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A Time-Dependent, Two-Dimensional Model for Predicting the Distribution of Drilling Muds Discharged to Shallow Water

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Introduction

In drilling exploratory and production oil wells in offshore areas it has become common practice to discharge the drilling muds and cuttings to marine waters. In general, the whole mud fraction has been found to be more toxic than the aqueous or particulate phases. The 96-hour LC_{50} values for drilling muds are as low as 100 mg/l(Petrazuolo(1981)) for some marine organisms. To protect water quality, National Pollution Discharge Elimination System (NPDES) permits issued for such discharges must be in compliance with Ocean Discharge Criteria (40 CFR Part 125).

In order to write the permits for specific discharges it is necessary to have methods for estimating water quality impacts of the discharge. Brandsma et al (1983), for example, have described a model predicting the short-term fate of drilling muds discharged to the marine environment. This model, called the Offshore Operating Committee (OOC) Model, is based upon the work of Koh and Chang (1973). The model has been used to simulate field test conditions in the Gulf of Mexico (Ayers et al(1982)). This model describes the behavior of drilling muds in terms of three processes: 1) convective descent; 2) dynamic collapse; and 3) passive diffusion and has reproduced observed features of drilling mud discharges.

The reported applications of the OOC Model have been in water depths of greater than 20 meters. Many of the proposed offshore drilling sites are in waters as shallow as five meters. Two important assumptions made in the OOC Model lead to plume characteristics in shallow water which can be adequately described by a simpler model. The first of these assumptions is that the extremely fine material with low settling velocity is forced from the jet when the discharge is characterized by low densimetric Froude numbers, $Fr < 2.0$, where:

$$Fr = \frac{u}{\sqrt{g \frac{\rho - \rho_a}{\rho} D}}$$

and,

g = the acceleration due to gravity, 9.8 meters/sec^2,

ρ_a = the ambient density kg/meters^3,

ρ = the fluid density, kg/meters^3,

D = the diameter of the discharge pipe, meters,

u = the discharge velocity, meters/second.

For these particles, if the settling time, H/w_i, where H is the water depth, is greater than the vertical mixing time, H^2/κ_v, where κ_v is the coefficient of turbulent diffusion in the vertical, then the three-dimensional problem can be approximated by a two-dimensional analysis. This is the case for fine material with settling velocities of 10^{-4} meters/second, in water depths of 10 meters, or less, and assuming a coefficient of turbulent diffusion of $5\text{x}10^{-3}$ meters^2/second.

The second assumption is that the settling speed of a cloud of particles is greater than the settling speed of individual particles. Brandsma et al (1983) suggest the use of an enhancement factor, F, such that.

$$F = 0.013\ C^{4/3}$$

where C is the local concentration of suspended material in mg/l. In the OOC Model, F is restricted to the range 1 to 28. For drilling muds, maximum particle settling rates are 10^{-3} meters/second. Concentrations of drilling muds are typically greater than 1000 mg/l in the vicinity of the discharge, giving rise to a maximum enhancement factor of 28. In water depths of 10 meters and for current speed of the order of 0.2 meters/second, dimensional analysis shows that the OOC Model would predict that the convective descent and dynamic collapse phases would occur primarily in a region within 100 meters of the discharge. Beyond this point, passive diffusion and settling of the remaining material would characterize the distribution of solids.

The OOC Model is a complex one, requiring large, sophisticated computing equipment for execution of the model software. In the case of shallow water discharges, the dimensional analysis above shows that the processes described by the OOC Model at distances from the discharge greater than 100 meters are relatively simple ones. Under these circumstances, it seems reasonable to apply simpler models requiring less computing time and smaller computers. For the processes of advection, passive diffusion and settling, analytical solutions to the advective-diffusion equation have been described for which such simple algorithms can be written.

In the following development, the modular solution technique, as described by Cleary and Adrian (1973) and Cleary et al (1974), has been used to develop a method for estimating the impact of drilling mud discharge in shallow waters. The method can be used for planning purposes, as well as for the design of permits. Simulations from this simple model, which can be implemented on a micro-computer, are compared to actual field data, as well as to test case results from the OOC Model. The comparisons with field data provide the potential user with measures for determining how well the simple model simulates actual conditions. Comparisons with the OOC Model can be used to evaluate differences in results between the simple model and the OOC Model and gives the user some perspective on the trade-off between model complexity and model accuracy.

Model Development

For discharges of drilling muds to shallow waters, the analysis assumes that important processes determining the distribution of solids in the water column include:

1. Horizontal mixing under conditions of isotropic turbulence
2. Horizontal advection
3. Settling of solids

In addition, the model all discharges are treated as vertical line sources. That is, the discharge is mixed instantaneously and uniformly from top to bottom at the point of discharge in a line of infinitely small radius and vertical extent equal to the water depth, H. The equation describing the mixing of the $\underline{i}^{th}$ particle class under these conditions is given by:

$$\frac{\partial C_i}{\partial t} + u\frac{\partial C_i}{\partial x} = K_x\frac{\partial^2 C_i}{\partial x^2} + K_y\frac{\partial^2 C_i}{\partial y^2} - \frac{w_i C_i}{H} + S(x,y,t) \quad (1)$$

where,

C_i = the concentration of the i^{th} particle class, mg/l,

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

w_i = the settling rate of the i^{th} particle class, meters/second,

D = the water depth, meters,

S = the strength of the source, mg/l/second,

κ_x = the coefficient of eddy diffusivity in the x-direction, meters^2/second,

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

x = the coordinate in the downstream direction, meters,

y = the coordinate in the crossstream direction, meters,

t = time, seconds.

For those conditions in which the influence of horizontal boundaries can be neglected and for which ocean currents are uniform and constant Equation (1) can be solved by transform techniques (Cleary et al (1973), Cleary et al (1974)). These methods are easier to apply if Equation (1) is put in the form:

$$\frac{\partial C_i'}{\partial t'} = K_x \frac{\partial^2 C_i'}{\partial x'^2} + K_y \frac{\partial^2 C_i'}{\partial y'^2} + S'(x',y',t') \qquad (2)$$

where the substitutions:

$x' = x - ut$

$y' = y$

$t' = t$

$C(x,y,t) = C'(x',y',t')e^{-wt'/D}$

$S(x,y,t) = S'(x',y',t')e^{-wt'/D}$

have been made.

In the x-, y-domain, the Fourier transform is appropriate for solving Equation (1) and the transform pair is defined as:

$$\hat{\hat{C}}'(\alpha,\beta,t') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} C'(x',y',t')\, e^{-j(\alpha x' + \beta y')}\, dx'dy' \qquad (3)$$

$$C'(x',y',t') = \iint \hat{\hat{C}}(\alpha,\beta,t')\, e^{j(\alpha x' + \beta y')}\, d\alpha\, d\beta \qquad (4)$$

Since the problem is concerned with the analysis of a discharge which begins at $t' = 0$, the Laplace transform is appropriate in the time domain:

$$\tilde{C}(x',y',p) = \int_{0}^{\infty} C(x',y',t')\, e^{-pt'}\, dt' \tag{5}$$

For the following boundary and initial conditions:

$S(x,y,t) = S_0(\tau)$ at $x = y = 0$,

$C(x,y,t) = 0 \quad -\infty < x < \infty \;, \; -\infty < y < \infty \;, \; t \;\; 0,$

$C(x,y,t) = 0$, $x \to \infty$, $y \to \infty$ for all t.

The general solution to Equation (1) using the above methods and for the given boundary and initial conditions is:

$$C(x,y,t) = \sum_{i=1}^{n} \int_{0}^{\tau} S_{oi}(t-\tau)\, G_i(x,y,\tau)\, d\tau \tag{6}$$

where

$$G_i(x,y,t) = \frac{e^{-\frac{(x-ut)^2}{4\alpha_x t}}\; e^{-\frac{y^2}{4\alpha_y t}}\; e^{-\frac{w_i t}{H}}}{4\pi H \sqrt{\alpha_x \alpha_y}\; t} \tag{7}$$

and is the solution to Equation (1) when $S_0(t)$ is a unit impulse:

$$S_0(t) = 1,\ t = 0,$$
$$= 0,\ \text{otherwise}$$

The results for a general source term, $S_0(t)$, are obtained from the superposition of scaled unit impulses which "add" up to make $S_0(t)$. A particular impulse is introduced at time, τ, and the effect of all (an infinite number, in theory) the impulses occurring between time, t=0, and time, $t=\tau$, are added up to determine the concentration at some location, (x,y) at time, t (see Figure 1). This formulation can be used to simulate the time-dependent distribution of extremely fine particles with low settling velocities which are separated from the plume. In addition, the effects of enhanced settling in the plume, due to elevated concentrations, can also be simulated crudely by the choice of an appropriate, enhanced settling rate.

An algorithm incorporating the concepts expressed in Equations (6) and (7) has been coded in FORTRAN and implemented on the EPA Region 10 PDP 11/70. In addition to predicting concentrations of suspended sediments, the code includes an expression for integrating the flux of sediment through the bottom boundary. The resulting quantity is used to estimate deposition rates along the plume centerline. If there is a need to estimate the concentration of dissolved substances in the water column, it is a simple matter to include that in the code, as well. A listing of the source code and a description of input variables and their format are given in Appendix I.

Model Application

Field Studies

Simulations of solids concentrations were obtained using Equation (6) and compared with the results of three field studies. Two of the studies were conducted in the summer of 1978 from the drilling rig, Penrod 63, in the Gulf of Mexico. The third test was conducted at the Norton Sound COST well in the Bering Sea during September 1982. Oceanographic and drilling mud discharge parameters for each test are given in Table 1. The diffusion coefficient, K , was estimated from the relationship given in Brooks (1960):

$$K = 4.64 \times 10^{-4} \; L^{4/3} \qquad (8)$$

where the constant, 4.64×10^{-4}, leads to values of the diffusion coefficient in mks units corresponding to the value of 0.01 suggested by Brooks for cgs units. Since the mixing zone is of primary concern in the development of permits, the characteristic length, L, was chosen to be 100 meters, that being a typical mixing zone size for drilling mud discharges. It should be kept in mind that this mixing zone has no physical significance, but was chosen so that the analysis would be consistent with the mixing zone size defined in the Ocean Dumping Criteria.

Drilling muds vary in type and composition. The characteristics of the drilling muds used by Brandsma et al (1980) in the Gulf of Mexico tests are given (Table 2). No comparable data are available from the Norton Sound COST well test. The characteristics of the mud used in the Gulf of Mexico tests were, for want of better information, used for the COST well simulations, as well.

Comparisons of model simulations and field results are shown in Figures 2 through 4. For each test condition, two different simulations using the simple model (Equation 1) were performed. The first, designated as Model I, uses settling rates for the individual particle classes (Table 2). The second, Model II, is an attempt to incorporate the two mechanisms for settling described by Brandsma et al (1983) and discussed earlier in the Introduction. In Model II, 90% of the solids have a settling rate which is ten times that of Particle Class 1, 6.57×10^{-2} meters/second. The purpose of this is to provide for the enhancement of settling which occurs when the concentration of solids is high. The remaining 10% has a settling rates equal to the lowest rate used in Model I. This should result in the forced early separation from the jet of the extremely fine particles, as has been observed in actual field measurements. As Brandsma et al (1983) point out, there is as yet no physical explanation for this phenomenon. Rather it is an artificial mechanism incorporated into the model to duplicate what has been observed in field experiments.

For the tests conducted in the Gulf of Mexico, the field results shown in Figures 2 and 3 are maximum concentrations measured during the 60-minute period following the initiation of discharge. In the case of the 275 bbl/hr test, the discharge period was 54.5 minutes and 23.3 minutes for the 1000 bbl/hr test. Simulation results shown in Figures 2 and 3 are also the maximum values obtained during the 60-minute period following initiation of discharge. Although Ayers et al (1982) show the decline in maximum plume concentrations as a function of transport time, the scale used in their presentation makes comparison difficult. As a result, maximum simulated values are compared with maximum observed values at a given location, using the data in Table 4 of Ayers et al (1982). The time at which a maximum occurs at a given location may, therefore, be different between model results and field data. Furthermore, it should be kept in mind that the field results are maxima from some point in the water column, while the simulated results are maximum depth-averaged results.

In the case of the Norton Sound COST well, the duration of the discharge was 62 minutes, but measurement times were not reported. Values shown in Figure 4 are all those measured during the experiment and are also the maximum values observed at a particular point in the water column. The simulation results are the maximum depth-averaged values observed during the 62-minute period following the initiation of discharge. The time of the simulated maxima may not necessarily coincide with the observed maxima, but there is no way of determining this, given the available data.

Comparisons with the OOC Model

Tetra Tech (1983) has evaluated the OOC Model predictions of drilling mud dispersion in the outer continental shelf area of Alaska Seven of the test cases examined by Tetra Tech (Table 3) are compared with maximum depth-averaged concentrations obtained from Equation (6) using both Models I and II. In the test cases examined by Tetra Tech, the velocity profile varied linearly from zero at the bottom of the water column to some constant value at the surface. The solutions to Equation (6) in this report assume that the velocity profile is uniform. In each of the test cases, therefore, the average value of the current (one-half the surface current) was used to obtain results from Equation (6). Results of the comparisons are shown in Figures 5 through 11. The OOC Model results are maximum depth-averaged concentrations, too, although it is not clear from the Tetra Tech (1983) study what time is associated with each observation. Values reported for the solutions to Equation (6) (Model I and II) are the maximum values obtained during the two-hour simulation period following initiation of discharge. Discharge duration was either 30 or 60 minutes (Table 3).

Discussion

Comparisons of suspended solids concentrations estimated with Equation (6) and those obtained from the field studies (Figures 2 through 4) showed that Model I generally predicted concentrations higher than those observed, while Model II predicted lower concentrations. The exception to this was in the vicinity of discharge where maximum observed concentrations were several times higher than depth-averaged values predicted by the simple model. This is not surprising given that the characteristic vertical mixing times associated with actual field conditions are large compared to the time it takes for a particle to reach sampling points five to ten meters away from the discharge. For these locations the assumption that the water column is well-mixed is not a good one, and the depth-averaged values obtained from model will underestimate maximum observed concentrations.

Comparisons between the OOC Model and the Models I and II (Figures 5 through 11) show that Model I predicts generally higher concentrations than the OOC Model and Model II, except for the shallowest (five meters) discharge, predicts lower levels than the OOC Model. For the shallowest water the very large concentrations in the vicinity of the discharge give rise to maximum settling rates in the OOC Model which are 30 times that of Model I and three times that of Model II. Under these conditions the OOC Model predicts that the percentage of solids deposited within 15 meters of the discharge is 79% or greater (Appendix B in Tetra Tech (1983)). Similar results could be obtained from the simple model by substantially increasing the enhanced settling velocity in Model II. Whether or not this is warranted would have to be determined by laboratory and field testing.

In some cases, the slope of the concentration curves with respect to distance for both the OOC Model and for Models I and II showed a sharp change. For the OOC Model simulation this occurred in the shallowest discharges and appeared to be due to the large percentage of solids which settle out in the vicinity of the discharge. In the case of Models I and II the sharp change in slope was most noticeable in the case of low ambient current speed and was due to the fact that the simulation was not run long enough to reach the actual maximum.

Tetra Tech (1983) found that OOC Model predicted that at a fixed distance from the discharge dilution increased as velocity decreasesd. For the test cases in Table 3, the Models I and II obtained opposite results. The principal reason for this being that the vertical mixing in the OOC Model is not coupled directly to the magnitude of the ambient current as is the case for Models I and II. In Models I and II the discharge is distributed instantaneously over the water column and diluted by the ambient current. In the case of a steady state discharge this leads to an increase in dilution as velocity increases. However, for some time-dependent discharge schedules this will give rise to increases in dilution as velocity decreases, depending upon the ratio of discharge time to travel time and the ratio of settling time to travel time. For the OOC Model, the passive diffusion phase following convective descent and dynamic collapse includes vertical, as well as horizontal diffusion processes. If advection increases relative to these mixing processes and relative to the settling processes then during a given time period the advective length scale will increase while the diffusion and settling length scales will remain approximately constant In the OOC Model this will lead to an increase in concentration at a given point as the magnitude of the ambient current increases.

Conclusions

A simple model has been developed for evaluating the impact of drilling muds and cuttings discharged to shallow marine waters. Depth-averaged solids concentrations simulated by the model show reasonable agreement with results of field tests when particle settling rates are used. Agreement between predicted and observed maximum concentrations increases when an enhanced settling rate is applied to 90% of the discharged solids.

The simple model with individual particle settling rates (Model I) predicts higher depth-averaged concentrations than the OOC Model for several conditions representing shallow water discharges. The simple model with enhanced settling rates applied to 90% of the solids (Model II) predicts lower concentrations than the OOC Model except in the case of the shallowest (five meters) discharge. In general, the differences between the simple model described in this report and the OOC Model was greatest for the shallowest discharge. This discrepancy is due to the difference in initial plume dynamics between the OOC Model and Models I and II. This difference gives rise to higher deposition rates in the OOC Model than in Models I and II. Adjustment of the enhanced settling velocity in Model II would result in deposition rates similar to those predicted by the OOC Model.

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

	Norton	Gulf of Mexico	Gulf of Mexico
Discharge rate (meters**3/second)	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 (cm/sec)	30.	15.	12.

Table 2. Settling velocity and composition of components for drilling muds used in model studies.

	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	10.	10.	12.	20.	38.	10.

Table 3. Oceanographic and discharge parameters used for comparison of OOC Model and two-dimensional analytical solution (Equation 6).

	Test Case #						
	1	2	3	4	5	6	7
Discharge rate (meters**3/sec)	0.044	0.011	0.044	0.011	0.011	0.044	0.044
Initial concentration(mg/l)	1430000.						1430000.
Discharge period (minutes)	30.	60.	30.	60.	60.	30.	30.
Water depth (meters)	5.	5.	15.	15.	15.	5.	15.
Surface current speed(cm/sec)	10.	10.	10.	10.	2.	2.	30.

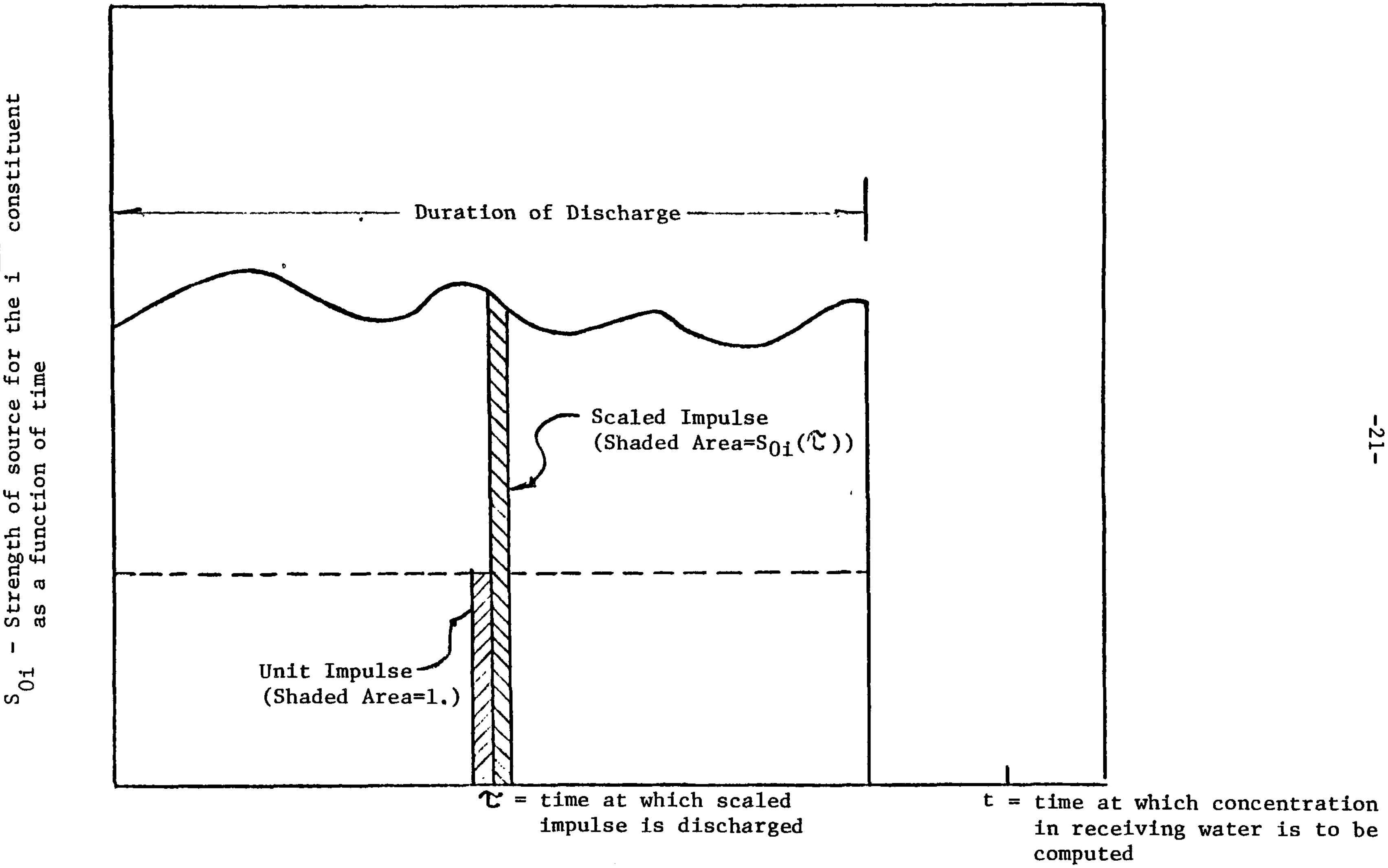


Figure 1. Schematic showing relationship between scaled impulse and unit impulse. Impact at time, t, is determined by summing up the effects of all the impulses discharged prior to time, t.

FIGURE 2. COMPARISON OF TWO-DIMENSIONAL MODEL RESULTS AND FIELD STUDIES IN THE GULF OF MEXICO - 275 BBL/HR TEST

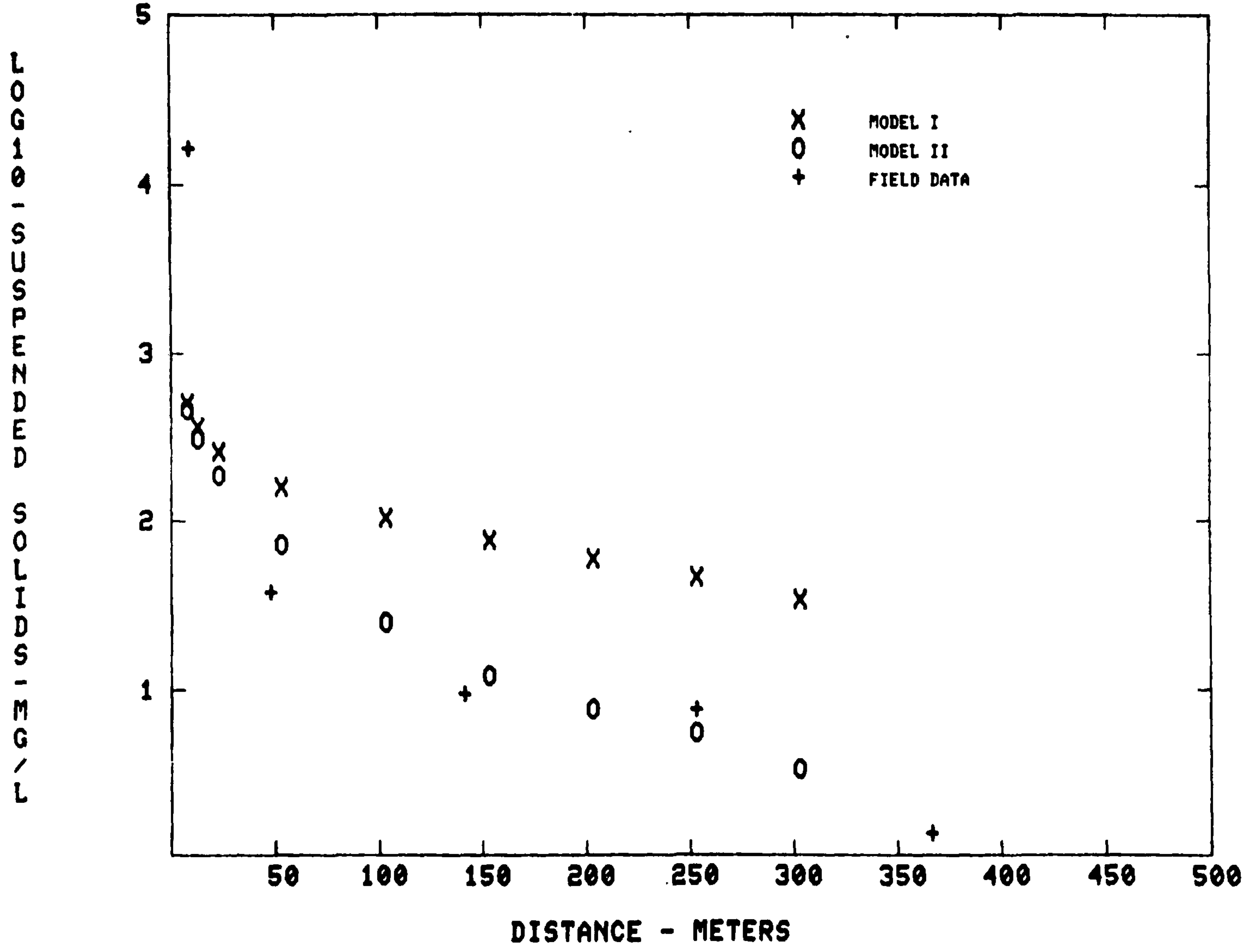


FIGURE 3. COMPARISON OF TWO-DIMENSIONAL MODEL RESULTS AND FIELD STUDIES IN THE GULF OF MEXICO - 1000 BBL/HR

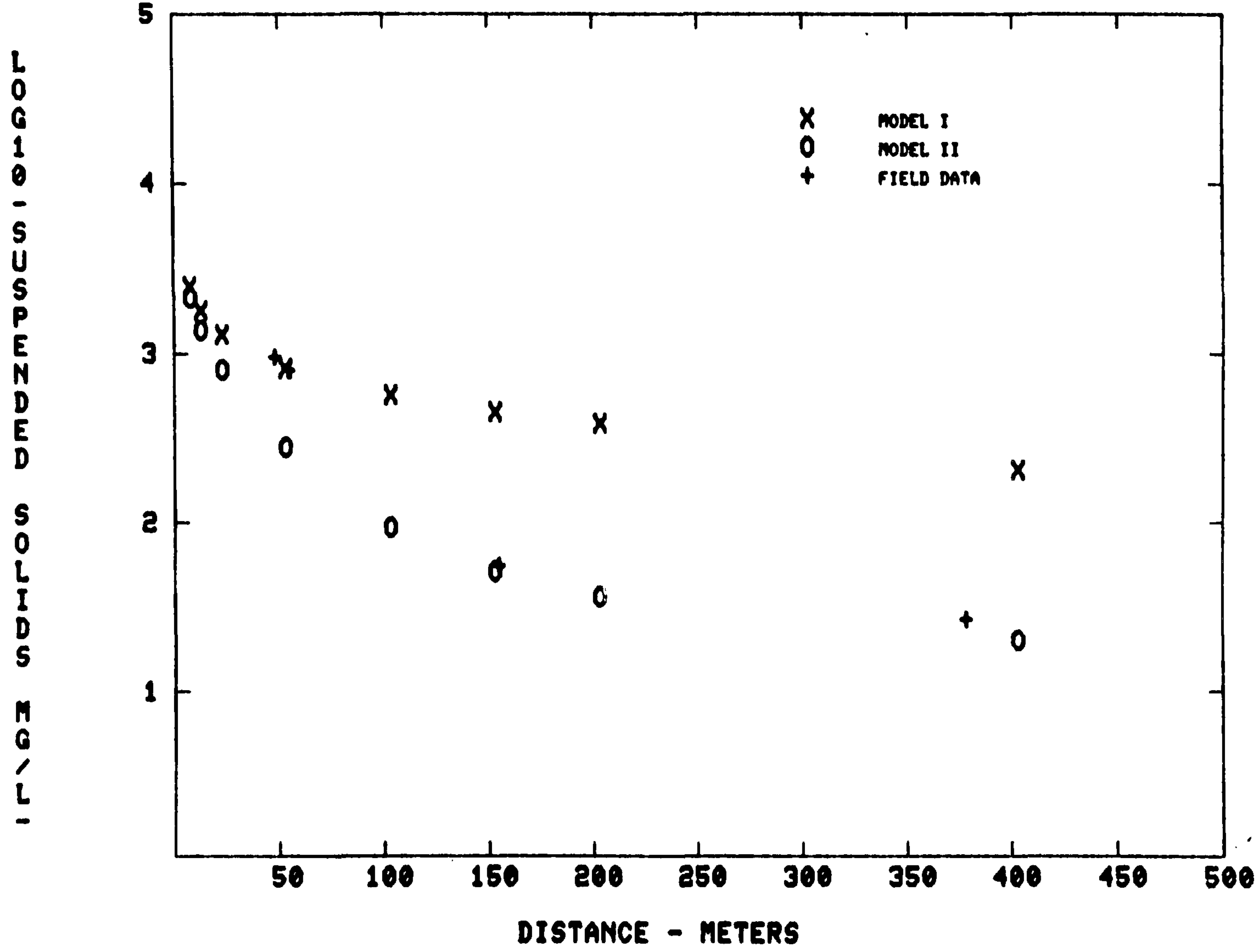


FIGURE 4. COMPARISON OF TWO-DIMENSIONAL MODEL RESULTS AND FIELD STUDIES AT THE NORTON SOUND COST WELL - 1065 BBL/HR

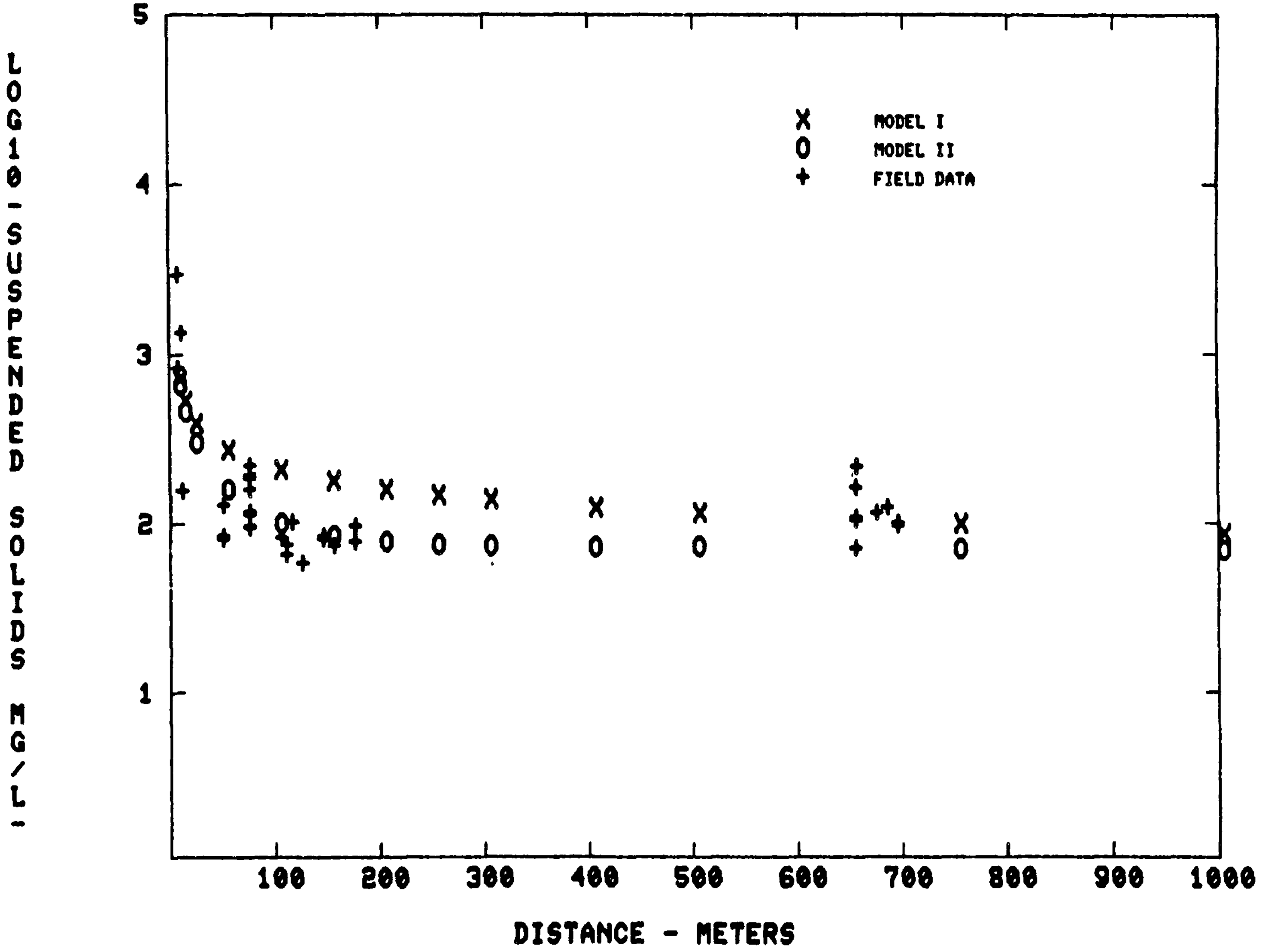


FIGURE 5. COMPARISON OF OOC MODEL AND TWO-DIMENSIONAL MODEL RESULTS. CASE #1 (TABLE 3)

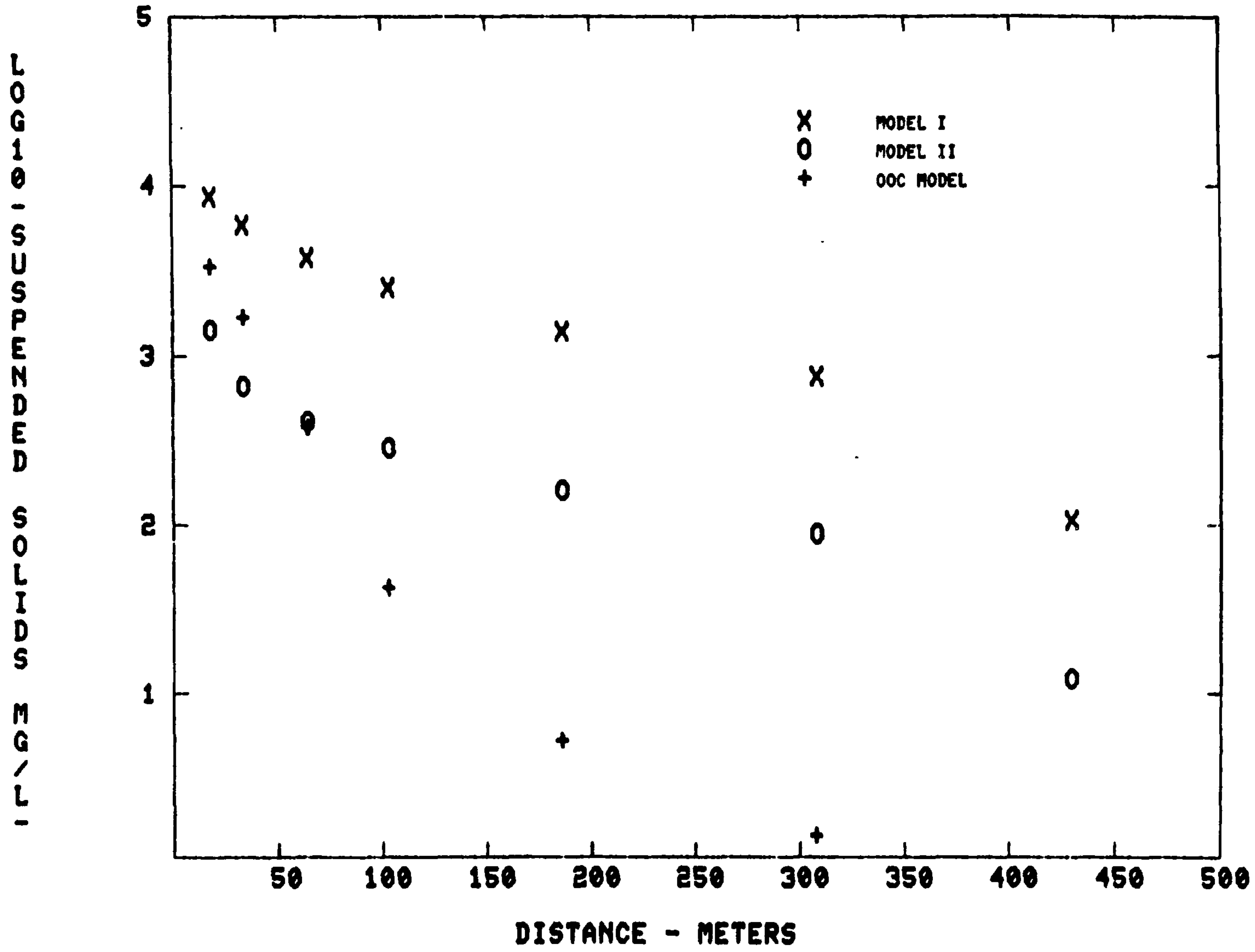


FIGURE 6. COMPARISON OF OOC MODEL AND TWO-DIMENSIONAL MODEL RESULTS. CASE #2 (TABLE 3)

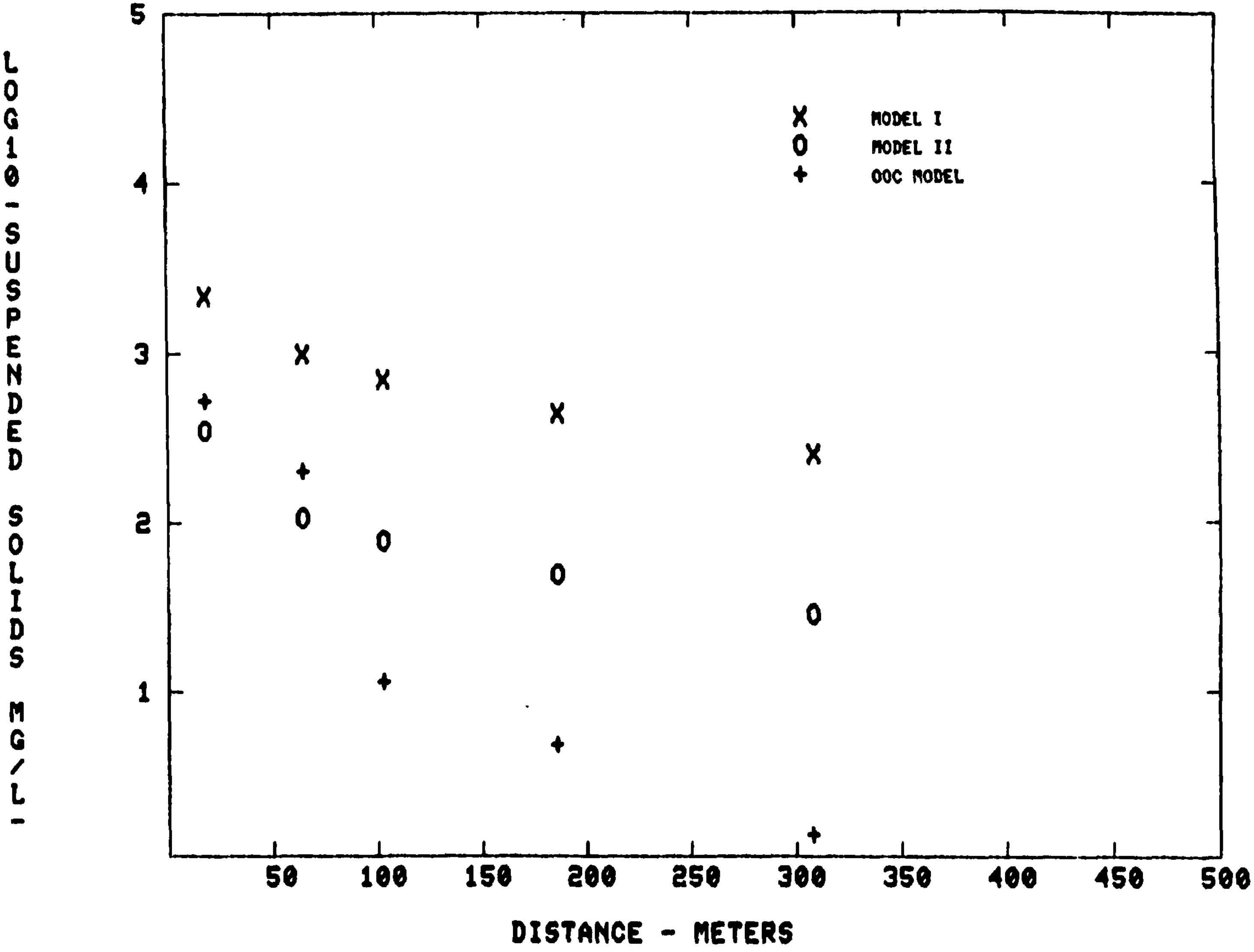


FIGURE 7. COMPARISON OF OOC MODEL AND TWO-DIMENSIONAL MODEL RESULTS. CASE #3 (TABLE 3)

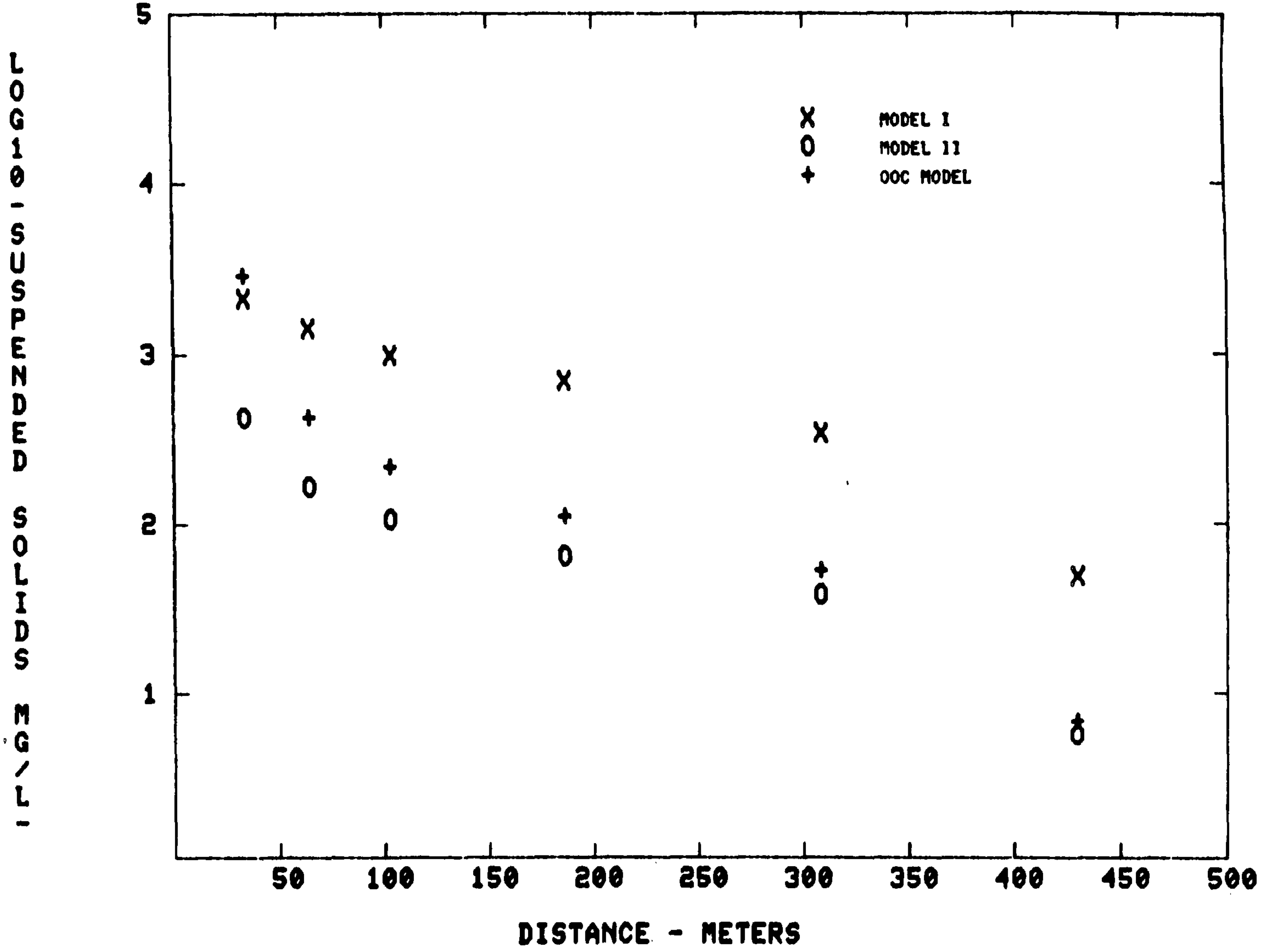


FIGURE 8. COMPARISON OF OOC MODEL AND TWO-DIMENSIONAL MODEL RESULTS. CASE #4 (TABLE 3)

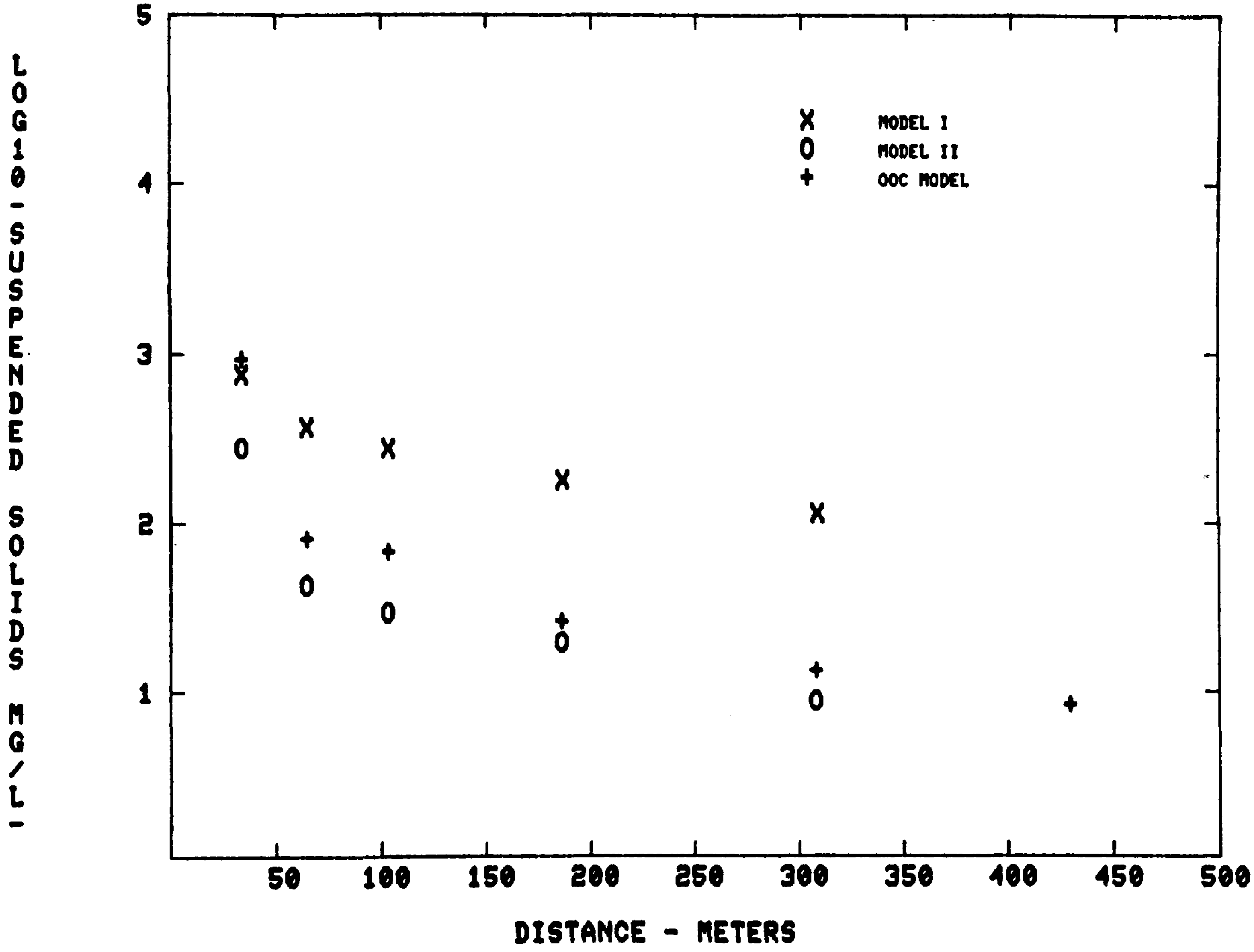
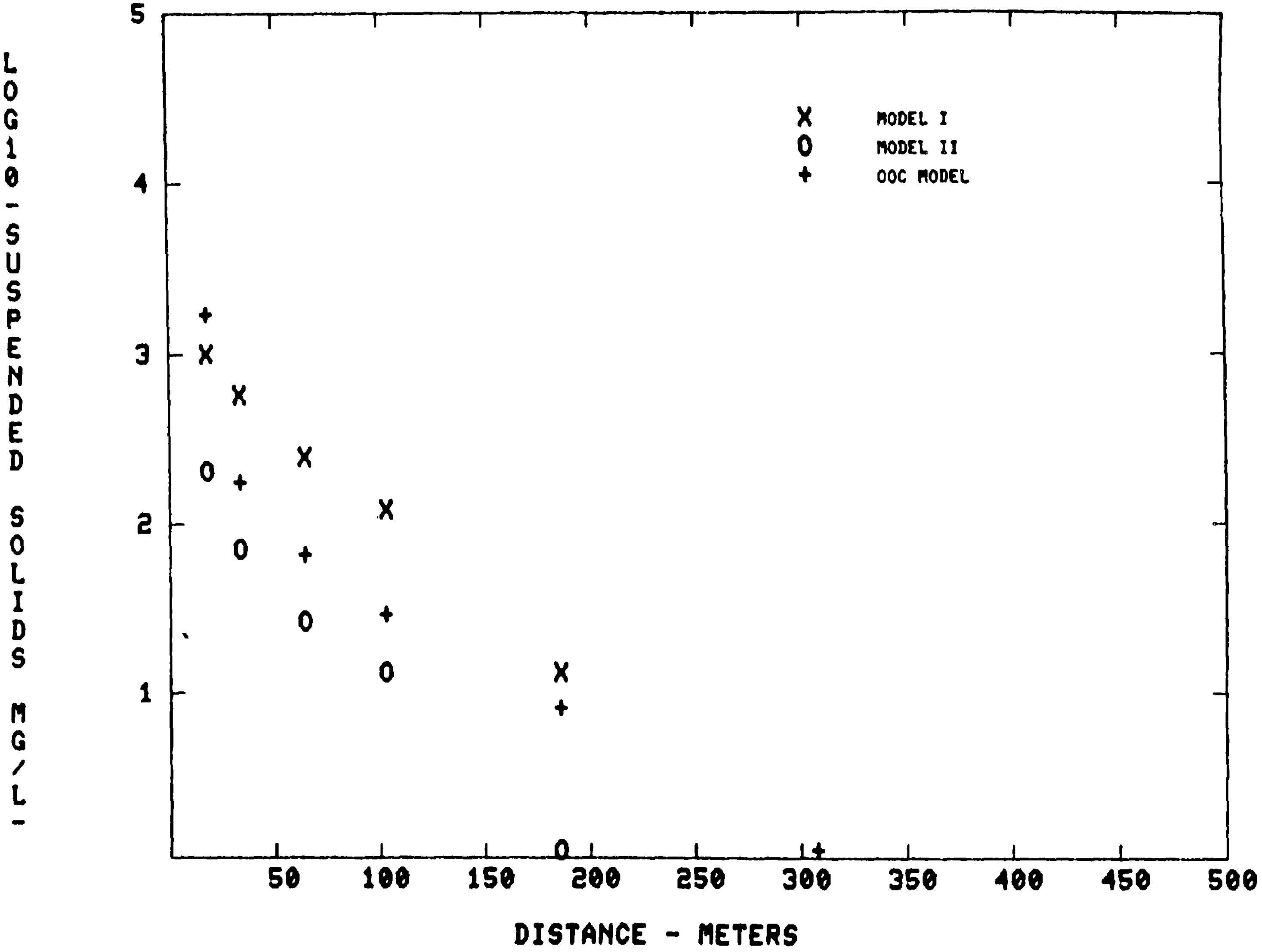


FIGURE 9. COMPARISON OF OOC MODEL AND TWO-DIMENSIONAL MODEL RESULTS. CASE #5 (TABLE 3)



FIQURE 10. COMPARISON OF OOC MODEL AND TWO-DIMENSIONAL MODEL RESULTS. CASE #6 (TABLE 3)

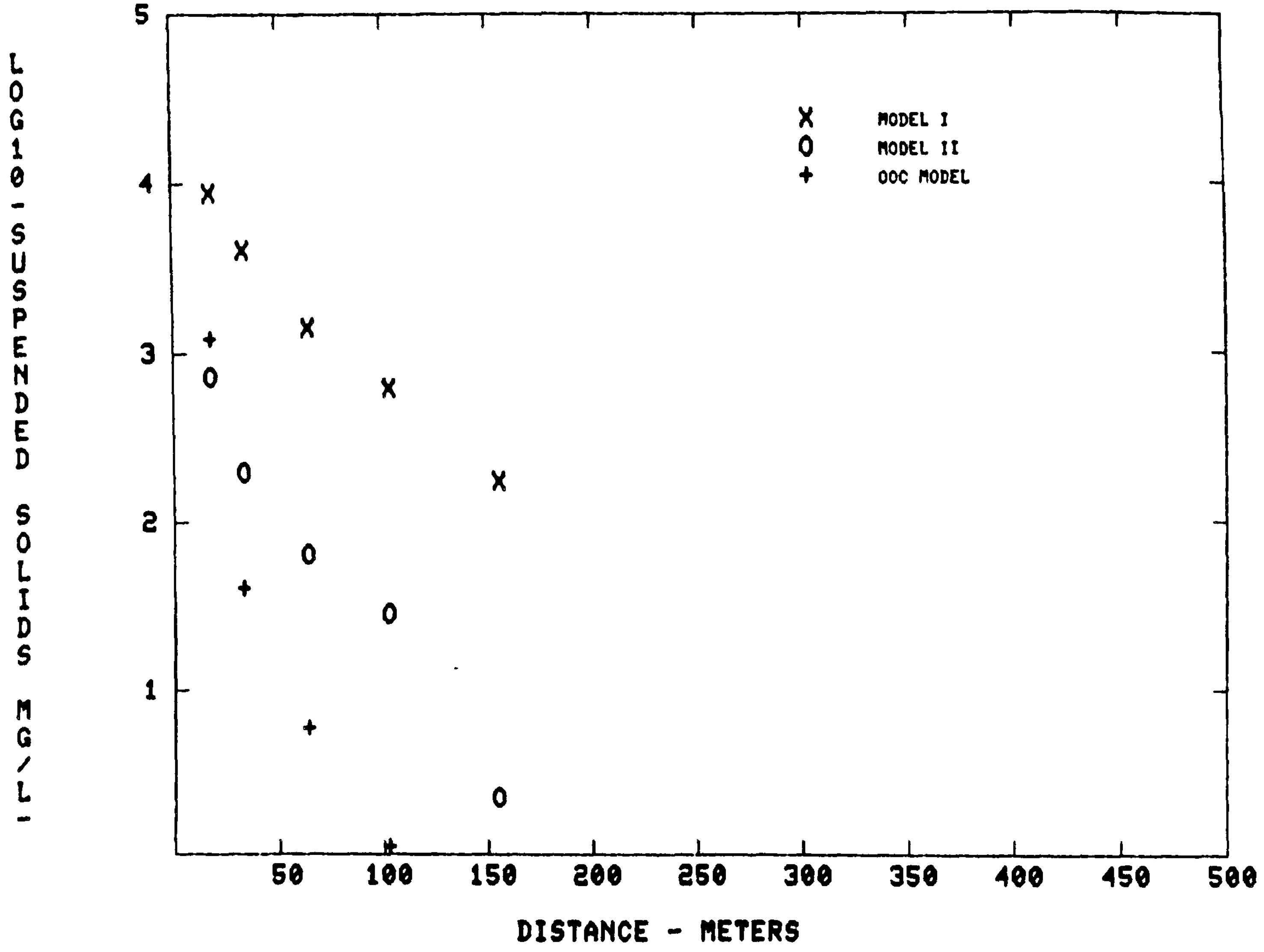
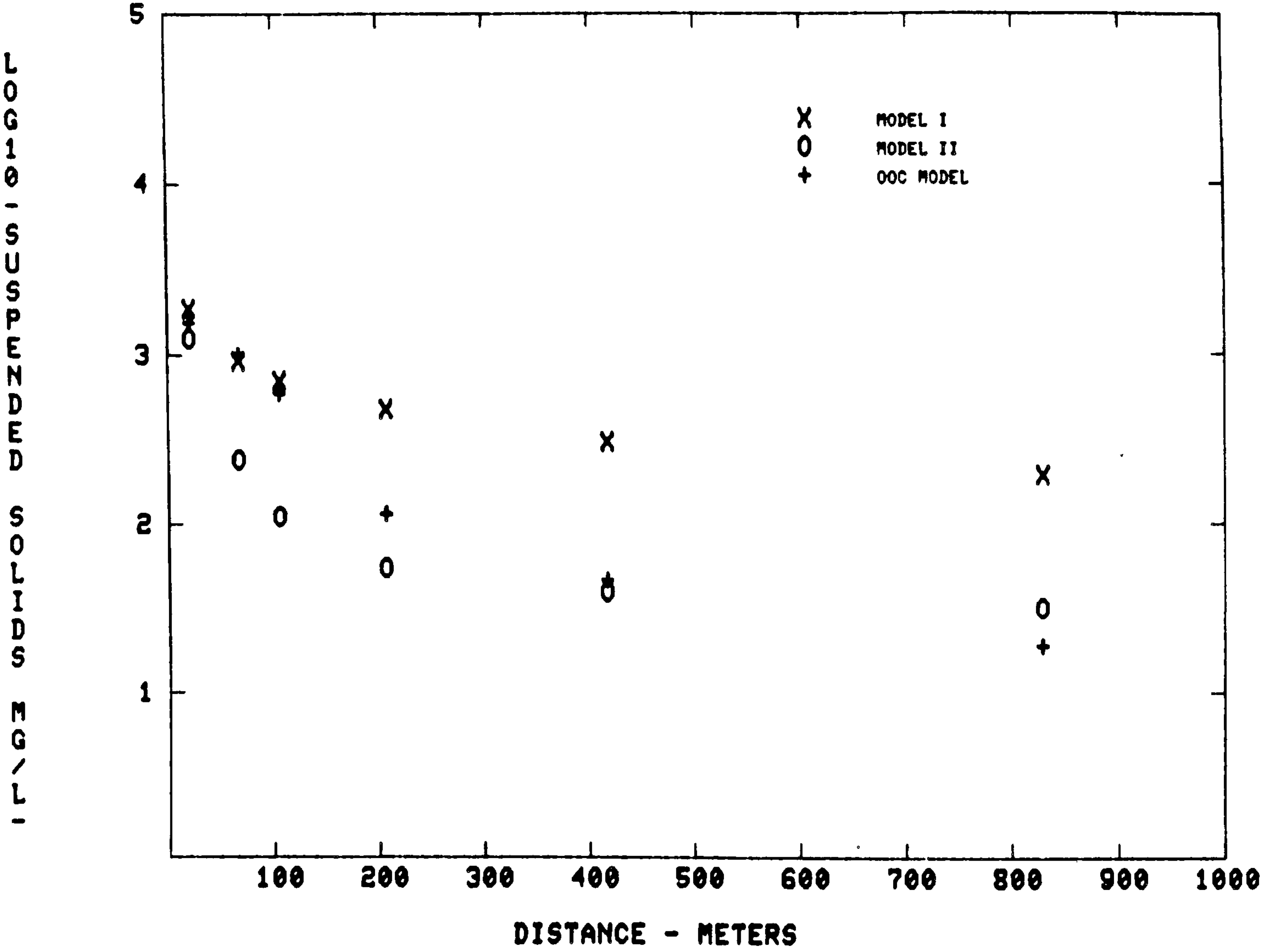


FIGURE 11. COMPARISON OF OOC MODEL AND TWO-DIMENSIONAL MODEL RESULTS. CASE #7 (TABLE 3)



Appendix I

Data Card Input

and

Source Code Listing

for

Two-Dimensional Model

Table 1-1. Data card input description for FORTRAN source code which solves Equation (6).

Card Type	Column	Format	FORTRAN Name	Description
1	1-5	I5	NWR	Unit number of output device (5=CRT,6=line printer)
1	6-10	I5	NTIME	Total number of time periods to be simulated
1	11-15	I5	NSCNDS	Number of seconds between time periods. Algorithm obtains solutions to Equation (6) at t=NSCNDS, 2*NSCNDS,-----,NTIME*NSCNDS
1	16-20	I5	NDX	Number of distances at which model output is desired (NDX 13)
2	1-8	F8.0	X(1)	Distance from discharge point at which output is desired, meters
	.	.	.	.
	.	.	.	.
2	73-80	F8.0	X(10)	Distance from discharge point at which output is desired, meters
2	1-8	F8.0	X(11)	Distance from discharge point at which output is desired, meters
	.	.	.	.
	.	.	.	.
2	17-24	F8.0	X(13)	Distance from discharge point at which output is desired, meters
3	1-10	F10.0	DEPTH	Water depth, meters
3	11-20	F10.0	DT	Integration time increment, seconds
3	21-30	F10.0	DIFF	Coefficient of eddy diffusivity, meters**2/second
3	31-40	F10.0	U	Ambient current speed,meters/second
3	41-50	F10.0	SRCE	Source strength, meters**3-mg/l/second
3	51-60	F10.0	TSTOP	Time at which discharge stops, seconds
3	61-70	F10.0	CBRGND	Background concentration, mg/l
3	71-80	F10.0	RHO	Density of drilling mud, grams/cubic centimeter

Card Type	Column	Format	FORTRAN Name	Description
4	1-10	F10.0	RATIO(1)	Decimal fraction of volume of particle class 1
4	11-20	F10.0	RATIO(2)	Decimal fraction of volume of particle class 2
	.	.	.	.
	.	.	.	.
	51-60	F10.0	RATIO(6)	Decimal fraction of volume of particle class 6
5	1-10	F10.0	W(1)	Settling velocity of particle class 1, meters/second
5	11-20	F10.0	W(2)	Settling velocity of particle class 2, meters/second
	.	.	.	.
	.	.	.	.
5	51-60	F10.0	W(6)	Settling velocity of particle class 6, meters/second

```
      DIMENSION RATIO(6),W(6),X(13),C(13),CTMP(6),SDMNT(13)
C
C     PROGRAM FOR PREDICTING DISTRIBUTION OF SUBSTANCE SUBJECT TO DIFFUSION
C     SETTLING AND HORIZONTAL ADVECTION IN A VERTICALLY WELL-MIXED
C     ENVIRONMENT.  DEVELOPED FOR SPECIFIC APPLICATION TO DISTRIBUTION OF
C     DRILLING MUDS IN A SHALLOW, MARINE ENVIRONMENT. SEE:
C     "A TIME-DEPENDENT, TWO-DIMENSIONAL MODEL FOR PREDICTING THE
C      DISTRIBUTION OF DRILLING MUDS DISCHARGED TO SHALLOW WATERS"
C                                  JOHN YEARSLEY
C                                  EPA REGION 10
C                                  SEATTLE, WASHINGTON
C                                  JANUARY 5, 1984
C
C
C     OPEN FILING CONTAINING CHARACTERISTICS OF PHYSICAL ENVIRONMENT, SETTLING
C     VELOCITIES OF SOLIDS AND MASS EMISSION RATES.  METHOD USED TO OPEN
C     FILE IS SPECIFIC TO PDP 11/70
C
      OPEN(UNIT=4,NAME='XFORM.DAT',TYPE='OLD')
C
C     READ DATA
C
C     CARD #1
      READ(4,1100) NWR,NTIME,NSCNDS,NDX
      DELT=NSCNDS
C
C     CARD#2
      READ(4,1500) (X(N),N=1,NDX)
      WRITE(NWR,2300) X
      WRITE(NWR,2350)
C
C     CARD #3
      READ(4,1200) DEPTH,DT,DIFF,U,SRCE,TSTOP,RHO,CBGRND
C
C     CARD #4
      READ(4,1200) RATIO
C
C     CARD #5
      READ(4,1200) W
      PI=3.14159
      NT=DT
C
C     BEGIN SIMULATION
C
      DO 199 I=1,NTIME
C
C     EXAMINE A TOTAL OF NDX POINTS ALONG THE PLUME CENTERLINE
C
      DO 189 II=1,NDX
      XL=X(II)
      NNT=I*NSCNDS
      XXNT=NNT
      HOUR=XXNT/3600.
      NINC=NNT/NT
      C(II)=0.0
      DO 49 III=1,6
      CTMP(III)=0.0
   49 CONTINUE
C
C     DIVIDE TIME STEP INTO NINC INCREMENTS.  THE LARGER NINC THE MORE
C     ACCURATE THE SIMULATION AND THE MORE CPU TIME REQUIRED.  NINC INCREASES
C     WITH TIME SO THAT MODEL WON'T "FORGET" ALL THE DISCHARGES THAT HAVE
C     OCCURRED IN THE PAST.
```

```
      TI=III
      TAU=DT*(TI-0.5)
      IF(TAU.GT.TSTOP) GO TO 149
      TPRIME=XXNT-TAU
      ARG=(XL-U*TPRIME)**2/(4.*DIFF*TPRIME)
      FCTR=(SRCE*DT/DEPTH)*EXP(-ARG)/(4.*PI*DIFF*TPRIME)
C
C     FOR PURPOSES OF REDUCING CPU TIME, NO COMPUTATIONS ARE MADE WHEN
C     FCTR IS LESS THAN 0.01.  THIS ALSO REDUCES ACCURACY SOMEWHAT, BUT
C     MAKES THE PROGRAM RUN MORE EFFICIENTLY, PARTICULARLY WHEN LONG TIME
C     PERIODS ARE BEING EVALUATED.
C
   50 IF(FCTR.LT.0.01) GO TO 149
      DO 99 IV=1,6
      CTMP(IV)=CTMP(IV)
     .     +RATIO(IV)*FCTR*EXP(-W(IV)*TPRIME/DEPTH)
   99 CONTINUE
  149 CONTINUE
      DO 169 III=1,6
C
C     COMPUTE SEDIMENTATION RATES
C
      SDMNT(II)=SDMNT(II)+1.0E-4*DELT*W(III)*CTMP(III)/RHO
C
C     ADD UP INDIVIDUAL PHASES TO OBTAIN TOTAL SUSPENDED SOLIDS
C
      C(II)=C(II)+CTMP(III)
  169 CONTINUE
C
C     ADD IN BACKGROUND CONCENTRATION, IF NECESSARY.  NOTE: BACKGROUND
C     CONCENTRATION MUST BE SUBTRACTED FROM MASS EMISSION RATE WHEN
C     COMPUTING THE VARIABLE "SRCE" IN THE THIRD DATA CARD.
C
      C(II)=C(II)+CBGRND
  189 CONTINUE
C
C     PRINT OUT RESULTS
C
      WRITE(NWR,2400) HOUR,(C(N),N=1,NDX)
      WRITE(NWR,2500) (SDMNT(N),N=1,NDX)
  199 CONTINUE
 1100 FORMAT(16I5)
 1200 FORMAT(8F10.0)
 1500 FORMAT(10F8.0)
 2200 FORMAT(6E13.4)
 2300 FORMAT('                DISTANCE FROM DISCHARGE(METERS)'/
     .       '  TIME ',F6.0,13F8.0/)
 2350 FORMAT(' (HOURS)              CONCENTRATION (MG/L)'/
     .       '                DEPOSITION THICKNESS (CENTIMETERS)'//)
 2400 FORMAT(F6.2,13F8.0)
 2500 FORMAT(6X,11F8.1)
      STOP
      END
```