Sediments

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Abstract

A new model for assessing the behaviour of sediment clouds due to open water disposal from barges is presented. The model takes into account the realistic physical condition that due to the large and finite amount of sediments typically carried by the barge, the disposed sediments will initially descend as a sediment plume (as if from a continuous release), and then transit into a discrete sediment cloud (as if from an instantaneous release) after the barged sediments are fully discharged. These aspects are not represented in existing models (i.e. STFATE, etc.) so far. The model also includes the geometrical factors of the barge, which can significantly affect the source conditions and thus the subsequent descent process. Two types of predictions are provided by the model: (i) qualitative predictions of the flow regimes of the sediment clouds along the descending path in the water column; and (ii) quantitative predictions of the gross characteristics such as the penetration rate and growth size of the sediment clouds due to entrainment. An experimental study was also carried out for model verification. The comparison between experimental data and model predictions was satisfactory, while predictions with the existing models were found to be inadequate due to their over-simplified

representations. Similar conclusions were also drawn in the comparison between available field data and model predictions.

Introduction

Various activities, such as land reclamation and management of dredged materials, often involve the open water disposal of sediments. The volume of sediments involved can be very substantial, for example Bever et al. (2014) reported that $\sim 2.3 \text{ mil m}^3$ of sediments are dredged annually from San Francisco Bay. To carry out these open water disposal operations typically require the pre-approval from regulatory agencies, and the approval requirements include the evaluation of water quality impact in the water column (EPA 2004, USEPA/USACE 1991, USEPA/USACE 1998). Hence, it is essential to be able to assess the fate and transport of the disposed sediments in the coastal environment with sufficient accuracy for the purpose of impact assessment.

The present study focuses on the open water disposal of sediments with split bottom barges, which are commonly deployed in real operations (Eisma 2006) due to their large carrying capacity, with up to $\sim 1000 \text{ m}^3$ of sediment volume that can be transported at a time (Miyamoto et al. 1993). The sediments are released to the underlying water column through the bottom opening of the barge beneath the water surface. The transport processes of the disposed sediments are categorized into near and far field regimes, distinguished by the mechanisms that govern the mixing and dynamics of the sediment cloud.

For the near field regimes, the field evaluation by Bokuniewicz et al. (1978) showed that the dynamic behaviour of the disposed sediments in the water column generally experiences three sequential phases: (i) convective descent phase, during which the flow behaviour is dominated by the source conditions and gravity (i.e. buoyant convective flow); (ii) dynamic collapse phase upon impact with the seabed, during which the horizontal spreading occurs; and (iii) passive-transport dispersion phase (or intermediate and far field), when the sediments are carried by the ambient currents and turbulence. Furthermore, in the convective descent phase, Rahimipour and Wilkinson (1992) suggested that the sediment cloud can also be distinguished into three stages: (i) acceleration stage,

within which the sediments move together as a solid body; (ii) self-preserving stage, within which the sediment cloud behaves like a miscible thermal and is characterized by strong internal circulation; and (iii) dispersive stage, within which the sediments leave the entrained fluid and settle at their own settling velocity. It is noted, however, that the distinction of the three stages by Rahimipour and Wilkinson is based on the assumption of an instantaneous release, which may not be valid when the sediment volume is large such as barged releases.

In the literature, there were two main studies performed to examine the near field transport of the disposed sediment from the open water barge disposal. Koh and Chang (1973) developed a mathematical model (referred as K&C model) based on the self-preserving miscible thermal to analyse the motion of the sediment cloud. The assumptions of point source and instantaneous release were adopted in their model for simplicity. Subsequently, Johnson and Fong (1995) established a numerical model, STFATE (short-term fate) to compute the water column concentration and bottom disposition due to barged releases. The basic formulation of STFATE follows Koh and Chang (1973), with the barged volume being discretized into a sequence of three-dimensional releases with varying insertion speed. STFATE has been widely used for engineering analysis in the industry (Bailey et al. 2004, Howlett 2003). However, we note that the point source axisymmetric assumption by STFATE enables an efficient analysis but does not actually represent the actual physical conditions in a realistic manner. Upon release from the barge, the sediment cloud should first descend as a two-dimensional (2D) sediment curtain before transiting to an axisymmetric three-dimensional (3D) bowl shape sediment cloud. The flow regime transitions should also be closely related to the barge's geometry. Furthermore, with the large amount of sediments involved in the barge disposal, the duration for the sediments to be fully discharged and the duration for the sediments to descend through the water column may be of the same order of magnitudes. Therefore, the sediment cloud may behave as a continuous release in the beginning rather than as an instantaneous point source approximated by the K&C and STFATE models. In summary, the existing models have oversimplified the complexity of the sediment cloud behaviour in the barge disposal operations.

Apart from these two models, there were also numerical studies that investigated the particle clouds dynamics within the convective descent phase using CFD (Harada et al. 2013, Lai et al. 2013,

Wang et al. 2014). The numerical results revealed comprehensive flow features of both the solid particle and entrained fluid phases, which were difficult to measure through experiments. However, the advanced numerical approaches require substantial computational resources, which are too demanding for engineering applications at the moment.

As mentioned earlier, the disposed sediment would eventually enter the far field regime, when the transport of the sediments is primarily driven by the ambient currents. A far field model can then be applied to predict the fate of suspended sediments and long-term bathymetry changes in the disposal sites. An example is the Surface-water Modeling System (SMS), which uses the particle tracking methods (Lackey and MacDonald 2007). These far field models generally cover a large area beyond the disposal and dredging locations for impact assessment, and require the input from near field models (e.g. STFATE) to provide the boundary conditions around the disposal location for their simulations.

The objective of this study is to develop a new model that can improve the representation of the physical conditions of barged sediments disposal in the convective descent phase (near field regime). An experimental investigation was performed in the present study to validate the model. The simulation of a field disposal operation was also presented as an application example. In the following, the development of the new model is first presented. The model predictions are then compared to the experimental results for assessment.

Model Description

The new barged sediments disposal model (called BSDM) is based on a classification scheme of the sediment cloud behaviour with six flow regimes (four asymptotic cases plus two cases pertaining to the dispersive phase). The gross characteristics of each regime are computed from the respective asymptotic solutions. The classification scheme is introduced in the following sub-sections, together with computation of the gross characteristics in the flow regimes.

Flow Regime Classification

The classification scheme classifies the flow regimes of the sediment cloud based on the comparisons of the physical length parameters that represent the dynamic influences on the cloud behaviour. The approach bears similarity to the one adopted by the popular software CORMIX for buoyant jets assessment. The scheme includes three dominant physical length parameters: the empty depth, z_e , transition depth, z_t and dispersive depth, z_d . Besides the three length parameters, the parameter, h is used to indicate the vertical location in the water column where the characteristics of the sediment cloud are assessed (the value can be defined by the users). Their definitions and illustrations are given in Table 1 and Fig. 1, respectively.

Fig. 2 shows a schematic diagram of the classification scheme. At the final stage of the classification, the flow regimes with the respective pictorial descriptions are presented. In the pictures, the boxes at the top represent the barge or disposal bin. The fluid entrained by the sediments is shaded in grey, and the dots denote the sediment particles. In the classification, the first step is to compare z_e with h . If the barged sediments are fully discharged before the sediment cloud front reaches h (i.e. $z_e < h$), the sediment cloud at that location will behave like an instantaneous thermal. Otherwise, the sediment cloud will behave like a continuous plume.

Towards the end of the thermal regime, the descent velocity of the sediment cloud decreases, approaching the particle settling velocity, w_s (Zhao et al. 2012). Hence, the settling motion of the particles would surpass the internal circulation of the thermal, and the particles would then separate from the entrained fluid. The depth where the sediment separates from the entrained fluid is defined as the dispersive depth, z_d (Rahimipour and Wilkinson 1992). In the classification scheme, when z_d is smaller than h , the sediment cloud will enter the dispersive phase at z_d .

For barges with a narrow bottom opening (i.e. large L/W ratios, where L is the disposal bin length and W the opening width), the sediment plume/thermal should be predominantly two-dimensional (2D) before transiting to three-dimensional (3D) with anisotropic entrainment. The difference between 2D and 3D flow regimes is also shown in Fig. 2. In the 2D flow regimes (C1, C3 and C5), the sediment cloud behaves as if it is released from a line source, and the spreading occurs mainly in the transverse

direction. However, in the 3D flow regimes (C2, C4 and C6), the spreading occurs axisymmetrically, and the sediment cloud behaves as if it is released from a round or point source. The 2D flow regimes transit to 3D flow regimes at z_t .

In the following, the dimensional analysis for z_e and z_t will be presented. The independent variables include the disposed sediment volume, V_o , median particle diameter, d_{50} , sediment density, ρ_s , ambient density, ρ_a and dimensions of the disposal bin bottom opening (L and W). Subsequently, the quantitative equations for z_d proposed by previous studies will also be presented.

Empty depth, z_e

As described in Table 1, the empty depth, z_e , is defined as the penetration depth of the sediment cloud front at the instance when all the sediments have been completely released (or emptied) from the barge. The formulation of z_e requires two steps: the first step occurs at the source (barge or disposal bin) and the second step involves the descending motion of the discharged sediment cloud.

The duration for the sediments to fully-empty from the barge, t_e , is considered first. The formulation of t_e is based on the idea that upon opening of the barge doors, a convective vertical exchange occurs between the underlying water and barged sediments through the bottom opening (L and W) of the disposal bin, being driven by the potential energy due to the depth of the sediments inside the bin $D_o (= V_o/(LW_b))$ where W_b is the disposal bin width). The other variables that can influence t_e are the reduced gravitational acceleration, $g' (= g(\rho_s - \rho_a)/\rho_a)$, where ρ_s is the sediment density and ρ_a the ambient density), d_{50} of the sediment particles, and the kinematic viscosity, ν of the ambient fluid. Hence,

$$t_e = f_1(L, W, V_o, g', d_{50}, \nu) \quad (1)$$

Here, V_o is used instead of D_o , because it better represents the physical meaning of t_e . Next, using dimensional analysis, we can obtain the following functional form:

$$t_e \sqrt{\frac{g'}{V_o^{1/3}}} = f_2\left(\frac{LW}{V_o^{2/3}}, \frac{L}{V_o^{1/3}}, \frac{W}{d_{50}}, D^*\right) \quad (2)$$

where $D^* = d_{50}g'^{1/3}/\nu^{2/3}$ is the dimensionless particles diameter (Aguirre-Pe et al. 2003). The π -term, $W/d_{50} (= R_{\text{barge}})$, is equivalent to the dimensionless radius, $R (= D/d_{50})$, D is the opening diameter of the

orifice) adopted in previous studies of particles discharge from an orifice (Janda et al. 2008, Mankoc et al. 2007). In particular, Mankoc et al. (2007) investigated the discharges of particles from 3D round and 2D line orifices through experimental and numerical studies. They found that in Beverloo's law, there is no dependence on the d_{50} when $D \gg d_{50}$, which would also be applicable to our situation. We shall also show later that the independency was also observed in the experimental data. Thus, Equation (2) can then be reduced to:

$$t_e \sqrt{\frac{g'}{V_o^{1/3}}} = f_3 \left(\frac{LW}{V_o^{2/3}}, \frac{L}{V_o^{1/3}}, D^* \right) \quad (3)$$

Furthermore, assuming that the effect of the aspect ratio of the bottom opening is not significant in determining the empty time as compared to the opening area, Equation (3) can then be simplified further as:

$$t_e \sqrt{\frac{g'}{V_o^{1/3}}} = f_3 \left(\frac{LW}{V_o^{2/3}}, D^* \right) \quad (4)$$

In the second step, the descending motion of the sediment cloud is governed by the bulk characteristics of the buoyancy of the barged release, i.e. V_o and g' together with t_e . Hence, with dimensional analysis, z_e can be expressed in the following form in Equation (5).

$$\frac{z_e}{V_o^{1/3}} = f_5 \left(t_e \sqrt{\frac{g'}{V_o^{1/3}}} \right) \quad (5)$$

Transition depth, z_t

Also described in Table 1, the transition depth, z_t is determined from the penetration depth of sediment cloud when the longitudinal spreading rate ($\alpha_L = dr_L/dz$) is equal to the transverse spreading rate ($\alpha_T = dr_T/dz$). In other words, z_t represents the location whereby the spreading becomes axisymmetric. Clearly, z_t is affected by the geometrical characteristics of the bottom opening, L and W . In addition, from the literature, the spreading rates of the starting plume and thermal regimes before z_t have been found to be distinctly different (Ching et al. 1993, Lee and Chu 2003). Hence, z_t would also be affected by the duration of the release, t_e . Thus, we have

$$z_t = f_6(t_e, L, W, g') \quad (6)$$

Using dimensional analysis again,

$$\frac{z_t}{L} = f_7\left(\frac{t_e \sqrt{g'}}{\sqrt{L}}, \frac{L}{W}\right) \quad (7)$$

The function f_7 has to fulfil two conditions: (i) when $L/W = 1$ (i.e. when the sediments are being released from a square or round (point) source), z_t should be equal to zero and the sediment cloud enters the 3D regimes directly, and (ii) when L/W increases, z_t should also increase.

From Equations (4), (5) and (7), the length parameters are dependent on W (both LW and L/W with fixed L) and d_{50} (D^*). We thus designed the experimental study by disposing various sizes of sediment from different opening widths. The experimental results were used to calibrate Equations (4), (5) and (7) as well as validate the model.

Dispersive depth, z_d

The value of z_d is determined based on empirical functions proposed by previous studies. Noh and Fernando (1993) examined the dispersive depth of a 2D sediment thermal by releasing a mixture of glass beads and fluorescent dye. They observed the separation of sediments from the entrained fluid after the sediment mixture travelled some distance away from the source, and defined this distance as the 2D dispersive depth, z_{d2D} . They then developed a proportional relationship with the source total buoyancy per unit length, $b_o (= g'V_o/L)$ as

$$\frac{z_{d2D} w_s}{\nu} \propto \left(\frac{b_o}{\nu w_s}\right)^C, \quad C \approx 0.3 \quad (8)$$

Adapting their results and including the effect of particle Reynolds number, $Re_p (= w_s d_{50}/\nu)$, Equation (8) can be further expressed as

$$z_{d2D} = 308 Re_p \left(\frac{g'V_o}{\nu w_s L}\right)^{0.3} \frac{\nu}{w_s} \quad (9)$$

Bush et al. (2003) studied the 3D transitional depth into the dispersive phase for round sediment thermals. In their study, z_{d3D} was found to be Re_p -dependent at low Re_p . This dependency was

attributed to the influence of particle-particle interactions, and decreased as Re_p increased. They proposed the following equation to compute z_{d3D} for Re_p in the range of 0.1 – 300:

$$z_{d3D} = (11 \pm 2) \left(\frac{(g'V_o)^{1/2}}{w_s d_{50}} \right)^{5/6} d_{50} \quad (10)$$

Equations (9) and (10) are employed in our model to estimate the dispersive depth of 2D and 3D sediment thermals, respectively.

Computation of Gross Characteristics

The transient development of the gross characteristics (i.e. frontal velocity, u_f , frontal position, z_f and cloud radius, r_T) of the sediment cloud is computed from the asymptotic solutions of the respective flow regime. In the computation, three assumptions have been made: (i) the transitions between two flow regimes occur instantaneously; (ii) the average buoyancy flux of the starting plumes is used during the release (i.e. buoyancy flux per unit length, $\dot{b}_o = B_o/Lt_e$ and buoyancy flux, $\dot{B}_o = B_o/t_e$, in other words the stem loss during the descent is negligible), and (iii) the sediment cloud in the starting plumes and thermals regimes has self-similar behaviour.

Here, we would like to note that STFATE computes the gross characteristics by discretizing the volume of barged sediments into a sequence of three-dimensional instantaneous releases for the analysis (Johnson and Fong 1995). The total buoyancy excess of each release is varied with the insertion speed determined based on the gravitational force by the sediment depth remaining in the barge as follow:

$$u_{in} = \frac{(\rho_{AV}gh - \rho_dgd)}{\frac{1}{2}\rho_{AV} \left[1.0 + f - \left(\frac{A_1}{A_o} \right)^2 \right]} \quad (11)$$

where ρ_{AV} is the average density of the remaining material in vessel, f is the friction factor; A_1 and A_o are the opening and inner areas of the disposal vessel. The number of releases, N (up to 6), can be specified by the user. Hence, the insertion speed is greatly influenced by N and t_e . Depending on the value inputted by the user, multiple possible solutions are computed for a single set of disposal

conditions (e.g. V_o , L , W , d_{50} , etc.) (Dong et al. 2007) which is not physically realistic. Comparatively, BSDM calculates t_e directly from the disposal conditions and provides only a single solution for every condition.

For the third assumption of self-similar behaviour, the concept of simultaneous virtual distance and time origins (Zhao et al. 2012) is adopted at the transition point to provide a continuous connection between two flow regimes. The concept can be explained schematically in Fig. 3. Essentially, both the virtual distance, z_o and time origins, t_o refer to the same virtual point source of buoyancy where the cloud originates with a zero radius. In the model, after the transition of flow regimes from 2D to 3D, the sediments are then assumed to be released from a virtual point source from the transition point onward.

Asymptotic Solutions

The gross characteristics of the sediment thermal in the self-preserving phase can be predicted by using the asymptotic solutions derived from miscible thermals with equivalent buoyancy (Rahimipour 1994). The solutions of u_f and r_T for the 2D starting plume were first derived by Tsang (1970) based on dimensional analysis as follow:

$$u_f = K_1 \dot{b}_o^{1/3} \quad (12)$$

$$r_T = \alpha_{2DSP} z_f \quad (13)$$

Ching et al. (1993) also obtained the same expressions but with different values of K_1 and α_{2DSP} of 1.20 and 0.30, respectively. In the current experiments (discussed in the following), the value of K_1 and α_{2DSP} are found to be 1.29 and 0.29, which are very close to those suggested by Ching et al. (1993). In BSDM, the values from the current experiments are adopted.

For the 3D starting plume, the asymptotic solutions are adopted from Ai et al. (2006) as follow:

$$u_f = \frac{3}{4} K_2 \dot{B}_o^{1/4} (t - t_{o1})^{-1/4} \quad (14)$$

$$r_T = \alpha_{3DSP} (z_f - z_{o1}) \quad (15)$$

Table 2 summarizes the values of K_2 and α_{3DSP} from previous studies (Ai et al. 2006, Diez et al. 2003, Middleton 1975, Turner 1962). The study by Ai et al. (2006) were performed with advanced Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) which had a higher level of accuracy than the measurement approaches in other previous studies. Hence, their values are adopted in the model. However, the reported values are quite close to each other overall, and small variations do not have a significant effect on the model predictions.

The derivation of the solutions for 2D thermal is shown in the Appendix I, with Equations (26) and (28) representing the solutions of r_T and u_f , respectively. The value of α_{2DT} is adopted from Noh and Fernando (1993) who suggested a value of 0.46 for α_{2DT} . On the other hand, the solutions for 3D thermal are based on semi-analytical solutions, and the derivation is shown in the Appendix II with Equations (34) and (35) being the solutions of u_f and r_T , respectively. Note that, Bush et al. (2003) reported a value of 0.25 for the spreading rate of 3D sediment thermal, α_{3DT} .

Computation Steps

To summarise, the model adopts the following computation steps for the classification:

1. Determine the characteristics of the barged sediments to be disposed, such as $\dot{b}_o$, $\dot{B}_o$, b_o and total excess buoyancy, $B_o (= g'V_o)$
2. Use the 2D starting plume solutions (Equations (12) and (13)) to calculate u_f and r_T until z_f reaches z_e or z_t
 - if $z_e < z_t$, the flow will transit into the 2D thermal regime first (Fig. 4), otherwise the flow will transit into the 3D starting plume regime
3. Compute the virtual distance (z_{o2}) and time origin (t_{o2}) of the 2D thermal by Equations (26) and (28), respectively, with u_f and r_T being the values at $z_f = z_e$
4. Substitute z_{o2} and t_{o2} from step 3 into Equations (26) and (28), and then use these two equations to compute the u_f and r_T in the 2D thermal regime until z_f reaches z_t , after which the flow transits into the 3D thermal regime

5. Compute the virtual distance (z_{o3}) and time origin (t_{o3}) for the 3D thermal by Equations (34) and (35) with u_f and r_T being the values at $z_f = z_t$
6. Substitute z_{o3} and t_{o3} calculated from step 5 into Equations (34) and (35), and then compute the u_f and r_T in the 3D thermal regime.

Experiments

Experimental Setup

The experiments in the present study were carried out in a water tank with dimensions of 2.4 m (length) $\times$ 2.2 m (height) $\times$ 1.2 m (width). The sides of the flume were constructed with glass to facilitate the image acquisition. Fresh water was used as the ambient fluid with a water depth of 2 m. A model barge (Fig. 5, made with two rectangular acrylic boxes) was designed from an actual barge scaled down through volumetric scaling (Appendix III) with dimensions of 20 cm (bin length, L) $\times$ 4 cm (bin height, D_b) $\times$ 4 cm (bin width, W_b). A finite amount (112g) of uniform-size particles (Ballotini Impact beads, Potters Industries, Inc.) with a density, ρ_s of 2.5 g/cm³ was used as the sediments for all tests. Once the experiment was initiated, the two rectangular boxes would rotate in opposite directions with an angular speed, ω ($= 1.5$ rad/s), forming an opening in the middle through which the glass beads were released. In the present study, four particle sizes were considered: size A1 with a median diameter, $d_{50} = 0.725$ mm, A2: 0.513 mm, A3: 0.256 mm and A4: 0.120 mm. The opening width, W ranged from 5 to 40 mm with the corresponding L/W and LW listed in Table 3. Note that since L was fixed in the model barge, a larger L/W in the present experiments corresponded directly to a smaller LW .

The motions of the disposed sediments were illuminated by a spotlight and recorded using two video cameras (SONY HDR-XR550E, with a resolution of 1920×1080 pixels at 25 fps) from both the longitudinal and transverse directions (placement of video cameras shown in Fig. 5). The extraction of gross characteristics of the sediment cloud from the experimental recorded videos was achieved through image analysis using a customized MATLAB program. In order to convert the pixel values into real dimensions, a scale factor was taken by placing a meter ruler vertically at the center of

the model barge before each batch of experiments. In the post-processing, the images recorded by the video camera had the background subtracted first, before the gray scale conversion. After that, the gray scale value on each pixel was summed up horizontally to produce a column vector at each time frame and then combined in the time series to yield a sequence of individual horizontally integrated images (Fig. 6). To trace the horizontal spreading, the same integration was also performed vertically (Fig. 6). The integrated images provided a quasi-steady representation of the transient flow phenomenon, and qualitatively described the spatial and temporal distributions of particles. The frontal position, z_f and cloud sizes, r_T and r_L were determined from the horizontal and vertical integrated images, respectively.

Each test condition was repeated 5 times to ensure repeatability. The average results with the error bars showing the scattering were reported in the subsequent analyses.

Experimental Observations

The descending motion of the sediment clouds after the barge release is shown in Fig. 7. The dark pixels (or area) illustrate the area covered by sediments. The value of t_e for each experiment is indicated in the figure. Clearly, when $t < t_e$, the sediments can be observed to discharge continuously from the barge opening with a ‘thermal-like’ front head, and the sediment cloud had a typical tadpole shape similar to the buoyant starting plume described by Tsang (1970) and Ai et al. (2006). After the sediments were emptied from the barge at a larger time when $t > t_e$, the sediment cloud then descended in a self-preserving manner. Later on, the sediment cloud entered the dispersive phase when the descending velocity slowed to the level of particle settling velocity.

In some experiments (e.g. A1LW05), the starting plume regime only lasted momentarily after the release was initiated. When L/W increased (e.g. Experiment A1LW40), the sediments would discharge at a slower rate due to the narrower opening width. As a result, the starting plume regime was extended for a longer time. Comparing Experiments A1LW05 and A4LW05 with the same L/W , the value of t_e increased when d_{50} decreased. Thus, the starting plume regime was easier to be

achieved with smaller d_{50} and larger L/W . For example, comparing Experiments A1LW05 and A4LW40, the tadpole shape of the starting plume regime was easily captured in the later case.

Fig. 8 illustrates the development of the sediment cloud during Experiment A3LW40 in both longitudinal and transverse directions. The black horizontal line marks the vertical location where the transition from two-dimensional (2D) to three-dimensional (3D) flow regimes occurred. The depth of this transition point is defined as the transition depth, z_t . The dashed lines plot the spreading of the sediment cloud, with the slope representing the spreading rate, α . From the figure, it can be seen that the spreading rate in the longitudinal direction, α_{L1} was less than the transverse direction, α_T in the beginning of the descent process. When the transverse radius, r_T subsequently reached a size comparable to the longitudinal radius, r_L , it began to grow at the same rate ($\alpha_{L2} \approx \alpha_T$). Viewed from the top, the observation above showed that the sediment cloud transited from approximately elliptical to circular. Hence, the flow regimes were governed by the comparative spreading rates in the two directions. In 2D flow regimes, α_L is generally small compared to α_T . However, in 3D flow regimes, the spreading in both directions are similar. For barge releases, the sediment cloud behaves in a 2D manner in the beginning of the descent process, and then transits to 3D when the frontal position of the sediment cloud reaches z_t .

In summary, the flow regimes experienced by the sediment cloud can be categorized into starting plumes and thermals as well as 2D and 3D flow regimes. The experimental results also suggested that the transition depths, z_e and z_t are strongly related to the geometry of the barge opening and d_{50} .

Two-dimensional Starting Plume Regime

In all the experiments, at the beginning of the descent process, a 2D starting plume regime typically occurred with the sediments continuously released from the barge and negligible longitudinal entrainment. The results at the initial time were compared to the asymptotic solution of a 2D starting plume. Note that Tsang (1970) and Ching et al. (1993) found a linear relationship between the frontal position of a starting plume and the time of discharge, t (i.e. $z_f \sim t$) with the coefficient of proportionality, K_1 ranging from 1 to 1.2.

Fig. 9 plots the transient development of the sediment cloud frontal position with time. The data are plotted in the region where $z_f < z_e$ and/or z_t . The characteristics scales, L_n and T_n are defined as

$$L_n = \dot{b}_o^{2/3} g'^{-1}, T_n = \dot{b}_o^{1/3} g'^{-1} \quad (16)$$

and they are used to normalise the experimental results in the 2D starting plume regime. The values of $\dot{b}_o$ are assumed to be constant for each test condition within the starting plume regime. In the figure, the normalised results tend to collapse into a single linear curve, with an average slope of 1.29. The linearity of the curves illustrates that the assumption of constant $\dot{b}_o$ is valid and the slope indicates that starting sediment plumes descend slightly faster than the corresponding single phase starting plume. Fig. 10 shows the lateral growth of a 2D starting plume in the transverse direction. The fitted spreading rate, α_{2DSP} is 0.29, which is very similar to the spreading rate of a single phase starting plume.

Equations Calibration

In order to determine the functional forms of t_e , z_e and z_t , Equations (4), (5) and (7) were calibrated with t_e , z_e and z_t obtained from the experiments. The variations of dimensionless t_e with $LW/V_o^{2/3}$ are shown in Fig. 11. The linearity of the logarithmic plotted data illustrates the following relationship:

$$t_e \sqrt{\frac{g'}{V_o^{1/3}}} \sim \left(\frac{LW}{V_o^{2/3}} \right)^a \quad (17)$$

with $a = -0.55$, from the slope of the best-fitted lines. Thus, Equations (4) can be expressed as

$$t_e \sqrt{\frac{g'}{V_o^{1/3}}} / \left(\frac{LW}{V_o^{2/3}} \right)^{-0.55} = f_8(D^*) \quad (18)$$

Subsequently, by plotting t_e against D^* as shown in Fig. 12, we obtain:

$$t_e = C_1 (D^*)^{a_1} \left(\frac{LW}{V_o^{2/3}} \right)^{-0.55} \sqrt{\frac{V_o^{1/3}}{g'}} \quad (19)$$

with $C_1 = 481$ and $a_1 = -0.96$ from the best-fitted results from Fig. 12.

The variations of z_e from the experimental results are plotted in Fig. 13. The following form can be established from the data:

$$z_e = C_2 \left(\frac{t_e \sqrt{g'}}{V_o^{1/6}} \right)^{a_2} V_o^{1/3} \quad (20)$$

where C_2 and a_2 are found to be 1.0 and 0.61, respectively, based on the best-fitted curves plotted in Fig. 13.

The relationship between z_t and L/W as well as t_e is presented in Fig. 14. The x-axis was formulated to fulfil the two following conditions discussed previously (i.e. $z_t = 0$ when $L/W = 1$ and z_t increases with L/W). Note that z_t increased with t_e due to the fact that the spreading of starting plumes is less than that of round thermals (i.e. $\alpha_{2DSP} = 0.29 < \alpha_{2DT} = 0.46$) in the 2D regimes. In Fig. 14, the best-fitted line of the data yields

$$z_t = C_3 \left[\left(\frac{t_e \sqrt{g'}}{\sqrt{L}} \right) \log \left(\frac{L}{W} \right) \right]^{a_3} L \quad (21)$$

with $C_3 = 0.62$ and $a_3 = 0.33$. In the subsequent analyses, Equations (19), (20) and (21) are employed to compute t_e , z_e and z_t , respectively for the comparisons of flow regimes and gross characteristics.

Comparison of Model Predictions with Experimental Data

Flow Regime Analysis

Here, a total of four asymptotic cases (2D and 3D starting plumes as well as thermals) and two different cases of dispersive phases are analyzed. The frontal velocity, u_f , and z_f are plotted in logarithmic scale, and the slope, n of the line is compared with the n value of the asymptotic cases as follow:

$$u_f \sim z_f^n \quad (22)$$

From the literature, the values of n for the four asymptotic cases are summarized in Table 4. The data plots from Figs. 15 to 18 are obtained from the experiments. The solid and dash lines in the figures represent z_e and z_t from Equations (20) and (21), respectively. The values of z_d are marked in the figures with solid lines and crosses at the ends.

The length parameters, z_e , z_t and z_d , divide the plot into different regions. The value of n in each region is stated on the graph and compared with the flow regime predicted by BSDM. The

comparison indicates that the experimental results and model predictions are generally in good agreement; the few exceptions are marked in *italics*.

With $L/W = 5$, Fig. 15 shows that the experimental results generally agree with the model predictions, but that results from two regions have some small differences. For Experiments A1LW05 and A2LW05, in the regions between z_t and z_d , the model suggests that the sediment cloud had entered the 3D thermal regime (C4) while the value of n implied otherwise. This can be explained by the fact that the transition of the sediment clouds from the thermal phase to the dispersive phase is gradual and not abrupt as assumed in the present model. However, the differences due to the assumption are small, and the detailed two-phase behaviour can only be described accurately with two-phase approaches such as Lai et al. (2013).

In the initial stage of the settling process, the 2D starting plume regime (C1) was generally predicted and observed as discussed in previous section. However, in some cases (i.e. A4LW10, A4LW24, A3LW24 and A3LW40), the values of n implied otherwise. This may be due to the existence of a momentum-dominated region that is usually found before the starting plume regime (Tsang 1970). Figs. 16 to 18 suggest that the effect of this region increases when L/W increases.

Gross Characteristics Comparison

In Fig. 19, the transient development of the frontal position, z_f with radius, r_T from four experiments (A3LW05, A3LW40, A4LW05 and A4LW40) are compared with model predictions. Note that the length scale ratio between the laboratory and field was calculated to be approximately equal to 230 (Appendix III). Hence, the comparison covers the realistic depth of most disposal sites. For Experiment A3LW05, the geometric characteristics of the sediment cloud were well predicted by the present model. For Experiment A3LW40, the present model performed very well as shown in Fig. 19 c and d. The slight deviation in the penetration depth prediction might be due to the momentum-dominated region, which shifted the virtual origin of the starting plume.

For Experiment A4LW05, the geometric characteristics of the sediment cloud were again well predicted by the present model, despite the under-estimation in r_T at the beginning. In Experiment

A4LW40, the penetration depth was under-estimated by $\sim 14\%$, which might also be due to the momentum-dominated region. The prediction for the cloud size was however very good as shown in Fig. 19 (h).

Fig. 19 also includes the simulated results from the earlier K&C and STFATE models. The predictions from K&C's model are the same for every case because the effects of L/W and d_{50} are not considered; and in STFATE, L/W only affects the insertion speed of the sediment layer. Overall, our model has substantially improved the predictions of the gross characteristics of the barge disposed sediments as shown in the figure.

As stated above, there remain at least two limitations in our model. First, the momentum-dominated region is not considered which might be significant when L/W is large. Second, the transitions between flow regimes in the model are assumed to be abrupt, with sharp transitions between two adjacent regimes, whereas in reality the transitions are more gradual. However, the analysis indicates that the two effects were not overly significant within the experimental range.

Comparison of Model Predictions with Field Data

As an application example, we simulated the field disposal operation (Disposal No. 7 at the Lake Ontario in Rochester, NY) recorded in Bokuniewicz et al. (1978) with BSDM. Based on the Table 10 in Bokuniewicz et al. (1978) that summarized the operation conditions, 443 m^3 of dredged material was discharged through the U. S. Hopper Dredge Lyman. The discharged material consisted of mainly watery disposal material with the density of $1.2 \times 10^3 \text{ kg/m}^3$. The descent of the leading edge of the cloud, z_f was recorded with an echo sounder.

The difference between the disposal from a hopper dredge and barge is that the disposed sediments from a single hopper will descend as an individual cloud at the beginning. When the size of the cloud, r_T exceeds half of the spacing between the openings of adjacent hoppers (i.e. $r_T > S/2$, S is the spacing), the sediment clouds will merge and descend as a group (as shown in Fig. 1 in Bokuniewicz et al. (1978)). In BSDM simulations, we have taken that the data recorded in Bokuniewicz et al. (1978) was the horizontal integration of 4 individual descending clouds (i.e. 4 hoppers were used). Thus, $V_o = 111 \text{ m}^3$ (volume carried by a single hopper), $t_e = 54 \text{ s}$, $L = W = 1.01 \text{ m}$

(bottom opening area of a single hopper was 1.03 m^2) and $\rho_s = 1.2 \times 10^3 \text{ kg/m}^3$. The z_f predicted by BSDM is compared with the field observation in Fig. 20.

The comparison shows that the present model performed very well, with the time for the sediment cloud to impact the sea bed only differing from data by $\sim 20 \%$. The prediction from STFATE, however, was far off and unavailable when $t < 10.5 \text{ s}$. This might be due to the fact that the first layer of sediment was still discharging when $t < 10.5 \text{ s}$, and the simulation only began when the first layer was fully discharged. Furthermore, the sediment cloud velocity upon impact on the seabed (dz_f/dt at $z = 14 \text{ m}$), which might affect the subsequent horizontal spreading of the collapsed cloud, was also well predicted by the present model.

Summary and Conclusions

In the present study, a new model (BSDM) is developed for the assessment of the open water disposal of barged sediments based on the classification scheme with six different flow regimes (four asymptotic cases: two- and three-dimensional starting plumes as well as thermals plus two cases of dispersive phases). Each regime is quantified with equations either from the present experiments or data from past literature. The model provides both qualitative and quantitative predictions of the behaviour of barged disposed sediment cloud. An experimental investigation was carried out for the verification. The experimental results showed that the predictions from BSDM are substantially better than the existing models of K&C and STFATE. The predictions of the actual field disposal operation of Bokuniewicz et al. (1978) was also in good agreement with the recorded field data.

From engineering perspectives, BSDM can be used to determine the parameters of the disposal operation (i.e. barge geometry with the opening aspect ratio, L/W , etc.) to target a specific regime for the convective descent phase in consideration of the size of the sediments being disposed. For example, to reduce the possibility of losing the sediments to ambient currents and waves as turbidity (Gensheimer et al. 2012, Zhao et al. 2013), it would be desirable for the sediment cloud to be maintained in the thermal/plume regime before the bottom impact (Johnson et al. 2008). The assessment from BSDM is expected to be more accurate compared to STAFTE, which is widely used

in the industry at present (Bailey et al. 2004, Dong et al. 2007, EPA 2004, Howlett 2003). The gross characteristics of the sediment cloud at the bottom impact can also be computed to evaluate the penetration potential of the cloud into the seabed deposit, for consideration in the dumping of sand covers over confined bottom cells for contaminated sediments (Eek et al. 2008). Looking ahead, we shall also continue to develop BSDM to incorporate the analysis of the dynamic collapse phase from the different flow regimes.

Appendix I. Asymptotic solution for two-dimensional (2D) sediment thermal

A 2D thermal is the motion formed when a line of buoyant fluid is released from rest instantaneously (Lee and Chu 2003) as illustrated in Fig. 21. The motion of the line thermal can be described by an integral model tracking the change in its mass per unit length m' , momentum per unit length M' and buoyancy per unit length b .

$$\frac{dm'}{dt} = 2\pi\gamma r_T \alpha_{2DT} \rho_a u_f \quad (23)$$

$$\frac{dM'}{dt} = b \quad (24)$$

$$\frac{db}{dt} = 0 \quad (25)$$

where $m' = \rho V/L$; $M' = (1+C_M)\rho\pi\gamma r_T^2 u_f$; $b = V(\rho-\rho_a)g/L$; $V = LA_{2DT} = \pi\gamma r_T^2 L$ is the total volume; A_{2DT} is the cross-sectional area of the line thermal; ρ is the mean density of the sediment thermal; and γ is the height to width ratio of the sediment thermal. Lee and Chu (2003) suggested $\gamma = 0.69$ and $C_M = 1$ for a two-dimensional thermal, and the same values are adopted in the present study. Equation (23) is based on the entrainment assumption (i.e. the rate of entrainment at the edge is proportional to the characteristic velocity of the thermal) by Morton et al. (1956). The proportionality constant is referred to as the entrainment coefficient, denoted as α_{2DT} in Equation (23). Equation (24) is based on the conservation of momentum due to buoyancy and added mass (C_M); and Equation (25) is based on the assumption that there is no buoyancy loss to the wake and thus b is a constant ($= (\rho_s - \rho_a)gV_o/L$).

The above equations can be solved analytically within the Boussinesq range (i.e. $\rho \approx \rho_a$), with initial conditions applied at the virtual point source (i.e. $z_f = z_{o2}$, $r_T = 0$, and $M = 0$ at $t = t_{o2}$), yielding:

$$r_T = \alpha_{2DT} (z_f - z_{o2}) \quad (26)$$

$$z_f = \left(\frac{3b_o}{2(1+C_M)\pi\gamma\alpha_{2DT}^2} \right)^{1/3} (t - t_{o2})^{2/3} + z_{o2} \quad (27)$$

Equations (26) and (27) describe the growth and penetration behaviour of the two-dimensional sediment thermal. Lee and Chu (2003) deduced the value of α_{2DT} to be 0.46, which is similar to the growth rate of two-dimensional sediment thermal observed in the experiments of Noh and Fernando

(1993). By substituting $\gamma = 0.69$, $C_M = 1$ and $\alpha_{2DT} = 0.46$, the frontal velocity, u_f can be derived by differentiating Equation (27) and expressed as:

$$u_f = 0.79b_o^{1/3} (t - t_{o2})^{-1/3} \quad (28)$$

Appendix II. Asymptotic solution for three-dimensional (3D) sediment thermal

The model for the three-dimensional sediment thermal is based on the assumptions that the discrete solid and water phases within the sediment thermal can be approximated as a miscible dense fluid with equivalent buoyancy excess, and the Boussinesq approximation can be adopted (Ruggaber 2000). The governing equations of the model can be simplified by neglecting the effect of added mass and drag forces as suggested by Bush et al. (2003) yielding:

$$\frac{dm}{dt} = \eta 4\pi \alpha_{3DT} r_T^2 \rho_a u_f \quad (29)$$

$$\frac{dM}{dt} = B \quad (30)$$

$$\frac{dB}{dt} = 0 \quad (31)$$

where m is the total mass of a sediment thermal including both solid and liquid phases; B is the total buoyancy force (i.e. $B = (\rho - \rho_a) gV$); $V = 4\pi\eta r_T^3/3$ is the sediment thermal total volume where η is a shape factor to account for the non-spherical shape of the cloud as an oblate ellipsoid with width r and height ηr . Scorer (1957) suggested that $\eta = 9/4\pi$ and the same value is applied in present study. Note that Equation (31) is based on the assumption that no sediment loss is induced by the wake and thus that the total buoyancy force, B is a constant ($= (\rho_s - \rho_a) gV_o$).

The above equations can be solved analytically within the Boussinesq range (i.e. $\rho \approx \rho_a$) and applying the initial conditions at the virtual point source (i.e. $z_f = z_o$, $r = 0$, and $M = 0$ at $t = t_o$), the solution can be expressed as:

$$r_T = \left(\frac{3\alpha_{3DT} B_o}{2\pi\eta} \right)^{1/4} (t - t_{o3})^{1/2} \quad (32)$$

$$z = \left(\frac{3B_0}{2\pi\eta\alpha_{3DT}^3} \right)^{1/4} (t - t_{o3})^{1/2} + z_{o3} \quad (33)$$

Equations (32) and (33) describe the size and penetration behaviour of the 3D sediment thermal, respectively. By substituting $\eta = 9/4\pi$ and $\alpha_{3DT} = 0.25$ (Bush et al., 2003), the frontal velocity, u_f can be derived by differentiating Equation (33) as:

$$u_f = 1.28B_0^{1/4} (t - t_{o3})^{-1/2} \quad (34)$$

Using Equation (33), Equation (32) can also be expressed as:

$$r_T = \alpha_{3DT} (z_f - z_{o3}) \quad (35)$$

Appendix III. Scaling Analysis – Volumetric Scaling

The motion of sediment clouds in the convective descent phase is dominated by their total buoyancy rather than the properties of individual particles. Therefore, the laboratory dimensions from the present study can be linked to the field conditions through scaling analysis. It involves the length scale (L) derived from volumetric scaling, as well as the velocity (U) and time (T) scales based on Froude scaling (White 1979).

$$L_F = L_E \left(\frac{V_F}{V_E} \right)^{1/3}, U_F = U_E \sqrt{\frac{L_F}{L_E}}, T_F = T_E \sqrt{\frac{L_F}{L_E}} \quad (36)$$

where the subscript “ F ” and “ E ” denote the field and laboratory (experiment) scales. Using the typical volume of a barge for sediment disposal ($V_F = 1000 \text{ m}^3$) and the volume of sediments chosen in a single release in the laboratory ($V_E = 80 \text{ cm}^3$), a length ratio of $L_F/L_E \approx 230$ was derived. The length, velocity and time scales can also be applied for the water depth and barge opening speed.

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Tables

Table 1. Physical length parameters for barged sediments disposal

Physical length parameter	Descriptions
Empty depth, z_e	The distance at which the transition from plumes (continuous) to thermals (instantaneous) takes place
Transition depth, z_t	The distance at which the sediment cloud transits from two-dimensional into three-dimensional (3D) flow regimes
Dispersive depth, z_d	The distance at which the solid sediment particles leave the entrained fluid and settle at their respective settling velocities
Water depth, h	Water depth or depth of interest within the water column

Table 2. Summary of the values of K_2 and α_{3DSP} for 3D starting plumes

Previous studies	K_2	α_{3DSP}
Turner (1962)	2.54	0.18 ± 0.03
Middleton (1975)	2.43	0.18 ± 0.03
Diez et al. (2003)	2.70	0.16
Ai et al. (2006)	2.58	0.16 ± 0.03

Table 3. Experimental Conditions

Test No.	W [cm]	L/W	LW [cm ²]	d_{50} [mm]	Re_p
A1LW05	4	5	80	0.725	76.5
A1LW10	2	10	40		
A1LW24	0.8	24	17		
A1LW40	0.5	40	10		
A2LW05	4	5	80	0.513	36.5
A2LW10	2	10	40		
A2LW24	0.8	24	17		
A2LW40	0.5	40	10		
A3LW05	4	5	80	0.256	7.5
A3LW10	2	10	40		
A3LW24	0.8	24	17		
A3LW40	0.5	40	10		
A4LW05	4	5	80	0.120	1.2
A4LW10	2	10	40		
A4LW24	0.8	24	17		
A4LW40	0.5	40	10		

Table 4. Values of n (Equation (22)) for the four asymptotic cases

	Starting Plume	Thermal
2D	$C1 = 0$	$C3 = -0.5$
	(Tsang, 1970)	(Noh and Fernando, 1993)
3D	$C2 = -0.51 \sim -0.28$	$C4 = -1$
	(Turner, 1962)	(Scorer, 1957)

Figures

Fig. 1. Illustration for physical length parameters, (a) empty depth, z_e , (b) transition depth, z_t , (c) dispersive depth, z_d and (d) depth of interest, h

Fig. 2. Flow regime classification for the open water disposal of sediments from a bottom split-barge

Fig. 3. Simultaneous virtual distance and time origins (3D thermal)

Fig. 4. Development of flow regimes for barged sediments disposal

Fig. 5. Schematic of model barge (disposal bin) and definition of symbols

Fig. 6. Horizontal (top-left) and vertical (bottom-right) integrated images

Fig. 7. The descending motion of sediment clouds released from barge (cont'd)

Fig. 8. The development of the sediment clouds in (a) longitudinal and (b) transverse directions from Experiment A3LW40

Fig. 9. Normalized cloud frontal position, z_f/L_n versus time, t/T_n in the two-dimensional starting plume regime

Fig. 10. Cloud transverse radius, r_T versus frontal position, z_f in the two-dimensional starting plume regime

Fig. 11. Relationship between barge empty time, $t_e (g'/V_o^{1/3})^{1/2}$ and opening area, $LW/V_o^{2/3}$

Fig. 12. Relationship between barge empty time, $t_e (g'/V_o)^{1/3} / (LW/V_o^{2/3})^{-0.55}$ and dimensionless particle diameter, D^* (solid line represents the best-fitted line of the data)

Fig. 13. Relationship between empty depth, z_e and barge empty time, t_e (solid line represents the best-fitted line of the data)

Fig. 14. Relationship between transition depth, z_t and opening aspect ratio, L/W as well as barge empty time, t_e (solid line represents the best-fitted line of the data)

Fig. 15. Development of frontal velocity, u_f with distance ($L/W = 5$)

Fig. 16. Development of frontal velocity, u_f with distance ($L/W = 10$)

Fig. 17. Development of frontal velocity, u_f with distance ($L/W = 24$)

Fig. 18. Development of frontal velocity, u_f with distance ($L/W = 40$)

Fig. 19. Comparison between experimental results and model predictions for the development of normalized frontal position, z_f and radius, r_T versus time

Fig. 20. Comparison between field observation and model predictions for the development of frontal position, z_f versus time

Fig. 21. Line thermal generated by releasing a cylinder of negatively buoyant material instantaneously