AN EVALUATION OF EFFLUENT DISPERSION AND FATE MODELS FOR OCS PLATFORMS

VOLUME 2: CONTRIBUTED PAPERS

Proceedings of the Workshop
7-10 February 1983
Santa Barbara, California

Prepared for
Minerals Management Service
U. S. Department of the Interior
Contract No. 14-12-0001-29122

Prepared by
MBC Applied Environmental Sciences, and
Analytic and Computational Research, Inc.

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Edited by:
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PROJECT STAFF

An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms

Volume I: Summary and Recommendations

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PREFACE

The emphasis on leasing and development of offshore petroleum resources by the Minerals Management Service (MMS) of the U.S. Department of the Interior, and the ensuing disposal of drilling effluents resulting from exploratory and production operations, has resulted in increased concerns regarding the effects of these activities on the Outer Continental Shelf (OCS) marine environment. In an effort to better understand the behavior of the disposed materials in relation to the offshore environment, the MMS sponsored a Workshop entitled, "An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms." The Workshop was conducted by MBC Applied Environmental Sciences (MBC) and Analytic & Computational Research, Incorporated (ACRI) in Santa Barbara, California, from 7 through 10 February 1983. The objectives of the Workshop were to evaluate the existing mathematical models for dispersion of drilling effluents, to assess the state-of-the-art, and to make recommendations about future directions in the development of these models and research related to the fate of discharges.

The proceedings of the Workshop form the subject of this two volume document. This second volume contains the contributed papers presented at the Workshop dealing with a range of issues relevant to the discharge of drilling effluents in the OCS environment. The only exception is a paper presented by Dr. Petrazzuolo; this paper was not received from the authors in time for inclusion in this volume. The overall recommendations and conclusions are included in the Executive Summary with both Volume I and Volume II.

The first volume contains the background and introductory material, evaluation of the selected mathematical models, abstracts of the papers presented at the Workshop, and the conclusions and recommendations of the subgroups and the Scientific Advisory Panel.

These proceedings do not contain a transcript of the valuable discussions, and questions and answers during the three-and-a-half days of the Workshop. The essential elements of these discussions are reflected in the summary of conclusions, recommendations and subgroup chairmen's reports which are included in Volume I.

Every attempt was made to include representative models from all of the diverse models applicable to the disposal of drilling fluids in the program of the Workshop. If any known model was not included, it was either because a very similar model (possibly an improved version) was included in the program or because the model was not available for review and presentation.

In the Workshop proceedings, the authors and contributors are identified by their name only; their affiliation, mailing address and telephone number is given in Appendix B.

A number of persons contributed greatly to the success of the proceedings. The expert panel which provided overall technical guidance consisted of Dr. Robert C. Y. Koh (Chairman) of the California Institute of Technology, Dr. Lorin Davis of Oregon State University, and Dr. Anthony Policastro of Argonne National Laboratory. The subgroup chairmen, Dr. Robert Ayers, Jr. (Exxon Production Research Co.), Mr. Maynard Brandsma (Consulting engineer), Professor Wilbert Lick (University of California, Santa Barbara), Mr. F. Thomas Lovorn (Lockheed Ocean Science Lab), and Dr. Theodor C. Sauer, Jr. (Exxon Production Research Company), who moderated the group discussions and provided feedback, deserve special mention. All took time out of their busy schedules to summarize the often colorful and wide ranging discussions. In addition, a number of persons devoted their valuable time to application of the models and presentation of papers; this document is primarily a summary of their efforts. Their contribution is acknowledged gratefully and their names appear in the Proceedings where appropriate.

Akshai K. Runchal
Robert R. Ware

Los Angeles, California
July 1, 1983

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EXECUTIVE SUMMARY

THE PURPOSE AND OUTLINE OF THE WORKSHOP

The Minerals Management Service (MMS) of the Department of the Interior, by virtue of the Outer Continental Shelf Lands Act (1978), has jurisdiction over the Outer Continental Shelf (OCS) submerged lands. Among the responsibilities mandated for the MMS under this Act are those to conduct studies to predict, assess, and manage impacts from OCS oil and gas development activities in the marine environment. Other responsibilities include leasing land on the OCS for minerals development, permitting and regulating the development activities, and assessing and monitoring the environmental effects of these activities. One potentially significant impact of the OCS lease process is the discharge of effluents from offshore drilling rigs and production platforms.

Mathematical models, in conjunction with field studies, have played a crucial role in assessing the transport, fate and effect of marine effluents. In particular, models have played an important role in our understanding of the fate of thermal, sewage, and dredged material discharged into offshore waters. However, models for discharge of drilling effluents from OCS platforms are still at a preliminary and largely untested stage. The only part of the mixing process which has been compared with laboratory and field data is the initial descending phase (also called the convective descent phase) of the plume. Our understanding of the later phases in the physical and chemical processes relevant to transport and dispersion of drilling muds, cuttings and formation waters is limited. Further, very little data is available from the OCS environment to validate the models developed so far.

A comprehensive examination of available mathematical models and data would highlight the areas which may require further study. The MMS therefore sponsored a workshop to discuss the strengths and limitations of the available mathematical models for drilling effluent dispersion. The workshop entitled "An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms", was held from 7 through 10 February 1983 in Santa Barbara, California. Approximately 100 invited individuals from a wide range of affiliations and disciplines attended.

The primary objective of the workshop was to survey and consolidate the state-of-the-art knowledge in modeling of the transport and fate of the drilling muds, cuttings and formation waters in the OCS environment. To achieve this objective, a number of models for drilling effluents were identified and standard data sets were developed to assess the model performance in a comparative mode. A number of leading experts were invited to deliver keynote addresses on issues dealing with the physics and chemistry of drilling effluent dispersion. Further, the workshop participants were asked to review the state-of-the-art in their respective fields and to identify the processes related to the physics and chemistry of the discharge plume which are adequately understood and those which require further investigation.

Another objective of the workshop was to educate Federal, State, and local agency personnel in the uses and limitations of the numerical models, compare the uses of and needs for modeling of plumes of discharged materials in relation to the mission responsibilities of MMS and EPA, and to provide feedback from MMS and EPA model users to the scientists involved in developing and testing numerical models.

The total duration of the workshop was three and a half days. Of this period, the first two days were devoted primarily to the technical assessment of the existing information related to drilling effluent discharges. As such, the presentations consisted of the description of the various models and their application to the standard data sets. Presented papers also addressed various aspects of drilling mud discharges. Among the papers presented were those on the review of the existing knowledge, the standard data sets, laboratory experiments in plume behavior, drilling mud composition, sedimentation, resuspension and flocculation processes, EPA modeling needs, and the relationship of biological information needs to modeling of discharges and prediction of pollutant concentrations in the ocean.

During the third day of the proceedings, the participants met in small groups to discuss specific aspects related to modeling of drilling effluent discharges. The topics of discussion were (1) the near field physics, chemistry and dynamics of a discharged drilling effluent, (2) the dynamic effects of the ambient oceanographic conditions on drilling effluent in the near and intermediate-field, (3) the long-term oceanographic features of the transport and fate of drilling effluents, and (4) the role of models in predicting the behavior of, and assessing the effects of a drilling effluent. These groups also discussed future needs for numerical modeling and related studies. The final day of the workshop was held in plenary session to summarize the group discussions and make recommendations for future directions.

CONCLUSIONS OF THE WORKSHOP

Models And Modeling Methodology

The available models should only be applied for short-term simulation of the transport and fate of drilling effluents. Their applicability beyond a time scale on the order of a day is questionable. The models provide reasonable prediction concerning the behavior of the discharge in the near-field. However, these models remain largely unvalidated with field and laboratory data in the lower densimetric Froude number range encountered with mud and produced water discharges. Most of the models were developed and calibrated for plumes using laboratory data having high initial densimetric Froude numbers. Since such data are not directly applicable to the drilling mud discharges, and because the plume buoyancy has a pronounced effect on near-field dispersion and mixing, separate calibration of the models for low Froude number range is required. After the initial buoyancy and momentum of the mud plume have subsided, the plume enters a passive diffusion phase. This diffusion phase is thought to be the least accurate portion of the short-term fate models.

In general, the predictions of plume behavior from the several short-term models for the standard data sets were in agreement. However, the bottom deposition rates predicted by the models varied by an order of magnitude. The short-term models take reasonable account of the transfer and mixing processes in the initial dilution and dispersion phases. It should be noted that quite often the bulk of the dilution of discharge occurs during these initial phases.

The processes of flocculation and deflocculation, deposition and resuspension, and wake effects are either missing from the models or are inadequately treated by the existing models. Further, certain initial processes such as predilution in the discharge pipe and separation of the fine particle sizes from the main plume, which have been noticed in field or laboratory studies, are at present poorly understood. The standard data sets tested only the treatment of the jet phase in the mud plume dispersion; the data did not address the passive diffusion phase.

Two methodologies for the long-term predictions (day and longer) are currently available - The deterministic and the probabilistic. Models representing both of these methodologies were presented at the workshop; however none is considered satisfactory for application to the OCS environment.

The deterministic method suffers from the drawback that it requires very detailed synoptic description of oceanographic conditions for accurate predictions. Such data are not likely to be available. Further, this method requires considerable computer resources which may well prove prohibitive for most OCS applications. A deterministic model, with examples of applications to river estuaries, was presented at the workshop (Section 6.3). However such models are judged to be of general predictive utility in the OCS environment because of the requirements of site-specific calibration and high cost.

The probabilistic method does provide a promising alternative but has been poorly explored for OCS applications. The primary advantage of this method is that it can rely upon representative samples of oceanographic data rather than synoptic conditions. It is likely to be much cheaper than the deterministic method. The only model of this kind presented at the workshop (see Section 3.5) employed long-term current averages and did not account for dynamic or time-series effects. The results from such a model thus have limited usefulness.

Field Data

Adequate field or laboratory data for verification and calibration of models is limited. The available field data does not provide the synoptic information on ambient currents, density structure and plume measurements to adequately verify mathematical models. Some laboratory data exist to provide near-field verification of models, but the scope of these data is limited and can at best only provide partial verification of near-field components of the model.

RECOMMENDATIONS OF THE WORKSHOP

Modeling

It was recommended that a feasibility study be conducted to identify a suitable methodology for a long-term model of drilling effluents. It is recognized that such a model would rely heavily on probabilistic rather than deterministic approaches and would require coordination with existing MMS studies in physical oceanography and meteorology. The long-term feasibility study should be multidisciplinary, involving experts in meteorology, physical oceanography, geology, and biology.

Some research effort may be directed towards verification and refinement of short-term models and inclusion of phenomena at present missing from these models. In terms of verification, the models may be tested and improved in modular form (jet phase, convective descent phase, passive diffusion phase) using data from related fields until more laboratory and field data specific to the OCS discharges is available. In terms of refinement of models, it is possible to include the phenomena of plume separation during the initial stage, and pre-mixing of the discharge effluent due to influx of ambient water in the discharge pipe. However, this research effort was recognized to have a lower priority than that related to development of long-term models.

Laboratory Studies

Several processes which may play a significant role in the fate and behavior of discharges from OCS platforms are at present poorly understood. The nature of these processes is such that laboratory investigations would lead to a better understanding of their significance in the long-term fate of the effluents. Of these, the processes of flocculation, deflocculation, sedimentation, and resuspension were identified for priority consideration.

Additionally, the phenomena of interaction of the discharge plume with the bottom, the dilution due to wake effects of the discharge structure, initial separation of certain constituents of the discharge, and initial dilution due to pre-mixing need further investigation.

Field Data

It was recommended that field data be collected for the purpose of validation of short-term models and development of long-term models. This data base should preferably consist of synoptic data relevant to dispersal of drilling effluents in the OCS environment. The data collected should include that pertaining to ambient currents (including statistical parameters), temperature and salinity, natural and artificial sedimentation rates, and sediment transport near the bottom. It was suggested that such a field data effort is likely to be most cost-effective if conducted concurrently with, or pursuant to, the development of a long-term fate model.

1. A SURVEY OF MAJOR TECHNICAL ISSUES

1.1 Characteristics of Drilling Discharges

by

Robert C. Ayers, Jr.

CHARACTERISTICS OF DRILLING DISCHARGES

Robert C. Ayers, Jr.
Exxon Production Research Company

Presented at the Minerals Management Service Workshop on "An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms", Santa Barbara, California, February 7-10, 1983

CHARACTERISTICS OF DRILLING DISCHARGES

Robert C. Ayers, Jr.
Exxon Production Research Company

This paper considers the nature of water base drilling mud and cuttings discharges. It discusses drilling discharge practices as well as the composition, quantity, and rate of these discharges. This overview is presented for use as background material to aid in understanding other papers addressing the fate of these discharges.

Quantities and Rates of Drilling Discharges

A schematic diagram of a drilling mud circulation system is shown in Figure 1. The mud components are added through the hopper and mixed in the mud tanks. Drilling mud is pumped from the mud pits down the drill string and through the bit. Here it sweeps the crushed rock cuttings from beneath the bit and carries them back up the annular space between the drill string and the borehole or casing to the surface. This action permits drilling to continue and is the fluid's most important function.

Back at the surface, the drilling mud is passed through mechanical separation equipment to remove the formation drill solids (cuttings). The solids control equipment is an integrated system that consists of shale shaker screens that remove the coarse particles and hydrocyclones that remove the sand and silt fractions from the mud. The drill solids separated by the solids control equipment are discharged to the ocean. This type of discharge is continuous in the sense that it occurs while drilling is in progress. Typically, this is about half the time the rig is on location.

The rates of this type of discharge vary from about one to ten barrels per hour. The higher number is more characteristic of the shallow part of the hole when drilling is fast and the bit diameter is large. Over the life of a well some 3,000-6,000 barrels of wet solids (20-50% water) from the solids control equipment are discharged.

After the mud passes through the solids control equipment and the solids are separated, it goes back to the mud pits for recirculation. Here another type of discharge may be required. The solids control equipment cannot remove the fine clay and colloidal sized particles that are generated from the formation solids that are drilled up. As time goes on, the concentration of these fine particles continues to increase and eventually reaches a point where the mud becomes too viscous. At this time a portion of the mud is discharged and the discarded volume is replaced with water and appropriate quantities of mud additives. This is done to bring the concentration of fine solids back to an acceptable level. This method of reducing the concentration of fines in the mud system is called the "Dilution Method". On a less frequent basis, bulk mud discharges occur if the mud type needs to be changed prior to penetrating a particular formation or if the mud becomes seriously contaminated. In addition, it is also necessary to discharge the entire mud system at the end of each exploratory well.

Bulk mud discharges occur only intermittently. These discharge volumes normally range from 100-1,000 barrels. Typically, every one to three days a small volume, 100-200 barrels, might be discharged. A 1,000 barrel type discharge is more characteristic of what occurs at the end of the well or if for some reason it is necessary to change out the mud system.

Bulk discharge rates are normally in the 500-2,000 barrels per hour range and only last for a few minutes. Over the life of a well some 3,000-30,000 barrels of mud are discharged. Discharges from exploratory wells tend toward the upper end of this range while development well discharges tend toward the lower end. Development wells are normally shallower, smaller in diameter and require less time to drill. Furthermore, in some cases a portion of the mud used on one development well can be used on the next. Because many development wells are directionally drilled at high angles, a portion of the hole may be drilled with an oil mud or a water base mud containing 2-4% oil to prevent the drill string from sticking. Since oil muds and water base muds containing sufficient oil to cause a sheen are disposed of onshore this is another factor limiting discharges from development wells.

Differences in the water content of the mud is another reason why the range of mud volumes discharged is broad. For lightly treated, low density muds which are not expensive, the dilution method (discharge and make up) is a cost efficient way to control the concentration of fine solids. Discharge volumes will usually be higher for this type of system since most of the material discharged is water and the make up cost is low. On the other hand, for heavily treated, high density muds which are expensive it is especially desirable to minimize bulk mud discharges. This is accomplished by more extensive use of solids control equipment (centrifuge) and by increasing the concentration of chrome lignosulfonate to deflocculate the fine clay particles and reduce mud viscosity. In these cases, discharge volumes will be low compared to the inexpensive, low density mud systems.

The well to well variation in quantities of discharged material becomes considerably less if one considers only the quantity of solids - everything but water - that is discharged. From both bulk mud and solids control equipment discharges, about 1000 cubic meters (~2,000 tons) of dry solids (formation solids plus mud additives) will be discharged over the life of a typical exploratory well. Mud additives account for roughly half of this value and formation solids account for the other half. For development wells about 750 cubic meters (~1500 tons) is a better estimate because the quantity of mud additives discharged is reduced by about 50% due to the factors mentioned above.

Methods of Discharge

In most situations drilling mud and cuttings are discharged to the ocean from drilling rigs or platforms in two ways. They are either discharged beneath the surface through a large diameter (~10") shunt pipe or they are allowed to free fall through the air to the ocean surface. An exception to these methods of discharge occurs when the first 300 ft or so of the hole in drilled from a floater (semi-submersible or drillship). This is the portion of the hole in which the first string of casing (called structural casing) is set. When a jack-up rig or platform is involved the structural pipe is usually driven and no drilling fluid is used. On the other hand, when a floater is used the hole must be drilled because of the relative motion between the vessel and the ocean bottom. No return line (riser) can be present to recirculate mud and cuttings to the surface and the drilling fluid and cuttings are discharged directly to the seafloor. Seawater is used as the drilling fluid during this period. After the structural hole is drilled, a clay-water drilling fluid is spotted in the hole before the bit is withdrawn. Then the structural casing, suspended on the drill pipe, is run into the hole and cemented in place. After the structural casing is set, a riser is run and connected to the casing. Then mud and cuttings are circulated back to the surface for discharge in one of the normal ways during the rest of the drilling operation.

Composition of Drilling Discharges

Solids control equipment discharges and mud discharges have different compositions. The former contains primarily formation solids and the latter contains primarily mud additives. The compositions of example shale shaker discharge samples (cuttings) obtained from two wells drilled in the Mid-Atlantic and offshore California are illustrated in Table 1. The small amount of barium sulfate results from barite particles that have adhered to the cuttings particles. The montmorillonite clay comes from both added bentonite and from formation clays. The remaining material is representative of the formation being drilled at the time and consists primarily of clays, quartz, and low concentrations of other minerals (calcite, pyrite, and siderite). The analyses are presented on a dry weight basis. Typically, the water content of these discharges falls in the 20-50% range.

Mud compositions vary with both depth and location. In the shallow portion of the hole the mud will consist of low concentrations of bentonite and caustic soda in seawater. As hole depth increases the system may be converted to fresh water and more bentonite and caustic soda plus lignite, lignosulfonate and barite are added. Also if hole problems occur, low concentrations of specialty chemicals may be required. Total usage rates for these materials are low. As seen in Figure 2, barite, bentonite, lignite, chrome lignosulfonate, and caustic soda account for 92% of drilling mud additives used. These materials will account for over 92% of the additives discharged since a significant portion of the remaining 8% consists of oil or oil-base mud additives which are not discharged offshore. Moseley has discussed specialty additives used in drilling mud formulation.

EPA Region IX has required that all muds discharged to the California OCS fall into one of the eight generic mud categories (see attached paper "The Generic Mud Concept for Offshore Drilling NPDES Permitting). Samples of these mud types have been bioassayed and shown to be of low toxicity. If specialty additives are needed only those which do not significantly increase mud toxicity are approved for use in mud that is discharged.

The vast majority of muds discharged on the OCS will resemble the two example mud compositions shown in Table 2. The high density example was the final mud composition used in a well in the Gulf of Mexico and the low density example was used in the latter stages of a Mid-Atlantic well. The high density mud contains 62% barite and 30% water while the low density mud contains 15% barite and 75% water. The concentration of most of the other ingredients are similar.

Trace metals in drilling discharges originate from both formation solids and mud additives. Metals concentrations for mud and cuttings samples taken from wells in the Mid-Atlantic and offshore California are shown in Table 3. For comparative purposes mean metal concentrations of sedimentary rocks are also shown. The presence of barite causes the barium concentration to be much higher than any of the other metals. The barium is in the form of insoluble barium sulfate. The only other metal that is sometimes significantly higher than what is normally seen in sedimentary rock is chromium. The source of the chromium is chrome lignosulfonate. Approximately 3% of the chrome lignosulfonate is chromium which is present in the trivalent state. Both barium and chromium concentrations are higher in the mud than in the cuttings samples. This is because the major source of these metals are mud additives and only a minor amount of the mud components adhere to the cuttings when they are screened out.

DRILLING MUD CIRCULATION SYSTEM

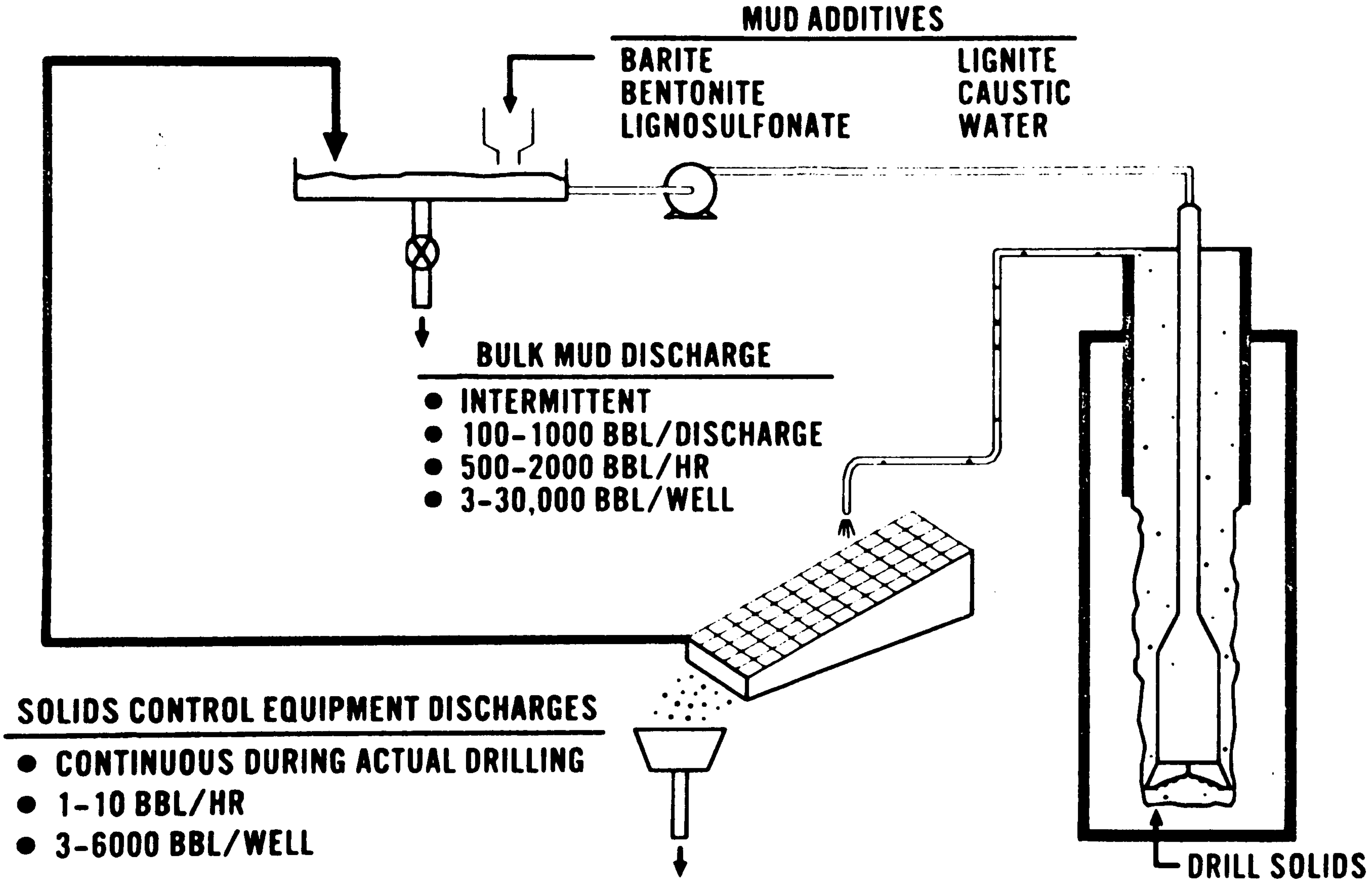

Figure 1

DISTRIBUTION OF U.S. CONSUMPTION RATES OF DRILLING FLUID ADDITIVES

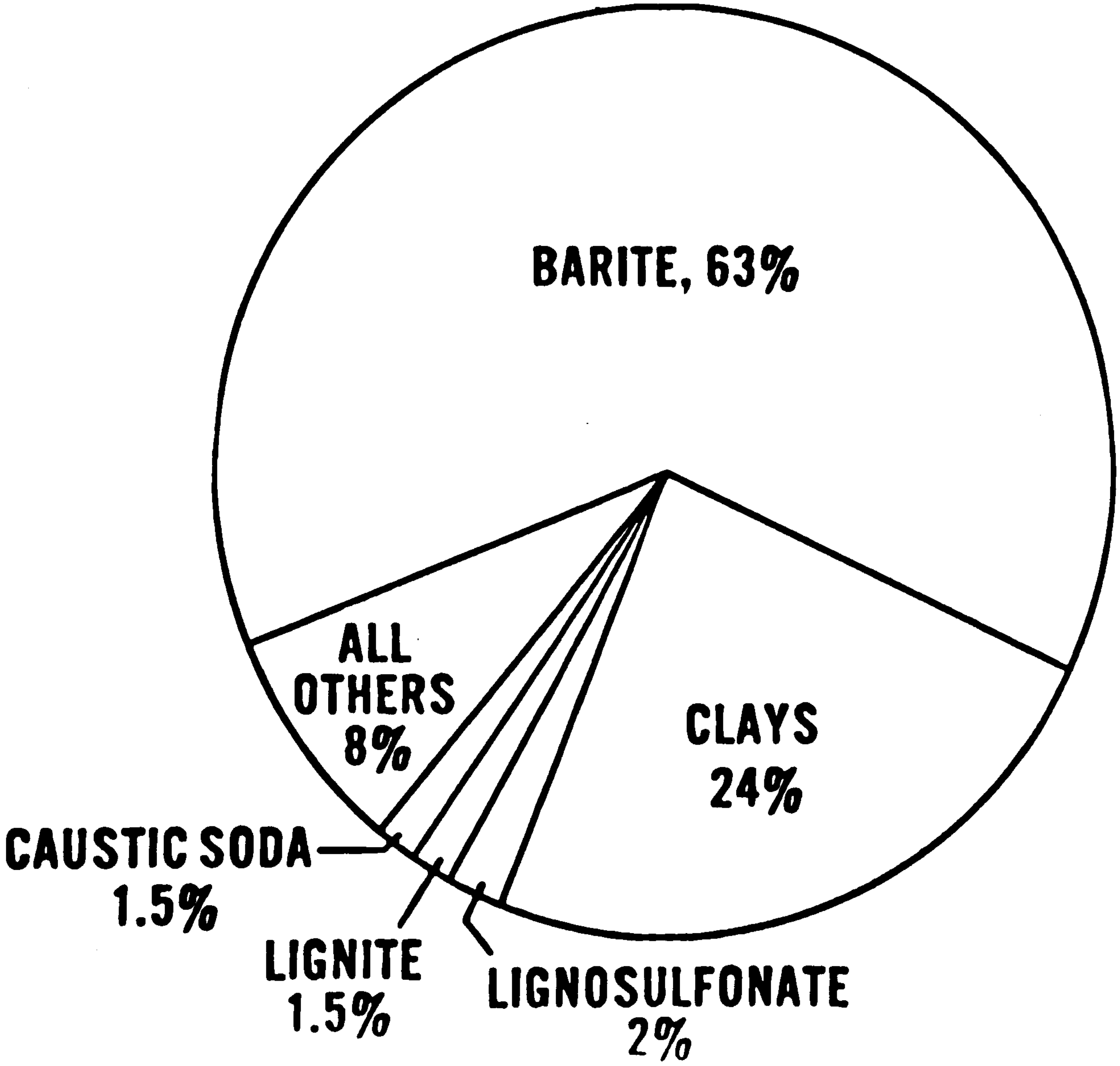

Figure 2

Table 1
Example X-ray Diffraction Analyses of Shale Shaker Samples (Cuttings) From Two Offshore Wells, wt% (Dry Basis)

Mineral	Mid-Atlantic Well	California Well
Barium Sulfate	3	5
Monmorillonite	21	39
Illite	11	25
Kaolinite	11	--
Chlorite	6	3
Muscovite	5	--
Quartz	23	9
Feldspar	8	9
Calcite	5	--
Cristobalite	--	5
Pyrite	2	2
Siderite	4	--

Table 2
Example Mud Compositions from Two Offshore Wells

Component	Concentration, wt %	
	Low Density Mud Mid-Atlantic	High Density Mud Gulf of Mexico
Barite	15.0	62.0
Low Gravity Solids (Bentonite plus formation drill solids)	6.5	5.9
Chrome Lignosulfonate	1.0	0.9
Lignite	1.0	0.9
Inorganic salts	0.7	0.5
Water	75.8	29.8
Density	1.19	2.09
pH	11.4	12.4

Table 3
Example Metal Concentrations in Mud and Cuttings Discharge Samples Taken From Two Offshore Wells, Mg/Kg (Dry wt. Basis)

Metal	California Well		Mid-Atlantic Well		Sedimentary Rocks* (Mean Values)
	Cuttings	Mud	Cuttings	Mud	
Ba	95,840	356,589	4,100	178,000	80
Cr	139	190	57	910	150
Cd	4	0.2	<2	<2	0.3
Pb	24	7	14	16	20
Hg	0.2	0.2	<1	1.9	0.4
Ni	78	35	20	21	100
V	144	50	14	25	130
Zn	61	136	104	236	80

*Pinta, M. "Modern Methods for Trace Metal Analysis", Ann Arbor. Science Publishers Inc., 1978 p.414.

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1.2 The Physics and Processes Related to Discharge of Marine Effluents

by

Robert C.Y. Koh

THE PHYSICS AND PROCESSES RELATED TO DISCHARGE OF MARINE EFFLUENTS

by

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Mathematical models are useful predictive tools. Their effectiveness requires that (i) the underlying processes are correctly formulated, and (ii) the model results are properly interpreted. It is a rare model in which all relevant processes are accurately formulated. While such a model can still be a useful tool in experienced hands when the results are interpreted with judgment, blind acceptance of model predictions on faith often lead to erroneous conclusions.

Formulation of underlying processes involves three steps: (i) identification, (ii) qualitative understanding, and (iii) quantitative formulation. In the following, the major physical processes involved in waste discharge in the ocean are identified and briefly described qualitatively. The degree to which they are currently predictable quantitatively will also be discussed.

Wastes which have been discharged into the sea include sewage effluent, sewage sludge, industrial wastes, thermal effluents, dredged materials, cellar dirt, toxic chemicals, radioactive materials, drilling mud and produced water. Numerous processes contribute to determine their transport and fate. These include (i) various phenomena in density-stratified flow, (ii) particulate coagulation, ablation and breakup, (iii) turbulent dispersion and resuspension.

There are principally two methods of discharge: (i) via pipeline and (ii) from a vessel. Pipeline discharge may include the use of a diffuser (a number of small discharge jets instead of a single open-ended pipe). Discharge from vessels may be rapid or slow (e.g. into the vessel wake to promote much initial mixing). Drilling mud discharge from offshore platforms are more like discharge from a vessel. In some cases, the mud is allowed to free fall from the elevated tank. In others, a submerged pipe is used. The wake of the drilling platform structure can play a significant (and difficult-to-predict) role in nearfield mixing.

Most wastes may be regarded as a mixture of a liquid and a suspension of solid particles. An important physical property is its bulk density. If the discharged waste is heavier than the receiving water it will sink towards the bottom. Similarly, if it is lighter, it will rise towards the water surface. Because of the continuous mixing which occurs in the process, this sinking or rising may terminate before the diluted waste reaches the fluid boundary if there is sufficient density stratification in the receiving water. Research in the past two decades have greatly improved the ability to predict this phase of the transport process for those wastes where particulates do not contribute significantly to the dynamics of the mixing process.

Following the rise (or fall) due to differences in bulk density the diluted waste would next tend to spread out horizontally and collapse vertically. This gravitational spreading can lead to quite rapid horizontal movements often much more than would have been the case without density effects. Both the buoyant rise (or fall) and the gravitational spreading phenomena are manifestations of density-stratified flow. Their occurrences are not peculiar to waste discharge. Related phenomena abound in nature: e.g., rise of thermals, spreading of river discharge at its mouth, avalanches, turbidity currents, plumes from fires.

The presence of solid particles introduces another family of processes which affect the fate and transport of waste materials. Particulates are of special significance because of adsorption of toxics and metals to their surfaces.

One important phenomenon affecting particulates is particle coagulation (flocculation). Smaller particles adhere together after collision and become larger ones. Collisions are promoted by Brownian motion, fluid shear (turbulence), and differential setting. Adherence is affected by the very nearfield flow and forces as particles are brought to close proximity.

Because of the high ionic strength of seawater, wastes which contain mainly fresh water when discharged into the sea often show a high tendency to flocculate. Present understanding of the details of this phenomenon is fragmentary.

Fluid shear can promote not only particle coagulation but also particle breakup. If the discharged material is largely dry (such as soil), the wetting of the larger consolidated aggregates and their breakup are relevant processes for which little information is available.

Another process involving particulates is that of deposition and resuspension, and the boundary condition at the bottom. This is not yet fully understood.

The effect of particles and density stratification in combination with gravity can also affect the fluid dynamics internal in the discharge pipeline. The discharge may be neither homogeneous across the exit nor steady in time. These inhomogeneities would alter the transport and fate of the discharges.

Beyond the nearfield, transport and further mixing are affected by ocean currents and ocean turbulence, both of which are quite site specific. Success of modeling in the farfield depends primarily on adequacy of field data. In the longer term, the disposition of the particulates is also subject to periodic redistribution by episodic events such as storms.

1.3 Entrainment, Deposition and Long-Term Transport of Fine-Grained Sediments

by

Wilbert Lick

ABSTRACT

Entrainment, Deposition and Long-Term Transport of Fine-Grained Sediments

Wilbert Lick

Recent work on the settling, diffusion, entrainment, and deposition of fine-grained sediments will be reviewed and synthesized. Particular attention will be given to the dependence of these processes on sediment properties such as particle size. The application of this knowledge to the analysis and numerical modeling of the long-term transport of fine-grained sediments will also be discussed. The discussion will primarily be based on (1) entrainment, net entrainment, and deposition experiments performed on sediments from Lake Erie and also artificial uniform-size, fine-grain sediments, and (2) field data (turbidity) from water intakes as well as from satellites.

1.4 A State-of-the-Art Review of Modeling of Drilling Fluids and Cuttings

by

Maynard G. Brandsma

A STATE-OF-THE-ART REVIEW OF MODELING OF DRILLING FLUIDS AND CUTTINGS

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ABSTRACT

Modeling of discharges from drilling rigs is reviewed.

The review begins with a summary of drilling rig discharges. Then reasons for modeling drilling effluents are discussed along with the view that modeling is an art because of the imperfect nature of the science.

Accuracy of effluent modeling cannot be set in absolute terms. The desired accuracy can only be set in terms relative to the accuracy desired for impacts assessment.

Models appropriate for modeling drilling mud discharges and models appropriate for modeling cuttings discharges are named.

Mechanisms effecting discharges are reviewed: pre-dilution in the discharge pipe, drilling rig wake effects, flocculation, resuspension, and the effects of heavy, fast settling particles.

Long-term modeling is discussed.

Recommendations for field verification of models are made.

INTRODUCTION

I was invited to give this paper with the impressive title of "A State-of-the-Art Review of...". Participants at this workshop have been talking for two days about the state-of-the-art, so I am going to try to cover some different ground.

Since the models available for drilling fluids and cuttings are discussed elsewhere in these proceedings, my discussion of them is brief. Instead I will address the issues of modeling philosophy and model selection before naming the various models. Then I will discuss some aspects of the drilling effluents problem that are important, but not well understood.

WHAT IS DISCHARGED?

The discharged materials are by-products of the drilling process, cuttings and drilling mud. Formation water produced during the production phase will not be explicitly considered.

Cuttings These are the formation solids with sizes less than 0.25 inch. Their specific gravity is in the range 2.5 - 2.7. Cuttings are discharged continuously at a low rate (typically 10 bbl/hour) while drilling. The total volume is 3000 - 6000 bbl/well. Cuttings have a coating of drilling mud when they are discharged.

Drilling Mud This is chiefly a mixture of clays and barites with particle sizes less than 100 microns. Specific gravity of the bulk mud is typically 1.0 - 2.5. The mud solids have specific gravities of 2.6 for the clay fractions and 4.2 for the barites. Drilling mud discharges are high rate (200 - 1000 bbl/hour) and intermittent during the life of the well. High rate, high volume discharges are made at well completion or when the mud system is changed. The total volume of drilling mud discharged is 5,000 - 30,000 bbl/well.

Observed Features of Drilling Discharges

1. When a heavy mud is discharged, its particles get to the bottom much faster than can be explained by settling velocities alone. (Ecomar, 1980)

2. Quick separation of coarse and fine particles, forming two plumes, has been observed in the field, though not in the laboratory. The upper plume contains little mass, but the highly visible fine particles remain in suspension at or near the surface. Heavier particles move quickly to the bottom and settle there near the rig. (Ecomar, 1980; Ayers, 1980)

3. Strong wake effects have been observed, consisting of general turbulence and wake upwash. At drilling rig length scales, only 0.1 knot currents are necessary to get a turbulent wake.

WHY MODEL?

There are two reasons to model. The first is to evaluate discharges as part of the permitting process. The second is to design mitigation measures. The design tradeoffs are dispersal versus containment and water column effects versus benthic effects.

The quantities of interest in assessing the impact of drilling effluent are the water column volume effected, concentrations and exposure time. The accumulation of material on the bottom is also of interest.

MODELING IS AN ART

The model of any physical process can be physical, numerical, or analytical. The physical modeler builds a scale model of the prototype in the laboratory, observing dimensional similitude. The numerical modeler uses a computer. The analytical modeler uses an equation or two.

Physical models are not practical for daily use because of their expense, and because of the difficulties in modeling density stratified flows.

Analytical models are easy to use, and give good estimates of conditions for a minimum of effort. However, they are useful only in simplified ambient conditions.

Numerical models represent nature by having a computer solve a set of equations written to approximate important processes. Natural processes are complex and cannot be exactly specified. So, any model is an abstraction--some properties are reproduced, some are not. Therefore, modeling is an art.

The modeler must have an idea of which processes are important to his problem and which are not. The most important step in solving a problem by modeling is the selection of the right model for the problem. There are a few questions that should be asked.

Does a simple model represent all the important processes?

Do you have all the input data needed to run a complex model?

Will analysis by hand answer the question? If all you are interested in is the zone of settling of drilling effluent solids on the bottom, simple plume rise formulas and trajectory calculations will suffice. Plume rise formulas will give the equilibrium depth of the discharge jet, and this dictates how far solids must settle to reach the bottom, which dictates how far from the discharge point they can travel on the ambient currents.

HOW ACCURATE?

For many numerical models, you are doing well to consistently get answers within a factor of two of the real world. Some aspects consistently do much better (e.g. jet theory). Some aspects do worse. The reasons for poor results might be: processes not accounted for, incorrect account of a process, or input data not available or incorrect.

What accuracy do you need? In drilling effluent modeling, the primary impacts are biological ones. Therefore the accuracy of biological models determines the desired accuracy of effluent modeling.

HOW TO MODEL?

It is not practical to routinely do laboratory studies of drilling effluent plumes, and the environment is usually too complex for analytical techniques. So the question becomes, what numerical model should be used?

Cuttings usually have a low discharge rate and large settling velocities. These characteristics suggest that use of a trajectory model would be appropriate, since particles can be treated independently. One possible model is the DRIFT model of Dames and Moore (1978). In a high rate cuttings discharge, group dynamics are important initially (particles are treated as an assembly), and a model such as Krishnappan´s (1975) might be appropriate.

Drilling mud discharges are high rate and act like dense fluids. The dynamics must be represented correctly <u>first</u> to have any chance of doing diffusion correctly. Here, models of the Koh-Chang (1973) or OOC (1983) type are appropriate. For vertical discharges in shallow water, NORTEC (1980) has used a wall jet formulation. Nortec´s formula does not consider density differences and therefore assumes an infinite Froude number.

MODELS FOR DRILLING MUD

<u>U.S. EPA (Koh-Chang, 1973)</u> This is the first model to assemble several pieces of the plume dispersion problem in one place. It has three discharge options:

1. Instantaneous dump
2. Continuous discharge through a nozzle
3. Discharge into the wake of a moving vessel.

The transport of the discharged material is divided into three phases: convective descent, dynamic collapse, and passive diffusion. The first two phases use the conservation laws for mass, momentum, buoyancy, and solids. The dynamic collapse phase models the collapse of the discharged material into its level of neutral buoyancy or on the bottom. The passive diffusion phase solves the advection-diffusion equation using the method of moments in many layers. This model requires constant depths and velocity distributions. The velocity distribution is limited to a particular shape. Analysis of plume dynamic history is used as an initial condition for passive diffusion. Each solid class is broken into small clouds that are individually integrated into the Gaussian distribution at the appropriate layer.

U.S. Army Corps of Engineers (Brandsma and Divoky, 1976) This is actually two models: one for instantaneous dumped discharges, and one for continuous discharges.

Dynamics for this model were taken from the Koh-Chang model and modified. The passive diffusion phase was that of Fischer (1968) for variable depths and currents.

The dependency of the horizontal diffusion coefficient on grid spacing and time step makes general application of this model difficult.

Recently, Tetra Tech, Inc. has added a treatment for resuspension to this model.

OOC[1] Model (Brandsma and Sauer, 1983) This model handles continuous jet discharges only. Passive diffusion is done by a new LaGrangian scheme, developed for this model. The dynamics are the same as Koh-Chang except for many changes made to improve reliability in difficult computational situations. A routine to handle plume collapse on the surface was also added.

This model allows the most general ambient conditions: currents are variable in three dimensions and in time. Density profiles can change with time. Variable depths and land boundaries are allowed.

Wake effects are handled by defining a zone of wake turbulence and adding additional entrainment within this zone as well as random fluctuations of position.

Many additional features are included for ease of use in evaluation of drilling discharges. A more complete description of the OOC model is in a paper included in these proceedings.

MODELS FOR CUTTINGS

DRIFT (Dames and Moore, 1978) This is a set of trajectory models used on the ARCO C.O.S.T. well in Cook Inlet, Alaska. The name DRIFT was attached to the model set later after an option for submerged discharge was added--the models

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[1] Offshore Operators Committee

can now work with the DHKPLM or Fan models.[2] Dames and Moore (1978) obtained long term (life of well drilling) distributions of cuttings around the well by making many runs for different current conditions taken from statistical current distributions gathered at the site.

Canada Center for Inland Waters (Krishnappan, 1975)

This is a solution to the instantaneous dump problem with no initial momentum. Behavior of the dumped material is described in two phases: the entrainment phase and the settling phase. Krishnappan does not use a collapse phase because behavior of silt and sand sized particles in a discharge is different than a heavy fluid. This model does not consider density stratification--instead the density of the entrained fluid is assumed to be the average of that in the receiving water. This model was developed using dimensional analysis and experiments. The experiments showed an instantaneously dumped cloud of solid particles of a particular size moving as a cloud. The cloud size increased quickly at first and at a slower rate later until the cloud attained a constant size. After this, the cloud simply settled vertically downward at a speed dictated by the settling velocity of its constituent particles.

DETAILS

There are several factors that influence drilling effluent plumes. These are:

- pre-dilution in discharge pipe
- effects of drilling rig wake
- flocculation
- resuspension
- heavy, fast settling particles

All these are important, and are poorly understood at present.

Pre-Dilution This has been observed in field studies, but not in laboratory tests. The field studies have all been at low Froude numbers, while one laboratory test was at a low Froude number and the rest at high Froude numbers. It is suspected that besides causing lower than expected concentrations at the discharge pipe, this pre-dilution contributes to the formation of the surface plume commonly observed in the field. The mechanism is unknown, but Figure 1 provides one possibility.

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[2] Personal communication, Dr. Aki Runchal. The DHKPLM model by Davis (1975) models merged plumes in flowing stratified ambient conditions. The model by Fan (1967) deals with turbulent buoyant jets in stratified and flowing ambient fluids.

<u>Rig Wake Effects</u> The wake of a semi-submersible drilling rig can strongly effect at least the surface plume. Jack up drilling rigs use latticework legs, and these are somewhat transparent to the ambient current. At length scales characteristic of drilling rigs, a turbulent wake can be expected at current speed of 0.1 knot or greater. It is impossible to account for the detailed structure of the wake. At present the best course is to define a wake zone and, within this zone modify the plume to account for the gross effects of the wake. Lin and Pao (1979) reviewed the literature on wakes in stratified fluids.

<u>Flocculation</u> Flocculation is poorly understood as it applies to drilling mud. Tests done at Exxon Production Research Co. show dramatic differences in the settling velocity distribution for the same muds tested in fresh water and sea water. EPR's tests show flocculation to be complete after 2 minutes. Tests by Gibbs (1982) performed on sewage sludge at various dilutions showed flocculation to be nearly complete after 20 minutes.

For the present, the best treatment for modeling seems to be to specify settling velocities as <u>flocculated</u> settling velocities. This will have no effect during the seconds or minutes of the dynamic phase and a strong effect during the hours of the passive diffusion phase. Settling velocity distributions should be determined using the hydrometer or Andreason pipetting methods, modified to use a settling medium with some salinity to cause flocculation.

<u>Resuspension</u> Resuspension is an important process in long term sediment migration. Its effects in the first few hours, however, are probably small in most discharge areas. (The Cook Inlet area in Alaska is an exception.) Therefore it is recommended that the effects of resuspension be neglected in short term fate models.

<u>Heavy, Fast Settling Particles</u> Dittmars and McCarthy (1975) did a laboratory study to determine the effects of heavy, fast settling particles on jets. Their speculation was that jets containing fluid and particles and having the same Froude number would act differently if the jet contained sewage sludge than if it contained steel balls. They did a laboratory study of 4 jets at the same Froude number. One was a salt water jet and three were particle laden. They observed a different jet behavior in each case. Their conclusion was that if the ratio of particle settling velocity to jet exit velocity was less than 0.05, then the particles had little effect on jet behavior. If this ratio was greater than 0.05, the rate of spreading of the particles and of the jet was reduced.

LONG TERM MODELING

After the initial deposition of sediment from a discharge, long term (greater than a few hours in duration) tranport processes take over. The long term processes are dependent on the local climatology and isolated storm events. There is a choice in modeling methods: deterministic versus probabilistic. Deterministic methods have the disadvantage of requiring much more data for this type of application.

Presently, no models are available for long term migration of sediments from drilling fluids. The driving processes are not fully understood. The ambient current and wave data that would be necessary for such a model is not available in quantity over a large area. A feasibility study for a long term migration model would be a good starting point for such a model.

FIELD MEASUREMENTS FOR VERIFICATION

The various plume models provide a picture of average plume behavior. It is important then that field measurements taken for verification purposes allow the construction of the average plume concentrations in the water column. This means that stations should be selected so that profiles will pass through the surface plume or the main plume. Then several profiles of concentrations should be taken through the plumes at different times. The depths of the samples of each profile should be the same. This will allow time averaging of the concentrations at each profile depth.

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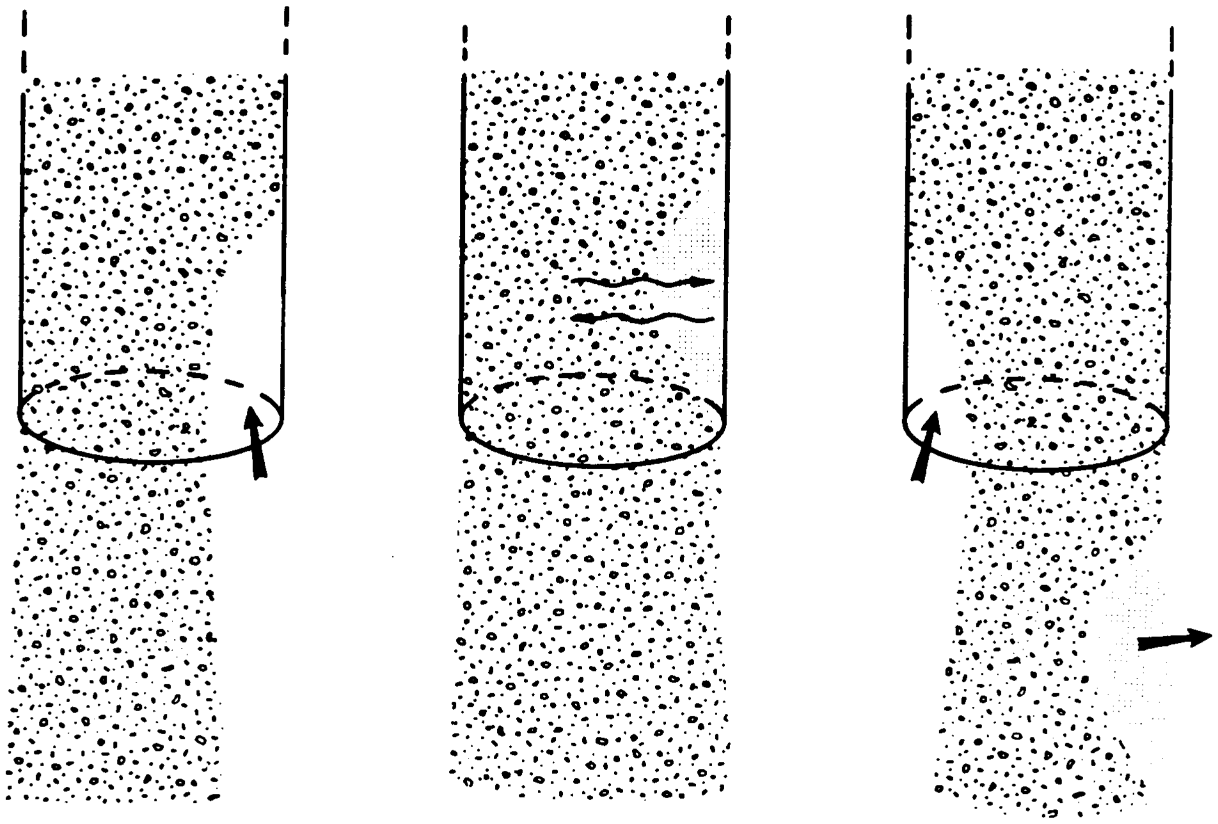

Figure 1. Sketch of possible mechanism of pre-dilution and surface plume formation. The end of the discharge pipe is shown at three different instants. Time increases from left to right. Drilling effluent discharged at a low Froude number allows ambient water to intrude into the pipe. Mixing occurs between the slug of ambient water and the effluent (second picture). Eventually, the mixed ambient fluid is cast out along with the effluent, and a new slug of ambient water intrudes (third picture). The cast out slug of ambient water, containing a small amount of drilling effluent, quickly separates from the main portion of the plume because its density is still much different than the effluent. Thus is formed the so-called surface plume. Also, the effluent density is reduced because some of the ambient fluid is mixed into it within the pipe.

2. A DISCUSSION OF THE REGULATORY ISSUES

2.1 Automating the Section 403(c) Determination

by

William S. Beller

(For presentation at the Minerals Management Service Workshop, "An Evaluation of Effluent Dispersion and Fate Models for OCS Platforms," Feb. 7-10, 1983, Santa Barbara, Calif.)

AUTOMATING THE SECTION 403(c) DETERMINATION+

William S. Beller*

ABSTRACT

The nation's accelerated schedule for leasing offshore land for oil/gas operations shortens the time available for the Environmental Protection Agency (EPA) to formulate National Pollutant Discharge Elimination System (NPDES) permit conditions. To work within the time allotted, EPA is developing a computer model based on (1) Section 403(c) of the "Clean Water Act," and (2) "Ocean Discharge Criteria," an EPA policy document. A first model is on hand, but improvements are needed, especially in terms of acquiring realistic plume models of the discharges.

INTRODUCTION

There are about one billion acres of seabed on the outer continental shelf (OCS) that the Department of the Interior is considering leasing for oil/gas operations through June 1987. This acreage includes most of the offshore Federal land. For whatever acreage is actually leased in this accelerated program, the Environmental Protection Agency (EPA) will have to write National Pollutant Elimination System (NPDES) permits. To do this in a timely

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+ The opinions expressed here are not necessarily those of the U.S. Environmental Protection Agency.

* Chief, Ocean Programs Branch, U.S. Environmental Protection Agency, Washington, D.C.

way, the agency is looking for ways to streamline its analyses and procedures. One of these ways is to automate the Section 403(c) determination.

We have developed the first model that makes such a determination, if we input the characteristics of the discharge and of the discharge area. We can demonstrate the model here if we can get a terminal.

Before going any further, I'd like to tell you that the point of view of this paper is that of the permit writer, the person who puts the NPDES permits together. He does his work based on the applicable law (1), in this instance the "Clean Water Act," in particular Section 403(c); and published policy, in this instance the "Ocean Discharge Criteria" (2). He adopts the procedures and definitions given in these documents. Where they are hazy or silent, the permit writer to the best of his ability suggests compatible definitions and procedures.

I've labored this obvious point because it is the crux of what we have done. The givens are the law and the policy. We have followed both in the analyses we made and the computer program we wrote. Some vital pieces of the program are presently weak, and these include the models for the plumes and depositions of discharges from oil/gas drilling platforms.

The stress here is on oil/gas operations. However, the 403(c) determination and NPDES permit are needed for any point discharges into marine areas where the United States asserts jurisdiction. Such discharges could come during OCS mining of hard mineral resources such as sand and gravel; the mining of phosphates; deepsea mining of manganese nodules, and of polymetallic sulfides. All these operations would have their discharge plumes, which govern the fate and effects of their constituents.

Section 403(c) Determination

The Clean Water Act lays down the considerations EPA must take into account before issuing an NPDES permit. The analysis we make to be sure these considerations are addressed we call the "Section 403(c) Determination."

These considerations include:

(A) the effect of disposal of pollutants on human health or welfare, including but not limited to plankton, fish, shellfish, wildlife, shorelines, and beaches;

(B) the effect of disposal of pollutants on marine life including the transfer, concentration, and dispersal of pollutants or their by-products through biological, physical, and chemical processes; changes in marine exosystem diversity, productivity, and stability; and species and community population changes;

(C) the effect of disposal, of pollutants on esthetic, recreation, and economic values;

(D) the persistence and permanence of the effects of disposal of pollutants;

(E) the effect of the disposal at varying rates, of particular volumes and concentrations of pollutants;

(F) other possible locations and methods of disposal or recycling of pollutants including land-based alternatives; and

(G) the effect on alternate uses of the oceans, such as mineral exploitation and scientific study.

The "Ocean Discharge Criteria" (2) explain and lay down guidelines to be used in applying the Section 403(c) considerations. These criteria introduce several new terms including "unreasonable degradation" of the marine environment, and "irreparable harm." They are qualitatively defined, which we quantified in order to automate the determination.

The flow diagram in Fig. 1 shows the procedure for meeting the requirements of Section 403(c). In essence, EPA can give a permit if a discharge will not unreasonably degrade or irreparably harm the marine environment. On one point, we are allowed uncertainty, that of unreasonable degradation. If we don't know whether it will happen, we can prescribe monitoring to see if it will; and stop operations if it does. We have no such leeway will respect to irreparable harm. We have to resolve any uncertainties before we can issue a permit.

FLOW FOR NPDES 403 (c) PROCEDURE

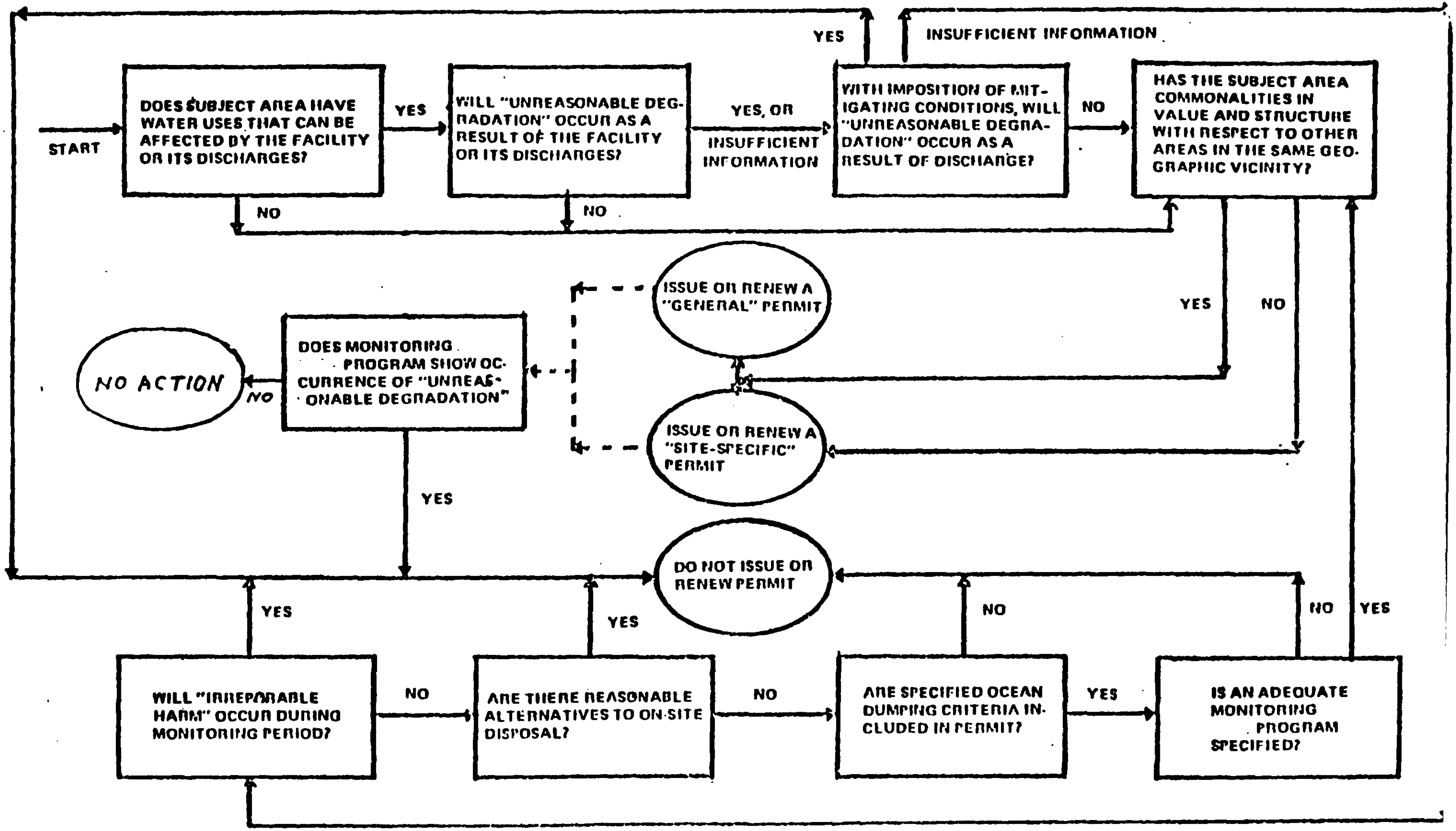

Figure 1

The agency has turned to giving "general" instead of "site-specific" NPDES permits. This change is reasonable where there are similarities in the discharges, and where the area of impact does not vary much in its ecological features. Other times, the agency would turn to site-specific permits. As you perceive, the general permit also is an economical way to issue permits, especially when much acreage is involved.

Minimum permit conditions are prescribed by EPA's effluent guidelines, which are technology based. They are in the process of being revised for oil/gas offshore operations. At the present time, the most well-known condition prohibits any discharges of free oil.

The automating process is skewed toward issuing general permits. The result of the 403(c) determination is a set of NPDES conditions tailored to the area for which operators seek permits. Therefore, the conditions will probably be additional to the minimum ones prescribed by effluent quidelines.

Suiting the Work to the Task

What our task comes down to is protecting the uses of the marine waters that the nation holds valuable. These uses, as expressed by Section 403(c), and by the "Ocean Discharge Criteria," include the following:

- breeding, spawning and feeding grounds for marine fish and shellfish;

- uses identified with high productivity of marine biomass;
- marine aquatic life migration routes;
- scientific, educational or aesthetic use;
- recreational use;
- commercial and sport fishing uses
- habitat of threatened, rare, or endangered marine life; and
- distinctive habitats of limited distribution, e.g., coral reefs, seagrass meadows, and kelp beds.

Where the use is very valuable, and when it might be threatened by a toxic mud, we have to spend much time on the analysis for permit conditions. On the other hand, if the use is not of any exceptional value, and the mud is close to benign, then we want to streamline the analysis. This is the way our model works, and is shown in Figures 2 and 3.

The Sieve Approach

Before describing Figure 3, let me stress the key problem I hope this meeting can help us solve! We need models, based on minimum oceanographic data, that will tell us the concentration, or dispersion, of a discharge in the water column, and on the benthos. We would put these models into our automated system. We would hope the models could make their predictions based on the depth of the water; prevailing currents, preferably surface currents; water column stratification; depth of discharge; and character of discharge. We would also like to

DEGREE OF ANALYSIS

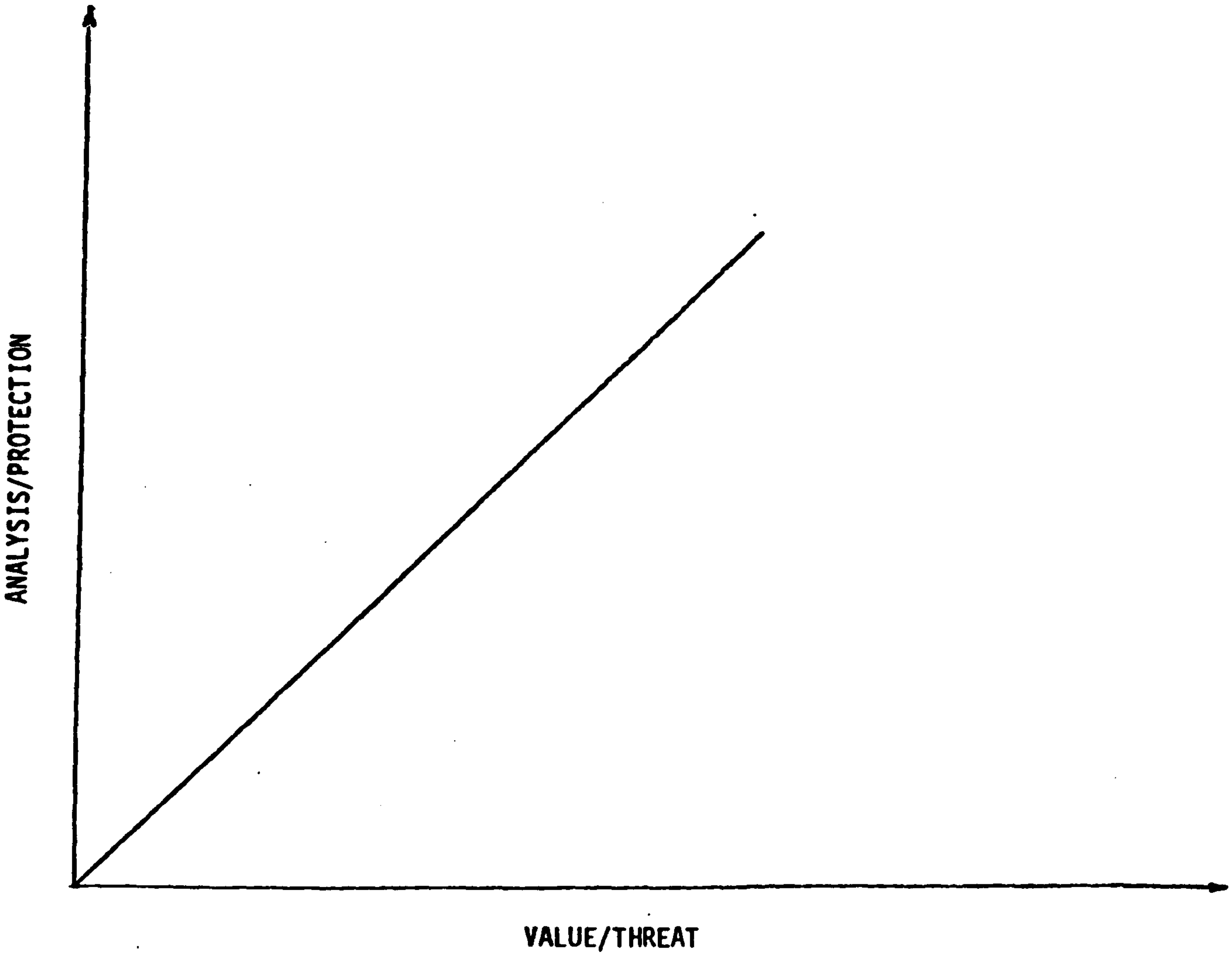

Figure 2

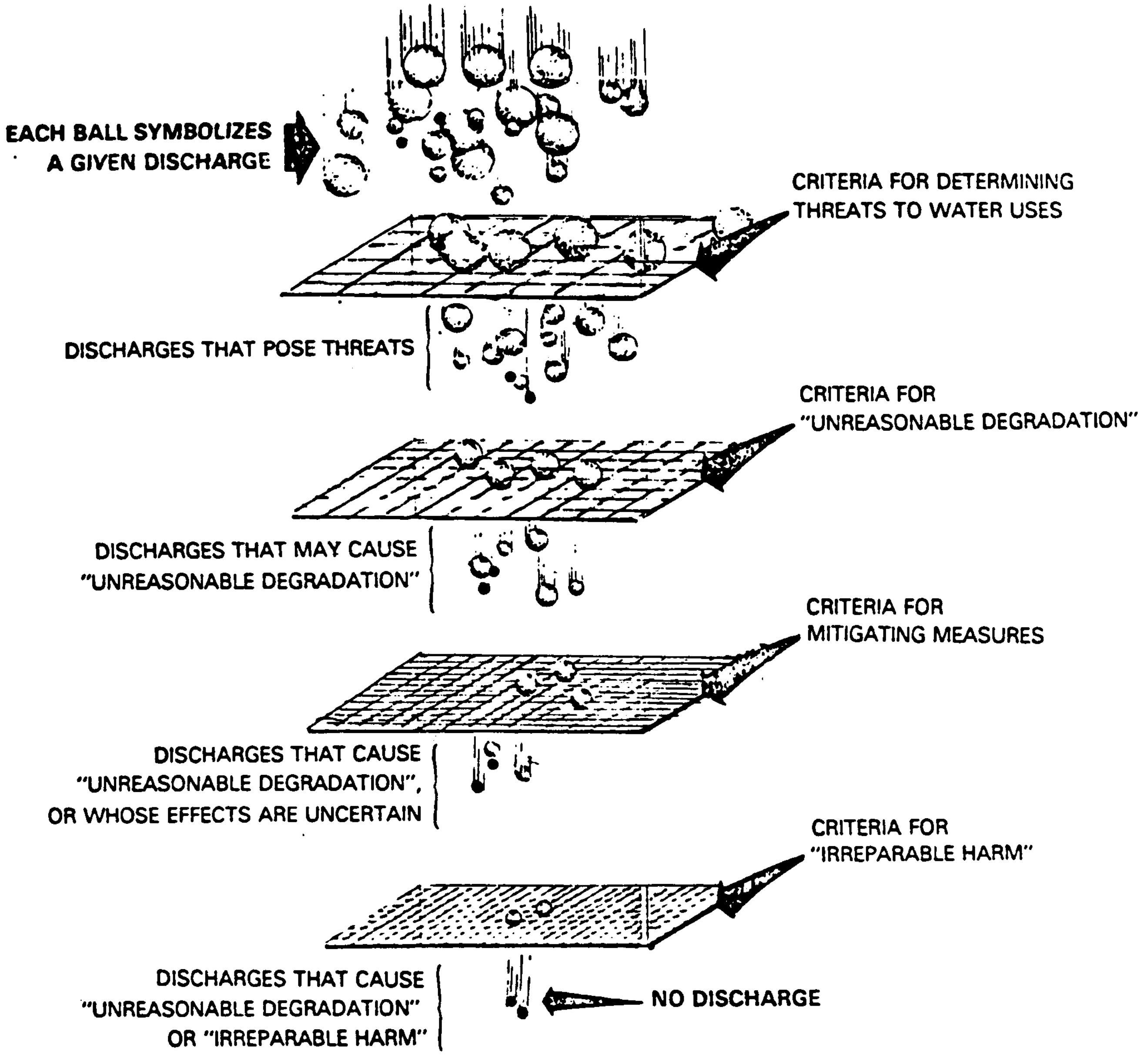

FIG. 3 BASIS FOR AUTOMATING THE 403(c) DETERMINATION

The characteristics of discharges, and the water uses they affect, dictate the degree of analysis a permit writer should undertake for a Section 403(c) determination for an NPDES permit. For example, if a discharge poses no threat to a water use, the analyst should stop at the first sieve and write an appropriate general permit. Fig. 1 lays out the steps for complete analysis.

know under what conditions the models would fail, for example, shallow water, discharge close to seabed, and so forth.

Now back to Fig. 3! This is really Figure 1, the Flow Diagram, shown as a series of sieves. At the top of the figure, you see a cluster of balls, each ball symbolizing a discharge of given ingredients. Each sieve symbolizes a set of criteria. These are given in the "Section 403(c) Handbook" (3).

The hope of the permit writer is that the discharge he is concerned about is stopped by an early sieve so that his analysis is foreshortened.

The first sieve says in effect, "If you're not close to a water use of importance, or if what you're discharging is essentially non-toxic, like seawater, then give a general permit with minimum conditions." We show the criteria on Table 1.

The second sieve tests the discharge for unreasonable degradation. Here we invoke both water column and benthic criteria, and suggest the radius of "mixing zones" for their application. These zones are shown in Table 2.

If the ball falls through the second sieve, then the discharge may cause unreasonable degradation. Would a mitigating measure help? That is the question sieve 3 asks. If yes, a permit is given with the appropriate measure. This becomes a permit condition. If not, then

TABLE 1

CRITERIA FOR SIEVE 1

1. ARE THE DISPERSION CHARACTERISTICS OF THE DISCHARGE OR THE OCEANOGRAPHIC CHARACTERISTICS OF THE AREA SUCH THAT THE COMPONENTS WILL REACH AN AREA OF IMPORTANT WATER USE IN CONCENTRATIONS EXCEEDING THE WATER QUALITY CRITERIA FOR PRIORITY POLLUTANTS (45 FR 79318)?

2. DOES THE DISCHARGE HAVE A 96-HOUR LC50 MORE TOXIC THAN 100,000 PPM ON APPROPRIATE MARINE LIFE?

3. ARE THERE FEATURES OR DISCHARGES THAT WILL SIGNIFICANTLY IMPAIR THE AESTHETIC VALUES OF THE SUBJECT AREA, E.G., WATER CLARITY, BEACH CONDITIONS?

4. ARE THERE DISCHARGES THAT CAN SIGNIFICANTLY DAMAGE MARINE AREAS THAT SUPPORT RECREATION FISHING, BOATING, OR OTHER COMMERCIAL ENDEAVORS, OR AFFECT ALTERNATE USES OF THE OCEAN, E.G., SCIENTIFIC STUDY?

TABLE 2

BOUNDARIES FOR APPLICATION OF CRITERIA FOR DETERMINING UNREASONABLE DEGRADATION OF MARINE ORGANISMS

Habitat Type	(1) Water Column Criteria		(2) Benthic Criteria	
	(a): boundary where water quality criteria may not be exceeded for priority pollutants	(b): boundary where toxicity may not exceed 0.01 x 96-hr LC50 in most sensitive appropriate species	Field* data: boundary for specimen collection	Lab**data: boundary where toxicity may not exceed 0.01 x 96-hr LC50 in most sensitive appropriate species
Soft bottom -sand -silt/clay	1000-meter-radius vertical cylinder around discharge point, extending from sea surface to seafloor		1000-meter-radius circle projected from discharge point onto seabed; 500-m. circle for commercial shellfish beds	
Hard bottom -rock -gravel Sandbanks & shoals Drowned reef			Boundary as above, or that radius within which 25% of total area of habitat of this type occurs, whichever is the lesser radius	
Reefs -coral -algal Submerged macrophtyte beds-kelp forest Submarine canyons Topographic highs Artificial reefs & structures	Within habitat boundary			

*Based on an average reduction in diversity for a given community, or in population of a dominant or commercially important species, using a minimum of 8 transects

**Alternate criterion, distance not a factor: effluent passes ocean-dumping, 10-day, solid-phase bioassay test the discharge is tested for its causing irreparable harm. If it does, or if unreasonable degradation is asserted, then the ball passes through the last sieve, and no discharge is allowed.

The place of the plume models we are seeking should now be clear. They would be used at the boundaries of the mixing zone where we invoke water column and benthic criteria to determine whether unreasonable degradation is taking place. Right now we are using one model based on Gary Petrazzuollo's work (4) at the Flower Gardens, in the Gulf of Mexico. The model we use to help us determine the radius of benthic effects is based on an empirical relationship developed by Petrazzuolo and modified at the Adaptive Environmental Assessment Modeling Workshop (5).

Everybody agrees that these are very rough approximations, both the water-column and benthic models, and we are looking for better ones through the energies of the present workshop.

Future Work

If we had the fully automated 403(c) system in hand, here's what we could do: we could go to the computer, key in the lease sale and block number of interest, key in a standard mud or the contituents of a proposed mud, and then see the suggested permit conditions printed as the output.

To get to this point, we need several things, which we either have or are on our way to acquiring:

- A methodology. We believe that the one shown here will suffice for the present.

- Criteria and their application. We have ones on hand that we can use, but we are seeking refinements such as better plume models.

- Ecological and oceanographic descriptions of the discharge areas, entered in terms of latitude and longitude. This is our biggest data need; for this we are working closely with the National Oceanographic Data Center (NOAA), and the Minerals Management Service (DOI). I must note that much of these data exist, which we shall access.

- Overall feasibility study and systems design. This is the phase we are in today.

Last year we used the criteria we have and the methodology shown here to automate the 403(c) determinations for several hypothetical ocean areas of described values. We sat at a computer, entered our values, an analysis was displayed, and finally, NPDES permit conditions presented. We hope in the near future to have a more refined system operating, one that uses adequate plume models and actual ecological and oceanographic conditions.

3. THE REQUIREMENTS OF MODELS FOR BIOLOGICAL IMPACT STUDY

3.1 Comments on the Link Between Fates and Effects Models

by

Ruthann Corwin

Minerals Management Service Workshop
"An Evalution of Effluent Dispersion and Fate Models for OCS Platforms"
February 7-10, 1983

Dr. Ruthann Corwin
OCS Consultant, Marin County

COMMENTS ON THE LINK BETWEEN FATES AND EFFECTS MODELS

Thank you very much for allowing me to make this presentation. I taught environmental impact assessment at Berkeley and at Santa Barbara in the 1970's, and was a professor of environmental planning at UCLA in the School of Architecture and Urban Planning until 1979. During those years I looked at the first accelerated Federal lease sales in southern California for the California Office of Planning and Research, and at developments in the Santa Barbara Channel for the County and the State. Two years ago I worked on an oil spill damage assessment model for NOAA under the Dept. of Ocean Engineering at MIT. Currently I am working for local governments in California, in the area of marine impact assessment and toxicology. I appreciate the opportunity to make a few points at this stage of the proceedings.

I have a fairly good understanding of the biological aspects of oil development impacts, and a general grounding in the physics and chemistry of the impact processes. I have been listening very patiently to the explanations of the dispersion models, and I recognize the difficulty of getting into the specifics of the physical processes. The complexities of the problems do warrant concentration on those factors in detail at a meeting such as this. But the discussion of those problems should be framed at the outset by an understanding of the biological impact and mitigation policy questions that will use this knowledge, and at the end, by your conclusions as to how well you are able to provide the answers.

The topics have been extremely interesting. What I was paying particular attention to were the descriptions of the input parameters and, also, the output parameters in terms of the links with biological models. I would certainly like to thank everyone for their patient presentations and to thank a number of you for answers to my specific questions.

I didn't consider presenting a paper because the nature of the workshop was explained as being aimed specifically at the fate dynamics and not at the effects. Although biological contributions were not desired, it is clear that the problem of the dynamics needs to be bounded by a discussion of the interface with various needs for impact assessment analysis and evaluation of the effectiveness of mitigation measures. It is not only one biologist that you need to hear from, but from several that can present perspectives for the various ecosystems that are potentially affected.

I would like to stress the fact that biologists are also modellers, and not just people who identify critters and take them apart to see what makes them tick. Quite a number of biologists are population biology modellers and are ecologists who have been attempting to create quantitative analyses for prediction of population dynamics and the fluxes in the natural environment. In these models, pollution effects, or changes in habitat suitability, are classes of inputs to the morbidity considerations for different organisms. These models also attempt to look at all the various lif stages of organisms, their different sensitivities and mortality factors. Ecologists, by the very nature of their studies, work on th interrelationship between the elements in a given ecosystem, includir the physical and chemical parameters, as well as who eats whom, so that you have a sense from ecological models of how things move through the ecosystems and what the effects might be to organisms higher up in the food chain.

I felt that this workshop discussion was excellent in the abstract and I learned a great deal about the kinds of dispersion models. I'm impressed with the efforts that have been made in verification of these physical models and how close they are to reasonable approximations of what goes on under certain limited circumstances that may be found in the environment and under certain conditions. Biological and chemical models are also difficult to validate and they take expensive studies as well. There are lab studies, field efforts and so on. The efforts that are made to understand and verify the models of the those processes with which th dispersion models are linked, should be commensurate with the effort that are made regarding the physical processes. We are talking here about only one portion of a complex system, all of which needs to be adequately described in order to arrive at safe and reasonable publi policy decisions.

I would like to recommend that before the Minerals Managemen Service proceeds further with a feasibility study on effluent dispersion model validation, or with some specific funding of a mode that they consider convening (and this is a specific recommendation that I hope this workshop will make), a workshop of California and other marine biologists. I stress California both because the State has a 'frontier' area which needs more attention to study of the marine ecosystems and which would also provide true control areas, a because it can provide information on the variability of ecosystems and oceanographic conditions nationwide, due to the variability of i offshore environment.

The emphasis should be in inviting people with specialities marine organism population biology, marine pollution, biochemistry, and ecology - biological scientists from the state and local government agencies, independent academic sceintists, and those from private firms and interests. This would be appropriate as a joint workshop with the EPA so that the mitigation measures that could be applied to specific circumstances could be examined.

I would also suggest, as Lorin Davis recommended, that this be an interdisciplinary effort, and that this panel, and the panel from the California ocean circulation workshop last spring, be invited. It would certainly be very appropriate to invite Buzz Bernstein, Dudley Chelton, and Chris Mooers due to their general overall knowledge of ocean circulation issues, and to invite Dynalysis and MBC to also participate in the presentation and get feedback from the biologists. It would be appropriate to apply such knowledge not only to platform effluent discharges, but also to the three dimensional understanding of oil spill fates and effects.

Some of the things that could be learned would be specifics regarding mitigation possibilities. For an example that hasn't been brought up at this conference because you haven't heard about biological factors would be something like the vertical migration of fish and plankton in the water column. If you are looking at a discharge mitgation which talks about shunting the discharge to some layer but you shunt it into a layer where organisms have gone at that particular time, then you could have the actual inverse effect from what was intended by the mitgation measure. Biological knowledge is necessary to evaluate the effectiveness of various dilution measures.

The workshop could be used to gain an understanding of the ranges of sensitivity of various species and the kinds of dilution limits that must be considered to prevent adverse effects. One of the things that biologists have been very concerned about in all of the studies that have been done, Mineral Management Services and others, is the lack of specific knowledge of California marine plants and invertebrate organisms. We know we have some unique organisms out here. We have endemic species - ones that are located nowhere else. A large number of rare invertebrates were identified in one of the few thorough studies that was done in the Central California waters.

I think many of you have heard me say a little bit here and there in the conference that we do not have benchline information for most fish and algae, and all invertebrate marine organisms, north of Point Conception. From Point Conception to the Oregon border you have real mystery in the deeper waters. Those few studies that have been done are turning up new invertebrate species at a rate which indicates that we have diversities something like a tropical rain forest out there, and we've got species that we've never seen before. To proceed thoughtlessly with industrial impacts is equivalent to the situation of cutting trees indiscriminately in the tropical rain forest, where you are wiping out species before you even know what you have.

Some of our California marine biochemists are looking at our plants and invertebrate organisms for the complex biological polymers that they produce which are useful in pharmaceuticals and industrial chemicals. These are treasure troves of genetic information, structures we cannot even begin to synthesize. Some organisms produc chemicals which have anti-cancer and anti-virus properties. Now I know that it sounds extreme to say that the cure for cancer may be found in these waters, but I want to make the point that we have an incredibly rich and diverse environment out there, equivalent in term of biological diversity to southern coral reefs. This is especially true for the marine biological transistion zone centered around Point Conception. With the overlap of northern and southern waters you hav an increase in total diversity of species as well as endemic species restricted to limited habitat areas.

It is necessary to put this kind of information in conjunctio with ocean circulation patterns and their interaction with possible effluent dynamics. We discussed a little in our workshop yesterday, although it didn't really come up in the summary presentation today. some of the vertical gradients where we have northward flowing warm currents intersecting with cold currents that are flowing southward give us one kind of gradient. Recent research has also described eddies of various strength and length of duration that occur off the coast, which trap nutrients and plankton along sharp circular gradients in temperature and current dynamics. The models also need consider the upwellings which make this area so rich because they bring nutrients to the surface. These also have patterns and reoccurences which the physical and chemical oceanographers have been studying and which biologists have been eager to see studied because of their importance to the marine ecosystems of the nearshore and th shelf as a whole.

Armed with this knowledge, we could then review the standard for regulatory control, such as the EPA is suggesting. We could then suggest some very specific models and we can look at the difference between areas that are well-studied and those that are poorly known terms of a realistic priority of study needs.

For impact assessment, the biologists need to have area-specific multiple well dispersion estimates, such as Ian Austin described, in order to make cumulative effects predictions. If the M is considering permitting something like 200 wells, say within 50 square miles or some small area, it is entirely possible that the entire habitats of several rare or endemic species could disappear. I promised I wouldn't say anything about effects, but in fact, you have to have some understanding to better define the kind of fates modelling needed. One of my personal biological concerns is the potential for decreasing diversity of organisms in the California transistion zone before we barely have had a chance to get out there and take a look at them.

I would like to strongly recommend that such a workshop be convened to examine these questions. I certainly volunteer to participate and present a paper. Thank you for your attention.

4. A DESCRIPTION OF THE MODELS SELECTED FOR COMPARATIVE EVALUATION

4.1 The OOC Model: Prediction of Short Term Fate of Drilling Mud in the Ocean

4.1.1 Part 1 - Model Description

by

Maynard G. Brandsma and Theodor C. Sauer, Jr.

THE OOC MODEL: PREDICTION OF SHORT TERM FATE OF DRILLING MUD IN THE OCEAN
PART 1: MODEL DESCRIPTION

Maynard G. Brandsma
and
Theodor C. Sauer, Jr.

THE OOC MODEL: PREDICTION OF SHORT TERM FATE OF DRILLING MUD IN THE OCEAN[1]
PART 1: MODEL DESCRIPTION

Maynard G. Brandsma[2]
and
Theodor C. Sauer, Jr.[3]

ABSTRACT

The Offshore Operators Committee (OOC) and Exxon Production Research Company have funded the development of a computer model to describe the fate of offshore drilling mud discharges. The model is an evolution of earlier models for dredged material discharges developed for the U.S. Environmental Protection Agency and for the Army Corps of Engineers.

Drilling mud goes through three phases after its release: descent of the jet of material through the water column, dynamic collapse in which the material spreads out on the bottom or within the water column, and passive diffusion. The dynamic calculations are derived from the Koh-Chang model with numerous changes. The passive diffusion phase begins when the transport and spreading of the plume are determined more by ambient currents than by any dynamic character of the plume.

The passive diffusion portion of the model is a LaGrangian formulation. It is based on the idea that groups of particles leaving the dynamic plume, and the plume itself, can be represented by many small, independent, Gaussian distributed clouds of material. Each cloud is independently advected, diffused, and settled according to local conditions. The concentration of material at any given point is the sum of the contributions from each cloud.

Model performance has been compared with field studies of mud discharge plumes. Some observed features such as drilling rig wake effects, initial dilution within the discharge pipe, and early separation of fine solids from the main part of the plume (which forms the observed surface plume) are included in the model. The pipe dilution mechanism proved ineffectual and needs more study. The mechanism which estimates the early separation of fine solids from the plume strongly influences the distribution of material in the water column.

Comparison of model results and field and laboratory measurements have shown that the model reproduces several observed features of mud plume behavior. There are, however, some features such as drilling rig wake effects and predilution in the discharge pipe that need to be investigated further.

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INTRODUCTION

Industry and regulatory agencies have identified the need for a general prediction capability of the fate of drilling mud discharges in the ocean. In 1977, the Offshore Operators Committee began funding a research project under the direction of Exxon Production Research Co. to develop a mud discharge model which would predict the fate of drilling discharges in most areas under a variety of environmental and discharge conditions. This paper describes a model for that purpose.

Drilling mud is a slurry of various sizes and densities of solid particles combined with water and many different additives. The solids are a combination of clays and cuttings (specific gravity around 2.6) and barite (specific gravity 4.2). The mud solids are divided into classes (up to 12); each described by its specific gravity, settling velocity and the volume fraction it occupies in the whole mud. The fluid which may contain trace metals and organic compounds can have a density between that of fresh water and sea water. The bulk density of drilling mud is usually much higher than that of ambient sea water.

The numerical prediction of the fate of material discharged into an ocean or estuary is a complex endeavor. The discharge environment may include time-dependent currents varying significantly in three dimensions together with time varying density stratification and a bathymetry of variable depth. The discharge may contain solids ranging from extremely fine colliodal particles to fast settling formation cuttings. Flocculation and cohesiveness of discharged mud has also been observed.

Several models for prediction of the fate of marine discharges have been developed over many years. The initial efforts were directed at the development of individual models for passive diffusion of pollutants in the deep ocean, and the behavior of buoyant plumes from thermal discharges. Koh and Chang (1973) assembled some of these models together and added a treatment for particulate solids contained in the discharge. This model assumed a constant depth and steady currents. Brandsma and Divoky (1976) built on the Koh-Chang model and a passive diffusion model by Fischer (1970) to develop a generalized model for variable depth and currents and up to 12 different solids.

This paper describes a new model, MUD, developed from the earlier ones. Observations of mud discharges in the Gulf of Alaska, the Gulf of Mexico, and the eastern coast of the United States have guided its development. While MUD and its ancestors are research tools, much effort has been devoted to tailoring the model to the needs of the offshore operators and the regulatory agencies. The complexity of the model has been made transparent to its users as much as possible. Although MUD can produce large amounts of detailed output, this can be controlled by program switches so that operators and regulators can get to "the bottom line" quickly.

The "bottom line" for mud discharges is the distribution of total mud solids on the bottom after the end of the discharge. Concentrations of total mud solids and mud filtrate in the water column at given times after the end of the discharge are also of interest. MUD provides these displays in a format aimed at regulatory use. In addition, MUD provides other types of displays geared toward research and model verification. These include simulated sediment traps, displays of bottom accumulation and water column concentration of single solids classes, and profiles of water column concentrations from the surface to the bottom.

A draft version of MUD was released to some of the members of the Offshore Operators Committee for their review and evaluation. Many helpful comments have been received and most are being incorporated into the model. A more detailed account of the model description that follows is available in Brandsma and Sauer (1983).

DESCRIPTION OF MODEL

MUD operates using global and local space coordinates, and global and local time coordinates. A grid defined on the global coordinate system is used for defining ambient velocities and water depths, and for output of mass distributions within the water column and on the bottom (Figure 1). The global coordinate system is used only as a frame of reference for the passive diffusion calculations. Within the global grid defining the field of interest, there is a local coordinate system with its axes attached to the point where the discharge pipe penetrates the surface. The local coordinates are used for the dynamic plume calculations.

In this paper the word "plume" is used in several senses. The term dynamic plume refers to the mathematical entity that tracks the discharged material from when it leaves the discharge pipe to when it completes its collapse on the bottom or in the water column. The word plume refers to the plume as a whole, dynamic or passive, originating from the drilling rig. The term surface plume refers to the fine solids that separate from the plume early and remain near the surface, a small amount of material that is highly visible.

The release of spent drilling mud is taken to originate as a jet from a submerged pipe at a near vertical orientation. The release occurs in a ocean characterized by stratification and an arbitrary velocity distribution. After discharge, the material goes through three distinct phases: convective descent (jet), dynamic collapse, and passive diffusion, as shown in Figure 2.

In the jet phase, the plume, influenced by gravity, descends through the water column, entraining ambient fluid while bending in the direction of the ambient currents. The collapse phase begins when the plume encounters the level of neutral buoyancy or the ocean floor, where descent is retarded and horizontal spreading dominates. After spreading out into a thin layer, the transport and spreading of the plume is determined more by the ambient currents and turbulence than by any dynamic character of its own. Here passive diffusion begins.

During a long discharge, the plume may be envisioned as a "leaky pipe" within which all three processes go on at once. As one packet of material enters the "pipe" and begins convective descent, another, in the middle of the "pipe," undergoes dynamic collapse, and a third is spewed out the end of the pipe and into passive diffusion. Throughout this process the various classes of solid particles settle out of the dynamic plume (leak out of the pipe) at times determined by their characters and that of the dynamic plume.

The dynamic plume determines the initial conditions for the passive diffusion phase. These calculations establish the initial position of all discharged material that we wish to track to its final deposition on the bottom. The mud plume as a whole behaves very differently than its constituent particles.

The dynamic portion of the model is much the same as that originally formulated by Koh and Chang. Many changes have been made, among them:

- Refinement of the calculations to ensure conservation of momentum (except that lost to friction) during bottom encounter at near vertical trajectories.
- Discharge plume interaction with the sea surface (surface collapse routine added).
- Early separation of fine solids from the dynamic plume to form the visible surface plume.
- Modification of transition conditions between computational phases and guidance of trial solutions.

The passive diffusion scheme is a LaGrangian one, developed for this model. Once the dynamic plume is calculated, a complete history is available of the entry of solid particles and fluid into passive diffusion. This history is used in creating many small clouds of material at various positions in space and time. Each of these clouds is free to move and grow according to local ambient velocities. The clouds are assumed to have a Gaussian distribution in concentrations, and the concentration of material at any point is the sum of the contributions from each nearby cloud. There are three advantages of this scheme. First, there are no numerical dispersion problems since there is no grid. Each cloud is described by its coordinates and variances, and by the amount of material it contains. Secondly, computer memory is used more efficiently, since all memory is devoted to representing the diffusing material and none is devoted to representing the absence of material (viz., large areas of zeros in a finite difference model). Thirdly, it is possible to obtain results in whatever format desired: a horizontal plane, a vertical plane, a single vertical profile, or whatever. Many different forms of output can be created once a given distribution of clouds has been calculated.

The simple concepts presented above can be represented mathematically. An outline of the mathematics will be presented next, and later, a discussion of the additional features added to the model to account for plume behavior observed in the field.

CONVECTIVE DESCENT

The equations describing a sinking, negatively buoyant jet in a stratified ambient fluid are those for conservation of mass, momentum, buoyancy and solids. The jet consists of up to 12 discrete classes of particles and a fluid fraction. Each particle class is described by its concentration, C_i; its density, ρ_i; and its settling velocity, V_i. The jet properties are described by its radius, b; its velocity along the jet axis, U, and its density, ρ. The cross-sectional variation of jet properties is assumed to be represented by "top-hat" shaped profiles (uniform across the jet, and zero outside it). The dynamic behavior of the jet is described from a set of coordinate axes fixed on the water surface at the discharge location. The y-axis is vertical and is positive downward, as shown in Figure 3. The ambient density and ambient current are designated by $\rho_a(y,t)$ and $U_a(x,y,z,t)$. Changes in the quantities describing the jet occur with distance, s, along the jet axis. The conservation equations are:

Mass flux $$\frac{dQ}{ds} = E\rho_a - \sum S_i \rho_i \tag{1}$$

Momentum flux $$\frac{d\vec{M}}{ds} = B\vec{j} + E\ {}_a\vec{U}_a - \sum S_i \rho_i \vec{U} - \vec{F} \tag{2}$$

Buoyancy flux $$\frac{dB}{ds} = E(\rho_a(0) - \rho_a) - \sum S_i(\rho_a(0) - \rho i) \tag{3}$$

Solids flux of the ith particle class

$$\frac{dP_i}{ds}i = -S_i \tag{4}$$

In the momentum equation above, B is the relative buoyancy and $\vec{F}$ is the drag exerted on the jet by the ambient fluid.

From Abraham (1970), the entrainment function is assumed to be the sum of contributions due to the momentum jet entrainment, E_m, and the entrainment experienced by a two-dimensional thermal, E_t. The sine of the angle of the jet above the vertical is used as a convenient way to turn on the thermal type of entrainment as the jet bends over in the horizontal direction:

$$E = E_m + E_t \sin \theta_2 \tag{5}$$

The settling of solid particles from the dynamic plume is a most complicated phenomenon on which little research has been done. Jet turbulence tends to keep solid particles within the jet while gravitational forces tend to cause them to separate. Koh and Chang (1973) used dimensional analysis to show that the dimensionless mass rate of settling is a function of the ratio of the descent velocity of the jet and the settling velocity of the particles, V_i; the concentration of each particle class, C_i; and the total concentration of all particles within the jet, $\sum C_i$. The volume flux per unit length of the i^{th} solid leaving the jet is:

$$S_i = 2b\,|V_i|\,C_i(1 - \beta_i) \tag{6}$$

where β_i is a settling coefficient that depends on V_i, C_i, and $\sum C_i$. At present, β_i is either on (=0) or off (=1).

The above set of equations together with several auxiliary equations and initial conditions is integrated using a fourth-order Runge-Kutta routine. When the jet encounters the sea bottom or a depth where the jet density equals the ambient density, the calculation is switched to the dynamic collapse phase.

DYNAMIC COLLAPSE

At this point, the discharged material still possesses a dynamic character, but its vertical motion is arrested by the density stratification of the sea and it tends to collapse into its level of neutral buoyancy. Without a strong enough density stratification, the jet will hit the bottom and collapse there because its density is greater than that of the surrounding fluid. The collapsing plume is assumed to have an elliptical cross-section with semi-major axis b, semi-minor axis a, and a length L (Figure 4). The conservation laws are still written with respect to distance, s, along the plume. They are:

Mass

$$\frac{d}{ds}(\rho\pi ab|\vec{U}|) = E\rho_a - S_i\rho_i \tag{7}$$

Momentum

$$\frac{d\vec{M}}{ds} = \pi abg(\rho_a(0) - \rho)\vec{j} - \vec{D}_c + E_c\rho_a\vec{U}_a - S_i\rho_i\vec{U} \tag{8}$$

Buoyancy

$$\frac{dB}{ds} = E_c(\rho_a(0) - \rho_a) - S_{ci}(\rho_a(0) - \rho_i) \tag{9}$$

Solids in the i^{th} particle class

$$\frac{dP_i}{ds} = -S_{ci} \tag{10}$$

An additional equation is needed to describe the collapse of the elliptical cross-section that characterizes the plume. The inertia force of a quadrant of the collapsing plume is equal to the collapse driving force due to the difference in density gradients inside and outside the plume, plus the collapse driving force due to the differences in the mean densities inside and outside the plume minus the sum of the form drag, skin friction drag and bottom friction drag (if the plume is on the bottom):

$$\frac{d}{dt}\left(\frac{ab}{3}\rho L V_1\right) = F_{dg} + F_{md} - (D_f - D_s + D_{bf}) \qquad (11)$$

where V_1 is the horizontal spreading velocity due to collapse.

The entrainment function is now the sum of contributions due to the advection of the element through the ambient fluid and due to the collapse of the element.

The rate of settling of the i^{th} component out of the element is:

$$S_{ci} = 2bL\,|V_i|\,C_i(1 - \beta_i) \qquad (12)$$

where β_i is the settling coefficient described earlier.

The above set of equations uses the jet characteristics at the end of the convective descent phase as initial conditions. When combined with the necessary auxiliary equations, the equation set is integrated using a fourth-order Runge-Kutta routine. The integration continues until the rate of horizontal spreading due to dynamic effects becomes less than the rate of spreading due to passive diffusion. The calculation then switches to the passive diffusion phase.

PASSIVE DIFFUSION

In this last phase, the plume has become dynamically passive, and is subject only to turbulent diffusion, advection, and settling of the solid particles.

In MUD, we have introduced a LaGrangian scheme of diffusion in which the plume is divided into many small Gaussian clouds each of which contains particles from only one class. Figure 5 is an idealized picture of one such cloud. These clouds are initially distributed as determined by the dynamic plume. They are advected, diffused, and settled independently, using a time step of several minutes duration, according to the ambient currents, diffusion coefficients, and the particle settling velocity. The result is a time varying distribution of clouds of particles, and from this distribution we can calculate the concentration at any point as the sum of contributions from these clouds. This method sacrifices some mathematical rigor in exchange for the ability to obtain a better approximation of plume behavior in the water column than has been available using more sophisticated methods.

The building block of the method is the concentration distribution surrounding a single Gaussian cloud of material (Slade, 1968).

$$C = \frac{m}{(2\pi)^{1.5}\,\sigma_x\sigma_y\sigma_z}\,\exp\left(-\frac{1}{2}\left[\frac{(x-x_0)^2}{\sigma_x^2}+\frac{(y-y_0)^2}{\sigma_y^2}+\frac{(z-z_0)^2}{\sigma_z^2}\right]\right) \qquad (13)$$

where x,y,z are the coordinates of the point of interest
x_0,y_0,z_0 are the coordinates of the cloud centroid
$\sigma_x,\sigma_y,\sigma_z$ are the standard deviations of the distribution
and m is the mass contained in the cloud.

This equation is a solution of the Fickian diffusion equation (constant diffusion coefficients) and strictly speaking is applicable only to homogeneous and stationary conditions at large diffusion times. The drilling mud problem does not satisfy these conditions, but we take comfort in Batchelor's (1949) statement that the Gaussian function provides a general description of average plume diffusion because of the essentially random nature of this phenomenon. The use of this solution is probably justified since the horizontal diffusion coefficients will be known only to an order of magnitude accuracy (Koh, 1982).

The concentration at a given point (x,y,z) is then given as the sum of contributions from individual clouds:

$$C_t = \sum_i \frac{m}{(2\pi)^{1.5}\,\sigma_{xi}\sigma_{yi}\sigma_{zi}}\,\exp\left\{-\frac{1}{2}\left[\frac{(x-x_i)^2}{\sigma_{xi}^2}+\frac{(y-y_i)^2}{\sigma_{yi}^2}+\frac{(z-z_i)^2}{\sigma_{zi}^2}\right]\right\} \qquad (14)$$

The clouds are created by doing intricate mass bookkeeping on the results of the dynamic calculations. The volume flux of each particle class through the dynamic plume is known. This flux decreases or stays constant for each solid class as it passes through the dynamic plume. MUD determines the flux differences from one step of the dynamic plume to the next, and uses the differences as source terms for the generation of Gaussian clouds. (If the flux decreases, material must have left the dynamic plume). Then the path of the dynamic plume is viewed as a line of cloud sources. Time is divided into discrete steps. As time passes, corresponding discrete clouds are liberated from the line source calculated from the dynamic plume. These clouds, assumed to have Gaussian distributed concentrations, are henceforth free to migrate through the discharge area according to local conditions. The initial standard deviations of a cloud liberated from a particular place in the dynamic plume are estimated from the size of the dynamic plume at that place.

The plume calculations are done in local space-time coordinates $(x,y,z,t)_0$. Local time for a single particle originates as zero as the particle leaves the discharge nozzle. Local coordinates of the Gaussian clouds are translated to global space-time coordinates (X,Y,Z,T) as the last step of the creation process. Each cloud has a unique creation time; the time at which it is cast into the passive diffusion phase. This accounts for the fact that although the same local point in the dynamic plume spawns clouds continuously within the duration of the plume, time elapses during this process. At the end of a time step, those clouds created from the dynamic plume early on will have been advected farther downstream than those created later.

An analogous but greatly simplified process accounts for solids that reach the end of the plume before passing into the passive diffusion phase.

Once a cloud is created, it is advected according to the local currents, it grows horizontally according to the four-thirds power law, it grows vertically according to the local vertical diffusion coefficient and it settles through the water column according to the settling velocity of its constituent particles.

Cloud advection results in a change of cloud position given by

$$\begin{aligned} X_{new} &= X_{old} + U_i \Delta t \\ Z_{new} &= Z_{old} + W_i \Delta t \end{aligned} \qquad (15)$$

where X, Z is the cloud position
U_i, W_i are the local ambient horizontal velocities
Δt is the time step (a function of the creation time of the cloud).

Cloud diffusion is accomplished by increasing the size of the cloud. The horizontal size of the cloud changes according the $4/3^{rds}$ power law. Any power law formulation relies on the assumption that turbulent eddies of all sizes are available to make a diffusing cloud grow. Cloud growth is given by the formulation of Koh (1971):

$$\sigma = \sigma_o \left[1 + 4^{1.33} \ \frac{2}{3} \ \frac{A_L \Delta t}{\sigma_o^{0.66}} \right]^{1.5} \qquad (16)$$

Here, the standard deviation, σ_o, is characteristic of the original size of the cloud, and σ is characteristic of the new size of the cloud. Two standard deviations on both sides of the center contain 95 percent of material in the cloud.

Vertical diffusion is accomplished by assuming Fickian (constant diffusion coefficient) diffusion. The change in the size of the vertical standard deviation of the cloud is given by:

$$\Delta \sigma_y = \frac{K_y}{\sigma_y} \Delta t \qquad (17)$$

The horizontal diffusion coefficient is a function of the dissipation parameter that is specified as a constant by the user if he chooses not to use the program's built in value.

The vertical diffusion coefficient may be specified by the user as a constant. If the user does not, a vertical diffusion coefficient profile is estimated by MUD based on sea state and density profile information.

Settling of Gaussian clouds is done by increasing the cloud depth according to the settling velocity of the constituent particles and the time increment used for horizontal advection. The water surface is considered a reflecting boundary and the bottom is an absorbing boundary for the particles composing the cloud. Once material from a cloud settles to the bottom, it stays there. Resuspension is not presently included in MUD.

A Gaussian cloud sinking to the bottom poses some special problems in dealing with the bookkeeping of particles settling to the bottom. Brandsma and Sauer (1983) give an expression for the amount of mass that is caused to be deposited on the bottom when a three-dimensional Gaussian cloud settles a distance $y = y_2 - y_1$. In other words, the amount of mass between two horizontal planes in a Gaussian cloud is:

$$T = \exp((y_2 - y_o)/\sigma_y) - \exp((y_1 - y_o)/\sigma_y) \qquad (18)$$

where

$y_1 - y_o$ = distance from the cloud centroid to the bottom before settling
$y_2 - y_o$ = distance from the cloud centroid to the bottom after settling
σ_y = vertical standard deviation of the cloud.

As the material settles to the bottom, it is collected in bins defined on the global grid so that bottom distributions may be displayed at the end of the calculation. Simulated sediment traps of arbitrary aperture size may be placed anywhere within the global coordinate system.

The LaGrangian method presented here does not work well in regions of rapidly varying conditions (say a strong current shear). The Gaussian cloud formulation tends to underpredict diffusion or overpredict concentrations. To address this problem, the size of the cloud could be periodically checked against the velocity gradients at the cloud. If the cloud is large enough, and the gradients are strong enough, individual clouds should be subdivided into two or more smaller clouds. Each of the smaller clouds is then better able to respond to local velocities. In practice, the clouds are thin enough that this procedure has not proved necessary.

MODIFICATIONS IN RESPONSE TO OBSERVED MUD PLUME BEHAVIOR

Field studies sponsored by Exxon Production Research Company (Ayers, et al., 1980a) and by Shell Oil Company (Ecomar, 1978) have shown several features of real discharges that need to be accounted for. These are:

1. A pronounced dilution of the discharged mud before it ever leaves the discharge pipe. This occurs at densimetric Froude numbers less than about 2 and corresponds to a pulsating discharge wherein ambient water is alternately introduced into and expelled from the discharge pipe, causing an initial mixing and dilution.

2. At low discharge Froude numbers (the usual condition), fine and coarse solids in the mud quickly separate from the plume containing most of the mud, forming a visible plume near the surface).

3. In field tests, the settling speed of a group of particles has been observed to be considerably more than the settling speed characteristic of the individual particles themselves.

4. The turbulent wake of a drilling rig effects the discharge, especially the visible plume near the surface.

5. Flocculation of particles occurs at low salinities, effecting the particle settling velocities of the mud solids.

Each of these will be briefly reviewed. Detailed accounts are available in Brandsma and Sauer (1983).

In-Pipe Dilution Discharged mud sampled at the end of the discharge pipe has shown a pronounced dilution before ever leaving the pipe (Ayers, et.al., 1980a). This occurs at densimetric Froude numbers less than about 2 and corresponds to a pulsating discharge wherein ambient water is alternately introduced into and is expelled from the discharge pipe with the mud, causing an initial mixing and dilution of the mud. Underwater films of mud discharges show them as a series of semi-discrete pulses, not continuous jets.

A literature search revealed no work done on the subject of internal pipe dilution at low Froude numbers. Since the phenomenon has been observed in the field, we attempted to add a simple initial dilution calculation to the model.

There appear to be two mechanisms. The first is an oscillation set up of the mud and ambient water inside the pipe. The oscillation appears to be created when the pressure within the pipe is momentarily increased as the mud discharge begins and before the existing fluid in the pipe is set in motion. This pressure pulse apparently initiates the oscillation, with ambient water and mud surging back and forth within the pipe. The surging is maintained by the pipe not flowing full. This phenomenon has been observed even at times when there was little wave activity. The model does not attempt to include this mechanism of initial dilution. The mechanism is a likely candidate for additional research.

The other contributing mechanism is orbital motion of the surface water induced by waves. An attempt was made to add an initial dilution due to wave motion by introducing an additional flow rate of water cycling in and out of the discharge pipe. This caused an increase in the discharge flow rate, and a decrease in the bulk density and concentration of the solids in the discharge. Experience with this feature has shown that it has little effect on the discharge. That is, the dilutions calculated by this method are low compared to the high dilutions observed in the field. As a result, this dilution feature has been disabled in the model. Perhaps future research will illuminate this mechanism more clearly.

Early Separation: Fine and Coarse Mud Solids Another feature observed at low Froude numbers is that fine particles are quickly thrown out of the main body of the descending plume. These fine particles account for only a small fraction of the mass discharged, but they are responsible for the highly visible surface plume.

The OOC mud model has a mechanism to force early separation of fines from the jet under discharge conditions characterized by low Froude numbers. This early separation creates a plume of material that remains near the surface. The authors were unable to find quantitative work on this subject in the literature. To estimate this mechanism, therefore, the equation for settling of solid particles was modified for particle classes of low concentration and low settling velocity. The modification was made to constituents with low settling velocities because field observations have shown them to leave the main plume early when the discharge Froude number is less than 2. It is unclear at present what concentration shall be considered "low," but field measurements by Ayers et. al. (1980b) indicate that the surface plume contains only 5 to 7 percent of the total solids discharged.

The model has provisions to force release of the two slowest settling constituents. The program limits the total amount of forced separation to 10 percent of the total mud solids. This percentage can be changed by the user. The rate at which solids separate from the dynamic plume during the jet phase is set by requiring the particle volume flux be reduced at each integration step of the dynamic plume by 1 "n^{th}" of its original volume flux at discharge. "n" is the number of integration steps in the jet phase over which separation is forced to occur, and presently has the value 150. (The number of integration steps in the jet phase is required to be between 100 and 200.) The number n is probably a function of the discharge Froude number; the release rate decreasing as Froude number increases until there is no forced release at Froude numbers greater than 2. This procedure causes the model to reproduce behavior seen in the field although the precise physical process is not well understood.

After the fine solids are separated from the discharge jet, they lie within the turbulent wake of the drilling rig. Wake turbulence causes the solids to be mixed and distributed across the wake zone, horizontally and vertically. This is the origin of the visible plume.

Enhanced Settling Bowers and Goldenblatt (1978) observed settling speeds of groups of particles considerably more than the settling speed characteristic of the individual particles. They present a relation for an accelerated settling factor based on field data from dredged material in their Figure 28.

This relation, when normalized by their minimum settling velocity gives:

$$F_e = 0.013\ C_t^{4/3} \tag{19}$$

where C_t is the total local concentration in mg/liter.

In the model, the settling velocity of any cloud of particles is the characteristic settling velocity times the factor F_e computed for the cloud. The factor F_e is restricted to the range 1 to 28, according to Bowers and Goldenblatt's data.

Effects of Drilling Rig Wake The wake of a drilling rig introduces turbulent energy in the flow field that effects the visible plume. We have mentioned that separation of fine solids from the jet occurs at low discharge Froude numbers. The coarse particles tend to quickly settle below the zone of wake turbulence. The fine particles tend to be carried to the surface by the wake turbulence where they form the visible plume.

Apart from the general turbulence introduced by the drilling rig, field observations have shown the presence of an "upwash" effect downstream of the rig. That is, one effect of the presence of the rig is to cause an upward directed velocity immediately downstream.

The drilling rig, whether moored or jackup, is a fixed obstacle placed in the path of the ambient currents. Wind tunnel tests of complicated structures have shown that the presence of a structure at a solid boundary tends to displace the streamlines away from the boundary and over the structure. Once past the structure, the streamlines tend to return toward the boundary, although in a disorganized, turbulent fashion.

The effect of the drilling rig on the local flow field is analogous. Here, however, the "solid" boundary is the sea surface. The streamlines are displaced downward or around the rig to some degree and then return downstream of the rig. The various structural members of the rig all shed vortices or contribute turbulent energy. It is expected that the turbulence immediately downstream from the lattice like structure of a drilling rig will resemble the turbulence generated by a uniform grid in that it is isotropic.

Wake turbulence behind a drilling rig is extremely complex. It could be the subject of a research program in its own right. Therefore the model's treatment of wake turbulence is an attempt to represent the observed effects, and is not a detailed treatment of the physics involved. At length scales characteristic of drilling rigs, a turbulent wake can be expected at current speeds of more than 0.05 ft/sec.

The size and character of a wake zone generated by the rig is estimated following the criteria of Lin and Pao (1979). The Reynolds number indicates the type of turbulence involved. The gradient Richardson number indicates whether upstream blocking caused by stratification will occur. The Brunt-Vaisala frequency indicates the length of the wake zone. A stability parameter indicates whether vortex shedding is occuring from the rig.

In the model, the effect of wake turbulence is accounted for in two ways: by instantaneously increasing the size of some clouds of solid particles as they are created from the dynamic plume, and by introducing a random fluctuation of position that is added to the position that would occur when the cloud left the dynamic plume. The parameters given above are used by the model to determine whether these actions are taken. In addition, any cloud created within one "rig diameter" and at a depth of less than 1.3 times the rig's draft is subjected to a wake "upwash" effect where the cloud is displaced toward the surface by an amount equal to one-half its original depth. The numerical values used are guesses based on field observations and are subject to improvement. Each cloud is displaced and diluted only once if it lies within the wake zone.

Flocculation There is no consideration of flocculation in the model. Instead, the user must specify to the model the settling velocities of flocculated particles, not the settling velocities of the individual particles as would be obtained from the normal sediment analysis. The settling velocity distribution should be measured using the hydrometer or Andreason pipetting methods, modified to use a settling medium with some salinity to cause flocculation.

CONVENIENCE FEATURES

Even though the process modeled is complex, the model is intended to be as simple to use as possible. The following is a representative list of features for ease of use.

Multiple Trials for Dynamic Calculations A feature inherited from the original Koh-Chang model is that the model will automatically guess a value for the integration steps used in the dynamic calculations. It will make five attempts to get good solutions, adjusting the integration step each time. Since the dynamic phase is normally where any problems arise, this allows a good solution in the majority of cases.

Dynamic Memory Allocation The model adjusts array sizes it uses in accordance with input it gets from the user. The various arrays used by the model are allocated out of a single large block of storage. This feature makes it easy to use array dimensions suited to the user's problem. It is not necessary to go through the 52 subroutines of the model changing array dimensions for each new case.

Automatic Estimation of Vertical Diffusion Coefficient The model has an option to automatically estimate the vertical diffusion coefficient profile based on surface wave heights and periods and ambient density profiles.

INPUT DATA REQUIREMENTS

The model has been designed with the ability to model an exceedingly complex situation. Accordingly, the input to describe it can be quite involved. For example, currents and density profiles may change at every global time step. Currents, in fact, may vary spatially from time step to time step. In contrast to this complexity, experience has shown that, commonly, only a single density profile and current speed and direction at a few depths are available for modeling purposes. The input preparation in this case is relatively simple and quick.

The model needs data in four categories:

(1) Mud characteristics
  (a) Bulk density
  (b) Number of discrete particle classes (up to 12)
  (c) Volume concentration, density, and settling velocity for each particle class

(2) Discharge characteristics
  (a) Rate
  (b) Duration
  (c) Radius and orientation of discharge nozzle
  (d) Position of rig within global coordinate system

(3) Ambient characteristics
  (a) Times when ambient data are available
  (b) Density profile(s)
  (c) Current velocity distribution(s)
  (d) Wave height(s) and period(s)

(4) Guidance of model actions
  (a) Input options
  (b) Output control

OUTPUT FORMAT DESCRIPTION

The output for a single simulation consists of three parts: documentation of input, dynamic calculations, and passive diffusion results.

The <u>documentation of input</u> is self-explanatory, consisting of a recapitulation of the input values, together with the results of some preliminary calculations, such as vertical diffusion coefficient results and dimensionless parameters for the wake effect calculations.

The output for the <u>dynamic calculations</u> (convective descent and dynamic collapse phases) consists of tabular and graphical output describing the behavior of the dynamic plume from the time it leaves the discharge pipe to the time it is dominated by passive diffusion effects. The dynamic plume description is given in local space-time coordinates.

In the passive diffusion phase, each mud constituent (solid fractions and liquid) is simulated separately from the beginning to the end of the simulation duration. The output for each mud constituent is then given sequentially from the first to the last global time step.

The diffusion output for each constituent may include the following items:

1. A mass distribution summary in 6 lines giving the weight of the constituent remaining in the discharge tank, the weight in the dynamic plume, the weight in passive diffusion, the weight of the constituent settled to the bottom, and the total weight.

2. Several types of plan views of the distribution of this constituent are available: total weight of the constituent present in each cell of the global grid, mean depth of the constituent at each cell, horizontal distribution of this constituent within layers of arbitrary thickness in the water column, and distribution of solids on the bottom.

3. Several types of water column profiles for suspended solids and fluid tracer concentrations (in milligrams/liter) can be generated. These are sketched in Figure 6.

   Plume curtain profiles are a set of 12 water column concentration profiles spaced at unequal intervals and passing through the dynamic plume centerline. The first profile is near the discharge point; the last is at the end of the plume. The position of the individual profiles can be chosen by the user or the selection can be left to the program.

   Spot profiles are individual profiles, the coordinates of which are specified by the user (up to 20).

   Downstream radius profiles are a set of water column concentration profiles (12) which give a cross-sectional distribution of concentration (of limited arc) at a single selected distance downstream from the discharge. The actual profile points are selected by the user when the user specifies the downstream radius, the general direction of the profiles, and the distance between the profiles in the arc.

At the conclusion of the simulation, the same outputs are generated for the combined solids. Also, there is a single page summary of all the 6 line distribution summaries of each solid class printed at the end of the simulation.

CLOSURE

The mathematical model presented here is essentially complete. Preliminary comparison with field data and experience shows that the model now reproduces several observed features of drill mud discharges. This suggests that the modeling approach is a valid one. Operational experience with the model and additional field data will allow further refinement of the coefficients and other model features.

Part 2 of this paper (included in the workshop proceedings) gives the results generated by the OOC mud model for the three test cases to be used in the workshop for model evaluation.

ACKNOWLEDGEMENTS

The work reported here was supported by the Offshore Operators Committee and by Exxon Production Research Company. The authors are indebted to R.C. Ayers, Jr., of Exxon Production Research Co., and Lorin C. Davis, of Oregon State University, who were instrumental in initiating this effort. The authors are also indebted to R.C.Y. Koh, whose dynamic plume model formed an important part of the OOC mud model.

LIST OF SYMBOLS

A_L	Dissipation parameter used with four-thirds diffusion law
a	Semi-minor axis of dynamic plume cross-section
B	Buoyancy flux
b	Semi-major axis of dynamic plume cross-section
C	Concentration within a single Gaussian cloud
C_i	Volume fraction of i^{th} solids class in dynamic plume
C_t	Total concentration due to a group of Gaussian clouds
E	Entrainment rate in jet phase
E_c	Entrainment rate during dynamic collapse phase
E_m	Entrainment rate of momentum jet
E_t	Entrainment rate of two-dimensional thermal
D_c	Drag force on plume during dynamic collapse
D_{bf}	Bottom friction resisting collapse on bottom
D_f	Form drag resisting collapse
D_s	Skin friction drag resisting collapse
F	Drag force on jet phase of dynamic plume
F_{dg}	Collapse driving force due to density gradient difference
F_e	Enhanced settling factor
F_{md}	Collapse driving force due to density difference
g	Acceleration of gravity
j	Unit vector in vertical direction
K_y	Vertical diffusion coefficient
L	Element length of dynamic plume
$\vec{M}$	Momentum flux
m	Mass of a single Gaussian cloud
P_i	Flux of i^{th} solids class
Q	Mass flux
S_{ci}	Rate of i^{th} solids class leaving dynamic plume (collapse)
S_i	Rate of i^{th} solids class leaving dynamic plume (jet)
s	Arc length along dynamic plume
$\vec{U}$	Centerline velocity of dynamic plume
$\vec{U}_a$	Ambient velocity
V_i	Settling velocity of i^{th} solids class
V_l	Horizontal spreading velocity due to collapse
x,y,z	Coordinates in space
x_i,y_i,z_i	Coordinates of i^{th} Gaussian cloud
x_o,y_o,z_o	Coordinates of center of Gaussian cloud
β_i	Settling coefficient for i^{th} solids class
Δt	Time increment
θ_2	Angle of dynamic plume, measured from vertically downward
ρ_a	Ambient density
$\rho_a(0)$	Ambient density at surface
ρ_i	Density of i^{th} particle class
σ,σ_o	Standard deviations representing size of Gaussian cloud
$\sigma_x,\sigma_y,\sigma_z$	Standard deviations of Gaussian cloud
$\sigma_{xi},\sigma_{yi},\sigma_{zi}$	Standard deviations of i^{th} Gaussian cloud

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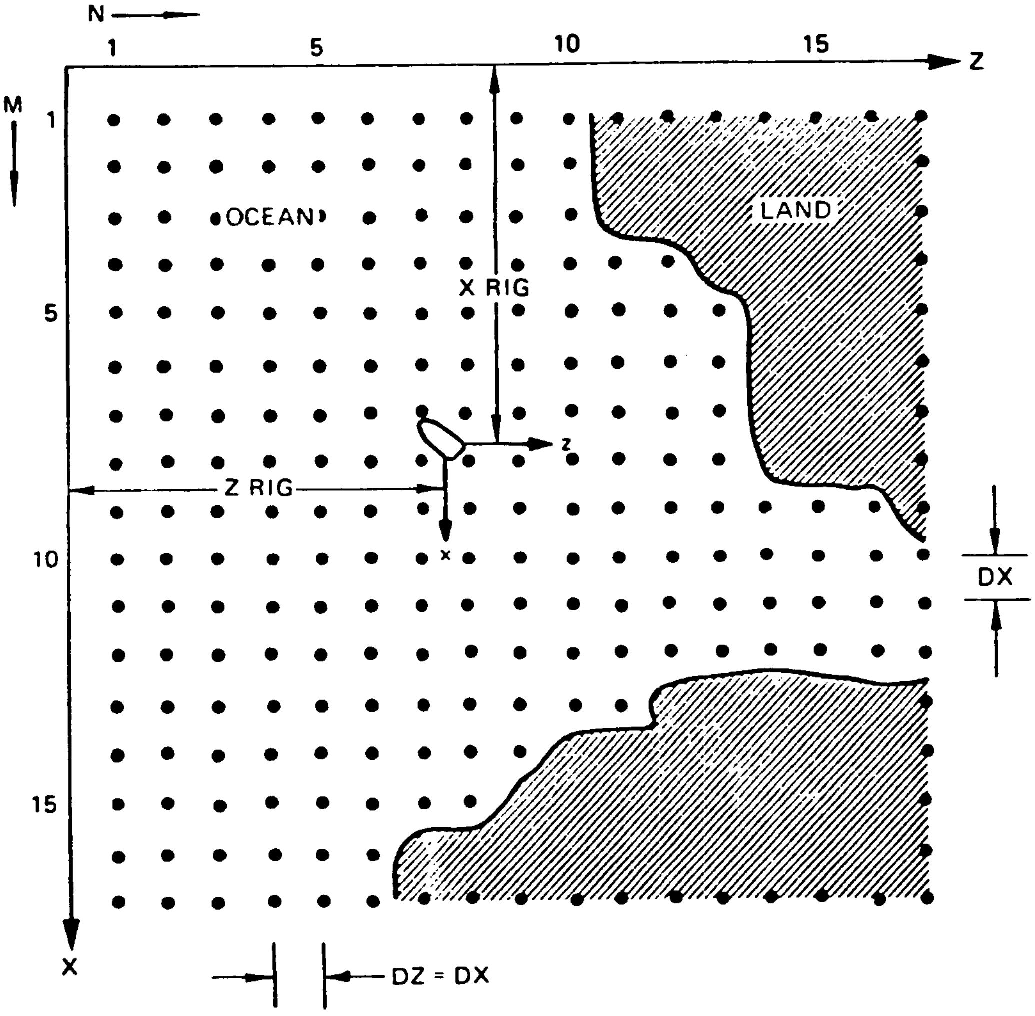


Figure 1. Sketch of coordinate system used by MUD. Grid is used for water column plan views and bottom accumulation displays. X-Z is the global coordinate system and x-z is the local coordinate system.

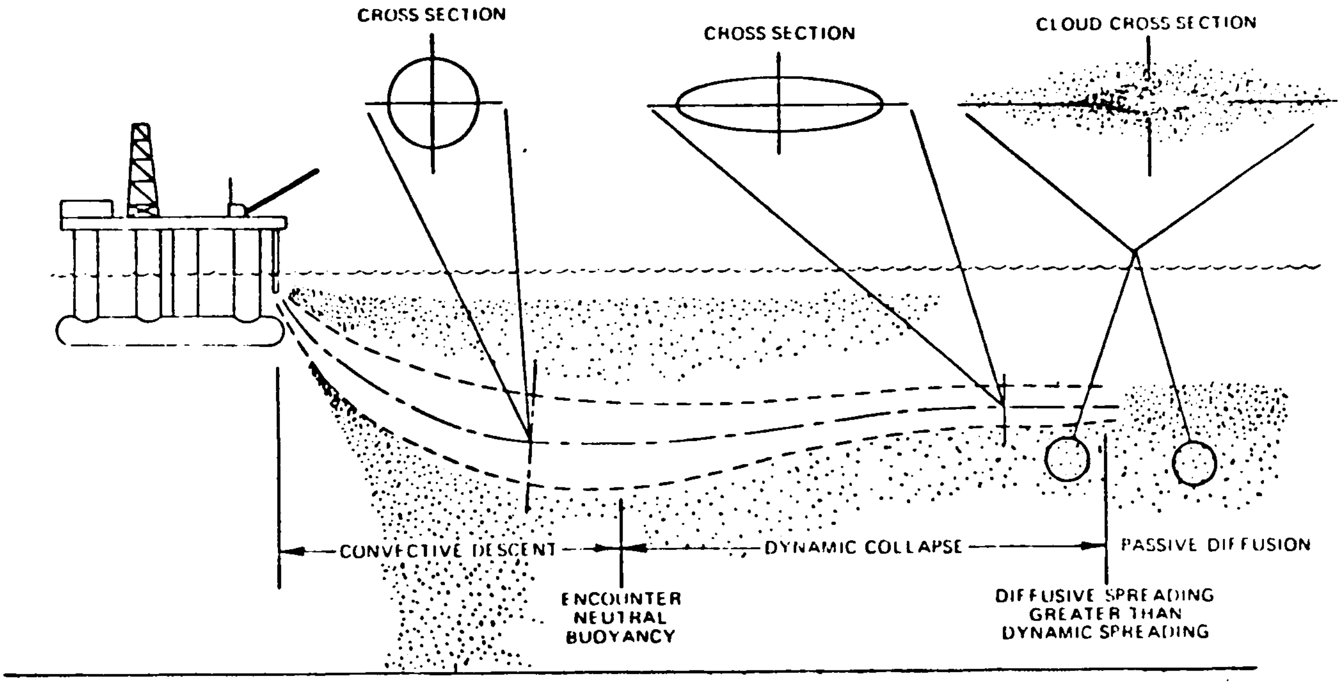
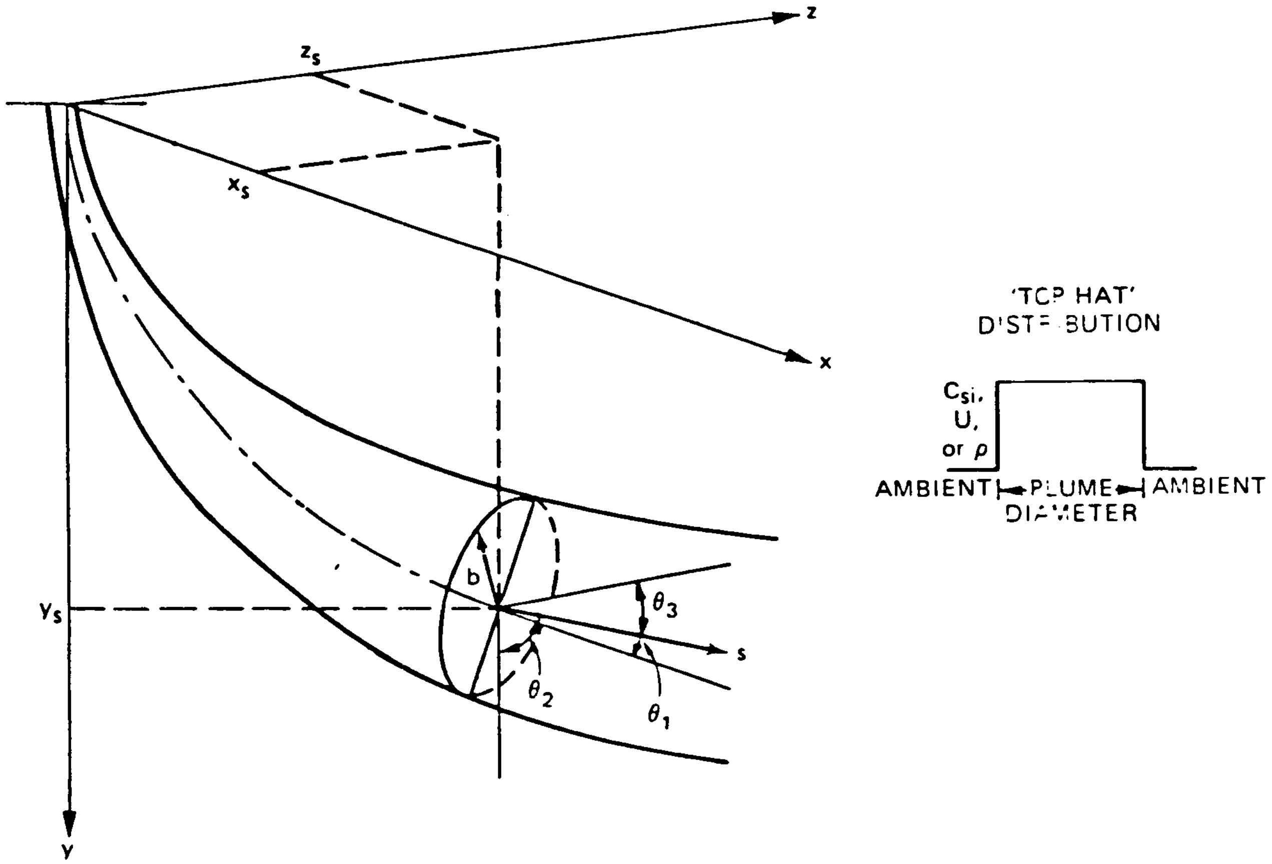
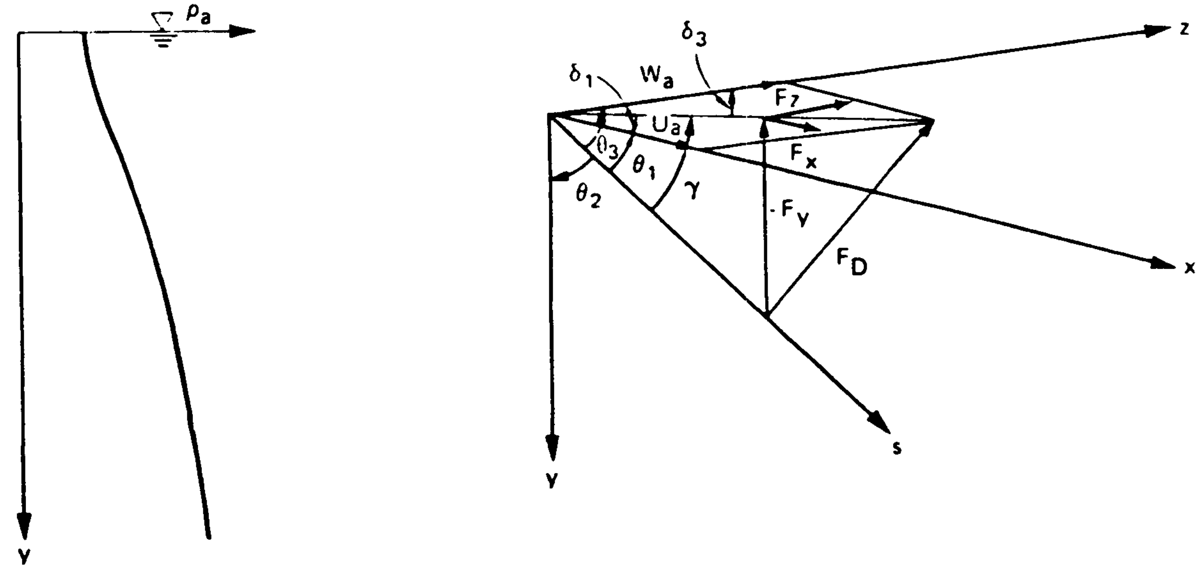


Figure 2. Idealized jet discharge described by OOC model. Cross-sections are shown at three stages of the plume. A heavy class of particles is depicted settling out of the plume at an early stage. Lighter particles are shown settling during the collapse phase. Very fine particles are shown leaving the plume shortly after discharge and remaining near the surface to form the visible plume.



a) JET CONFIGURATION



b) AMBIENT DENSITY PROFILE

c) AMBIENT VELOCITY AND DRAG FORCES

Figure 3. Local coordinate system and definition sketch.

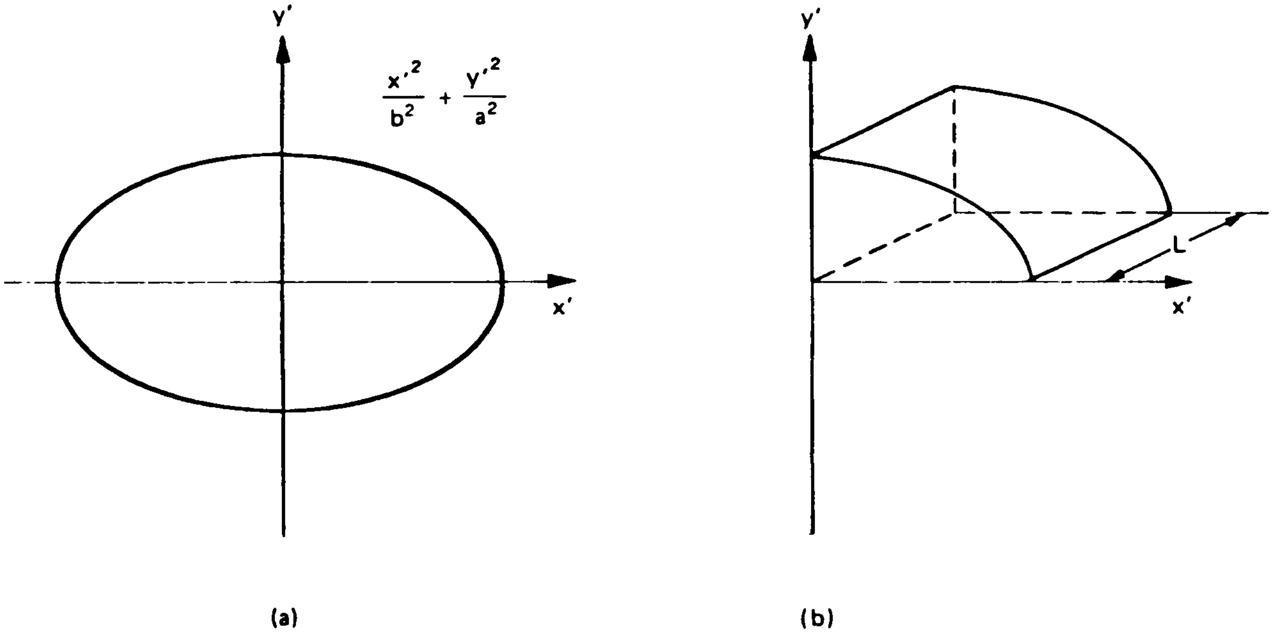


Figure 4. Geometry of the collapsing plume.

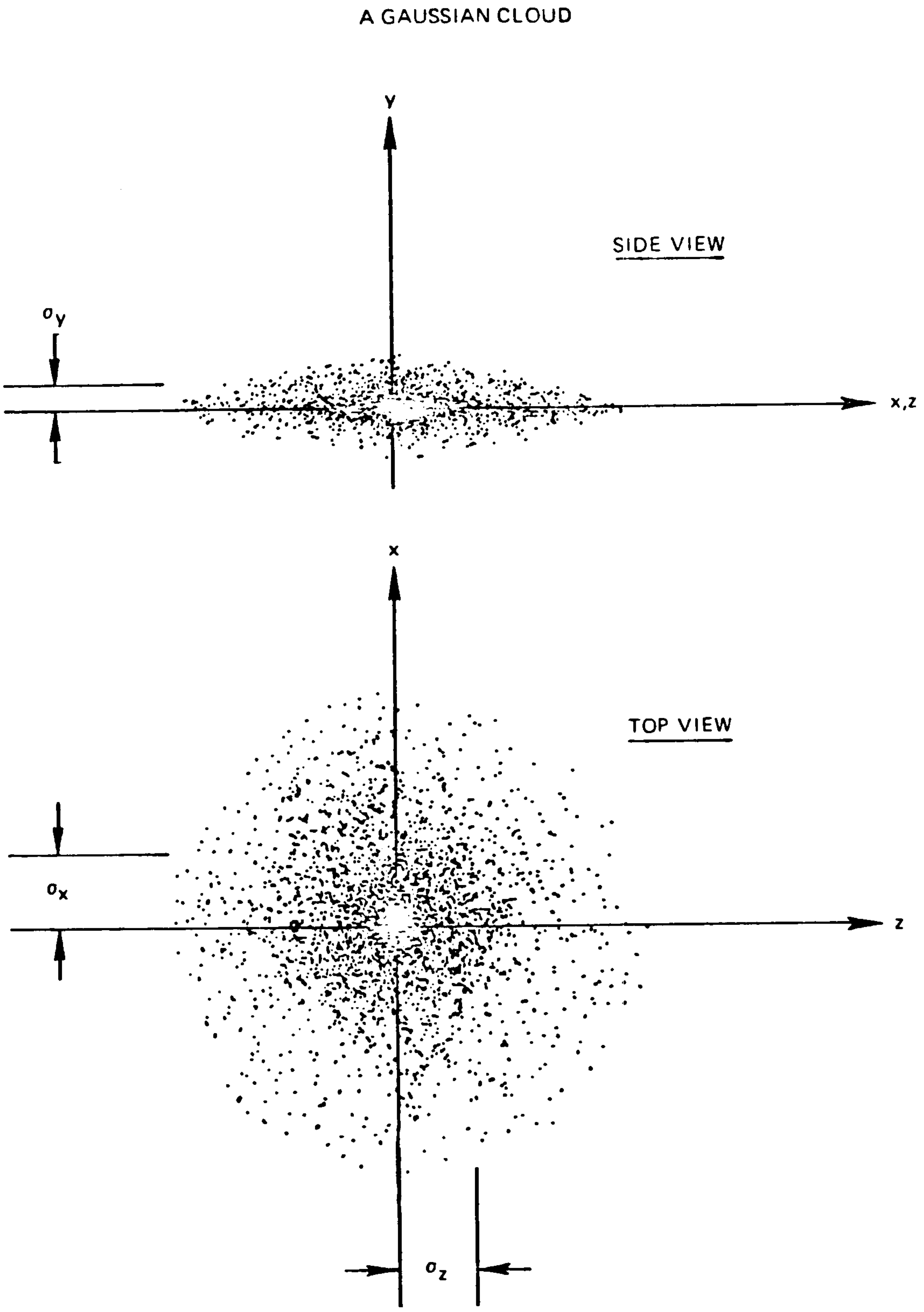


Figure 5. A three-dimensional Gaussian distributed cloud of material.

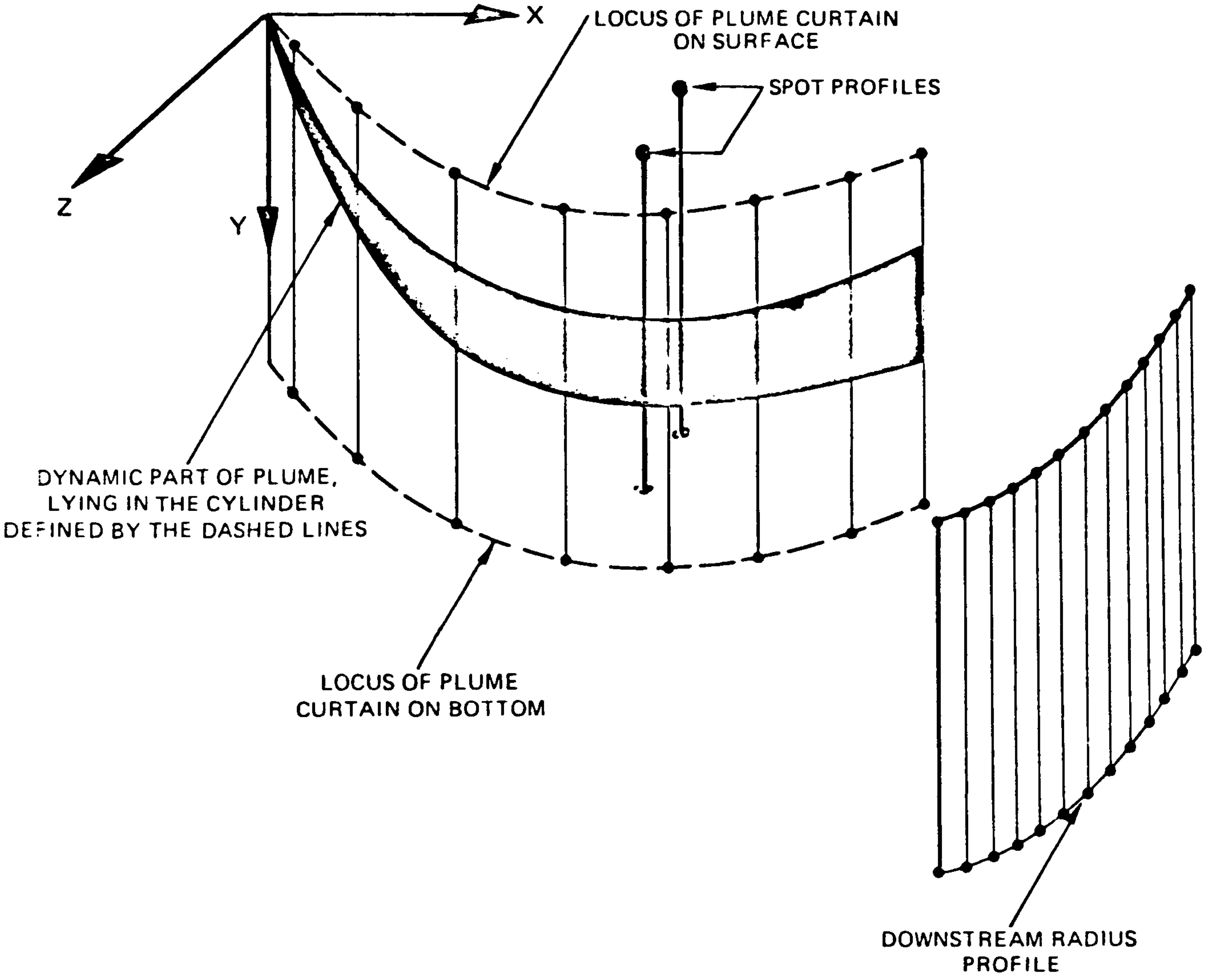


Figure 6. Sketch of the forms of output profiles used to display concentration of solids in the water column.

4.1.2 Part 2 - Model Results

by

Maynard G. Brandsma and Theodor C. Sauer, Jr.

THE OOC MODEL: PREDICTION OF SHORT TERM FATE OF DRILLING MUD IN THE OCEAN
PART 2: MODEL RESULTS

Maynard G. Brandsma
and
Theodor C. Sauer, Jr.

THE OOC MODEL: PREDICTION OF SHORT TERM FATE OF DRILLING MUD IN THE OCEAN[1]
PART 2: MODEL RESULTS

Maynard G. Brandsma[2]
and
Theodor C. Sauer, Jr.[3]

ABSTRACT

Three test simulations were made of the model described in Part 1. The simulations were of a laboratory thermal plume, a laboratory mud plume, and a field study of a mud plume.

Although not designed for thermal plumes, the OOC model gave a reasonable comparison with the trajectory and initial surface spreading of the thermal plume.

The laboratory mud plume gave the best comparison of total suspended solids with the model. The trajectory and centerline suspended solids showed good agreement between the model and the experiment.

The model simulation of the field study showed qualitative agreement on the surface plume, but there were not sufficient plume measurements to provide verification. Measurements were concentrated on the visible surface plume and not the deeper plume containing most of the material. The field placement of sediment traps, away from the main part of the mud plume, did not permit correlation with model sediment trap results.

The dynamic plume calculations of the model match laboratory measurements quite well. Insufficient field data on the distribution of drilling mud accumulated on the bottom did not allow for comparisons with results from the model.

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INTRODUCTION

Part 1 of this paper[1] was a description of the OOC mud discharge model. Part 2 presents the results for three test runs.

The organizers of the Mineral Management Service Workshop have selected three sets of experimental data on which to evaluate models of drilling mud discharges. The intent of having three standard data sets was to provide consistent reference points for model comparisons.

The standard data sets will be described first. Then the application of the OOC model to each data set and the resulting output will be described.

STANDARD DATA SET

Three standard data sets were provided by the workshop organizers. The data sets (summarized in Table 1) are:

1. A buoyant jet discharged horizontally in a non-stratified environment.
2. A laboratory simulation of a mud discharge under controlled conditions.
3. A field study of mud discharged from a drilling rig in the Gulf of Mexico.

The first two data sets were obtained under controlled laboratory conditions and are considered to be highly reliable.[2] The field study has some problems caused by the presence of a strong current shear. Because of the shear, the experimenters were misled in the placement of sediment traps and in the taking of water column samples. The field study gives a good qualitative picture of a prototype discharge; however, the results are concentrated on the highly visible surface plume that contained only 5 to 7 percent of the material discharged (Ayers, et.al. 1980).

None of the test cases include reliable distributions of discharged mud accumulated on the bottom (a major goal of the OOC model).

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[1] Elsewhere in these proceedings.

[2] Personal communication from Dr. A. K. Runchal indicated that the three data sets had been reviewed by Dr. Bob Koh, Prof. Lorin Davis, and Dr. Toni Policastro.

DATA SET NO. 1 - BUOYANT JET IN A NON-STRATIFIED ENVIRONMENT

The first test is the simulation of a laboratory study by Koester (1976), tracking thermal plumes in a non-stratified tank. The plume was dyed so that its trajectory could be followed. The experimental measurements were temperatures obtained by thermistor probes. The study consisted of 49 experiments from which the panel for this workshop selected one.

The selected experiment is Koester's Run No. 3. The discharge is a horizontal one into a still, non-stratified tank. The only density information given is that the tank and the discharge were pure water, and the temperature difference between the two was 18.4°F. The other experimental parameters were:

Tank depth (ft)	0.67
Current speed (ft/sec)	0.0
Discharge nozzle diameter (ft)	0.106
Discharge velocity at nozzle (ft/sec)	1.13
Discharge Froude No.	13.2
Discharge depth/tank depth	0.67

The experimental results were shown by Koester as plots of:

Jet centerline trajectory
Surface half width
Jet centerline temperature decay.

The OOC model does not account for thermal effects at all! Nevertheless, the test was simulated. The OOC model had to be "tricked" into running this case.

The first task was to figure out the water densities in the tank and in the discharge, since these are not given in Koester's paper. The tank was in an indoor laboratory, so it was assumed that the water temperature in the tank was the same as room temperature, 65°F (18.3°C). Since the temperature difference was 18.4°F, the discharge temperature was 83.4°F (28.6°C). The water densities calculated from these temperatures were: tank - 0.9986 gm/cm^3; discharge - 0.9960 gm/cm^3.

The OOC model requires that at least one solid class be prescribed in the "mud." A solid was defined with the same density as the discharge (0.9960 gm/cm^3), a volume concentration of 0.001 ft^3 solid / ft^3 "mud," and a settling velocity of 1.0 x 10^{-6} ft/sec (small enough to prevent settling--the model's early separation mechanism was disabled).

The OOC model requires that ocean wave height and period data be given. A wave height of 0.1 ft and a period of 8.0 seconds was specified. This information is used in estimating the vertical diffusion coefficient which is not important for this run.

The tank depth was 0.67 feet. The OOC model makes geometrical tests for the transition from the jet phase to dynamic collapse at the surface or bottom. The extreme shallowness interfered with numerical values in these tests and caused errors in the model. The remedy was to increase the water depth to 2.0 feet, preserving the discharge depth of 0.45 feet below the surface. Thus the zero current and constant ambient density were prescribed down to 2.0 feet instead of 0.67 feet.

The test case was run through the dynamic phases only, since in the passive diffusion phase, heat transfer between the surface and the air could not be modeled.

The results of the test run are shown in Figures 1 to 3. Figure 1 is a plot of the jet centerline trajectories calculated by the model and the results of the experiment. Figure 2 compares the computed and measured surface half widths. Figure 3 shows the measured jet centerline temperature decay normalized by the initial temperature and the OOC model computed fluid concentration normalized by the initial fluid concentration. This figure is included to demonstrate the comparable mixing between the OOC model and the experiment.

The dynamic calculations were only carried to a small fraction of the dimensionless horizontal distance covered by the experiment because at that point, the OOC model wants to switch to passive diffusion calculations. It was not deemed worthwhile to pursue the simulation further since the model and the experiment are treating fundamentally different situations.

DATA SET NO. 2 - LABORATORY SIMULATION OF MUD DUMP

The second test was a simulation of a laboratory study by Davis (1982) where drilling mud was discharged in a tank. The mud was a mixture of high gravity (4.2 specific gravity) and low gravity (2.6 specific gravity) solids and fresh water. The tank was stratified by using a salt solution. The samples were taken with an array of sampling tubes, each connected to its own reservoir. A vacuum source was the motive power for the sampling. The samples were taken as vertical profiles from top to bottom through the plume centerline. The horizontal coordinates were given as fixed values of horizontal distance normalized by the discharge pipe diameter. Vertical coordinates were given as the depth of the plume below the discharge normalized by the pipe diameter. Samples were taken at four or five depths for each sample profile. Each sample was then analyzed for total suspended solids concentration, high gravity solids concentration, and low gravity solids concentration (all in mg/gram of sample).

The experimental parameters were scaled for the laboratory. The results were reported in non-dimensional form, or in the prototype dimensions. The prototype parameters are listed in Table 2.

Davis's experimental results are summarized by contour plots of suspended solids concentrations for total solids and for high gravity solids. He also gives a tabulation of the experimental measurements. The contour plots are shown in a coordinate system that is non-dimensional depth versus non-dimensional distance downstream in the plume centerline.

Preliminary results for the mud plume were obtained from a microcomputer version of the OOC model that runs only the dynamic calculations. The dynamic calculations provided plume positions and volume fractions in the plume of each mud constituent. Since the experimental results were given in units of milligrams/gram of sample, it was necessary to compute the density of the dynamic plume at each point. This enabled the results of the dynamic plume calculation to be translated into experimental units. The dynamic calculations assume "top-hat" shaped concentration profiles through the plume. To compare the calculated centerline concentrations with the experimental results, it was necessary to adjust the concentrations computed assuming a top-hat profile to a Gaussian shaped profile as is expected in an experiment. This was done by dividing the top-hat concentration by the factor 0.4166, the average value under a Gaussian distribution with a peak value of 1.

The comparison between the OOC model dynamic calculations and the experiment is shown in Figure 4. The experimental results were plotted over Davis's Figure 2. Davis used concentration notations between contour lines suggesting areas of constant concentration. These notations were changed from showing regions of equal concentration to showing regions where the concentration was less than or equal to the amounts shown in Davis's figure. Superimposed on the contour plot is the jet centerline computed by the OOC model. Computed centerline concentrations are noted at several places. The vertical scaled lines show the plume's vertical size at several points.

The results look good. The computed plume trajectory is a little deeper than the measured one. The centerline concentrations are reasonably close. This is the first set of reliable data that allows a comparison of concentrations computed by the model with those found experimentally.

DATA SET NO. 3 - FIELD STUDY OF MUD DISCHARGE IN THE GULF OF MEXICO

The third test case is of a mud plume created by a 275 bbl/hr discharge from a drilling site in the Gulf of Mexico, (Ecomar, 1980, and Ayers et al. 1980). The mud was a mixture of high gravity and low gravity solids and water. There was an extensive program of hydrographic and mud plume measurements. A helicopter transported instrument package sampled the hydrographic characteristics in the water column. The same instrument package contained remote controlled sample bottles for taking samples of the plume. The samples were taken in the midpoint of the visible plume as vertical profiles from top to bottom through the plume centerline. The depth of the plume was gauged using a transmissometer on board the instrument package. Each plume sample was analyzed for total suspended solids and various chemical tracers. Besides the water column samples, several sediment traps were deployed beneath the visible plume.

This was a very strong field experimental effort providing a wealth of good information. However, there are some problems in the data that make it difficult to use for model verification. The problems were caused by a strong current shear on the day of the test. Analysis of the data showed that the observed plume was an upper plume composed of fine particles and soluble components. Most of the discharged material formed a lower plume that settled quickly to the ocean floor along a path different than that of the upper plume (the effects of the shear current). Plume samples were taken based on tracking of the visible plume by helicopter. The sediment traps used in the test collected little material because the prevailing shear currents presumably caused the bulk of the discharged material to bypass the trap locations.

The experimental parameters for the field test are listed in Table 3.

The current profile used for the test was the average of the values given in Table 9 of the Ecomar (1980) report, with the additional condition that the current speed was zero at the bottom:

Depth (ft)	Speed (ft/sec)	Direction (Degrees)
0.0	0.065	154
10.0	0.065	154
23.0	0.55	216
46.0	0.72	324
69.0	0.03	154
75.4	0.0	154

This current structure leads to the expectation that the various classes of material discharged will be dispersed in a double plume. The slowly settling fines deposited in the surface layer, above the pycnocline, will be carried off to the southwest (216°). Heavy material that penetrates to the deeper layer will be carried off to the northwest (324°). Intermediate materials will be smeared out between. Sometimes samples were taken or sediment traps placed that did not collect much material. In a qualitative sense, the <u>absence</u> of material in a sample or trap gives us information that is as useful as that from a sample or trap that was full of material.

Forced separation of solid no. 6 (SOL6) was used in the test run, because in the field test, fine material was observed leaving the plume immediately after discharge from the pipe.

There were 20 samples taken for the entire surface plume during the discharge. For comparison purposes, the authors grouped the samples in five distance categories: 42 meters, 60 meters, 136 meters, 181 meters, and 250 meters.

The OOC model's profiles of total suspended solids are sensitive to the position of the profiles where conditions vary rapidly as in this test. Also, the model tends to show marked concentration fluctuations just as in the prototype. To smooth out these effects and to reduce the effect of any possible errors in the sampling positions reported by Ecomar, several runs were made for this test. One run used the bearings and distances reported by Ecomar for the plume sample positions. Three others used constant bearings centered on the surface current bearing, 4 degrees to one side of the surface current bearing, and 9 degrees to one side of the surface current bearing. The distances used by all three runs were those reported by Ecomar. The profiles from all the runs were averaged for the 24 minute and 48 minute times shown in Ecomar's Figure 15. Then the 24 minute and 48 minute profiles were averaged and plotted together with the sample results for total suspended solids as shown in Figure 5. One interesting feature is that the model results show the visible plume remaining above the pycnocline. The average plume calculated by the model shows a smooth decline in concentrations. In contrast, the trend of the sample results is not readily apparent.

Figure 6 shows a contour plot of total solids concentrations computed in the visible plume extending to the southwest of the drilling rig. The surface plume portion of the contours (depth less than 12 meters) was defined using the profiles of Figure 5. Therefore the contours, attempting to show a steady, time-averaged plume, are smoothed somewhat. Concentrations at depths greater than 12 meters near the rig are those of the main plume. Average concentration profiles at the two plume curtain points closest to the rig were also plotted on Figure 6 and the contours extended smoothly to include these. Figure 6 should be compared with Ecomar's Figure 15 and their Tables 11 and 12.

The calculated visible plume does display the correct general behavior; its concentration decreasing markedly as it moves downcurrent at the level of the pycnocline. The calculated plume consists almost entirely of solid number 6, comprising approximately 10 percent of the discharged solids. This roughly agrees with the field observation of 5 to 7 percent of discharge solids in the upper plume (Ayers et al. 1980).

It should be noted that the model's simulation is of a slowly varying and continuous process, while, in fact, the discharge was somewhat erratic. Divers reported a "puffy" appearance to the plume and the measurements show instances of rapid variations in concentration as a function of position and time.

Figure 7 shows plan views of the total suspended solids as a function of depth. The double plume pattern is quite clear. The fine material that forms the surface plume is carried to the southwest, while the heavier material, sinking deeper, is carried to the northwest because of the shift of current direction with increasing depth. At intermediate depths, material is smeared out between these two directions. The time of this distribution is 4,320 seconds, 1,050 seconds after the end of the discharge.

Figure 8 shows a contour plot of the total solids accumulation on the bottom 3,930 seconds after the end of the discharge. The contour units are lbs/ft^2. The centroids of each solid class are also plotted to show the segregation of solids. The sediment trap locations to the southwest of the rig are also shown. From this figure, the reason the sediment traps did not capture much material in the field test is clear. They are outside the settling zone of this discharge. The model calculations for sediment traps show near zero accumulations while the measured accumulations averaged 25 milligrams per trap. The trap aperture was 0.1 meter^2.

Finally, there is a particularly interesting correspondence between field measurements and computer simulation. Both show high dilutions occurring very quickly after discharge. In the 275 bbl/hr discharge, and in other tests, dilutions have been typically 100 to 1, ten seconds after discharge and 1000 to 1, one minute after discharge.

CLOSURE

The OOC model appears to give valid results on a variety of cases. The model behaves well in simulations at the edge of its capabilities. At this stage it is still a research tool. Wider application should probably await additional tests to better verify the model's treatment of phenomena observed in the field. In particular, this means the forced separation of fine solids from the plume. There are several coefficients or mechanisms that need verification. They are intertwined, and deal with

settling of heavy solids from the plume,
plume entrainment at low Froude numbers,
the added mass coefficient, and
the spreading of a heavy mud on a shallow bottom.

The authors have noticed a particular tendency of model users to run simulations of high weight muds in shallow water with low currents. The model was never originally designed to cope with this situation. Much effort has been expended in making the model "survive" these types of conditions. For near vertical trajectories at bottom encounter, it may be best to add an option to show the plume spreading out radially from the point of impact, as in a wall jet.

ACKNOWLEDGEMENTS

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TABLE 1.

SUMMARY OF STANDARD DATA SETS

Set No.	1	2	3
Reference	Koester	Davis	Ecomar
Discharge density (gm/cc)	0.9960	1.184	2.084
Ambient density at discharge	0.9985	1.014	1.014
Discharge rate (ft3/sec)	0.01	0.414	0.43
Discharge nozzle diameter (ft)	0.106	0.333	0.333
Discharge Froude No.	13.2	0.63	0.21
Discharge angle	Horizontal	Vertical	Vertical
Currents (ft/sec)	none	uniform 1.0	variable 0.06 at discharge
Stratification	no	yes	yes

TABLE 2.

PROTOTYPE PARAMETERS -- LABORATORY SIMULATION OF MUD DUMP TEST CASE NO. 2

Current speed (ft/sec, uniform)	1.0	
Discharge rate (bbl/hr)	256.5	(0.414 ft^3/sec)
Discharge nozzle diameter (ft)	0.667	
Discharge velocity at nozzle (ft/sec)	1.19	
Discharge Froude No.	0.63	
Discharge depth/tank depth	0.0	
Bulk density (gm/cm^3)	1.184	(9.9 lbs/gal)

The mud components and settling velocities were:

Component	Concentration (volume fraction)	Settling Velocity (ft/sec)
High grav 1	0.00071	0.043
High grav 2	0.00896	0.008
High grav 3	0.00888	0.0008
High grav 4	0.00566	0.00006
Low grav 1	0.00075	0.030
Low grav 2	0.00981	0.005
Low grav 3	0.01121	0.0005
Low grav 4	0.04482	0.0000000001
Water	0.90921	

The ambient density profile (from Davis's Figure 1) was:

Depth (ft)	Sigma-t
0.0	14.0
8.5	15.3
22.6	16.2
47.2	17.6
72.3	18.6

TABLE 3.

DISCHARGE PARAMETERS -- MAXIMUM MUD STUDY
TEST CASE NO. 3.

Discharge rate (bbl/hr)	275	(0.43 ft^3/sec)
Discharge nozzle diameter (ft)	0.667	
Discharge velocity at nozzle (ft/sec)	1.23	
Discharge Froude No.	0.21	
Discharge depth (ft)	10.0	
Bulk density (gm/cm^3)	2.084	(17.4 lbs/gal)
Water depth (ft)	75.4	
Current speed (ft/sec, maximum)	0.79	
Wave height (ft)	2.0	
Wave period (sec)	12.0	

The mud components and settling velocities were:

Component	Concentration (volume fraction)	Settling Velocity (ft/sec)
SOL1	0.0364	0.0216
SOL2	0.0364	0.00682
SOL3	0.04368	0.00278
SOL4	0.07280	0.00143
SOL5	0.1383	0.000758
SOL6	0.0364	0.000427
FLUID	0.636	

High and low gravity solids were mixed in each settling velocity class. The average density for all six classes of solids was 3.959 gm/cm^3. The fluid density was 1.016 gm/cm^3.

The ambient density profile for the 275 bbl/hr test was obtained by averaging the density profile measurement depicted in Figure 13 of Ecomar (1980):

Depth (ft)	Density (gm/cm^3)
0.0	1.014
22.3	1.014
42.6	1.020
55.8	1.022
75.4	1.023

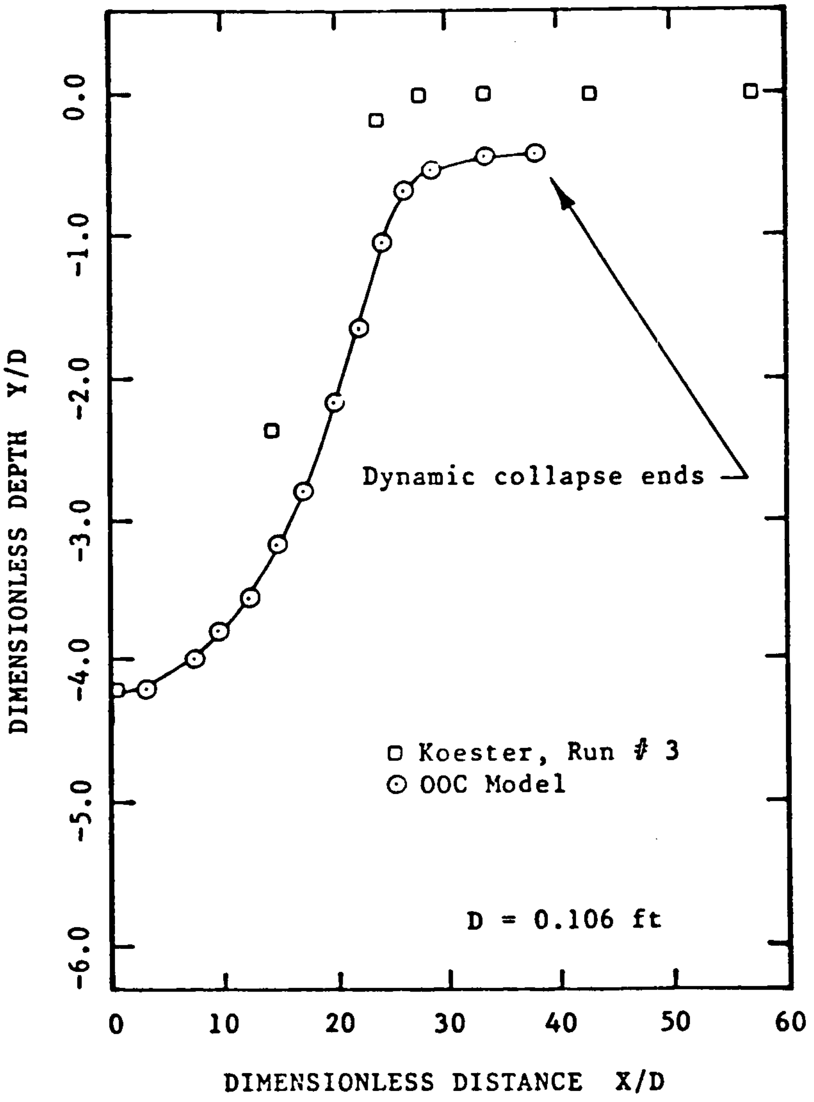


Figure 1. Test case no. 1. Jet trajectory.

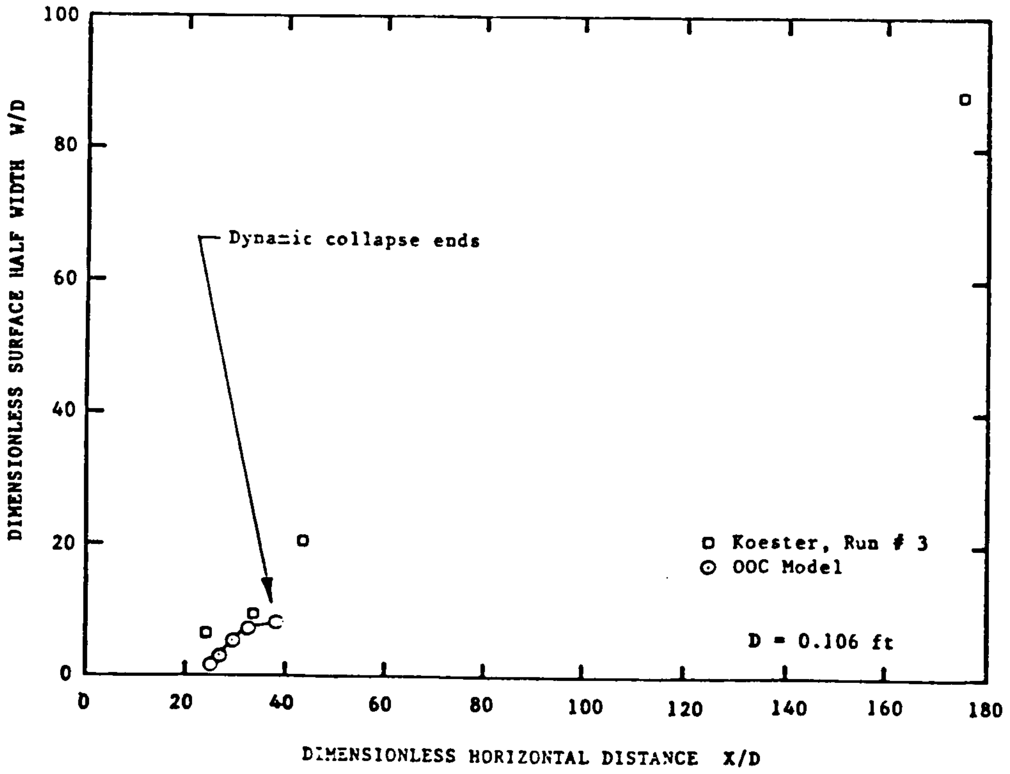


Figure 2. Test case no. 1. Surface half-widths.

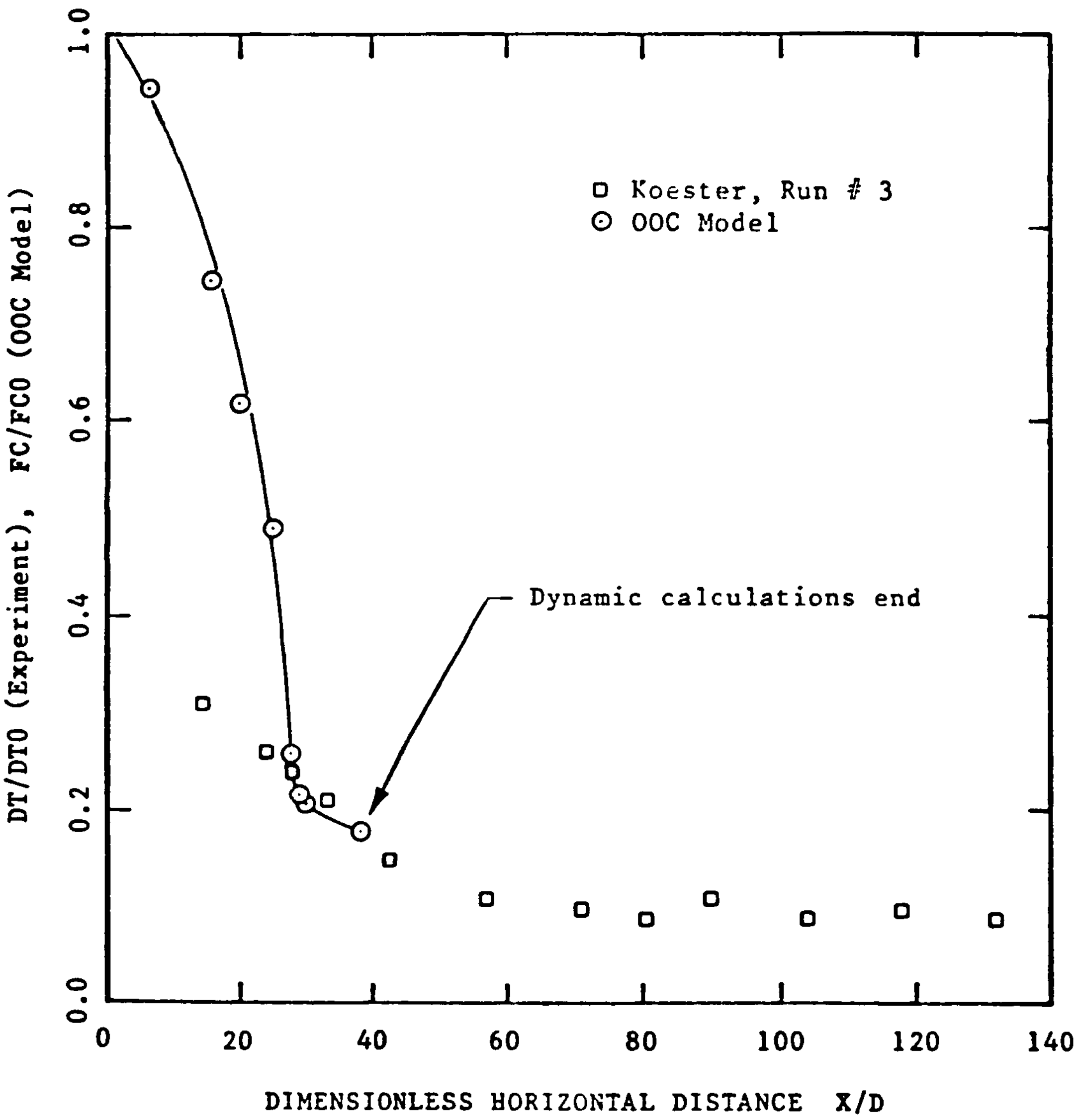


Figure 3. Test case no. 1. Jet centerline temperature normalized by initial temperature versus calculated jet centerline fluid concentration normalized by initial fluid concentration.

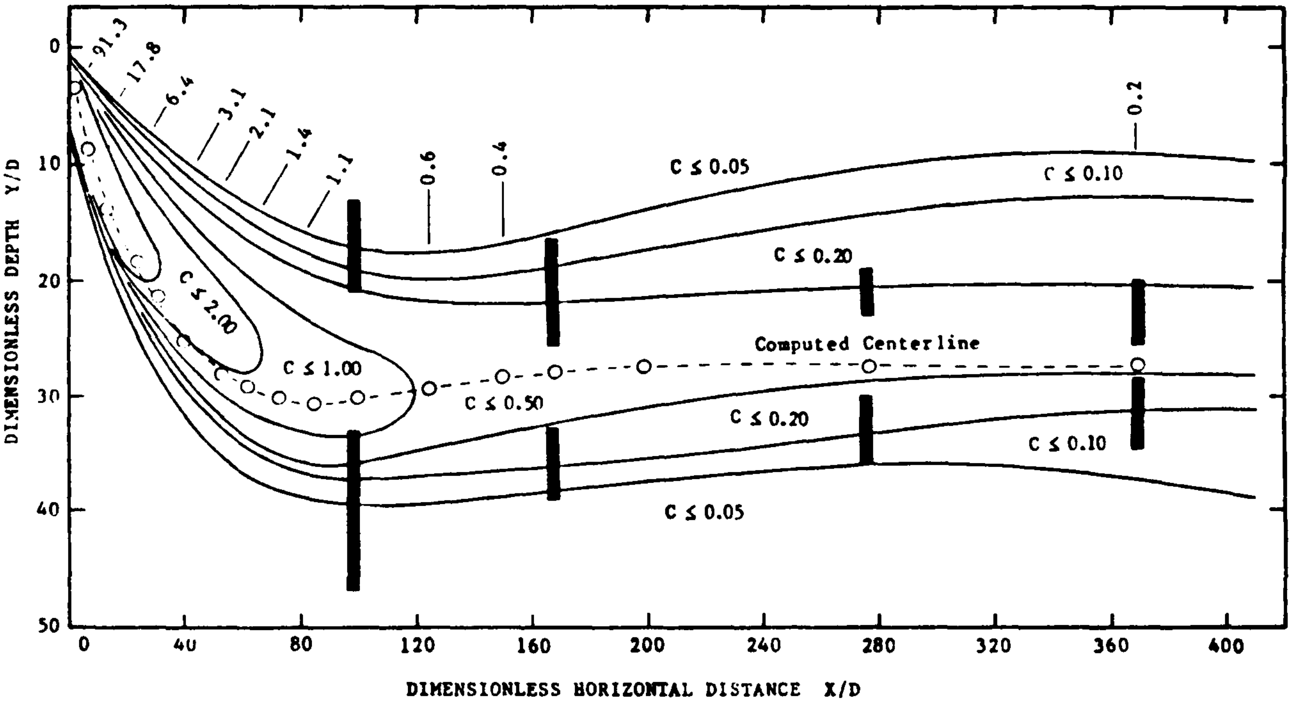


Figure 4. Test case no. 2. Contour plot of measured suspended solids (mg/gram sampled) compared with computed jet centerline trajectory (dashed line) and computed suspended solids (mg/gram sample) at the centerline (noted above plume). This is plotted using the results of the dynamic calculations only. The heavy vertical bars show the vertical extent of the calculated plume at various distances from the discharge.

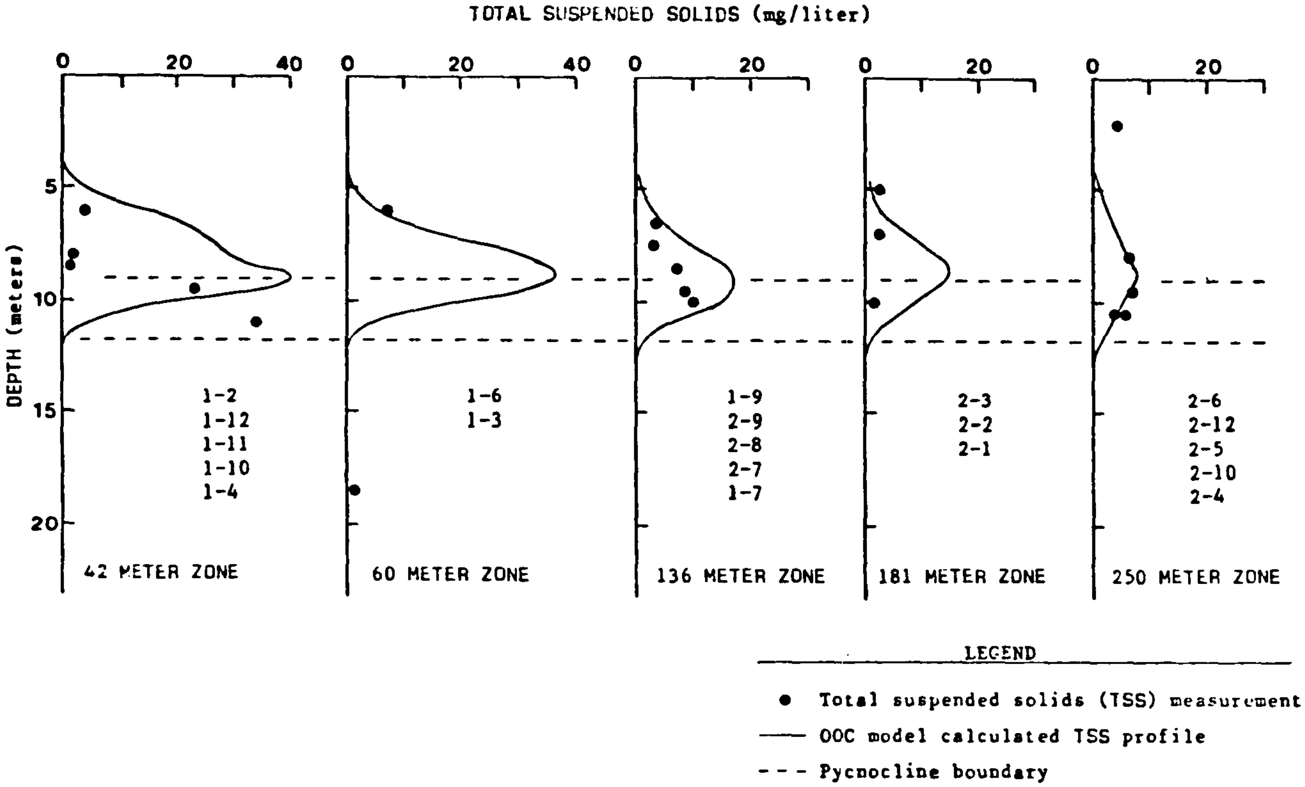


Figure 5. Test case no. 3. Total suspended solids in surface plume. Measurements reported by Ecomar (1980) were grouped in zones various distances downcurrent from the discharge. The dots are the measurement points, and the corresponding sample numbers are listed in each zone. Average profiles of total suspended solids were made by the OOC model at these zones.

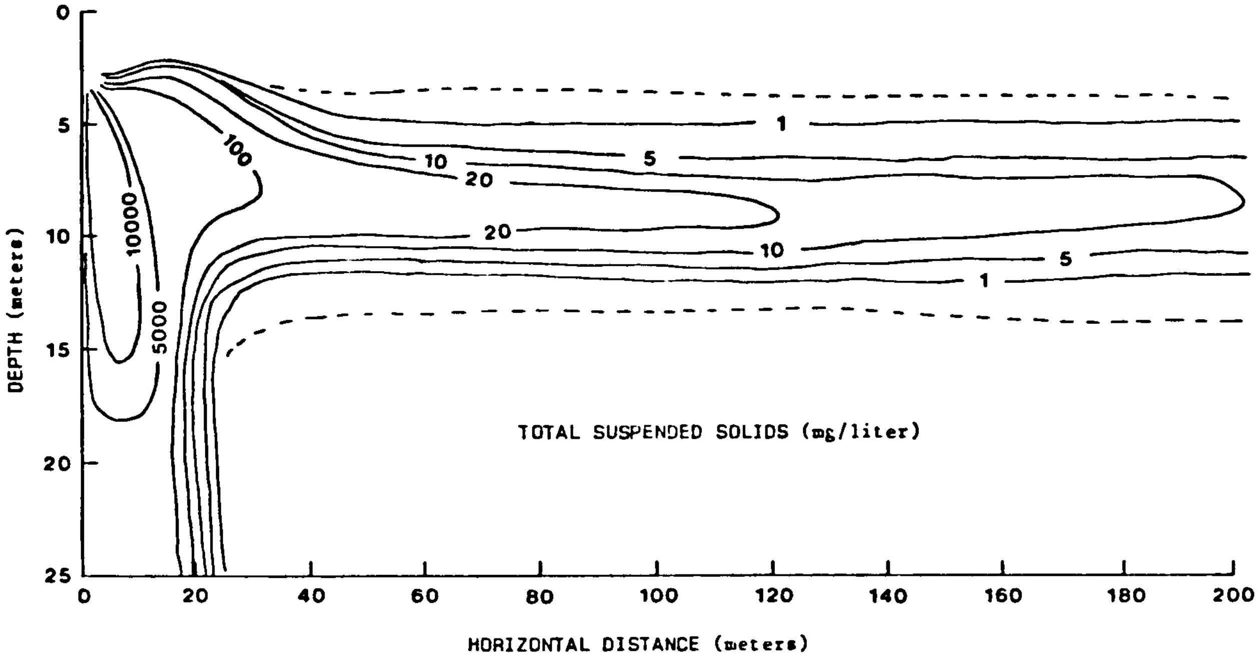


Figure 6. Test case no. 3. Contour plot of computed total suspended solids. Contours were drawn from the surface profiles of Figure 5 and profiles of the deep plume near the discharge. High concentrations below the discharge agree with diver samples of 14756 mg/liter (8 meters down, 6 meters distant) and 5450 mg/liter (10 meters down, 15 meters distant).

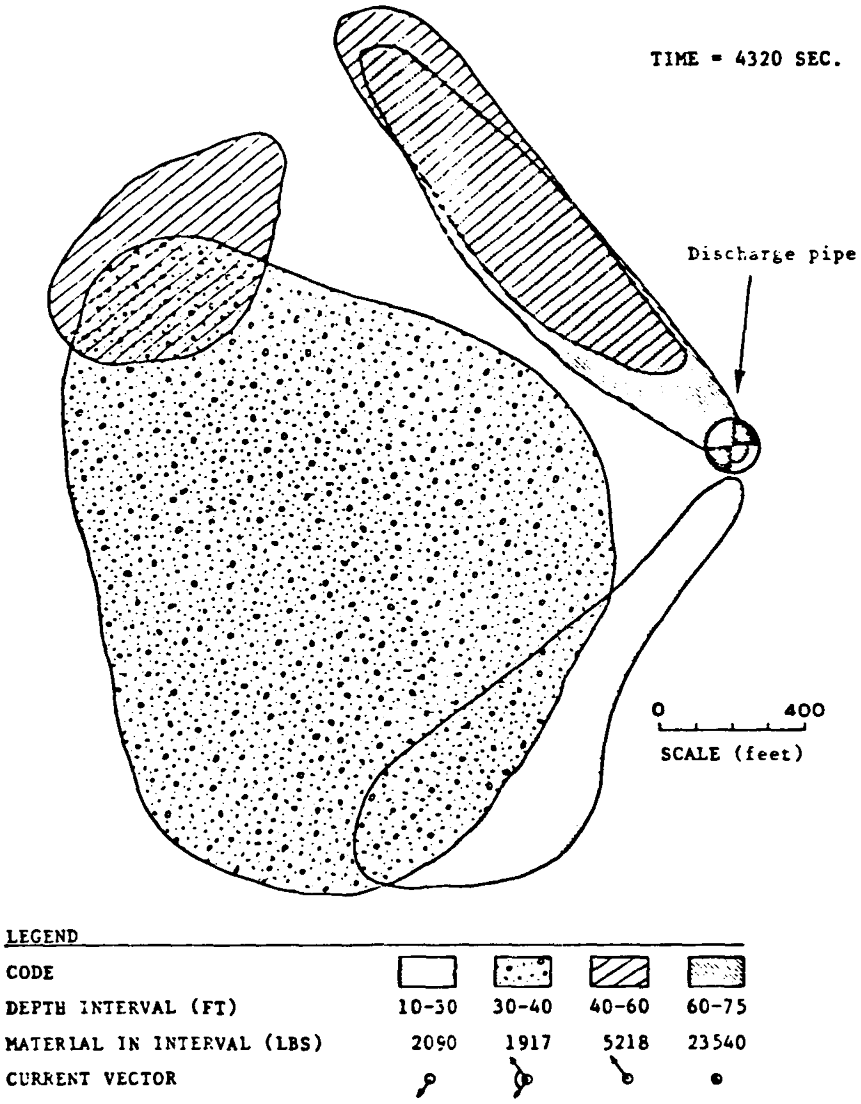
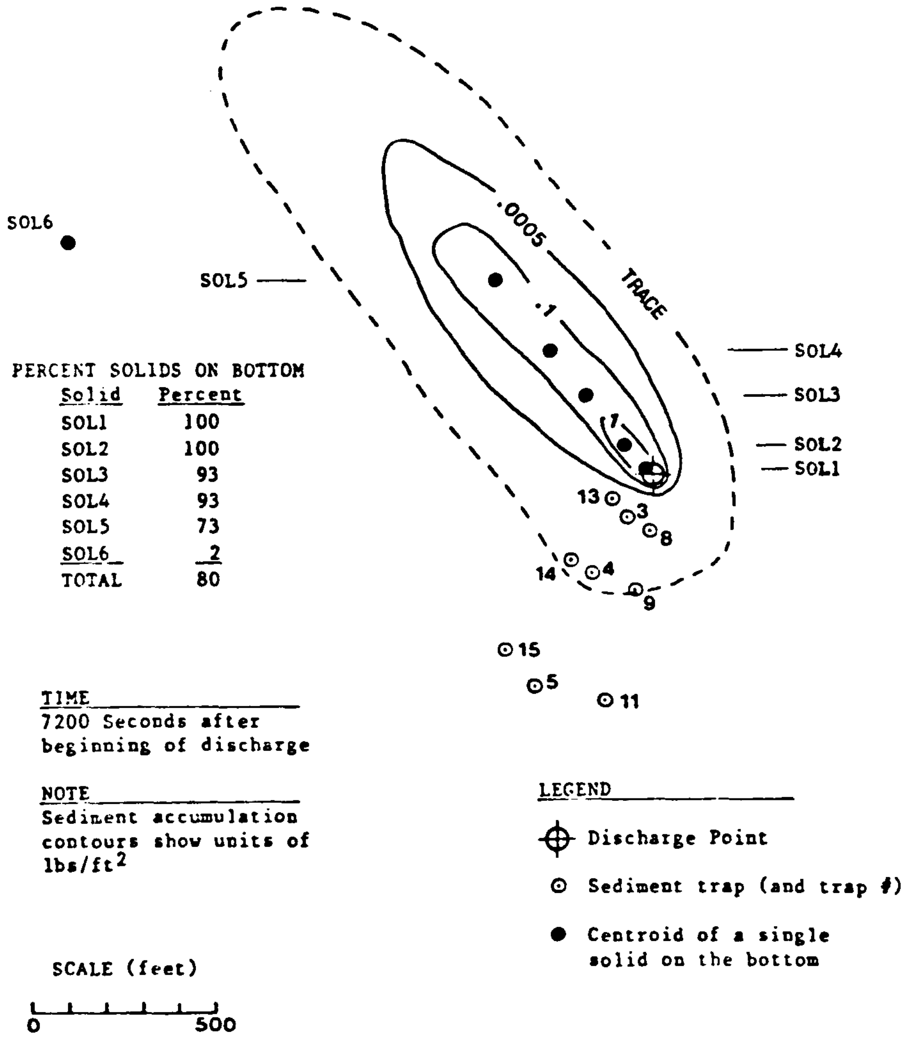


Figure 7. Test case no. 3. Horizontal distribution (plan view) of total solids as a function of depth, 4,320 seconds after the beginning of the discharge. This shows the effect of the strong current shear on the day of the test. The contours show the areas where any material was present. The surface plume (10-30 feet deep) was the object of most measurement activity.



PERCENT SOLIDS ON BOTTOM

Solid	Percent
SOL1	100
SOL2	100
SOL3	93
SOL4	93
SOL5	73
SOL6	2
TOTAL	80

TIME
7200 Seconds after beginning of discharge

NOTE
Sediment accumulation contours show units of lbs/ft^2

LEGEND

⊕ Discharge Point

⊙ Sediment trap (and trap #)

● Centroid of a single solid on the bottom

Figure 8. Test case no. 3. Accumulation of solids on the bottom (lbs/ft^2) 65 minutes after the end of the discharge. Sediment traps placed under the surface plume caught only traces of the material settling to the bottom because of the current shear.

4.2 Modified Koh-Chang Model

by

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MODIFIED KOH-CHANG MODEL

by

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ABSTRACT

Mathematical and numerical models were developed describing the behavior of drilling mud plumes. The formulations of these models are based on the model developed by Koh and Chang (1973) for the simulation of dispersion, diffusion, and settling of the barged waste disposal. The predictions of the Koh-Chang Model compare very well with the experimental results in the short-term part of simulation. Verification of the long-term part of simulation is needed.

The drilling mud plume is assumed to consist of solid and liquid phases. The solid phase is characterized by constituents with various densities and fall velocities. The material is discharged through a submerged nozzle into the ocean. The effects of ambient current profiles, density stratification, variation of diffusion coefficients are incorporated in the model.

The short-term and long-term dynamic characteristics of plume are simulated by the numerical model. The short-term plume simulation includes convective and collapse phases. The collapse phase will include a bottom spreading phase if the plume encounters the sea bottom. The long-term dispersion and diffusion equation is solved by method of moment in the Koh-Chang Model. Brandsma and Divoky (1978) adopted Fischer's (1970) passive diffusion scheme to simulate the long-term phase of dispersion and diffusion. Recently, Leung and Wu (1982) incorporated a resuspension mechanism due to waves and currents into Brandsma - Divoky's long-term passive diffusion model.

The convective descent phase describes the dynamic behavior of a sinking jet. The dynamic collapse phase occurs when the descending plume either encounters the bottom, or arrives at the neutral buoyancy stage at which vertical movement is retarded and horizontal spreading dominates. The long-term passive diffusion occurs when ambient currents and turbulence dominate the transport and spreading of the plume. Transition between phases are accomplished automatically in the numerical model. Special efforts have been made to minimize the amount of input required by the numerical model. Solutions at any phase of simulation are displayed. Graphic output is also incorporated.

1. Introduction

The evaluation of environmental inpact due to drilling mud discharge has been a great concern in relation to offshore drilling activity. The laboratory and field measurement programs would help in understanding the fate of drilling mud discharge. In practice, a general computer model based on the dispersion and diffusion of mud plumes is needed by operators and regulatory agencies to predict the fate of drilling mud discharges under various oceanographic conditions.

Drilling mud plumes consists of various sizes and densities of solid particles, combined with water and many different additives. The computer model developed by Koh and Chang (1973) for the simulation of dispersion and settling of barge disposed wastes in the ocean can be applied directly to the drilling mud simulation. This model was developed for the U.S. Environmental Protection Agency and employed the research results of Morton, Taylor, and Turner (1956), Brooks and Koh (1965), Singamsetti (1966), Koh and Fan (1968), and Abraham (1970), associated with buoyant jet discharging into a stratified cross current ambient. This model assumed a constant water depth and uniform current, and compared very well with measurements. Brandsma and Divoky (1976) modified Koh-Chang's long-term phase by adopting Fischer's (1970) passive diffusion model for variable water depths and currents. This model was developed for the U.S. Army Corps of Engineers. Leung and Wu (1982) recently incorporated a resuspension model into the long-term phase of the Brandsma-Divoky model. This modified version of the Koh-Chang Model needs further verification.

2. Mathematical Model

The simulation of dispersion and diffusion processes of the discharged drilling mud plume includes three phases: a) convective descent, b) dynamic collapse, and c) passive diffusion as shown in Figure 1. The mathematical formulations of the governing equations for each phase are described as follows:

2.1 Convective Descent

The dynamic behavior and the trajectory of a sinking jet discharged into a stratified cross current ambient can be described by the equations of conservation of mass, momentum, buoyancy, solid particles, equations of center line trajectory, equations of entrainment, drag forces, and settling of particles. The jet is assumed to be a round jet with a top-hat velocity, density, and concentration of drilling mud distribution. Figure 2 shows the coordinate system and trajectory of the jet. The conservation equations can be written as follows:

Conservation of Mass $$\frac{dV}{ds} = E \rho_a - \sum_i \sum_j S_{ij} \rho_{si} \qquad (1)$$

Conservation of Momentum (2)

$$\frac{d\vec{M}}{ds} = F\vec{j} + E\rho_a\vec{U}_a - \sum_i\sum_j S_{ij}\rho_{s_i}\vec{U} - \vec{F}_D$$

Conservation of Buoyancy (3)

$$\frac{dB}{ds} = E(\rho_a(0) - \rho_a) - \sum_i\sum_j S_{ij}(\rho_a(0) - \rho_{s_i})$$

Conservation of Particles (4)

$$\frac{dP_{ij}}{ds} = -S_{ij}$$

where $V = \pi b^2 \rho U$ is mass flux; $\vec{M} = \pi b^2 \rho U \vec{U}$ is momentum flux; $B = (\rho_a(0) - \rho)\pi b^2 U$ is buoyancy flux; $P_{ij} = \pi b^2 U C_{s_{ij}}$ is solid particle flux; $F = \pi b^2 g(\rho - \rho_a)$ is buoyancy force per unit length; b, U, ρ, $C_{s_{ij}}$, ρ_a, U_a are the radius, velocity, density, concentration of discharged mud plume, ambient density, and ambient cross current, respectively. The entrainment function, $E = E_M + E_T \sin\theta_2$, is the sum of the entrainment due to momentum jet, E_M, and a two-dimentional thermal, E_T. $\sin\theta_2$ is arbitrarily chosen to control the contribution of the thermal type of entrainment. $\vec{F}_D$ is the drag force of ambient cross current exerted on the jet. $S_{ij} = 2b|W_{s_{ij}}| \; C_{s_{ij}} \; (1-\beta_{ij})$ describes the settling of the solid particles due to the balance of gravity and turbulence in the jet. β is the settling coefficient depending on the settling velocity W and concentration, C.

The geometric relationship of a jet center line orientation is

$$\cos^2\theta_1 + \cos^2\theta_2 + \cos^2\theta_3 = 1 \tag{5}$$

Equations (1) to (5) constitute seven simultaneous ordinary differential equations for seven unknowns: U, b, ρ, $C_{s_{ij}}$, θ_1, θ_2, and θ_3. The equations can be solved by giving initial conditions and using fourth-order Runge-Kutta method to integrate them, Consequently, the trajectory of the jet center line is determined by the following equations:

$$\frac{dx}{ds} = \cos\theta_1 \; ; \qquad \frac{dy}{ds} = \cos\theta_2 \; ; \qquad \frac{dz}{ds} = \cos\theta_3 \tag{6}$$

and the dynamic behavior of a jet, i.e., U, b, ρ, and $C_{s_{ij}}$ are also determined.

2.2 Dynamic Collapse

When the jet reaches a neutral buoyancy level where the jet density equals the ambient density, the jet no longer behaves like a jet, and tends to collapse vertically and spreads out horizontally, seeking a hydrostatic equilibrium state. At this stage, the plume would be more like a two-dimensional thermal and is approximated by an ellipse shaped thermal with a length L as shown in Figure 3. Since the plume velocity has become close to that of the ambient, the conservation equations are written with respect to time to describe the dynamics of convection and collapse of the plume. The conservation equations are:

Conservation of Mass $\frac{dV}{dt} = E\rho_a - \sum_i \sum_j S_{ij}\,\rho_{s_i}$ (7)

Conservation of Momentum $\frac{d\vec{M}}{dt} = F\vec{j} + E\rho_a \vec{U}_a - \sum_i \sum_j S_{ij}\rho_{s_i}\vec{U} - \vec{D}$ (8)

Conservation of Buoyancy $\frac{dB}{dt} = E(\rho_a(0) - \rho_a) - \sum_i \sum_j S_{ij}(\rho_a(0) - \rho_{s_i})$ (9)

Conservation of Particles $\frac{dP_{ij}}{dt} = - S_{ij}$ (10)

where $V = \rho\pi a b L$ is the total mass in the buoyant element; $\vec{M} = C_m \rho\pi a b L\vec{U}$ is momentum; $B = \pi a b L\,(\rho_a(0)) - \rho)$ is buoyancy; $P_{ij} = \pi a b L\, c_{s_{ij}}$ is solid volume in the buoyant element; $F = \pi a b L(\rho - \rho_a)g$ is the buoyancy force; $\vec{D}$ is drag force; $E = 2\pi L\sqrt{a^2 + b^2}\,/2 \cdot (\alpha_3\,|\vec{U} - \vec{U}_a| + \alpha_4 \frac{db}{dt}\,)$ is total entrainment in volume, and α_3 and α_4 are entrainment coefficients for convection and collapse respectively; and $S_{ij} = 2bL\,|W_{s_{ij}}|\,C_{s_{ij}}(1 - \beta_{ij})$ is settled solids in volume.

An additional equation is needed to describe the dynamic collapse of a quadrant of the elliptical cylinder with length L, which is

$$I = F_D - D_D - F_f \tag{11}$$

where $I = \frac{d}{dt}(\frac{ab}{3}L\rho V_1)$ is inertia force; $F_D = g\rho_a \frac{1}{6} L(1 - \frac{a_0}{a}\gamma)\varepsilon a^3$ is the driving force due to the difference of density gradients inside and outside the plume; $D_D = C_D \frac{a\rho_a}{2} L V_2\,|V_2|$ is form drag; $F_f = C_f \frac{b}{a} L V_2$ is skin friction; C_D and C_f are drag and friction coefficients; V_1 is the tip velocity due to collapse; V_2 is the combination of the tip velocity due to dynamic collapse and that due to the stretching of L (and V_3 is the contribution of tip velocity from entrainment by instantaneously holding ρ, a, and L constant).

The trajectory of the two-dimensional buoyant element is described by

$$\frac{dx}{dt} = u; \quad \frac{dy}{dt} = v; \quad \text{and} \quad \frac{dz}{dt} = w \qquad (12)$$

The same numerical method is adopted to solve equations (7) to (11), with the initial conditions obtained from the end of the convective descent phase.

For some cases, if the ambient density stratification is not strong enough to arrest the vertical descent of a jet in the water column, or the jet has strong initial momentum and is discharged into the relatively shallow water region, this jet can reach the sea bottom and spread out. The mathematical model which describes the convection and collapse of this kind of jet is similar to that of equations (7) to (11), except a bottom friction force term needs to be added in equations (8) and (11). The simulation of the dynamic collapse phase will be terminated when the rate of horizontal spreading due to plume dynamic effects becomes less than that due to passive turbulent diffusion.

2.3 Passive Diffusion

2.3.1 Koh-Chang Model

The discharged drilling mud phase will become dynamically passive after the initial phases of convection and collapse. In this long-term diffusion phase, the plume will be subjected only to turbulent diffusion, advection and settling of the solid particles, which can be described by the following equation of conservation of material, i.e.,

$$\frac{\partial C}{\partial t} + u_a \frac{\partial C}{\partial x} + w_a \frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(K_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial C}{\partial z}\right) - \frac{\partial}{\partial y}(w_s C) \qquad (13)$$

Where C is the time averaged concentration of the discharged material, u_a and w_a are ambient horizontal currents, w_s is the fall velocity, K_x, K_y, and K_z are the diffusion coefficients corresponding to x, y, and z directions, respectively, and the coordinate system is defined in Figure 4. A set of proper boundary conditions at the ocean surface and bottom for both fluid and solid particles are required in order to solve equation (13). For fluid, there is no diffusion of material through the boundaries and the boundaries act as reflecting barriers to the diffusion material. For solid particles, the boundary conditions indicate that the combined actions of diffusion, entrainment, and settling contributes no net transport across the boundary. Since equation (13) will require considerable storage and computer time to solve it directly, therefore the method of moment is adopted. This method solves several moments of the concentration C (x, y, z, t) and deposited material W (x,y,z,t) across horizontal planes, which are as follows:

$$C_{k,\ell} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x^{k} z^{\ell} C \; dx \, dz \tag{14}$$

$$M_{k,\ell} = \int_{0}^{H} C_{k,\ell} \; dy \tag{15}$$

$$W_{k,\ell} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x^{k} z^{\ell} W \; dx \, dz \tag{16}$$

These terms represent respectively the k, ℓ th moment of the horizontal distribution. If $k=\ell=0$, equations (14) to (16) represent the amount of dispersant contained in a unit thickness layer at depth y, respectively, all the discharged material in suspension, and the amount of dispersant on the bed or surface. The sum of $M_{k,\ell}$ and $W_{k,\ell}$ is the k,ℓth moment of the horizontal distribution of all the discharged material. Equation (13) can be transformed to equation (17) with multiplication of each term by $x^{k}z^{\ell}$ and integration over the xz plane.

$$\begin{aligned} \frac{\partial}{\partial t} C_{k,\ell} - k U_a C_{k-1,\ell} - \ell w_a C_{k,\ell-1} = {} & k(k-1) K_x C_{k-2,\ell} \\ & + \ell(\ell-1) K_z C_{k,\ell-2} + \frac{\partial}{\partial y}\left(K_y \frac{\partial C_{k,\ell}}{\partial y} - w_s C_{k,\ell} \right) \end{aligned} \tag{17}$$

Similarly, the initial and boundary conditions have to follow the same transformation. Equation (17) would be much simpler to be solved. Although the solutions are in terms of the moments of the horizontal distribution of the discharged material, it is believed that these moments provide a sufficient basis for the description of the dispersion process. In practice, only the first three moments, which describe the volume under the concentration curve, mean displacement, and variance, are usually required.

The diffusion coefficients are important to the dispersion process. The vertical diffusion coefficient, K_y is assumed to be minimum at the thermocline, and maximum in the mixed layer. The horizontal diffusion coefficients will follow the 4/3 - power law. In general, the Koh-Chang Model can handle the cases that u_a, w_a, K_x, K_y, and K_z are functions of time and depth. However, the model is limited to the uniform ambient condition. This limitation is considered to be minor in an open ocean because the ambient condition is usually slowly varying around the dump site. The average ambient condition within the pool of plume should be a good approximation for solving the problem. It is also noted that the Koh-Chang Model is assumed to be applied in an open sea bounded only by horizontal surface and bottom boundaries. Care must be taken in applying the Koh-Chang Model in a lake or a bay.

2.3.2 Brandsma - Divoky Model

In the Brandsma - Divoky Model, they adopted Fischer's (1970) scheme of diffusion in which the plume is divided into many small Gaussian clouds which contain particles from only one class. These small clouds are initially distributed as determined by the dynamic behavior of the jet plume and then convected, diffused, and settled independently due to the effects of ambient currents, turbulent diffusion, and the particle settling velocity. The resultant concentration at any point can be calculated by summarizing the contributions from all the neighboring small clouds. The concentration distribution surrounding a single Gaussian cloud material can be written as (Slade, 1968):

$$C = \frac{m}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left\{-\frac{1}{2}\left[\frac{(x-x_0)^2}{\sigma_x^2}+\frac{(y-y_0)^2}{\sigma_y^2}+\frac{(z-z_0)^2}{\sigma_z^2}\right]\right\} \qquad (18)$$

Where x, y, z are all the coordinates of the point of interest; x_0, y_0, z_0 are the coordinates of the cloud centroid; σ_x , σ_y , σ_z are the standard deviations of the distribution; and m is the mass contained in the cloud. Equation (18) is a solution of the Fickian diffusion equation for constant diffusion coefficients, homogeneous and stationary turbulence. Although drilling mud discharge does not satisfy the assumptions of the solution, the assumed Gaussian distribution within each cloud would somewhat provide an average diffusion process in relation to the random nature of this problem. The resultant concentration at a given point can be calculated by the following equation:

$$C = (2\pi)^{-3/2}\sum_i \frac{m_i}{\sigma_{x_i}\sigma_{y_i}\sigma_{z_i}}\exp\left\{-\frac{1}{2}\left[\frac{(x-x_i)^2}{\sigma_{x_i}^2}+\frac{(y-y_i)^2}{\sigma_{y_i}^2}+\frac{(z-z_i)^2}{\sigma_{z_i}^2}\right]\right\} \qquad (19)$$

where m_i, σ_{xi}, σ_{yi}, σ_{zi}, x_i, y_i, and z_i are unique for each of the contributing clouds. If an individual cloud grows to the size of the passive diffusion grid, the solid particles it contains are injected into the appropriate grid. As the solid particles settle to the bottom, they are collected in a grid of bins on the bottom. The amounts and locations of the bottom particles are displayed at the end of the calculation.

2.3.3 Leung-Wu's Implementation of Resuspension Mechanism

In the passive diffusion phase, the plume becomes dynamically passive, subject only to turbulent diffusion, advection and settling of the solid particles. Let us denote the solid particles that have settled to the bottom as sediments. Brandsma and Divoky (1976) do not allow the sediments to go back into the water column, so that there is no treatment of resuspension. Koh and Chang (1973) specify a coefficient to control the rate of resuspension at the sea bottom boundary. Since the user of this model is free to choose a number for this coefficient, the treatment of resuspension becomes rather arbitrary. The water depth at which sediments feel the surface wave effect, depending on the wave conditions, is about 100 meters. Komar et. al., (1972) found oscillatory ripples in the bottom photographs on the Oregon continental shelf in water depths as great as 125 meters. Therefore, the problem of resuspension cannot be neglected if the operation of disposal is carried out in shallow water. In order to provide a better simulation of the fate of the disposed materials, a resuspension model is added to the Brandsma - Divoky Model.

With the effect of periodic wave action in the water column, the water particles move circularly and elliptically in deep and intermediate water depths, respectively. At the sea bottom, the water particles will follow the wave action and move back and forth in a horizontal line. When the horizontal velocity of the water particles is strong enough, the sediments would start to be perturbed. But, there is little or no net transport of the sediments, because the orbits of the water particles are closed. After the sediments have been stirred up from the sea bed, transport of the sediments is accomplished by the effect of the ambient current. Thus, the mechanism of resuspension and transport of the sediments on the continental shelf can be viewed as a combination of the perturbing effect of the wave action and the transporting effect of the ambient current. Similar phenomenon may occur for strong bottom currents where shear stress is larger than the critical shear stress.

A subroutine modeling the resuspension of the sediments has been incorporated into the passive diffusion phase of the Brandsma - Divoky Model. The function of this subroutine is to detect the initiation of motion of the sediments from the given wave height and period. If the water particle velocity near the bottom is strong enough to stir up the sediments, resuspension of the sediments would occur. Then the resuspended sediments are injected into the appropriate grid squares of the passive diffusion subroutine and are subject to further dispersion and settling of the solid particles along with the rest of the plume.

3. Numerical Model

In sections 2.1 and 2.2, the convective descent and dynamic collapse phases consist of a system of ordinary non-linear differential equations which are readily solvable given a set of initial conditions. A standard fourth order Runge Kutta Method is employed to integrate the equations.

In the long-term passive diffusion phase of simulation, the Crank-Nicolson Method, a relaxation factor of 0.5, is used to solve equation (17) of the Koh-Chang Model. The forward, backward, and control difference schemes are adopted for different differential terms under different conditions. Finally, the implicit scheme of the governing equation and the boundary conditions will form a system of equations. This system of equations is related to a tridiagonal matrix, and is solved by Thomas Algorithm (Ames, 1965). In regard to the determination and change of grid size, and computation time step, the program will handle it automatically by considering the vertical speed of the plume, the fall velocity of the solid particles, and the vertical diffusion coefficient. The primary result of the calculation is the k,ℓth moment of the concentration as a function of time and depth.

In Brandsma - Divoky's long-term phase simulation, no numerical scheme is involved. It is a straightforward calculation which is based on the analytical approach described in Section 2.3.2. Leung-Wu's resuspension calculation is also a straightforward checking procedure, and directly interacts with Brandsma - Divoky's long-term diffusion model.

4. Verification of the Numerical Model

Two sets of computation were carried out by Koh and Chang (1973) to compare with Fan's (1967) experimental data and theoretical predictions. The comparisons are found to be very good as shown in Figure 5. The Koh-Chang Model can simulate the phenomena of thermal discharge so well that no effort was spent in simulating Test Case 1 conducted by Koester (1974), and Test Cases 4 and 5, conducted by Fan (1967).

Test Case 2, which was conducted by Davis (1982), is a laboratory simulation of a mud dump. A comparison of the predictions of the numerical model and the measurements are shown in Figure 6. The open circles represent the predicted trajectory of the center line of the mud plume.

Test Case 3, which was conducted by ECOMAR (1980), is a field study of mud dumps in the Gulf of Mexico. All of the field data were taken after the mud dump, in pursuit of the highly visibile upper plume. This plume, which contained about 5 per cent of the total solids discharged, stayed at a water depth of about 8 meters and was heading southwest. This was the direction of the ambient current recorded at the depth of 7 meters. However, the numerical model predicted that the plume reached neutral buoyancy at about 17 meters depth and was heading northwest. This was the direction of the ambient current recorded at a depth of 14 meters. Therefore, the comparison of this study is not conclusive.

5. Conclusion and Recommendations

Based on the Koh-Chang Model, Tetra Tech developed an integrated drilling mud plume model which includes Brandsma - Divoky's passive diffusion model, and Leung - Wu's resuspension model. This model can predict the physical fate of the discharged drilling mud plume. The dynamic behavior, trajectory, and the amount of suspended and deposited material of the drilling mud plume are simulated by the convective descent, dynamic collapse, and passive diffusion phases of the plume. The predicted results of the short-term plume compared very well with the measured laboratory data. The model can be applied to the conditions of variable water depth, unsteady and nonuniform currents, land boundary, and resuspension. This model is usually applied together with the ambient current model. The computer code is particularly designed for easy input and output.

For the future OCSS Research Program, the following subjects are strongly recommended: (a) performing field and laboratory experiments to determine some coefficients and also to further verify the model, (b) separating surface fine particle plume from the sinking plume, (c) studying the initial dilution near the exit of the discharge pipe, and (d) modifying the momentum balance equation when the jet crashes at the sea bottom with a relatively large angle of attack.

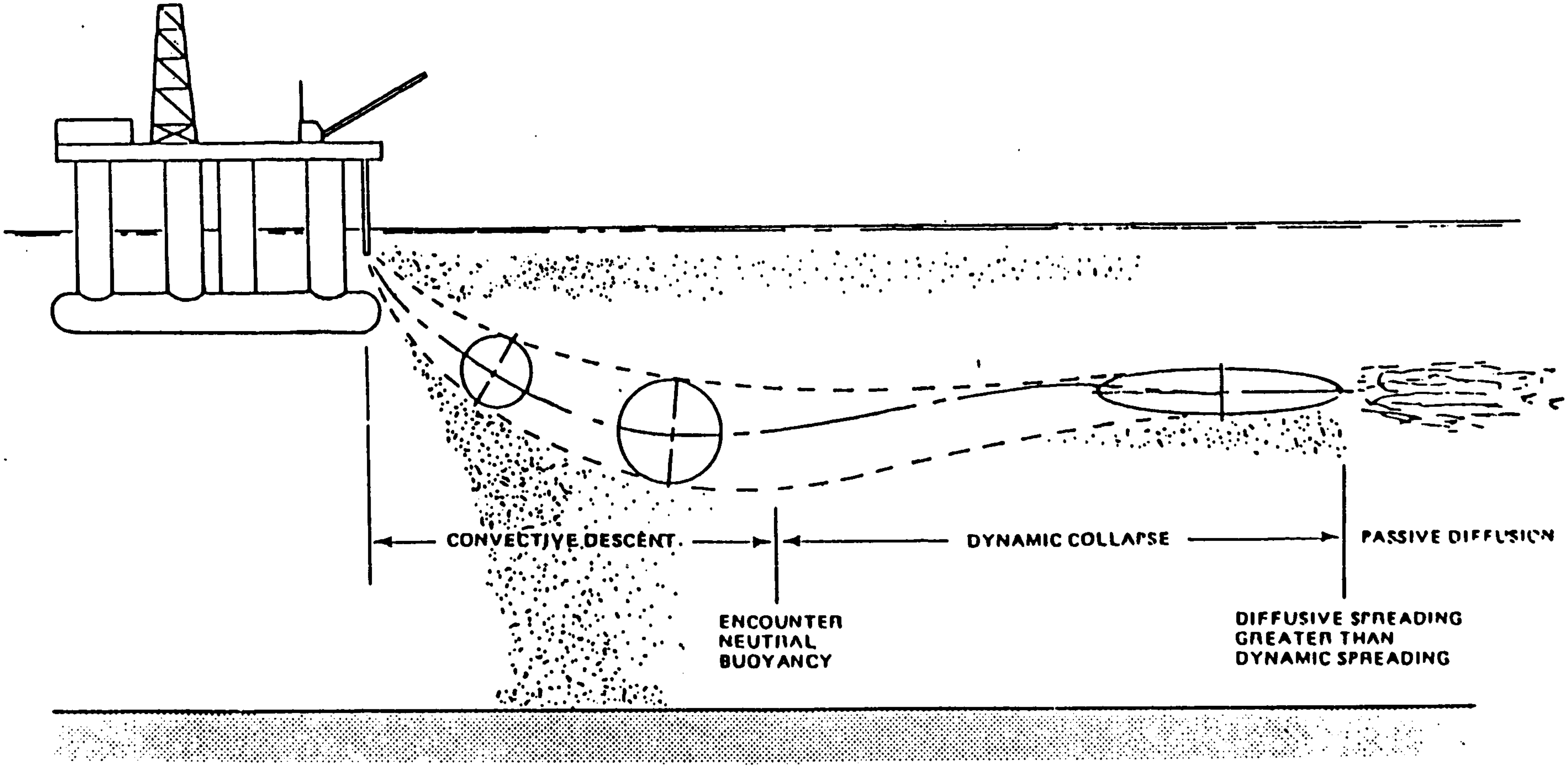
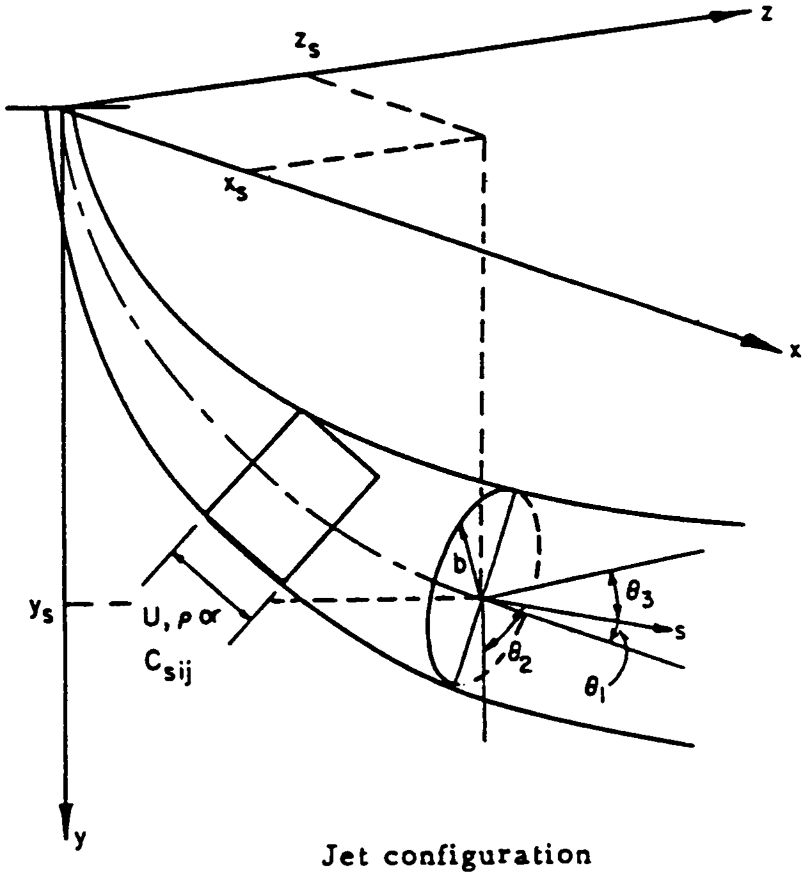


Figure 1. Idealized jet discharge



Jet configuration

Figure 2

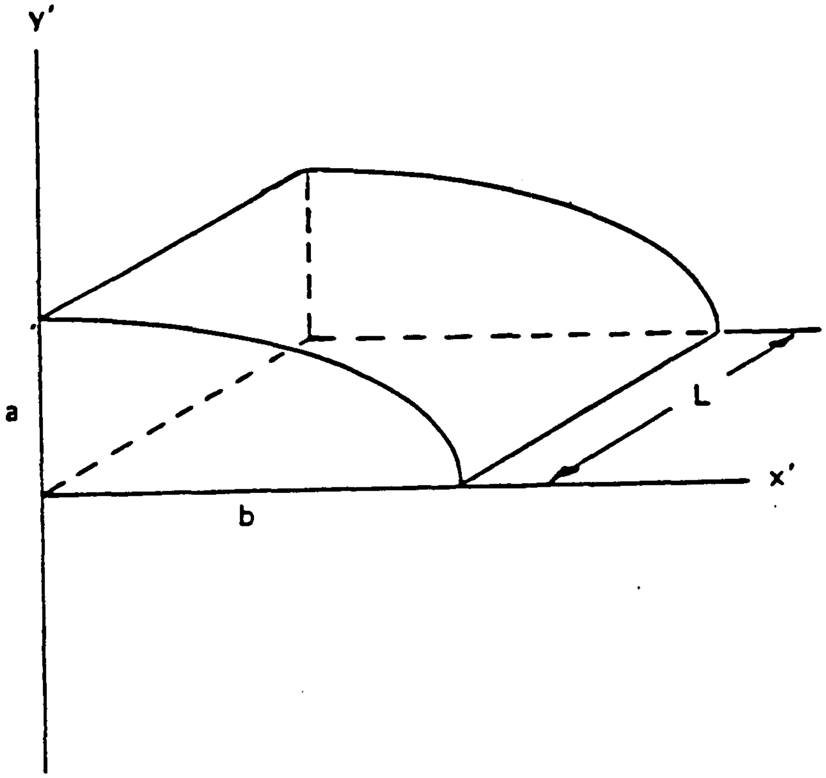
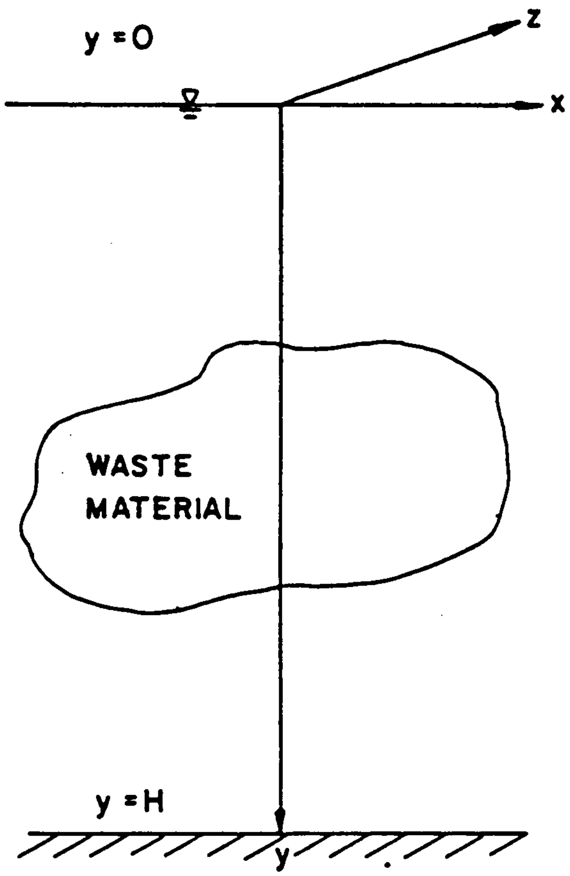
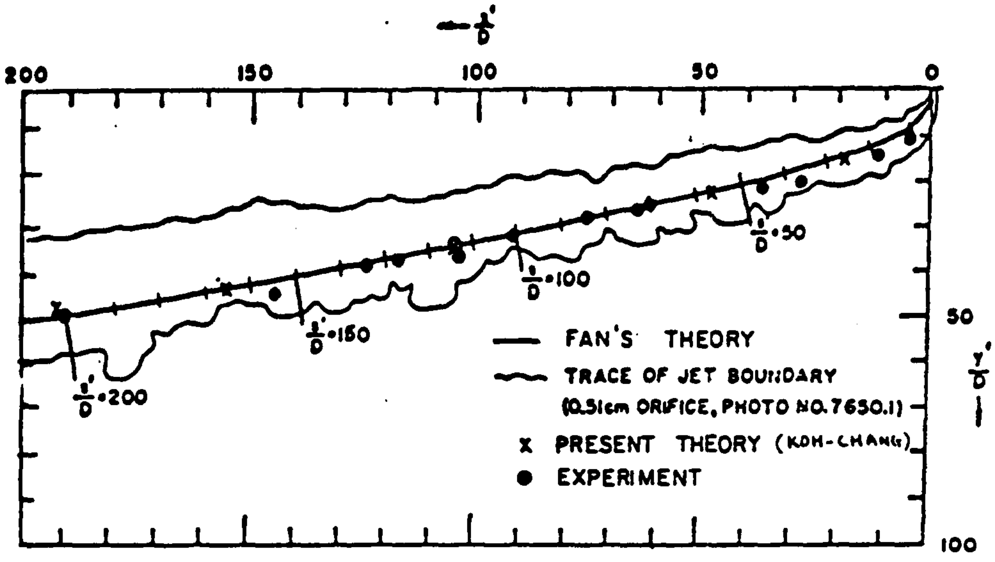


Figure 3. Geometry of the collapsing plume.



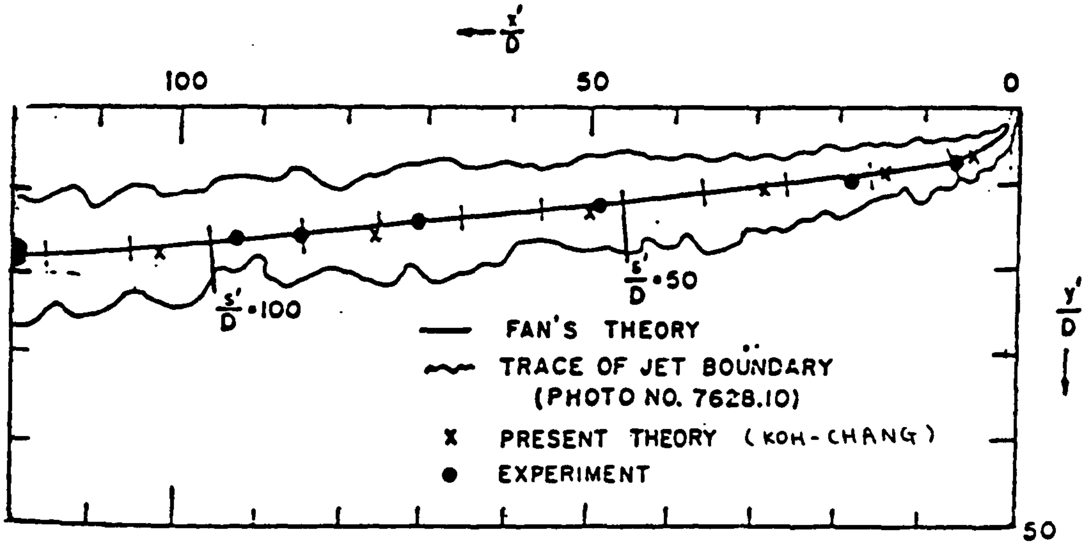
Coordinate System

Figure 4



F=20 k=8

a)



b) F=20 k=4

Figure 5. Comparison of Koh-Chang's Results with Fan's experiments.

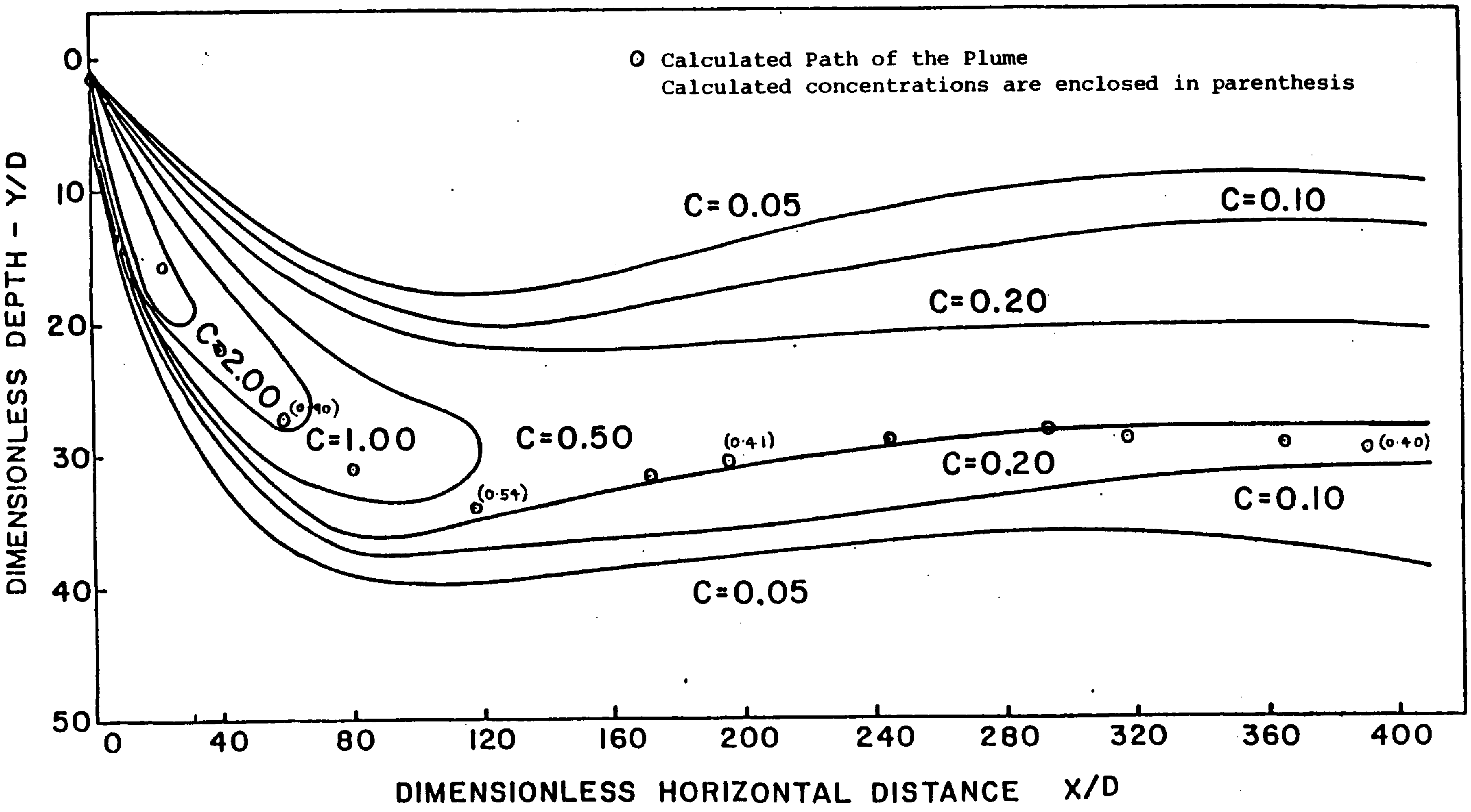


Figure 6 Average Total Suspended Solid Concentrations (mg/g of solution)

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4.3 Dispersion of Dredged Spoil when Dumped as a Slug in Deep Water: The Krishnappan Model

by

B. G. Krishnappan

DISPERSION OF DREDGED SPOIL WHEN DUMPED AS A SLUG IN DEEP WATER: THE KRISHNAPPAN MODEL

by

B. G. Krishnappan

INTRODUCTION

In some of the existing methods for studying the dispersion of dredged spoil when dumped as a slug in deep water such as the Koh-Chang method (1) and the Edge-Dysart method (2), it is assumed that the dredged spoil behaves in the same manner as a denser liquid of equivalent density. Krishnappan (3, 4) had demonstrated using laboratory experiments that the behaviour of the clouds formed by the solid particles is different from those formed by the denser liquids. He formulated the motion of clouds formed by solid particles of uniform size using the theory of dimensions and proposed a model to predict the behaviour of the dredged spoil which consists of sand particles of varying sizes using a "superposition" principle. The details of this model together with the formulation of the motion of uniform-size particle clouds and some illustrative examples are described in this paper.

BEHAVIOUR OF CLOUDS OF UNIFORM-SIZE PARTICLES

Laboratory experiments of Krishnappan indicated that the motion of the clouds of uniform-size particles resulting from the release of a slug of solid particles without any initial downward momentum in a body of stagnant water can be considered in two distinct phases, namely, the initial "entrainment" phase when the size of the cloud increased mainly due to the incorporation of the surrounding water into the cloud and the final "settling" phase when the downward velocity of the cloud coincided with the terminal fall velocity of the individual solid particles constituting the cloud. The theoretical formulation of the entrainment phase was made using the theory of dimensions similar to the approach of Batchelor (5) who considered the motion of the "liquid-clouds". Accordingly, the vertical downward velocity of the cloud, W, and the horizontal dimension (radius) of the cloud, R, are expressed as:

$$\left.\begin{array}{l} W = \frac{\beta F^{1/2}}{Z} \\ \text{and} \\ R = \alpha Z \end{array}\right\} \qquad (1)$$

where F is the total negative buoyancy of the solid particles forming the cloud, given in terms of the density of the solid particles, ρ_s, the density of the receiving fluid medium, ρ, the acceleration due to gravity, g, and the volume of the solid particles, V_s, as:

$$F = \frac{\rho_s - \rho}{\rho} g V_s \qquad (2)$$

Z is the position of the cloud measured from the virtual origin as shown in Fig. 1 and α and β are dimensionless parameters and were treated as functions of dimensionless variable $(\gamma_s \rho D^3/\mu^2)$ where γ_s is the submerged specific weight of the solid particles, i.e.

$$\gamma_s = (\rho_s - \rho) g \qquad (3)$$

D is the size of the solid particles and μ is the absolute viscosity of the fluid medium. In other words, α and β were expressed as:

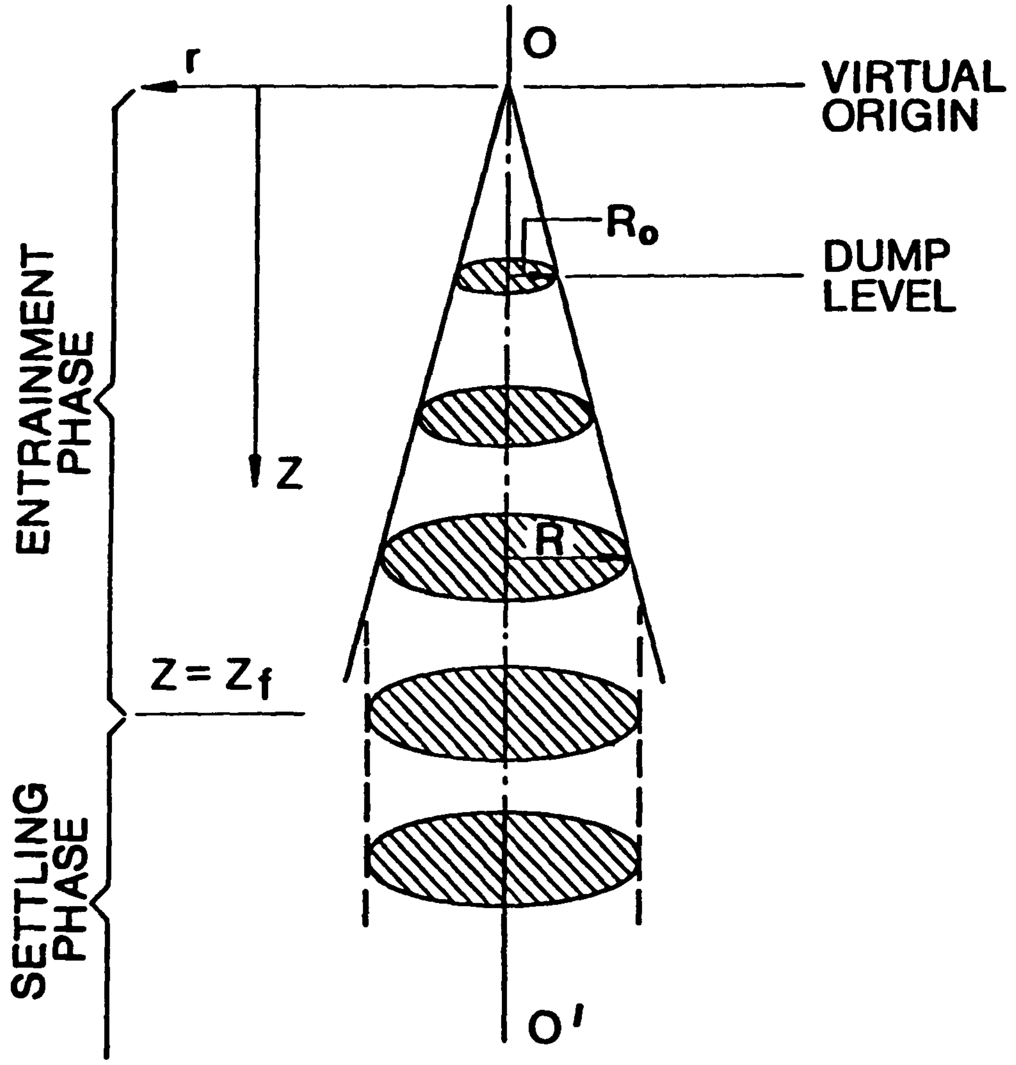


Fig. 1 Co-ordinate system for the motion of uniform size particle clouds in stagnant water

$$\left.\begin{aligned} \alpha &= \psi_\alpha \left(\frac{\gamma_s \rho D^3}{\mu^2} \right) \\ \\ \beta &= \psi_\beta \left(\frac{\gamma_s \rho D^3}{\mu^2} \right) \end{aligned}\right\} \qquad (4)$$

The form of the functions ψ_α and ψ_β were determined experimentally by Krishnappan and are shown here in Figs. 2 and 3 respectively.

The "settling" phase of the solid particle-clouds was considered to start when the vertical downward velocity W of the cloud reached the fall velocity (terminal velocity ω) of the individual particles forming the cloud. Therefore, the distance from the virtual origin (Z_f) at which the settling phase begins can be evaluated as:

$$Z_f = \frac{\beta F^{1/2}}{\omega} \qquad (5)$$

and the size (R_f) of the cloud at the beginning of the settling phase is:

$$R_f = \alpha Z_f \qquad (6)$$

Krishnappan adopted the method of Koh (6) for predicting the spread of solid particles during the settling phase. According to this method which considers only the horizontal turbulent diffusion (effects of vertical diffusion and hindered settling are neglected), the distribution of the concentration of the solid particles is assumed to be Gaussian and the horizontal turbulent diffusion coefficient, K, is assumed to follow the 4/3 power law commonly used in ocean turbulence studies.

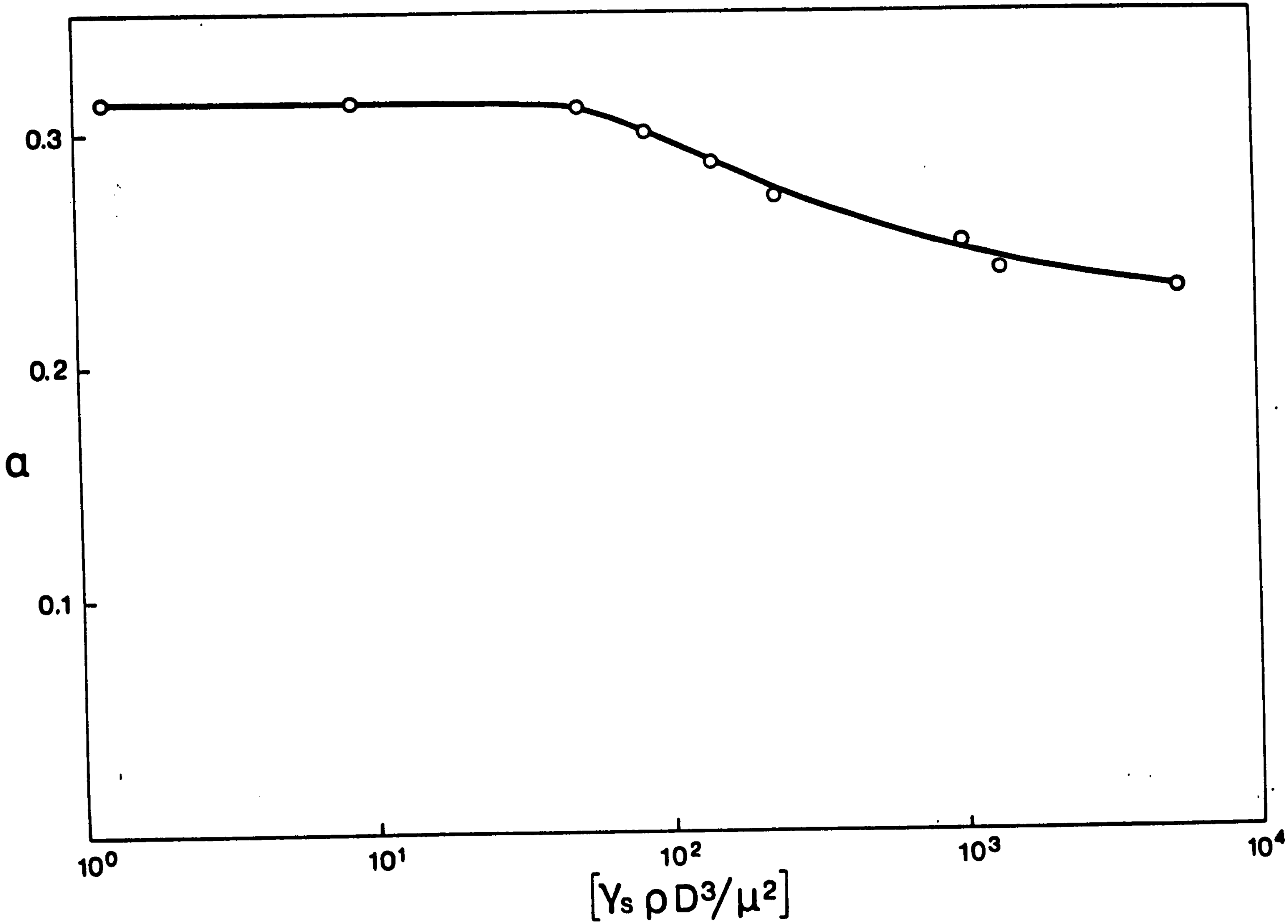


Fig. 2 Graph representing ψ_a

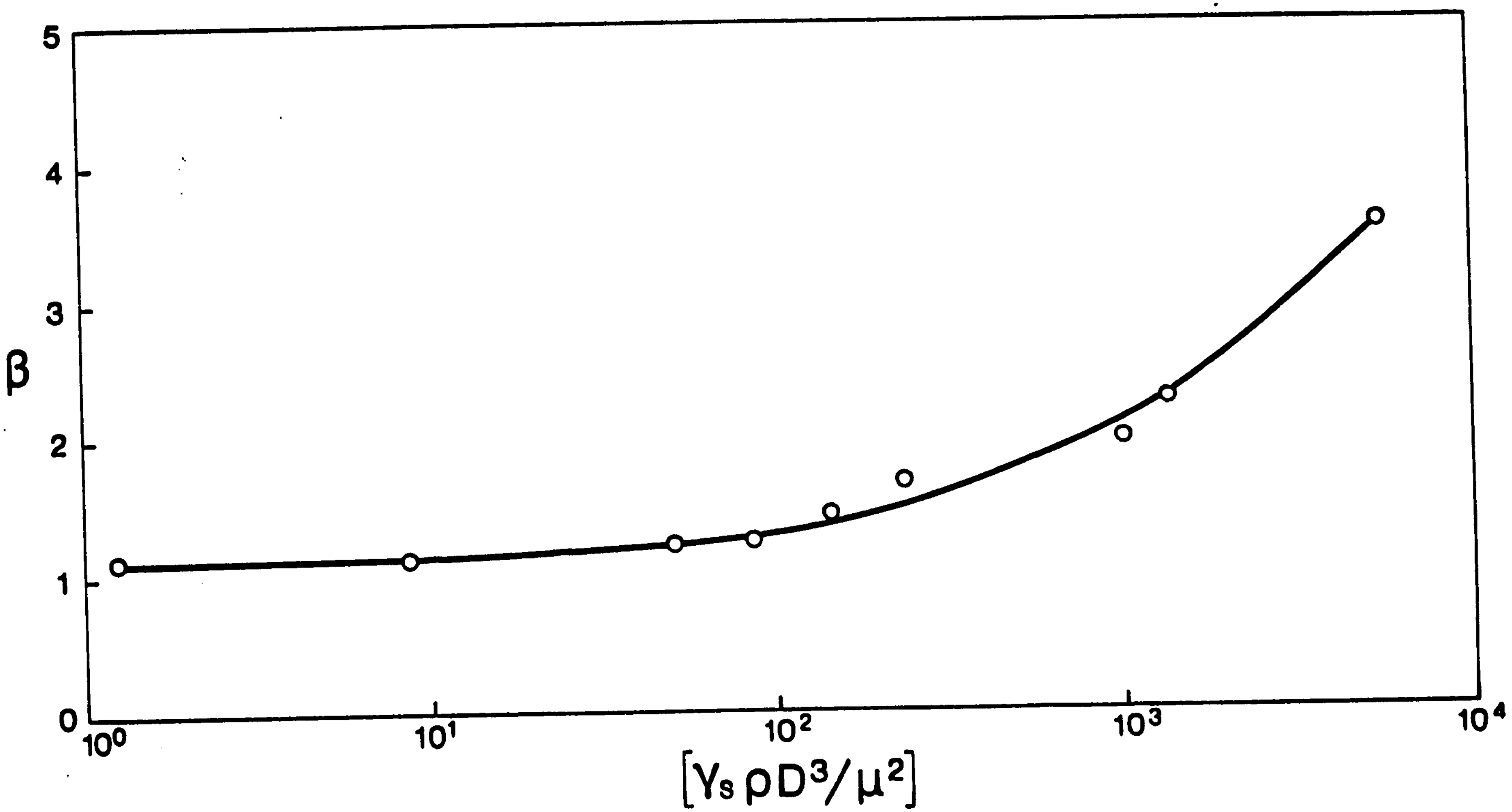


Fig. 3 Graph representing ψ_β

Accordingly, knowing the standard deviation at the beginning of the settling phase, σ_0, which can be related to the size of the cloud at the beginning of the settling phase, R_f, as:

$$\sigma_0 = R_f/4 \qquad (7)^1$$

the standard deviation at any other time from the beginning of the settling phase, σ_t is given by:

$$\sigma_t = \sigma_0 \left[1 + 4^{4/3} \frac{2}{3} \frac{At}{\sigma_0^{2/3}} \right]^{3/2} \qquad (8)$$

where A is the dissipation parameter that appears in the 4/3 power law for the diffusion coefficient, i.e.

$$K = A\ (4\ \sigma_t)^{4/3} \qquad (9)$$

and the time, t, is measured from the start of the settling phase. The height of the mound produced at the bed of the deep water as a result of the settling of the solid particles is also considered to be distributed according to the Gaussian distribution with the standard deviation σ_t. In other words the height of the mount, h, is given by:

$$h = h_{max} \exp \left[- \frac{r^2}{2\ \sigma_t^2} \right] ; \quad - 4\sigma_t \leq r \leq 4\sigma_t \qquad (10)$$

---

[1] The Gaussian distribution with σ_0 as given by Equation 7 encompasses 99.994% of the solid particles within the radius of R_f.

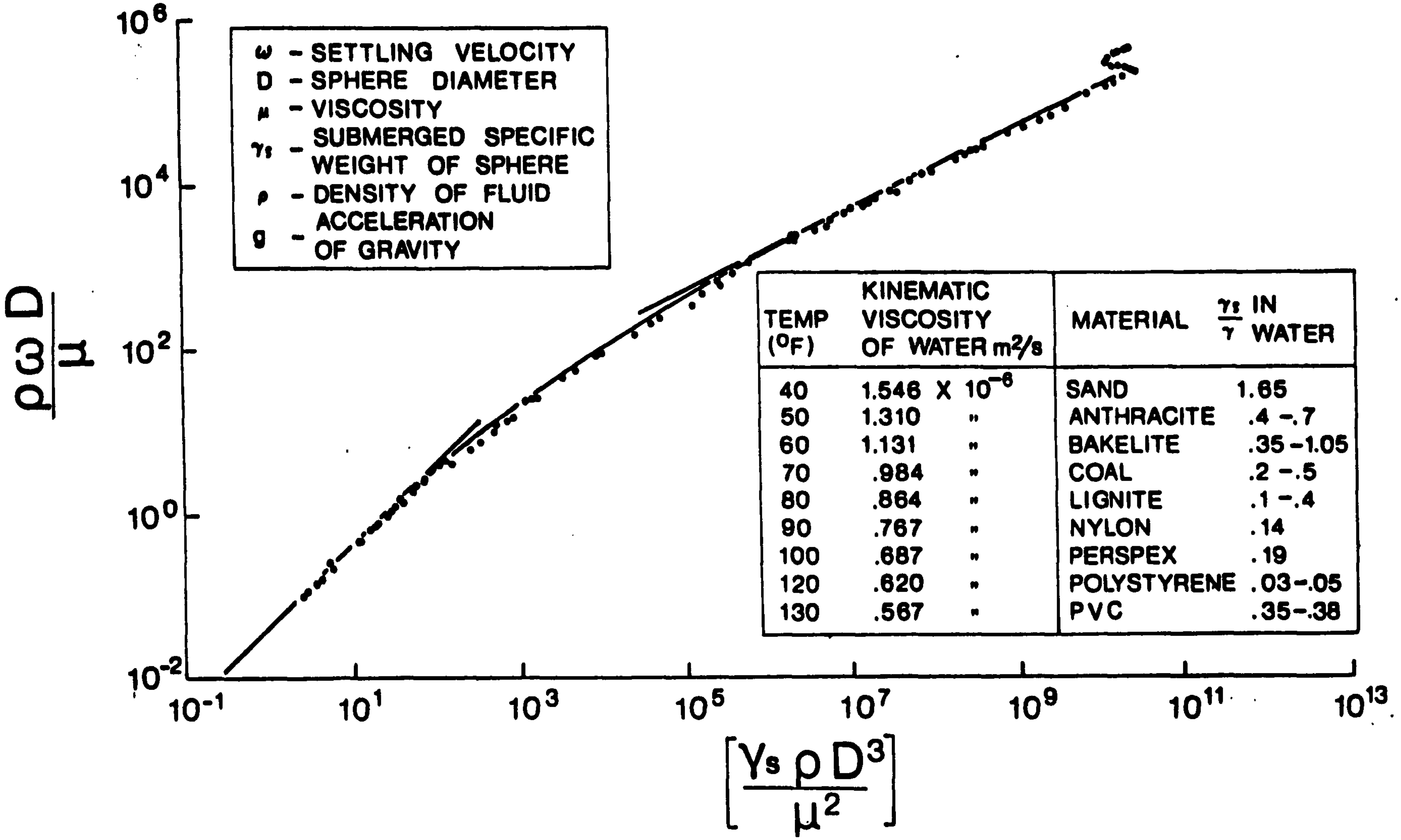
The value of h_{max} can be computed knowing the volume of the solid particles V_s and the porosity, n, of the mound formed as:

$$h_{max} = \frac{V_s}{(1-n)\ 2\pi\ \sigma_t^2} \tag{11}$$

To solve the motion of the cloud of solid particles during the settling phase, the fall velocity ω of the solid particles has to be known. This can be obtained from the measurements made for the spherical particles as given in Fig. 4. The effect of the particle shape on its fall velocity is not very well established as yet. Until a better method is devised which would correctly include the effects of the shape of particles, Fig. 4 can be used to predict the fall velocity of the particles constituting the dredged spoil. Note that the parameter $(\gamma_s \cdot \rho D^3/\mu^2)$ governing the parameters of the entrainment phase also governs the fall velocity of the solid particles.

BEHAVIOUR OF THE DREDGED SPOIL

In the model formulated by Krishnappan to predict the behaviour of the dredged spoil, it is assumed that the turbulence of the receiving body of water has negligible effect during entrainment phase and it becomes important only during the settling phase. The effect of density gradient of the receiving body of water is considered to be small since a majority of the dredged spoil is quartz and the density differential between the particles and the water is large compared to the variation of density of water over the depth. The receiving body of water is considered to have a uniform current of magnitude U. The total volume of the dredged material dumped is V_s and the depth of



TEMP (°F)	KINEMATIC VISCOSITY OF WATER m²/s	MATERIAL	$\frac{\gamma_s}{\gamma}$ IN WATER
40	1.546×10^{-6}	SAND	1.65
50	1.310 "	ANTHRACITE	.4 -.7
60	1.131 "	BAKELITE	.35-1.05
70	.984 "	COAL	.2 -.5
80	.864 "	LIGNITE	.1 -.4
90	.767 "	NYLON	.14
100	.687 "	PERSPEX	.19
120	.620 "	POLYSTYRENE	.03-.05
130	.567 "	PVC	.35-.38

Fig. 4 Fall velocity of spherical particles

water is d. The dredged spoil is considered to consist of particles of different specific weights and grain sizes. V_{sij} is the volume of a fraction whose submerged specific weight is γ_{si} and the grain size is D_j.

Entrainment Phase

The position of the dump is taken as the origin and the vertical distance is measured from the level of dump and is represented by ζ (see Fig. 5). Therefore, the relationship between ζ and Z becomes

$$Z = \zeta + \frac{R_o}{\alpha_m} \tag{12}$$

where R_o is the size of the dump and it is equated to the initial size of the cloud and α_m is the entrainment coefficient corresponding to the mixture of particles. When the mixture of different specific weight and grain-size materials are moving together as a cloud, it is hypothesized that each fraction exerts influence on the total behaviour of the cloud in the same proportion as its negative buoyancy. In other words, if F_{ij} is the buoyancy of the fraction (ij) and F is the total buoyancy, then the influence of the fraction (ij) on the total behaviour of the cloud (or on the coefficients describing the total behaviour) is proportional to F_{ij}/F. The ratios F_{ij}/F can be termed "weighting coefficients" which determine the behaviour of the whole cloud from the behaviour of the individual fractions. For example, if α_m and β_m are the dimensionless coefficients governing the motion of the total cloud, then they can be evaluated using the above "weighting coefficients" as follows:

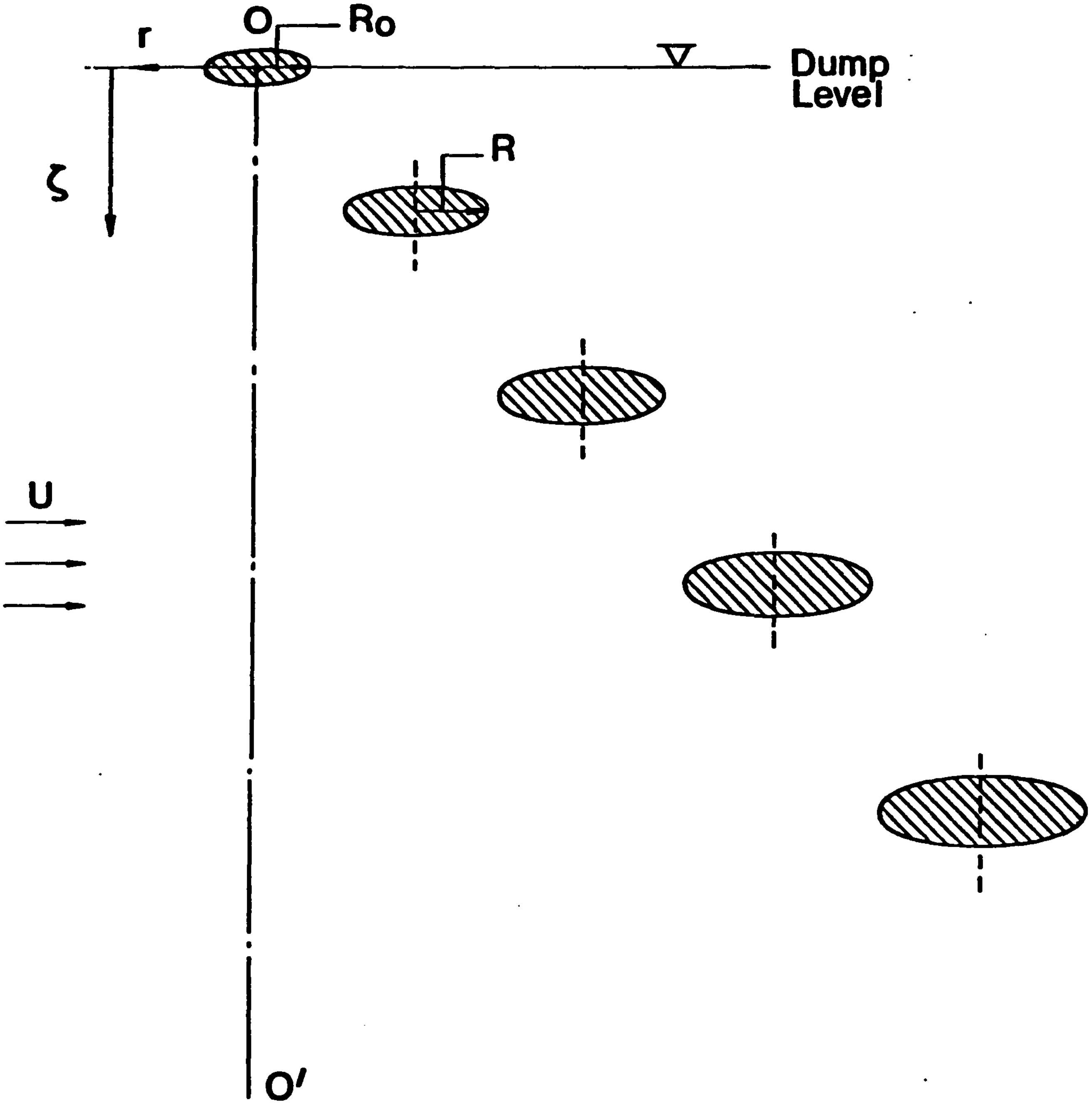


Fig. 5 Co-ordinate system used for the motion of the dredged spoil

$$\alpha_m = \sum_i \sum_j \frac{F_{ij}}{F} \alpha_{ij} \qquad (12)$$

where

$$\left. \begin{aligned} F_{ij} &= \frac{\gamma_{si} V_{sij}}{\rho} \\ &\text{and} \\ F &= \sum_i \sum_j F_{ij} \end{aligned} \right\} \qquad (13)$$

a_{ij} and β_{ij} are the dimensionless coefficients that can be determined from Figs. 2 and 3 corresponding to parameter $(\gamma_{si} \rho D_j^3)$.

The behaviour of the cloud of mixture of particles can, therefore, be expressed as:

$$\left. \begin{aligned} R &= R_o + \alpha_m \zeta \\ &\text{and} \\ W &= \frac{\beta_m F^{1/2}}{(\zeta + R_o/\alpha_m)} \end{aligned} \right\{ \qquad (14)$$

As the cloud of the dredged spoil moves down, the downward velocity decreases and it might become less than the fall velocity of one of its constituents. In such a case, the fraction having the fall velocity greater than the cloud velocity is assumed to separate out of the main cloud and to undergo settling phase while the main cloud still undergoes entrainment phase: but, now, the total buoyancy has been reduced by the amount of the buoyancy of the separated fraction, say, $F_{k\ell}$. Therefore, the total buoyancy of the main cloud F' is

$$F' = F - F_{k\ell} \qquad (15)$$

and hence the weighting coefficients would also be altered as:

$$w'_{ij} = \frac{F_{ij}}{F'} \quad \text{for } i \neq k \text{ and } j \neq \ell \qquad (16)$$

and consequently the parameters defining the motion of the new cloud become:

$$\left.\begin{array}{l} \alpha'_m = \sum_{i \neq k} \sum_{j \neq \ell} w'_{ij} \, \alpha_{ij} \\ \\ \beta'_m = \sum_{i \neq k} \sum_{j \neq \ell} w_{ij} \, \beta_{ij} \end{array}\right\} \qquad (17)$$

The level at which such a separation would occur can be calculated knowing the fall velocity of the separated fraction, say, $\omega_{k,\ell}$. Denoting this level by $\zeta_{fk\ell}$, it can be evaluated as:

$$\zeta_{fk\ell} = \left(\frac{\beta_m F^{1/2}}{\omega k\ell} - \frac{R_o}{\alpha_m} \right) \qquad (18)$$

The size of the main cloud, which is also the size of the separated cloud is:

$$R_{fk\ell} = R_o + \alpha_m \zeta_{fk\ell} \qquad (19)$$

The time elapsed from the instant the material is dumped and the instant the fraction (k,ℓ) separated, denoted by $t_{fk\ell}$ can be calcualted using Equation 14 as follows:

Since $W = d\zeta/df$, Equation 14 can be rearranged as:

$$\left(\zeta + \frac{R_o}{\alpha_m} \right) d\zeta = \beta_m F^{1/2} \, dt \qquad (20)$$

Integrating the above equation and using the condition that at $t=0$, $\zeta = \zeta_{fk\ell}$, $t_{fk\ell}$ can be evaluated as

$$t_{fk\ell} = \frac{\left(\frac{\zeta_{fk\ell}}{2} + \frac{R_o}{\alpha_m}\right)}{\beta_m F^{1/2}} \zeta_{fk\ell} \tag{21}$$

The lateral distance travelled by the cloud ($L_{k\ell}$) at the time of separation due to the ambient current can be calculated as:

$$L_{k\ell} = U t_{fk\ell} \tag{22}$$

After the separation of the fraction ($k\ell$) the behaviour of the main cloud is described by:

$$\left.\begin{aligned} R &= R_{fk\ell} + \alpha'_m (\zeta - \zeta_{fk\ell}) \\ W &= \frac{\beta'_m F'^{1/2}}{\left(\zeta + \frac{R_o}{\alpha_m}\right)} \end{aligned}\right\} \text{ for } \zeta > \zeta_{fk\ell} \qquad (23$$

Again, as can be seen from Equation 23, the downward velocity of the cloud decreases as the cloud moves down and it could reach a value equal to the fall velocity of the next heavier fraction, say, (pq). In this case, the fraction (pq) will settle out of the cloud and would undergo settling while the main cloud undergoes entrainment. The new buoyancy F'' is given by:

$$F'' = F - (F_{k\ell} + F_{pq}) \tag{24}$$

The weighting coefficients are:

$$w''_{ij} = \frac{F_{ij}}{F''} \quad \text{for } i \neq k,\ p \text{ and } j \neq \ell, q \tag{25}$$

α''_m and β''_m are given by:

$$\begin{aligned} \alpha''_m &= \sum_{i \neq k,p} \; \sum_{j \neq \ell,q} \; w''_{ij} \; \alpha_{ij} \\ \beta''_m &= \sum_{i \neq k,p} \; \sum_{j \neq \ell q} \; w''_{ij} \; \beta_{ij} \end{aligned} \tag{26}$$

The level at which the second separation occurs is given by:

$$\zeta_{fpq} = \left(\frac{\beta'_m \; F'^{1/2}}{\omega pq} - \frac{R_o}{\alpha_m} \right) \tag{27}$$

The size of the cloud at the time of second separation is

$$R_{fpq} = R_{fk\ell} + \alpha'_m \quad (\zeta_{fpq} - \zeta_{fk\ell})$$

The time at which the second separation occurs can be calculated from:

$$(t_{fpq} - t_{fk\ell}) = \frac{\left(\frac{\zeta^2_{fpq} - \zeta^2_{fk\ell}}{2}\right) - \frac{R_o}{\alpha_m} (\zeta_{fpq} - \zeta_{fk\ell})}{\beta'_m \; F'^{1/2}} \tag{28}$$

The lateral distance travelled by the main cloud:

$$L_{pq} = U\, t_{fpq} \tag{29}$$

The behaviour of the main cloud after ζ_{fpq} is given by:

$$\left.\begin{aligned} R &= R_{fpq} + \alpha_m^{*} (\zeta - \zeta_{fpq}) \\ W &= \frac{\beta_m^{*} \; F^{*1/2}}{(\zeta + \frac{R_o}{\alpha_m})} \end{aligned}\right\} \quad \zeta > \zeta_{fpq} \tag{30}$$

and the process continues until all the fractions are settled out of the cloud and/or the bottom of the deep water is reached.

Settling Phase

The fractions that separate out of the main cloud undergo settling phase. The motion of the fraction (k,ℓ) is considered here as an example. The level at which the separation from the main cloud occurred is $\zeta_{fk\ell}$ and the size of the fraction at time of separation is $R_{fk\ell}$. The time at which the separation occurred is $t_{fk\ell}$. Adopting the method described earlier for the settling phase, the standard deviation $\sigma_{ok\ell}$ of the distribution of the particles at the time of separation is given by:

$$\sigma_{ok\ell} = R_{fk\ell}/4.0 \tag{31}$$

The standard deviation of the distribution of the particles at the time of deposition at the bed of deep water is given by:

$$\sigma_{fk\ell} = \sigma_{ok\ell} \left[1 + 4^{4/3} \; \frac{2}{3} \; \frac{A}{\sigma_{ok\ell}^{2/3}} \; \left(\frac{d - \zeta_{fk\ell}}{\omega_{k\ell}}\right) \right]^{3/2} \tag{32}$$

The height distribution of the mound formed at the bed due to the settlement of the fraction ($k\ell$) is:

$$h_{k,\ell} = h_{maxk,\ell} \exp \left[- \frac{\{r - U\,(t_{fk\ell} + \frac{(d-\zeta_{fk\ell})}{\omega k\ell})\}^2}{2\,\sigma^2_{fk\ell}} \right] \qquad (33)$$

where $h_{maxk\ell}$ is given by:

$$hmax_{k\ell} = \frac{V_{sk\ell}}{(1-n)\;2\pi\;\sigma^2_{fk\ell}} \qquad (34)$$

Similar expressions can be derived for all the fractions that settle out of the main cloud and hence the total height of mound formed by all the fractions can be obtained by simply superimposing them as:

$$h = \sum_k \sum_\ell h_{k\ell} \qquad (35)$$

When the cloud reaches the bottom before the separation of any of the fractions, which is possible for shallow waters, the mound formed at the bottom can be calculated by assuming that the Gaussian distribution for the concentration of solid particles is valid even during the entrainment phase. However, when the cloud undergoing entrainment phase hits the bottom, further spreading will occur which has not been considered in the model of Krishnappan.

EXAMPLES TO ILLUSTRATE THE APPLICATION OF THE MODEL

The following three examples are selected to illustrate the application of the Krishnappan model.

Example 1: 8 m^3 of dredged material with the following size and specific weight distributions were dumped as a slug in a deep water where the depth is 150 m.

Fraction	Grain Size	Specific Weight in Water	% by Volume
1	0.700	1650 kg/m^3	10
2	0.253	1650 kg/m^3	20
3	0.180	1650 kg/m^3	30
4	0.044	1650 kg/m^3	40

Assuming that the radius of the cloud at the dump level is 2 m, determine the size of the mound formed due to this dump. Assume also the numerical value of the dissipation parameter A=.000068 $m^{2/3}$/sec and the porosity of the mound formed is 0.333.

Solution: Since the specific weight of all the constituents is the same, the subscript i will be dropped and j varies from 1 to 4.

i) Evaluation of the Weighting Coefficients: $w_j = F_j/F$

$$F = \frac{\gamma_s V_s}{\rho} = \frac{\gamma_s}{\gamma} g V_s = 1.65 \times 9.81 \times 8 = 129.49 \ m^4/sec^2$$

$$F_1 = 1.65 \times 9.81 \times 0.8 = 12.949 \ m^4/sec^2$$

$$F_2 = 1.65 \times 9.81 \times 1.6 = 25.898 \ m^4/sec^2$$

$$F_3 = 1.65 \times 9.81 \times 2.4 = 38.847 \ m^4/sec^2$$

$$F_4 = 1.65 \times 9.81 \times 3.2 = 51.796 \ m^4/sec^2$$

$$w_1 = F_1/F = 0.1$$

$$w_2 = F_2/F = 0.2$$

$$w_3 = F_3/F = 0.3$$

$$w^4 = F^4/F = 0.4$$

ii) Determination of α_j, β_j and ω_j

The parameter $(\gamma_s \rho D^3{}_j/\nu^2)$ for each fraction and the values of α_j, β_j and ω_j obtained from Figs. 2, 3 and 4 respectively are as follows:

Fraction	Grain Size (mm)	$(\gamma_s \rho D^3{}_j/\nu^2)$	α_j	β_j	ω_j cm/s
1	0.700	5552.0	0.232	3.54	10.0
2	0.253	262.0	0.272	1.52	2.8
3	0.100	94.4	0.295	1.30	1.9
4	0.044	1.38	0.312	1.10	0.16

$$\alpha_m = \sum_{j=1}^{4} w_j \alpha_j = (0.1x0.232)+(0.2x0.272)+(0.3x0.295)+(0.4x0.312)$$

$$= \underline{0.291}$$

$$\beta_m = \sum_{j=1}^{4} \omega_j \beta_j = (0.1x3.54)+(0.2x1.52)+0.3x1.30)+(0.4x1.10)$$

$$= \underline{1.488}$$

The equations describing the behaviour of the dumped material are:

$R = 2 + 0.291\,\zeta$ (taking R_0 as 2m)

$$W = \frac{1.488x129.49^{1/2}}{\zeta + \dfrac{2}{0.291}} = \frac{16.93}{\zeta + 6.87} \qquad (36)$$

To check whether Fraction 1 would separate out of the cloud before the cloud reaches the bottom:

Equating W and ω_1 and solving for ζ in Equation 36, we get:

$$\zeta_{f_1} = \frac{16.93}{0.1} - 6.87 = 169.3 - 6.87 = 162.46 \text{ metres.}$$

Since the depth is only 150 m, the separation will not occur and the whole cloud undergoes entrainment phase until it hits the bottom.

The radius of the cloud when it hits the bottom is:

$$R_f = 2 + 0.291 \times 150 = 45.65 \text{ m}$$

The standard deviation of the distribution of the material is:

$$\sigma_f = R_f/4.0 = 45.65/4 = 11.41 \text{ m}$$

The maximum height of the mound formed at the bottom:

$$h_{max} = \frac{V_s}{(1-n)\ 2\pi\sigma_f^2} = \frac{8}{0.667 \times 2\pi \times 11.41^2} = \underline{.015} \text{ m}$$

<u>Example 2</u>: The size of the dump is reduced to 1 m^3 while everything else remains the same as in Example 1. (Assume the initial radius of the cloud is 1 m.)

<u>Solution</u>: The weighting coefficients and α_m and β_m take values that are the same as in Example 1.

The equation describing the motion of the cloud is:

$$R = 1.0 + 0.291\ \zeta$$

$$W = \frac{1.488 \times (1.65\times9.81\times1)^{1/2}}{\zeta + (\frac{1.0}{0.291})} = \frac{5.987}{\zeta + 3.44} \tag{37}$$

To check whether separation of Fraction 1 will occur:

The depth required for separation is:

$$\zeta_{f_1} = \frac{5.987}{0.1} - 3.44 = 56.43$$

Since the total depth is 150 m, the separation of 0.70 mm fraction will occur at the depth of 56.43 m and it would undergo settling phase while the main cloud undergoes entrainment phase.

The radius of the cloud at the instant of separation is:

$$R_{f_1} = 1 + 0.291 \times 56.43 = 17.42 \text{ m}$$

The time required for the first separation is:

$$t_{f_1} = \frac{(\frac{\zeta_{f_1}}{2} + \frac{R_o}{\alpha_m})\ \zeta f_1}{\beta_m\ F^{\ 1/2}} = \frac{(\frac{56.43}{2} + 3.44)\ 56.43}{5.986} = \underline{4.97} \text{ min}$$

<u>Motion of the Main Cloud after the Separation of Fraction 1</u>

$$F^1 = F - F_1 = 1.65 \times 9.81 \times 1 - 1.65 \times 9.81 \times 0.1$$
$$= 14.567 \text{ m}^4/\text{sec}^2$$
$$F_2 = 1.65 \times 9.81 \times 0.2 = 3.237 \text{ m}^4/\text{sec}^2$$
$$F_3 = 1.65 \times 9.81 \times 0.3 = 4.856 \text{ m}^4/\text{sec}^2$$
$$F_4 = 1.65 \times 9.81 \times 0.4 = 6.475 \text{ m}^4/\text{sec}^2$$

$$w_2 = \frac{F_2}{F^1} = \frac{3.237}{14.567} = 0.222$$

$$w_3 = \frac{F_3}{F^1} = \frac{4.856}{14.567} = 0.333$$

$$w_4 = \frac{F_4}{F^1} = \frac{6{,}475}{14.567} = 0.444$$

$$\alpha_m' = \sum_{j=2}^{4} w_j \, \alpha_j = (0.222 \text{x} 0.272) + (0.333 \text{x} 0.295) + (0.444 \text{x} 0.312)$$

$$= \underline{0.297}$$

$$\beta_m' = \sum_{j=2}^{4} \omega_j \, \beta_j = (0.222 \text{x} 1.52) + (0.333 \text{x} 1.30) + (0.444 \text{x} 1.10)$$

$$= \underline{1.260}$$

The equations describing the behaviour of the cloud become:

$$R = 17.42 + 0.297 \, (\zeta - 56.43) \text{ for } \zeta > 56.43 \text{ m}$$

(38)

$$W = \frac{1.260 \text{ x } (14.567)^{1/2}}{\zeta + 3.44} = \frac{4.809}{\zeta + 3.44}$$

To check whether the separation of Fraction 2 will occur:

The depth required for the second separation is:

$$\zeta_{f_2} = \frac{4.809}{.028} - 3.44 = \underline{170.36} \text{ m}$$

Since the depth is only 150 m, the separation of Fraction 2 will not occur and the cloud reaches the bottom while undergoing entrainment phase.

The radius of the cloud when it hits the bottom is:

$$R_f = 17.42 + 0.297\ (150 - 56.43) = 45.21 \text{ m}$$

The standard deviation of the particle distribution is:

$$\sigma_f = R_f/4 = 45.21/4 = \underline{11.30} \text{ m}$$

The maximum height of the mound formed at the bottom owing to the main cloud is:

$$h_{max} = \frac{V_s - V_{s_1}}{(1-n)\ 2\pi\sigma_f^2} = \frac{0.9}{0.667 \times 2\pi \times (11.30)^2} = \underline{.00168} \text{ m}$$

Motion of Fraction 1 Undergoing Settling Phase

The standard deviation of the distribution of the particles at the instant of separation (initial distribution) is:

$$\sigma_o = \frac{R_f}{4} = \frac{17.42}{4} = 4.36 \text{ m}$$

The time required for the settling particles to reach the bottom t_1 is:

$$t_1 = \frac{d - \zeta_{f_1}}{\omega_1} = \frac{150 - 56.43}{0.1} = 935.7 \text{ secs}$$

The standard deviation of the distribution of the particles settling at the bottom is:

$$\sigma_f = 4.36 \left[1 + 4^{4/3} \frac{2}{3} \cdot \frac{0.000068}{(4.36)^{2/3}} \times 935.7 \right] = \underline{5.04} \text{ m}$$

The radius of the cloud when hitting the bottom is:

$$R_{f_1} = 4\sigma_f = 4 \times 5.04 = 20.16 \text{ m}$$

The maximum height of the mound formed owing to the settling fraction is:

$$h_{max} = \frac{V_{s_1}}{(1-n)\ 2\pi\sigma_f^2} = \frac{0.1}{0.667 \times 2\pi \times (5.04)^2} = \underline{0.00094} \text{ m}$$

Therefore, the total height of the mound formed because of the dumping of 1 m^3 of the dredged material is:

.00168 + .00094 = .00262 m

If eight such dumps are made then the maximum height of the mound will be

.00262 x 8 = .021 m

Note that if all 8 m^3 of the dredged material were dumped as one slug, the maximum height of the mound formed is only .015 m. The radius of the cloud in both cases is more or less the same.

Example 3: An ambient current of 0.10 m/sec is assumed for Example 2.

Solution: For this case, when Fraction 1 separates from the main cloud, the cloud would have been displaced in the horizontal direction an amount, L, equal to:

$$L_1 = U\,t_{f_1} = \frac{U\left[\frac{\zeta_{f_1}}{2} + \frac{R_o}{\alpha_m}\right]\zeta_{f_1}}{\beta_m\,F^{1/2}} = 0.1 \times 298 = \underline{29.8}\ \text{m}$$

After the first separation, the main cloud would have moved horizontally a distance of L_2 before hitting the ground. The distance L_2 is given by:

$$L_2 = U\,(t_f - t_{f_1})$$

The value of t_f can be determined from the equation governing the motion of the main cloud, i.e.

$$W = \frac{4.809}{\zeta + 3.44}$$

or

$$\frac{d\zeta}{dt} = \frac{4.809}{\zeta + 3.44}$$

Rearranging and integrating we get:

$$\frac{\zeta^2}{2} + 3.44\,\zeta = 4.809\,t + C \quad \text{(C is a constant of integration)}$$

when $t = t_{f_1}$, $\zeta = \zeta_{f_1} = 56.43$

$$t_f = 2127 \text{ secs}$$

Therefore, L_2 can be calculated as $\underline{182.9}$ m.

The total horizontal distance moved by the cloud undergoing entrainment is:

$L = 182.9 + 29.8 = \underline{212.7}$ m

The height distribution of the mound formed at the bottom due to this cloud is:

$$h = h_{max} \exp\left[- \frac{(r - 212.7)^2}{2 \times (11.30)^2} \right]$$

where $h_{max} = .00168$ m

Consider the Fraction Undergoing Settling Phase

The lateral distance travelled during settling phase is

$L_s = Ut_1 = 0.1 \times 935.7 = \underline{93.57}$ m

The total horizontal displacement = 93.58 + 29.8 = 123.38 m.

The distribution of the height of mound formed by the settling fraction is:

$$h_1 = h_{max_1} \exp\left[- \frac{(r - 123.38)^2}{2 \times (5.04)^2} \right]$$

where $h_{max_1} = .00094$ m

The net weight distribution of both mounds is:

$$h = h + h_1 = .00168 \exp\left[- \frac{(r-212.7)^2}{255.4}\right] + .00094 \exp\left[- \frac{(r-123.38)^2}{50.8}\right]$$

$$h_{212.7} = .00168 + .00094 \exp\left[- 157.05\right] = .00168 \text{ m}$$

$$h_{123.38} = .00168 \exp\left[-31.23\right] + .00094 = .00094 \text{ m}$$

The maximum height formed is .0168 m. Note that the cloud in this case has been broken up into two pieces and they are deposited on the bottom, far apart from each other. If there were eight such dumps, then the maximum height formed would only be .013 m and it would occur at a lateral distance of 213 m from the location of the dump.

SUMMARY

The Krishnappan model for predicting the dispersion of the dredged spoil when dumped as a slug in deep water is described in detail along with three illustrative examples showing the application of the model. In this model, the deredged spoil is considered in various fractions of uniform size particles and it is assumed that each fraction exerts influence on the total behaviour of the dredged spoil in proportion to its negative buoyancy. The behaviour of the uniform size particles has been formulated using the theory of dimensions and laboratory experiments. The method can be used to predict the vertical height and the horizontal size distribution of the "mound" formed due to the deposition of the dredged spoil at the bed of deep water. The model indicates how the characteristics of the mound depend on the volume of dump, the size distribution of the dredged spoil, the water depth and the ambient current and the turbulence characteristics, thereby providing guidance for the selection of optimum dump size and location for the disposal of the dredged spoil.

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4.4 The Drift Model

4.4.1 Theory and Development of the Model

by

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THE DRIFT MODEL: THEORY AND DEVELOPMENT OF THE MODEL

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ABSTRACT

The Drilling Effluent Fate and Transport model, DRIFT, employs a probabilistic approach for predicting the long-term fate and transport of drilling effluents. The model is, in fact, a combination of short- and long-term models coupled with the observed occurrence frequencies of the current structure for the specific site under consideration. The observed current pattern is divided into a number of speed and direction categories by depth and horizontal location. Interpolation is employed to obtain values at locations intermediate to those at which the measurements are available. Each of these categories is then assigned a probability of occurrence and it is assumed that the effluent is under the influence of each of these categories in proportion to its probability of occurrence. For each category, a short-term and a long-term model is then employed and the final results are obtained by the method of superimposition.

For the short-term fate, any of the available models for the formation waters of cuttings can be employed within the framework of the DRIFT model. For the long-term fate, the present version of the model employs a simple transport algorithm incorporating advection, settling and deposition. Other phenomena such as dispersion, and resuspension may be included without much modification to the framework of the model. At present, the DRIFT model only provides the expected values for the concentrations or travel times and distances for the drilling effluents. The standard deviation may be calculated without much modification to the mathematical framework of the model if the variance of the currents is available from the field data. The model has been employed, in conjunction with field studies, at Lower Cook Inlet, Alaska and to a data base in the Santa Barbara Channel offshore of California.

1. INTRODUCTION

By their very nature, the drilling effluent discharges in the offshore environment are often intermittent, time varying and occur over a long period of time. The composition of the discharge changes with the drilling depth and the flow field in the immediate vicinity of a drilling platform is often strongly influenced by the structure of the drilling platform itself. In addition the currents are stochastic in nature and vary considerably in both space and time. The resulting flow field is a complex, unsteady, three-dimensional field of motion which is generated by the interaction of this structure with the ocean currents.

The present generation of mathematical models available for the analysis of the fate and transport of drilling effluents are limited in many respects. All the models presently available are based upon the dynamics and mixing of buoyant jets discharged in a large body of water and are geared towards the analysis of steady-state, one or two-dimensional flow-fields. Typically these models incorporate only the mechanisms of entrainment, buoyancy, turbulent dispersion, and settling of particles.

The field measurements of the concentrations from actual or simulated drilling mud discharges often show dilutions on the order of hundreds and thousands within a short distance of release (or a few minutes). Dilutions such as those observed can only be caused by mechanisms of convective mixing caused by the complex three-dimensional flow-field created by the structure itself. The present generation of models are unable to predict such dilution rates. Further, the available models are essentially short-term models and their application and validity for long-term analysis (beyond a day or so) is open to question. In contrast, the primary interest in assessing the biological or ecological impact of the effluents is in the long-term time scales.

It is thus apparent that alternative approaches need to be developed for the prediction of the fate of mud and cuttings. One such approach, embodied in the DRIFT (for Drilling Effluents Fate and Transport) Model (Runchal, 1983; Atlantic Richfield Company, 1978), forms the subject of this paper.

This paper presents the theory of the DRIFT model and an application to a field study in the Lower Cook Inlet, Alaska, which was made during the development phase of the model. The field study was conducted as part of the Continental Offshore Stratigraphic Test (C.O.S.T.) Well which was drilled between June 7, 1977 and September 26, 1977. A companion paper presents a recent application of the model to a generic application in the Santa Barbara Channel (Austin, 1983).

2. APPROACH TO MODELING

2.1 General Description

Drilling discharges are primarily composed of three constituents: the drill cuttings, the drilling mud and, the formation water. Of these, the cuttings are generally much heavier than the rest of the discharge or the ambient water. Typically the specific gravity of these cuttings is approximately 2.6 and, in general, they are quite coarse with a size range between 0.1 mm and 10 mm. Thus, they tend to quickly settle out from the discharged material and collect on the bottom of the sea. The rest of the discharge, consisting primarily of formation water and the drilling mud with small amounts of finer sized cuttings, is transported and dispersed with the ambient currents.

The DRIFT model employs a probabilistic approach for separate analysis of each of these two components. It is essentially composed of two components: a model for drill cuttings and, a model for drilling mud and formation water. For long-term prediction, these models are then coupled to the appropriate site-specific current pattern based upon the measured occurrence frequency.

The model relies upon the availability of the occurrence frequency of the currents over a period of time. It is essential that the period of measurement should be representative of the time period of interest in the fate of the effluent. It is assumed that, on the average, the effluent is likely to encounter a specific current in direct proportion of its occurrence.

To implement the method, the observed long-term current pattern is divided into a number of speed and direction categories by depth and horizontal location. Interpolation is employed to obtain values at locations intermediate to those at which the measurements are available. Each of these categories is then assigned a probability of occurrence and it is assumed that the effluent is under the influence of each of these categories in proportion to its probability of occurrence. For each category, a cuttings and a drilling mud model is then employed and the final results are obtained by the method of superimposition.

2.2 The Drill Cuttings Model

The cuttings analysis is performed on the assumption that the primary factors responsible for their dispersal and deposition are the currents and the settling velocities of these cuttings. The cuttings are divided into a number of categories based on their size and settling velocities. The governing transport equations for each category are given by:

$$dr/dt = U(z), \quad \text{and} \tag{2.2.1}$$

$$dz/dt = W(S), \tag{2.2.2}$$

where,

r is the horizontal distance measured from the point of discharge in the direction of the current,

z is the distance measured vertically from the point of discharge,

t is the time,

$U(z)$ is the current speed as a function of depth, z, and

$W(S)$ is the settling velocity of the cutting as a function of the particle size, S.

These equations can be solved for a complete complete range of currents observed during the data collection phase for a number of representative particle sizes.

2.3 The Drilling Mud and Formation Water Model

2.3.1 THE WAKE DILUTION COMPONENT

Any material discharged in the wake of a structure, provided that the concentration of this material is small in comparison to the flow in the wake, is dispersed and transported in accordance with the laws of wake dispersion and growth. A detailed discussion of the wake created by a solid body and the mechanisms influencing the mixing in wakes is available, for example, in Schlichting (1968).

The DRIFT model allows for the effect of the structure by incorporating a wake dilution factor. This provides the starting conditions for the mud plume analysis by a suitable model. The approach is based upon the empirical data coupled with the analytical expressions for dilution in the wake of a regular structure. The starting concentration after initial wake mixing and dilution, C_s, is calculated as:

$$C_s = Q C / (U W D) , \tag{2.3.1}$$

where Q is the discharge, C is the discharge concentration, U is the ambient current, W is the width of the mixing zone, and D is the depth of the mixing zone.

The growth of the wake is a strong function of the nature of the structure and that of the flow. The present version of DRIFT allows for incorporation of any suitable formula for the growth of the wake. Two of these are that of the rate of growth of the width proportional to $x^{1/2}$ (appropriate for the wake behind a single cylinder) and that of the growth proportional to x (appropriate for the wake behind a row of cylinders, see eg., Schlichting, (1968).

2.3.2 THE DYNAMIC PLUME TRANSPORT MODEL

The present version of the DRIFT model provides three basic options for the dynamic analysis of the formation water and the drilling mud. These are the DKHPLM model (Kannberg and Davis, 1976), the Fan (1967) model, and the PDS model (Shirazi and Davis, 1974). The first two of these are the models for the analysis of a submerged buoyant discharge whereas the third is a model for a buoyant surface discharge. All of these models have been extensively tested and validated for buoyant thermal discharges. A mathematical description of these models is available elsewhere and is not repeated here.

The framework of the DRIFT model, however, is such that any suitable drilling effluent model can be coupled to it. It therefore does not need any modification to be coupled to any of the other available models (Brandsma, 1983) for short term fate of drilling effluents. The formation water model merely provides the short-term predictions which the DRIFT then uses to couple to the long-term site-specific currents.

3. THE LOWER COOK INLET APPLICATION

3.1 The Field Data

The Lower Cook Inlet Continental Offshore Stratigraphic Test (C.O.S.T.) Well was drilled between June 7, 1977 and September 26, 1977 with the **Ocean Ranger**, a semi-submersible drilling vessel. The physical setting of the well, and the drilling vessel are described in detail in Atlantic Richfield Company (1978) and Houghton et al. (1980). The offshore environment in the immediate vicinity of the Lower Cook Inlet is dominated by large tidal fluctuations and strong currents. The currents were measured over a period of approximately 3 months at the C.O.S.T. well with drogues and two Endeco 105 current meter arrays. The current meters in the arrays were located near the bottom, the mid-depth and the surface. The current meter data was analysed to provide the percent occurrence frequency by speed and direction at each depth. This frequency distribution was then employed as the input for the various model components. Complete details of these data are given in Atlantic Richfield Company (1978).

3.2 The Cuttings Analysis

The composition of the drilling mud effluent was obtained from laboratory analysis of appropriately collected samples. The cuttings were separated from the discharge and the cutting samples from various depths were analyzed to categorize the cuttings in terms of different sizes. From these results, a generic cuttings sample was prepared to represent the complete range of cuttings from various depths. The settling velocities for these were obtained from Johnson (1974). The size distribution of the generic sample, and the settling velocities, are given in Table 1.

TABLE 1: LOWER COOK INLET GENERIC DRILL CUTTINGS SAMPLE

Nominal Size (mm)	Percent Composition by Weight (Percent)	Percent Composition by Numbers (Percent)	Setting Velocities (cm/sec)
5.0	11	0.0012	29.99
2.5	19	0.0163	21.24
1.0	28	0.378	11.03
0.6	26	1.627	6.52
0.2	10	16.89	2.04
0.1	6	81.08	0.67

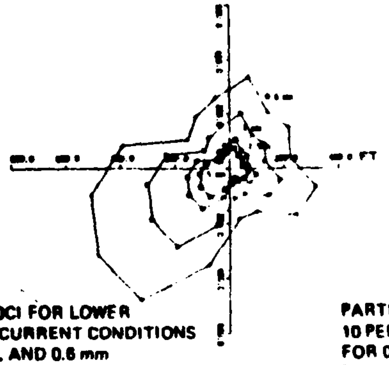
The currents applicable were obtained from the oceanographic data. This data was analyzed for its frequency distribution by speed and direction for the three current meters, designated Stations 14, 31 and 52, for the top, mid and bottom locations (Atlantic Richfield Company, 1978). These data were unaffected by the drilling vessel and were thought to best represent the currents affecting the long-term dispersal of cuttings.

The first set of results for the cuttings was obtained by selecting three representative current speeds in each of the 22.5 degree direction segments employed for frequency analysis. The current speeds were taken to be those representing the lower 10 percent, the upper 10 percent and the 50 percent occurrence for each of the current meters at Stations 14, 31 and 52. A complete current profile with depth, as required by Equation 2.2.1, was constructed by linear interpolation between the stations. An illustrative example of the final results, in terms of the horizontal distance of travel to reach the sea bottom for each particle size in each direction segment, is shown in Figure 1. It is seen that the predicted contours of the particle loci form an ellipsoidal distribution which is in qualitative agreement with the bi-modal current pattern observed. At the low speed end, however, as is to be expected, the particles are seen to have a considerable scatter.

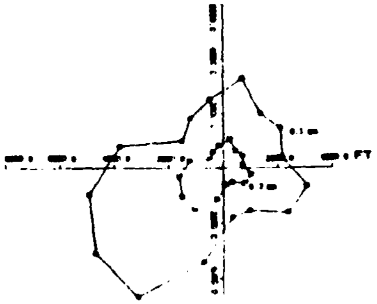
A second and more general outcome of the cuttings analysis is the particle distribution frequency and particle flux for the period July 17, 1977 to September 17, 1977. The current data for these results was obtained by appropriately weighting the occurrence frequency for the three stations to produce a composite current frequency table. The outcome of this analysis is the percentage frequency of the discharged particles for each of the 6 separate representative sizes for a complete range of directions and distances ranging up to 12.2 km from the point of discharge. These results, given in detail in Atlantic Richfield Company (1978), thus represent the percentage, by numbers, of the likelihood of deposition of particles of certain size in certain direction and at a certain distance. These data are easily weighted for a given sample and combined to produce a table for overall frequency of particle deposition and the particle flux by weight. For a generic cutting sample, the frequency of particle deposition, in terms of a contour plot of the particle fluxes by weight, is shown as Figure 2. A predominantly bi-modal distribution along the primary current direction, with some scatter, especially for the smaller size particles, is observed.

3.3 The Drilling Mud and Formation Water Analysis

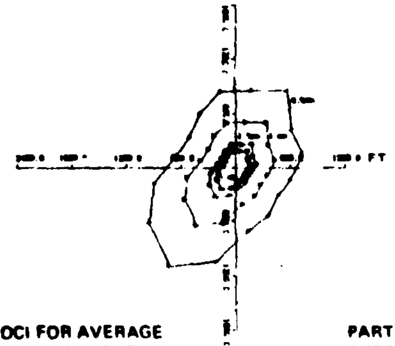
For an analysis of the mud and formation water disposal, it was assumed that immediately after the discharge of the effluent, the coarse sized and heavy cuttings settle out of the effluent. The resulting mixture consists of micron sized particles in a carrier of fresh and sea water. Because of the relatively small amount of mud in the mixture, the density of the effluent is extremely close to that of the ambient waters. From the field data analysis, it became clear that the discharge was extensively diluted in the near-field due to the prevailing three-dimensional flow pattern created by the interaction of the drilling vessel with the current. Typically dilutions on



PARTICLE LOCI FOR LOWER 10 PERCENT CURRENT CONDITIONS FOR 5., 2.5, 1. AND 0.6 mm SIZED PARTICLES.



PARTICLE LOCI FOR LOWER 10 PERCENT CURRENT CONDITIONS FOR 0.2 and 0.1 mm SIZED PARTICLES.



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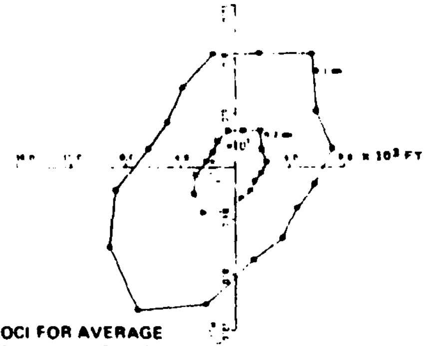

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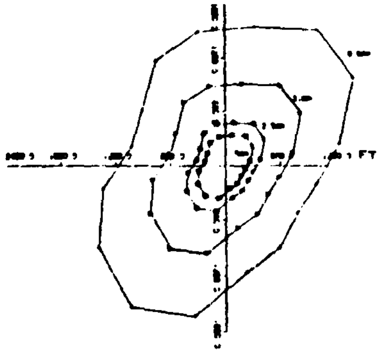
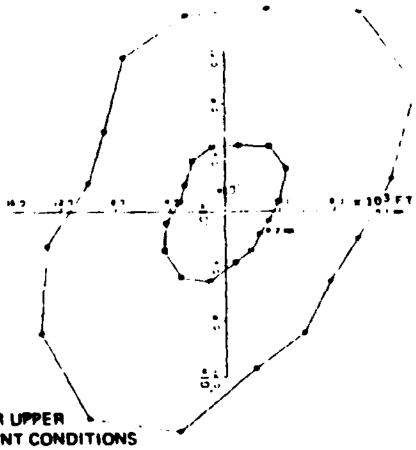
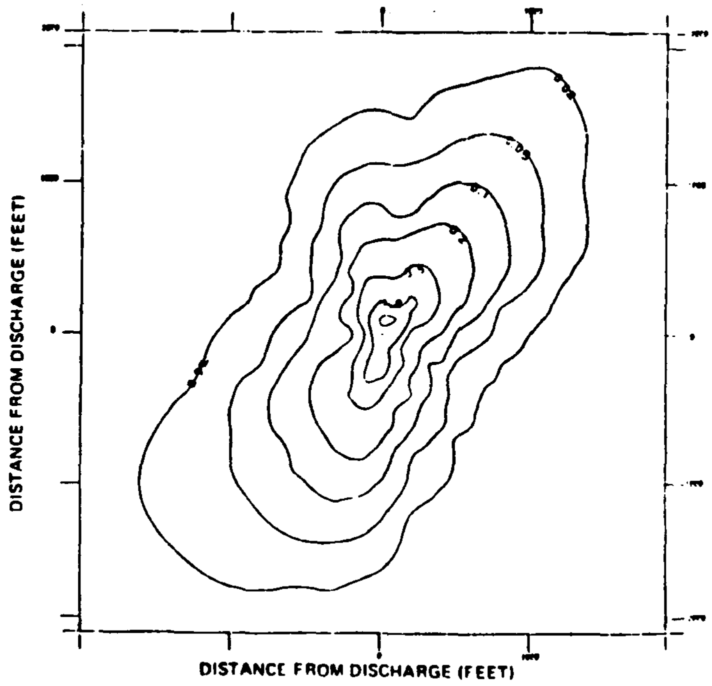


PARTICLE LOCI FOR UPPER 10 PERCENT CURRENT CONDITIONS FOR 5., 2.5, 1. AND 0.6 mm SIZED PARTICLES.



PARTICLE LOCI FOR UPPER 10 PERCENT CURRENT CONDITIONS FOR 0.2 AND 0.1 mm PARTICLES.

FIGURE 1: PREDICTED LOCI OF CUTTINGS ON THE OCEAN BOTTOM



IGURE 2: CONTOUR PLOT OF FLUX OF CUTTINGS BY WEIGHT PER MILLION PARTS DISCHARGED.

the order of 10,000 and higher were measured for dye concentrations within a few hundred feet of the point of discharge.

For the analysis of the mud plume, it was assumed that the current conditions, for the duration of the interest, were steady state. For this analysis, three specific discharge cases were considered: (1) continuous discharge from normal drilling from Shaker only; (2) continuous discharge from Shaker, desander and desilter; and (3) mud discharge from purging the sand pit. The discharge rates and fractions for each of these cases are given in Table 2. It is seen from this table that once the cutting and other coarse particles are taken out of the mixture, the differences between the cases (1) and (2) are minor.

TABLE 2: COMPOSITION OF THE DRILLING MUD DISCHARGE

Case	Fraction	Discharge (m /hr)	Vol. Ratio (percent)	Density (gm/cc)
1	Sea Water	83.47	99.62	1.022
	Fresh Water	0.14	0.16	0.997
	Solids Less Cuttings	0.02	0.03	4.2
	Cuttings	0.16	0.19	2.6
	TOTAL	83.78	100.00	1.026
2	Sea Water	83.47	95.98	1.022
	Fresh Water	2.52	2.90	0.997
	Solids Less Cuttings	0.09	0.10	4.2
	Silt	0.61	0.70	2.6
	Sand	0.12	0.14	2.6
	Cuttings	0.16	0.18	2.6
	TOTAL	86.96	100.00	1.041
3	Sea Water	6.96	33.20	1.022
	Fresh Water	10.14	48.43	0.997
	Solids Less Cuttings	1.05	5.01	4.2
	Sand	2.80	13.36	2.6
	TOTAL	20.95	100.00	1.380

The starting conditions for the drilling mud modeling study were obtained from the empirical data obtained during the dye release experiments. Based upon this analysis, it was assumed that the initial mixing-zone concentration, calculated from Equation 2.3.1, was reached at a distance of 150m (500 ft) from the discharge point and that the plume at that point was 45m (150 ft) wide and 11m (37.5 ft) deep.

It was noticed from the field data that the discharge effluent, less the cuttings, was slightly positively buoyant due to the elevated temperature and the presence of fresh water. It surfaced within a 150m or so of the discharge point and behaved like a surface plume. It was therefore analyzed as a surface plume by the Shirazi-Davis model (1974). Though the surface plume analogy is rather thinly stretched for the mud dispersal, it was felt that some useful indications about the behavior of the plume would be obtained.

The field test data for the August 29 and 30, 1977 experiments are shown plotted in Figure 3 in terms of the measured maximum dye concentration versus the discharge. In all cases, a drastic reduction in the concentration is seen to occur between the discharge point and the first point of measurement. In comparison, it is seen that the Fan model underpredicts the dilution by more than two orders of magnitude. It is to be concluded, therefore, that the mechanisms affecting this discharge are other than those normally treated by jet type of models and that such models are, therefore, inappropriate under the complicating geometry and flow conditions encountered downstream of a drilling structure.

The results from the Shirazi-Davis model and the wake hypotheses are shown in Figures 3 and 4. The measured and predicted concentrations are seen plotted against the distance of travel. Two of the three sets of field data relate to mud discharges and the third to a continuous release. The predicted values are, in general, higher than the measured values; the qualitative trends are correctly predicted. The measured and predicted plume widths are plotted against the distance of travel in Figure 4. The measured plume widths are those for the two bulk mud discharges. Also, plotted in this figure are the predicted plume widths on the basis of the linear and the square-root wake hypotheses. Further, the model predictions from the Shirazi-Davis model are

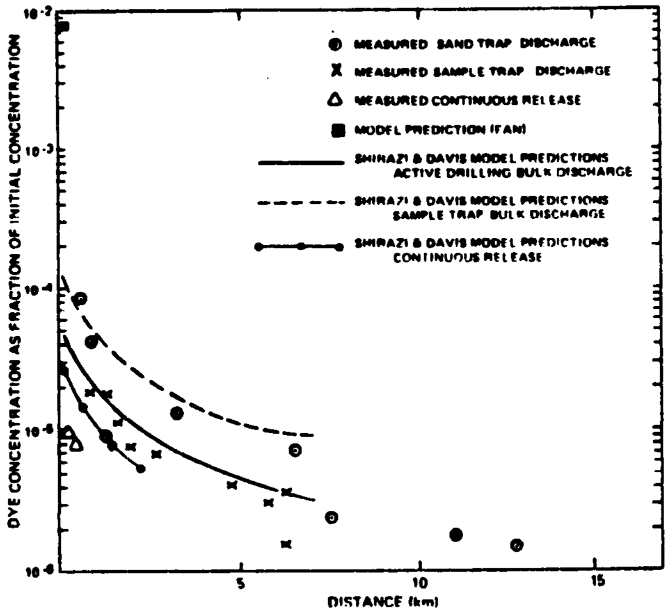


FIGURE 3: DECAY OF DYE CONCENTRATION WITH DISTANCE FROM FIELD STUDY AND MATHEMATICAL MODELING.

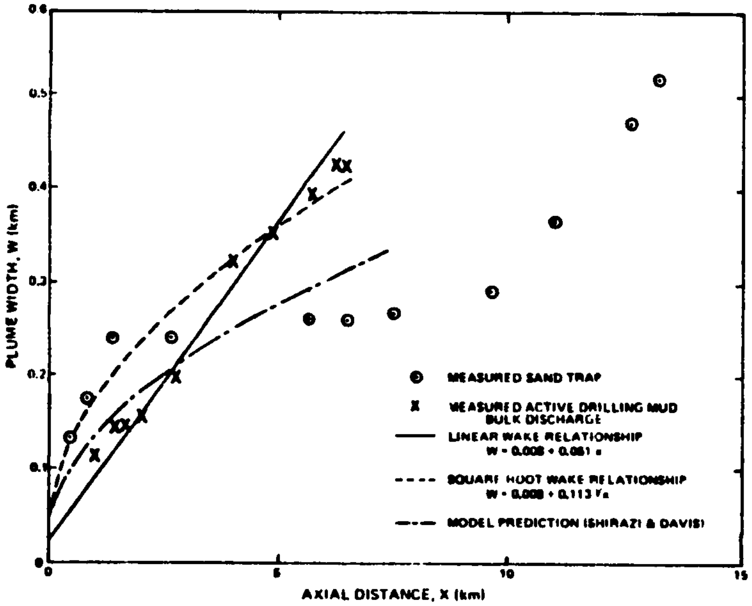
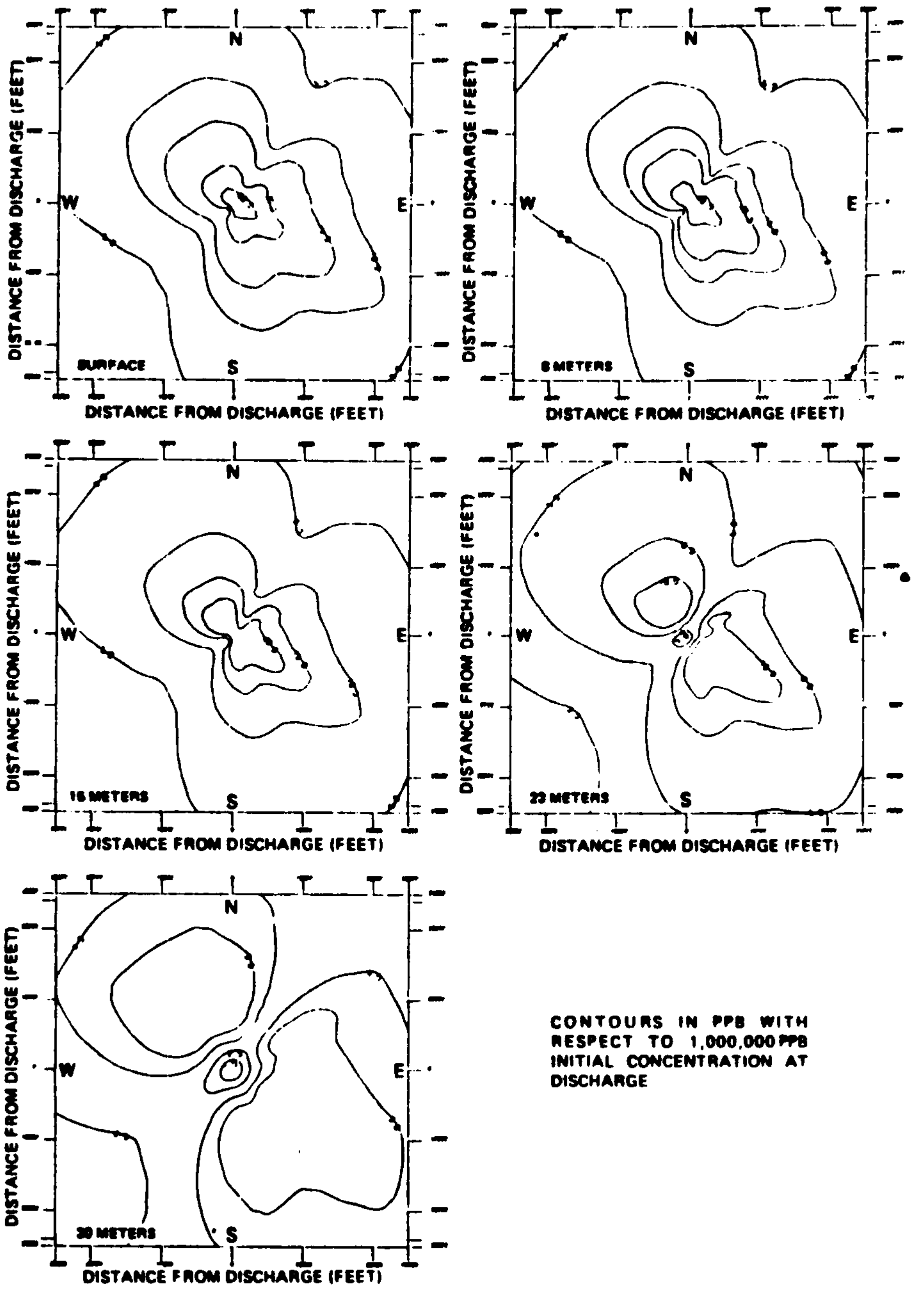


FIGURE 4: GROWTH OF PLUME WIDTH WITH DISTANCE FROM FIELD STUDY AND MATHEMATICAL MODELING.

included for comparison. It is seen that one of the plumes is in fair agreement with the observations, whereas the other plume is seen to be poorly predicted. It seems that some factors, such as, the complex flow field which are not accounted for in these simple approaches, significantly affect the behavior of these plume.

It should be mentioned here that the Shirazi-Davis model is intended for continuous discharges under steady-state conditions; the comparison is thus to some extent misleading. However, the dispersion processes in continuous and instantaneous releases are to some extent similar and hence qualitative comparisons are justified under such circumstances.

After completion of the field data simulation by the approaches discussed above, a generic simulation of the mud plume was undertaken. The approach used was that of the empirically based mixing analysis (Equation 2.3.1) combined with the Shirazi-Davis model. For this set of simulations, a surface current speed of highest occurrence in each of the sixteen direction segments was selected. The surface current speed was taken to be that given by Station 46. The discharge flow was taken to be 0.85 cfs (corresponding to Case 2, Table 2) and the initial concentration as 1 part per thousand (million ppb). The combined empirical mixing analysis and Shirazi-Davis model were then used to predict the plume travel in each of the direction segments. For these predictions, it was assumed that enough time lapse occurred between the change of current direction so that the background concentration of the ambient waters was negligible. The predicted contours of plume centerline concentrations at five different horizontal planes, for the highest occurrence conditions of current speed, are shown in Figure 5. The contour values represent ppb given a discharge concentration of one million ppb. For any other conditions, such as the lower 10 percent conditions, the resulting contours will be different. An estimate of the changes in the starting concentrations and hence in the resulting predictions, can be obtained by reference to Equation 2.3.1.



CONTOURS IN PPB WITH RESPECT TO 1,000,000 PPB INITIAL CONCENTRATION AT DISCHARGE

FIGURE 5: CONTOURS OF CONCENTRATIONS AT PLUME CENTERLINE FOR SELECTED WATER DEPTHS.

CONCLUSIONS

1. The interaction of the prevailing currents with the discharge structure often leads to a complex, unsteady, three-dimensional flow field in the immediate vicinity of the structure. This, in turn, strongly influences the near-field dilutions of any drilling effluent. The currently available mathematical models are unable to take a satisfactory account of this phenomena.

2. The available mathematical models are geared primarily towards the short-term analysis of the fate and transport of drilling effluent. In contrast, for biological and ecological considerations, the interest is often in the long-term fate and transport of the drilling discharges.

3. A methodology has been proposed to couple the presently available short-term models with the long-term, site-specific, currents to provide probability distribution of the long-term fate and transport of drilling effluents.

4. The methodology has been embodied in a flexible model, DRIFT, which was applied to a field study in the Lower Cook Inlet, Alaska.

5. The model accounts, in an approximate way, for the initial dilution due to the interaction of the currents with the structure.

6. The predictions from the model are in qualitative agreement with the field data; however sufficient field data was not available to provide a definitive validation of the model.

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4.4.2 Applications of the Drill Cuttings DRIFT Model

by

D. Ian Austin

Applications of the Drill Cuttings DRIFT Model

D. Ian Austin, Dames & Moore *

Introduction

This workshop has been called to address the question of the capabilities, merits and applicability of models available for predicting the dispersion and fate of effluents discharged from outer continental shelf platforms. Most of the models presented deal with the short term deterministic analysis of mud jets and the resulting plume dispersion. However one of the major purposes of the effluent modeling is to aid in the biological assessment of the effluent impact. This assessment typically requires long term - on the order of weeks or months - estimates of the rate and extent of mud and cutting impact upon the benthos; water column impact appears to be of secondary importance.

This paper presents a computer model which addresses the question of the long term fate of drill cuttings. The DRIFT model was developed as part of a study into the effects of drilling effluents upon biota in the neighborhood of a shelf platform. It is intended to be used in conjunction with a mud plume model as it does not address the question of drilling mud fate. The model is oriented towards use in studies where a long-term probabilistic prediction, rather than a short-term explicit prediction of the drill cuttings fate is required. The model is both conceptually simple and economic to run when compared with the associated mud plume models. The model is designed to use data which, in our experience, is typical of that collected during EIR or similar report preparations.

The standard test case data sets distributed prior to the workshop are primarily directed at the short term prediction of mud jets and plumes. Dames & Moore uses either a modified Koy-Fan model or a Shirazi-Davis model for plume modeling and, as authors of both models are in attendance and will be discussing their models, the standard test cases were not run. Rather, examples of the use of the cuttings model DRIFT, which is normally used in conjunction with a plume model, are presented.

Two examples of the DRIFT model usage will be presented. The first example demonstrates the model usage in a relatively calm deep water environment in the Santa Barbara Channel. The second example is taken from a shallow water site in the Lower Cook Inlet, Alaska, where a dynamic wave and current regime exists.

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Example 1 - Platform "Pescado A", Santa Barbara Channel

Exxon is proposing to expand its Santa Ynez Unit in the Santa Barbara Channel, to which end Dames and Moore recently completed an Environmental Report (1). The field data used in this example of the DRIFT model was collected during the preparation of that report and, as such, is typical of field data collected during EIR preparation.

The basic data requirements of the DRIFT model are a statistical or climatological description of current velocities, e.g., current roses, the settling velocities of the drill cuttings and a description of the cutting size distribution by particle number or weight. In the DRIFT model the accuracy of predicted results is a function of the accuracy of the input data, in particular, the current data. Consequently greater detail in the available current velocity data will be reflected by greater accuracy in the predicted drill cuttings fate. The settling velocities used in the two examples are those of Johnson (2).

Figure 1 shows the location of the platform site in approximately 1100 feet of water on the northern Santa Barbara Channel shelf. If put into operation some 60 wells will be drilled from the platform over an approximately three year period. Approximately 700,000 cubic feet of drill cuttings will be produced during the drilling stage.

The position of current meter arrays deployed during the three month study are shown in Figure 2. For this example data recovered from the Pescado A site meters and the bottom current meter C have been used. The surface currents in the platform area flow in a predominantly westward direction as shown by the current rose in Figure 3. The surface currents at this depth (50 feet) appear to be primarily of geostrophic origin with little wind induced flows. The mid-depth (600 feet) current meter (Figure 4) shows greater variability while the bottom (1050 feet) current meter (Figure 5) shows no predominant flow direction as shore-normal up-canyon flows, shore-parallel geostrophic and upwelling flows all act. While the current data shown only covers a period of a few months longer term data collection (as in the next example) would allow a statistical seasonal variation in the currents to be determined and hence used in the model.

The DRIFT model has two components, one which predicts the final locations of a range of particle sizes by compass segment and a second component which predicts the probability of particle location by particle size per unit discharge and the associated particle flux. Results from the second component are shown in this example.

A linear distribution of particle size by weight ranging from 13 mm to 0.1 mm was assumed as an actual distribution was unavailable. This distribution is based on measurements previous drilling samples (see for example Figure 10). Below approximately 1.5 mm, the particle behavior is no longer dominated by gravational effects as is implicitly assumed in the DRIFT model formulation except in extremely calm conditions. Using the settling velocities of Johnson (2) and the data in the current roses described above, the DRIFT model predicted a flux of cuttings as shown in Figure 6. The effect of predominantly westward surface current can be clearly seen. The final distribution of cuttings are shown three-dimensionally in Figure 7. The two humps are the result of the current velocity distributions rather than particle size sorting due to turbulent verses laminar effects. While the westerly currents dominate for approximately 85 percent of the time creating the "downstream" or westerly hump, during the remaining 15 percent the time relatively calm conditions result in a near vertical deposition.

Example 2 - The ARCO C.O.S.T. Well, Lower Cook Inlet

Dames & Moore's involvement in the modeling of effluent dispersion and fate began with a contract to study the physical and biological effects of drilling discharges during the drilling of the Lower Cook Inlet C.O.S.T. Well in Alaska (3). The study involved both the short term mud plume analysis, for which the Shirazi-Davis model - discussed at this workshop by Davis - was used, and the prediction of the longer term impact of drilling cuttings.

The site of the C.O.S.T. Well is shown in Figure 9. It is located approximately 35 miles west of Homer Alaska in 60 meters of water. The region is fairly dynamic in an oceanographic sense with currents measured on a flood tide ranging form 1.5 knots at the surface to 1.0 knots at 52 meters depth. The currents in Lower Cook Inlet have been extensively studied, one current pattern is shown in Figure 10. The figure shows strong rip currents and large scale eddies. The bottom sediments in the region vary form coarse gravelly silts to fine sands. A typical distribution is shown in Figure 10.

The extensive current data collection and measurement near the platform site allows the data to be statistically analyzed and presented as frequency of occurrence of current velocity by direction. For the purposes of drill cutting modeling 16 compass direction bins were used.

The first component of the DRIFT model predicts the furthest location of particle position by size. The results of this component are shown in Figure 11. The current velocity frequency distributions associated with the lowest 10 percent occurrence of currents, middle 50 percent occurrence and upper 10 percent occurrence are shown. As might be expected the distributions show that the upper 10 percent currents result in the greatest spreading of material with probably the least biological impact. The middle 50 percent currents create the less spreading and hence the greater fluxes. The lower 10 percent currents result in the least spreading and greatest fluxes. The flux of material associated with the middle 50 percent currents is shown in Figure 12. A printer rastor plot of the flux is shown in Figure 13. The final distribution is shown in a three-dimensional plot, Figure 14. The figure shows a bimodal distribution associated with the tidal dominated currents.

Discussion

In an model such as DRIFT the are many implicit and explicit assumptions which must be recognized when interpreting the model results. The flux and final distributions assume material is not swept away by storms or advected vertically through the bottom sediments by benthic dwellers. In the case of the deep Santa Barbara platform where bottom currents are small and surface effects are not felt this assumption is probably valid. However in the shallow C.O.S.T. platform the assumption is more questionable. Figure 10 shows a sieve distribution of the drilling cuttings found in a bottom sample at the C.O.S.T. site. The cuttings were distributed through 8 to 9 cm of sediment due to the reworking of bottom sediments by wave and current action.

At the moment the model assumes a constant rate of discharge of material over the drilling stages of a platform operation. Consequently the fluxes predicted are a mean flux over the same period. A history of the flux variations (and hence the maximum flux which is of interest to biologists) could easily be obtained by inputing the predicted rate and occurrence interval of cuttings discharge.

This presentation is intended to both indicate the techniques we have used in drill cutting modeling and to ask what is this the most appropriate technique for modeling the long term fate of drill cuttings and muds as required for EIR's and other biological investigations. The model accuracy should be consistent with the quality of the economically available data and provide the biologists with sufficient information to assess both the short and long term the impact of a proposed platform operation. For drill cuttings at least, an overly elaborate deterministic model does not seem warranted. Rather, as predictions are to be made for timescales measured in years a probabalitic approach appears appropriate.

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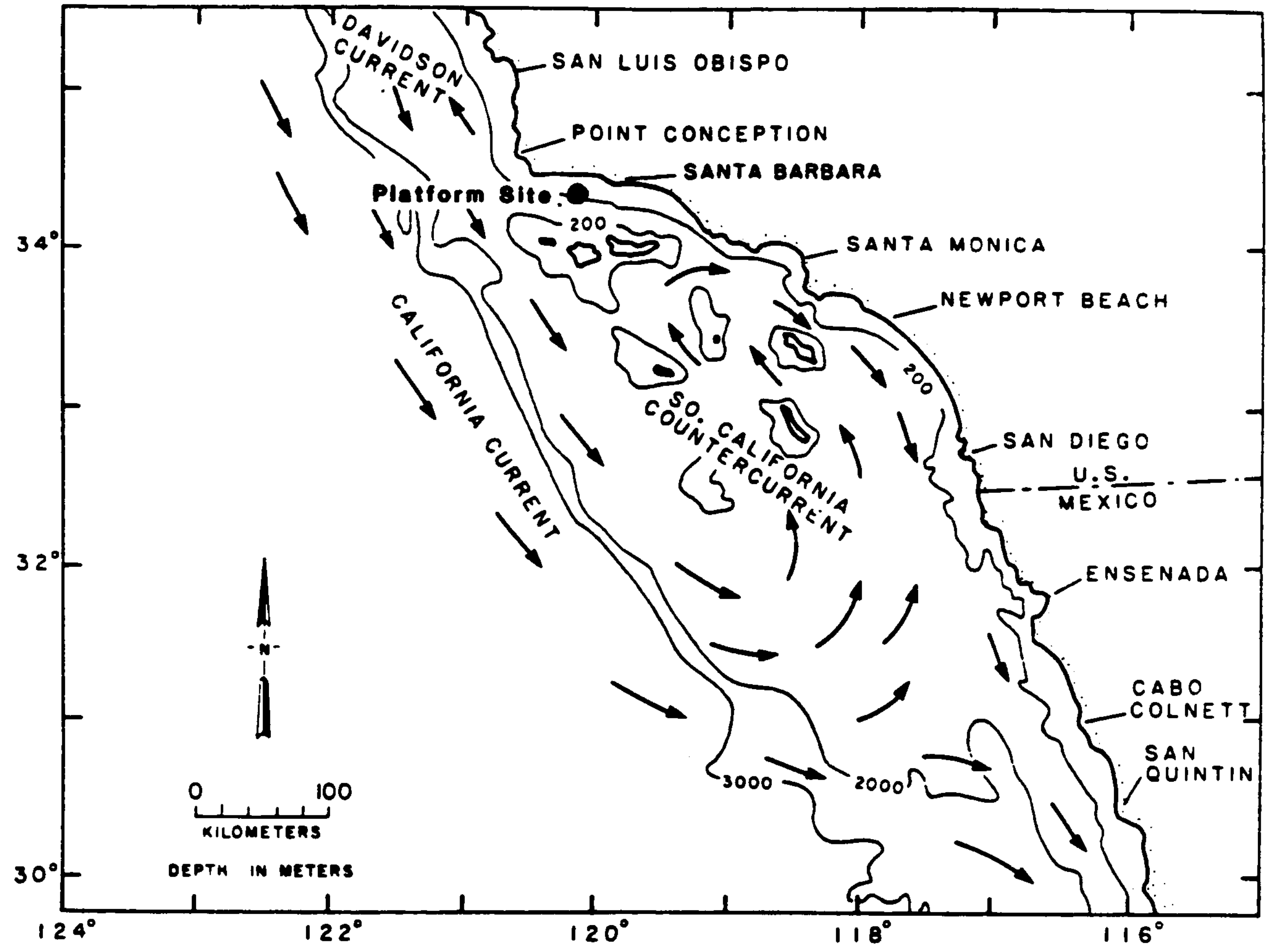


FROM SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT (1973).

Figure 1

SURFACE CIRCULATION (0-100m) IN THE SOUTHERN CALIFORNIA BIGHT

Figure 2

CURRENT METER LOCATIONS

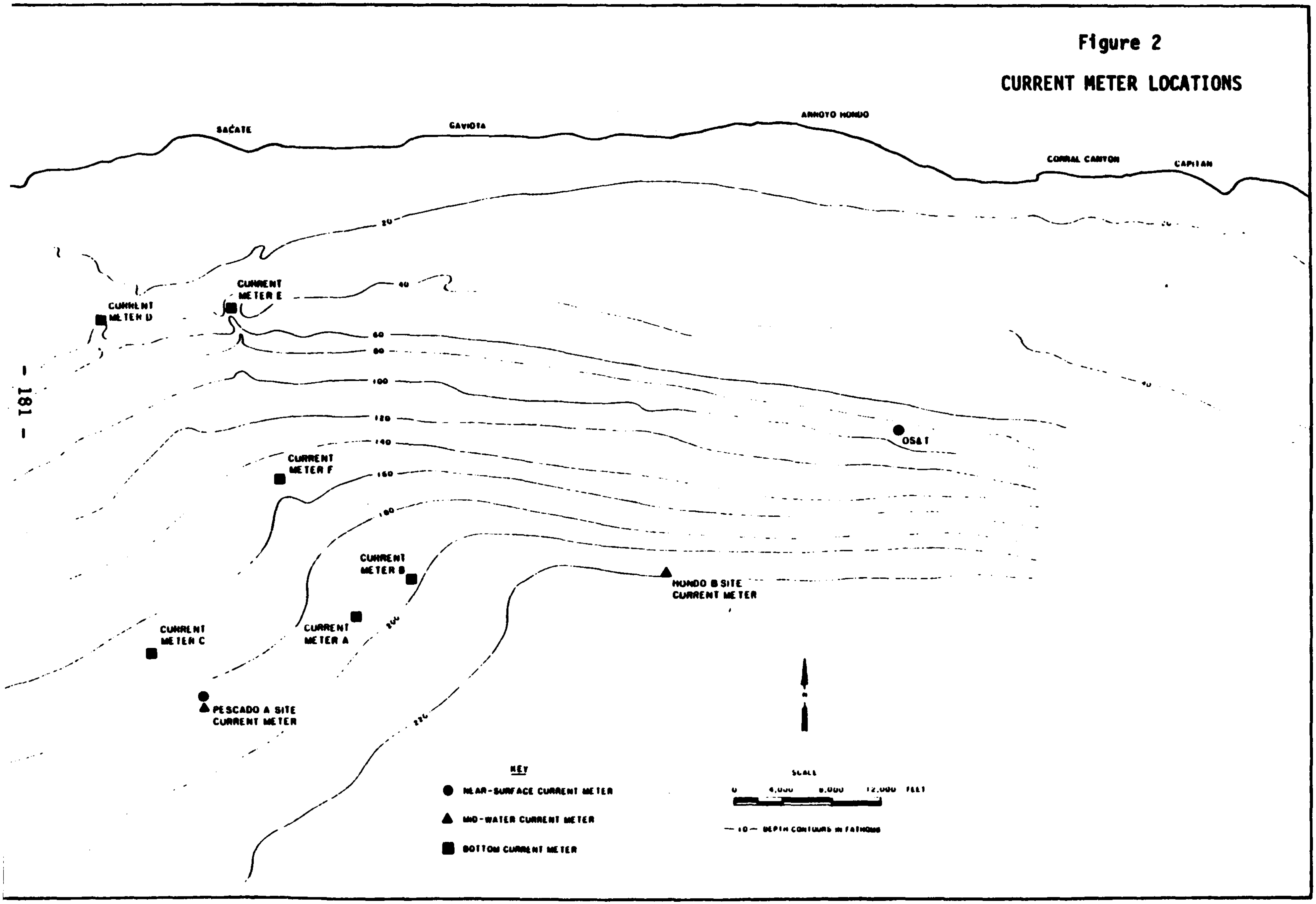
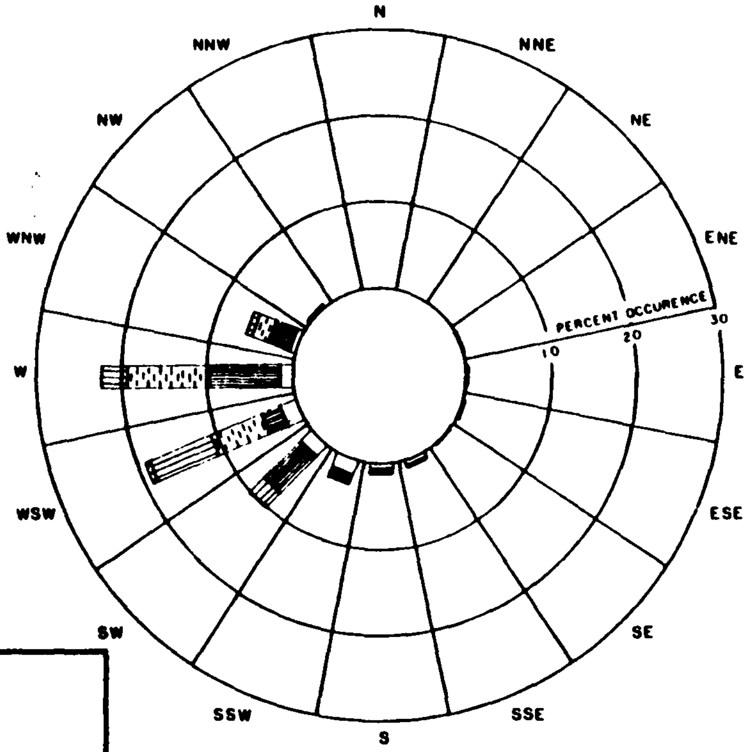


Figure 3

NEAR-SURFACE CURRENTS

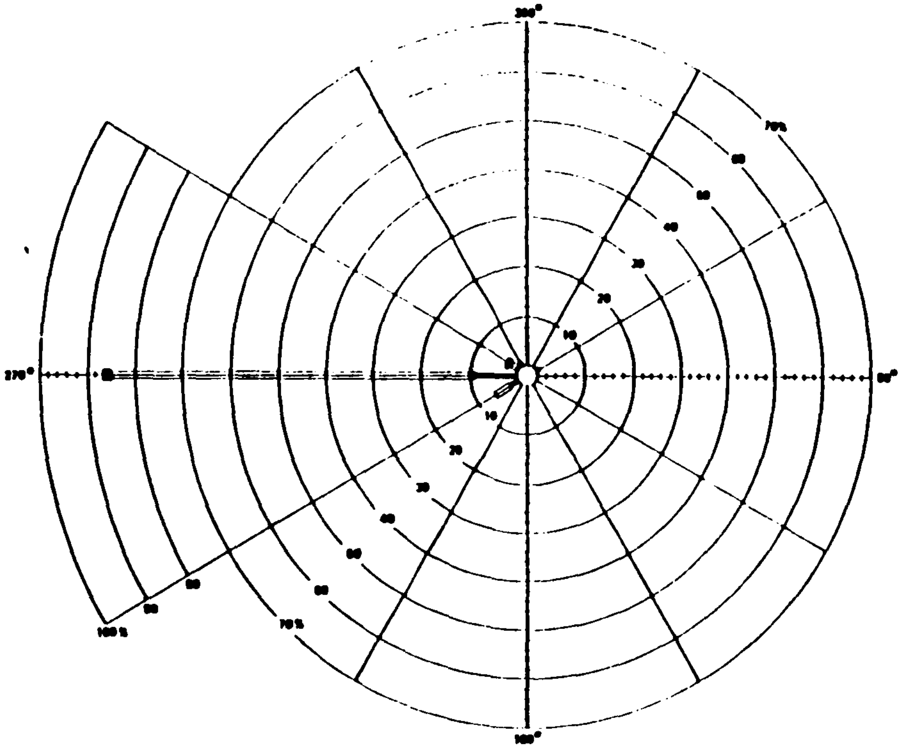


CURRENTS MEASURED
AT OS&T

KEY

☐ 0 TO 0.10 M/S
■ 0.11 TO 0.20 M/S
▤ 0.21 TO 0.30 M/S
▥ 0.31 TO 0.40 M/S
▩ 0.41 TO 0.50 M/S
■ >0.50 M/S

DATA FROM EXXON
PRODUCTION RESEARCH
CO.



CURRENTS MEASURED
AT PROPOSED PESCADO A SITE

KEY

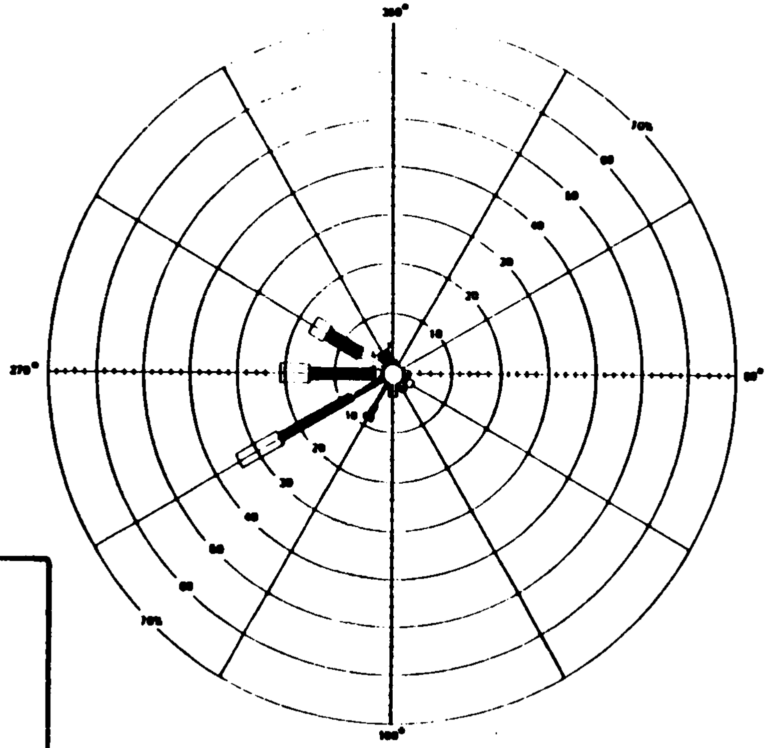
| 0 TO 0.10 M/S
▯ 0.11 TO 0.20 M/S
▮ 0.21 TO 0.30 M/S
☐ 0.31 TO 0.40 M/S

DATA FROM DAMES & MOORE.

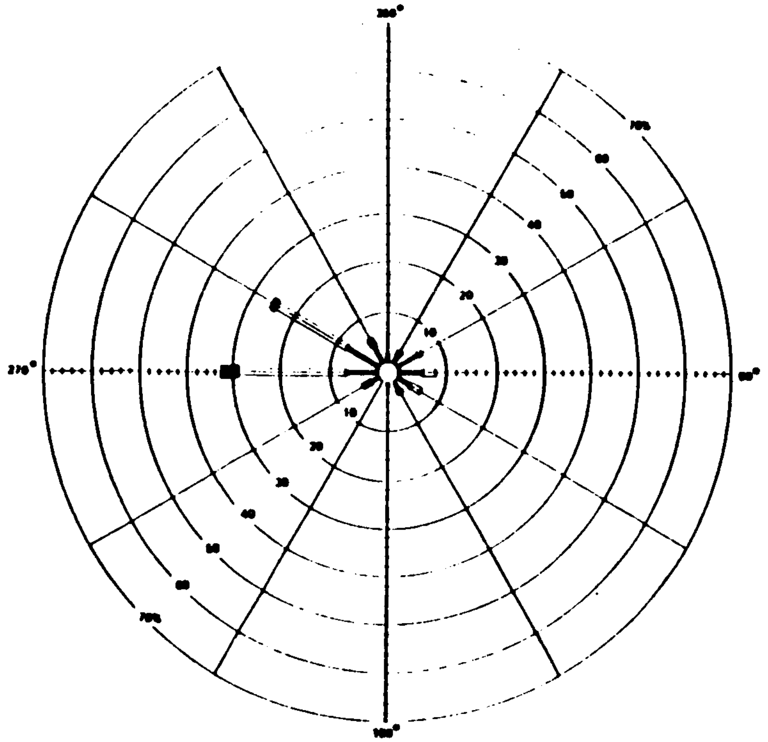
NOTE: 1. CURRENT METER LOCATIONS SHOWN
ON FIGURE 2.4-4.
2. DATA OBTAINED DURING JULY
AND AUGUST, 1981.

Figure 4

MID-WATER CURRENTS



CURRENTS MEASURED
AT PESCADO FIELD LOCATION

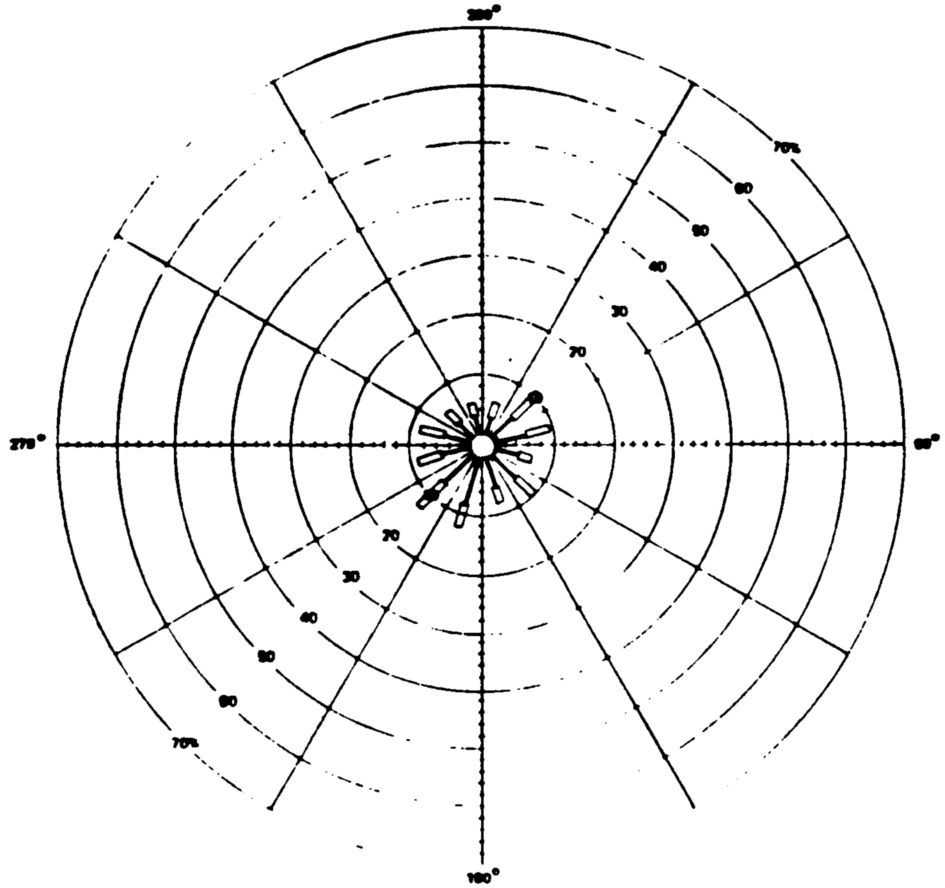


CURRENTS MEASURED
AT HONDO FIELD LOCATION

KEY

I	0 TO 0.10 M/S
▯	0.11 TO 0.20 M/S
█	0.21 TO 0.30 M/S
☐	0.31 TO 0.40 M/S

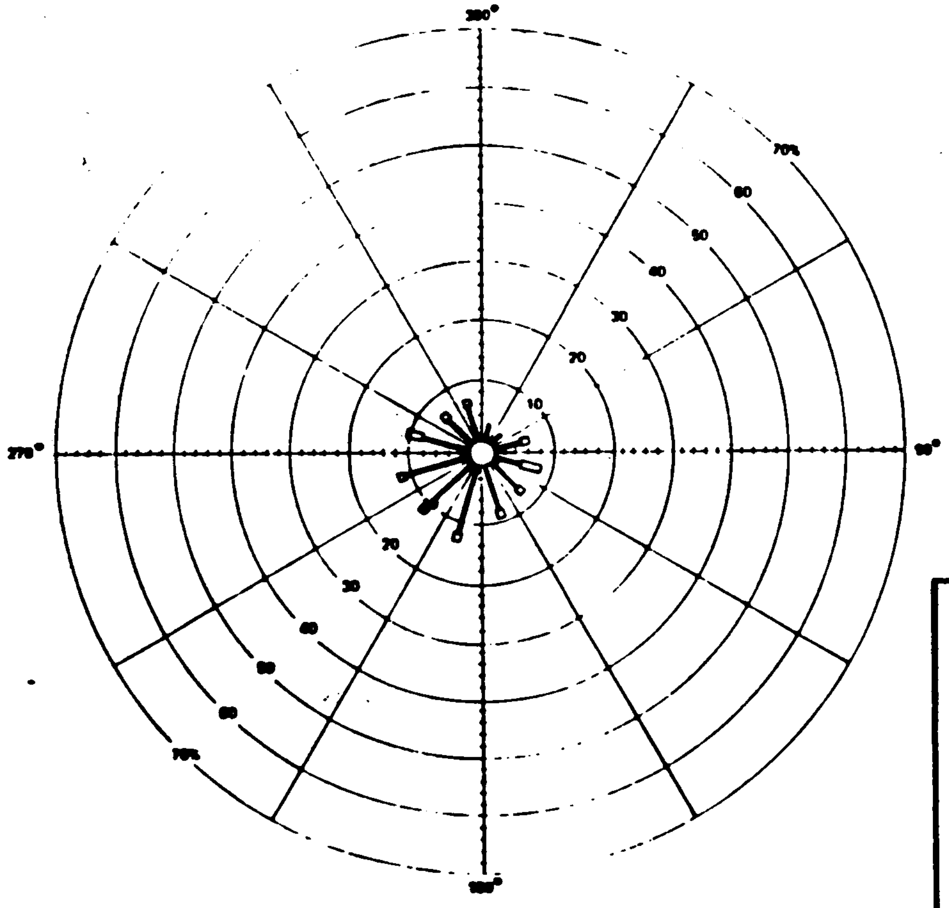
NOTE: 1. CURRENT METER LOCATIONS SHOWN ON FIGURE 2.4-4.
2. DATA WAS OBTAINED DURING JULY AND AUGUST, 1981 BY DAMES & MOORE.
3. 360° = MAGNETIC NORTH.



STATION C

KEY

❙	0 TO 0.10 M/S
▯	0.11 TO 0.20 M/S
▮	0.21 TO 0.30 M/S
□	0.31 TO 0.40 M/S



STATION F

NOTE: 1. CURRENT METER LOCATIONS SHO
FIGURE 2.4-4.
2. DATA OBTAINED DURING JULY AND
AUGUST, 1981 BY MESA^2 INC.
3. 360°= MAGNETIC NORTH.

Figure 5

BOTTOM CURRENTS

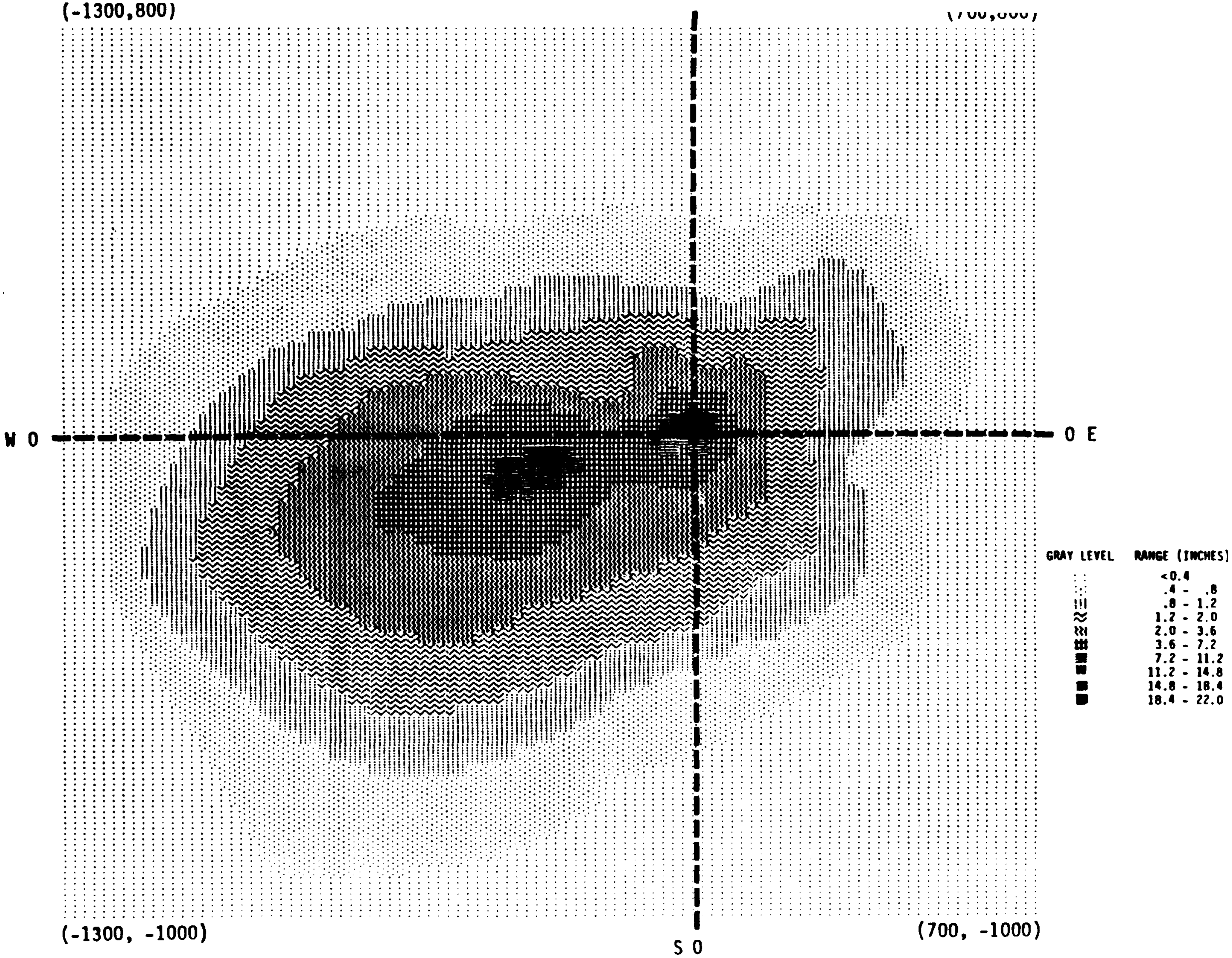


Figure 6 **PESCADO SITE: MEAN FLUX OF DRILL CUTTINGS IN INCHES PER YEAR**

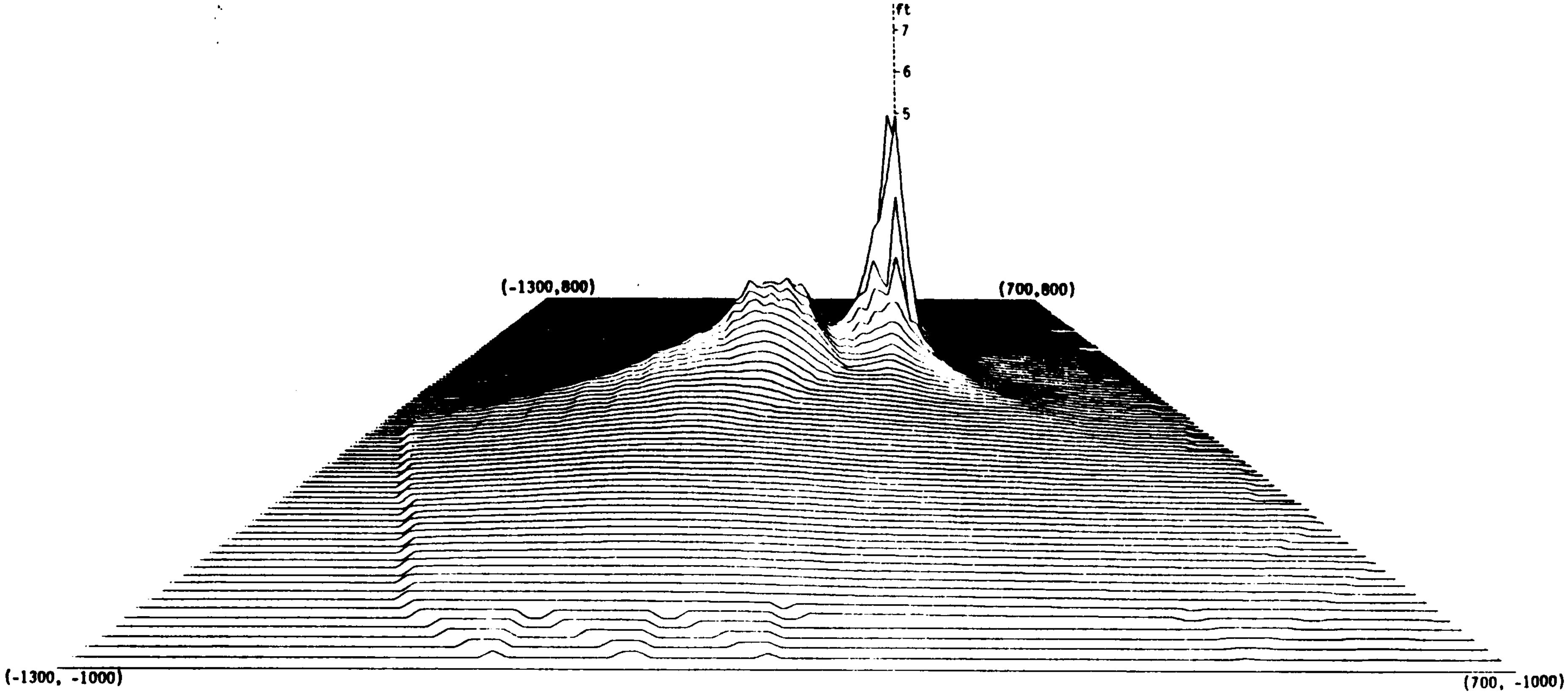


Figure 7

PESCADO SITE: TOTAL PRODUCTION DRILLING DEPOSITION (VIEW FROM THE SOUTH)

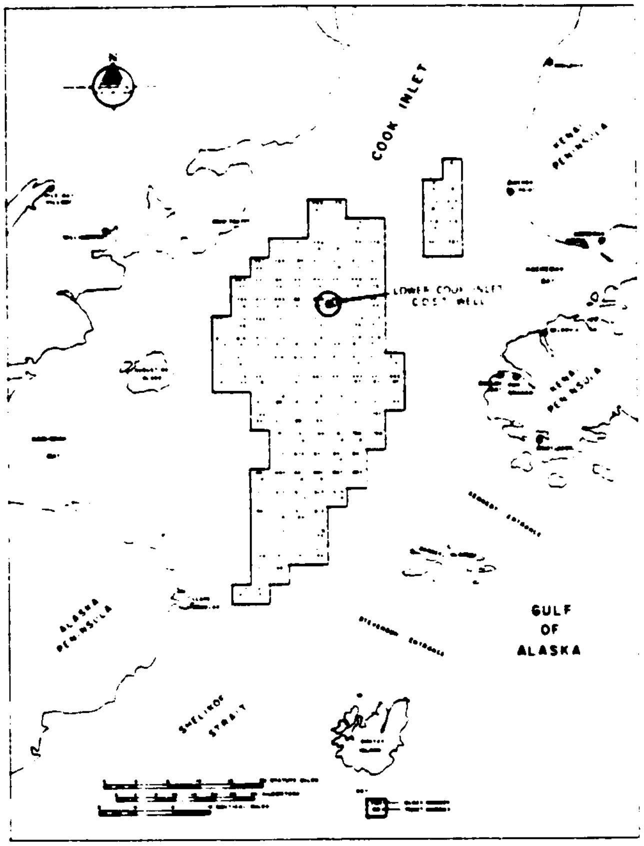


Figure 8 *Location map for the Lower Cook Inlet C.O.S.T. Well.*

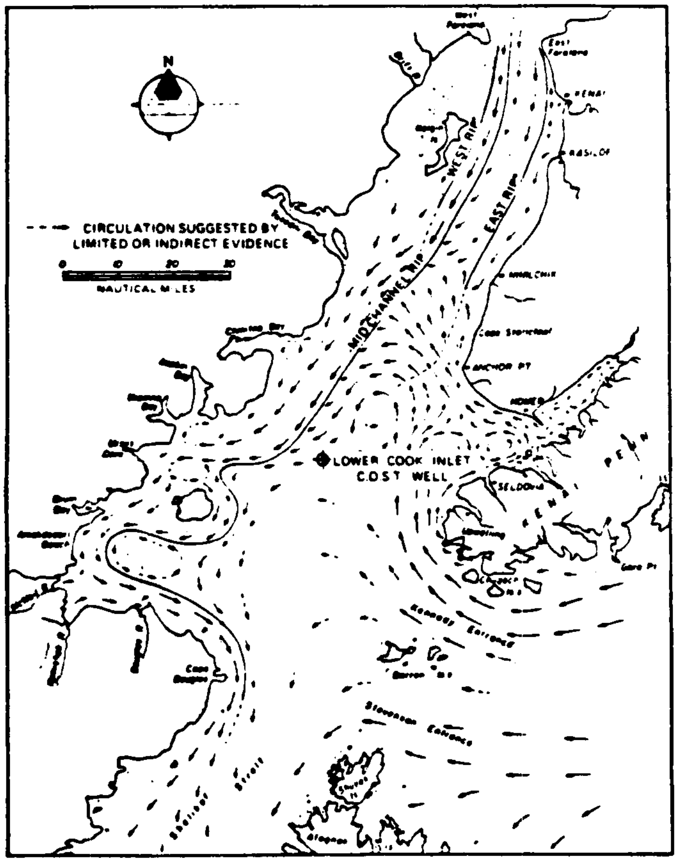
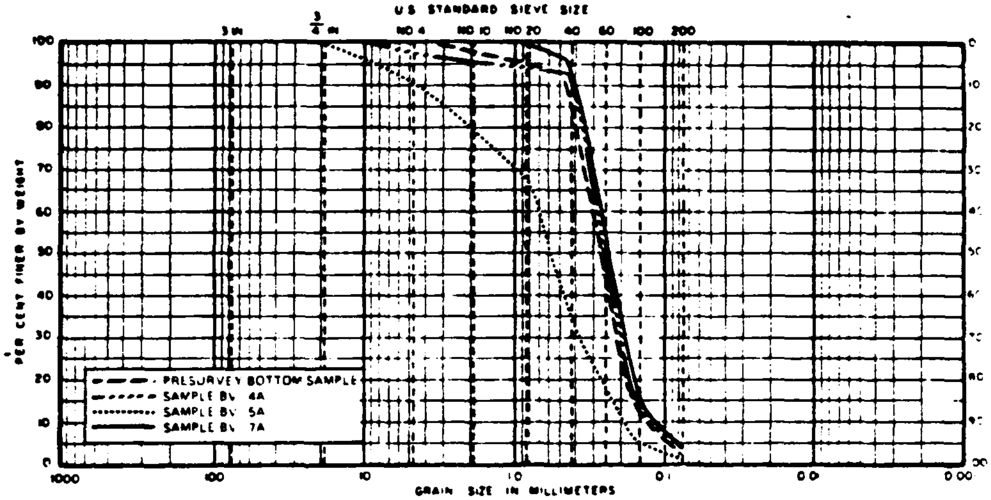


Figure 9 *Net circulation in Lower Cook Inlet (from Burbank, 1977).*



Grain size distributions for selected post-drilling bottom samples.

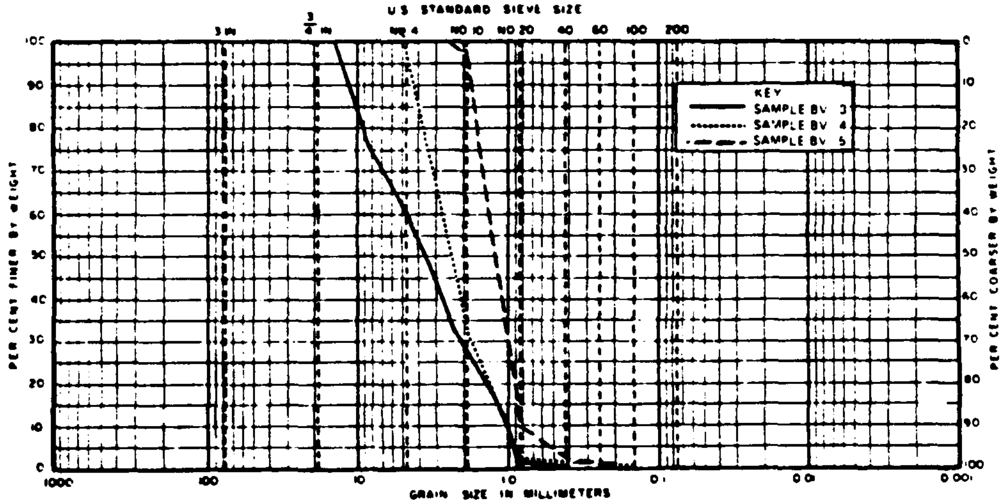
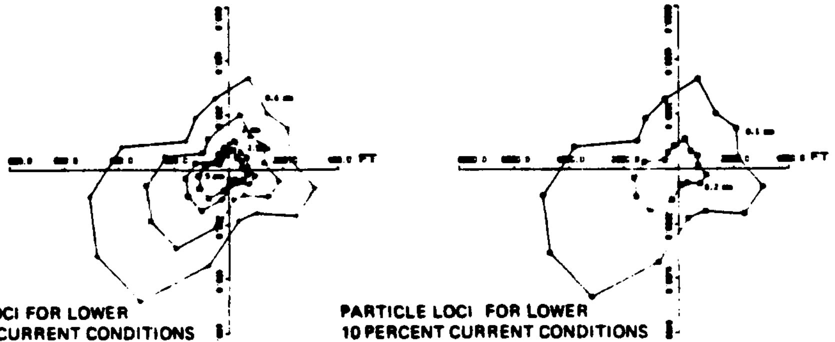
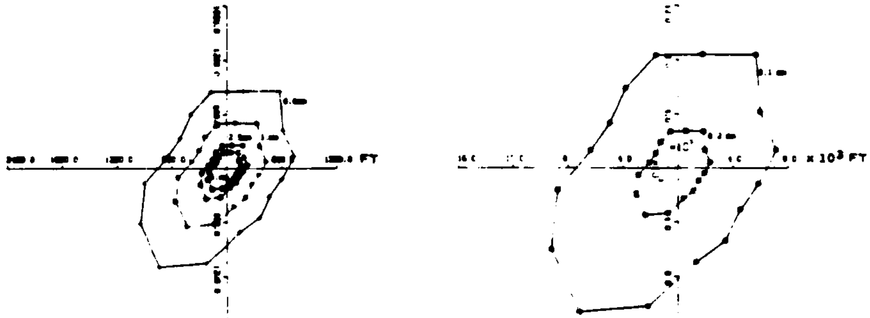


Figure 10 *Grain size distribution of cuttings (>0.85 mm) in selected Soutar-Van Veen cores.*



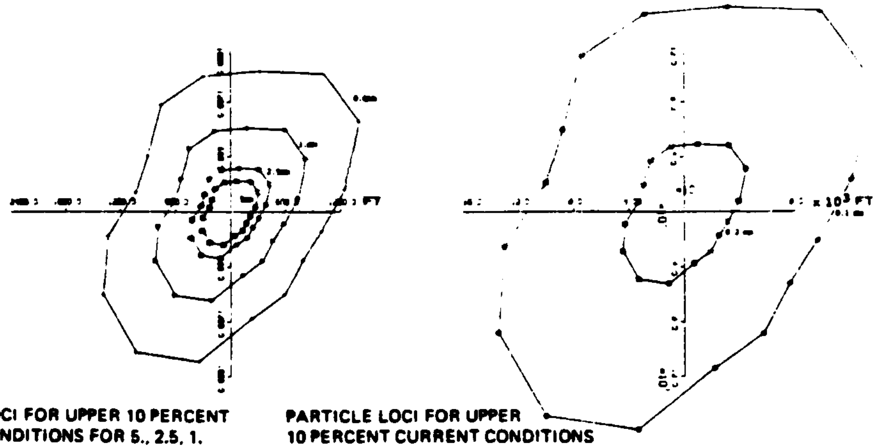
PARTICLE LOCI FOR LOWER 10 PERCENT CURRENT CONDITIONS FOR 5., 2.5, 1. AND 0.6 mm SIZED PARTICLES.

PARTICLE LOCI FOR LOWER 10 PERCENT CURRENT CONDITIONS FOR 0.2 and 0.1 mm SIZED PARTICLES.



PARTICLE LOCI FOR AVERAGE CURRENT CONDITIONS FOR 5., 2.5, 1. AND 0.6 mm SIZED PARTICLES.

PARTICLE LOCI FOR AVERAGE CURRENT CONDITIONS FOR 0.2 AND 0.1 mm SIZED PARTICLES.



PARTICLE LOCI FOR UPPER 10 PERCENT CURRENT CONDITIONS FOR 5., 2.5, 1. AND 0.6 mm SIZED PARTICLES.

PARTICLE LOCI FOR UPPER 10 PERCENT CURRENT CONDITIONS FOR 0.2 AND 0.1 mm PARTICLES.

Figure 11 *Prediction of cutting loci by cutting size.*

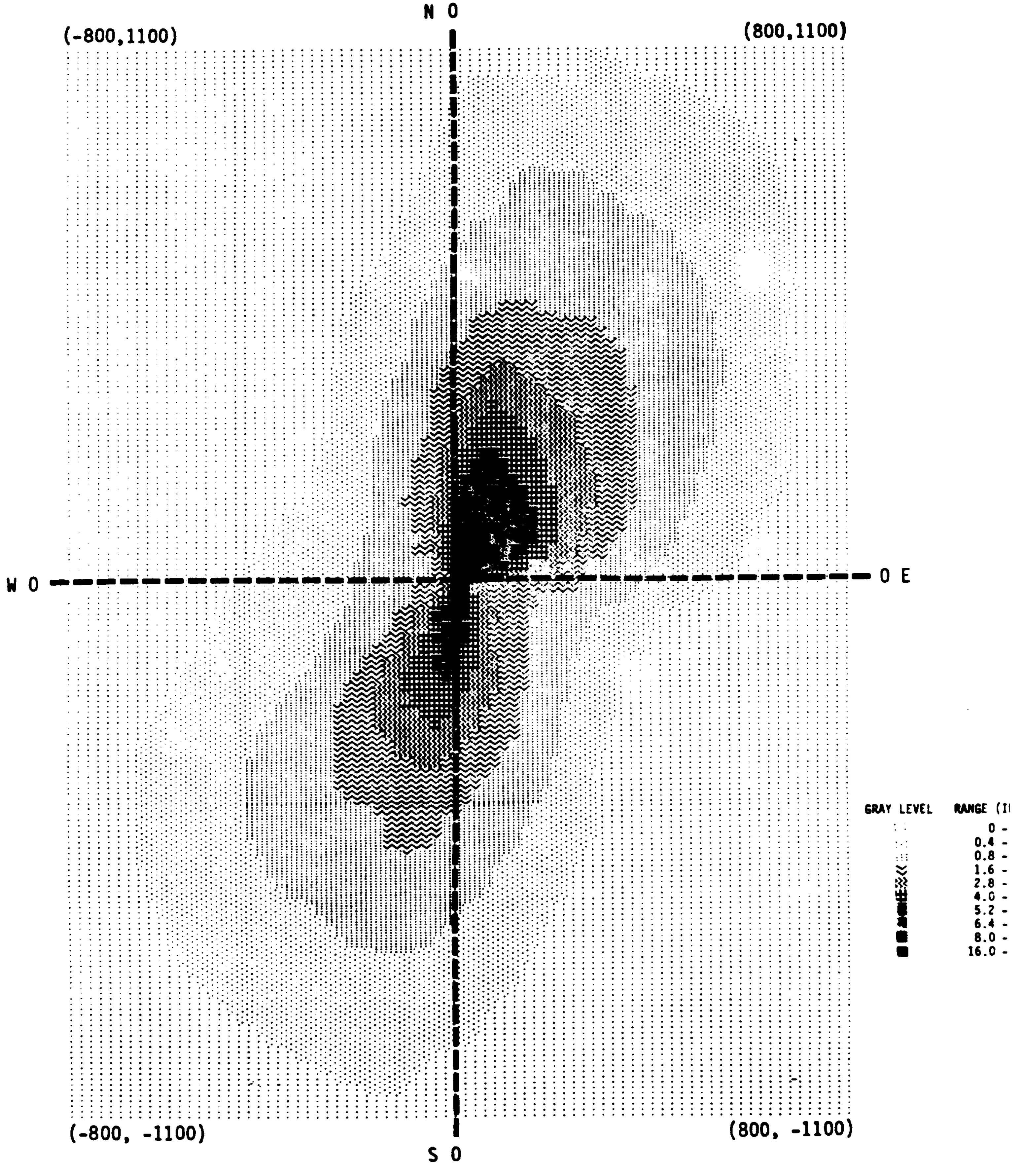


Figure 13 **LOWER COOK INLET SITE: MEAN FLUX OF DRILL CUTTINGS IN INCHES PER YEAR**

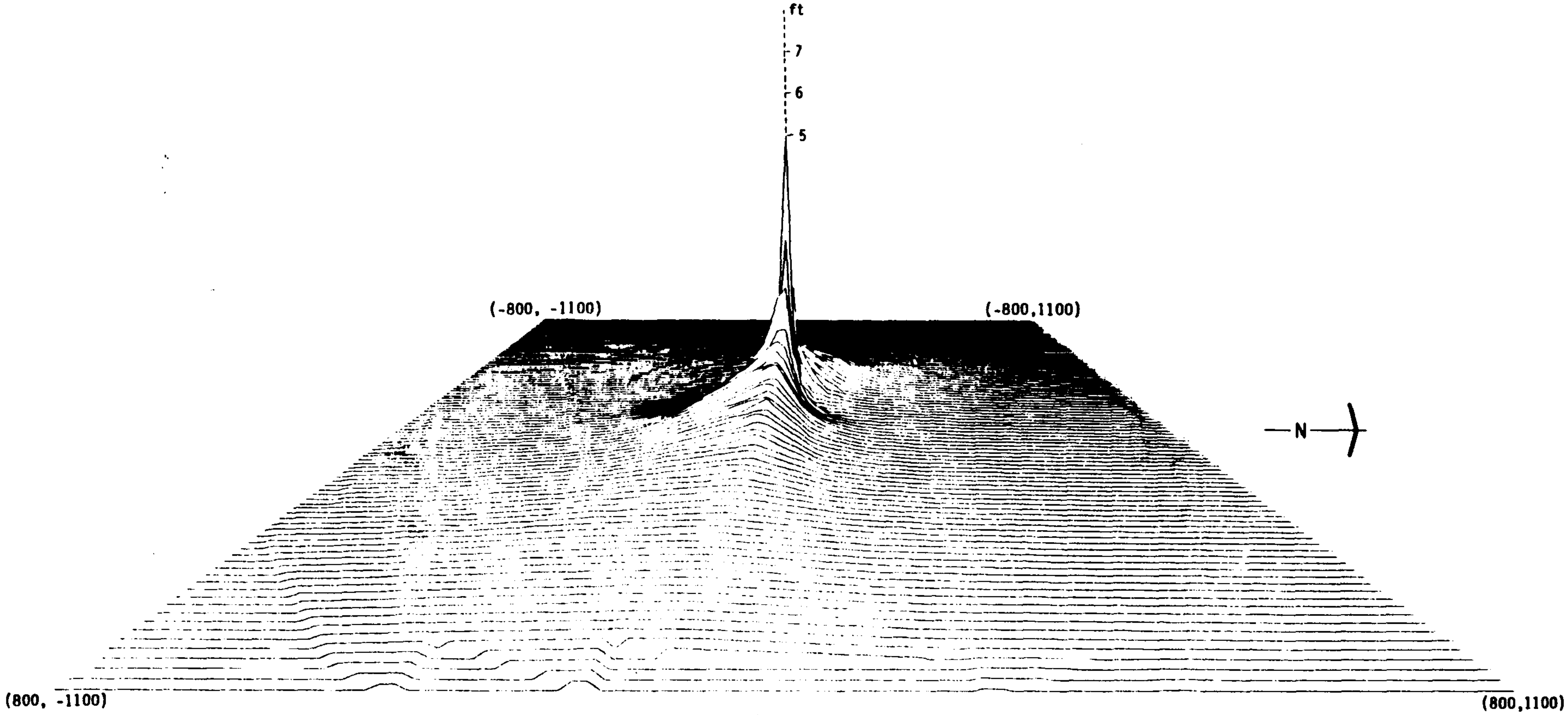


Figure 14

LOWER COOK INLET SITE: TOTAL PRODUCTION DRILLING DEPOSITION (VIEW FROM THE EAST)

4.5 The Formation Water Models: PDS/DKHPLM/OUTPLM/PLUME

by

Lorin R. Davis

THE FORMATION WATER MODELS: PDS/DKHPLM/OUTPLM/PLUME

There are several models that have been developed to predict the fate of buoyant jets that do not contain suspended particles. They include simple empirical expressions that approximate behavior using dimensionless parameters, integral models that solve the energy, momentum, and continuity equations by integrating over assumed velocity and concentration profiles, and complicated numerical models that divide the receiving body into a large number of grid points and solve the governing equations at each grid point assuming turbulent diffusion coefficients throughout the field. Integral models have been the most widely used because of their simplicity and relative accuracy in predicting the fate of the effluent. There are several integral computer models that have been developed to predict the fate of buoyant plumes that do not contain suspended solids. This paper presents four such models that have been accepted for use by the EPA.

PDS Surface Plume Model

The PDS model is a surface plume model that describes the fate of a buoyant discharge of a water at the surface of a receiving body. It was originally developed by Prych [1] and later modified and tuned by Shirazi and Davis [2]. It considers a rectangular discharge structure and an arbitrary angle of discharge relative to the ambient current. The model solves the three-dimensional momentum, energy and continuity equations using an integral method and superimposes jet and buoyant spreading. Buoyant spreading is a function of the plume local aspect ratio and density difference. The program calculates the plume trajectory, width, depth, excess temperature at the centerline of the plume and the enclosed area within surface isotherms. It also gives local average and centerline dilution and the time of travel from the discharge to the printout point.

The PDS model does not consider ambient stratification since it is assumed that the plume floats on the surface, is thin and that ambient density differences in this thin layer would be minor. It also assumes that the plume is not attached to the bottom. It the model is used for shallow receiving bodies, the predicted dilution will be too high. PDS can be used to approximate shore attached plumes using a method of images. Other boundary effects such as impingement with the far shore are not simulated.

PLUME Single Port Submerged Jet Model

The PLUME model considers a submerged buoyant jet issuing at an arbitrary angle into a stagnant, stratified environment [3,4]. Since ambient currents are not considered, the PLUME model is good for determining worst case conditions for plume dilution and maximum height of rise. It approximates the development zone near the discharge after which it is assumed that temperature and velocity profiles within the plume are similar and Gaussian in shape. It calculates the plume two-dimensional trajectory, local dilutions, and the trapping level if it exists. In addition to ambient currents, it also does not consider interaction with the free surface or other boundaries.

OUTLM Single Port Submerged Jet Model with Ambient Currents

The OUTPLM model is a single port submerged plume model that includes the effects of ambient currents and stratification [5]. It solves the momentum, energy, and continuity equations in an approximate manner assuming "top hat" profiles along the whole plume trajectory. It follows a fixed "puff" of effluent and determines its dilution and movement in a Lagrangian integration scheme. It has been found to predict the trajectory of the plume vary well, but it tends to over predict the dilution. Because of its simplicity, it can be used on small computers and has few computational difficulties.

DKHPLM Multiple Port Submerged Jet Model with Ambient Currents

The DKHPLM model considers the discharge of a single submerged jet or multiple port diffuser into a flowing stratified environment. It is an approach to the problem of merging plumes which considers the detailed dynamics of the process instead of simplifying the problem to an idealized slot plume or to a combination of single plume and slot plume. It considers three zones of plume behavior in detail; zones of flow establishment, single plume flow, and merging multiple plume flow. The first two zones are based on the analysis of Hirst [6] for a plume in a stratified, flowing environment. The model was modified by Davis [7] to include the merging zone. In this zone plumes are superimposed which allows for a smooth transition as single plumes begin to compete for dilution water and then merge with their neighbors. Three-dimensional equations for the conservation of mass, pollutant, energy, and momentum are developed for all three zones. Entrainment is an explicit function dependent on the local Froude number, plume spacing, excess velocity, and ambient velocity. Similar lateral profiles, a 3/2 power approximation of a

Gaussian profile are assumed. The model was tuned by Kannberg and Davis [8] so that it predicts trajectory, dilution, and trapping level fairly well.

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2. Shirazi, Mostafa A., and Davis, Lorin R., "Workbook of Thermal Plume Prediction: Volume 2, Surface Discharge," US EPA Report EPA-R2-72-005b, Pacific Northwest Environmental Research Laboratory, May 1974.
3. Baumgartner, D.J., and Trent, D.S., "Ocean Outfall Design: Part I. Literature Review and Theoretical Development," US Department of Interior, Federal Water Quality Adm. (NTIS No. PB-203 749).
4. Baumgartner, D.J., Trent, D.S., and Byram, K.V. "User's Guide and Documentation for Outfall Plume Model," US EPA Pacific Northwest Water Laboratory, 1971, (NTIS No. #PB 204-577/BA).
5. Winiarski, L.D., and Frick, W.E., "Cooling Tower Plume Model," US EPA Report EPA-600/3-76-100, Corvallis Environmental Research Laboratory, 1975.
6. Hirst, E.A., "Analysis of Round, Turbulent, Buoyant Jets Discharged into Flowing Stratified Ambients," US Atomic Energy Commission, Oak Ridge National Laboratory Report ORNL-4685, 1971, Oak Ridge, Tennessee.
7. Davis, L.R., "Analysis of Multiple Cell Mechanical Drift Cooling Towers," US EPA Corvallis Environmental Research Laboratory Report, EPA-660/3-75-039, 1975, Corvallis, Oregon.
8. Kannbers, L.D., and Davis, L.R., "An Experimental/Analytical Investigation of Deep Submerged Multiple Buoyant Jets," US EPA Corvallis Environmental Research Laboratory Report, EPA-600/3-76-001, 1976, Corvallis, Oregon.

5. CONTRIBUTED PAPERS ON OTHER MODELS AND RELATED METHODOLOGY

5.1 Modeling the Coagulation of a Solid Waste Discharge

by

F. T. Lovorn

MODELING THE COAGULATION OF A SOLID WASTE DISCHARGE

ABSTRACT[1]

Simple sedimentation tests using mixtures of seawater or freshwater and simulated tailings from a research-scale hydrometallurgical processing scheme show that the net vertical flux of the solids is greatly affected by the total solids concentration. The results of the tests, throughout much of the concentration range tested, are consistent with a model in which the flux rate is completely determined by simple second order coagulation of fine-grained solids. A comparison of results from a plume dispersion model incorporating coagulation processes indicates an important discharge scale effect. Because of the relationship of scale size to coagulation, settling rates estimated from relatively small scale field test observations may dramatically underestimate the settling rates for a full-scale operation.

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(1) Extracted from: MODELING THE COAGULATION OF A SOLID WASTE DISHCARGE FROM A MANGANESE NODULE PROCESSING PLANT, Charles L. Morgan and F. T. Lovorn In: Wastes in the Ocean, Volume V: Deep-Sea Waste Disposal, John Wiley & Sons, Inc. Publishers (In Press)

5.2 A Two-Dimensional Model for Estimating Impacts of Drilling Mud Discharges in Shallow Water

by

John Yearsley

A Two-Dimensional Model for Estimating Impacts of Drilling Mud Discharges in Shallow Water

John Yearsley, EPA Region 10

Introduction

This paper describes a method used to make estimates of solids distribution in a fluid containing several classes of particles. The model simulates the distribution of the various classes assuming that the important processes are horizontal advection, horizontal eddy diffusion, and sinking. The model ignores the dynamics of the convective descent and dynamic collapse phases of the plume and assumes that the discharge is well-mixed in the vicinity of the drilling platform.

Method

Brandsma et al (1980) have described a model for predicting the short term fate of drilling discharges in the marine environment. Their model, based upon earlier work by Koh and Chang (1973) has been used to simulate field test conditions in the Gulf of Mexico (Ayers et al., 1982) and the Arctic (Northern Technical Services, 1981). ECOMAR Inc (draft) has reported the preliminary results of mud dispersion study in Norton Sound in the Bering Sea, but do not describe any comparisons of model simulations and field studies.

The model developed by Brandsma et al. (1980) describes the behavior of drilling muds in terms of three phases: convective descent, dynamic collapse and passive diffusion. From the results of the testing performed in the Gulf of Mexico, Brandsma et al. (1980) concluded that the model produces a number of observed features of drilling mud discharges and that model development should continue. However, the reported applications have been in water depths greater than 20 meters. As the water depth decreases, it is likely that the effect of the bottom upon plume dynamics becomes more and more important. Given these limitations and the preliminary nature of the model, there has been little application of the model to discharges in shallow water. Under these circumstances a more simplified model seems appropriate so long as it includes the following:

1. Horizontal mixing
2. Advection by steady and tidally-varying currents
3. Settling of solids
4. Time-dependence of the discharge.

The following equations describe the mixing of i particles classes in a vertically well-mixed environment in which the horizontal mixing can be described by Fickian diffusion:

$$\frac{\partial C_i}{\partial t} + u\frac{\partial C_i}{\partial x} + v\frac{\partial C_i}{\partial y} = \frac{\partial}{\partial x}\left(K_x\frac{\partial C_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial C_i}{\partial y}\right) - \frac{w_i C_i}{D} + S(x,y,t) \qquad (1)$$

where,

C_i = Concentration of solid in the i^{th} phase, mg/l,

x = horizontal coordinate parallel to current direction, meters,

y = horizontal coordinate perendicular to current direction, meters,

t = time, seconds,

u = current speed in x-direction, meters/second,

v = current speed in y-direction, meters/second,

= 0 by the way in which the system of coordinates has been defined,

K_x = coefficient of eddy diffusivity in x-direction, meters^2/seconds,

K_y = coefficient of eddy diffusivity in y-direction, meters^2/second,

w_i = sinking rate for i^{th} particle class, meters/second,

D = water depth, meters,

$S(x,y,t)$ = strength of source, mg/l/second.

A finite difference scheme using an explicit formulation of the time-dependence was used to solve Equation (1).

Model Testing

Studies for comparing model simulations with field results are available for water depths of 12 meters (ECOMAR, Inc.; draft) and 23 meters (Ayers et al., 1982). The model was used to simulate conditions for each of the tests performed in the studies. The parameters for the simulations are given in Table 1 and the results are shown in Figures 1-3.

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Ayers, R.C. Jr., R.P. Meek, T.C. Sauer, Jr., and D.O. Stuebner. An environmental study to assess the effect of drilling fluids on water quality parameters during high-rate, high-volume discharges to the ocean. Journal of Petroleum Technology. 165-173. January 1982.

Brandsma, M.G., L.R. Davis, R.C. Ayers, Jr., and T.C. Sauer, Jr. A computer model to predict the short term fate of drilling discharges in the marine environment. Symposium on Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Proceedings: Volume I. pp 588-610. January 21-24, 1980

Koh, R.C.Y., and Y.C. Chang. Mathematical model for barged ocean disposal of wastes. U.S. Environmental Agency. EPA-660/2-73-029. 1973.

Northern technical Services. Beaufort Sea drilling effluent disposal study. Prepared for the Reindeer Island stratigraphic test well participants. 329 pp. April 1981.

Table 1. Oceanographic and discharge parameters used to simulate conditions of various drilling mud dispersion studies.

	Norton Sound COST Well	Gulf of Mexico Test A	Gulf of Mexico Test B
Discharge Rate (meters**3/sec)	0.047	0.011	0.044
Initial Concentration (mg/l)	302000	1430000	1430000
Discharge Period (minutes)	62	54	23
Water Depth (meters)	12	23	23
Current Speed (meters/sec)	0.30	0.15	0.12
Coefficient of Eddy Diffusivity (meters**2/sec)	0.21	0.21	0.21

Table 2. Settling velocity and composition of components for drilling mud used in analysis of permit conditions.

	Particle Class					
	1	2	3	4	5	6
Settling Velocity (cm/sec)	0.657	0.208	0.0849	0.0437	0.0231	0.0130
% Volume	0.10	0.10	0.12	0.20	0.38	0.10

FIGURE 1. COMPARISON OF SIMULATED AND OBSERVED SUSPENDED SOLIDS - GULF OF MEXICO MUD DISPERSION STUDY - LOW DISCHARGE

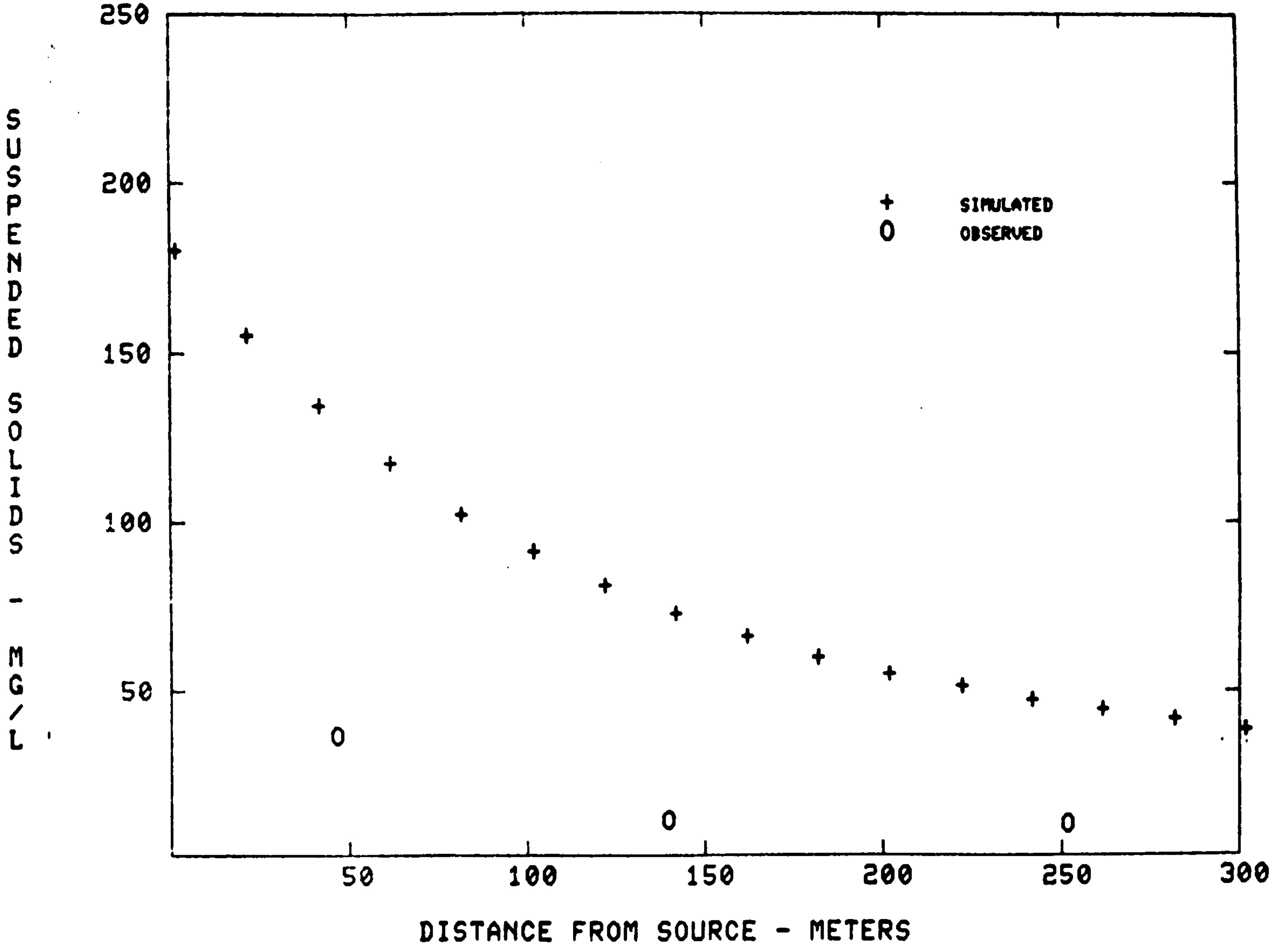


FIGURE 2. COMPARISON OF SIMULATED AND OBSERVED SUSPENDED SOLIDS - GULF OF MEXICO MUD DISPERSION STUDY - HIGH DISCHARGE

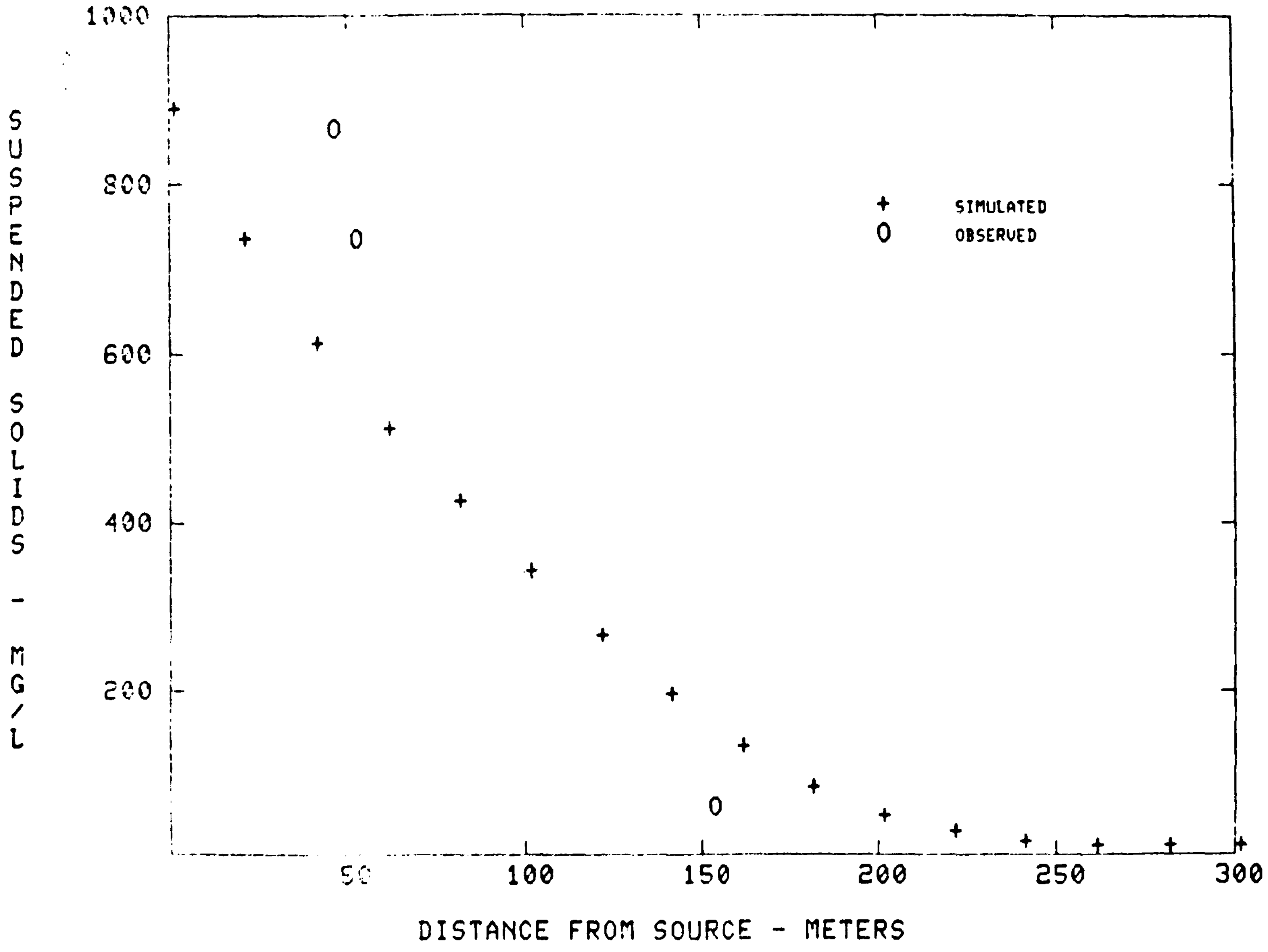
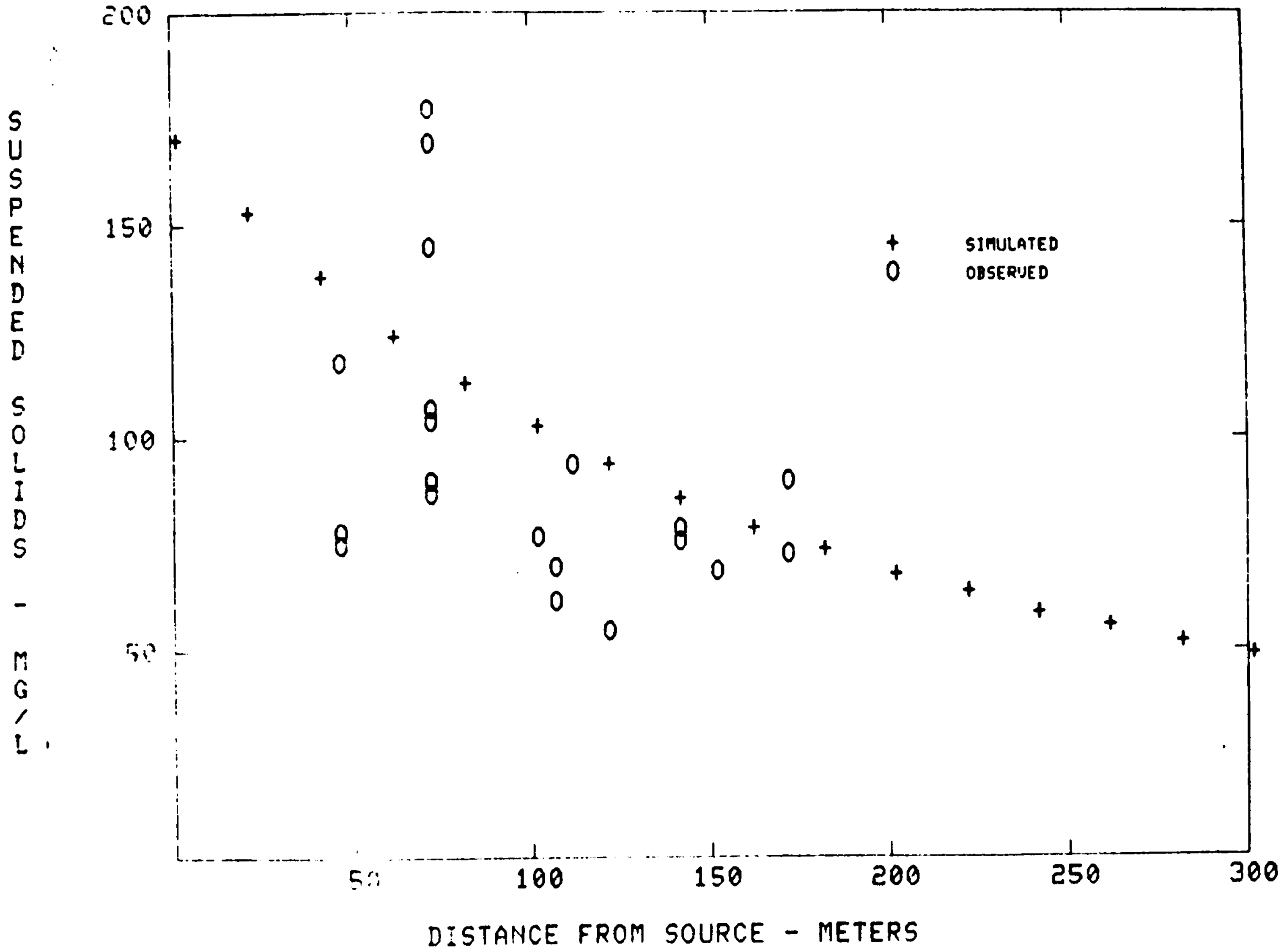


FIGURE 3. COMPARISON OF SIMULATED AND OBSERVED SUSPENDED SOLIDS - NORTON SOUND COST WELL MUD DISPERSION STUDY



5.3 Long-Term Simulation of Sediment and Contaminant Transport

by

Y. Onishi and D. S. Trent

LONG-TERM SIMULATION OF SEDIMENT AND CONTAMINANT TRANSPORT

Y. Onishi and D. S. Trent
Pacific Northwest Laboratory, Richland, Washington

INTRODUCTION

The recent decision by the U.S. Department of Interior to expand and accelerate the leasing of offshore land for oil and gas operations imposes the further need to assess the impact of these operations. To evaluate the potential adverse impact of drilling mud and cuttings in a receiving water body, the short- and long-term migration and fate of sediment and contaminants must be determined. The distribution of contaminants in surface waters is controlled by four distinct transport/transformation processes subject to different source conditions of drilling mud and cuttings:

- Transport
  - Water movement
    - a. Discharge-induced advection and dispersion
    - b. Ambient advection and dispersion
  - Sediment movement
  - Bioturbation
- Intermedia transfer
  - Adsorption/desorption
  - Precipitation/dissolution
  - Volatilization (if any)
- Degradation
  - Chemical degradation
  - Biological degradation
- Transformation
  - Yield of degradation product (if any)

One of the most important needs for understanding the long-term migration of drilling mud and cuttings is accurate simulation of sediment transport and its effects on contaminant migration.

We have developed and applied four unsteady sediment-contaminant (both dissolved and particulate contaminants) transport models that incorporate sediment-contaminant interactions such as adsorption/desorption, and transport, deposition and resuspension of sediment and thus also sediment-sorbed contaminants. These four models are: the one-dimensional model TODAM (Onishi et al. 1982); the two-dimensional models FETRA (lateral and longitudinal) (Onishi 1981) and SERATRA (vertical and longitudinal) (Onishi et al. 1980); and the three-dimensional model FLESCOT (Onishi and Trent 1982). Although often applied to determining transport of radionuclides, these models are equally applicable and have been applied to pesticides, heavy metals, and other toxic chemicals.

All of these models calculate time-varying distributions of sediments for each sediment size fraction or type (e.g., sand, silt, clay, or organic matter), dissolved contaminant, and particulate contaminant adsorbed by sediments. They also predict changes in bed conditions including bed elevation changes due to sediment erosion and/or deposition, bed sediment size distribution changes, and particulate contaminant distributions within the bed.

Because two- or three-dimensional models are required to simulate the long-term (far-field) migration of drilling mud and cuttings in coastal waters, we will discuss the FLESCOT and FETRA models here.

FLESCOT MODEL

MODEL DESCRIPTION

Because of the importance of vertical distributions of velocity and density distributions and lateral flow circulation to estuarine, coastal and ocean waters, and consequently sediment and contaminant migration, the unsteady, three-dimensional, finite difference model FLESCOT was synthesized. FLESCOT predicts distributions of flow, water temperature, salinity, sediments and contaminants coupled to include their interactions. Equations governing fluid motion and transport of thermal energy, salinity, sediment and contaminants used in FLESCOT are based on the following conservation principles:

- conservation of mass for fluid (Continuity Equation)
- conservation of momentum (Navier-Stokes equations)
- conservation of energy (First Law of Thermodynamics)
- conservation of mass for salinity
- conservation of mass for sediment
- conservation of mass for a dissolved contaminant
- conservation of mass for a particulate contaminant.

In addition, the Equation of State is used to define the fluid density depending on temperature, salinity and if necessary a sediment concentration.

The FLESCOT model can be used possibly with minor modifications to simulate the long-term (far-field) migration and fate of drilling mud and cuttings, as well as their short-term, near-field behavior affected by complex phenomena, such as a negative density jet of drilling mud, entrainment of ambient flow to the drilling mud effluent inside and outside of the discharge pipe, stratification of the ambient flow, and wake behind a platform.

MODEL APPLICATION

FLESCOT was tested first with simple cases to examine the basic validity of its code which allows the use of variable size computational cells with large aspect ratios (e.g., $\Delta x:\Delta y:\Delta z$ = 10000:300:1). FLESCOT was then applied to a 106-km reach of the Hudson River between Chelsea (River Kilometer 106 or Mile Point 66) and the mouth of the river, as shown in Figure 1 (Onishi and

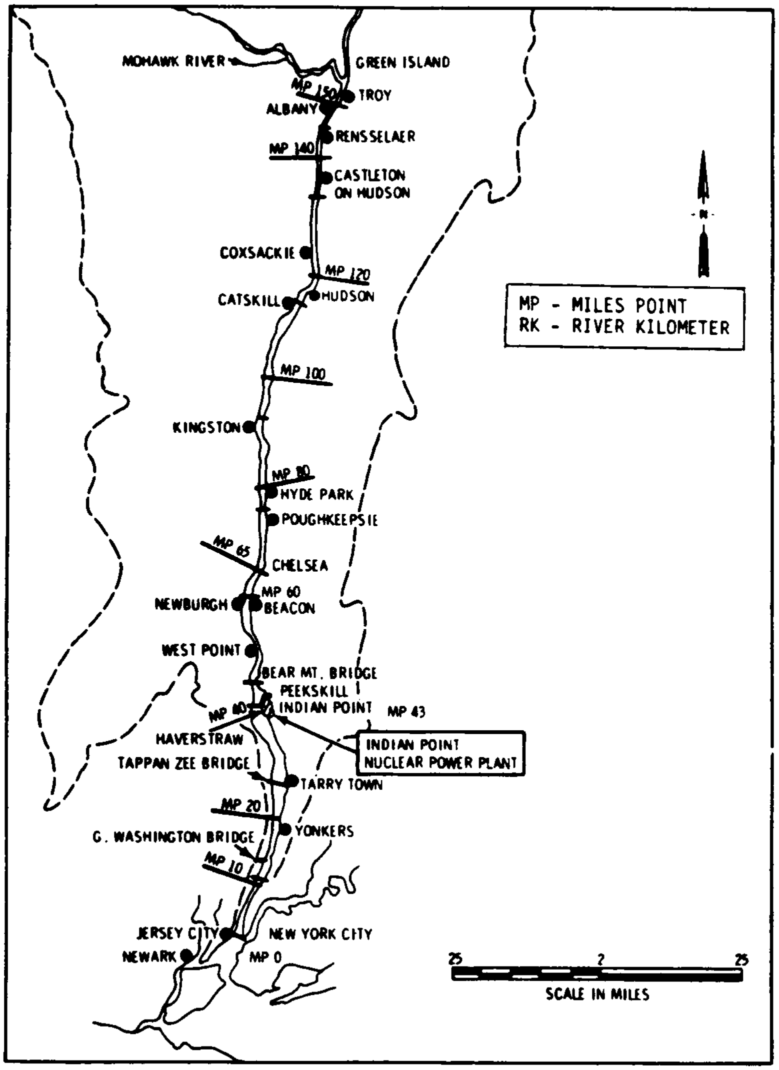


FIGURE 1. Hudson River Estuary

Trent 1982). In this case, FLESCOT predicted distributions of tidally varying flow, salinity, and concentrations of sand, silt, clay, dissolved ^{137}Cs, and particulate ^{137}Cs adsorbed by sand, silt and clay in a water column as well as river bed conditions including bed elevation change, bed sediment size distributions and distributions of particulate ^{137}Cs adsorbed by bed sediments (i.e., sand, silt, and clay) within the bed.

FLESCOT can use 1) different contaminant distribution coefficients, Kd, for each sediment size fraction; 2) different Kd for adsorption and desorption; and 3) Kd as a function of salinity. In the Hudson River application, for each sediment size fraction, two Kd values were assigned, one for adsorption and the other for desorption. Moreover, these two Kd values changed at every location and time step as a function of salinity (Jinks and Wrenn 1975).

According to the model prediction, most of the suspended sediment in the area is silt. Also the clay distribution is almost completely vertically uniform due to its very small fall velocity, while sand has a very steep vertical distribution. Comparison of computed and measured sediment concentrations (total sediment) along 1200 m from the east bank (close to the main channel) at the 40th simulation day indicates a reasonable agreement, as shown in Figure 2.

Comparisons of predicted, dissolved, particulate and total ^{137}Cs in a water column after 40.5 days of simulation with measured data (Wrenn et al. 1972) at 5 meters below the water surface along the longitudinal direction close to the main channel of the Hudson River estuary are shown in Figure 3. Although there are some discrepancies, considering the uncertainty of input data, we judged the agreements to be fairly good. According to the model results, bed conditions of sediments and particulate ^{137}Cs did not change appreciably during the over 40-day simulation period.

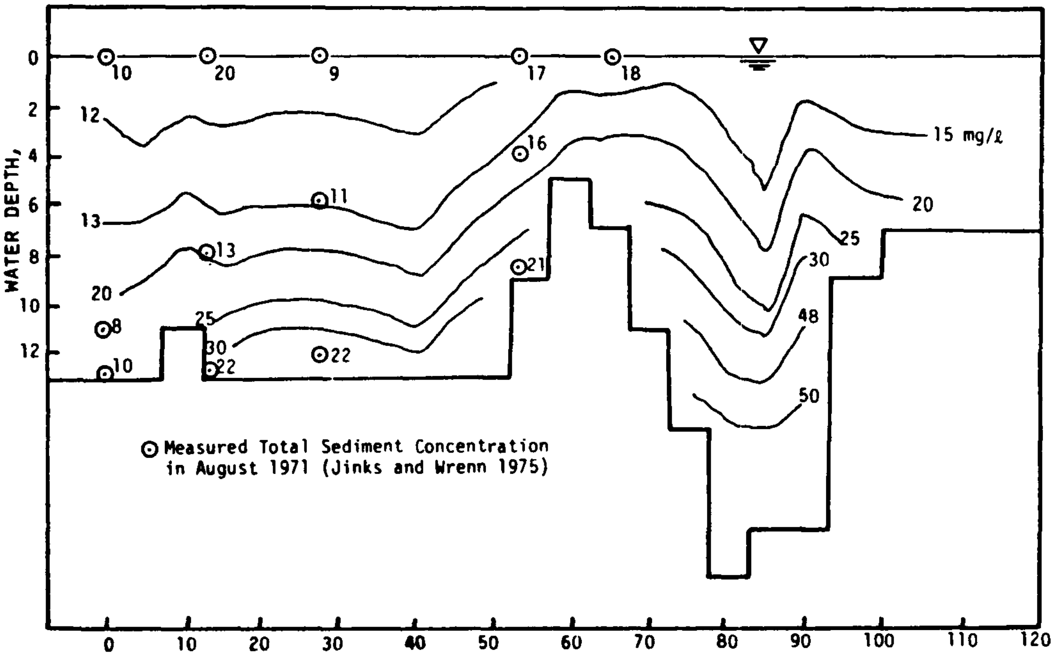


FIGURE 2. Comparison of Computed and Measured Total Sediment the Longitudinal Direction 1200 m from the East Bank (close to the main channel)

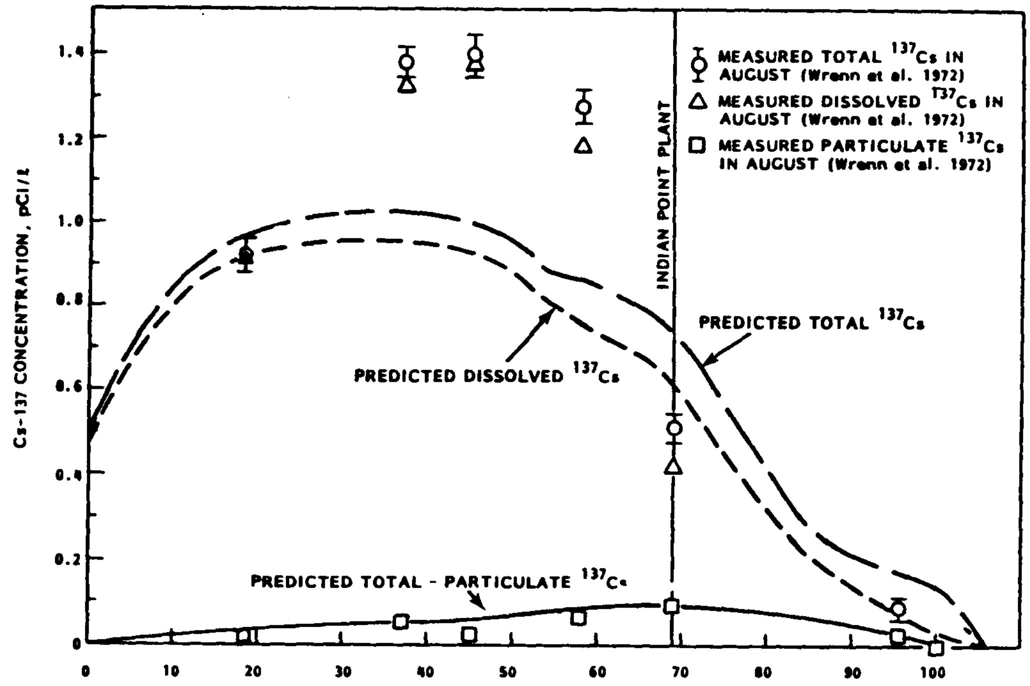


FIGURE 3. Predicted and Measured ^{137}Cs Distributions Along 1200 m from the East Bank (close to the main channel) Five Meters Below Water Surface

FETRA MODEL

MODEL DESCRIPTION

The sediment-contaminant transport model, FETRA, consists of three submodels that were coupled to account for sediment/contaminant interactions. The submodels simulate 1) sediment transport, 2) dissolved contaminant transport, and 3) particulate contaminant transport. (Particulate contaminants are those contaminants adsorbed by sediments.)

Sediment Transport Submodel

Similar to the FLESCOT model, sediment movements and particulate contaminant transport are modeled separately for three sediment size fractions or sediment types. The sediment transport submodel includes the mechanisms of: 1) advection and dispersion of sediments, 2) fall velocity and cohesiveness, 3) wave effects to suspend sediments, 4) deposition on the sea- or river-bed, 5) erosion from the bed (bed erosion and armoring), and 6) sediment contributions from point/nonpoint sources, and subsequent mixing. This submodel also calculates changes in bed conditions, including bed elevation changes due to scouring or deposition, or both, and gives a three-dimensional distribution of sediment sizes within the bed.

To estimate the rates of erosion and deposition of cohesive sediment (e.g., silt, clay, and possibly organic matter), as a part of a sink/source term in the governing equation of the sediment transport, FETRA uses the Partheniades (1962) and Krone (1962) formulas.

For the noncohesive sediment (e.g., sand), the following concept was used in FETRA: If the amount of sand being transported is less than the flow can carry for given hydrodynamic conditions, the flow is assumed to scour sediment from the bed, thus increasing the sediment transport rate. This process occurs until the actual sediment transport rate becomes equal to the carrying capacity of the flow or until all the available bed sediments are scoured, whichever occurs first. The availability of the bed sediment includes the consideration of effects of bed armoring, which FETRA also simulates. Conversely, the flow was assumed to deposit sand if its actual sediment transport rate is above its capacity to carry sediment. When the wave effects to suspend the sediment are not considered (say in rivers and possibly some estuarine cases), DuBay's formula (Vanoni 1975) is used to estimate the total sediment transport capacity, which is then compared with the actual sediment transport rate to determine the erosion and deposition rates. However, when waves are present, wave motion is assumed to be a dominant mechanism to suspend the sediment (say in coastal waters and large lakes). In this case, instead of DuBay's formula, FETRA uses the wave-sediment formulas developed by Liang and Wang (1973) for offshore zones, and by Komar (1977) for surf zones. FETRA can either generate the wave characteristics internally based on local wind conditions, or accept them as input data.

Dissolved Contaminant Transport Submodel

Dissolved contaminants interact both with sediments in motion (suspended and bed-load sediments) and with stationary sediments in the sea- or riverbed. To account for these interactions, this submodel includes the mechanisms of 1) advection and dispersion of dissolved contaminants; 2) adsorption of dissolved contaminants by both moving and stationary sediments or desorption from the sediments into water; 3) chemical and biological degradation, or radionuclide decay of contaminants (if applicable); and 4) contaminant contribution from point/nonpoint sources, and subsequent mixing.

Particulate Contaminant Transport Submodel

The transport of sediment-attached contaminants is solved separately for each sediment size fraction. This submodel includes the mechanisms of 1) advection and dispersion of particulate contaminants; 2) adsorption/desorption of dissolved contaminants with sediment; 3) chemical and biological degradation, or radionuclide decay of contaminants (if applicable); 4) deposition of particulate contaminants on the bed or erosion from the bed; and 5) contaminant contribution from point/nonpoint sources and subsequent mixing. The three-dimensional distribution of the particulate contaminant within the bed is also computed, as mentioned earlier.

MODEL APPLICATIONS

FETRA is suitable for application to estuaries, coastal waters, and large lakes (e.g., the Great Lakes) where the wave mechanism to suspend the sediment may become important. FETRA, together with the hydrodynamic model CAFE-II (Wang and Connor 1975), and the wave refraction model LO3D (Ecker and Degraca 1974), was applied to a coastal water to simulate contaminant migration and accumulation. The model is currently being applied to predict migration and accumulation of radionuclides in the Irish Sea.

In this paper we will discuss briefly the application of the model to the James River estuary (Virginia) to predict the migration of a pesticide, Kepone, and to determine the effectiveness of proposed cleanup activities. From 1966 to 1975, a highly chlorinated pesticide, Kepone, was discharged to the environment around Hopewell, Virginia. Much of the Kepone that reached the James River estuary was adsorbed by river sediment and has remained in the river-bed (U.S. EPA 1978). To assess the situation and determine how the river can be cleaned, the FETRA model was applied to an 86-km river reach between Bailey and Burwell Bays (Figure 4). In this case, FETRA simulated movements of seven substances: sand, cohesive sediment (i.e., silt and clay), organic matter, dissolved Kepone and particulate Kepone adsorbed by these three sediment groups, under tidal flow conditions.

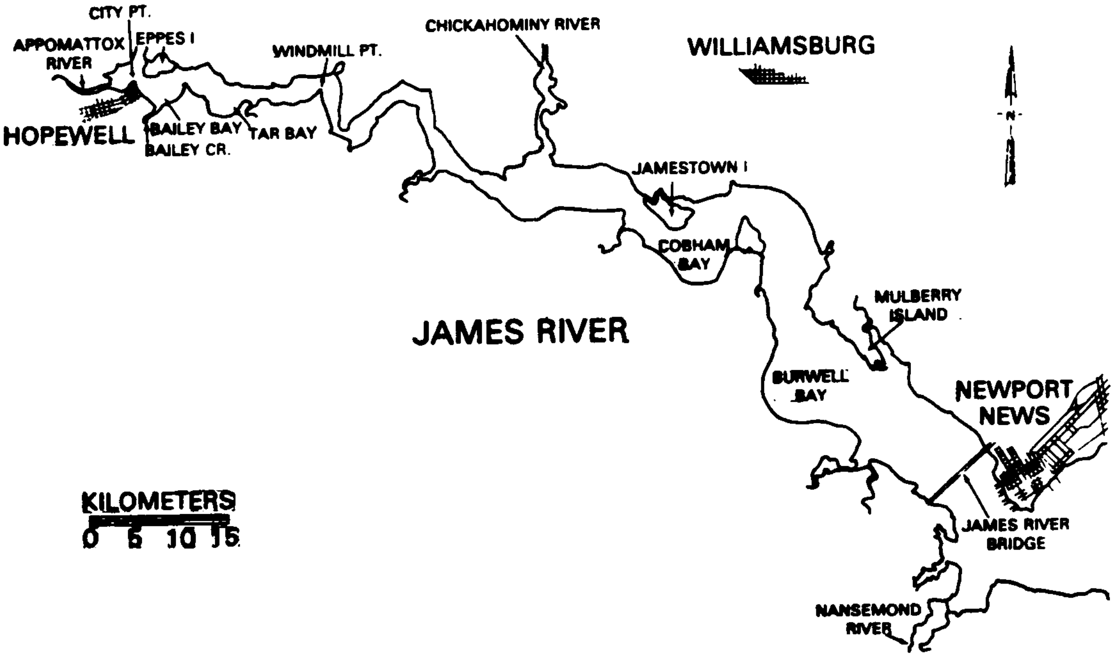


FIGURE 4. James River Estuary

The model was calibrated for the net freshwater discharge of 58.3 m^3/s (2050 cfs) and verified for the net mean-annual freshwater discharge of 247 m^3/s (8700 cfs). Verification results of sediment transport modeling are shown in Figure 5, presenting predicted concentrations of sand, cohesive sediment, organic matter and total sediment, together with measured total sediment concentrations. Comparison of predicted and measured sediment concentrations show a good agreement.

Since the contaminated bed sediment is the major source of long-term Kepone contamination through resuspension and/or desorption, it is important to know how Kepone contamination changes with time. Figure 6 shows that the predicted change in Kepone concentrations on the very surface of the bed occurred during the 1-month simulation under tidally varying flow with the net freshwater discharge of 247 m^3/s (8700 cfs). A trend is evident, with decreasing Kepone levels in the upper reach of the estuary due to combinations of burial effects of contaminated sediment by cleaner sediment from upriver and a net seaward movement of contaminated sediment, and increasing levels in the lower reach of the river with time due primarily to the net seaward movement of contaminated sediment. Although this trend is clear, the movement of Kepone toward Chesapeake Bay (seaward) was very slow.

To determine the optimal locations for Kepone removal operations (e.g., dredging) and the effectiveness of such cleanup activities, the potential Kepone cleanup locations (referred to as Cases A through J) were selected for

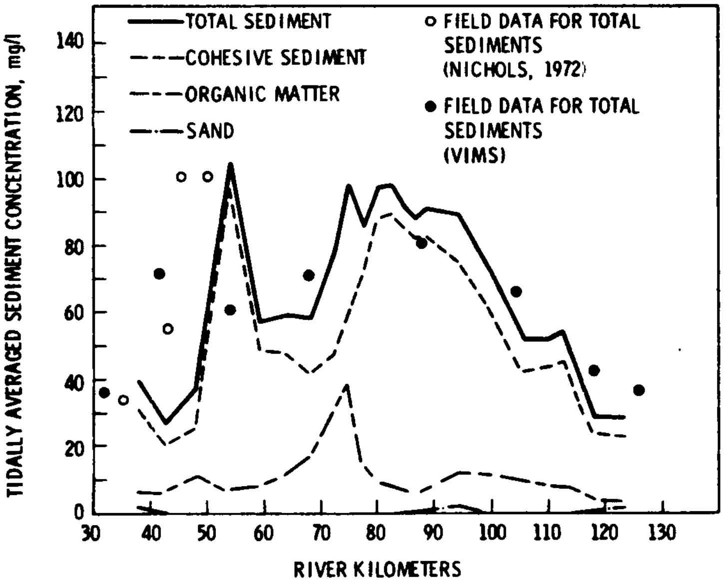


FIGURE 5. Predicted Tidally Averaged Sediment Concentration of Each Sediment Type for the Net Freshwater Input Discharge of 247 m^3/sec

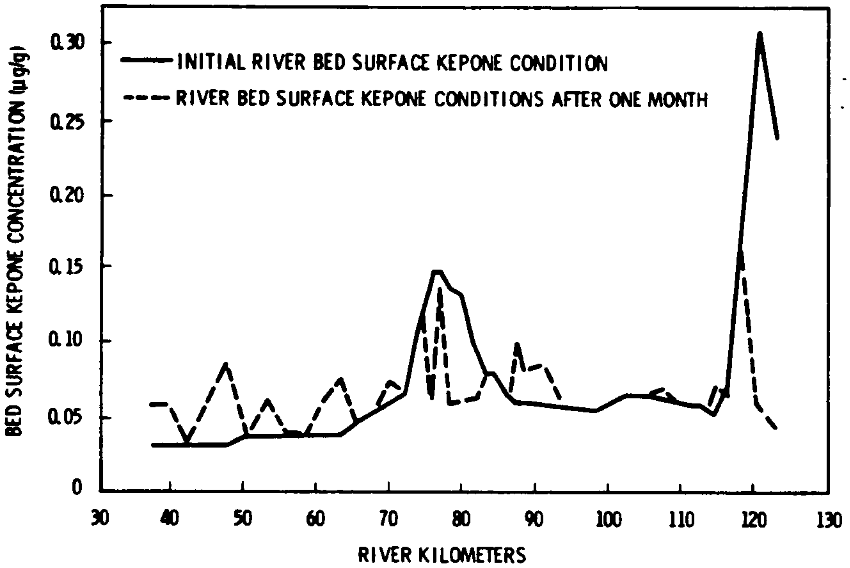


FIGURE 6. Predicted Change in Bed Surface Kepone Concentration that Occurred During 1-Month Simulation for the Net Freshwater Discharge of 247 m^3/s

further testing. These cleanup locations are shown in the lower portions of Figures 7, 8, and 9. Sediment and Kepone migration under the tidal flow with the net freshwater discharge of 247 m^3/s (8700 cfs) were then simulated for Cases A through J on the assumption that Kepone was initially removed from the river bed at the corresponding reaches of the James River estuary. Comparisons of resulting predicted particulate, dissolved and total Kepone concentrations in the water column after one-month simulation are shown in Figures 7, 8, and 9, together with the base-line case without a cleanup activity (Case 1).

Of the ten cases reviewed, Cases D and E show the most significant reduction of Kepone concentrations--up to 55% and 48%, respectively--especially in the middle reaches of the estuary. It should be noted that the major reductions in Kepone concentrations are manifested in the middle of the river. However, predicted Kepone reductions in the lower estuary for all test cases are not high enough to significantly curtail Kepone migration from the James River to Chesapeake Bay.

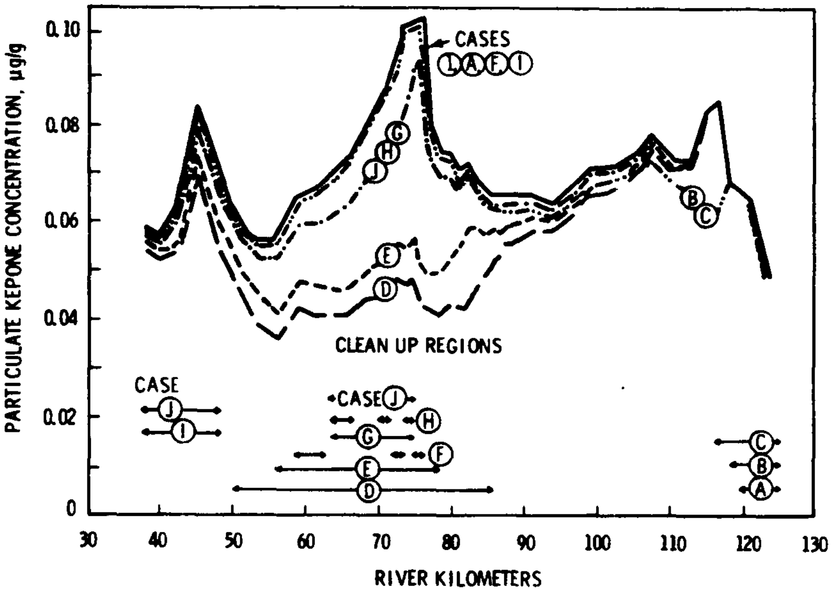


FIGURE 7. Predicted Changes in Particulate Kepone Concentrations In a Water Column Due to Partial Kepone Cleanup Activities

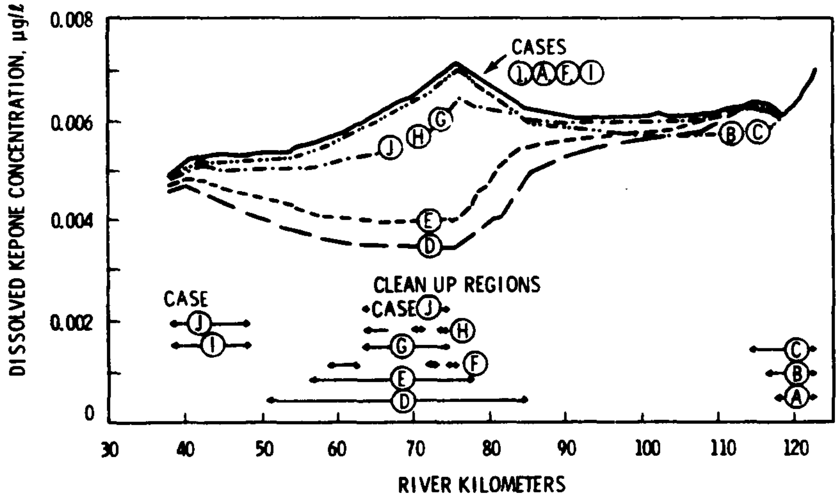


FIGURE 8. Predicted Changes in Dissolved Kepone Concentrations In a Water Column Due to Partial Kepone Cleanup Activities

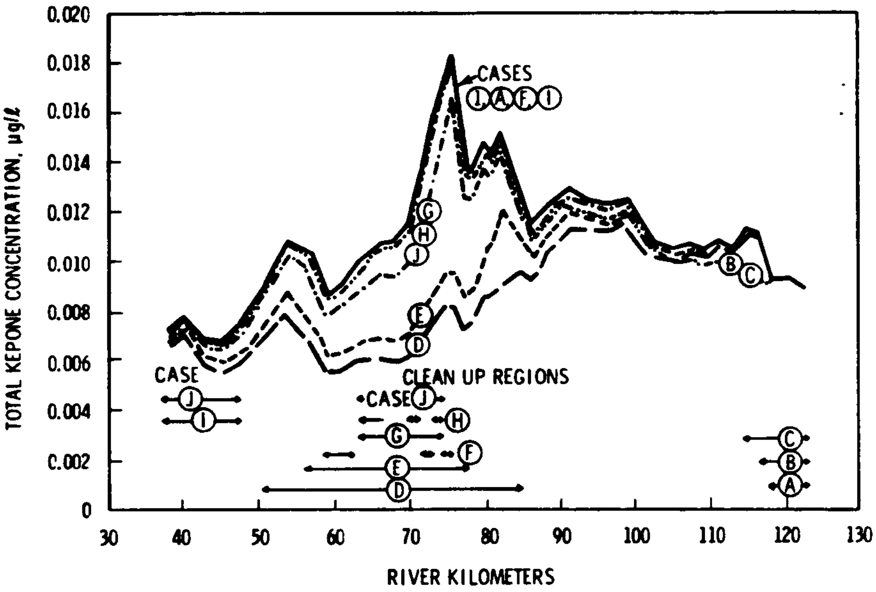


FIGURE 9. Predicted Changes in Total Kepone Concentrations In a Water Column Due to Partial Kepone Cleanup Activities

CONCLUSIONS

Drilling mud and cuttings released to the surface water undergo very complex interactions with flow, water temperature, salinity, sediment, chemicals and possibly aquatic biota. The three-dimensional model, FLESCOT, and the two-dimensional model, FETRA, have been used to predict long-term (far-field) sediment-contaminant migration and accumulation. Since these models include most of the major mechanisms affecting the long-term migration and fate of drilling mud and cuttings, these models can be served as a basis for long-term prediction tools for the assessment of potential impacts of drilling mud and cuttings.

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5.4 Measurements and Observations of Drilling, and Other Negatively Buoyant Fluids Discharged into Stratified and Static Seawater

by

Robert J. Ozretich and Donald J. Baumgartner

Measurements and Observations of Drilling, and Other Negatively Buoyant Fluids Discharged Into Stratified and Static Seawater.

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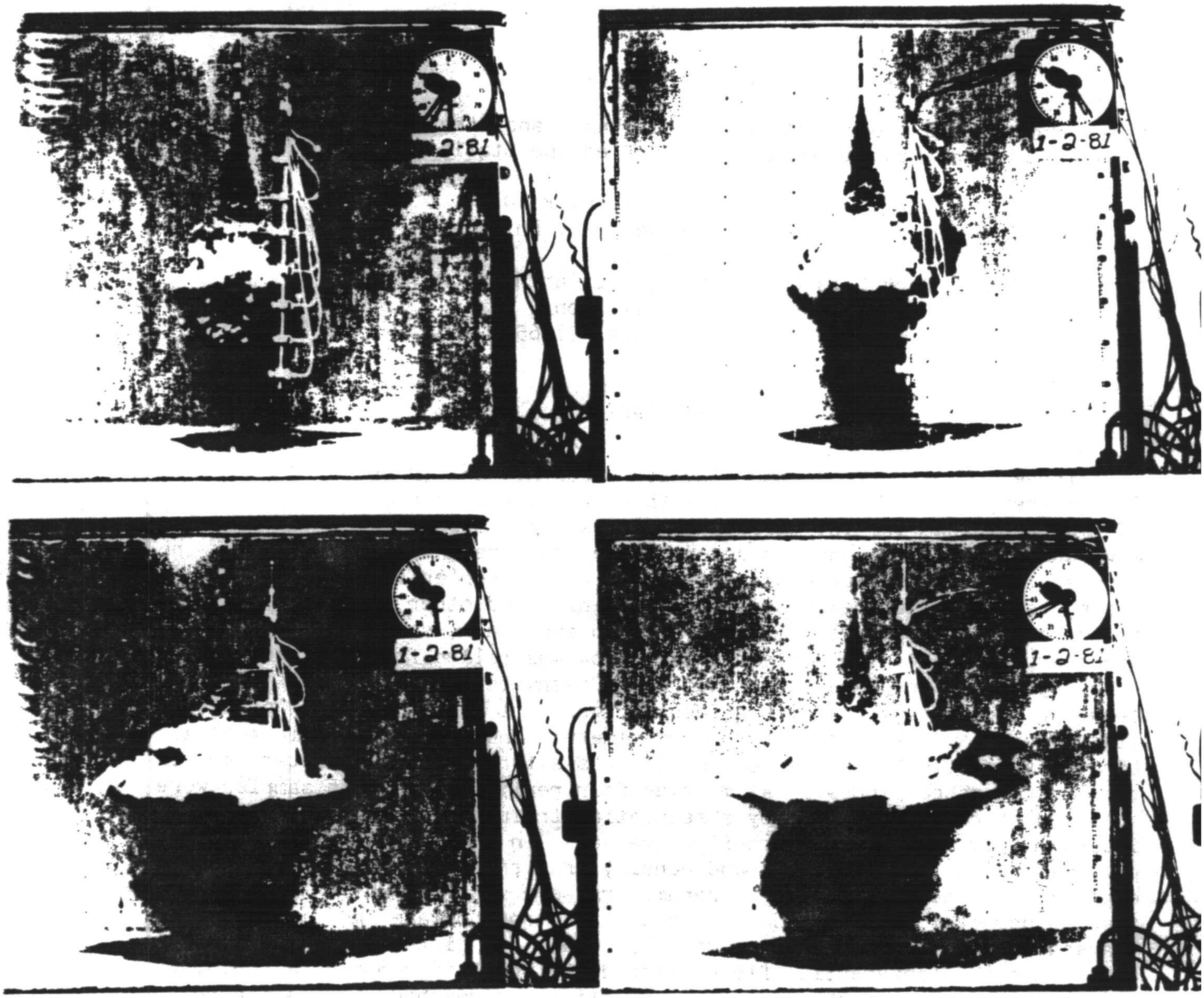
ABSTRACT

Three computer programs PLUME, OUTPLM, and DKHPLM (Teeter and Baumgartner, 1979) have been used with confidence by EPA and municipalities in determining initial dilutions of sewage discharged into marine environments. The research described in this presentation evaluates the accuracy of the three programs in predicting the centerline dilution, trap depth, and maximum penetration of drilling, and other negatively buoyant fluids discharged downward into stratified and static seawater. A tank (8' diameter, 4' deep) with a plexiglass window was filled from the bottom with 7 layers of filtered seawater mixed with freshwater, (50% to 100% filtered seawater) resulting in a linear density gradient within the tank prior to discharge. Samples were taken for gravimetric and/or colorimetric analysis through seven (1/8" I.D. by 8" long) ports extending to the centerline of the photographed plumes. As many as four replicate synoptic samples were obtained through each port by a sequential train of evacuated test tubes incorporating a unique cork-float valve. In order to use the three programs with the discharge and density gradient characteristics of the experiment, the program input parameters were modified while maintaining the densimetric Froude number and the appropriate gradient sign. Transparencies were presented which showed: 1) pictures of developing plume and the (apparently) flocculated drilling fluid components "raining" out of the plume once the maximum penetration was reached. 2) a figure of sigma-t versus depth in the tank - indicating the linearity of the density profiles. 3) a figure showing measured and predicted centerline dilutions. 4 and 5) figures showing the observed versus predicted trap depths and maximum penetrations with PLUME. The conclusions of this work are: 1) the solid and soluble components of drilling fluids dilute at essentially the same rates within the buoyancy and momentum-dominated initial dilution phase. 2) flocculation occurs rapidly during early plume development. 3) the computer programs PLUME, OUTPLM, and DKHPLM predict the measured dilutions and plume features to a high degree of accuracy.

Teeter, A. M. and D. J. Baumgartner. 1979.
Prediction of initial mixing for municipal ocean discharges. Publication 043. U.S.E.P.A. Corvallis Environmental Research Laboratory. Corvallis, Oregon 97330.

- DISCLAIMER -

Although the research described in this presentation has been funded wholly or in part by the U.S. Environmental Protection Agency, it has not been subjected to Agency's required peer and policy review and therefore does not necessarily reflect the views of the Agency.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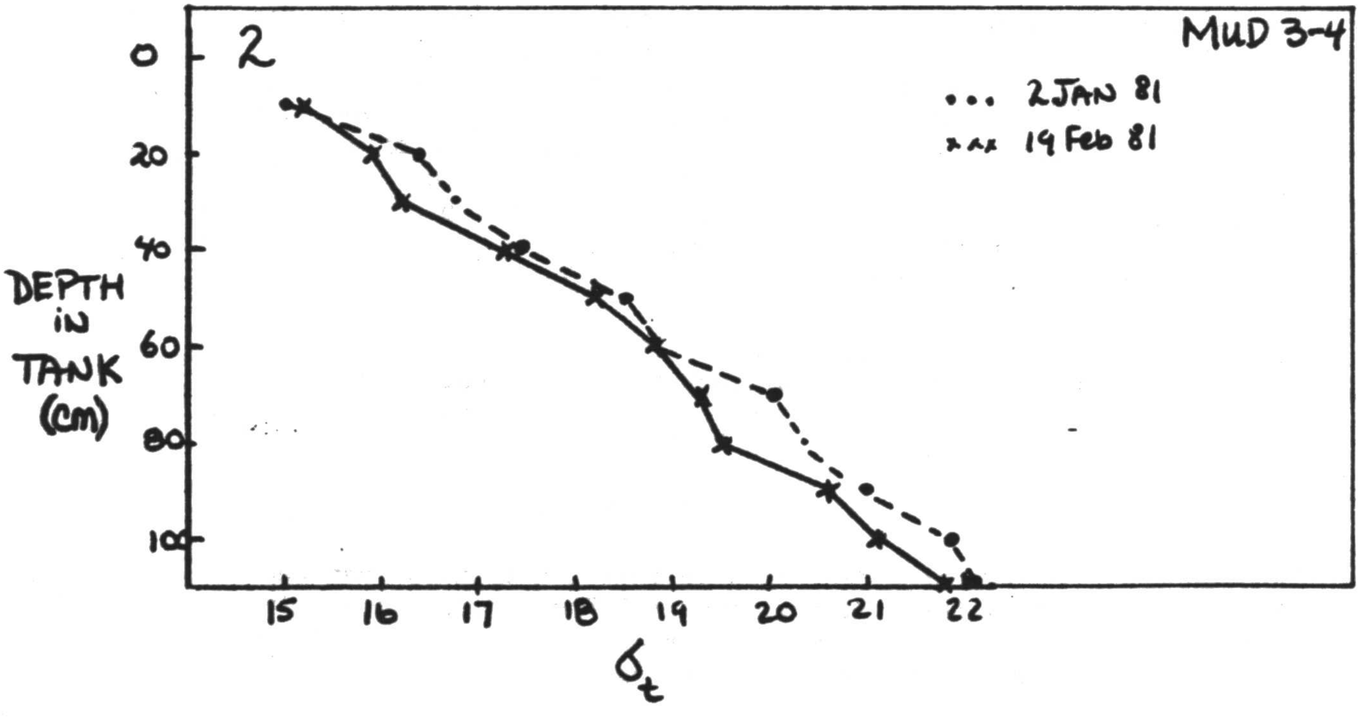
2
MUD 3-4
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15
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19
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21
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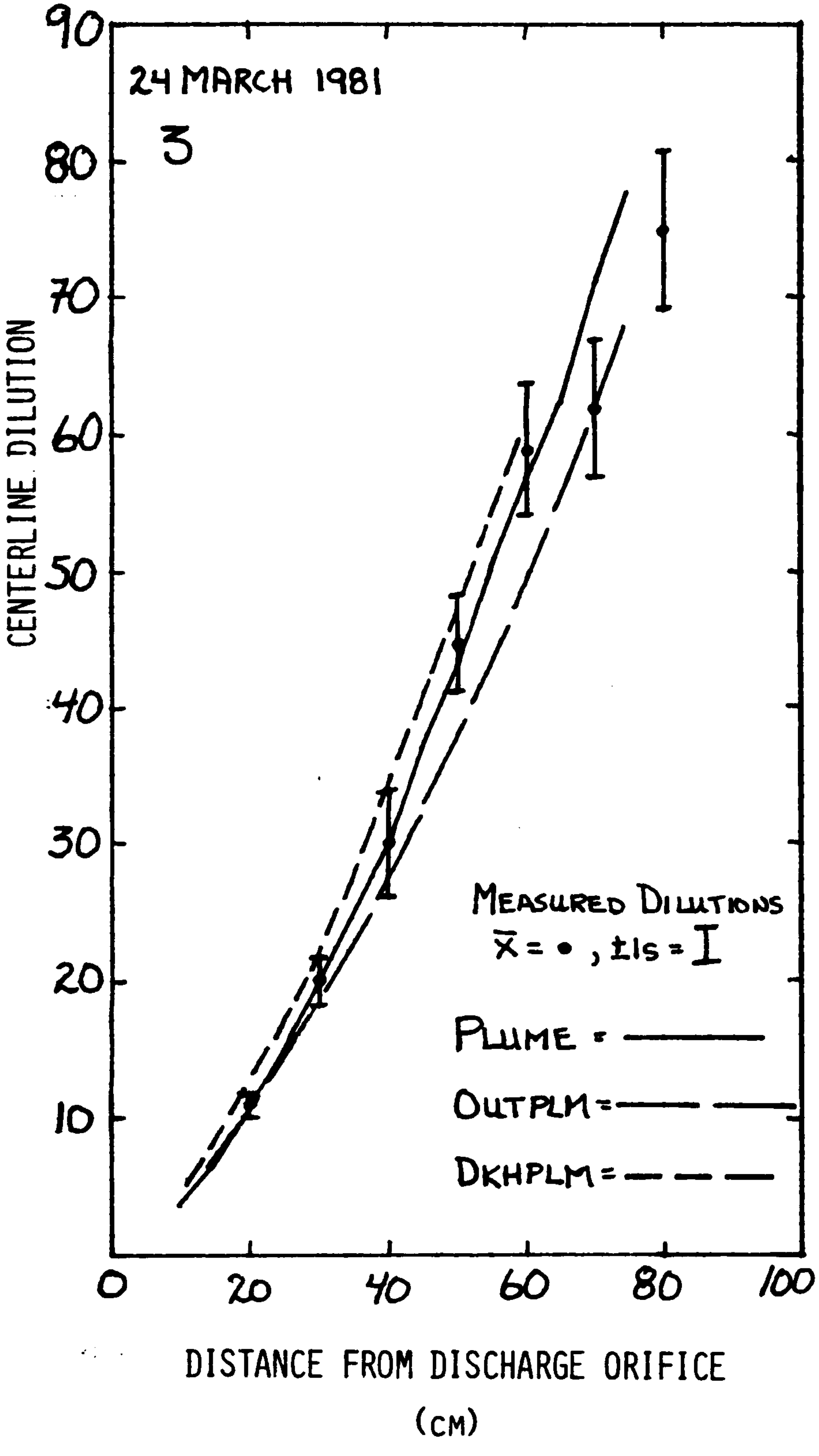
σ_t


24 MARCH 1981
3
CENTERLINE DILUTION
90
80
70
60
50
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30
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10
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20
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DISTANCE FROM DISCHARGE ORIFICE
(CM)
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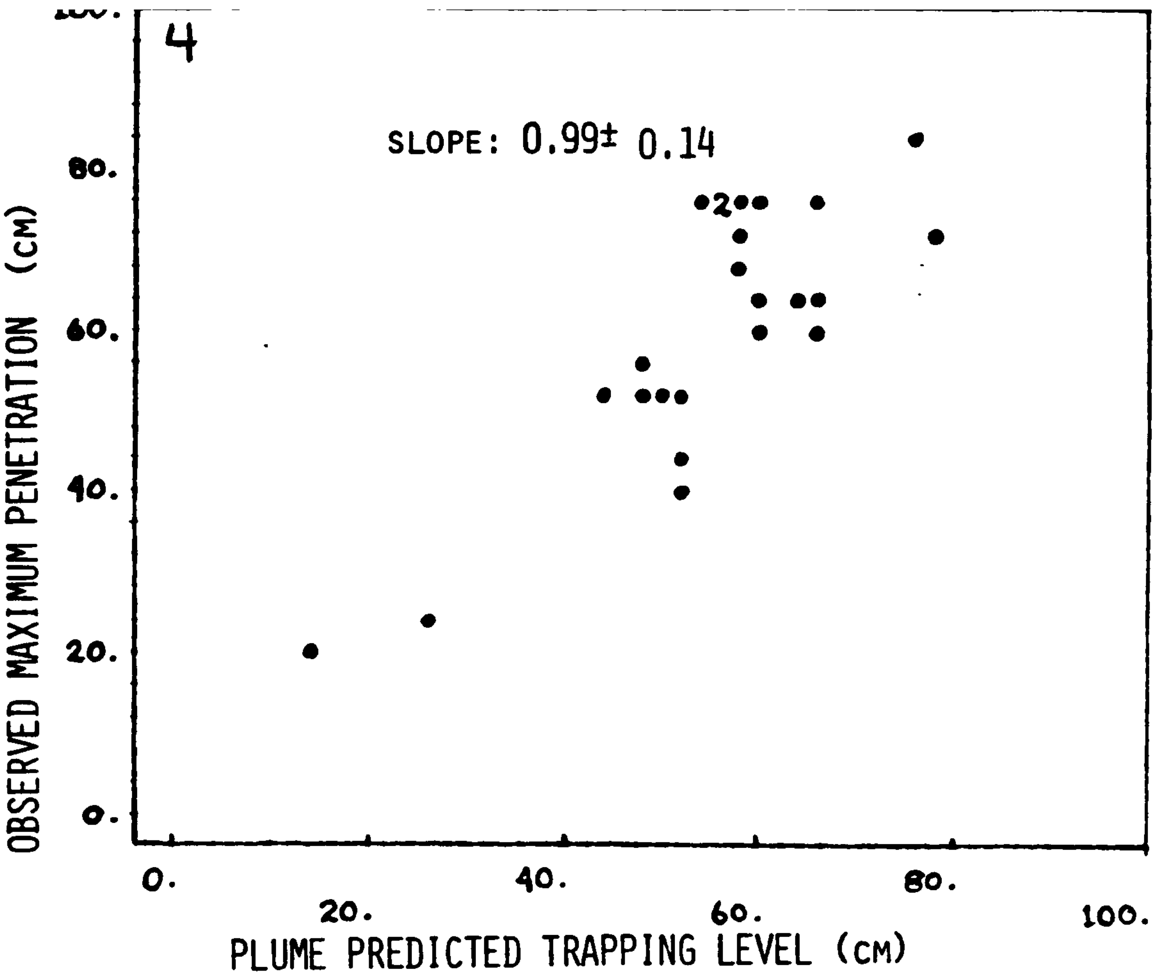
4
SLOPE: 0.99± 0.14
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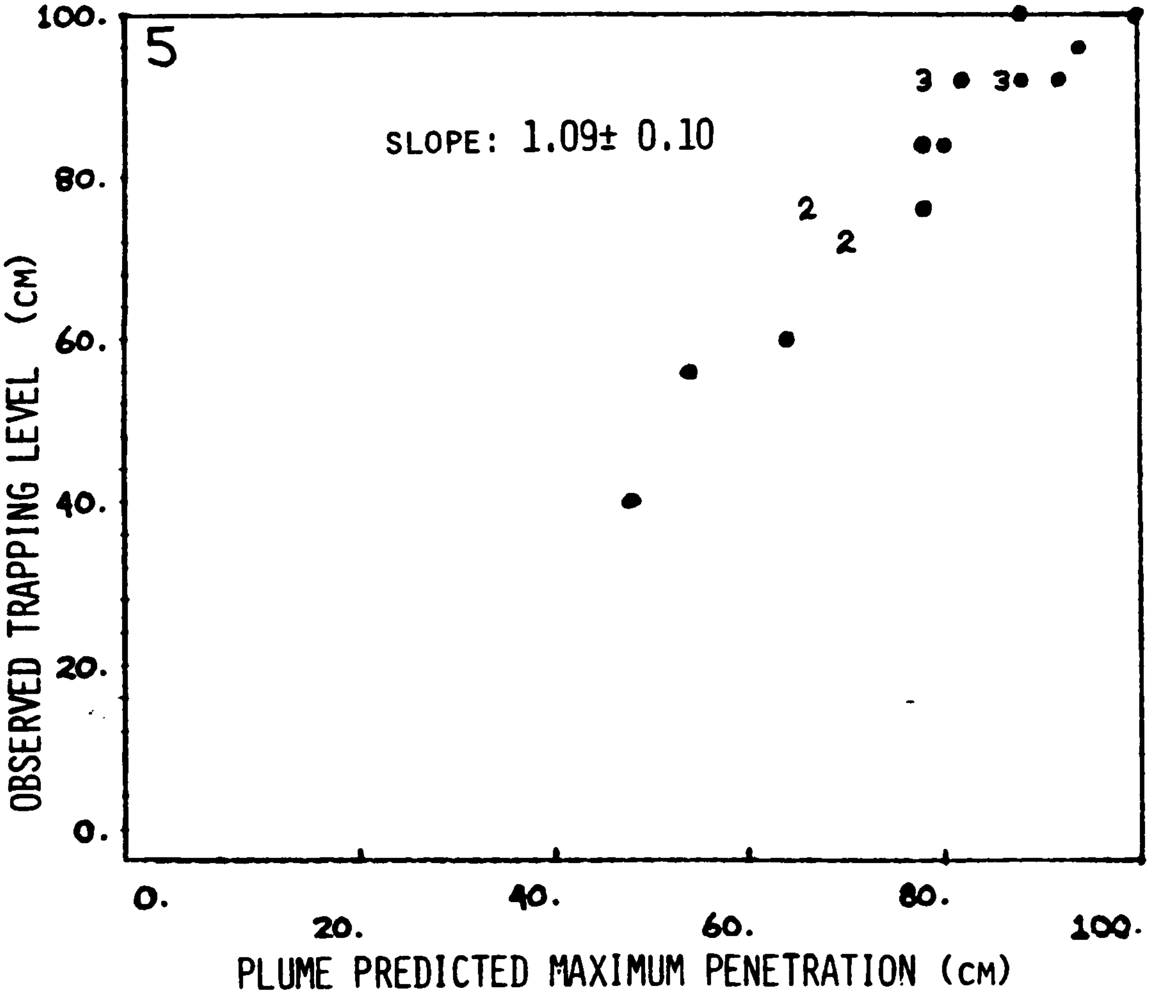
PLUME PREDICTED TRAPPING LEVEL (CM)


5
SLOPE: 1.09± 0.10
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OBSERVED TRAPPING LEVEL (CM)
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PLUME PREDICTED MAXIMUM PENETRATION (CM)

5.5 A Model of the Dispersion of Mud discharged beneath Sea Ice in Shallow Arctic Waters

by

Richard Miller, Robert Britch and Richard Shafer

A MODEL OF THE DISPERSION OF MUD DISCHARGED BENEATH SEA ICE IN SHALLOW ARCTIC WATERS

Richard Miller, Nortec
Robert Britch, Nortec
Richard Shafer, Sohio Alaska Petroleum Company

ABSTRACT

Since 1979 Sohio Alaska Petroleum Company (Sohio) has contracted with Northern Technical Services (Nortec) for a series of investigations on the effects of discharge of waste drilling fluid in the Beaufort Sea. This program was conducted on behalf of Sohio and a number of other interested oil companies. Major tasks included oceanographic data collection, effluent modeling, bioassay testing, and benthic effects studies. This presentation focuses on effluent modeling.

Below ice disposal tests were conducted at two locations near Prudhoe Bay. Tests included discharge of dyed drilling effluents through holes augered in the sea ice, monitoring of various physical and chemical parameters, and measurement of bottom deposition. To supplement field results, a laboratory model was constructed and time lapse photography was used to record the physical dimensions of the discharge plume under a variety of conditions.

Results from field and laboratory tests showed that the effluent plume acts as a vertical jet which upon bottom encounter behaves as a radial wall jet. The wall jet thickness was found to increase proportionally to the radial distance to the 1.1 power, and velocity was found to be inversely proportional to radial distance to the 1.24 power.

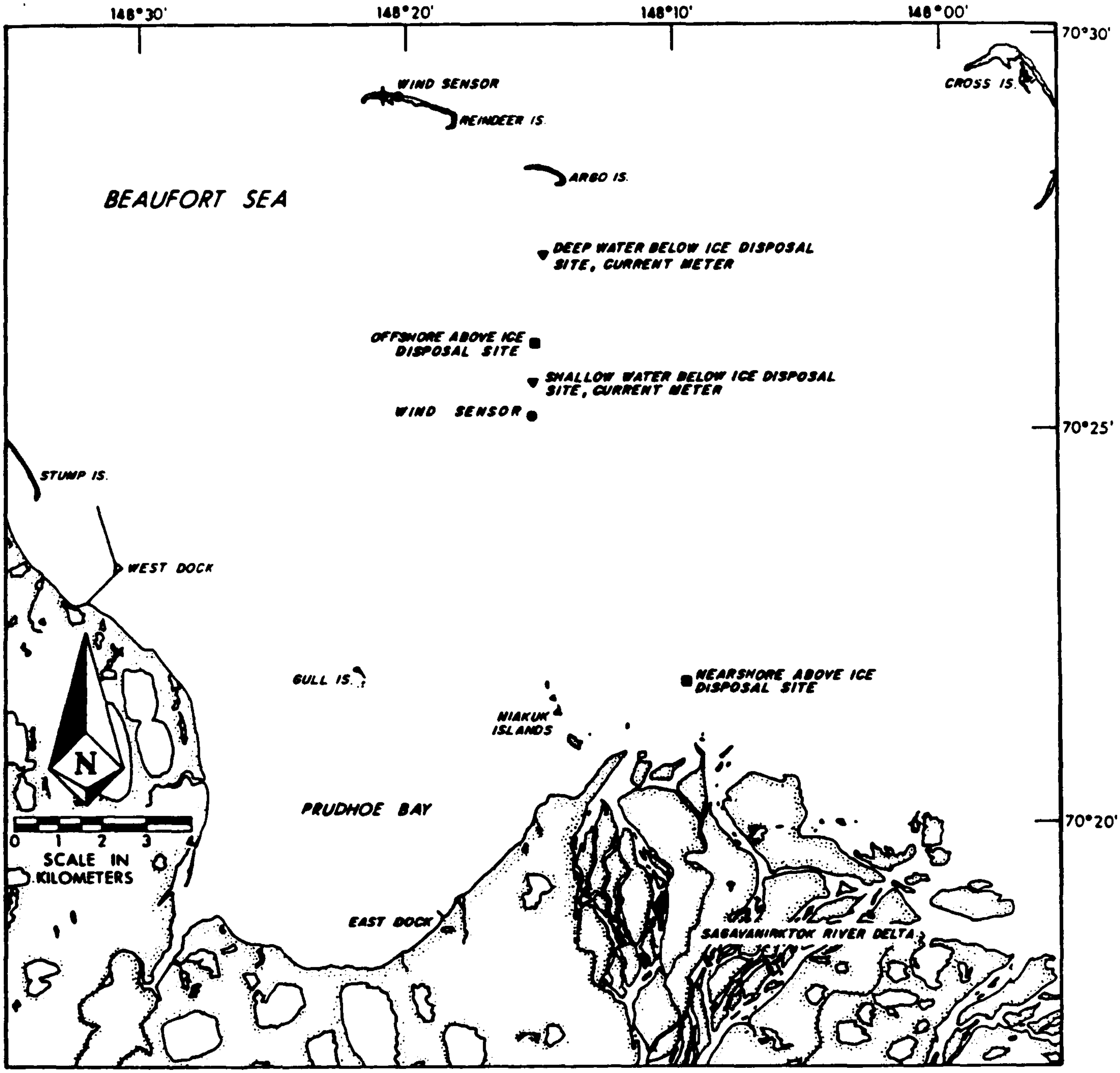

Figure 1. Location map for field investigations.

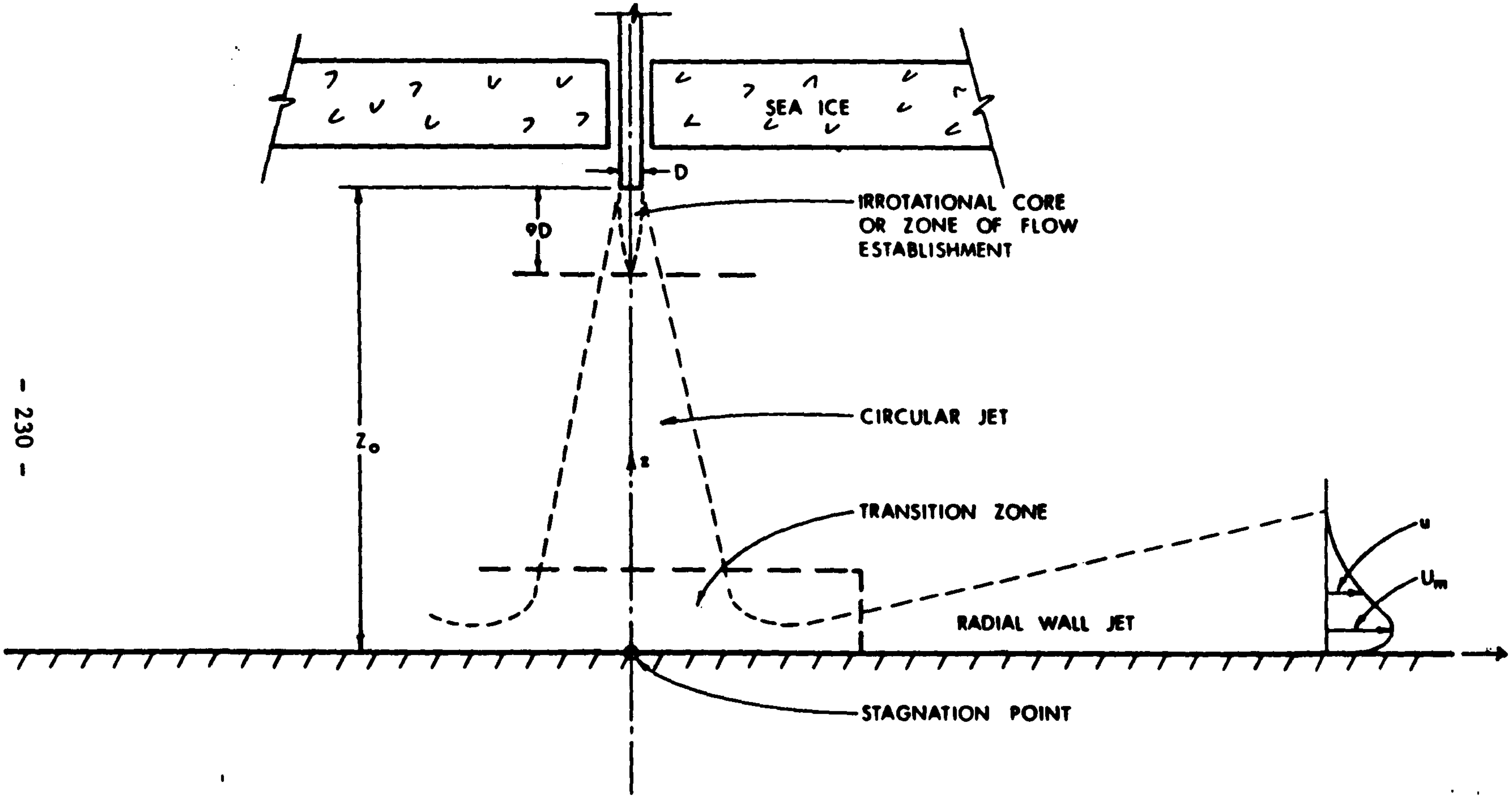

Figure 2. Schematic cross-section of circular jet impinging on the sea floor. The jet is discharged through a pipe with an orifice diameter D. The coordinate system used to describe flow has its origin at the stagnation point with r denoting the radial distance and z the vertical distance from the origin. The flow profile in the radial wall jet is described by a maximum velocity U_m and mean velocity u.

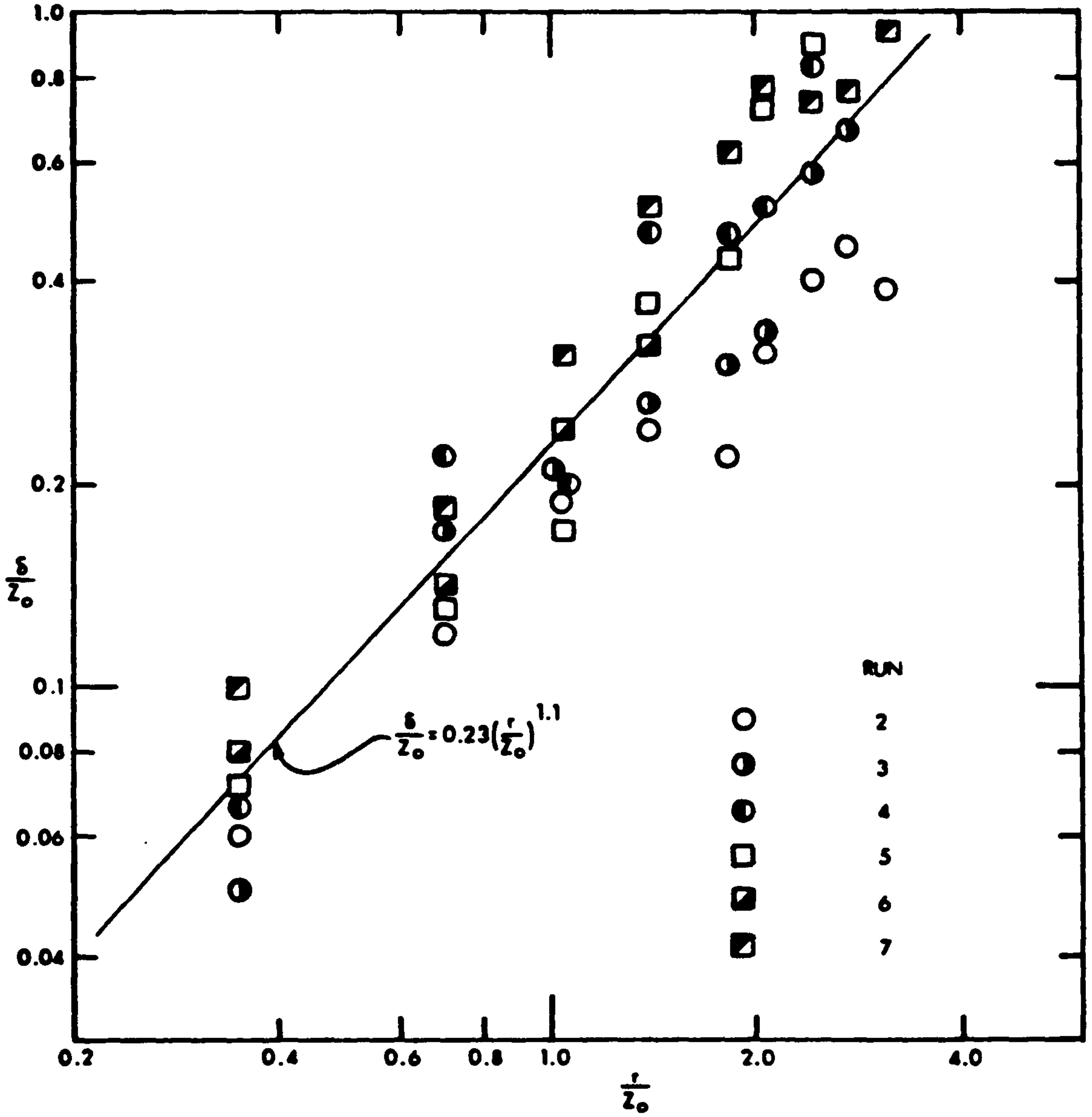

Figure 3. Dimensionless plot of test tank data showing the increase in thickness, δ, of the radial wall jet with increasing radial distance. Conditions for various runs are presented in Table 1.

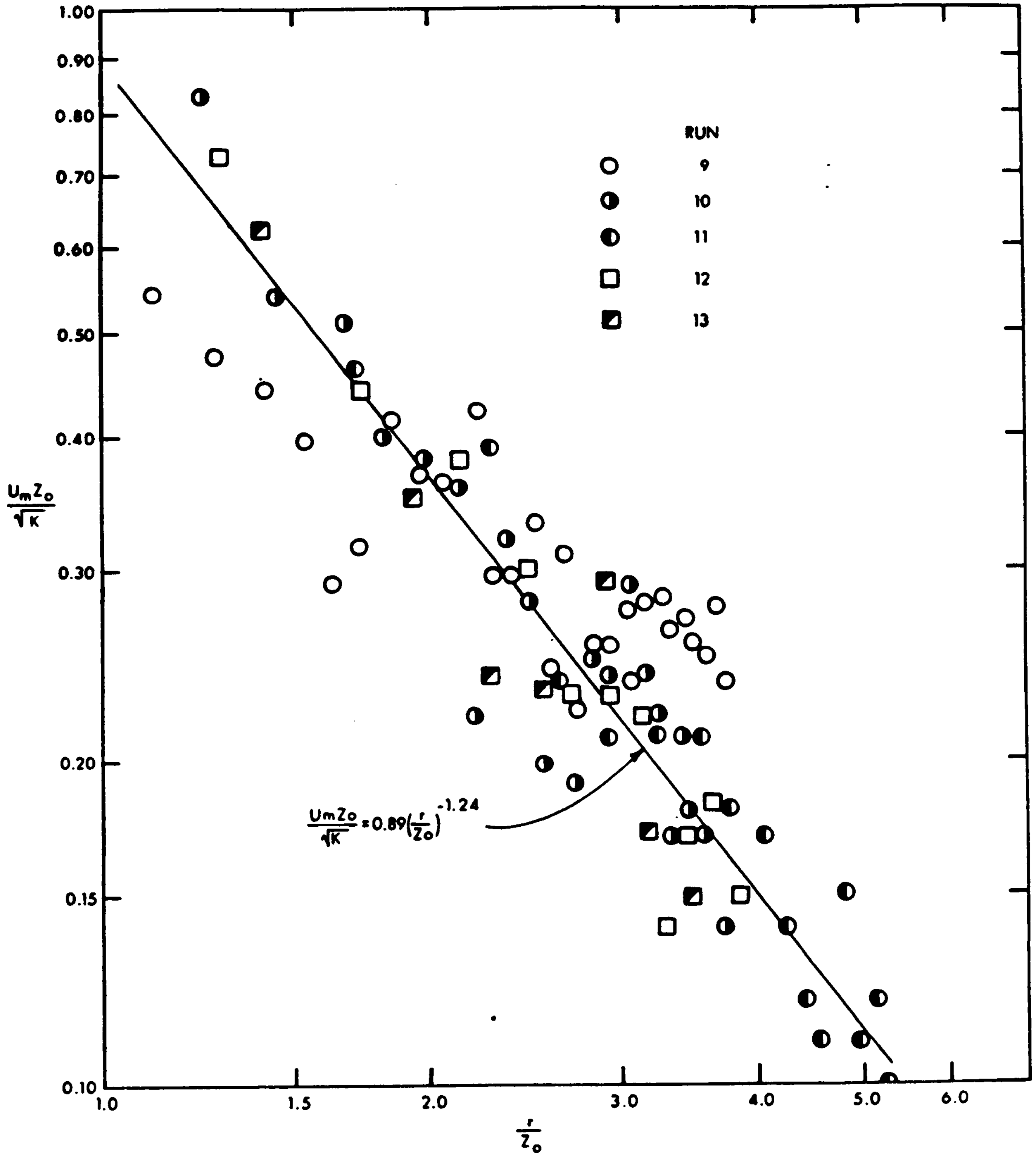

Figure 4. Dimensionless plot of test tank data showing the decrease in maximum velocity, U_m, in the radial wall jet with increasing radial distance. Conditions for various runs are presented on Table 1.

MARCH 3, 1849

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.