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SUSPENDED SEDIMENT DISTRIBUTIO[N] IN A WAVE FIELD

by

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SUSPENDED SEDIMENT DISTRIBUTION IN A WAVE FIELD

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ABSTRACT

Sediment resuspension due to wave agitation has been formulated using the diffusional approach. The classical Schmidt equation is solved to obtain the vertical distribution for time-averaged sediment concentration. The diffusion coefficient is assumed to be proportional to the product of shear velocity at the bed and orbital velocity just outside of the boundary layer. A bed layer concept is proposed to evaluate the absolute values of sediment concentration as a function of the height from the bed knowing the wave parameters such as the wave height, period and the mean water depth and the sediment characteristics such as the grain size and the specific gravity. Laboratory experiments are used to evaluate the dimensionless diffusion coefficient and the bed layer thickness in terms of the dimensionless parameters controlling the phenomenon. The present formulation is compared with the experimental data of other investigators and a reasonable agreement between the two is obtained.

KEYWORDS: suspended-sediments, waves, vertical distribution, bed-load, bed-layer, water-quality.

RÉSUMÉ

La remise en suspension des sédiments, due aux vagues a été formulée à partir du principe de la diffusion. La résolution de l'équation classique de Schmidt donne la distribution verticale des moyennes temporelles des concentrations des sédiments. Le coefficient de diffusion est supposé proportionnel au produit de la vitesse de cisaillement dans le fond par la vitesse orbitale juste an dehors de la couche limite. Le concept de couche de fond est proposé pour évaluer la concentration absolue des sédiments en fonction de la hauteur à partir du fond, si l'on connaît les paramètres des vagues comme leur hauteur et leur période, la hauteur moyenne de l'eau, et les caractéristiques des sédiments comme la taille des grains et la masse volumique. Des expériences de laboratoire permettent une évaluation du coefficient de diffusion sans dimensions et de l'épaisseur de la couche de fond en fonction des paramètres sans dimensions qui régissent le phénomène. Une étude comparative a montré un accord raisonnable entre les résultats de cette formulation et les résultats expérimentaux d'autres chercheurs.

MANAGEMENT PERSPECTIVE

Progressive waves, in shallow water, may bring bottom sediments into suspension. Knowledge of the concentrations of sediment in the vertical are of significance where water depths may be manipulated or changed.

Suspended sediment in reservoirs may affect spawning areas and water intakes. Light extinction, altered by changes in water depth, in turn bring about an altered biological regime which may radically alter the growth and distribution of aquatic vegetation.

This paper improves the knowledge of sediment movements created by waves and provides a technique for calculating vertical concentrations of sand sized bottom sediments. The results are a milestone in progress towards a coastal model of shoreline development.

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PERSPECTIVE DE GESTION

Les ondes progressives, en eau peu profonde, peuvent remettre les sédiments en suspension. Il est important de connaître le profil vertical des concentrations des sédiments là où la hauteur d'eau peut varier.

Les sédiments en suspension dans les réservoirs peuvent nuire aux frayères et aux prises d'eau. L'amortissement de la lumière, modifié par des changements dans la hauteur d'eau, provoque à son tour des perturbations dans le régime biologique qui peuvent changer radicalement la croissance et la distribution de la végétation aquatique.

Ce rapport permet d'approfondir les connaissances des mouvements des sédiments causés par les vagues et propose une technique de calcul du profil vertical des concentrations des sédiments de la taille du sable. Les résultats marquent une étape importante dans le progrès vers un modèle d'évolution des littoraux.

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Chef de la Division d'hydraulique

5 november 1981

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INTRODUCTION

Sediment resuspension due to wave agitation can significantly affect the water quality in shallow lakes. The knowledge of the interaction between the wave motion and the sediment forming the lake bottom is an essential tool in the water quality management of such shallow lakes. When waves are present, the orbital motion of the water particles associated with the wave motion can penetrate all the way down to the lake bottom imparting shear stresses at the sediment-water interface. If the shear stress exceeds a certain critical value, the sediment begins to move back and forth. In the beginning when the sand bed is flat, the vertical excursions of the sand particles are confined to a very narrow ribbon in the vicinity of the bed. But as the process continues, the flat bottom gradually deforms into a wavy one and finally attains a steady bed form called "ripples". When such ripples begin to develop, the oscillatory motions of the water particles set up "vortices" at the troughs which are "convected" towards the crests and "diffused" upwards into the body of water to a considerable distance from the bed. These vortices pick up sediment which travels with the vortices, and at the same time, settles due to the negative buoyancy. Under this condition, the vertical excursions of the sediment particles extend to a considerable distance from the sand bed and the sediment is said to have come in suspension. The concentration of the suspended sediment varies with the distance from the sand

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bed and also depends on the wave parameters and the sediment characteristics. A quantitative knowledge of the vertical distribution of the suspended sediment is also very useful in engineering designs such as the positioning of water intakes for domestic and industrial uses.

REVIEW OF PREVIOUS WORK

There are several studies relating to suspended sediment distribution under wave action in the literature (see References 1 to 9). A concise summary of the various studies was given in a comprehensive paper by J. F. Kennedy and F. A. Locher (11).

The pioneering work in this problem area was carried out in 1958 by Shinohara, Tsubaki, Yoshitaka and Agemori (16) who measured the sediment concentrations using a siphon-type sediment sampler in a laboratory wave tank. Their measurements indicated that the vertical distribution of the time-averaged concentration followed an exponential curve, suggesting that the vertical diffusion coefficient which appears in the steady-state diffusion equation has to be a constant. In 1962, M. Hom-ma and K. Horikawa (6) analyzed the vertical distribution of sediment suspension by progressive waves over a horizontal, rippled bottom, using the steady-state diffusion-convection equation for sediment motion. They expressed the vertical diffusion coefficient ϵ_y as follows:

$$\epsilon_y = \beta b^2 \left| \frac{\partial u}{\partial y} \right| \tag{1}$$

where β is an empirical constant, b is the minor radius of an orbit, u is the horizontal velocity component of a water particle and y is the vertical coordinate. They further assumed that the instantaneous concentration C varied along the horizontal distance, x and time t as:

$$C = \bar{C}(y) \left[1 + \xi \sin 2 (kx - \frac{2\pi t}{T}) \right] \qquad (2)$$

where k is the wave number, T is the wave period, ξ is a constant and $\bar{C}$ is the time-averaged concentration. Their resulting expression for the mean sediment concentration distribution was compared with laboratory and field measurements and a favorable agreement was obtained. However, as pointed out by Kennedy and Locher (11), the theory put forward by Hom-ma and Horikawa (6) has three major shortcomings. First, the expression for ε_y as given by Eq. 1 goes to zero for shallow-water waves. This is unrealistic since the long waves are very effective in entraining and sustaining the sediment suspension. Second, the turbulence in a wave field originates as turbulence produced near the bed and diffused into the body of water rather than as a result of turbulence production by the velocity gradient. Third, the variation of sediment concentration as given by Eq. 2 is an over simplification. In a later paper, Hom-ma and Horikawa (7) reported concentration measurements using an optical type of instrument and observed that the sediment concentration at a point exhibits, in general, four peaks within a wave period.

In 1965, Hom-ma, Horikawa and Kajima (8) put forward a revised theoretical model for sediment suspension under wave action. In this work, they evaluated the vertical diffusion coefficient ε_y as follows:

$$\varepsilon_y = \frac{1}{K} \frac{\eta c}{\sinh kd} \cdot \frac{\sinh^3 ky}{\cosh^2 ky} \qquad (3)$$

where K is a constant, c is the wave celerity, η is wave amplitude and d is the water depth. From their experimental results, the authors concluded that K is a function of the ripple geometry and an empirical relation for K was derived and substituted in Eq. 3. The vertical distribution of the mean sediment concentration was then derived by integrating the steady-state diffusion equation with ε_y as given by Eq. 3. This analysis also suffers the same shortcomings as that of the previous analysis (6), but in this analysis the authors indicted the importance of the bed geometry in analyzing the suspended sediment concentration distributions.

In 1969, Hattori (5) studied the vertical and horizontal distributions of mean sediment concentration under a standing wave. He introduced a concept of a "delay distance" to account for the particle inertia. The difference between the particle and fluid velocity was expressed as the product of the "delay distance" and the local velocity gradient. He used a constant value for the vertical diffusion coefficient ε_y and solved the diffusion equation to obtain the expression for the mean sediment concentration under a standing wave.

In his work, Hattori (5) did not give a method to calculate or estimate the value of the "delay distance".

In 1970, Horikawa and Watanabe (9) presented a study on the direct measurement of the variation of the diffusion coefficient ε_y. They measured the turbulent velocity fluctuations u' and v' as well as the rms values of the deviation of the sediment concentration from mean value directly. The authors admitted that the instrumentation and data analysis needed further improvement.

In 1972, Kennedy and Locher (11) proposed analytical models for sediment suspension. They began their analysis with the equation for continuity of sediment motion as:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(u_s C) + \frac{\partial}{\partial y}(v_s C) - \frac{\partial}{\partial y}(wC) = 0 \qquad (4)$$

where C is the volumetric concentration, u_s and v_s are the sediment particle velocities in the x and y directions respectively, w is the fall velocity of the sediment particles. Introducing Hattori's concept of "delay time" and expressing the instantaneous concentration C as a sum of three components, namely, the time-averaged concentration $\bar{C}$, a periodic time-dependent component C_p and a random component C' and also expressing the fluid velocity v as the sum of a periodic component v_p and a random component v' and performing a time-averaging procedure on Eq. 4 the authors arrived at the following simplified general equation:

$$\overline{C_p \left\{ v_p - \tau \frac{\partial v_p}{\partial t} \right\}} + \overline{C' \left\{ v' - \tau \frac{\partial v'}{\partial t} \right\}} = w\bar{C} \qquad (5)$$

where the symbol τ stands for the delay time. In arriving at the above equation, the authors dropped the gradient term in the x direction based on their experimental observation that the gradients in the x direction are small compared to those in the y direction.

The authors further assumed that the term resulting from the fluctuating (random) part of C and v, i.e. the term $\overline{C' \; v' - \tau \; \partial v'/\partial t}$ includes all the effects of turbulence and hence can be represented by a diffusion type term, in which case, Eq. 5 becomes:

$$C_p \left\{ v_p - \tau \frac{\partial v_p}{\partial t} \right\} - \varepsilon_y \frac{dC}{dy} = w\bar{C} \qquad (6)$$

The authors investigated different assumptions to evaluate the term containing the periodic component of C and v and for the variation of ε_y over depth. They used the experimental data of Bhattacharya (1) to compare the resulting distributions and came to the conclusion that practically any estimate for ε_y and for the term containing the periodic components of C and v can yield a fairly accurate prediction for the distribution of $\bar{C}$. Even the case wherein the entire term containing the periodic components was dropped, i.e. the classical Schmidt equation produced distributions which agreed favourably with the experimental data.

PRESENT APPROACH

The conclusion arrived at by Kennedy and Locher (11) has far reaching implications on future research efforts in this area. Because of the insensitive nature of the mean concentration to the variation of the diffusion coefficient and the transport due to the periodic component, no further understanding of the basic mechanisms controlling the phenomenon can be achieved by looking at the time-averaged properties. Rather, direct measurements of the various transport terms are necessary. This was attempted by T. Nakato, F. A. Locher, R. Glover and J. F. Kennedy (15) in a recent paper. Their results are not conclusive due to limitations of the instruments used. Further work need to be done to improve the instrumentation and data analysis techniques.

The conclusion of Kennedy and Locher (11) has a brighter side. It implies that the success of formulating theoretical models to predict, for instance, the mean concentration distributions in a wave field is almost guaranteed. Such models can be used for making predictions for practical engineering problems with reasonable accuracy. The purpose of the present paper is to develop a simple mathematical model to predict the mean concentration distributions in a wave field which can be used by practising engineers to solve engineering and environmental problems. As noted earlier, such an approach is not going to advance scientific knowledge on the phenomenon, but will form a useful tool for practical applications.

The classical Schmidt equation will be employed in the present model. The coordinate system is as shown in Fig. 1. In this coordinate system the equation can be written as follows:

$$\varepsilon_y \frac{d\bar{C}}{dy} + w\bar{C} = 0 \qquad (7)$$

where w is the fall velocity directed in the negative y direction. The diffusion coefficient ε_y is evaluated using the following expression:

$$\varepsilon_y = \beta \cdot a_\delta v_* \qquad (8)$$

where β is a proportionality constant, a_δ is the orbital length just outside of the boundary layer and v_* is the shear velocity.

The integration of Eq. 7 with ε_y as given by Eq. 8 gives the vertical distribution of the mean concentration $\bar{C}$ as follows:

$$\frac{\bar{C}}{\bar{C}_a} = \exp\left[-\frac{w}{v_*} \cdot \frac{1}{\beta} \cdot \frac{y-a}{a_\delta}\right] \qquad (9)$$

where $\bar{C}_a$ is the mean concentration at a reference lever y=a from the bed.

The value of the reference concentration $\bar{C}_a$ is evaluated using an approach similar to that described by Brown (2) for the case of the uni-directional flows. According to this approach, the reference level is chosen to be the level that can be considered as the ceiling of a layer (of thickness 'a') in which the bed-load transport of the sediment takes place. The concentration within the layer due to the bed-load transport of sediment is assumed to be constant.

Therefore, knowing the time-averaged bed-load sediment transport rate, say, $\bar{q}_s$ and the transport velocity which can be taken as the orbital velocity u_δ the reference concentration $\bar{C}_a$ can be computed as:

$$\bar{C}_a = \frac{\bar{q}_s}{a\, u_\delta} \qquad (10)$$

The absolute mean concentration distribution, therefore, becomes:

$$\bar{C} = \frac{\bar{q}_s}{a\, u_\delta} \exp\left[- \frac{w}{v_*} \frac{1}{\beta} \cdot \frac{y-a}{a_\delta} \right] \tag{11}$$

In the present work, the quantities a_δ and u_δ are computed using the first order wave theory as:

$$\left. \begin{aligned} u_\delta &= \frac{\pi H}{T \sinh \frac{2\pi d}{L}} \\ &\text{and} \\ a_\delta &= \frac{H}{2 \sinh \frac{2\pi d}{L}} \end{aligned} \right\} \tag{12}$$

where H is the wave height, T is the wave period, L is the wave length and d is the water depth.

The fall velocity, w, of the sediment particle can be calculated using the measured values of the drag coefficient for spheres from Fig. 1.5 of H. Schlichting (17). The Stokes Theory overestimates the fall velocities since the flow regime surrounding the particles is outside of the laminar regime. If the flow regime surrounding the particles is laminar, then the free velocity can be determined from the Stokes equation:

$$w = \frac{g}{18\nu} (s - 1)\, D^2 \tag{13}$$

ν in the above equation is the kinematic viscosity of water, s is the specific gravity, and D is the sediment grain diameter.

The shear velocity v_* can be computed from the friction factor diagram of Kamphius (10). The relative roughness parameter is formed using the height of the ripples instead of the sediment size.

The average bed-load transport rate $\bar{q}_s$ is computed using the Einstein-Brown formula which was modified by Madsen and Grant (13) for the wave fields. The form of the equation is as follows:

$$\bar{\Phi} = 12.5 \quad {\Psi'_m}^3 \tag{14}$$

where $\bar{\Phi}$ and Ψ'_m represent the following dimensionless groups:

$$\bar{\Phi} = \frac{\bar{q}_s}{wD}$$

and (15)

$$\Psi'_m = \frac{v_*'^2}{g\,(s-1)\,D}$$

In the above relation, D stands for the sediment grain diameter, v'_* is the shear stress associated with the skin friction stress, s is the specific gravity of sediment particles and g is the acceleration due to gravity. Equation 14 has been tested by Madsen and Grant (13) for the case of ripple beds and has been found to predict the sediment transport rate reasonably well. The shear stress associated with the skin friction is estimated from the friction factor diagram of Kamphius (10). The relative roughness parameter, in this case, has to be related to the sediment size rather than the height of the ripples.

Equation 11, which gives the distribution of $\bar{C}$ over the vertical contains two more parameters, namely, the dimensionless diffusion coefficient β as defined by Eq. 8 and the height of the reference level 'a' from the bed. Under the present state of knowledge, it is not possible to estimate these two parameters theoretically and the only possibility is to determine them empirically from measurements. Therefore, laboratory measurements of sediment concentrations were undertaken in a wave flume. The description of the equipment and the experimental procedure will be taken up before outlining the details of the evaluation of β and 'a' using the measured data.

EXPERIMENTAL EQUIPMENT

The experiments were performed in a wave flume 10 m long, 0.3 m wide and 0.6 m deep. Monochromatic waves were generated with a hinged paddle, driven by an electric motor through a variable speed transmission. A beach with slope 1 to 8, covered with 10 cm of rubberized animal hair, was installed at the end opposite the paddle. Wave filters, made of several layers of wire cloth (2 mm wire on a mesh of 2.5 cm), were located in front of the paddle and the beach to reduce the size of the reflected waves.

The waves were monitored with two capacitance wave probes. The active element of these probes was a teflon insulated wire of about 1 mm in outside diameter, located on the centreline of the flume. The probes were carefully calibrated and their linear voltage outputs were sampled by an analog to digital converter connected to a minicomputer. Initial tests to determine the amount of wave reflection were done using the technique described by Goda and Suzuki (4). The ratio of reflected wave heights to incident wave heights was from 2% to 6% for the range of wave parameters used during the experiments.

A 10 cm layer of glass beads was placed on the bottom of the flume. A faired step was placed at the paddle end of the bed so that there was a smooth transition to the flume floor. The beads had a density of 2500 kg/m^3, and they were sieved, yielding a size range of from 0.125 to 0.177 mm.

The temperature of the water varied considerably from day to day due to large changes in the air temperature in the laboratory. The water temperature was monitored closely so that the correct values of kinematic viscosity could be determined.

The suspended sediment was measured with an Iowa Sediment Concentration Measuring System (ISCMS). Descriptions of this instrument may be found in Kennedy and Locher (11) and Locher, Glover and Nakato (12). Briefly, the ISCMS is an electro-optical device which measures the amount of light attenuation between a source and sensor, as caused by particles passing through the light beam. The probe was modified from their design because of difficulties due to water leakage. The source and sensor were relocated into the large diameter section of the support tube, and well sealed. Two coherent fibre optic image conduits were used to conduct the light. They were arranged in a fork fashion with the ends of the tynes facing each other so that the light path in the water had similar dimensions to the original probe.

The voltage output of the ISCMS was monitored on a chart recorder and an oscilloscope, and the frequency output on a frequency counter. These devices and the zero indicator lights on the ISCMS were used to adjust the zero level (no sediment in suspension) of the instrument. Ambient light was constant throughout the experiment.

The voltage output was measured with the analog to digital converter previously mentioned. The voltage output was a series of pulses caused by the extinction of light due to one or more particles passing through the light path.

The sample rate of the converter was selected so that, on average, at least 3-1/2 samples were taken in the duration of the upper half amplitude of the narrowest pulses. 32,512 samples were taken, and the rate was such that the total sampling time correponded to exactly 40 waves. (The range of sample rate was about 700 to 1000 samples per second.) In this way enough detail of the pulses was observed, and a sufficient number of them observed to successfully determine the average voltage output under all suspended sediment measurements. At regular intervals during the experiment and the calibration procedure, the instrument output was sampled with no sediment in suspension, to determine the noise level. The readings were then corrected for this noise level.

The instrument was calibrated in a turbulence jar, similar to that described by Locher, Glover and Nakato (12). Small ports were made in the side of the jar at the probe elevation, and the samples of water and sediment for calibration were extracted horizontally through them. The instrument output was sampled 32,512 times at 1000 samples per second while a 50 cm^3 volume was extracted, thus reproducing as closely as possible the conditions in the wave flume. The range of concentration measured covered the range encountered in the wave flume. The resulting calibration curve is shown in Fig. 2.

EXPERIMENTAL PROCEDURE

A preliminary test was run before each experiment to select the wave conditions and to make qualitative observations of the suspended sediment. Once the wave conditions were selected and measured, the bed of glass beads was levelled, and the wave machine started. Typically after about two hours the ripples on the bed had reached steady state and the experiment could begin. The ripple height (Δ) and length (Λ) were measured.

The sediment concentration was measured directly over the crest and the trough of the bedform. The first measurement was made well above the bed, to avoid scour due to the presence of the probe. At least two scans of the instrument output were run at each elevation and averaged. The location of the probe both in phase and in elevation relative to the bedform was checked at regular intervals to ensure that the bedform had not moved appreciably. Minor movements in the bedform were accounted for by moving the probe correspondingly. If the bedform moved significantly, the experiment was aborted. The probe was raised in increments and measurements repeated up to the elevation where the readings were the same as the background noise. The probe was then lowered closer to the bedform from the starting elevation and measurements continued, until the probe was close enough to cause scour of the bedform (typically about 1/3 to 1/2 of the ripple height above the crests, and about 2/3 of the height above the troughs). The measurements taken when scour was evident were rejected.

Average values of concentration as a function of height above crest and trough and all other information such as maximum orbital velocity, water density and viscosity were stored in computer files for later processing.

A summary of all experimental conditions is given in Table 1.

DETERMINATION OF β

Using the measured values of the mean concentrations, a semi-log plot of $\bar{C}$ and y was constructed for each run. From the slope of the best fit line the value of β was evaluated knowing w, v_* and a_δ. The procedure was repeated for all the runs and β values for each run were established. The values are tabulated in Table 1. The β values varied from run to run. The variation is from .053 to

0.168. An attempt was made to correlate the values of β with the characteristic parameters of the phenomenon. Among the various possibilities, the correlation between β and $(v_* D/\nu)$ appeared to be the best. The graph showing log β and log $(v_* D/\nu)$ is given in Fig. 3. The equation of the best fit line is:

$$\beta = 8.7 \left(\frac{v_* D}{\nu}\right)^{-2.2} \qquad (16)$$

DETERMINATION OF a

The reference level 'a' was determined by first selecting an arbitrary reference height and rewriting Eq. 9 using the measured concentration at the reference height. The value of $\bar{C}$ at y=a obtained from this equation was then equated to $\bar{C}_a$ from Eq. 10. The resulting implicit equation was solved using a Newton-Raphson iteration scheme. The bed layer thickness 'a' was made dimensionless using the sediment size D. The values of ratio (a/D) calculated for all the runs are tabulated in Table 1. The ratios varied from run to run ranging from 0.86 to 7.28 with an average value of 3.0. The variations in (a/D) include at least three different possible components:

a) errors in the prediction of the bed load transport using the formula of Einstein and Brown

b) experimental scatter, and

c) systematic variation of the thickness of bed layer with the flow parameters.

Owing to this reason, no attempt was made to correlate the ratio (a/D) with the other dimensionless parameters govering this flow. Instead the average value

$$\frac{a}{D} = 3.0 \qquad (17)$$

was chosen. It is worth noting here that, for unidirectional flows, the bed layer thickness has often been taken as two times the grain diameter.

VERTICAL DISTRIBUTION OF CONCENTRATION

The method outlined in the paper facilitates the determination of the vertical distribution of the mean concentration of the suspended sediment in a wave field once the wave parameters such as the wave height H, wave period T, wave length L, water depth d, and the sediment parameters such as the sediment grain diameter D, specific gravity s, and the fluid property such as the kinematic viscosity ν are known. The step-by-step procedure to establish the vertical distribution of $\bar{C}$ is summarized below.

Step 1: Knowing the sediment size D, specific gravity s, and the kinematic viscosity ν, compute the fall velocity w either using Eq. 13, or from the sphere drag coefficient curve from any standard text book.

Step 2: Knowing H, T, L and d, compute u_δ and a_δ using Eq. 12.

Step 3: Determine v_* and v'_* from the friction-factor diagram of Kamphius (10). If the height of ripples is not known, use the design curves of Mogridge and Kamphius (14) to predict the height of the ripples. The friction factor diagram of Kamphius and the design curves of Mogridge and Kamphius for the prediction of ripple heights are given in Appendices III and IV respectively for easy reference.

Step 4: Knowing U_*, D and ν using Fig. 3 or Eq. 16 determine β.

Step 5: Knowing D and using Eq. 17 determine a.

Step 6: Knowling v'_* and using Eqs. 14 and 15 determine $\bar{q}_s$.

Step 7: Using Eq. 11 determine $\bar{C}$ as a function of y.

DISCUSSION OF RESULTS

Figures 4 to 8 show the comparison between the measured distributions of the mean concentration and the distributions computed according to the present method for some of the runs. Comparisons for the remaining runs are not shown here due to the limitation on the length of the paper, but the agreement for these runs is comparable to that of the runs shown in Figures 4 to 8. It can be seen from these figures that the slope of the predicted lines compares very favourably with that of the experimental points for all the runs whereas the same cannot be said for the absolute values of the predicted concentration. For example, for run no. 6 (Fig. 4), the predicted concentration is consistently larger than the measured values for all the heights. For run no. 8 (Fig. 7), the values are consistently lower though the difference is not as large as for run no. 6.

The reason for such a result is the use of Eq. 17 for the thickness of the bed layer. Indeed, for run no. 6, the actual value of the bed layer thickness is 5.58 times the grain diameter and, for run no. 8, it is 1.28 times the grain diameter. Since an average value of three times the grain diameter was used in the predictions, over-prediction in the case of run no. 6 and under-prediction in the case of run no. 8 have occurred.

The dimensionless diffusion coefficient, β, governs the slope of the predicted lines in Figs. 4 to 8 whereas the thickness of the bed layer 'a' influences the absolute values of the predicted concentrations. Since the discrepancy between the measurement and prediction is noticed only in the absolute values of the predicted concentrations and not in the slope, it can be concluded that the β values as given by Eq. 16 can be considered as adequate for practical applications. As for the thickness of the bed layer 'a', further improvement for its estimation could be attempted as new and more accurate relationships to predict the bed load transport rates in wave induced flows become available.

The method was tested against the experimental data of Kennedy and Locher (11). The ripple size was estimated using the method of Mogridge and Kamphius (14). The water temperature was assumed to be 20°C. The present formulation uses elevation above the local bed whereas Kennedy and Locher reported their elevations above the mean bed level. In Fig. 9, which is taken from Kennedy and Locher, the prediction resulting from the present method is shown. The comparison should be made between the dark and half-filled circles and the curve. Only the two sets of points correspond to the mean bed level.

The value of the dimensionless parameter $(v_* D/\nu)$ for the data of Kennedy and Locher used in Fig. 9 is 10.71 which is outside the range of the present experiments. In spite of this, the present formulation predicts the concentration distribution reasonably well. However, this does not mean that the method is applicable for the whole range of the parameter $(v_* D/\nu)$. The form of Eq. 16 suggests that as $(v_* D/\nu)$ increases, the value of β decreases approaching zero when $(v_* D/\nu$ approaches infinity. Such a form does not reflect the truth, because β cannot become zero. It is possible that β, indeed, decreases with $(v_* D/\nu)$. More experimental data are required to test the above hypothesis and also to extend the range of applicability of the present formulation.

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APPENDIX II. - NOTATION

The following symbols are used in this paper:

a = thickness of bed layer;

a_δ = orbital length of a fluid particle just outside the boundary layer;

b = minor radius of a particle orbit;

c = wave clarity;

C = volumetric concentration of suspended sediment;

$\bar{C}$ = time average value of C;

C_p = periodic time dependent component of C;

C' = random component of C;

d = water depth;

D = sediment grain diameter;

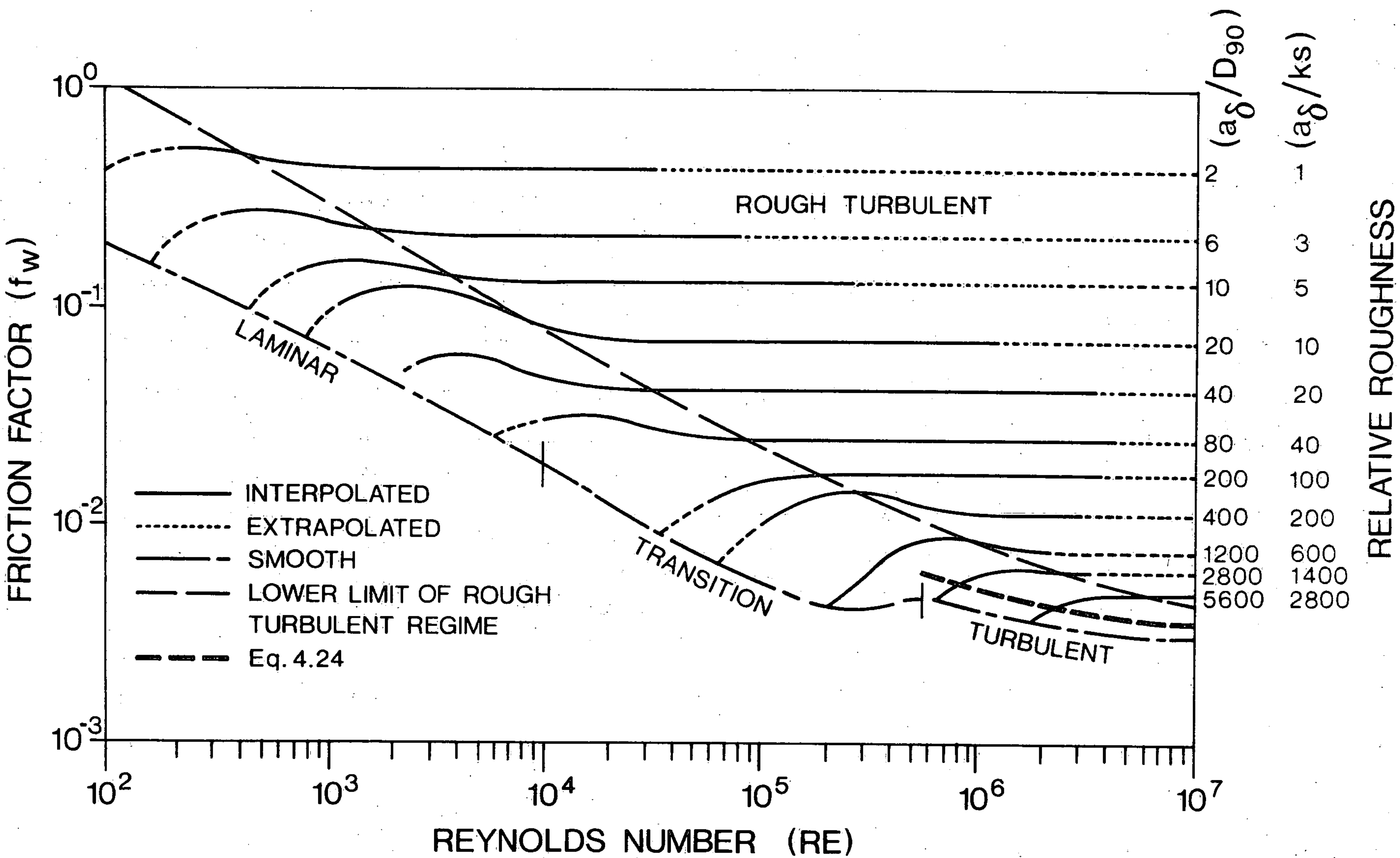
g = acceleration due to gravity;

H	=	wave height;
K	=	a constant;
k	=	wave number;
L	=	wave length;
q_s	=	time average bed load sediment transport rate;
s	=	specific gravity;
T	=	wave period;
u	=	horizontal velocity component of a fluid particle;
u_δ	=	orbital velocity of a fluid particle;
u_s	=	horizontal velocity component of a sediment particle;
v_s	=	vertical velocity component of a sediment particle;
v_*	=	total shear velocity;
v'_*	=	shear velocity associated with skin friction;
w	=	fall velocity of sediment particles;
x	=	horizontal coordinate;
y	=	vertical coordinate;
β	=	dimensionless mass transfer coefficient;
ε_y	=	mass transfer coefficient in the vertical direction;
ν	=	kinematic viscosity of fluid;
ϕ	=	dimensionless form of $\bar{q}_s$;
Ψ'_m	=	mobility parameter.

APPENDIX. - III

Friction factor diagram of Kamphius

RE	=	maximum amplitude Reynolds number for sinusoidal motion
	=	$u\ a_{\delta}/\nu$
f_w	=	wave friction factor
	=	$2\,(v_*/u_{\delta})^2$
k_s	=	equivalent sand grain roughness parameter



FRICTION FACTOR (f_w)
10^0
10^-1
10^-2
10^-3
REYNOLDS NUMBER (RE)
10^2
10^3
10^4
10^5
10^6
10^7
(a_δ/D_90)
(a_δ/ks)
RELATIVE ROUGHNESS
2 1
6 3
10 5
20 10
40 20
80 40
200 100
400 200
1200 600
2800 1400
5600 2800
ROUGH TURBULENT
LAMINAR
TRANSITION
TURBULENT
INTERPOLATED
EXTRAPOLATED
SMOOTH
LOWER LIMIT OF ROUGH TURBULENT REGIME
Eq. 4.24

APPENDIX. - IV

Design curves of Mogridge to predict ripple characteristics in waves

Λ = ripple length

Δ = ripple height

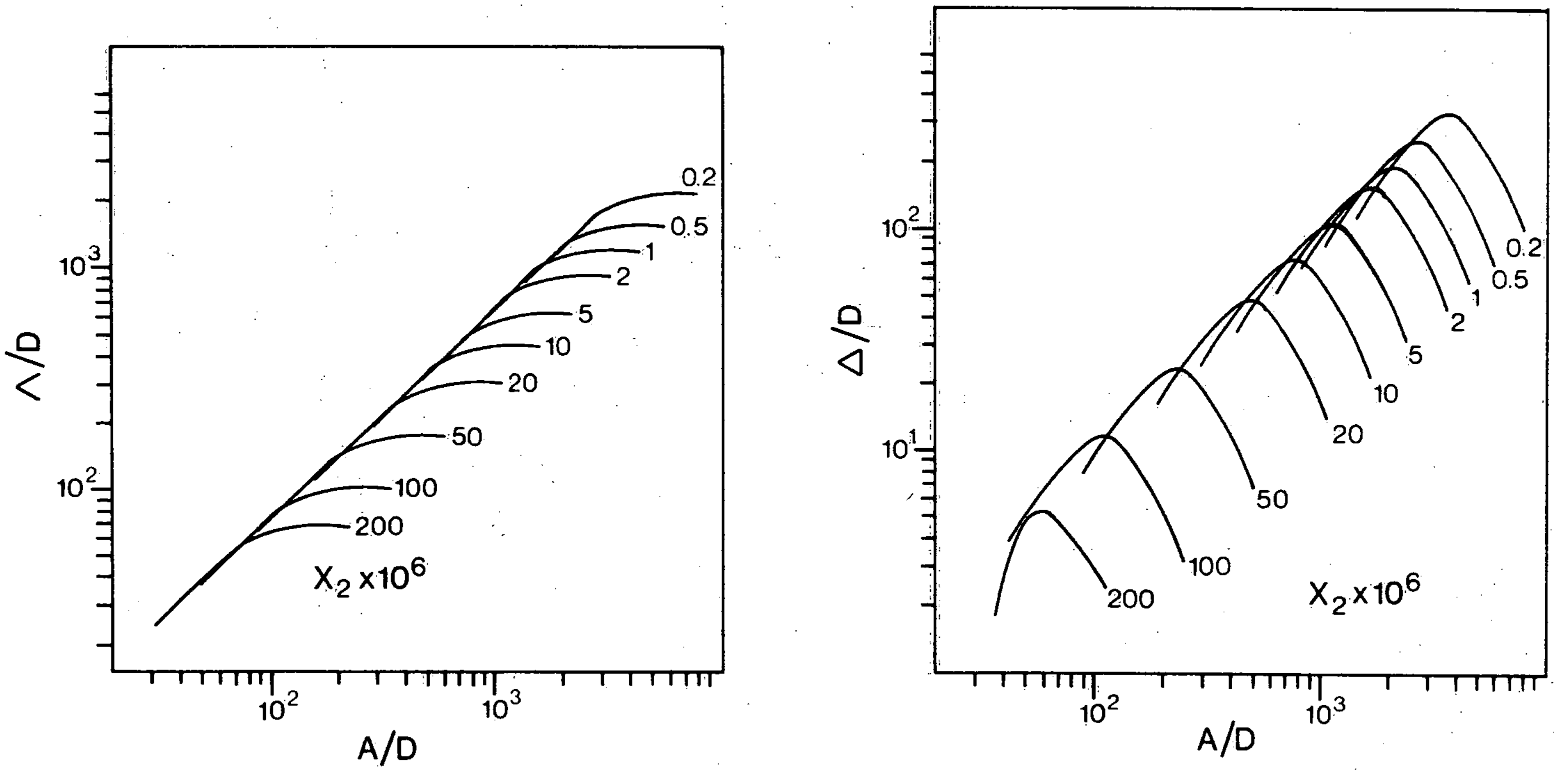
D = sediment grain diameter

X_2 = $D/(s - 1)\,gT^2$

A = $2\,a_\delta$

Left hand figure: Design Curves for Bed Form Length

Right hand figure: Design Curves for Bed Form Height


Λ/D
10^3
10^2
0.2
0.5
1
2
5
10
20
50
100
200
X2 x10^6
10^2
10^3
A/D
Δ/D
10^2
10^1
0.2
0.5
1
2
5
10
20
50
100
200
X2 x10^6
10^2
10^3
A/D

Tables

TABLE 1. - Experimental Results. The symbols are defined in the text.

Run No.	T s	H m	d m	Temp. °C	a_δ m	u_δ m/s	Λ mm	Λ mm	f_w	$\frac{v_* D}{\nu}$	β* using w from Schl.	a/D
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	1.010	0.063	0.15	23.5	0.033	0.202	36**	7.4**	0.13	8.38	0.099	3.91
											0.053	0.86
2	1.051	0.058	0.15	21.7	0.032	0.191	45	6.5	0.14	7.87	0.084	1.93
											0.090	0.85
3	1.046	0.051	0.15	24.8	0.028	0.166	33	5.8	0.14	7.37	0.087	7.35
											0.101	2.60
4	1.122	0.054	0.15	26.0	0.033	0.183	36	6.8	0.14	8.29	0.068	2.57
											0.087	1.87
5	0.886	0.049	0.15	24.4	0.021	0.147	29	4.5	0.15	6.66	0.137	7.28
											0.106	2.66
6	1.114	0.049	0.15	22.3	0.029	0.164	41	7.2	0.16	7.37	0.131	5.58
											0.092	1.95
7	1.010	0.053	0.15	23.7	0.027	0.170	19	6.6	0.16	7.89	0.080	3.37
											0.097	2.68
8	0.822	0.052	0.15	25.2	0.019	0.146	29	4.9	0.17	7.24	0.168	3.01
											0.119	1.28
9	0.903	0.058	0.15	26.2	0.025	0.176	35	6.4	0.17	8.78	-	-
											0.087	2.23

* The first value is that obtained from measurements over a ripple crest and the second is from over a ripple trough.

** Estimated.

Figures

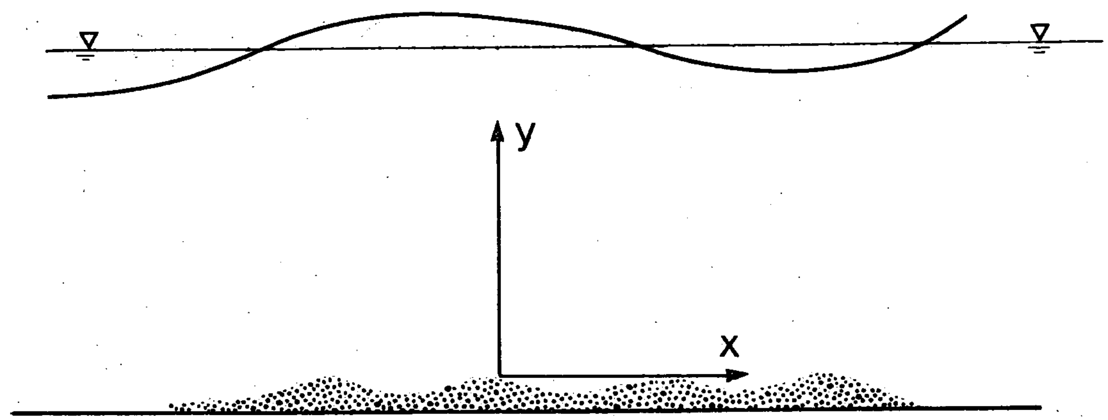


Fig. 1 Coordinate system is positioned such that the x-axis is at the local elevation of the bed, and the y-axis is vertically up.

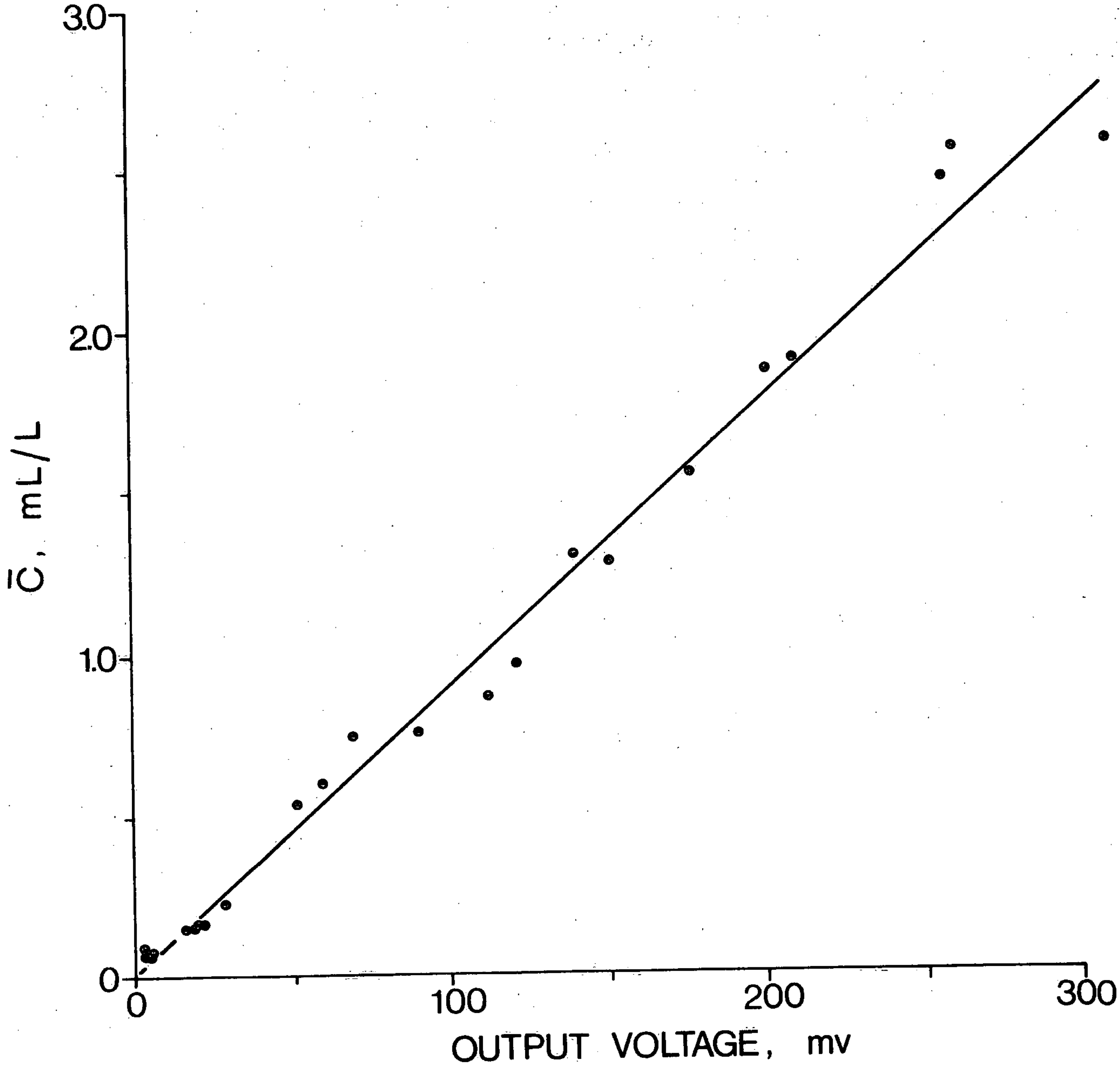


Fig. 2 Calibration curve for the ISCMS. The equation is $\bar{C}$=0.0091V + 0.00443 with a correlation coefficient of 0.994. ($\bar{C}$ is mean concentration, and V is mean output voltage).

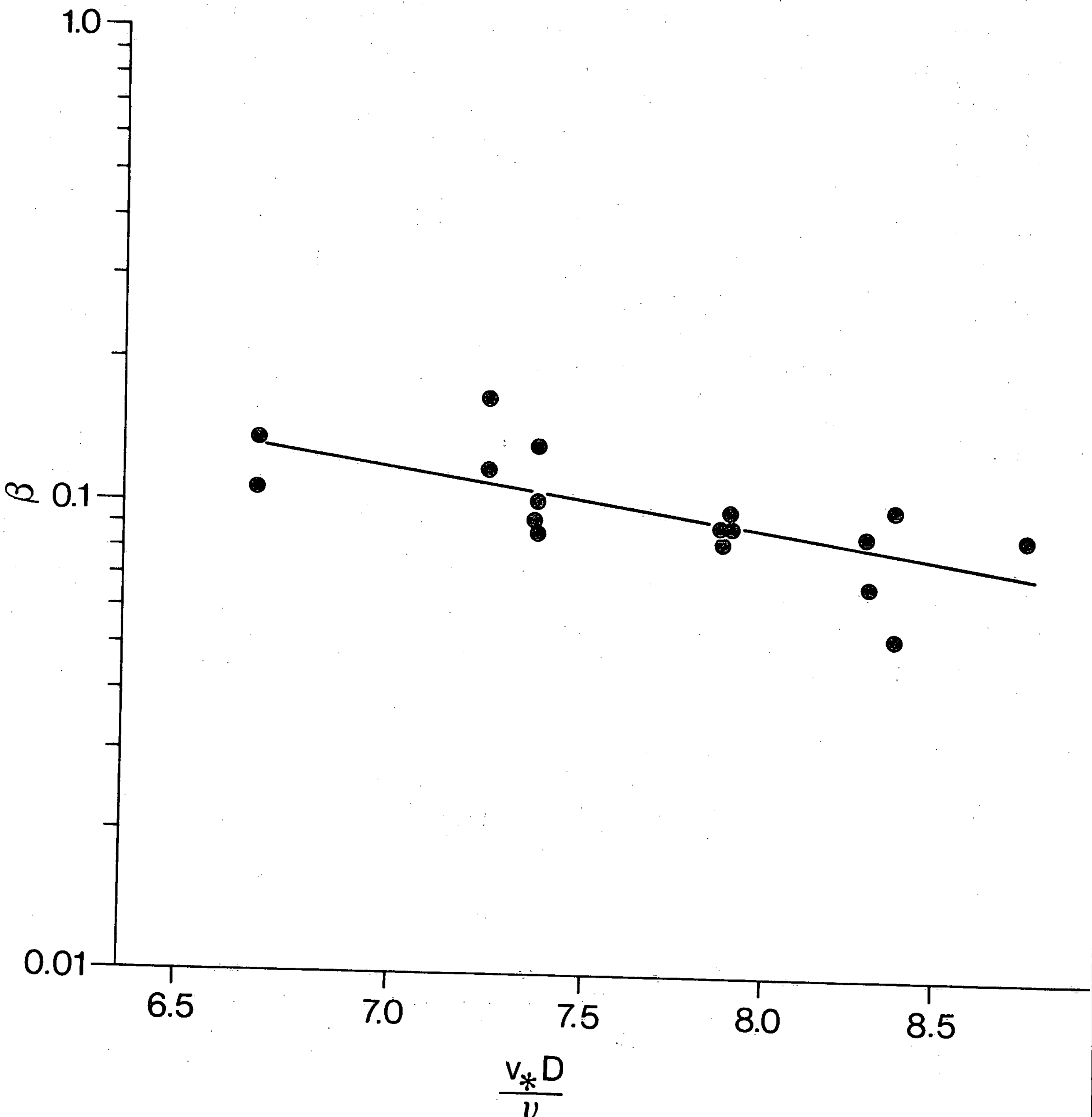


Fig. 3 Non-dimensional diffusion coefficient, β, as a function of $v_*/D/\nu$.

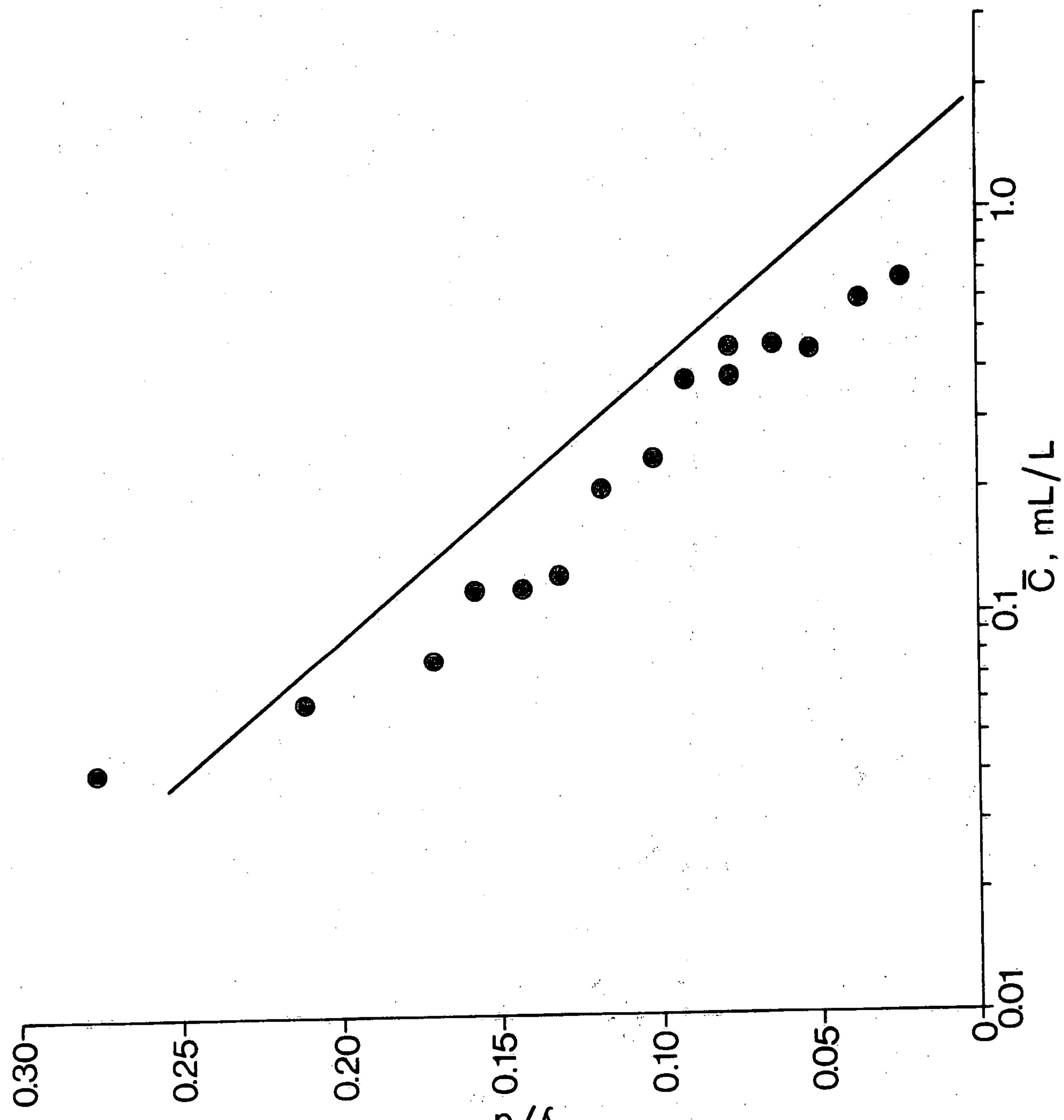


Fig. 4 Measured and computed concentration over ripple crest for run 6 of Table 1.

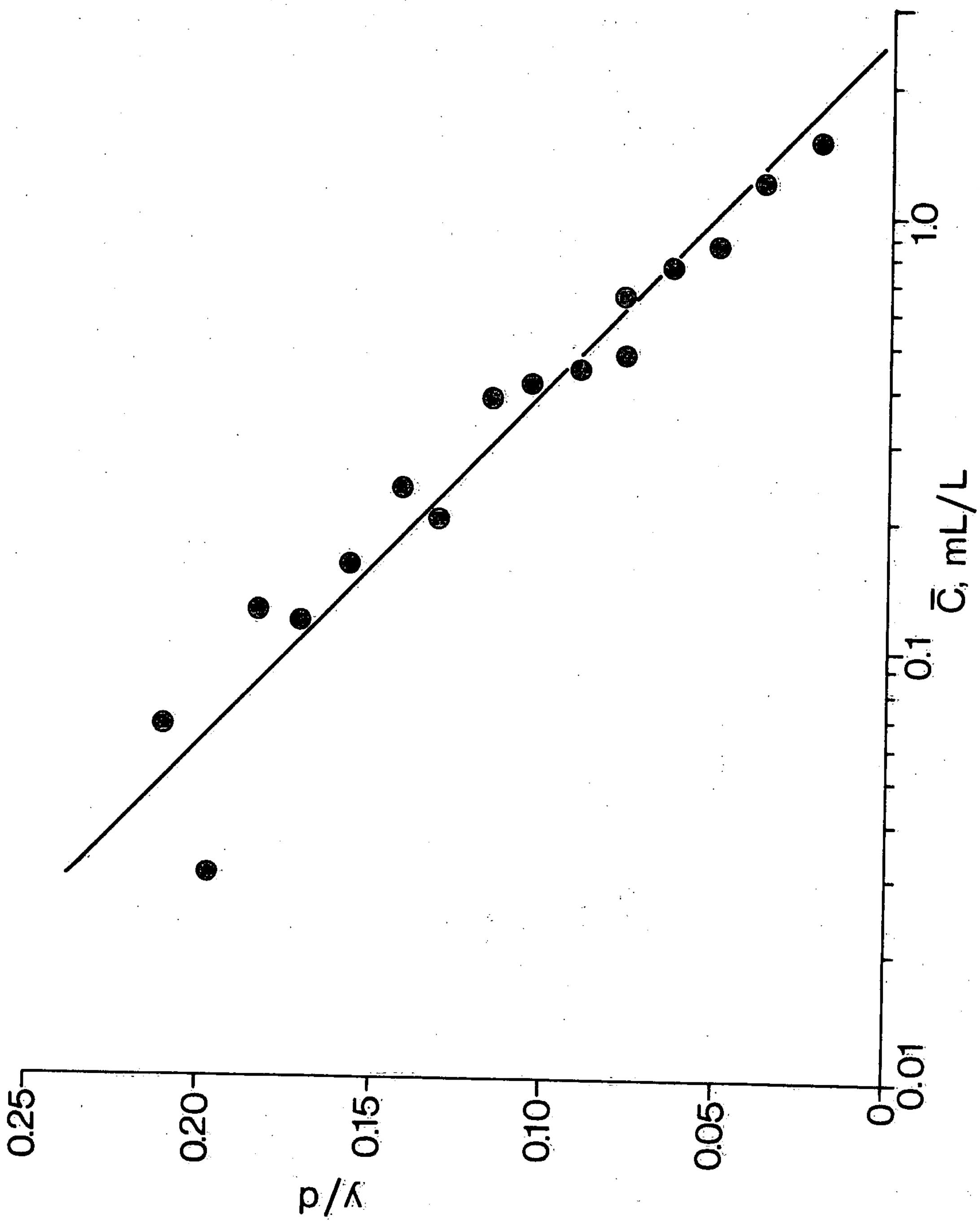


Fig. 5 Measured and computed concentration over ripple troughs for run 7 of Table 1

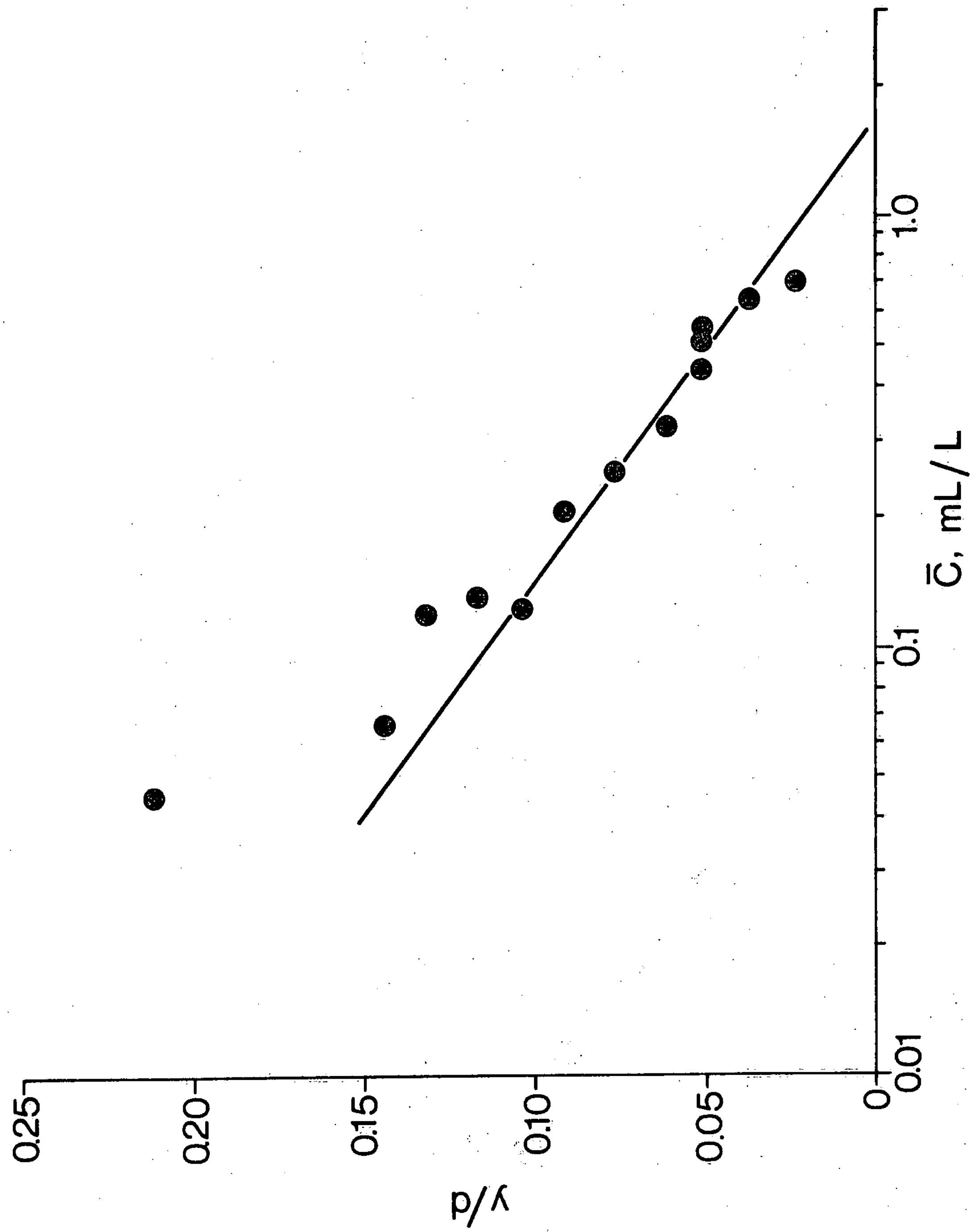


Fig. 6 Measured and computed concentration over ripple crests for un 8 of Table 1

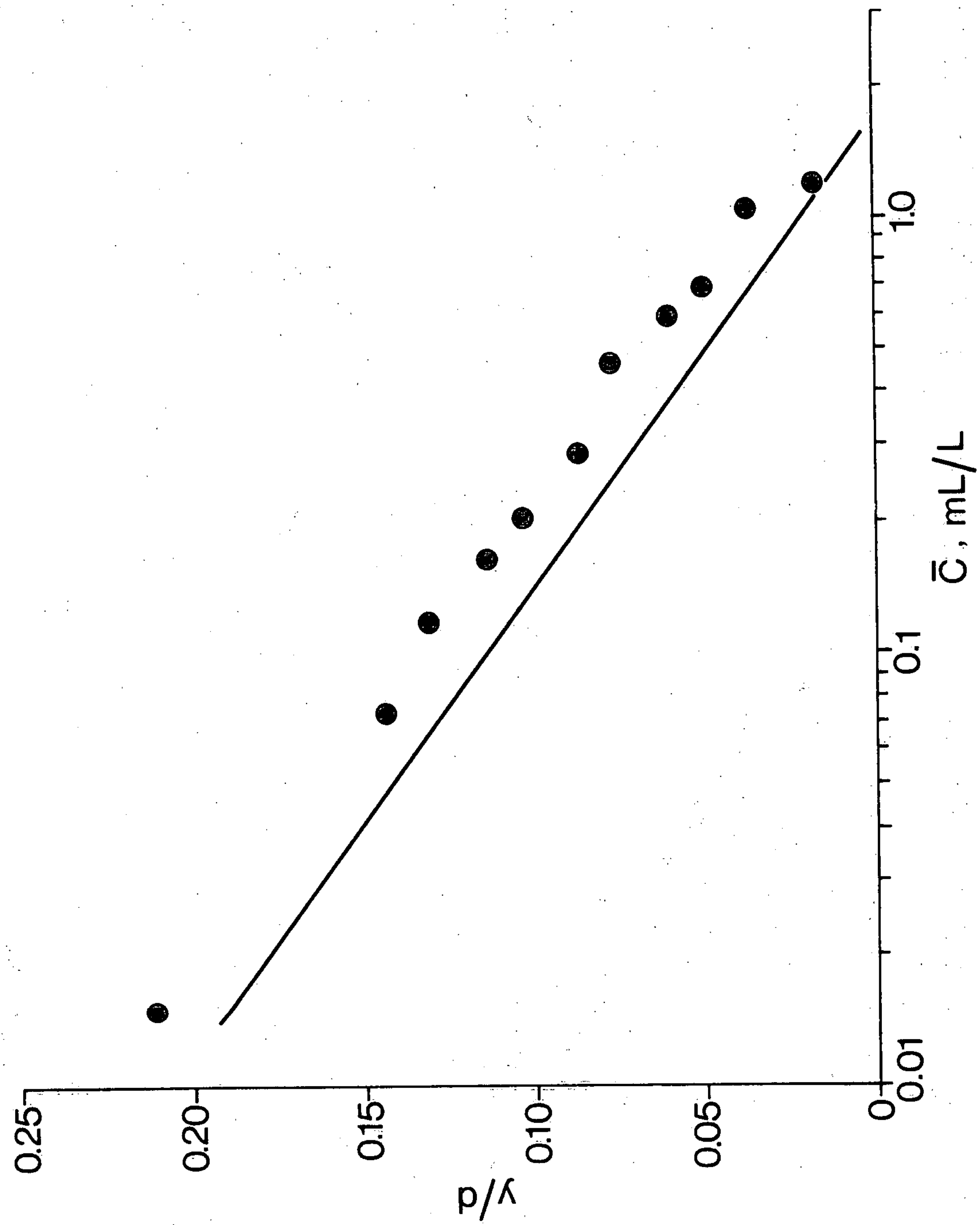


Fig. 7 Measured and computed concentration over ripple troughs for run 8 of Table 1

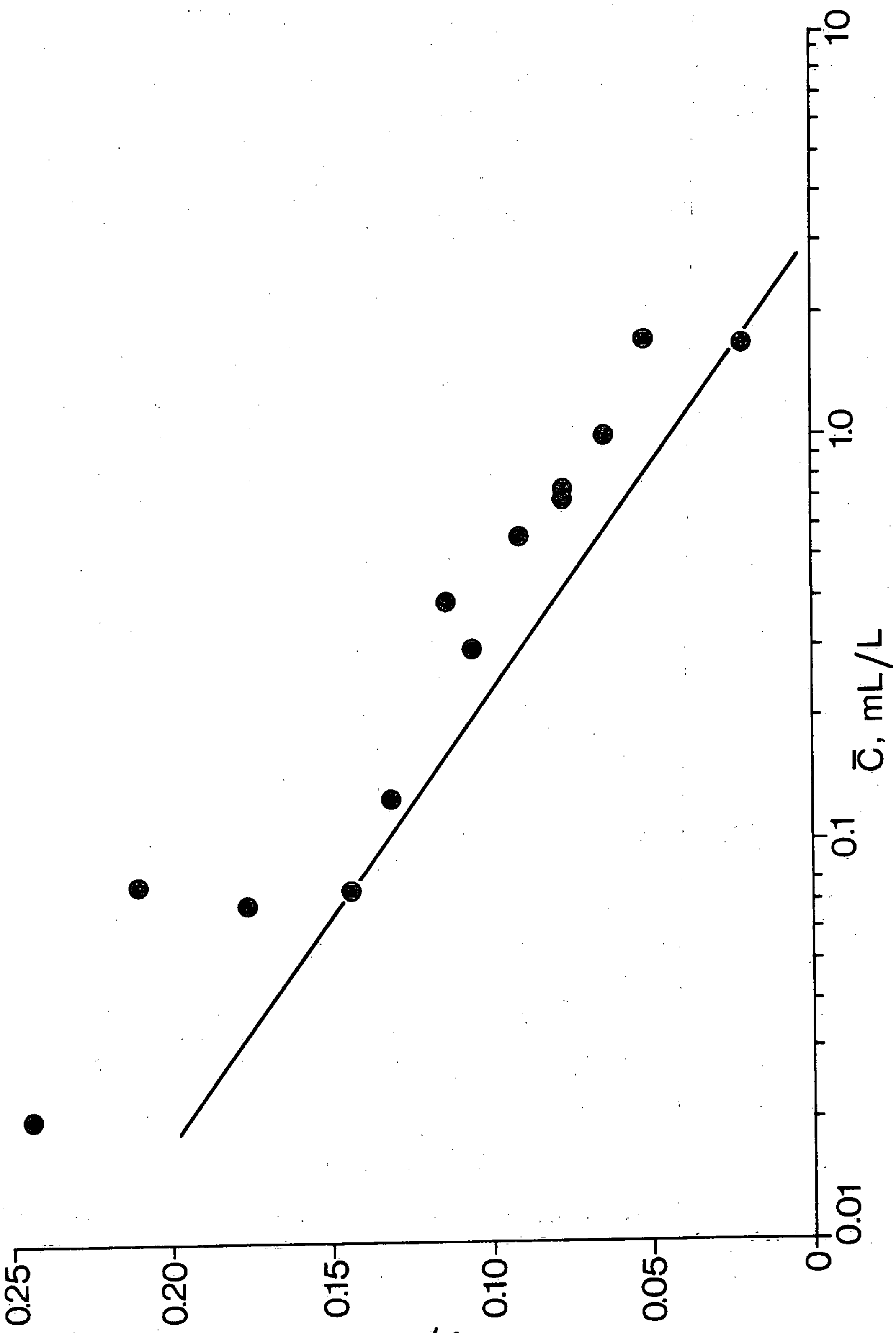


Fig. 8 Measured and computed concentration over ripple troughs for run 9 of Table 1

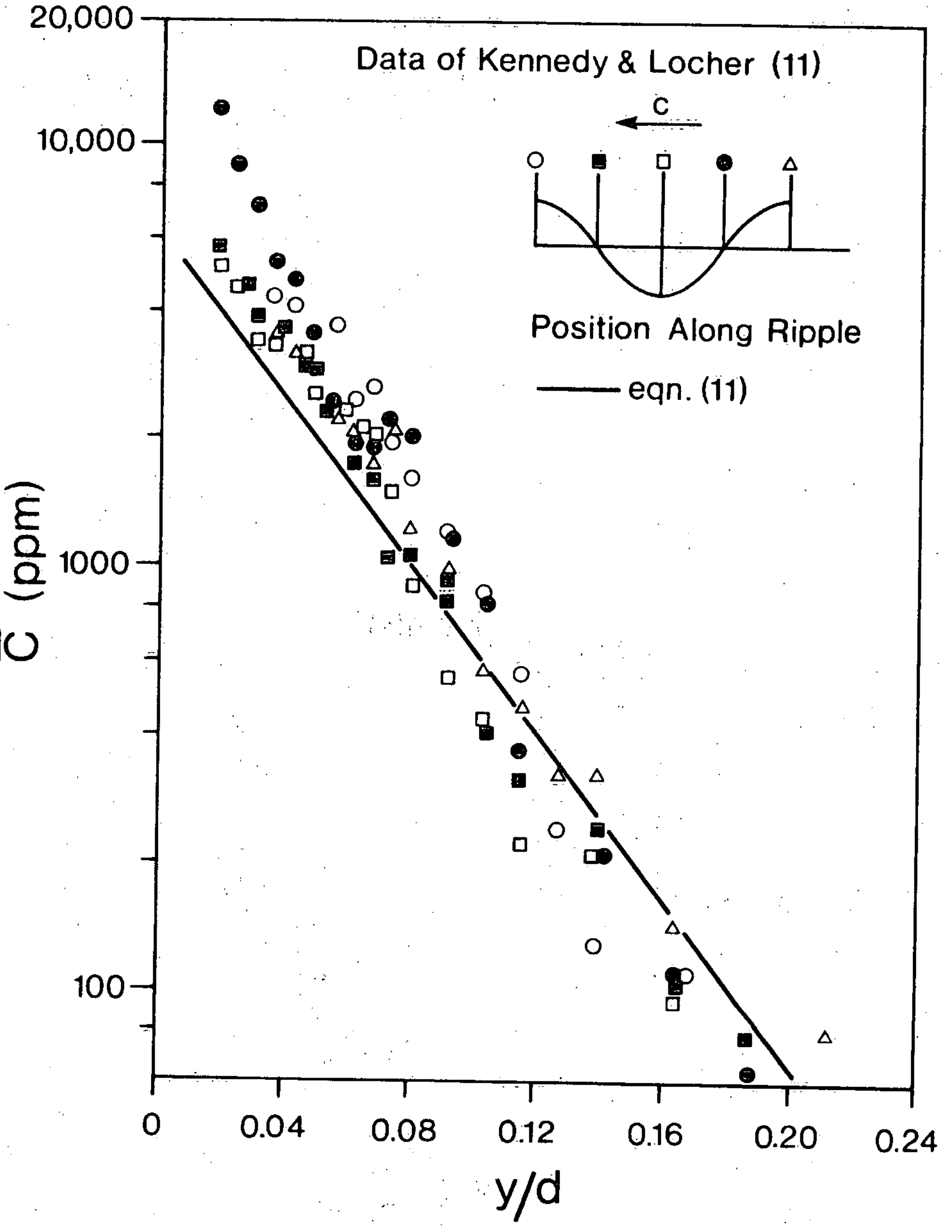


Fig. 9 Comparison of the present formulation with the experimental data of Kennedy and Locher (11).