CHAPTER 125

HYDRODYNAMIC ANALYSIS OF SLUDGE DUMPED IN COASTAL WATERS

Billy L. Edge, A.M. ASCE[1]

ABSTRACT

Due to increased environmental pressures, there is a rapidly growing tendency to shift from traditional land disposal of dredged material to offshore or ocean disposal. The quantities of such materials are quite large, resulting in a very serious disposal problem. For example, maintenance dredging alone produces approximately six million cubic yards of material annually in Charleston Harbor. Existing techniques are reasonably adequate to describe the transport and settling characteristics of coarse, sandy dredge materials discharged from barges or hopper dredges at sea. However, such approaches need to be modified to describe the transport of fine-grained clay and silt materials. This material constitutes a significant portion of the dredged material resulting from both new harbor and channel construction and maintenance dredging along the coast of the Carolinas and Georgia. These fine-grained materials are subject to many additional physical forces as well as chemical phenomena, e.g., flocculation, salinity and temperature variations, etc. A hydrodynamic model for fine-grained dredged material has been developed which considers many of these forces. It is also applicable for describing the transport mechanisms associated with barge disposal of wastewater sludges from municipal and industrial sources. The results of the model indicate what discharge strategies are necessary for placing the sludge at a desired location or depth with a predetermined concentration.

INTRODUCTION

Increased industrialization and urbanization has resulted in an increasing demand for siting activities in estuarine areas. As a result, there is little room left for creating fill areas on land or in the marshes to dispose of the great quantities of dredged material. In addition, many of the fill or disposal areas which have been used in the past are thought to be creating environmental problems and may never serve any beneficial purpose. Because of these ecological problems and as a consequence of demands for increased dredging depths, consideration is being given to disposing of most dredged materials in the future into the ocean environment. More than 112 sites are already being used for offshore disposal of waste and dredged material. A significant and growing portion of the public as well as some governmental agencies see this as a serious problem whereas other groups view this as the only economic solution for future dredging.

In the ocean environment, much of the dumped material is subject to complicated energy forces which vary from hour to hour. Wind forces appear to exert very strong influences in shallow waters; however, in deeper areas

[1]Associate Professor, Department of Civil Engineering, Clemson University, Clemson, South Carolina, 29631.

a different relationship exists among the governing forces. Because of this complex situation, much more information is needed on winds, tides, currents, and other hydrological phenomena before the fate of dumped materials can be predicted with any reasonable accuracy and an effective program of disposal wisely managed. Additional information would also provide a firmer basis for setting standards and providing guidelines for disposal.

One of the important quantifiable variables that affects the ultimate location of the dumped material is the disposal characteristics of the barge or dredge. The officer in charge may not be particularly concerned with dumping fine-grained sediment or "fluff" directly over the disposal areas since the material if dumped just outside of the dredging site or channel on the littoral downstream side may pass over the disposal area. Physically the material is then out of the channel, but the determination of its ultimate location for a true evaluation of the environmental impact will be impossible under these circumstances using currently-employed techniques.

A characteristic of a large percentage of the dredged material is that it is very fine-grained and therefore has a very low settling rate. An additional complicating factor in the disposal of fine-grained sediments is the effect of the thermocline on the settling and flocculation characteristics of the sediments. It has been shown that some of the fine-grained taconite tailings which are being dumped in Lake Superior are settling only to the thermocline (21). The tailings are then transported with the natural current along the surface of the thermocline as on a conveyor belt to some other location where they ultimately settle out of suspension. The same phenomena may very well be occurring with a significant proportion of the fine-grained material that is currently being dumped at sea as suggested by Amos et al. (2).

The disposal of dredged material quite often results in increased turbidities and changes the bottom configuration as well as alters the hydrodynamic characteristics of the local area. All of these factors can adversely or beneficially affect the aquatic environment. According to Horne, et al. (14), an accumulation of as little as 30 cm/yr may be great enough to exterminate certain benthic organisms. Conceivably, dredging may be offered as a tool for removing objectionable bottom deposits such as the sludge banks below municipal and industrial wastewater treatment plants in large coastal cities. The disposal of such material is of prime importance when it is recognized that the ultimate location will be yet another benthic community.

The Corps of Engineers has estimated that about 45 percent of the dredged material on the Atlantic Coast is polluted (8). The sources of this pollution are quite numerous and include industries, municipalities, and agriculture as well as natural benthic sources. Dredge spoils account for 80 percent, or 34 million tons annually, of all ocean dumping.

New and improved techniques for determining sedimentation rates have been recommended as a high-priority research area by a recent study (20). That study recommended "increased knowledge of the effects of offshore and nearshore dumping" and "increased knowledge of the sources and rates of sedimentation and the effects of sedimentation on the ecosystem."

The National Academy of Sciences and the National Academy of Engineering provided advice to the Federal government on management of waste in the coastal marine environment (18). An extensive study was carried out by a group of consultants to answer various questions concerning the effect of dumping waste in the ocean. Some of the conclusions of their study were:

1. For barge dumping of *sludges* in the ocean, research is needed on flows generated by suddenly released sinking sludge in a stratified environment.

2. There is need to develop *predictive models* for gross spreading of patches and plumes in the ocean from the combined effects of eddy diffusion (both horizontal and vertical) and shear in the mean velocity field.

3. A study should be made of the physical-chemical factors and the role of organisms in effecting the *flocculation rates* of sediments in estuaries and coastal waters. (Emphasis added.)

Pollution resulting from the dumping of waste material into the ocean is now recognized as a serious, complex, and rapidly-growing problem in the management and use of the Nation's ocean resources. The public has become very aware of the existing and potential adverse environmental effects from the discharge of waste material on the continental shelf. The lack of reliable means to determine the ultimate effects of the dumped materials has caused much concern and apprehension over the present, oftentimes seemingly arbitrary, approach to dumping at various sites throughout the Nation's coastal zone. The work outlined in this paper is aimed directly at this problem and should provide a useful tool for evaluating the ultimate location of waste material which is dumped on the continental shelf. The results of this study should be quite beneficial to those agencies responsible for establishing disposal criteria as well as for those who must prepare environmental impact statements for their dredging programs.

SIMULATION MODEL

Because of the many forces, both physical and chemical, which influence the dynamics of material which is dumped into the ocean, it is necessary to make several assumptions regarding the forces which have a significant influence in this problem. The developed simulation procedure, then, does not include all forces which enter into this problem. Instead a mathematical model has been built for those parameters and forces which are considered to be most significant. In this framework, the model can be used as a tool together with sound judgment to provide a description of the transport mechanisms which can be used in evaluating various dumping operations.

The mathematical model for simulating the disposal of wastes at sea is composed of a combination of jet theory and sedimentation theory. The model is essentially composed of two parts: first, a simulation of a negatively-buoyant jet discharged downward into a stratified environment; and, second, sedimentation theory is used to provide a description of the transport of material from the end of the jet to the floor of the ocean. A similar approach is presented by Clark et al. (7) in which they present a technique for analyzing disposal from a hopper barge.

As shown in Figure 1, the transport of the discharged material to the bottom begins from an outlet which is located some distance below the water surface and through which is pumped the waste to be disposed. In the figure is shown the disposal system from a barge. The operating system considered here will be a barge which discharges through a set of large pipes. As the waste exits from the pipes, it follows a jet pattern and the waste will ultimately come to rest on the ocean floor since it is negatively buoyant. However, if the waste in the jet is sufficiently diluted with entrained fluid, then it may not necessarily reach the bottom before it becomes neutrally buoyant and stabilizes at some intermediate depth. As shown in the figure, when the jet reaches this equilibrium depth it still has a small amount of momentum and is carried somewhat below this depth but then rises up in the form of a buoyant plume. At this point, the inertia loses importance and the material is affected by local currents, flocculation, and gravitational attraction. The material then settles toward the bottom while being moved about by currents and turbulence. The ultimate location, spread, and density are the final results that must be obtained to completely and adequately describe the process of dumping wastes at sea.

There are several theories available for predicting the discharge of buoyant jets into still environments. All of these theories are based on the integral conservation equations. The general case of a buoyant jet inclined at an arbitrary angle has been studied by Fan and Brooks (10) for a linearly stratified, quiescent environment. Cederwall (6) has studied, experimentally, the flow of a buoyant slot jet into stagnant or flowing environments. Cederwall did not consider a stratified situation. A good summary of these studies is given by Baumgartner and Trent (4). The most general analytical treatments available are given by Ditmars (9) and Hirst (12). The formulation proposed by Hirst is for jets discharged to flowing, stratified environments. The development of the governing differential equations from their basic integral form can be found in Hirst (12).

Consider the pipe shown in Figure 2, from which is discharged a negatively buoyant jet. The assumptions made concerning the jet flow are:

1. steady flow
2. imcompressible flow
3. fully turbulent jet
4. similar, axisymmetric velocity profiles
5. hydrostatic pressure
6. small jet curvature
7. longitudinal turbulent transport is less than convective transport
8. constant fluid properties

The similarity profiles are Gaussian in form and are given as:

$$u^*(s,r) = \Delta u(s)e^{-r^2/b^2} + U\cos\theta \quad (1)$$

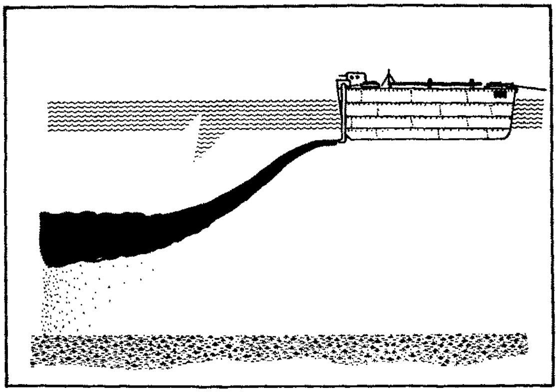


Figure 1. A towed barge discharging waste through a pumped system.

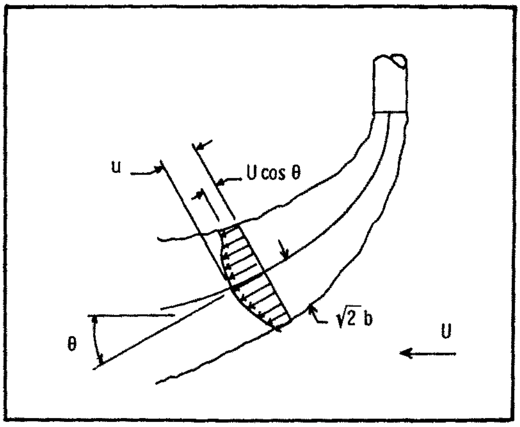


Figure 2. Geometry of a negatively-buoyant jet.

$$\rho^*(s,r) - \rho_\infty = \Delta\rho(s)e^{-r^2/(\lambda b)^2} \quad (2)$$

$$c^*(s,r) = c(s)e^{-r^2/(\lambda b)^2} \quad (3)$$

where

$$\Delta u = u - U\cos\theta$$

$$\Delta\rho = \rho - \rho_\infty$$

and where

$u(s)$ = centerline velocity

$\rho_\infty(s)$ = ambient density

$\rho(s)$ = centerline density

$c(s)$ = centerline tracer concentration

b = a measure of the jet radius

$1/\lambda^2$ = turbulent Schmidt number

$(\ )^*(s,r)$ = refers to parameters across the jet profile

U = speed of cross flow (speed of barge)

The parameter λ is considered the ratio between density and velocity profiles. The velocity $u(s)$ is an absolute velocity. To make the problem static, a uniform velocity has been added to the water column so that barge has zero velocity.

Use of the above assumptions and the similarity profiles with the integral equations yields the following differential equations:

$$\frac{d}{ds}\left[\frac{b^2}{2}\tilde{u}\right] = E \quad (4)$$

$$\frac{d}{ds}\left[\frac{b^2}{2}\left(\tilde{u} + (\lambda^2-1)U\cos\theta\right)\Delta\rho\right] = -\frac{1+\lambda^2}{\lambda^2}\frac{d\rho_\infty}{ds}\frac{b^2}{2}\tilde{u} \quad (5)$$

$$\frac{d}{ds}\left[\frac{b^2}{4}\tilde{u}^2\cos\theta\right] = EU + F_D\sin\theta \quad (6)$$

$$\frac{d}{ds}\left[\frac{b^2}{4}\tilde{u}^2\sin\theta\right] = -\frac{1}{2}g\lambda^2b^2\frac{\Delta\rho}{\rho_0} - F_D\cos\theta \quad (7)$$

where

$\tilde{u}$ = $u + U\cos\theta$

F_D = $C_D\sqrt{2}bU^2\sin^2\theta$

C_D = coefficient of drag

ρ_0 = initial ambient density at outlet

E = entrainment function

These equations represent the conservation of mass, momentum in the x and y directions and the buoyancy, respectively.

The entrainment coefficient, or volume flux relationship, is derived in general terms by Hirst (13). However, a more convenient and proven form is given by Abraham (1).

$$E = b\left(\alpha_m(u - U\cos\theta) - \alpha_b U\sin\theta\cos\theta\right) \qquad (8)$$

This equation is for a negatively-buoyant jet. The coefficient α_m is used to describe the entrainment due to the initial jet action and α_b is due to the negative buoyancy. Abraham gives a value of 0.5 for α_b.

Using Equation 8, Equations 4-7 can be rewritten, after some simplification, as:

$$\frac{d\bar{u}}{ds} = -\frac{4}{\bar{u}b^2}\left[\frac{1}{2} g\lambda^2 b^2 \frac{\Delta\rho}{\rho_0}\sin\theta - E(U\cos\theta - \frac{\bar{u}}{2})\right] \qquad (9)$$

$$\frac{d\theta}{ds} = -\frac{4}{\bar{u}^2 b^2}\left[\frac{1}{2} g\lambda^2 b^2 \frac{\Delta\rho}{\rho_0}\cos\theta + EU\sin\theta + F_D\right] \qquad (10)$$

$$\frac{db}{ds} = -\frac{1}{\bar{u}b}\left[\frac{b^2}{2}\frac{d\bar{u}}{ds} - E\right] \qquad (11)$$

$$\frac{d\Delta\rho}{ds} = -\frac{2}{b^2}\left(\bar{u} + (\lambda^2 - 1)U\cos\theta\right)^{-1}\left[\Delta\rho\left(E + (\lambda^2 - 1)bU(\cos\theta\frac{db}{ds} - \frac{b}{2}\sin\theta\frac{d\theta}{ds})\right) + \frac{1+\lambda^2}{\lambda^2}\sin\theta\frac{d\rho_\infty}{dy}\frac{b^2}{2}\bar{u}\right] \qquad (12)$$

These equations are combined with:

$$\frac{dx}{ds} = \cos\theta \qquad (13)$$

$$\frac{dy}{ds} = \sin\theta \qquad (14)$$

and can be solved simultaneously. A digital computer solution has been used for this system employing a Runge-Kutta-Gill integration technique.

To solve the above equations, it is necessary to have appropriate values of α_m and λ in addition to the initial jet characteristics. Fan and Brooks (10) found $\alpha = 0.082$ and $\lambda = 1.16$ to be quite satisfactory for their work in linearly stratified environments for buoyant jets. There is not sufficient data yet available to validate these coefficients for negatively-buoyant jets, but these numbers will be used for illustrative purposes until better numbers are available.

Since the above solution is only valid for the zone of established flow, the initial values of the jet characteristics must be corrected for the changes which occur in the zone of flow establishment. This zone of flow establishment has been analytically studied by Hirst (7). A simple method for correcting the jet characteristics is to consider that: (1) the jet issues from the pipe and travels a straight-line distance of 6.2D, where D is the pipe diameter; (2) at the end of the zone of flow establishment, (6.2)D, the initial jet half-width $b = D/\sqrt{2}$; and (3) the initial value of $\Delta\rho$, $\rho - \rho_\infty$, is $(1+\lambda^2)/2\lambda^2$ times the difference at the source. At this point, the above equations can be solved with these initial conditions.

If a tracer is contained in the jet, and is not present in the ambient fluid, the following equation can be used to describe the dilution of the substance:

$$\frac{d}{ds}\, cb(u - U\cos\theta) = 0 \qquad (15)$$

or:

$$cb(u - U\cos\theta) = c_0 b_0 (u_0 - U_0 \cos\theta_0) \qquad (16)$$

in which c_0 is the initial concentration at the beginning of the zone of established flow or $(1+\lambda^2)/2\lambda^2$ times the effluent concentration.

The analysis which has been presented thus far is for describing the transport of the dumped material from the barge down to a level of neutral buoyancy. Since the jet overshoots this neutral level, it will rise up to this level of velocity reversal. This is illustrated in Figure 3 which is from the results of Ditmars (9). It has been implied that the ocean floor is sufficiently below the maximum descent to keep from invalidating the technique. From the level of neutral buoyancy, the entrained material in the remaining fluid from the jet will begin to settle to the bottom under gravitational influence. From this point onward, the influencing forces are much more complicated than have been considered thus far. The material is now influenced by even the smallest prevailing currents, including harmonic tidal currents and local turbulence, as well as the chemical factors. If colloidal material is in suspension, it will settle in the form of flocs much more rapidly than otherwise. This flocculation is rapidly advanced in the initial stages of the sedimentation process. Within the process of flocculation a large complex of problems is involved since the flocculation characteristics of various mineral components of clays are at present unknown under saline conditions.

The flocculation rate and magnitude depend upon the different types of clays which are present. The most common clay minerals are kaolinite, illite, and montmorillonite which are hydrous silicates of aluminum, iron, and magnesium. Chemical and particle-size properties combine to produce different flocculation rates for the same concentration of suspended sediment; and, of course, the rate is heavily dependent upon the concentration. Moreover, the amount of flocculation decreases exponentially with time.

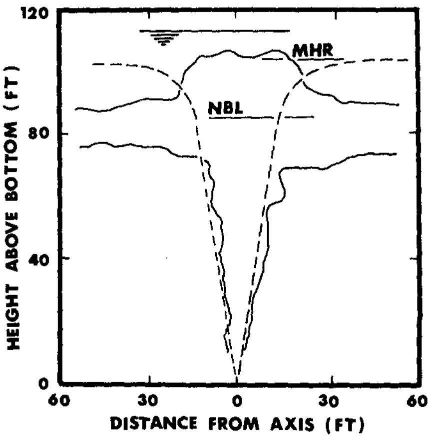


Figure 3. Comparison of a computed profile of a buoyant jet with an observed profile.

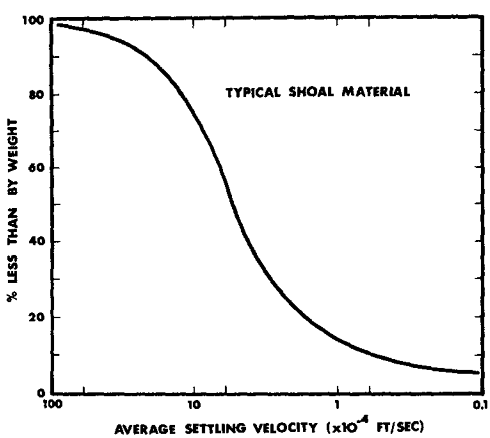


Figure 4. Distribution of settling velocity for shoal material in Charleston Harbor.

The flocs grow to a size and at a rate that is dependent upon the local turbulence. Brownian motion would be much too slow to provide the size flocs that actually exist. Rather, the presence of internal shear flows serve to bring particles into contact more rapidly than could Brownian motion alone. As the particles grow and begin to settle they make contact with other particles for additional growth. The local turbulence also acts to limit the maximum size of the flocs by breaking them apart if they grow too large.

To simplify this analysis, consider that a distribution of settling velocity is available for the material under consideration such as that shown in Figure 4. As the material settles from the cloud at the level of neutral buoyancy, it is affected by local turbulence and is dispersed in the horizontal direction. The scale of turbulent dispersion in the vertical direction is much smaller due to greater stability added by the stratification and will be neglected at this point. Consider also that there is a small cross-current, w, which is constant with depth. The 4/3 law of eddy dispersion:

$$D = CE_r^{1/3} L^{4/3} \qquad (17)$$

where:

- D = dispersion coefficient
- C = coefficient
- E_r = rate of energy dissipation per unit mass
- L = Lagrangian eddy size

has been assumed applicable to ocean dispersion in many cases, and will be used in this analysis.

Orlob (9) obtained the relationship:

$$D = 0.00016L^{4/3} \left[ft^2/sec\right] \qquad (18)$$

from field data taken by others. For a particular site, of course, a study should be undertaken to adequately evaluate the appropriate relationship. The eddy size is taken to be $L = 4\sigma$ where σ is the standard deviation of material in the moving, spreading patch. If the patch of material, with $\sigma = \sigma_b$, is at the level of neutral buoyancy, then Koh (17) has shown that the horizontal dispersion can be characterized by:

$$\sigma = \sigma_b \left(1 + 4^{2/3}\,\frac{2}{3}\,\frac{(0.00016)t}{\sigma^{2/3}}\right)^{2/3} \qquad (19)$$

in which t is the time after the cloud has moved from the line of neutral buoyancy. Now, since the different size particles settle at different velocities, the cloud will not maintain its integrity. The above equation can be used however by applying it for each particle size. In other words, the cloud will be growing at all depths at the same rate.

From knowledge of the distribution of material with settling velocity, the total accumulation of material can be obtained by application of the above equation. A simple extension of this describes the distribution of the material that accumulates on the bottom in the presence of a small current. In fact, this is the result that will be of most benefit in the description of the ultimate fate of dredged materials which are dumped at sea. This result will tell which materials may not have settled in the dumping area as well as the rate of growth (height) of the bottom in the disposal area.

ILLUSTRATIVE EXAMPLE

To provide a meaningful example of the application of this technique, the spoil material is taken as that found in shoals in Charleston Harbor, South Carolina. The settling velocity distribution for this material is shown in Figure 4. The material is assumed to be transported to sea in a 3,000 ton barge. The barge is fitted with two discharge pipes which are both 0.707 feet in diameter. Since the pipes discharge adjacent to one another, they are considered as a single outflow with a diameter of 1.00 feet. The discharge outlet is 10 feet below the water surface. The barge carries a slurry which consists of 300 tons of fixed solids with a specific gravity of 2.5. Thus the total volume of solids discharged per load is 4,320 cu. ft. The barge discharges in water 200 feet deep.

Several situations are considered in this example. First the barge is assumed to be stationary and the jet velocity is varied from 5 fps to 10 fps. The density profile shown in Figure 5 indicates a high degree of stratification and is typical of summer conditions. Conversely, the winter situation shown in this figure was used to compare the effect of highly stratified and slightly stratified ocean environments on the characteristics of the jet model. The winter condition was run only for a velocity of 5.00 fps.

The results for a velocity of 5 fps and 1.00 ft. diameter are shown in Figure 6. It is emphasized that in the description of the plume width, Figure 6, the ultimate width at the neutral buoyancy line is given by the width at the maximum point of travel shown in the figure. The neutral buoyancy level is indicated on the figures by the line of squares. The maximum point of travel of the jet is the level indicated in this figure. The results for a velocity of 10 fps are given in Figure 7. It can be seen from these figures that, as the initial jet velocity increases, the time required for the material to settle to the continental shelf decreased markedly. In Figure 8, the centerline velocity distribution for an initial velocity of 10 fps is presented. The apparent discontinuities in the profile are a result of the sharp breaks in the given density profile. The case of an initial velocity of 12.5 fps was considered, but the jet reached the bottom before it stopped. The theory on which this analysis is based does not consider this effect therefore the results were discarded.

In Figure 9, the total depth of bottom sediment from the discharge of

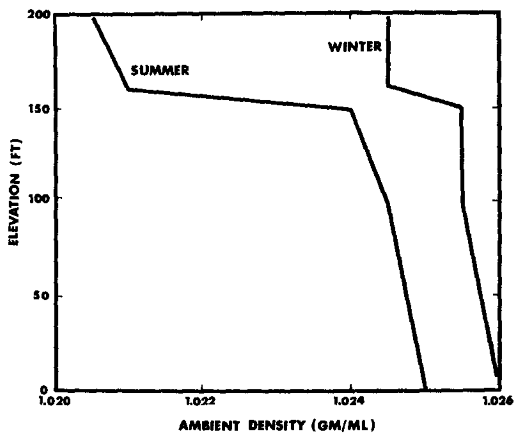
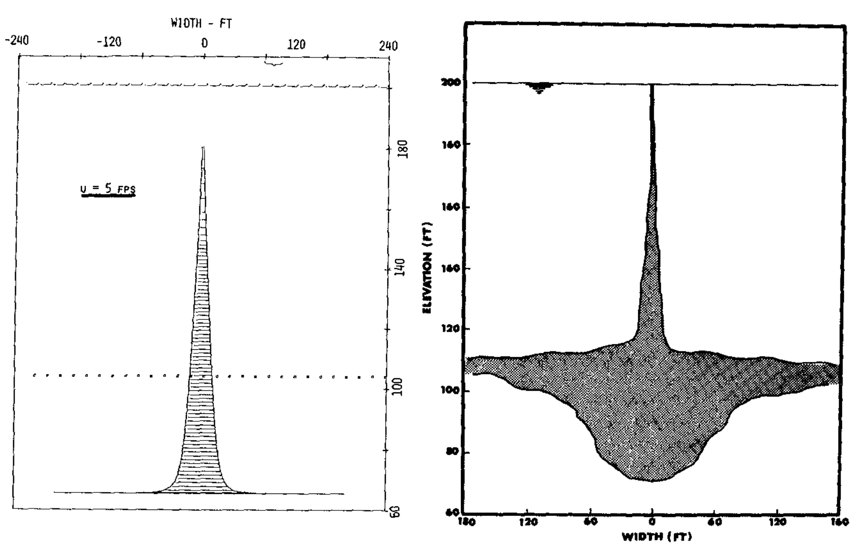


Figure 5. Density distribution during summer and winter conditions.



(a) Results of mathematical model (b) Physical interpretation of results

Figure 6. Variation of jet width with elevation (u_0 = 5 fps).

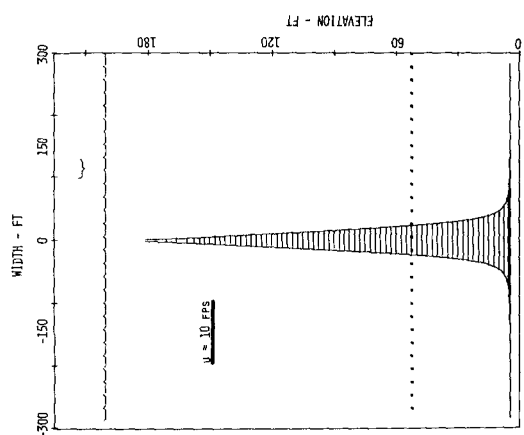


Figure 7. Variation of the jet width with elevation (u_0 = 10 fps).

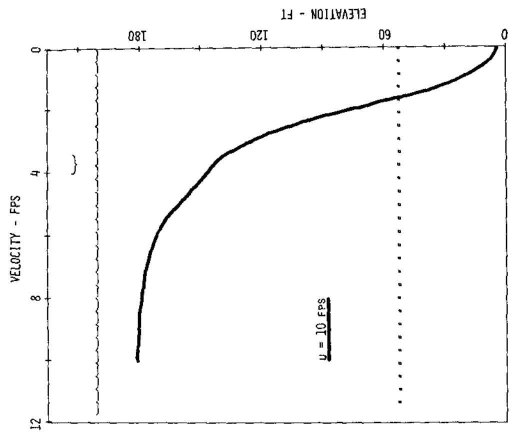


Figure 8. The centerline jet velocity variation with depth (u_0 = 10 fps).

one barge is given. This depth is across the center of the circular disposal pattern. It is emphasized that for this case there is no cross current. The top line gives the total depth while the bottom lines indicate the contribution from particles with different settling velocities. In Figure 10, the distribution of time for settlement is given for velocities of both 5 fps and 10 fps. It is obvious from the figure that very little material will settle out of the suspension within a day. If more than one load is dumped within a short interval of time, it is probable that the concentrations would increase to the extent that flocculation may occur and more rapid sedimentation could result. In this analysis it has been assumed that flocculation does not occur. This is a valid assumption since the volume percentage of sediment is less than 0.1% at the neutral buoyancy level.

The jet diameter was changed to 1.5 ft., and for an initial velocity of 5 fps the jet reached the bottom and established neutral buoyancy at an elevation of 40 ft. From this it would appear that the neutral buoyancy level and thus the ultimate sediment distribution on the bottom is more sensitive to changes in jet diameter than jet velocity. Also it may be desirable to keep the jet from reaching the bottom and resuspending the sediment there.

For the winter density profile, the jet plume reached the bottom while establishing neutral buoyancy at 30 ft. This case, with an initial velocity of 5 fps indicates a considerable difference in the ultimate location of the spoil material when compared with disposal under summer conditions. Although this result was anticipated, it nevertheless firmly establishes the large differences which can exist between the ultimate disposition of material dumped in the winter and the summer.

Lastly the settling material was exposed to an ambient current of 0.1 fps. This current was small enough to have no effect on the jet characteristics, yet it did have a significant effect on the material settling from the neutrally buoyant cloud. In Figure 11 is an illustration showing the ultimate location of the material. It is seen that much of the material has been carried a great distance from where it was originally dumped. The discontinuous nature of the results stems from the fact that the continuous settling distribution was divided into ten discrete segments. Thus it is very probable that if fine-grained material is dumped into an environment in which there is a small current the material could be carried a considerable distance before it settles. This partially explains the situation described by Baxter (3) in which he indicated that no traces of Philadelphia's digested sludge that was dumped into the Atlantic Ocean could be found. It is quite possible that the material was swept out of the 1-mile by 2-mile disposal area before it settled to the bottom.

Consider now the situation in which the barge is moving at a speed of 7 fps and discharging material at 10 fps. The movement of the material as shown in Figure 13 is from the barge with an initial angle of zero to the depth at which the jet stops. From this point the movement of the material is like a plume and not a jet. When the jet stops, however, the material contained in it is still heavier than the ambient water. Thus the material continues to travel downwards as a negatively-buoyant plume without momentum.

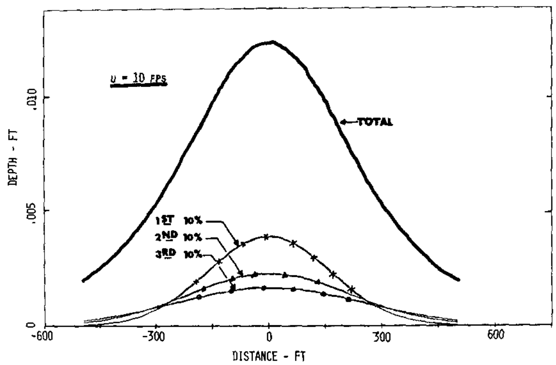


Figure 9. Total depth of bottom sediment discharged from one barge load and the contributions from each of the first three settling groups.

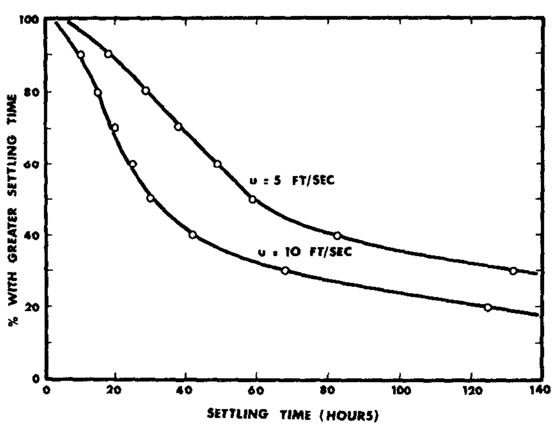


Figure 10. Distribution of time for settlement for initial jet velocities of 5 and 10 fps.

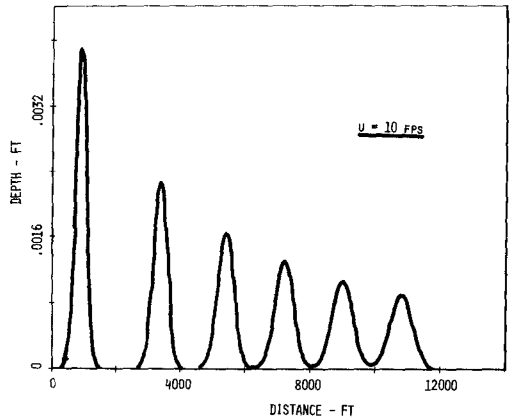


Figure 11. Total depth of bottom sediment discharged from one barge load in the presence of a current of 0.1 fps (u = 10 fps).

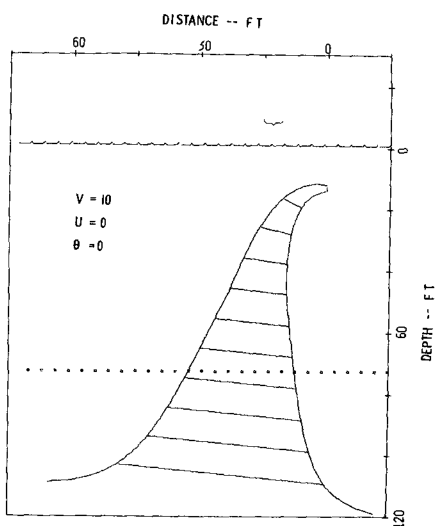


Figure 12. Trail of waste discharged from a stationary barge with an initial velocity of 10 fps and angle of zero. The width of the jet is at the same scale as the depth.

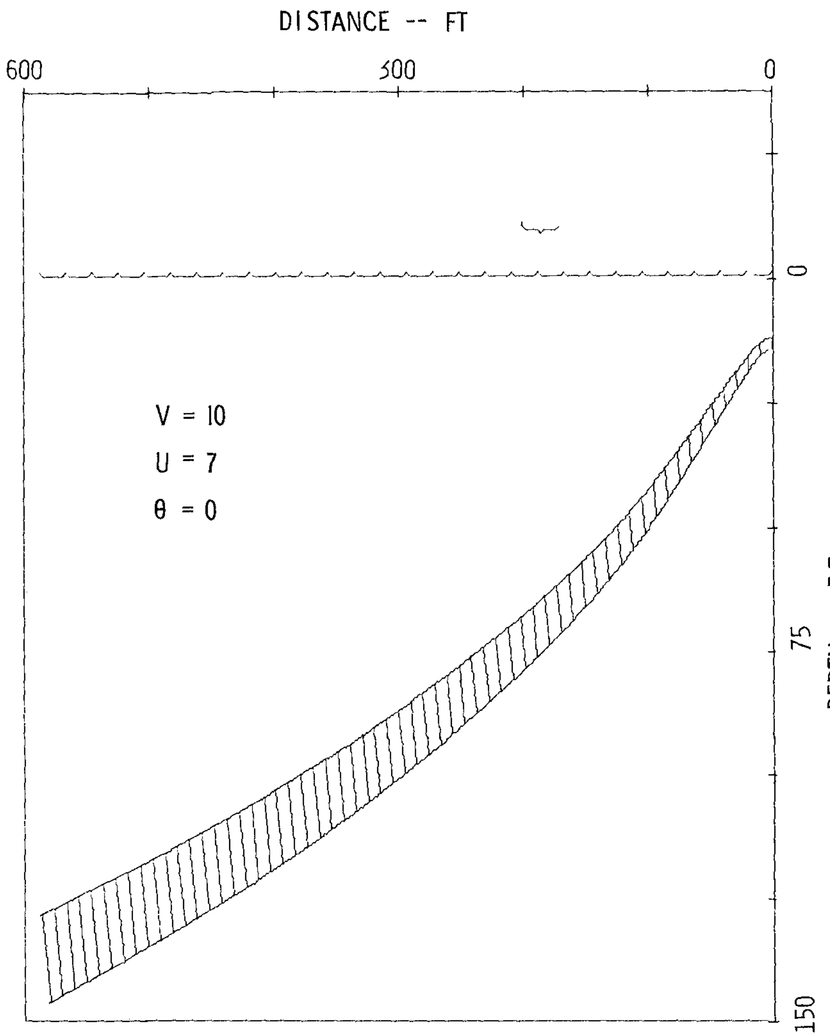


Figure 13. Trail of waste discharged from a barge moving at 7 fps, discharging at 10 fps, and at an initial angle of zero. The width of the jet is at the same scale as the depth.

On the other hand, if the barge is traveling slower, the material does reach a neutral-buoyancy level as shown in Figure 12 for the case of a stationary barge.

The effective dilution of the waste was not significantly different for the case of the barge moving, 76, than for the stationary case, 68. An interesting situation results for the discharge in the vertical direction; for no movement the dilution is 109, whereas for a barge velocity of 7 fps the dilution is only 33. The location where the jet breaks down into a plume or stops is significantly different for these situations.

It appears that through judicious discharge strategies the waste material can be placed at any desired depth at the necessary concentration according to the environmental conditions and requirements.

CONCLUSIONS

A mathematical model has been developed to simulate the transport of material that is discharged from a barge into the ocean. The objective of this simulation was to quantify the ultimate location of the material when it reaches the bottom. The first part of the mathematical model describes the action of the barge discharge as a negatively-buoyant jet which is moving into a stratified environment. This model describes the maximum depth of the jet travel and the level at which the fluid in the jet will come to rest and be neutrally buoyant. The second part of the model simulates the dispersion and transport characteristics of the sediment particles as they settle to the bottom.

The model was used to simulate the dumping of fine-grained sediment into a disposal area 200 ft. deep. In addition to showing the sensitivity of the model to the initial jet conditions, the model showed that the ultimate location of the material also depended largely on the initial jet characteristics. In the presence of a small cross-current much of the material was carried out of the designated disposal area before it could settle out of suspension. By varying the discharge conditions, however, the location of this material could be controlled to a greater extent. The disposal pattern is quite different for winter conditions than for the stratified, summer conditions. In the summer the material is much more likely to be carried out of the disposal area.

The model which was developed in this study has the capability to predict the ultimate location of waste that is discharged at sea. This capability is of course restricted by the assumptions made in the development of the model. The technique is restricted to a barge discharging to the open ocean through a pumping system while moving. With respect to these assumptions, this model offers much potential to assist in evaluating many ocean dumping operations.

From the results of this study, it appears quite obvious that discharge strategies can be developed that will allow the material to be placed on the ocean bottom with much more confidence than has been the case. In effect, the material can be discharged to any depth, at the end of the mixing region, with any desired concentration.

The discharge through a pumping system offers a clear advantage over disposal in the wake of the barge. Although the initial dilution may not be as great, the material is passed through the euphotic zone with the least possible damage. At the point where the material begins to spread and settle there may be considerably less marine life to be disturbed than on the ocean surface.

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