MECHANISTIC APPROACH TO TOTAL SEDIMENT LOAD TRANSPORT RATE

A Thesis

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TO MY PARENTS, HUSBAND AND CHILDREN

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ABSTRACT

The present study is devoted to examine and verify a proposed mechanistic approach to total sediment load determination.

Results of experimental work when analyzed and compared with values computed for other approaches showed that the present approach yields the least deviation. It was found that the concentration of bed-load at its mid thickness constitutes the lower limit of the suspended load concentration. Based on this evidence a method is developed to relate the suspended load to the bed-load, and a step by step method is proposed to calculate the total load rate for known values of channel slope, normal depth, mean velocity and sediment properties.

The experimental work also revealed that the von Karman turbulent constant is not a constant value but decreases affected by the steepness of the rippled formations on the bed and that the transport of sediment in suspension adds slightly to the flow resistance that it can be disregarded.

A criteria for incipient suspension was set and checked. The ratio of sediment diffusion to momentum transfer coefficients was found to be a function of the average suspended load concentration.

ACKNOWLEDGMENT

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SYMBOLS, QUANTITIES AND DIMENSIONS

The following are the main symbols used in this thesis. Any other symbols are defined wherever they appear.

Symbol	Quantity	Dimensions
a	Reference level	L
C	Sediment concentration	$M\ L^{-3}$
C_a	Sediment concentration at level a	$M\ L^{-3}$
d, K	Particle diameter	L
f	Friction factor	–
f_b	Friction factor associated with the bed of the channel	–
Fe	Froude number	–
g	Gravitational acceleration	$L\ T^{-2}$
g_B	Weight rate of sediment transport per unit length	$M\ T^{-3}$
g_{iB}	Immersed weight rate of transport per unit length	$M\ T^{-3}$
g_s	Suspended load rate of transport per unit length	$M\ T^{-3}$
g_{Ts}	Weight rate of total load transport per unit length	$M\ T^{-3}$
h	Height of bed features	L
k	Roughness coefficient, turbulent constant	
k_s	Sand grain roughness	
m_B	Fraction of the hydraulic radius	L

	appropriate to surface drag	
N	Volume concentration of solids	
N_*	Max. grain concentration by volume =0.46	
Q	Discharge	L^3T^{-1}
q	Discharge per unit width	L^2T^{-1}
q_B	Volume rate of bed-load transport per unit width	L^2T^{-1}
q_c	Critical discharge per unit width	L^2T^{-1}
q_s	Volume rate of suspended load discharge per unit width	L^2T^{-1}
q_T	Volume rate of total load discharge per unit width	L^2T^{-1}
R	Hydraulic radius	L
Re	Reynolds number	-
Re_*	Particle Reynolds number	-
S	Channel slope	-
S_s	Specific gravity of solids	
u,v	Velocity	$L\ T^{-1}$
u_*	Shear velocity	$L\ T^{-1}$
y	Depth of flow	L
y_n	Normal depth of flow	L
z	Exponent in the suspended load distribution	
α,β	Constants	
γ	Specific weight of fluid	$M\ L^{-2}T^{-2}$
γ_s	Specific weight of solids	$M\ L^{-2}T^{-2}$

δ	Boundary layer thickness	L
ε_m	Momentum transfer coefficient	
ε_s	Sediment transfer coefficient	
θ	Dimensionless shear stress	
ν	Kinematic viscosity	L^2T^{-1}
τ	Shear stress	$M\ L^{-1}T^{-2}$
τ_b	Average shear stress on bed	$M\ L^{-1}T^{-2}$
τ_c	Critical shear stress	$M\ L^{-1}T^{-2}$
τ_o	Boundary shear stress	$M\ L^{-1}T^{-2}$
w	Terminal velocity	LT^{-1}

CHAPTER I

INTRODUCTION

Sediments are fragmental material transported by water or air.

The transport of sediment by water in open channels is an important issue to mankind that has attracted the attention of hydraulic engineers due to its connection with river control, reservoir capacity, design of irrigation projects, interference with harbor operation, modification of water courses, erosion, scour and undermining.

Sediment transport occurs only if there is an interface between a moving fluid and an erodible boundary. The activity of this interface is extremely complex.

Once the sediment is being transported the flow is no longer a simple fluid flow since two materials are involved, namely water and sediment.

Typical types of sediment transportation are classified into:

a. Bed-load: That part of total load whose normal immersed weight component is in normal equilibrium with the tangential stress acting on the grains.

b. Suspended load: That part of the load whose weight component is in equilibrium with a normal fluid stress originating in impulse by turbulent eddies.

Total load is the sum of the bed-load and suspended load.

Numerous bed-load equations have been proposed of which the most important are:-

1- The Du Boys type equations considering shear stress relationship. The longitudinal component of fluid weight is assumed to be balanced by friction at the bed.

2- The Schoklitsch type equations considering the discharge relationship.

3- The Einstein type equations considering lift forces as being the sole agent in the initiation of grain motion.

4- Bed forms type equations considering bed forms motion.

Regarding the suspended load transport rate the analogy to diffusion dispersion process is found to explain many suspension problems.

The aforementioned treatments of suspended load and bed-load give good results for the transport rate of bed-load or the distribution of suspended sediment, however these two types of transportation are not unrelated. Concentration of suspended sediment must depend on how much the bed-load discharge is and so the suspended load must be directly affected by the bed load. Thus it may be desired to find an expression of the total load concentration distribution without introducing a reference level.

Two methods are used to determine the total sediment load, namely microscopic and macroscopic. In the first method the total sediment load is calculated by summing up the suspended load and the bed-load each calculated separately.

This concept was followed by *Lane and Kalinske*,(1) *Einstein*(2) and others.

The macroscopic method assumes that the hydrodynamic forces involved in the cases of bed-load and suspended load are the same, thus there is no need to distinguish between them. Instead the total load is related to shear and other flow parameters. The relationships proposed are based on dimensional analysis, intuition or complete empiricism. *Colby*,(3) *Laursen*(4) and *Bishop et al*(5) proposed some of these relationships which are mentioned in the next chapter.

The present study will be devoted to describe a mechanistic approach to total load determination and the experimental work required for the verification of the approach.

An attempt will be made to find a correlation between the suspended load concentration at various levels and that of the bed-load. The importance of the correlation lies in the idea that sediment load may be estimated by knowing few hydraulic parameters and sediment properties.

The measured values of bed load, suspended load and total load will be compared with findings of other investigators. Data collected by others will also be analysed according to the present approach.

The work will also include a study on the initiation of motion and the criteria for suspension, and the effect of sediment concentration on the velocity profile and turbulent coefficient in addition to the relation between the turbulent coefficient and ripple wave height and length.

General review of the previous work related to the subject is presented in Chapter II hoping that these information will serve as a useful supplement.

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CHAPTER II

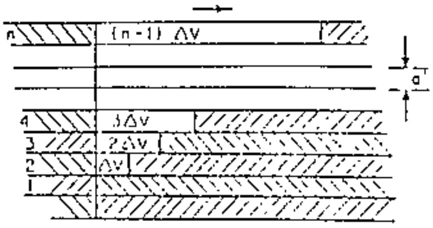
HISTORICAL REVIEW

The analysis of transport of sediment is usually seperated into two parts, bed load and suspended load. This subdivision does not rest on a physical basis and generally it is difficult to define where the suspended load starts.

2.1 BED-LOAD FORMULAE

Many of the bed load formulae are of the same form as the Du Boys formula.

Du Boys (1879)(1) assumes the bed to move as a series of superimposed layers of thickness d' presumably of the same magnitude as the particle diameter, and the velocity of the layers to vary lineary, Fig (2.1).



Fig(2.1)

If the n^{th} layer from the top remains at rest the surface layer must have a velocity $(n-1)\Delta V$ and the volume rate of bed load discharge per unit width is

$$q_B = \frac{1}{2} n \; d' (n-1) \Delta V \qquad \text{...........(2.1)}$$

The longitudinal component of fluid weight, $\gamma\ y_o S$, is assumed to be balanced by friction at the bed. The friction factor between successive layers is assumed constant, f_s, so that the force balance is

$$\gamma\ y_o S = f_s\ (\gamma_s - \gamma)\ n\ d` = \tau_o \qquad ....(2.2)$$

where :

γ is a specific weight of fluid

y_o is the normal depth of flow

S is the slope of the channel

γ_s is the specific weight of solids

τ_o is the boundary shear stress

The threshold conditions are given when the topmost layer just resists motion, i.e.when n=1

$$\tau_o = \tau_c = f_s (\gamma_s - \gamma) d`$$

and $$\tau_o = n\ \tau_c$$

or $$n = \tau_o\ /\ \tau_c \qquad ....(2.3)$$

substituting this value of n in q_B and rearranging

$$q_B = \frac{\Delta V\ d`}{2\tau_c^{\ 2}}\tau_o(\tau_o - \tau_c) = C_s \tau_o (\tau_o - \tau_c) \qquad ....(2.4)$$

where C_s is a function of the sediment in motion.

O'Brien and Rindlaub,(2) in 1934 argued Du Boys assumptions on the basis that it would produce a continuous acceleration, and the sliding layer should be kept in motion by the shear of moving fluid which should be transferred to the bottom unchangeable, but they overlooked the frictional resistance of the lower layers which should be increased due to the weight component of the material above. Accordingly they introduced the bed-load transport rate to be in the form:-

$$q_B = a(\tau - \tau_c)^B \qquad \text{...........(2.5)}$$

Where a & B are constants depending on sediment size.

Straub[3] in 1950, gave

$$C_s = \frac{0.17}{d^{3/4}}$$

Introducting from Manning formula

$$\tau_o / \gamma = yS = S^{7/10}(qn)^{3/5}$$

and

$$q_B = C_s \frac{S^{1.4} \gamma^2}{(1/n)^{1.2}} q^{3/5}(q^{3/5} - q_c^{3/5}) \qquad \text{.....(2.6)}$$

where

q_c is the critical discharge per unit width

q is the discharge per unit width

Schoklitsch[4] (1934) gave the weight rate of bed load transport per unit width g_B

as $$g_B = \frac{7000}{\sqrt{d}} S^{3/2}(q - q_c) \qquad \text{...........(2.7)}$$

to fit data for uniform sand from d = 0.305 mm to 7.02 mm and

$$q_c = 1.944 \frac{d \times 10^{-5}}{S^{3/4}} m^3/\text{sec} - m \qquad \text{.......(2.8)}$$

Schoklitsch modified his formula to

$$g_B = 2500 \quad S^{3/2}(q-q_c) \qquad \text{...............(2.9)}$$

in which

$$q_c = \frac{1}{n} \; y_c^{5/3} S^{1/2}$$

where for d ≥ 0.006 m

$$y_c = 0.076 \; \frac{\gamma_s - \gamma}{\gamma} \; \frac{d}{S}$$

and $n = 0.0525 \; d^{1/6}$

y_c = depth at initiation of motion

Meyer-Peter(5) (1934) suggested the following formula for bed-load:

$$g_B^{\,2/3} = 2.5 \; q^{2/3}S - 4.25 \; d \qquad \text{..........(2.10)}$$

This formula was fitted to laboratory data with gravel of d = 5.05 and 28.6 mm

The formula was extended by including data from experiments with material with a range of specific gravities:

$$\frac{q^{2/3}S}{d} - 9.57(\gamma_s-\gamma)^{10/9} = 0.462(\gamma_s-\gamma)^{1/3}\left(\frac{g_B(\gamma_s - \gamma)}{\gamma_s}\right)^{2/3}$$

...........(2.11)

A further modification includes the seperation of bed resistance due to grain roughness S\`, and bed forms S\`\`as

$$\frac{\gamma m(K/K`)^{3/2}}{(\gamma_s - \gamma)\; d} - 0.047 = 0.25 \; \frac{S\rho^{1/3}}{(\gamma_s - \gamma)\, d}\left(\frac{g_B(\gamma_s - \gamma)}{\gamma_s}\right)^{2/3}$$

..........(2.12)

where m is the hydraulic mean radius

$$K = \frac{S'}{S} = \left(\frac{K}{K'}\right)^{3/2}$$

$$K = \frac{26}{d_{90}^{1/6}} \quad m^{1/3} S$$

Shields,(6) (1936) gave

$$\gamma_s q_B = g_B$$

$$\frac{g_B}{\gamma q} \frac{\gamma_s - \gamma}{\gamma_s} = 10 \frac{\tau_o - \tau_c}{(\gamma_s - \gamma) d} \quad \ldots.(2.13)$$

The above equation is dimensionally homogeneous and is based on data in a range of γ_s/γ from 1.06 to 4.2 and sediment size from 1.56 mm to 2.47mm. Actual data indicate deviations up to 200 percent in the bed-load predicted by the above formula

Meyer-Peter & Muller(7) in (1948) offered their bed-load equation.

The bed load function $\varnothing$, and the shear stress function τ are the principal dimensionless variables used in describing bed-load.

$$\varnothing = \frac{q_s}{\gamma_s}\left[\left(\frac{\gamma_s}{\gamma} - 1\right) g\, d_{50}^{3}\right]^{-1/2} \quad \ldots\ldots\ldots.(2.14)$$

and $$\tau = \tau_o \left[(\gamma_s - \gamma)\, d_{50}\right]^{-1} \quad \ldots\ldots\ldots..(2.15)$$

The Meyer-Peter & Muller formula for a wide rectangular channel is

$$\gamma \frac{Q_B}{Q}\left(\frac{K_B}{K_G}\right)^{3/2} HS = 0.047\, \gamma_s'' D_E + 0.025\left(\frac{\gamma}{g}\right)^{1/3} (G_1'')^{2/3}$$

..............(2.16)

in which

γ = the specific weight of water

Q_B = the part of the discharge apportioned to the bed and considered responsible for the bed load

Q = total discharge

K_B = the total roughness coefficient for the bed

k_G = the flat-bed grain roughness

H = water depth

S = slope of the energy grade line

γ_s = specific weight of the sediment

$\gamma_s'' = \gamma_s - \gamma$

D_E = the effective diameter of the bed material

g = the acceleration due to gravity

G_1'' = the bed-load weighed under water

The Meyer Peter and Muller equation is of the threshold type. The bed-load is proportional to the difference between the mean shear stress raised to the 1.5 power .This threshold stress corresponds roughly to Shields critical tractive stress.

In the application of this equation in the region near the threshold, the transport may appear to be negative. In such cases the authors suggested replacing the coefficient 0.047 with 0.03.

The Meyer-Peter and Muller equation was based on data from experiments with steady uniform flow in flumes. The range of sediment properties of these tests was such that there is little or no suspended load. The effective diameter of the sediment particles varied between 0.4 mm to 30 mm. This range led to flows both with and without bed waves and so the bed form correction ratio K_B/K_a shown in the formula varied between 0.5 and 1. This wide range of sediment diameters also covered the cases of both fully-rough bed flow and flow with a viscous sublayer. In the latter case, the authors recommended the use of the channel Reynolds number and the relative roughness of the bed material to find the friction factor, f, from Nikuradse diagram. When the roughness, K_a, based on this f was combined in the ratio, K_B/K_a, the formula was considered valid for a wide range of sediment movements.

Amin & Murphy(8) in 1981 criticized the Meyer Peter and Muller equation in that the method predicts zero movement in cases where movement was observed. This type of predictive equation is especially troublesome when bed forms are present, since the seperation of form drag from bed particle drag makes the location of the threshold more difficult. These problems demonstrate that the Meyer-Peter and Muller equation should not be used for sand bottomed channels.

Einstein (1942,(9) 1950(10)) departed from mean tractive force concept. The starting point of his argument is that in the turbulent flow the fluid forces acting on the particle vary with respect to both time and space, and therefore the movement of any particle depends on the probability, P, that at a particular time and place the applied forces exceed the resisting force.

The probability of movement of a particle is expressed in terms of weight rate of sediment transport, the size and immersed weight of particles, and a characteristic time which is a function of particle size/fall velocity ratio. It is postulated that a given particle moves in a series of steps and that a given particle does not stay in motion continuously.

From these considerations a transport function is developed as

$$\emptyset = \frac{q_B}{g\rho_s} \sqrt{\left(\frac{\rho}{\rho_s - \rho} \quad \frac{1}{gd^3} \right)} = \frac{q_B}{\sqrt{(S_s - 1)gd^3}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2.17)$$

The probability is interpreted as the fraction of the bed on which, at any given time, the lift on a given particle is sufficient to cause motion. The flow parameters are based on the logarithmic velocity distribution. The expression derived is

$$\psi = \frac{\rho_s - \rho}{\rho} \frac{d}{m^{`} S_B} = \frac{1}{\emptyset^{`}} \qquad \ldots\ldots\ldots\ldots(2.18)$$

where $\emptyset$ is the Shields entrainment function. The total drag is subdivided into form and surface drag and $m^{`}_B$ is the fraction of the hydraulic mean radius appropriate to surface drag. The result is given as

$$\emptyset = f(\psi)$$

where $\emptyset$ is the intensity of bed load transport and ψ is the flow intensity.

Einstein developed his theory in 1950 and gave a new equation based on the concept that the continuous interchange between the active and static grains should be in such a way that the rate of depositon is equal to the rate of erosion. He defined the exchange probability, p, to be dependent on the fraction of bed-load in a given grain size, i_b.

The bed-load intensity relationship is written in the form

$$\frac{p}{1-p} = A_*\left(\frac{i_B}{i_b}\right) \quad \phi = A_*\phi_* \qquad .....(2.19)$$

where A_* is a constant = 43.5 determind by experiments, and ϕ_* is the intensity of transport for an individual grain size. The above equation was further developed and expressed in the form

$$1-\frac{1}{\sqrt{\pi}}\int_{-B_*\psi_*-1/n_o}^{B_*\psi_*-1/n_o} e^{-t^2}dt = p = \frac{A_*\phi_*}{1+A_*\phi_*} \qquad ....(2.20)$$

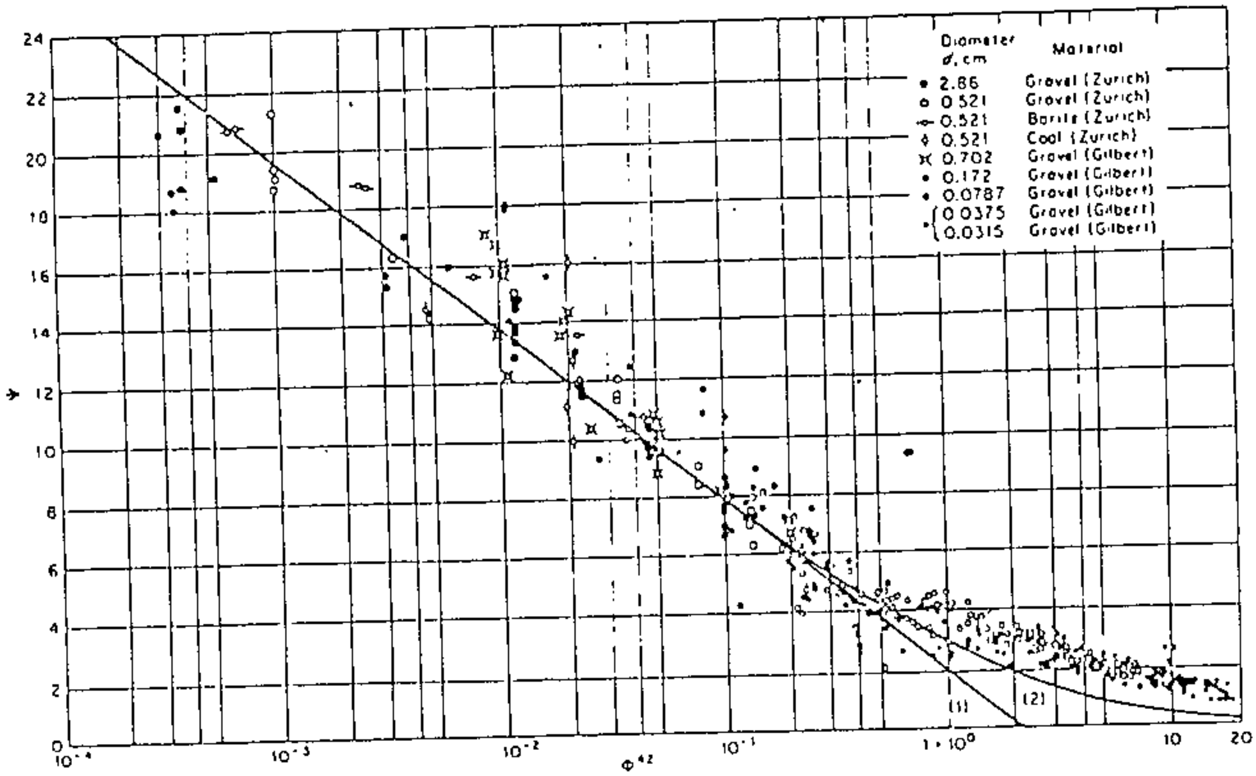
where $B_* = 1/7$, $\eta_o = 0.5$, t is a variable of integration, $\psi_* = \xi\ Y(\beta^2/\beta_x^2)\ \psi$ where ξ is the correction factor for sheltering of small particles and Y is the correction factor describing the change of the lift coeficient in mixtures with various roughness.

$\beta = \log 10.6$

$\beta_x = \log\left[10.6\ \frac{X}{\Delta}\right]$

$\delta = 11.5\nu/u_*$ =Laminar sublayer thickness

$\Delta = d_{65}$



Einstein's bedload equations. (*After* Einstein (*1942*).)

FIG.(2.2) EINSTEIN'S BED-LOAD EQUATION

$$X = 0.77\,\Delta \text{ for } \Delta / \delta > 1.8$$

$$X = 1.39\,\delta \text{ for } \Delta / \delta < 1.8$$

X is the scaling size of the mixture. Einstein formula incorporates a number of assumptions debatable by others, *Khalil*(11) in 1963 found that the physical reasoning of Einstein's theory is somewhat difficult to visualise; as for a rippled bed the scour exceeds the deposition over the gentle slope while the deposition exceeds the scour at the steep side and therefore the basic concept is not as envisaged by Einstein. Also the attribution of the initiation of grain motion to be solely due to lift forces seems not to be justified.

Another point which Khalil showed its disagreement with observations, regarding the grains moving in steps of definite length depending only on its diameter he showed that the path of grains coated with flourescent and photographically recorded, indicated that the length of these steps for small grains statistically increased with u_*.

Also the "universal constants" A_*, B_*, η_o are not constants as was late proved by *Bishop et al*(12) (1965). Also many queries arise from the development of the probabilities and the assumption that the normal component of the fluctuating force always acts upwards. Einstein formula of bed-load calculations was recently checked by *Misri et al*(13) (1984) with extensive experimental data both at macroscopic and microscopic levels. Misri's experiments on coarse sediments highlightened several important limitations on Einstein's method including the inadequacy of his ξ - K_s/X relation.

All fractions of data studied showed higher transport rate than that given by Einstein and was more pronounce in coarser fractions.

Khalil(11)(1963) introduced a direct relation between the ripple velocity and the rate of bed-load transport as

$$g_B = B\ V_r y + \text{const} \qquad \text{..............(2.21)}$$

where B is the bulk specific submerged weight of the bed material, V_r is the ripple velocity.

Considering the origin to be at the point of zero scour i.e. the demarcation border between forward surface creep and backward surface creep the above equation becomes

$$g_B = B.V_r.y \qquad \text{.........(2.22)}$$

The rate of transport per unit width is defined as the mass average of grains which in unit time passes a fixed cross section. y is supposed to vary for a fixed cross section with respect to time from a minimum of zero to a maximum = h. The elevation y varies with respect to x according to the ripple shape as :

$$\frac{\Sigma\ yx}{\Sigma\ x} = \alpha h \qquad \text{............(2.23)}$$

where α is constant for a particular shape of ripple and varies from 0.5 for triangular shape to 0.67 for parabolic shape of bed form. According to the above considerations and neglecting any saltating rate, the observations of Khalil gave the following :

$$g_B = 0.565\ B.V_r.\ h \qquad \text{............(2.24)}$$

for ripple shape factor $\alpha = 0.565$ Thus the bed load transport rate due to wave motion, when there is no saltation can be predicted by measuring the ripple height and velocity .

The *Toffaletti*(14) method (1969) for the calculation of the bed-load is a modification of the Einstein procedure for the calculation of both bed-load and suspended load. It focuses on channels with sand bottoms and assumes that part of the sand is moving as bed-load and part as suspended load. Thus the bed-load, BL, is found by evaluating the mass flux, UC, at $y = 2D$ and assuming that this flux is constant in the region, $0 \leq y \leq 2D$, near the bed.

$$BL = C_{\upsilon}\overline{U}\left(\frac{2D}{R}\right)^{z\upsilon} C_L\left(\frac{R}{2D}\right)^{zL} 2D \quad \text{........(2.25)}$$

in which $C_{\upsilon}\overline{U}(Y/R)^{z\upsilon}$ = a power law approximation of the velocity profile

$C_L\left(\frac{R}{Y}\right)^{zL}$ = sediment concentration distribution.

This velocity profile is roughly a 1/7 power law description based on the turbulent boundary layer profile and adjusted for water temperature. The concentration of particles of grain size, D, is determined by equating the suspended load in the region, $2D < y < R/11.24$.

Yalin (15)(1972) developed a bed-load equation incorporating reasoning similar to Einstein but with a number of refinements and additions.

He interprets the transport rate to be a rate of doing work

$$g_B = W_s \times u_s \qquad \text{...........(2.26)}$$

where W_s is the weight of solids moving over unit area of the bed at velocity u_s.

Yalin's transport equation is

$$\frac{g_B}{\gamma_s^* \, d u_*} = \text{const.}\left\{ s \left[1 - \frac{1}{as} \ln(1+as) \right] \right\} \qquad \text{.....(2.27)}$$

where

$$s = (\theta_o - \theta_c) / \theta_c$$

$$\theta_o = \rho \, u_*^2 / \gamma_s^* d$$

$$a = 2.45 \, (\rho u_{*c}^2 / \gamma_s^* d)^{0.5} / (\rho_s / \rho)^{0.4}$$

$$= 1.66 \sqrt{\theta_c}$$

this can be converted to Einstein equation by multiplying through with

$$(\rho u_*^2 / \gamma_s^* d)^{0.5} = \frac{1}{\sqrt{\psi}}$$

yielding

$$\phi = \frac{g_B \sqrt{\rho}}{(\gamma_s^* d)^{3/2}}$$

$$= 0.635 \frac{s}{\sqrt{\psi}} \left[1 - \frac{1}{as} \ln(1 + as) \right] \qquad \text{...(2.28)}$$

$$\text{or } \phi = f(\psi, \phi_c, \rho_s / \rho) \qquad \text{..........(2.29)}$$

This relation implies a set of curves which reduce to one family $\phi = f(\psi, \phi_c)$ for ρ_s/ρ = const.

Bagnold(10) (1973) attempted to make a discussion on the physics of the transport. The development starts with the energy statement:

Rate of work done in transport of solids

=(input power) x (efficiency)

The bed-load occurs as rolling, sliding or saltation and upward impulses are due only to contacts with stationary grains in the bed; that is due to bouncing. Saltation is the natural form of bed-load movement, of which the limiting case is the particle sliding along the bed. The grains are pushed forward by the fluid drag

$$F = \frac{1}{2} \rho C_1 A u_1^2 \qquad \text{..............(2.30)}$$

where u_1 is the relative velocity. This is expressed as the difference between the mean effective velocity of fluid u_n, acting at a distance y_n = nd above the bed, and the mean velocity of the solid.

At steady- state transport the mean force F, acting on the grain equals the submerged weight, W^*, of the grain times the friction factor tan α.

The submerged weight can be expressed through terminal velocity ω as $W^* = \frac{1}{2} \rho C_2 A \omega^2$ and assuming that the two drag forces are approximately equal, then

$$u_r^2 = \omega^2 \tan \alpha \qquad \text{...............(2.31)}$$

If the shear stress between the stationary and moving particles per unit area is f^*(submerged weight per unit area of material in transport times coefficient of friction, tan α) then the rate of work is $f^*(u_n - u_r)$ and the energy statement becomes ;

$$g_{ib}\tan\alpha = f^* u_n \left[\frac{u_n - u_r}{u_n}\right] \qquad \text{..................(2.32)}$$

where g_{ib} is the immersed weight rate of transport.
The shear stress f^* transmitted to the bed via saltating grains must vary from zero to τ_c. Assuming that the velocity distribution above y_n is logarithmic, then

$$u_y - u_n = 5.75\, u_* \log(y/nd) \qquad \text{........(2.33)}$$

substituting in (2.32) yields;

$$g_{ib} = \frac{f^*}{\tan\alpha}\, u_y \left[1 - \frac{5.75u_*\log(y/nd) + u_r}{u_y}\right]$$

...........(2.34)

The angle α is of the same order as the angle of repose which is for natural and cohesionless soils 32° and u_r is of the order of the fall velocity. In water the saltation height is only few diameters and the resistance to flow is controlled by bed features. Therefore, the model can only be used in situations where the bed is flat or where the bed material is coarse.

Using the observation that the mean velocity in open channels is at $y = 0.37\, y_o$, and defining the stream power P as the rate of conversion of potential energy into kinetic energy and then to heat per unit length and width of stream,

$$\rho g y_o S U = \tau_o U = P \qquad \text{..........(2.35)}$$

then

$$g_{iB} = \frac{u_* - u_{*c}}{u_*} \frac{p}{\tan\alpha} \left[1 - \frac{5.75 u_* \log(y/nd) + \omega}{\bar{U}} \right] \qquad \text{.................(2.36)}$$

It should be noted that if τ_o remains constant, conditions near the bed will remain the same whatever the depth is. Conversely, an increase in depth leads to an increase in the ratio of $\bar{U}/u_n$ and a decrease in transport efficiency.

Engelund and Fredsoe (17) in 1976, followed some of the concepts introduced by *Khalil* (11) in 1963 by equating the activating force on the grain and the resisting force thus the grain is moving at a constant velocity u_g

$$u_g / u_* = \alpha \left[1 - 0.7 \left(\tau_c / \tau_o \right)^{1/2} \right] \qquad \text{..........(2.37)}$$

with α = 9.0 and τ_c obtained from Shields' curve.

The bed-load transport rate was given by

$$g_B = \left(\frac{\pi}{6}\right) d^3 \left(\frac{P}{d^2}\right) u_g \gamma_s \qquad \text{..........(2.38)}$$

in which g_B is the transport rate on weight bases, P is the probability of the movement of grains in the surface layer, and $1/d^2$ represents the number of grains per unit area. Using Einstein's coordinates equation (2.38) can be written as

$$\emptyset = 5p(\tau_o - 0.7\ \tau_c) \qquad \text{........(2.39)}$$

An expression for p was obtained on the assumption that for plane bed, $(\tau_o - \tau_c)$ is transmitted as the drag on the moving particles, if N is the number of particles moving per unit area then,

$$(\tau_o - \tau_c) = N\left(\frac{\pi}{6}\right)d^3\ (\rho_s - \rho)g\beta \quad \text{.........(2.40)}$$

where β is the coefficient of dynamic friction and was taken to be 0.51, or quation (2.40) can be written as :

$$(\tau_o - \tau_c) = \left(\frac{\pi}{6}\right)\beta N d^2$$

or
$$\tau_o - \tau_c = \left(\frac{\pi}{6}\right)\beta p \quad \text{.........(2.41)}$$

Hence

$$\tau_o = \tau_c + 0.2668\ p \quad \text{.........(2.42)}$$

in which τ_c is taken as 0.05 from Shields' diagram .

Amin & Murphy(8) in 1981 related the bed-load transport rate to some important hydraulic parameters as the flow rate q, the bed shear τ_o and the flow velocity V, the resulting equations (in SI units) were :

$$q_B = 0.0594\ q^{4.27} \quad \text{..........(2.43)}$$

$$q_B = 0.00394\ (\tau_o V)^{2.70} \quad \text{..........(2.44)}$$

$$q_B = 5.25\ V^{0.90} \quad \text{..........(2.45)}$$

Engel & Lau(18) in 1981 introduced the concept of bed-load discharge coefficient, K, to compute the bed-load transport rate from bed profiles of migrating dunes, their final equation can be written as :

$$q_B = K\ \xi\ U_w \quad \text{...............(2.46)}$$

where ξ is the average departure of the bed elevation about the mean bed elevation, U_w is the average dune migration speed. The value of K depends on the dune shape; dune steepness and less sensitive to change in grain size of the bed material. For maximum dune steepness of 0.06, the value of K was found to be 1.32.

Engel & Lau findings are very much similar to Khalil's concept of bed-load transport rate.

Holtoroff.G(19) in 1983 developed a theory to predict the bed-load for steady fluid and sediment flow. The theory is based on the fact that the total power of the fluid and sediment flow is constant. The power of the sediment flow increases as the power of fluid flow decreases.

Wilson(20) in 1987 stated that in a well developed bed-load motion in open channels, the shear stress is often large enough to set up a sheared layer several grain diameters in thickness. The concentration of solids in the sheared layer decreases with height in an essentially linear fashion. This finding has already been used to calculate the velocity distribution within the sheared layer for a typical case where variation of shear stress with height may be ignored; this analysis has been extended to obtain the solids disharge per unit width of bed. The analysis predicts that the threshold of motion curve on the Shields diagram must approach a constant Y-value at sufficiently small abscissae.

2.2 SUSPENSION OF SEDIMENTS

The modern developments in the turbulent flow theory have created interest in the sediment suspension and heat flow problems. It was *Morrough P. O'Brien*(21) 1933 who first made use of the Taylor - Schmidt findings in deriving the equation for the distribution of suspended sand in a trubulent flow. By equating the rate of upward transfer, $-\epsilon_s \frac{dC}{dy}$, of suspended sediment resulting from turbulent exchange and the rate of settling, ωC, under gravitational force, O'Brien obtained the following equation

$$\epsilon_s \frac{dC}{dy} + \omega C = 0 \qquad \text{............(2.47)}$$

in which y is measured vertically upward; C is the concentration of suspended material; ω is the settling velocity of the sediment in still fluid; and ϵ_s is the transfer coefficient for the sediment.

Here the concentration of suspended material near the surface is zero.

Theodor von Karman (22) 1935 gave the analogy between the transfer of mass or of heat and the transfer of momentum. He showed that the coefficient of all these kinds of transfer should have the same form, but he stated that it was subject to further discussion as to whether those coefficients have the same values.

Another step was taken by *Sherwood and Woertz*(23) (1939) who found that the transfer coefficient for water vapor in a turbulent gas stream ϵ_s was not equal to the momentum transfer coefficient ϵ_m but they seemed to bear a constant relation to each other. Other investigation disclosed that this approximation can be assumed also in case of heat transfer. Therefore, it may be assumed that ϵ_s can be related linearly to ϵ_m:

$$\epsilon_s = B\,\epsilon_m \qquad \text{.................(2.48)}$$

in which B is the coefficient of proportionality.

For turbulent flow

$$\tau = \rho\epsilon_m \frac{du}{dy} \qquad \text{..........(2.49)}$$

where τ is the shear stress at any point, u is the velocity, and ρ is the density of the fluid.

For two dimensional flow

$$\tau = \tau_o(1-y/y_m) \qquad \text{...........(2.50)}$$

in which τ_o is the shear stress at the boundary and y_m is the vertical distance to the maximum velocity i. e. plane of zero shear. Thus,

$$\epsilon_m = \frac{\tau_o\ (\ 1-\ y/y_m\ )}{\rho\ du/dy} \qquad \text{..........(2.51)}$$

Evaluating du/dy by using the von Karman universal velocity defect law

$$\frac{u - u_{max}}{u_*} = \frac{1}{k} \log \frac{y}{y_o} \qquad \text{............(2.52)}$$

in which u_{max} is the max velocity and $u_* = \sqrt{\tau_o / \rho}$ the result is

$$\epsilon_m = k\ u_*\ y\ (1 - y/y_m) \qquad \text{..........(2.53)}$$

$$\text{or} \quad \epsilon_s = \beta\ k\ u_*\ y\ (1-y/y_m) \qquad \text{.........(2.54)}$$

here the distribution of ϵ_s with y is parabolic with ϵ_{smax}= 0.25 u_* β k y; at $y = y_o/2$; that is when the velocity distribution is logarithmic and the shear stress distribution is linear. The equation in dimensionless form is

$$\frac{\epsilon_s}{\beta k u_* y_m} = \frac{y}{y_m}(1-y/y_m) \qquad \ldots\ldots\ldots\ldots\ldots(2.55)$$

The universal constant k is used on the left hand side so that the right hand side will be a function of position. Going back to O'Brien's equation $\epsilon_s \frac{dC}{dy} + \omega C = 0$ and integrating considering two cases :

1- If ϵ_s is constant over a certain region then the integration for that region gives:

$$\mathrm{Log}\frac{C}{C_a} = \frac{\omega}{\epsilon_s}(\ y - a\ ) \qquad \ldots\ldots\ldots\ldots(2.56)$$

in which C_a is the concentration at any arbitrary reference level y = a.

2- If ϵ_s follows equation (2.54) in another region then the integration yields.

$$\log\frac{C}{C_a} = \frac{\omega}{\beta k u_*}\log\left[\frac{y_m - y}{y} \times \frac{a}{y_m - a}\right] \ldots(2.57)$$

or

$$\frac{C}{C_\alpha} = \left(\frac{h}{h_\alpha}\right)^z \qquad \ldots\ldots\ldots(2.58)$$

where $z = \frac{\omega}{\beta k u_*}$ and

$$h = \left(\frac{y_m}{y} - 1\right)$$

$$h_a = \left(\frac{y_m}{a} - 1\right)$$

For a given shear stress, z is proportional to ω, which means that fine-grained material has small values of Z and the particles are fairly uniformly distributed throughout the depth, whereas coarse grains will be near the bed. If $B=1$ and $k=0.4$, the ratio $\omega/u_* = 1$ corresponds to $z = 2.5$.

This simple analytical model gives surprisingly good results, compared with measurements, particularly for small values of Z. For larger values of Z, the observed exponent appears to be smaller than the calculated one, indicating that the distribution of the sediment is more uniform than that predicted by the above equation.

Vanoni(24) 1946 verified equation (2.57) and showed how well it fitted the experimental points in open channel. He also showed that the existence of suspended load tends to suppress or damp out the turbulence, causing a decrease in the value of k, the von Karman universal constant of turbulence. Equation (2.58) has been found to give a better fit to the observed distribution when in Z, the fall velocity ω is taken to 0.7 power as given by *Colby*,(25) 1955. If the concentration of suspended material at the surface(A)isnot zero then

$$C_b = \left[\frac{y_m - y}{y_m - a} \cdot \frac{a}{y}\right]^z C_a + \frac{A}{\omega}\left[\left[\frac{y_m - y}{y_m - a} \cdot \frac{a}{y}\right]^z - 1\right] \qquad \text{........(2.59)}$$

$$\frac{A}{\omega} = \frac{C_b - \left(\frac{y_m - b}{y_m - a} \cdot \frac{a}{b}\right)^z C_a}{\left[\left(\frac{y_m - b}{y_m - a} \cdot \frac{a}{b}\right)^z - 1\right]}$$

$$Z = \frac{\omega}{k u_*} \qquad \text{..........(2.60)}$$

where C_b is sediment concentration at $y = b$.

The prediction equations depend strongly on the distribution of the transfer coefficient and of velocity. Results of measurements of the transfer coefficients are few but for the momentum transfer they indicate the parabolic form as obtained from logarithmic velocity distribution. The distribution of ϵ_s appears to be a little asymmetric with the maximum being somewhat closer to the bed than predicted.

Colman(26) (1970) showed experimentally that $\epsilon_s/u_* y_o$ varies with y/y_o over the lower 30 % of the depth after which it tends to remain at a constant value up to the water surface. A small increase in $\epsilon_s/y_o u_*$ is apparent. These results indicate that ϵ_s has an inner and outer region.

Many refinements have been proposed to the diffusion solution of suspended sediment distribution. *Hunt* (1954,(27) 1969(28)) gave a very detailed derivation of the mass balance equations for sediment suspensions and differentiated between the diffusion coefficients.

The steady state of turbulent diffusion of uniform material and considering that $\epsilon = \epsilon_s$ is

$$\epsilon_{\bullet}\frac{dC}{dy} + (1-C)C\omega = 0 \qquad \ldots\ldots\ldots\ldots(2.61)$$

By using von Karman's definition of the mixing length, the logarithmic velocity distribution

$$\frac{u_{max} - u}{(gy_o S)^{1/2}} = \frac{1}{k}\left[\left(1-\frac{y}{y_o}\right)^{1/2} + B\ \ln\left[\frac{B - (1- y/y_o)^{1/2}}{B}\right]\right]$$

$$\ldots\ldots\ldots\ldots(2.62)$$

where B is a constant of integration, equal to one in clear water, and

$$\epsilon_{\bullet} = \frac{\tau_o\ (1-y/y_o)}{\rho du_{\bullet} / dy} = 2k_{\bullet}y_o(gy_o S\ )^{1/2}\left(1 - \frac{y}{y_o}\right)\left[B_{\bullet} -(1-\frac{y}{y_o})^{1/2}\right]$$

$$\ldots\ldots\ldots\ldots\ldots(2.63)$$

integration of equation (2.61) yields

$$\left(\frac{C}{1 - C}\right)\left(\frac{1 - C_a}{C_a}\right) = \left[\left(\frac{1-y/y_o}{1-a/y_o}\right)^{1/2}\left[\frac{B_{\bullet} - (1-a/y_o)^{1/2}}{B_{\bullet} - (1-y/y_o)^{1/2}}\right]\right]^{z}$$

$$\ldots\ldots\ldots\ldots(2.64)$$

where $z = \frac{\omega}{k_{\bullet}B_{\bullet}u_{*}}$

the subscript $\bullet$ refers to water with sediments.

For low concentration the left hand side of the above equation approximates to C/C_a

For the same data the fit of equation (2.64) is appreciablly better than that of equation (2.60)

Einstein and Chien (20) (1954) proposed a second order approximation. They argued that the difference in sediment concentration $\Delta y(dC/dy)$, where Δy is taken to be the mixing length of trubulent flow, may be true for fine sediment but for coarse sediment, higher order derivatives of C have to be included. They also reason that the process of turbulent mixing is much more active near the bed, where the turbulence is generated, than further away. Because of dissipation of turbulence further away from the bed, the characteristics of turbulence are not necessarily symmetrical, and the mixing lengths and instantaneous velocity distributions of the upward and downward flow may be different.

Navntoft(90) in 1970 treated the flow of sediment water mixture as a one-phase flow of fluid with density gradient. He assumed that the fluctuations in concentration with time at any level to be linearly related to the average concentration at that level. Using the mixing length hypothesis for the turbulent shear stress and the equation of continuity Navntoft gave an equation of the form:

$$C = B_1 \ln\left[\left(A_1 + (y/D)\right) / \left(A_1 + (y/D)\right)_{c=0} \right] \qquad \text{...........(2.65)}$$

where A_1 and B_1 are empirical constants and $(y/D)_{c=0}$ is the relative depth at which concentration is zero; it should be noticed that the above equation gives zero concentration some distance below the free surface.

Rubey (91) (1933) approached the sediment transport by flow as a problem of expenditure of stream energy. He found that the average suspended load concentration $\overline{C}$, is proportional to $R^{2/3}S^{1/2}$. Since q is proportional to

$R^{2/3}S^{1/2}$ from the Chezy equation, it can be written as

$$q_s = \bar{C}\, q\alpha\, R^2 S^{7/6} \qquad \text{..............(2.66)}$$

Several field engineers have reported relationship between q_s and q for different rivers as,

$$q_s \;\alpha\; q^b \qquad \text{.............(2.67)}$$

the value of b was found to have average of 2.00.

However, the major development of the concept is due to *Bagnold* (1956(92),1966(93)). Bagnold reasons that the excess weight of solids in motion must be supported by momentum transfer from solid or from fluid to solid, or both. The fluid must lift the solids at the same rate that these are falling under gravity. Hence the rate of work done by shear flow turbulence of the fluid is :

$$\text{work rate of suspended load} = m_s^* g\omega = g_{is}\frac{\omega}{u_s} \qquad \text{......(2.68)}$$

where $m_s g$ is the immersed weight g_{is} of sediment and u_s is the mean transport velocity of suspended solids. Hence, ω/u_s is analogous to the friction factor $\tan\alpha$. The fluid is The available power supply per unit area is

$$P = \rho g y_o SU = \tau_o U \qquad \text{.............(2.69)}$$

of which $\eta_b P$ is dissipated in bed-load transport, leaving $P(1-\eta_b)$ for suspended load. Hence

$$g_{is}\frac{\omega}{U_s} = \eta_s P\ (1-\eta_b)$$

or

$$g_{is} = \eta_s P\ \frac{U_s}{\omega}(1-\eta_b) \qquad \text{...............(2.70)}$$

The above approach tells us nothing about the distribution of sediment in suspension.

Velikanov[94] in 1954 set the gravitational theory for the solution of the transport of sediment problem. The time-averaged vertical transport of water and sediment must be zero, i. e the average upward transport per unit area and time must be equal to the settling, thus energy loss is all dissipated by friction.

Using the assumption of linear shear stress and logarithmic velocity distributions, Velikanov obtains

$$\frac{C}{C_a} = \exp\left[\frac{-\omega k\gamma_{s}^{*}}{u_* \ \gamma S} \int_{\eta_a}^{\eta} \frac{d_\eta}{(1-\eta)\ln \eta/a}\right] \qquad \ldots\ldots\ldots\ldots\ldots(2.71)$$

where $\eta = y/y_o$, η_a is a reference level just outside the limits of integration, and $a = k_s / 30\ y_o$.

This equation is of the same form as obtained from the diffusion theory except that the exchange coefficient has a different form. Since suspension is maintained by turbulence which is random by nature, it is only natural that the distribution of suspended sediment should be subject to description by probabilistic methods.

The studies of suspension which have led to statistical models started with attempts to relate the particle motion to turbulence.

One of the earliest theoretical treatments is that by *Tchen* (Delft Ph. D. Thesis 1947) which is summarized by *Hinze*[35] (1957).

The equation of motion was put in a form meaning that the force required to accelerate the particle is the sum of the :

1-viscous resistance force,

2-force due to pressure gradiant in the fluid surrounding the particle caused by acceleration of the fluid,

3-force required to accelerate the added mass of the particle relative to the ambient fluid,

4-the effect of the deviation of flow pattern from steady state,

5-external potential force.

Mikio Hino (96) (1963) tackled the problem from the equation of motion of turbulent flow. The treatment predicts that the von Karman constant will always decrease and that the turbulence intensity will increase with increasing concentration of buoyant particles. It also predicts a rapid decrease in the diffusion coefficient.

Yalin (15) (1972) describes a probabilistic model for application by computer. The computer will be programmed to displace a particle, discharged from a given source, at random and in keeping with a probability distribution. If such sources are uniformly distributed along the x-axis and the location - time history of a large number of particles has been determind, then the probability of occurence at any elevation becomes equivalent to concentration.

Based on Bagnold's energetics approach, *Pruszak* (97) in 1989 assumed the sediment transport to be controlled primarily by asymmetric oscillatory motion of water superimposed on a steady return current, gravity, and the critical conditions of incipient movement.

Whether diffusion, gravitational or statistical, the models are valid only by analogy. They tell us little about the mechanism of suspension and nothing about how much sediment can be suspended in a given flow. Even within the various theories there are analytical and conceptual problems to overcome.

The diffusion coefficient is a second order tensor and is not symmetrical in non-isotropic turbulence.

The solutions depend on the velocity and shear stress distribution in the flow and little is known about these. The velocity profile is apperciably changed by the presence of sediments in the water. Sediments reduce the value of von Karman's constant k, in addition the velocity distribution shows a reduction in velocity near the bed in sediment laden water.

From theory and observation it appears that the suspended sediment causes changes in the structure of turbulence. The dispersed matrix of solids acts as a screen through which the fluid flows and reduces the scale of turbulence, i. e. the amplitude of fluctuations.

2.2.1 SUSPENDED LOAD TRANSPORT RATE FORMULAE

The suspended load transport rate is obtained by integrating the product of velocity and concentration over the depth of flow,

$$q_s = \int_{y=a}^{y_o} CU \ dy \qquad \text{..........(2.72)}$$

Lane and Kalinske[98] (1941) suggested a simplified form for the integration by introducing a mean value of the diffusion coefficient ϵ_s

$$\omega C + \epsilon_s \ dC/dy = 0$$

$$\int_{C_a}^{C} \frac{dC}{C} = - \omega \int_{a}^{y} dy/\epsilon_s \qquad \text{..........(2.73)}$$

ϵ_s is not constant but varies with depth in the form

$$\epsilon_s = Ku_* \ y/y_o \ (y_o - y) \qquad \text{..........(2.74)}$$

The average value $\bar{\epsilon}_s$ is given by

$$\bar{\epsilon}_s = \int_{0}^{y_o} \epsilon_s \frac{dy}{y_o} = \frac{ku_*}{y_o^2} \int_{0}^{y_o} (y_o y - y^2) dy$$

for k =0.4

$$\epsilon_s = \frac{1}{15} u_* y_o$$

from (2.73)

$$\frac{C}{C_a} = \exp\left[-15 \quad \frac{\omega}{u_*} \quad \left(\frac{y-a}{y}\right)\right] \qquad \text{........(2,75)}$$

Also

$$u / u_* = 5.75 \log \frac{y}{k} + 8.5 \text{ ....(2.76)}$$

and

$$U / u_* = 5.75 \log \frac{y_o}{k} + 6.0 \text{ ......(2.77)}$$

thus

$$(u-U)/u_* = 5.75 \quad \log \quad \frac{y}{y_o} \quad + \quad 2.5$$

$$= \left(\frac{1}{k}\right)\left(\ln \frac{y}{y_o} \quad + 1\right) \qquad \text{.......(2.78)}$$

multiplying by $\frac{u_*}{U}$ yields

$$\frac{u}{U} \qquad = 1 + \left(\frac{u_*}{kU}\right) \left(\ln \frac{y}{y} +1\right) \text{ .....(2.79)}$$

Where $u_* = (gy_o S)^{1/2}$, and $\frac{u*}{kU} = 2.5\ g^{1/2} n/y^{1/6}$, for wide channels.

The total suspended load carried per unit time and width is obtained by introducing equation (2.79) and (2.73) into equation (2.72) yielding

$$q_s = \ U\ y_o C_a \quad \exp \left[\ 15 \quad \frac{\omega\ y}{y_o u_*}\right] P \qquad \text{......(2.80)}$$

where $P = f\left(\frac{\omega}{u_*}, \frac{u_*}{kU}\right)$. The function P may be evaluated and and plotted on log-log paper as P versus $\frac{\omega}{u_*}$ with $n/y_o^{1/6}$ as a parameter, as shown in Fig(2.3)

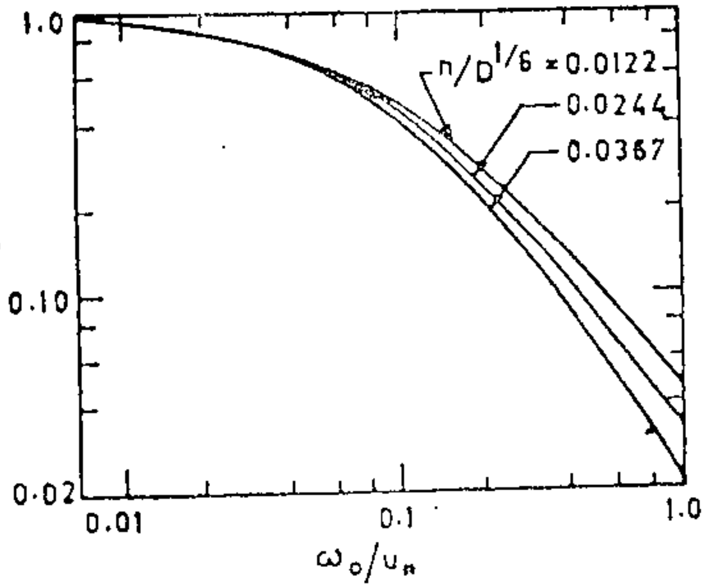


Fig (2.3) VARIATION OF P WITH ω_o / υ_* AND $n / D^{1/6}$

Einstein (10) (1950) expressed the suspended sediment transport as;

$$q_s = \int_{y}^{y_o} C_y u_y \, dy \quad ..$$

$$= \int_{a}^{y_o} C_a \left(\frac{y_o - y}{y} \cdot \frac{a}{y_o - a} \right] 5.75 \, u_* \log \left(30.2 \, y / \Delta \right) dy$$

..............(2.81)

where $\Delta = k_s / X$

k_s = roughness of the bed

X = correction factor.

u_* = shear velocity due to grain roughness only

C = reference concentration at y = 2x grain diameter

Replacing a by a dimension-less value $A = a/y_o$ yields;

$$q_s = \int_{a}^{y_o} c_y u_y dy = \int_{A}^{1} y_o c_y u_y dy \,/\, y_o$$

$$= y_o u_* C_a \left[A \,/\, (1 - A)\right] 5.57 \int_{A}^{1} \left[(1 - \eta)/\eta\right]^{Z}$$

$$\log \left[30.2y/(\Delta/y_o)\right] dy \qquad \ldots\ldots\ldots(2.82)$$

here $\eta = \frac{y}{m_b}$, m_b is the hydraulic mean radius.

For practical applications this is converted into :

$$q_s = 11.6\ u_* C_a a \left[2.303 \log (30.2\ y_o/\ \Delta) I_1 + I_2\right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.83)$$

where

$$I_1 = \left[0.216 A^{z-1}/(1-A)^z\right] \int_{A}^{1} \left[(1-y)/\ y\right] dy \qquad \ldots\ldots(2.84)$$

$$I_2 = \left[0.216 A^{z-1}/(1-A)^z\right] \int_{A}^{1} \left[(1-y)/y\right] \ln y\ dy \qquad \ldots\ldots\ldots(2.85)$$

In equation (2.83) 11.6 u_* is the velocity at the interface of the laminar sub-layer in the case of a hydraulically smooth bed, or the velocity at a distance 3.68 roughness diameters from the wall in case of rough boundaries. The value of I_1 and I_2 are given in graphical form, in Fig (2.4).

Making use of the logarithmic velocity distribution,

$$u = U + \frac{u_*}{k} + \frac{2.30 u_*}{k} \log \frac{y}{y_o} \qquad \ldots\ldots(2.86)$$

and the concentration distribution,

$$\frac{C}{C_a}=\left[\frac{y_o - y}{y_o - a}\cdot\frac{a}{y}\right]^z \qquad \text{............(2.87)}$$

and considering $a=y_o/2$, *Brooks*(09) (1965) developed an equation to determine the suspended load.

$$\frac{q_s}{q_{cmd}}=\left(1+\frac{u_*}{ku}\right)\int_{\eta_o}^{1}\left(\frac{1-\eta}{\eta}\right)^z d_\eta+\frac{u_*}{ku}\int_{\eta_o}^{1}\left(\frac{1-\eta}{\eta}\right)^z \ln\eta \, d\eta$$

...............(2.89)

where the integrals are the same as in Einstein's treatment and are given in tabular form.

2.3 THE TOTAL SEDIMENT LOAD

The methods of computation of the total sediment transport rate are classified into two main categories. The first category makes use of the equations used for the determination of suspended load and bed load and sums up the results to find the total load.

While in the second category determination of the total load is done directly without referring to the individual constituents.

According to *Einstein*(10) (1950) the total load for a size fraction i_T is $g_T i_T$ is equal to the sum of the suspended load for the size fraction $i_s(g_s i_s)$ and the bed load for the size fraction $i_B(g_B i_B)$

$$g_T i_T = g_s i_s + g_B i_B \qquad \text{.............(2.90)}$$

where all rates are given in weight per unit width and unit time .

$$g_T i_T = i_B g_B \left[1 + P_E I_1 + I_2\right] \qquad \text{........(2.91)}$$

where P_E is a transport parameter given by :

$$P_E = 2.303 \log (30.2\ y_o/\Delta) \qquad \text{........(2.92)}$$

other terms are previously defined.

The Einstein procedure estimates the bed load and suspended load for any related discharge from data on the geometry of the river and sediment grading. The procedure depends on field measurments which neglect the suspended load at depth near the bed.

The modified Einstien procedure developed by *Colby* and *Hembree*(25) (1950) estimates the total sediment discharge for a given stream at a given discharge from the measured depth integrated suspended load sample. The calculation is based on measured mean velocity and depth replaces hydraulic mean radius. Their method is applicable to laboratory flumes and underestimates total sediment load in natural rivers.

Einstein(40) (1964) simplified the equation given by Colby et al and gave it in the form

$$\frac{i_{Ts} g_{TS}}{i_{sm} g_{sm}} = \left(\frac{\eta_1}{\eta_o}\right)^{z-1} \left(\frac{1-\eta_o}{1-\eta_1}\right)^{z} \frac{(1 + P_E I_1 + I_2)\eta_o}{(P_E I_1 + I_2)\ \eta_1} \qquad \text{........(2.93)}$$

where g_{Ts} = the total sediment discharge per unit width

g_{sm} = the measured suspended discharge

$\eta_o = a/Y_o = A$

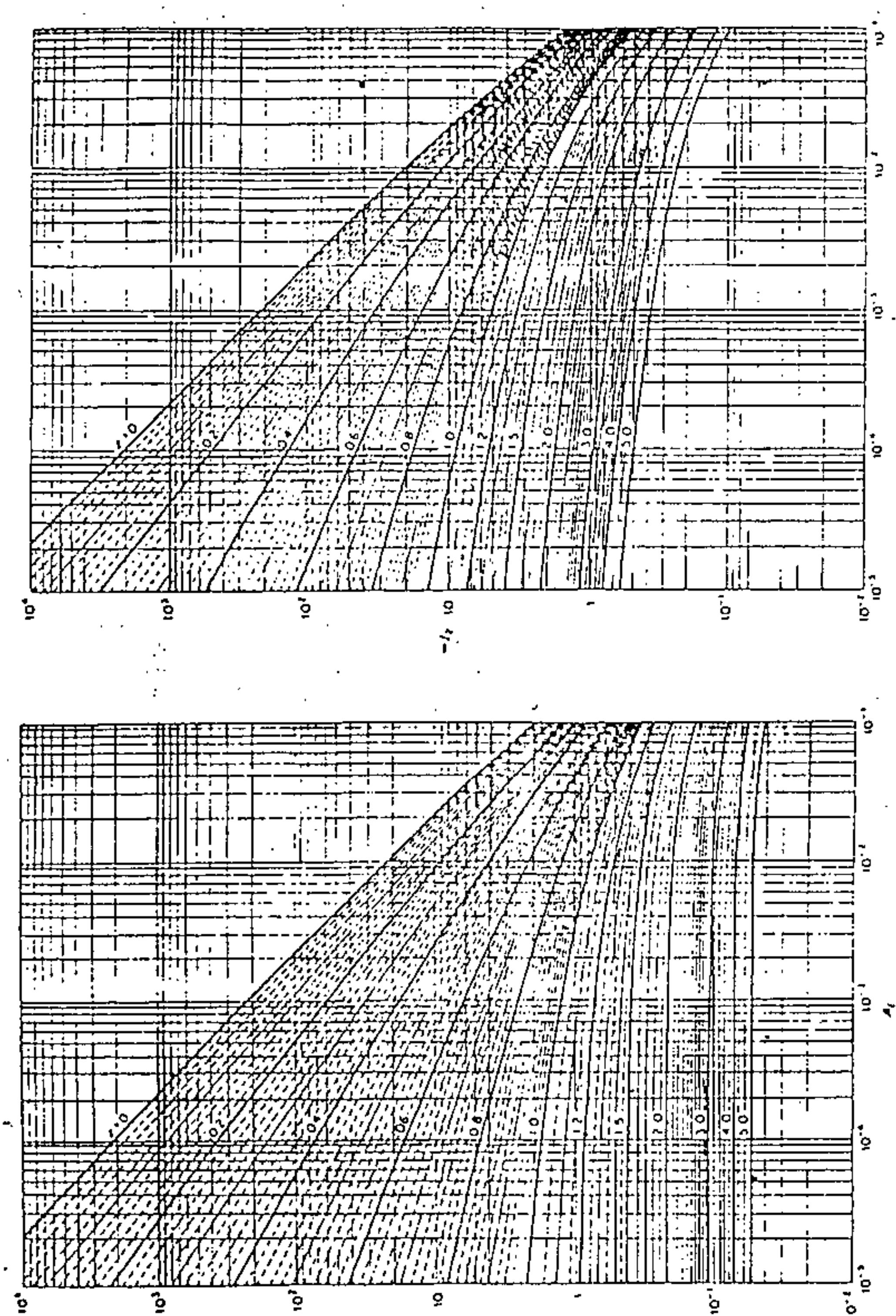


FIG.(2.4) EINSTEIN'S INTEGRAL I_1 AND I_2

$$\eta_1 = y_1/y_0$$

where y_1 is the lower limit for sampling

Laursen[41] (1958) proposed a total sediment transport formula for mean sediment concentration in terms of weight

$$\bar{C} = \sum i \left(\frac{d_i}{y_0}\right)^{7/6} \left(\frac{\tau_o'}{\tau} - 1\right) f(u_*/\omega_i) \qquad \text{......(2.94)}$$

where

d_i = mean grain size

τ_o' = bed shear stress due to grain resistance

$$= \frac{\rho U^2}{58} \left(\frac{d_i}{y}\right)^{1/3} \qquad \text{........(2.95)}$$

τ_c = critical shear stress for grain d_i

$$= \theta_c (\gamma_s - \gamma) d_i \qquad \text{........(2.96)}$$

$\sum i$ = contribution of all size fractions added to give total transport

the function $f(u_*/w_i)$ given in graphical form in Fig (2.5) .

The weight rate of transport is

$$g_{Ts} = \bar{C} S_s q \qquad \text{...........(2.97)}$$

$$S_s = 2.65$$

From point of view of general physics, *Bagnold*[93] (1966) argues that the existence and maintenance of upward supporting stresses equal to the immersed weight of the solids. The dry mass m and the immersed mass of the solid m\` are related,

$$m'g = (\rho_s - \rho/\rho_s) mg \qquad \text{..........(2.98)}$$

Thus the bed-load mass m'_b is defined as that part of the total load mass which is supported by a solid-transmitted stress $m'_b g$, while the suspended load mass m'_s is supported by the fluid - transmitted stress $m'_s g$. The transport rate of solids by immersed weight per unit width is given as i_T

$$i_T = i_b + i_s = (\rho_s - \rho/\rho_s) mgU = m'_b g U_b + m'_s g U_s \quad .....(2.99)$$

where

$U =$ mean transport velocity of solids

$U_b =$ mean transport velocity of solid moving as bed load.

$U_s =$ mean transport velocity of solid moving as suspended load .

Bagnold's equation gives dynamic transport rates which have dimensions of work rates. Stresses and velocities are not in the same direction thus a correction factor was introduced as follows :

The bed-load work rate $= i_b \tan\alpha = m'_b g u_b \tan\alpha$ ....(2.100)

The suspended load work rate $= i_s \frac{\omega}{u} = m'_s g u_s \frac{\omega}{u}$.(2.101)

where

$\tan\alpha =$ coefficient of solid friction

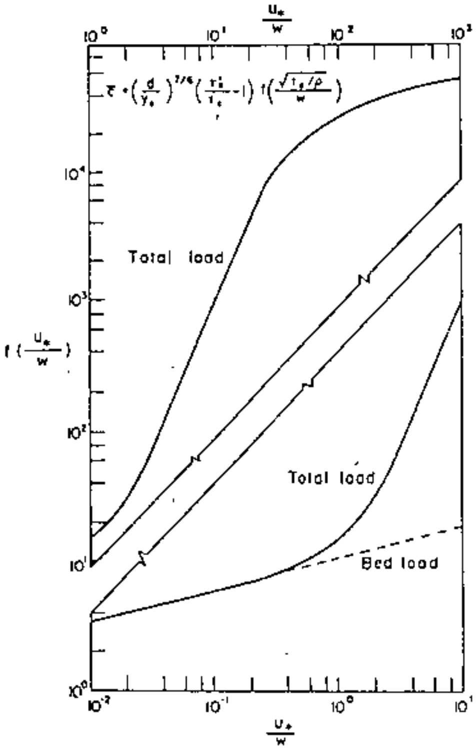
$\omega =$ terminal velocity

Bagnold also introduced the power equation which relates the rate of doing work with the available power by means of efficiency. The available power per unit length per unit width is ;

$$P = (\gamma\ Q\ S\ /\ B\ ) = \gamma\ y_o S\ U = \tau_o U \quad ....(2.102)$$

accordingly

$$i_b \tan\alpha = e_b\ P \quad ....(2.103)$$



Fig(2.5)

$$i_s(\omega/u_*) = e_s P(1-e_b) \qquad \text{........(2.104)}$$

where e_b and e_s represent the bed-load and suspended load efficiencies respectively. Thus the total rate

$$i_T = i_b + i_s = P\left[(\omega_b/\tan\alpha)+(e_s u_s/\omega\ )(1-e_b)\right] \qquad \text{..(2.105)}$$

may be obtained if four parameters, namely e_b, e_s, $\tan\alpha_*$ and u_* are known. If the flow is laminar then the second term of the equation disappears. Experimentally it was found that $e_s(1-e_b) = 0.01$, and assuming that the mean velocity of fluid and suspended solid velocity are equal then ;

$$i_T = \left[P \,(e_b / \tan \alpha + 0.01 \,(u/\omega)) \right] \qquad \text{........(2.106)}$$

This equation should be used when the flow is fully turbulent Considering that $P = \tau_o \, u$ and $\tau_o = \rho u^2$ then according to Bagnold

$$q_T \alpha \, u^4 \quad \text{or} \quad q_T \alpha \, \tau_o^2 \qquad \text{........(2.107)}$$

Which is the case of many field observations carried out for flows transporting heavy suspended load.

Shen and Hung⁽⁴²⁾ (1971) recommended that a relationship be fitted to the available data by regression techniques. The argument being that if past data are described by this relationship, future similar data should. Their equation is

$$\log C = a_o + a_1 X + a_2 X^2 + a_3 X^3 \qquad \text{.........(2.108)}$$

$$X = u^{a_4} \, S^{a_5} \, \omega^{a_6} \, y^{a_7}$$

where

C = bed material transport concentration by weight as the dependent variable .

Values of a_o to a_7 were given .

White⁽⁴⁹⁾ (1972) proposed a design chart of mobility F_{gr} versus a dimensionless grain size D_{gr}, Fig (2.6),

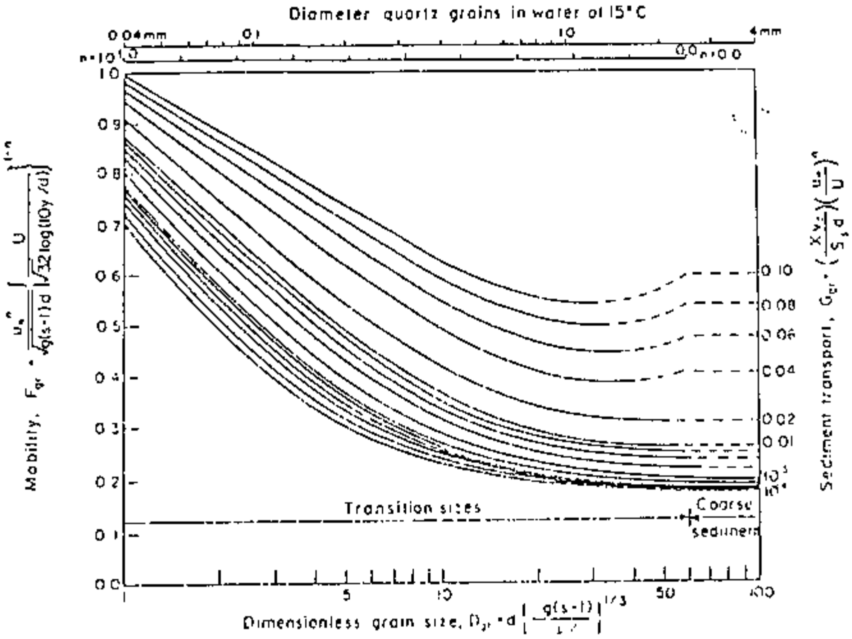


Fig (2.6)

$$F_{gr} = \frac{u_*^n}{\sqrt{(gd(S_s-1))}}\left\{\frac{u}{\sqrt{32\ \log 10\ y\ /d}}\right\}^{1-n}$$

........(2.109)

$$D_{gr} = d\left\{\frac{g(S_s-1)}{\nu^2}\right\}^{1/3}$$

...... (2.110)

in which the dimensionless sediment transport rate

$G_{gr} = \left(\frac{Xy_o}{S_s d}\right)\left(\frac{u_*}{U}\right)^n$ is a parameter and $d = d_{95}$.

$$G_{gr} = \frac{\text{shear force}}{\text{immersed weight}} \times \text{efficiency}$$

..........(2.111)

where

X = sediment transport (mass flux per unit mass flow rate)

$n = 0$ for coarse grains

$n = 1$ for fine grains

$n = f(D_{gr})$ in the transition region

The transport rates G_{gr} are related to F_{gr} by

$$G_{gr} = C \left(\frac{F_{gr}}{A} - 1\right)^{m} \quad ....(2.112)$$

The constants: A, C, m and n were determined with optimization techniques applied to existing data. However the scatter of points is quite appreciable.

Engelund[44] (1973) proposed a method for calculation of sediment transport when the bed material is graded. It is assumed that particles finer than a certain size will all enter into suspension while larger grains will move as bed load. The suspended load can be further subdivided according to selected particle size ranges.

Yang[45] (1976) approached the total transport from the energy rate or stream power concept previously introduced by Bagnold. Yangs equation relating sediment transport and stream power is;

$$\log C_t = \alpha + B \log (US - U_c S_*) \quad ....(2.113)$$

where $U_c S_*$ is the critical unit stream power required to start sediment motion.

Using available data and multiple regression techniques he obtained the following equation

$$\log C_t = 5.435 - 0.286 \log \frac{\omega d}{\nu} - 0.457 \log \frac{u_*}{\omega} + \left[1.799 - 0.409 \log \frac{\omega d}{\nu} - 0.314 \log \frac{u_*}{\omega}\right] \log\left[\frac{US}{\omega} - \frac{U_c S}{\omega}\right] \quad \ldots(2.114)$$

The equation has a correction coefficient of 0.971 and standard error of estimate of 0.188 in terms of logarithmic units.

Yang(46) (1979) developed a unit stream power equation for total load without using any criterion for incipient motion. Comparison between the measured results from laboratory flumes and natural rivers with the computed results from two stream power equations indicated that they are equally accurate in predicting the total sediment concentration.

A simplified unit stream power equation is:

$$\log C_t = 5.165 - 0.153 \log \frac{\omega d}{\nu} - 0.297 \log \frac{u_*}{\omega} + \left[1.78 - 0.360 \log \frac{\omega d}{\nu} - 0.48 \log \frac{u_*}{\omega}\right] \log \frac{US}{\omega} \quad \ldots\ldots(2.115)$$

In using the bed-load, suspended load and total load equations for a particular problem, extreme care should be taken to select the ones that have been developed under conditions similar to the problem under consideration.

The limitations of each set of equations ought to be realized and taken into consideration and the subsequent results viewed in this light.

Researchers have only resently paid attention to the importance of sediment transport problem. The beginning is encouraging and further fruitful results are to be expected.

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CHAPTER III

THE PRESENT APPROACH TO TOTAL SEDIMENT LOAD

3.1 INTRODUCTION

Under certain hydraulic conditions, sediment particles of a given diameter just start moving. The conditions for incipient motion of sediment particles composing the bed are best identified by the tractive force approach, which is based on the concept that the tractive force exerted by the flowing fluid on the channel bed in the direction of flow is mainly responsible for the starting of sediment particles motion.

Moving particles in contact with the bed whose normal immersed weight component is in normal equilibrium with the tangential stress acting on the grains are bed-load. Upon increasing the tangential stress, some particles start to saltate, these saltating particles are part of the bed-load.

Suspended load is that part of the load whose weight component is in equilibrium with the normal fluid stress. Suspension may and may not start along with the bed-load. Initiation of suspension seems to be a function of the applied shear stress and the grain diameter. More generally, the condition for incipient suspension seems to be a function of (θ, Re_*). If the stress applied is not enough to cause suspension, the total load is equal to the bed-load alone. Evaluation of wash load in the present study is neglected.

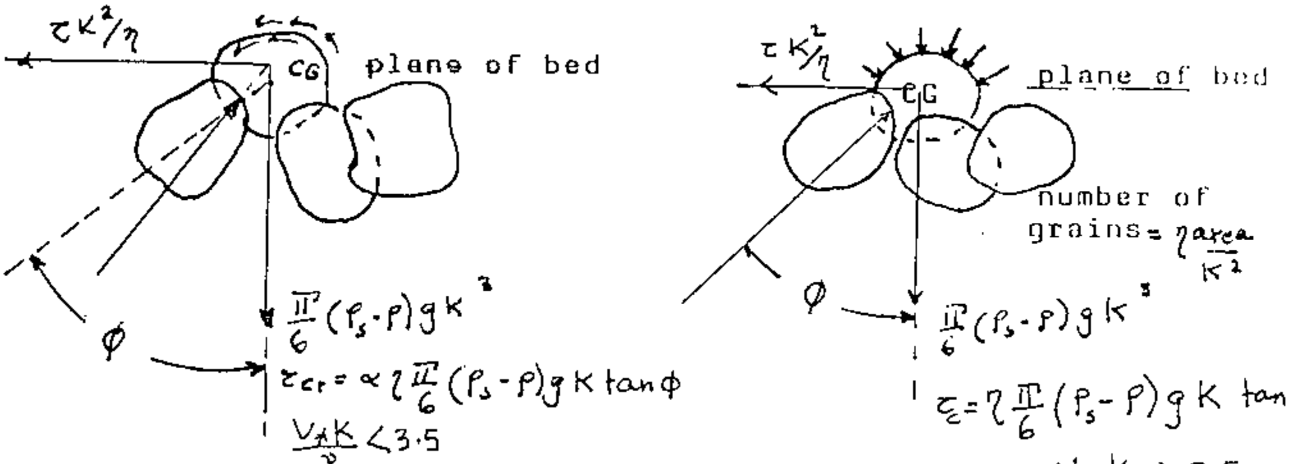
3.2 BED-LOAD

The hydraulic transport of solids as bed-load is treated as a special case of the problem of transport by traction. Solid grains in hydraulic conveyance are sheared over one another and over the stationary grains due to the forces supplied by the weight component of the driven fluid. The number of grains in motion on the bed can be determined in much the same way as determining the number of wagons that a given locomotive is able to transport. The number of wagons is known to depend on the total resistance contributed by the various retarding elements such as friction, gradient and air reistance to which also is added the force necessary to produce accelaration. In analogy with the "drawbar pull" of the locomotive, the tangential stress τ_b at the bed of the channel for a two dimensional parallel flow of steady mean velocity, is due to the weight component of the fluid, Fig (3.1), and is given by :

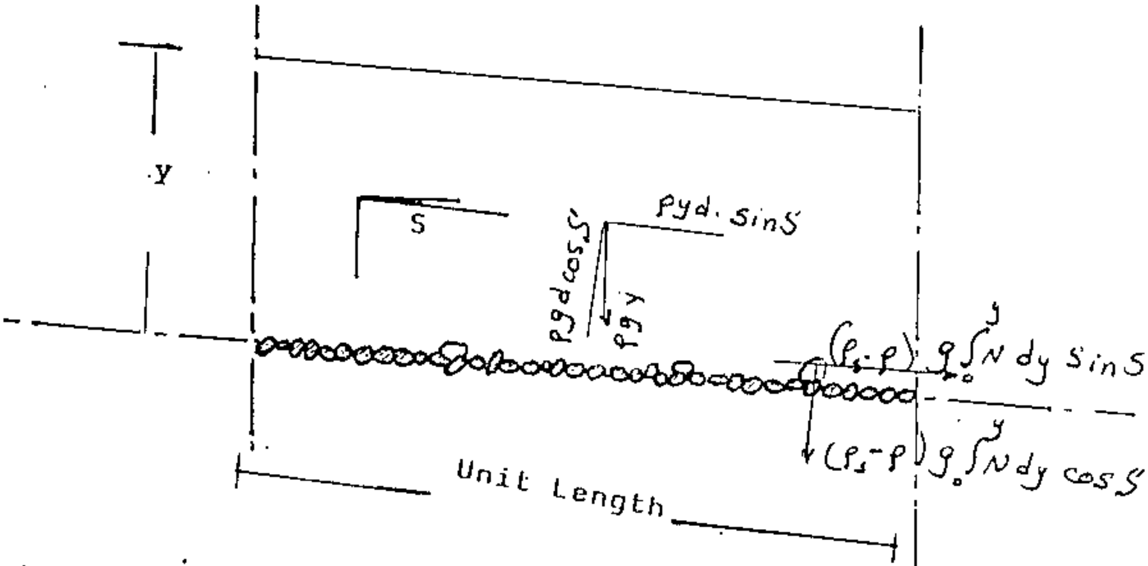
$$\tau_b=\rho gd \sin S \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

Whereas, the total resistance contributed by the various elements is partly due to frictional resistance r_f of moving grains, and partly due to the weight component r_v of the grains themselves to which also is added the portion of the stress r_s carried directly by the static grains without contributing to transport.

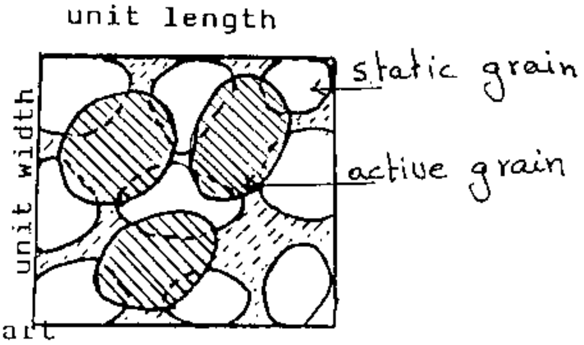
The theory of the critical stress, as already reviewed, established that static grains cannot be sheared without creating a normal stress between bed and grain so



(3.1) Equilibrium of an individual sand grain



(3.2) Definition sketch for the applied tangential stress two dimensional case of parallel steady flow.



(3.3) Key diagram explaining the part of stress carried by the static grain giving rise to a shear resistance sustained by the normal immersed weight of the grains and its interaction with surrounding grains. On this basis, the resistance of the moving grains due to friction can be expressed as

$$r_f = (\rho_s-\rho)g \cos S \tan \phi \int_0^y N \, dy \qquad ....(3.2)$$

where $\tan \phi$ the coefficient of friction of moving grains is nearly equal to the coefficient of friction at the initiation of motion. N is the volume concentration, a measure of the volume of moving grains per unit volume of space. When the bed has a gravity slope S, the resistance contributed by the weight of the moving grains is :

$$r_v = -(\rho_s - \rho)g \sin S \int_0^y N \, dy \qquad ....(3.3)$$

the negative sign is associated with a downward gravity slope. When the shear stress is raised to the critical value, it is supposed that all the grains composing the topmost layer of bed are likely to be dislodged, but none can be transported. When the stress is raised further to some value greater than the critical, some grains could be transported and while moving they continue to transfer their share of stress to the bed, whereas others since they cannot be supported as bed-load remain stationary again carrying critical stress. Therefore, as seen from Fig(3.3) the portion of the applied stress carried directly by the static grain is

$$r_s = \tau_{cr}(1- \frac{N}{N*}) \text{ for } \int_0^y N\,dy < N_* K \qquad ......(3.4)$$

where N_* is the maximum volume concentration in a single active grain layer. The equation indicates that r_s dwindles to zero when the number of the active grains approaches the maximum for a grain layer. The total resistance r_t, due to friction, gradient and static grains is therefore :

$$r_t=(\rho_s-\rho)g \cos S \ (\tan \varnothing - \tan S) \int_0^y N dy + \tau_c(1- \frac{N}{N_*}) \qquad ......(3.5)$$

Regarding the applied stress and the resisting forces, their equilibrium at the surface of a flat grain-bed can be used to predict the bed-load. When there is less than one complete layer of grains in transport i. e. $\int_0^y N\,dy < N_* K$, the volume of bed-load per unit area of place is :

$$\int_0^y N\,dy = \frac{\tau_b - \tau_{cr}\left(1- \frac{N}{N_*}\right)}{g(\rho_s - \rho) \cos S \ (\tan\varnothing - \tan S)} \qquad ....(3.6)$$

When there is a complete layer or more i.e. $\int N \ dy \geq N_* K$ the equation reduces to

$$\int_0^y N\,dy \geq \frac{\tau_b}{(\rho_s - \rho) g \cos S \ (\tan \varnothing - \tan S)} \qquad ....(3.7)$$

which gives the bed-load as predicted from the equilibrium of the grains just above the stationary surface. It remains now to discuss the stability of the grains just below the stationary surface. The applied stress is the same as given by equation (3.1), whereas the maximum resisting stress which can be developed by the top layer of the static grains can be obtained by replacing the term of equation (3.5) by the static resistance of one grain layer, so giving

$$(\rho_s-\rho)g\cos S\ N_b K(\tan\emptyset-\tan S)+(\rho_s-\rho)g\cos S\int_0^y Ndy(\tan\emptyset-\tan S) \qquad ....(3.8)$$

where N_b is the volume concentration of the static grains. The condition therefore that no static grains move is :

$$(\rho_s-\rho)\ g\cos S\ N_b\ K\ (\tan\emptyset-\tan S)\ +$$

$$(\rho_s-\rho)\cos S\int_0^y N\,dy\ (\tan\emptyset-\tan S)>\tau_b \qquad ....(3.9)$$

Using equation (3.6) to eliminate $\int_0^y Ndy$, equation (3.8) becomes

$$(\rho_s-\rho)g\cos S\ N_b\ K(\tan\emptyset-\tan S)>\tau_{cr}\left[1-\frac{N}{N_*}\right] \quad .(3.10)$$

which indicates that the static resistance is in excess of the applied stress and the bed grains are in stable equilibrium.

In the derivation of the bed-load, the motion was regarded as being steady and the forces necessary to accelerate the initially static grains to attain their speed was disregarded. However the number of grains supported as bed-load, can adjust itself by deposition or erosion of the bed according to the local demand of the available shear, though the ultimate load in steady transport should be consistent with that given by equation (3.6) or equation (3.7). The significance of the accelerative stress appears to be in creating an initial instability in the load which can lead to the formation of ripples.

The rate of transport g_s is defined as the total mass of grains which in unit time passes a unit width of the channel. To evaluate the average rate of transport, knowing the bed-load, i.e. knowing the total mass per square meter in motion, it is necessary to find the average speed of movement of the grains. The mechanism given here concerns the transfer of stress from the fluid to the moving grains and ultimately to the static grains. The transfer of the stress from the fluid to the grains necessitates the exertion of fluid drag on the grain which can be developed only when the grain is moving slower in the direction of flow relative to the local velocity of the stream.

It is assumed therefore that the speed of a single grain V_g is a fraction of the local velocity V_1 when suitably averaged over the distance $0 < y < K$. The grain speed is accordingly, expressible as :

$$V_g = B\ V_1 \qquad \ldots\ldots\ldots\ldots\ldots(3.11)$$

where B is a coefficient whose value is a function of the grains concentration in the form :

$$B = A\,(1-\alpha N^{9/7}) \qquad \ldots\ldots\ldots\ldots\ldots(3.12)$$

Multiplying this value of grain velocity by the load as given by equation (3.6), the rate of transport becomes :

$$g_b = \frac{\tau_b - \tau_{cr}\left[1-\dfrac{N}{N_*}\right]}{\cos S\,(\tan \phi - \tan S)} \cdot A\,(1-\alpha N^{9/7})\,V_1 \qquad \ldots\ldots\ldots\ldots\ldots(3.13)$$

when $\int_0^y N\,dy < N_* K$,

and when $\int_0^y N\,dy \geq N_* K$,

equation (3.13) reduces to

$$g_b = \frac{A\,\tau_b\,(1-\alpha N^{9/7})\,.\,V_1}{\cos S\,(\tan \phi - \tan S)} \qquad \ldots\ldots\ldots(3.14)$$

When the channel gradient S is small, the contribution of the gradient to the grain resistance can be disregarded.

As shown by Nikuradse and others, the velocity near the wall V_1 is a function of τ_b, depending also to some extent upon the nature of the flow surrounding the grain. The derivation of the transport rate (3.13) and (3.14) is for a flat surface. However on a rippled surface, the total stress is transfered to the bed partly as tangential stress and partly as normal stress. The part of the stress important in the movement of the bed-load seems to be that part acting tangentially on the gentle slope of the ripple, which no doubt exceeds the average due to the reversed stress acting at the leeward. From which is to be deducted the part of the stress consumed in accelerating the grain up to the ripple crest, since this part of the stress cannot be regained, the grains in general decelerate in regions of no transport.

Of equal importance to the above factors is the anomaly of the velocity distribution on the rippled surface. Unlike the rough flat bed where the local velocity is a function of U_*, on rippled beds the local velocity is a function of U_* and ripple dimensions.

In view of thes factors, an emperical constant C_g less than one may be inserted to correct formulae (3.13) and (3.14) to suit rippled beds, thus

$$g_b = C_g \frac{\tau_b - \tau_{cr}\left(1 - \frac{N}{N_*}\right)}{\cos S\ (\tan \text{Ø} - \tan S)} \cdot A(1 - \alpha N^{9/7})\ V ,$$

........(3.15)

when $\int_0^y N\,dy < N_* K$ and ,

$$g_b = C_g \frac{\tau_b}{\cos S\ (\tan Ø - \tan S\ )} . A(1 - \alpha N^{9/7}) V_1 \qquad ....(3.16)$$

when $\int_0^y N\, dy \geq N_* K$,

The above analysis for bed-load transport was developed by *Khalil*(1) in 1963, his experiments indicated that C_g=0.63, and that the maximum volume concentration per active layer, N_*, where general shear is possible is equal to 0.46, which is about 3/4 the concentration of grains as disclosed by void ratio on a static bed. The grain speed V_g is in linear relation with the local velocity V_1. The factor of proportionality A appears to vary systematically in an inverse manner with grain diameter having a value of 0.892 for grain size 0.3 mm, and 0.88 for grain size 0.65 mm, reducing to 0.83 for grain size 1.79 mm.

The grain concentration affects the grain speed, upon ploting $\frac{N}{N_*}$ versus the percentage reduction in the speed of a free grain, the maximum percentage reduction in grain speed is found by *Khalil*(1) as :

$$60\left(\frac{N}{N_*}\right)^{9/7}$$

Thus

$$V_g = 0.892 \left[1 - 0.6 \left(\frac{N}{N_*}\right)^{9/7} \right] V_1 \qquad ...(3.17)$$

For small values of bed slope, S, cos S ≈ 1 and tan S ≈ 0. Equations (3.15) and (3.16) are thus reduced to

$$g_b = 0.63 \frac{\tau_b - \tau_{cr} \left(1 - \frac{N}{N_*}\right)}{\tan \emptyset} \times 0.892 \left[1 - 0.6 \left(\frac{N}{0.46}\right)^{8/7} \right] V_1 \qquad \text{..........(3.18)}$$

for $\int_0^y N\, dy < N_* K$ and,

$$g_b = 0.63 \frac{\tau_b}{\tan \emptyset} \times 0.892 \times 0.4\, V_1 \qquad \text{.......(3.19)}$$

for $\int_0^y N\, dy \geq N_* K$.

The transport on a rippled bed is not like the flat, form drag, reversed stress, accelerated stress and deviations in velocity distribution all add to the deviations from the formulae given for transport on the flat beds.

3.3 SUSPENDED LOAD

Starting from the diffusion equation

$$\omega C + \epsilon_s \left(\frac{dC}{dy}\right) = 0 \qquad \text{...........(3.20)}$$

and assuming linear shear stress distribution as :

$$\tau_o / \tau_y = (y_o - y) / y \qquad \text{...........(3.21)}$$

with a logarithmic velocity distribution, a further relation can be written as :

$$\frac{du}{dy} = \frac{u_*}{ky} = (\tau_o / \rho)^{1/2} / ky \qquad \text{.............(3.22)}$$

where k is von-Karman's constant

Due to Reynolds' analogy, the shear stress can be expressed as:

$$\tau_y = - \rho \, \epsilon \, \frac{du}{dy} \qquad \text{............(3.23)}$$

Using these equations, the general suspended load distribution can be derived. This was given in Chapter (2) as

$$\frac{C}{C_a} = \left[\frac{y_o - y}{y_o - a} \cdot \frac{a}{y} \right]^z \qquad \text{..............(3.24)}$$

where $z = \frac{\omega}{\beta k u_*}$, and C_a is the concentration of the suspended load at any reference level. It remains to find a correlation between the bed-load and the suspended load. Remembering that, N is the volume concentration, a measure of the volume of moving grains per volume of space, and N_* is the maximum volume concentration per active layer = 0.46, it follows that the bed-load concentration when $N = N_*$ is

$$0.46(2650 - 1000) = 759 \text{ g/L},$$

based on submerged weight of sediment per unit volume of space. At a certain reference level, the concentration of the suspended-load is the same as that of the bed-load.

Einstein(2) assumed that the average concentration of the bed-load in the bed layer must be equal to the consentration of suspended load at a depth = 2d, where d is the grain diameter. This level was chosen arbitrarily by him but still needs further investigation. *Garde*(8) found that Einstein's assumption of thickness 2d is reasonable in the case of a plane bed, but the physical significance of the bed layer thickness in a rippled bed channel is rather ellusive.

Khalil said that the bed-load and the suspended load concentrations are equal at the mid depth of the moving bed thickness i.e.

$$a = \frac{md}{2} \qquad \text{..............(3.25)}$$

where;

m is the number of moving layers $= \frac{\int_0^y N\,dy}{N_* K}$, and d is the thickness of the bed layer. Knowing the number of layers in motion the concentration of suspended load at level a is known. The distribution of suspended load may be determined with the aid of equation (3.24)

3.4 TOTAL LOAD

The total suspended load transport rate is:

$$g_s = \int_a^y C \,.\, U \,.\, dy \qquad \text{...........(3.26)}$$

Neglecting wash load, the total load is the sum of suspended load and bed load i.e.

$$g_T = g_s + g_b$$

The experiments to follow were conducted to verify the aforementioned approach. If it is confirmed, then it becomes easy to determine the bed-load, suspended load and total load, if the sediment properties and flow parameters are known.

REFERENCES

1. *Khalil, M.B. (1963)*; "Mechanics of Bed Load Transport and the Characteristics of Rippled-Beds with Special Reference to Channel Roughness". Thesis Presented to the University of London for the Degree of Ph. D., March 1963.

2. *Einstein, H.A. (1950)*; "The Bed Load Function for Sediment Transportation in Open Channel Flows". Techn. Bull. No. 1026, Sept. 1950, Us. Dept. of Agriculture, Soil Conservation Service, Washington, D.C.

3. *Garde R.J. and K.G.R. Raju (1987)*; "Mechanism of Sediment Transportation and Alluvial Streams Problems". Second Edition. Wiley Eastern Limited, India.

CHAPTER IV

APPARATUS AND EXPERIMENTAL PROCEDURE AND RESULTS

4.1 INTRODUCTION

The experimental work was conducted in a 10-m long, glass sided tilting flume, located in the Hydraulics and Fluid Mechanics Laboratory in the Civil Engineering Department, at the University of Jordan.

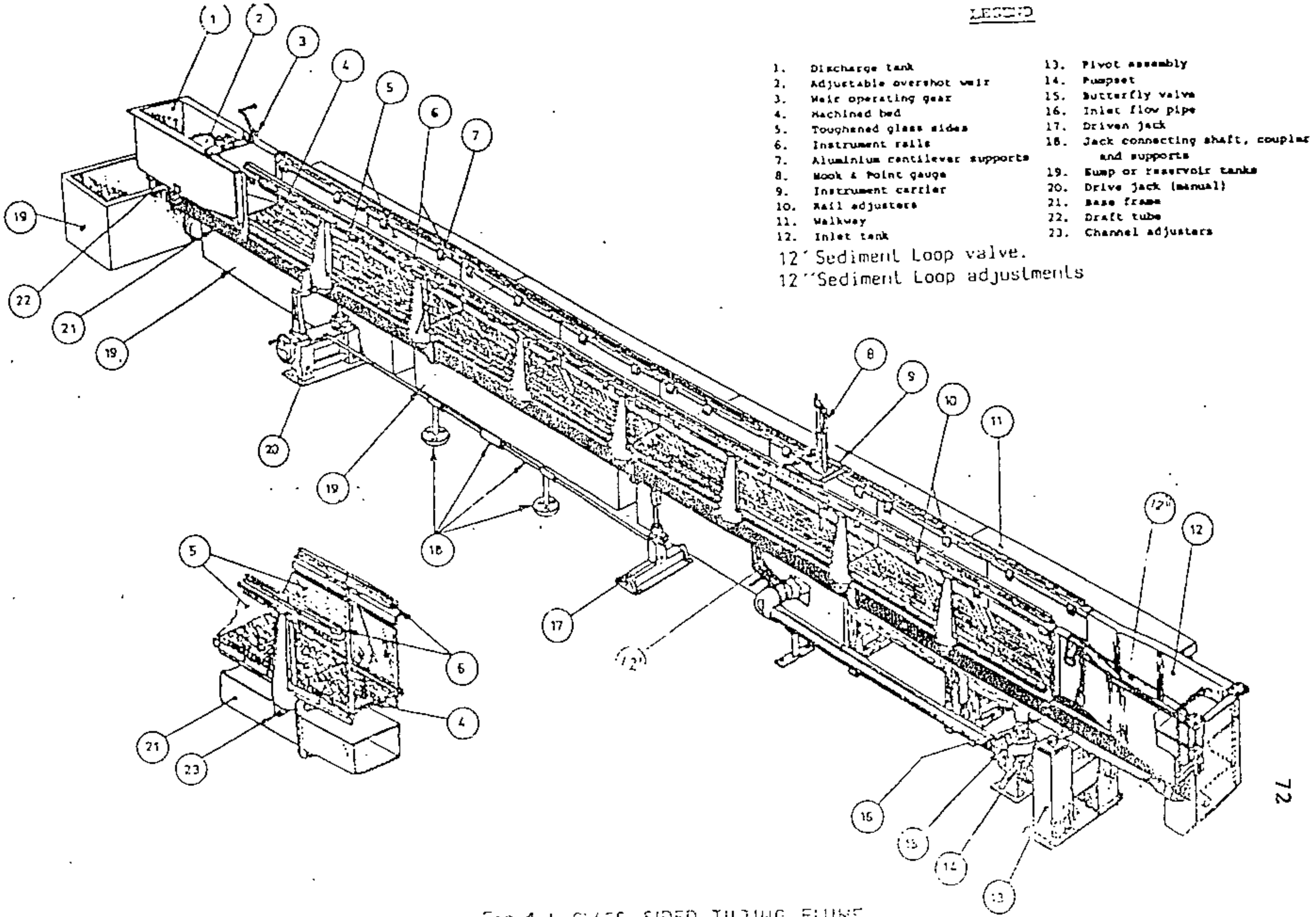
4.2 DESCRIPTION OF APPARATUS

4.2.1 THE TILTING FLUME

The glass sided tilting flume is a fully self contained 10 m. long, 0.3 m. wide and 0.45 m deep. The base frame is a steel box section, bolted together through end flange plates, the channel bed is manufactured from cold rolled steel, fully machined for accuracy. Pressure tappings are provided in the bed of the flume.

The sides are manufactured from toughened glass and are supported by aluminium cantilevers connected to the bed.

The flume is fed from an outside water source. After passing through the working section, the water travels by means of a pipe to the upstream end of the channel where a 10 cm diameter PVC pipe connection was provided to guide the water directly to the working section without deposition at the inlet of the flume .



LEGEND

1. Discharge tank
2. Adjustable overshot weir
3. Weir operating gear
4. Machined bed
5. Toughened glass sides
6. Instrument rails
7. Aluminium cantilever supports
8. Hook & Point gauge
9. Instrument carrier
10. Rail adjusters
11. Walkway
12. Inlet tank
13. Pivot assembly
14. Pumpset
15. Butterfly valve
16. Inlet flow pipe
17. Driven jack
18. Jack connecting shaft, coupler and supports
19. Sump or reservoir tanks
20. Drive jack (manual)
21. Base frame
22. Draft tube
23. Channel adjusters

12' Sediment Loop valve.
12'' Sediment Loop adjustments

Fig.4.1 GLASS SIDED TILTING FLUME

A pair of accurately aligned instrument rails is carried on the top flanges of the flume working section.

To one of these rails is affixed a longitudinal positioning scale calibrated in millimeters.

Carriages able to move in the x and y directions are positioned on the rails, thus measurements in the x,y and z directions are possible.

Electrically operated screw jacks are provided for bed slope variations in the negative and positive directions. A slope indicating scale is provided to give positive slopes up to 1:40 and negative slopes up to 1:200.

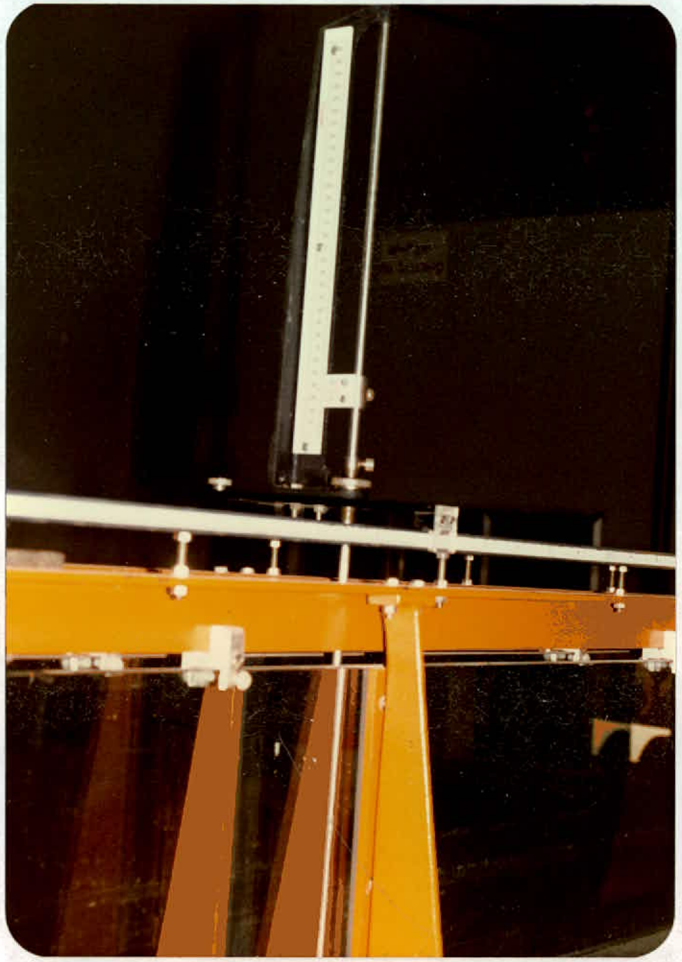
The control board contains buttons which electrically operate the pump set, the valve and the current meter read-out instrument.

4.2.2 MOVABLE CARRIAGES

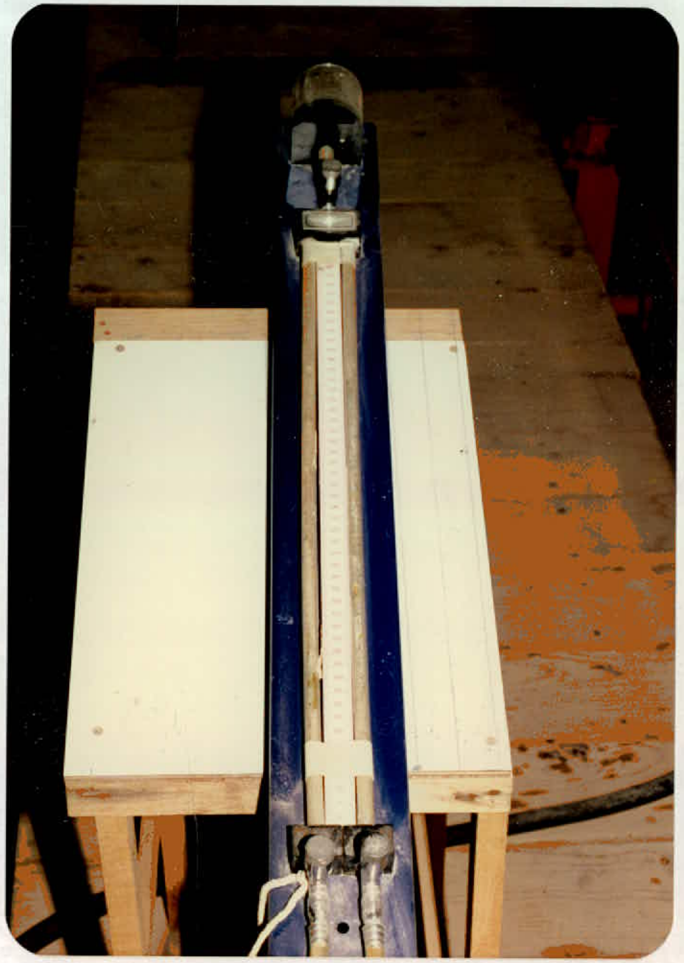
The flume is equipped with four carriages which can be moved on rails along the flume length. Each carriage has a jockey which moves in the traverse direction, thus measurements in three directions are possible. The four carriages are used to mount the depth gauge, the scraper, the suspended load sampler and the pitot tube. Movement of the carriages to any location within the working section is easy.

4.2.3 DEPTH GAUGE

Water surface level and channel bed level are measured by a point gauge supported on a sliding carriage. The pointed end is mounted on graduated scale and may be actuated by a slow motion screw equipped by a vernier with an accuracy of 0.1 mm.



DEPTH GAUGE



INCLINED MANOMETER

4.2.4 THE LEVELLING SCRAPER

Levelling the sand bed of the channel was done by a scraper made of perpex, just shorter than the flume width. Its lower surface was carefully smoothed to a straight edge. The perspex angle was clamped to a depth gauge mounted on one of the carriages and adjusted to the required level. The sand was levelled before each run by sliding the scraper over the wet sand with a thin film of water for several times.

4.2.5 SUSPENDED LOAD SAMPLER

The distribution of sediment was determined from samples siphoned from the flow through an "L" shaped glass tube 2.5 mm. internal diameter with tapered edge to minimize flow disturbance. The glass tube was clamped to a depth gauge mounted on a carriage. The other end of the tube was connected to a flexible tube 3.0 mm internal diameter, 1.5 m long to transmit the flow to the sampling bottles .

4.2.6 STATIC PITOT TUBE

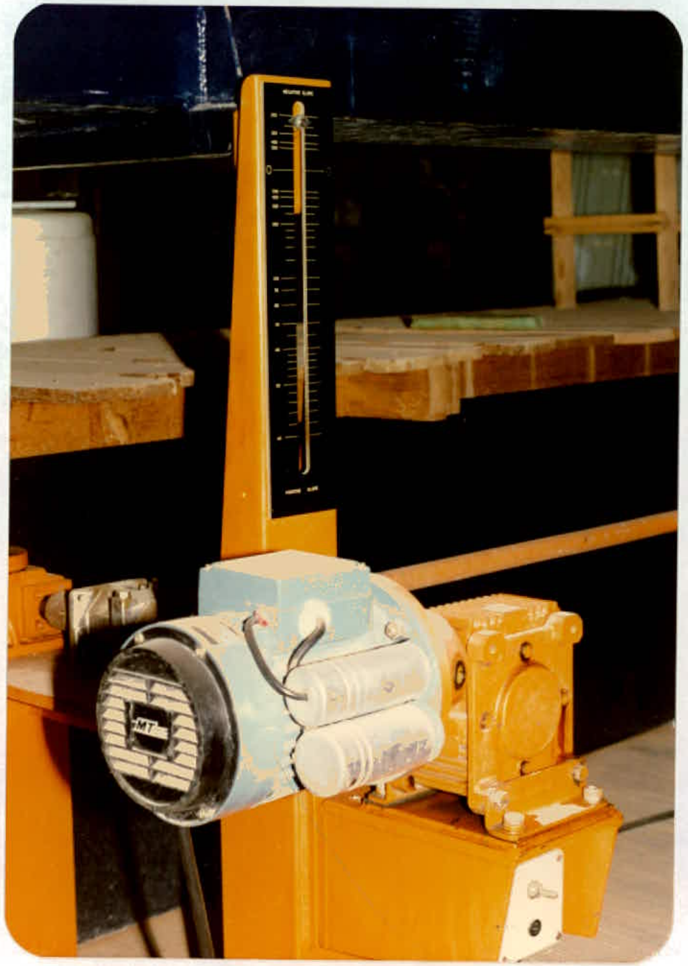
The velocity profiles were measured by the use of Prandtl-type Pitot tube with internal diameter of 1.0 mm. The pitot tube is clamped to a depth gauge and connected to a differential inclined manometer.

4.2.7 MANOMETER BOARD

The Pitot tube is connected by way of flexible tubes of 5.0 mm internal diameter to an inclined water manometer.

The inclination of the manometer is made to magnify the manometer reading. The magnification is 4.31 times greater than the normal vertical position.

Magnification is necessary because the velocity measured is small .



SLOPE INDICATOR

BED-LOAD TRAP AND SCRAPER

The manometer tubes are 8.0 mm internal diameter, which is large enough to eliminate capillary effect . The ends of the manometer tubes are open to the atmosphere. A scale is attached to the manometer board to allow reading to an accuracy of 1.00 mm.

4.2.8 SAMPLING BOTTLES

6 glass bottles with an average volume of 153 ml each were used for suspended load sampling. Each bottle was weighed empty, then it was filled with water and dried from the outside and weighed again to determine the exact volume of the bottle. The accuracy of the electrical balance used is 0.001 gms.

4.2.9 ELECTRICAL BALANCES

An electrical balance to weigh the suspended load sampling bottles with an accuracy of 0.001 gms. Another balance for measuring the bed load with an accuracy of 1 gm.

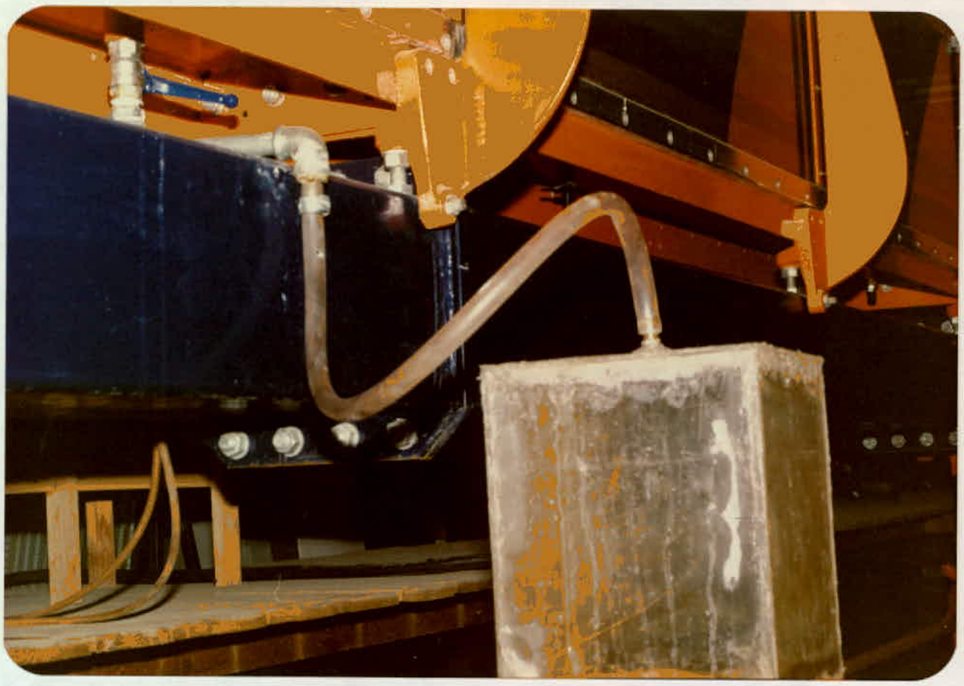
4.2.10 BED-LOAD TRAP

A bed-load trap of a funnel shape was used to measure the bed load rate. It is made of stainless steel 80 mm x 80 mm plan and 50 mm deep. The sides are sloping from the inside at an angle of 40° to the horizontal which is greater than the angle of repose of the experimental sand (30°) to ensure the instability of the sand grains on the sides. A brass wire mesh in the direction of flow was welded to the top of the trap to prevent the formation of vortices during bed load sampling . The bed load trap was fixed through one of the pressure tapping points located at the bottom of the tilting flume at

7.80 m from the beginning of the working section . The exit of the trap was connected to a ball type valve and then to a flexible pipe 12.5 mm diameter leading to the bed load collector .

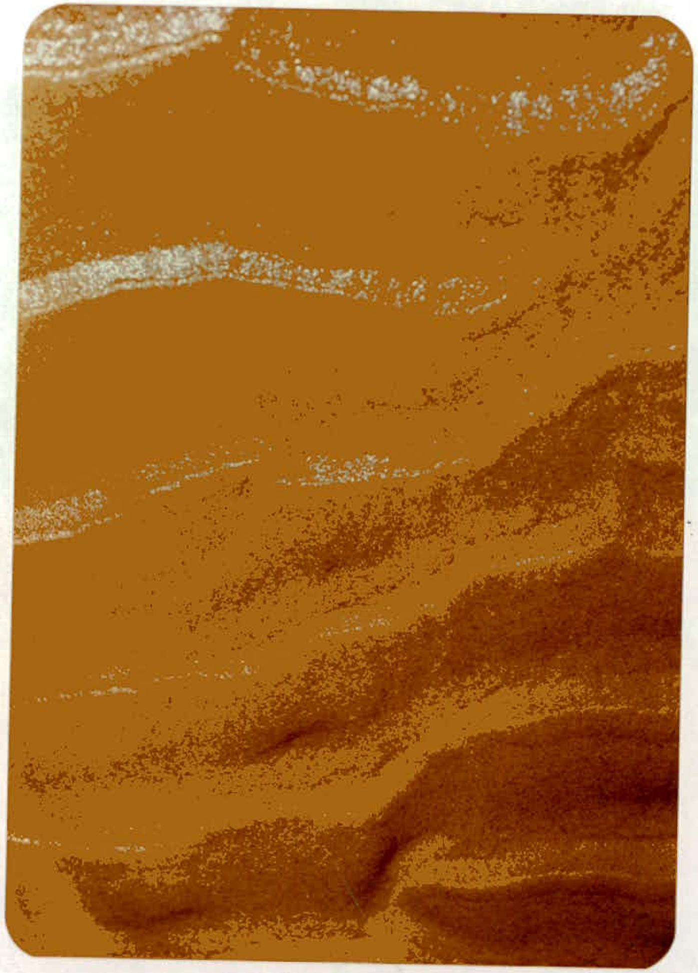
4.2.11 BED LOAD SAMPLING COLLECTOR

A tightly closed perspex container having a volume of 0.01 m^3 with a flexible pipe 12.5 mm diameter connection to the bed trap is used as bed-load collector. A valve at the lower side of the trap was installed to ease the evacuation of sand and cleaning of trap. The collector was filled with water and placed on a balance of 1.0 gm accuracy. The weight of the arrangement was recorded, any additional weight during the experiment is the submerged weight of the sand coming from the bed trap. No air was allowed into the system, thus any sand coming from the trap displaced an equal volume of water from the collector, hence avoiding disturbance of flow in the system.



BED-LOAD COLLECTOR

TILTING FLUME



BED FORMS

BED FORMS

4.3 EXPERIMENTAL SAND

The experimental sand was brought from the sand dunes of Wadi Araba south of Jordan.

The natural sand was sieved using six standard sieves shaken mechanically for twenty minutes. Sand contained between successive sieves was collected and stored in marked containers. The experimental sand used is that which passed sieve size 0.30 mm and was retained on sieve size 0.212mm. From each 1.2 kg sieved an average of 400 gms of the required sand could be collected. A total of 350 kg of experimental sand was required. After sieving the required size sand was washed well to remove dust, organic matter and soluble impurities, then it was oven dried overnight at 200°C.

It's colour is dark yellow, predominantly composed of silica and has specific gravity of 2.65, terminal velocity 0.04 m/sec and nominal diameter of 0.3mm.

The sand is quite subrounded since it was transported by wind from the Arabian desert thousands of kilometers away .

4.4 BED LEVEL FOLLOWER

The bed level follower consists of a probe which slides through two bushes from porous bronze filled with a PTFE and lead mixture.

The probe is driven by a brass pinion wheel mounted on the output of a geared d.c. positional servo drive.

The motor is mounted on an alloy block which is allowed to float on two slide rails. A rubber tyred idler wheel maintains contact with the probe on the same line as the pinion wheel through tension springs connected to the motor block. The drive assembly and bush mountings are fixed to a common plate on which is also attached the guides for the circuit boards and the plug mounting plate.

The complete unit is then housed in a polycarbonate box with a clear cover. The cover has slots at top and bottom to allow the probe to move freely.

The follower has two mounting brackets bolted to the main body. The brackets can be fitted to an adjustable instrument steadily positioned at the required operating point.

The bed level follower uses a probe consisting of a tube which at its upper end houses an infra red source and sensor and a printed circuit board to act as a driver for the source and an amplifier for the sensor.

The infra red source sends a signal which when reflected from the bed is detected by the sensor.The signal is then rectified and smoothed .The smoothed signal causes the probe to drive up away from the bed or down towards the bed thus keeping a constant distance from the datum. The drop or rise of the probe position gives an indication of the bed configuration along an axis.

4.5 APPARATUS SET UP

The flume was set to a horizontal position. This was checked by keeping an amount of still water in the working section then reading its depth at a number of stations. The readings were constant which indicates that the rails, water surface and channel bottom are all parallel and horizontal . The zero reading of the slope scale was checked.

The channel was tilted and the bed slope was determined by taking the difference in water depth at two stations and dividing it by the distance between the two stations ($\Delta y/\Delta x$). This was done at four different slopes to check the accuracy of the slope indicating scale.

Two well dressed marble sills 30 cm wide, 50 mm thick were placed 8.0 m apart at the upstream and downstream ends of the working section and were sealed by an adhesive material.

The recess between the two marble sills was then filled with the experimental sand and levelled using the scraper and a thin film of water. An additional amount of sand was added to circulate in the system.

The marble sills, experimental sand and sand trap have the same top level.

4.6 PROCEDURE

In performing the experiments, the slope and the water level are the independent variables, all other hydraulic parameters are the dependent variables.

The following procedure was done for each experimental run :

1- The bed was levelled using a thin film of water and the scraper, excess sand was removed or defficiencies filled .

2- The channel set to the required slope using the electrically operated screw jacks.

3- The channel was filled with water to some depth using an external source of water and a hose.

4- The pump was started.

5- The valve controlling the flow was gradually opened or closed until uniform flow throughout the working section was achieved.

6- The uniform depth of flow was recorded.

7- The Pitot static tube was placed at the location of the sand trap and was primed and connected to the inclined differential manometric board nearby.

8- The suspended load sampler was put nearby and ready for use.

9- Using the Pitot static tube the velocity profile was measured .The measurements extended over the whole depth of water in suitable steps.

10-Once the velocity was determined at any level, the suspended load sampler was brought to that level and the sediment-laden water was siphoned through a 2.5 mm internal diameter glass tube. The average velocity at which the sample entered the tip of the sampler was made equal to the stream velocity at the sampling point by adjusting the head on the siphon. This was done as follows :

The time required to fill the sampling bottle was calculated for each point from the measured streamvelocity and the cross sectional area of the sampler's tip. The head on the siphon for that rate of flow was determined by trial. The sampling bottle was lowered or raised if the time was less or more than required until the calculated and measured times were the same .

11-The sediment-laden water bottles were then weighed using an electrical balance of 0.001 gram accuracy. The difference in weight between the bottle filled with sediment water and the same bottle filled with clear water is the submerged weight of sediment at the point were the sample was taken.

12-The valve connecting the bed trap and the container was opened for about 15 minutes then closed and the weight of the container was recorded .The valve was again opened for about 30 minutes then closed .The weight was recorded again, the difference of the two weights is the submerged weight of bed load passing the bed trap during a certain time .

13-Bed forms height and length were measured using the bed level follower.

14-The temprature was recorded.

15-The procedure was repeated with a different slope and different water depth.

The experimental results are given in Appendix A.

CHAPTER V

ANALYSIS OF EXPERIMENTAL RESULTS

Analysis of Experimental results are given in this chapter. It includes the analysis of each of the variables used to reach an evaluation of the total load rate. A procedure for computation of the total load is given at the end of the chapter.

5.1 INCIPIENT MOTION CONDITIONS

The hydraulic conditions at which sediment particles of a given size just start moving are important in evaluating the transport rate of certain sediment flow. Many approaches have been introduced to set the conditions of incipient motion, of which the tractive force approach seems to be the most rational and sound. The tractive force approach is based on the concept that the tractive force exerted by the fluid on the channel bed in the direction of flow is mainly responsible for starting of sediment particls in motion.

The bed shear stress due to flowing fluid is given by

$$\tau_o=\rho gRS \qquad .....(5.1)$$

where ρg is the unit weight of fluid,

R is the hydraulic radius,

S is the channel slope

Many empirical formulae for the critical shear stress τ_c where given according to experimental data.

Kramer(1) in 1939, defined the critical shear stress as,

$$\tau_c = \frac{10^{-4}}{6} (\gamma_s - \gamma)\ d/M \qquad .....(5.2)$$

where M is the Kramer's uniformity coefficient varying from 0.256 to 1.00 , τ_c in N/m^2,
γ in N/m^2 and d in mm.

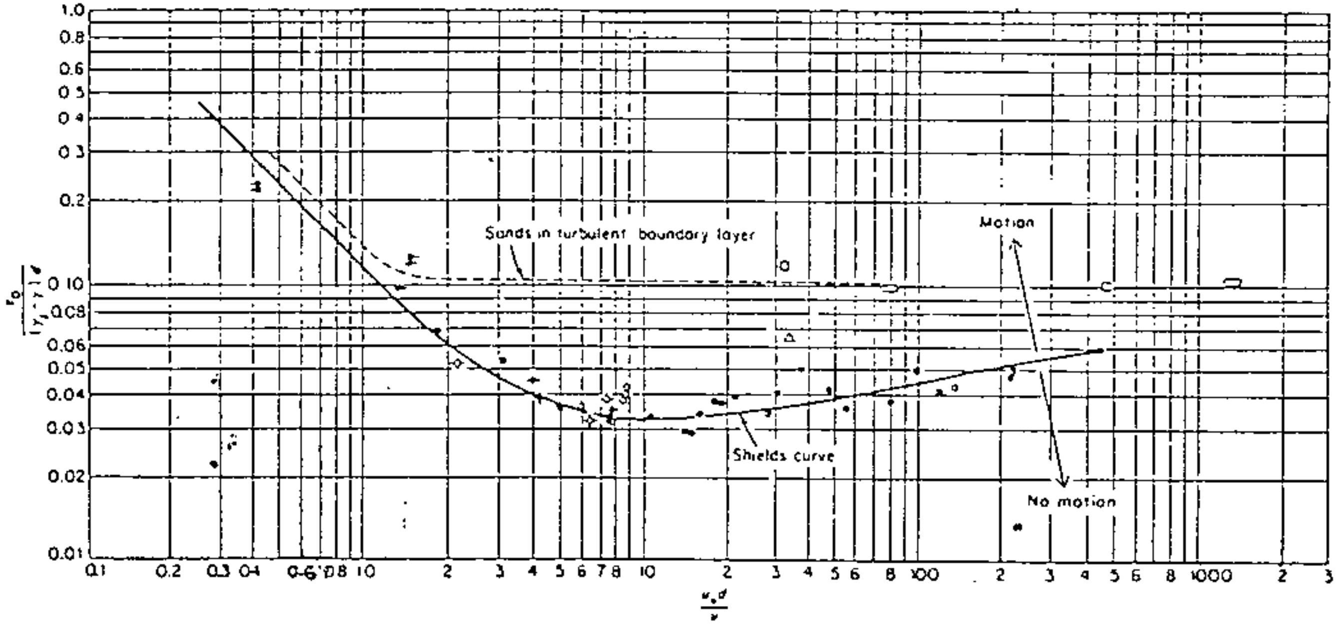
Kalinske(2) in 1947 expressed τ_c as:

$$\tau = 0.232(\gamma_s - \gamma)\ d \qquad .....(5.3)$$

Shields(3) in 1939 gave his famous Shields diagram which has been a "household item" in the field ever since. Based on experimental data Shields plotted the dimensionless shear stress $\frac{\tau_c}{(\gamma_s - \gamma)\ d}$, versus, particle Reynolds number; Re_*.The relation is given in Fig(5.1).
From Shields diagram the critical shear stress required for incipience of sediment motion may be found for a particular grain size. For grains of 0.30 mm diameter used in the present experimental work, the critical shear stress was ascertained based on Shields diagram to be 0.1942 N/m^2. For shear stresses less than this value no sediment motion was observed.

5.2 BED-LOAD RELATIONSHIPS

Many of the bed-load equations were discussed in Chapter II. The experimental results were analyzed using



Fully developed turbulent velocity profile

Sym	Description		γ_s, g/cm³
○	Amber	(Shields)	1.06
■	Lignite		1.27
●	Granite		2.7
●	Barite		4.25
●	Sand (Casey)		2.65
◇	Sand (Kramer)		2.65
✦	Sand (U S W E S)		2.65
●	Sand (Gilbert)		2.65

Turbulent boundary layer

⊸	Sand (Vanoni)	2.65
⊸	Glass beads (Vanoni)	2.49
○	Sand (White)	2.61
⬭	Sand in air (White)	2.10
△	Steel shot (White)	7.9

Shields'. diagram; dimensionless critical shear stress vs. shear Reynolds number. [*After* VANONI (*1964*).]

FIG.(5.1) SHIELDS' DIAGRAM

Schoklitsch, Kalinske, Meyer-Peter, Einstein and Khalil's approaches, which are discussed in detail in Chapter II and outlined in Appendix C. The above approaches were selected because they are the most popular and require few flow parameters to be measured in addition to having the least restrictions upon application.

Measured values were compared with values estimated by each of the above mentioned approaches. Numerical comparison is given in Table(5.1) and graphical representation is shown in Fig(5.2).

Table (5.1) Bed-Load Rate

Test	Schoklitsch	Kalinske	Meyer-Peter	Einstein	Khalil	Measured
1	2.00	18.7	5.23	11.03	8.23	10.1
2	1.78	19.8	5.7	11.73	8.76	10.3
3	2.83	20.95	6.91	14.8	9.65	10.7
4	3.1	21.067	9.02	15.9	11.06	12.1
5	3.3	22.6	9.04	19.66	11.1	12.2
6	4.3	24.6	11.64	25.87	12.85	14.0
7	3.33	26.37	13.27	31.04	13.9	14.6
8	3.13	27.4	14.9	34.5	14.48	15.3
9	4.3	27.7	15.5	41.39	14.96	16.2
10	6.72	27.4	15.21	37.94	14.3	14.1
11	5.5	46.72	34.9	103.48	41.35	46.1
12	7.1	39.63	22.96	68.98	46.84	57.1
13	9.47	40.84	65.3	131.34	56.98	66.3
14	10.06	57.79	72.29	189.7	64.71	75.1
15	14.34	65.03	65.03	121.89	83.16	85.3
16	18.39	73.54	157.9	241.4	107.47	105.1
17	22.79	47.88	106.4	167.3	82.77	84.2
18	24.51	52.79	181.5	181.3	104.87	103.0
19	16.0	85.17	221.7	275.95	131.98	127.0
20	23.6	74.62	67.46	224.2	78.1	80.1
21	39.9	55.04	198.5	295.3	114.27	108.0
22	22.23	96.53	285.5	345.0	173.60	152.0
23	20.68	94.91	236.9	327.7	160.82	148.0

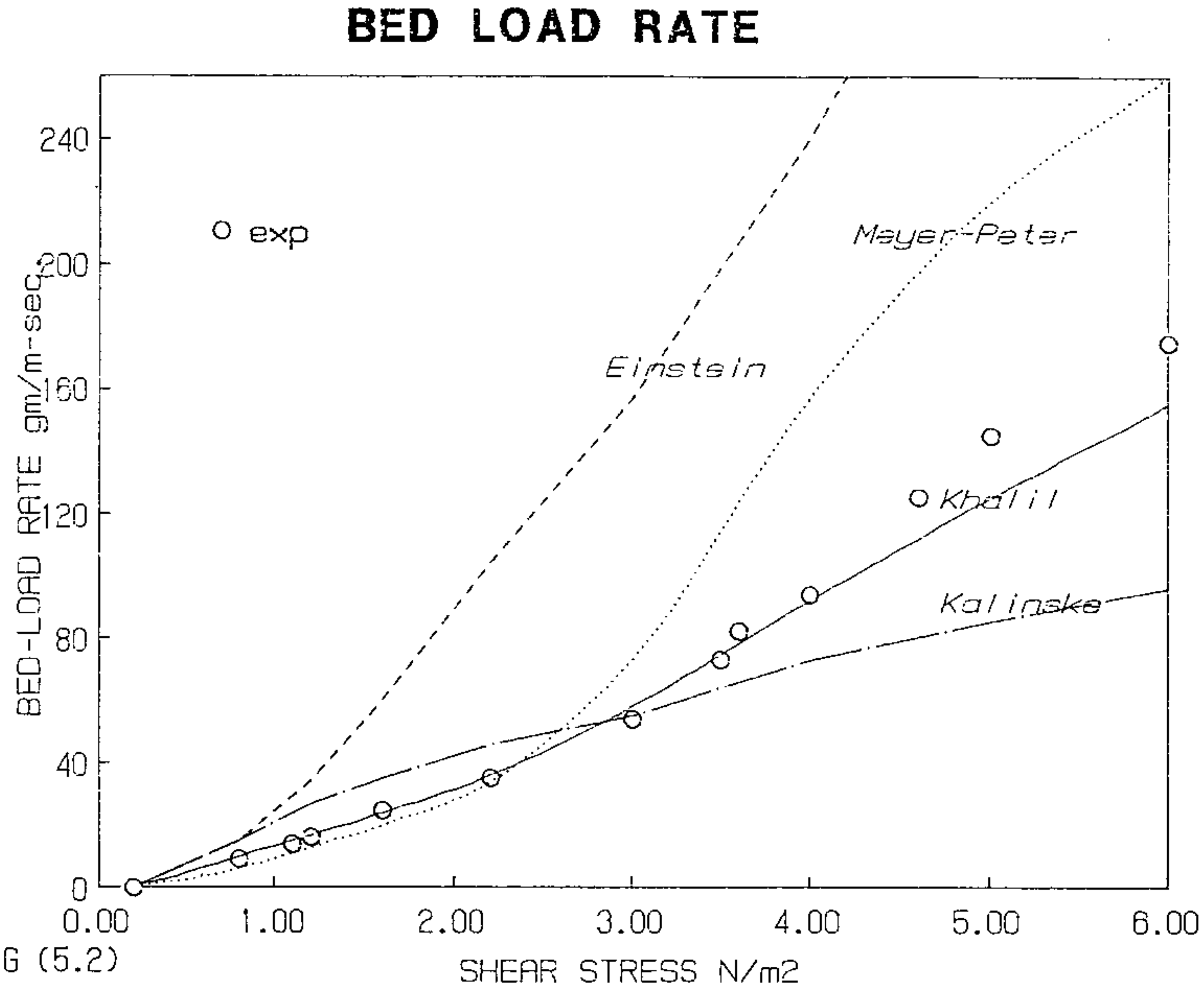

BED LOAD RATE
exp
Mayer-Peter
Einstein
Khalil
Kalinske
BED-LOAD RATE gm/m-sec
240
200
160
120
80
40
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
SHEAR STRESS N/m2

FIG (5.2)

The measured values of bed-load rates are found to be in good agreement with Khalil's approach. In this approach, the bed-load transport rate is expressed as:

$$g_B = \frac{\tau_b - \tau_c (1 - N/N_*)}{\tan\phi} \times 0.96\ (8.5\ u_*) \left[1 - 0.6(N/N_*)^{9/7}\right] \qquad \ldots.(5.4)$$

The above equation is used to estimate the transport rate on a flat bed. On a rippled surface, the total shear stress is transformed to the bed as tangential and normal stresses. The part of stresses which contributes to the bed-load transport seems to be the one acting tangentially on the gentle slope of the ripple which exceeds the average stress due to reversed stress acting on the leeward. Also the stress consumed to accelerate the grains up to the ripple crest should be subtracted from the tangential stress available, since this part of stress cannot be regained as the grains decelerate in the regions of no transport.

The velocity distribution on a rippled surface, as will be discussed later, is not a function of u_* only as the case of flat rough surface, but also depends on the ripple dimensions.

In view of these factors *Khalil* (4) introduced a correction factor to equation (5.4) to account for the effect of ripple formation on the bed-load transport. This empirical constant was estimated by him to be 0.63. In analogy to Khalil's empirical constant, the present results confirm his transport function and the constant is found to be 0.63 as shown in Fig (5.3).

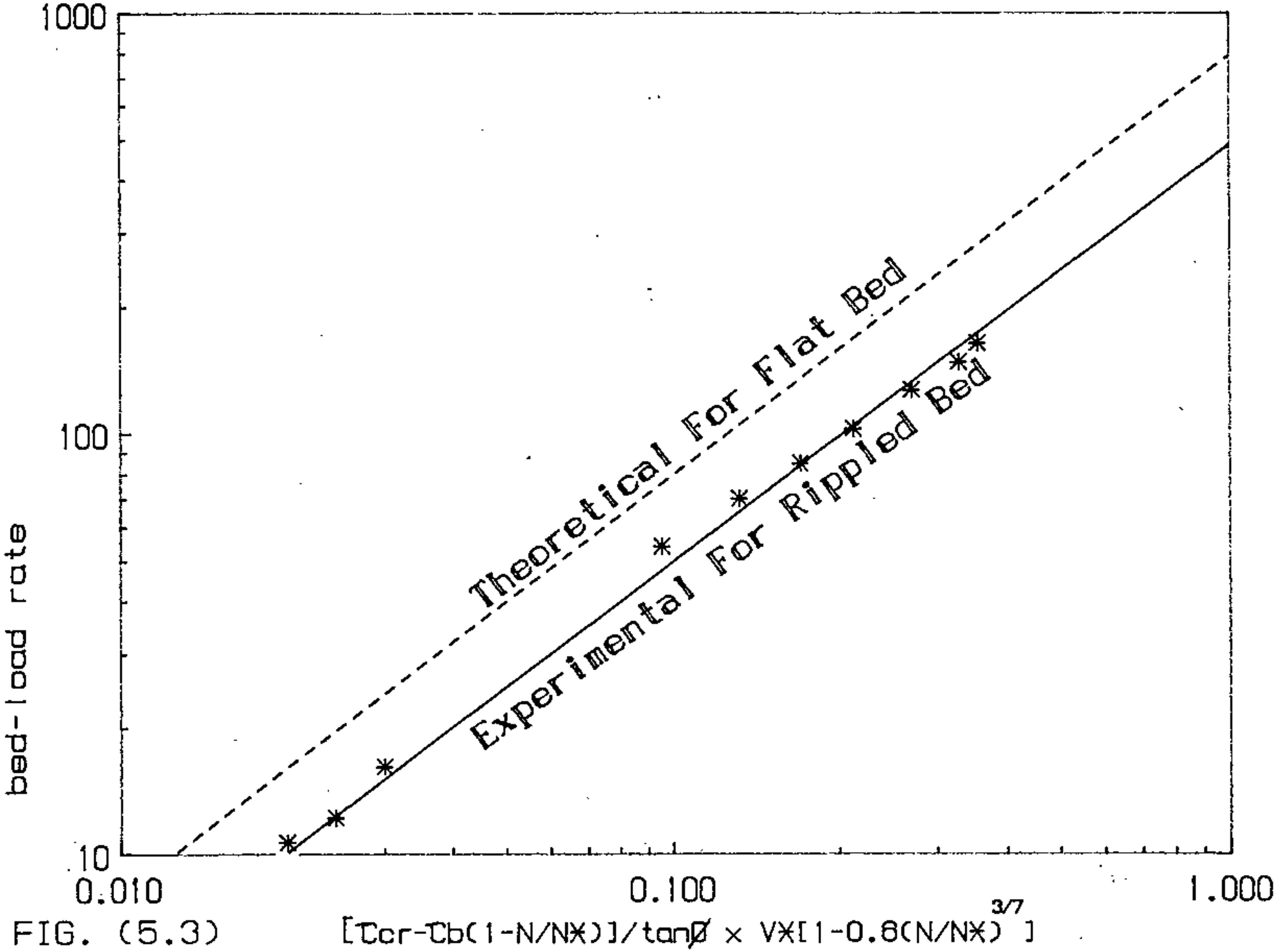

bed-load rate
1000
100
10
0.010
0.100
1.000
[τcr-τb(1-N/N*)]/tanØ × V*[1-0.8(N/N*)^3/7]
Theoretical For Flat Bed
Experimental For Rippled Bed

FIG. (5.3)

Khalil's approach was used to find the concentration of bed material at mid-depth of the moving layer.

The thickness of the moving layer is calculated as follows:

$$\int_0^y N\,dy = \left[\tau_b - \tau_c(1 - N/N_*)\right] \Big/ (\rho_s-\rho)g\tan\phi \quad ....(5.5)$$

For a given value of τ_b and considering $N_* = 0.46$, $\tau_c = 0.1942$ (from Shields diagram), $\tan\phi = \tan 30°$, the value of N is calculated. For grain size = 0.30 mm equation (5.5) is represented graphically in Fig (5.4). Knowing the bed shear stress, $\int N\,dy$ is read from the graph.

If $\int N\,dy < N_* K$ i.e. less than one grain layer in motion then

$$\int_0^y N\,dy = N \times d = N_* \times y' \quad ....(5.6)$$

or $N \times 0.3 = 0.46 \times y'$

where y' is a hypothetical thickness of a moving layer, with concentration equals 0.46; the maximum possible.

If the shear stress available is more than the required to set one grain layer in motion, equation (5.5) reduces to:

$$\int_0^y N\,dy = \tau_b/(\rho_s-\rho)g\tan\phi \quad ....(5.7)$$

the value of y' is then found using equation (5.6).

The concentration of bed-load at mid-depth of the moving layer is constant and is evaluated as follows:

concentration = 0.46 m^3 of grain /m^3 of water

= 0.46 x 1.65 x 1000 kg /m^3

= 759 kg sediments /m^3 of water

= 759 gm /liter based on submerged weight

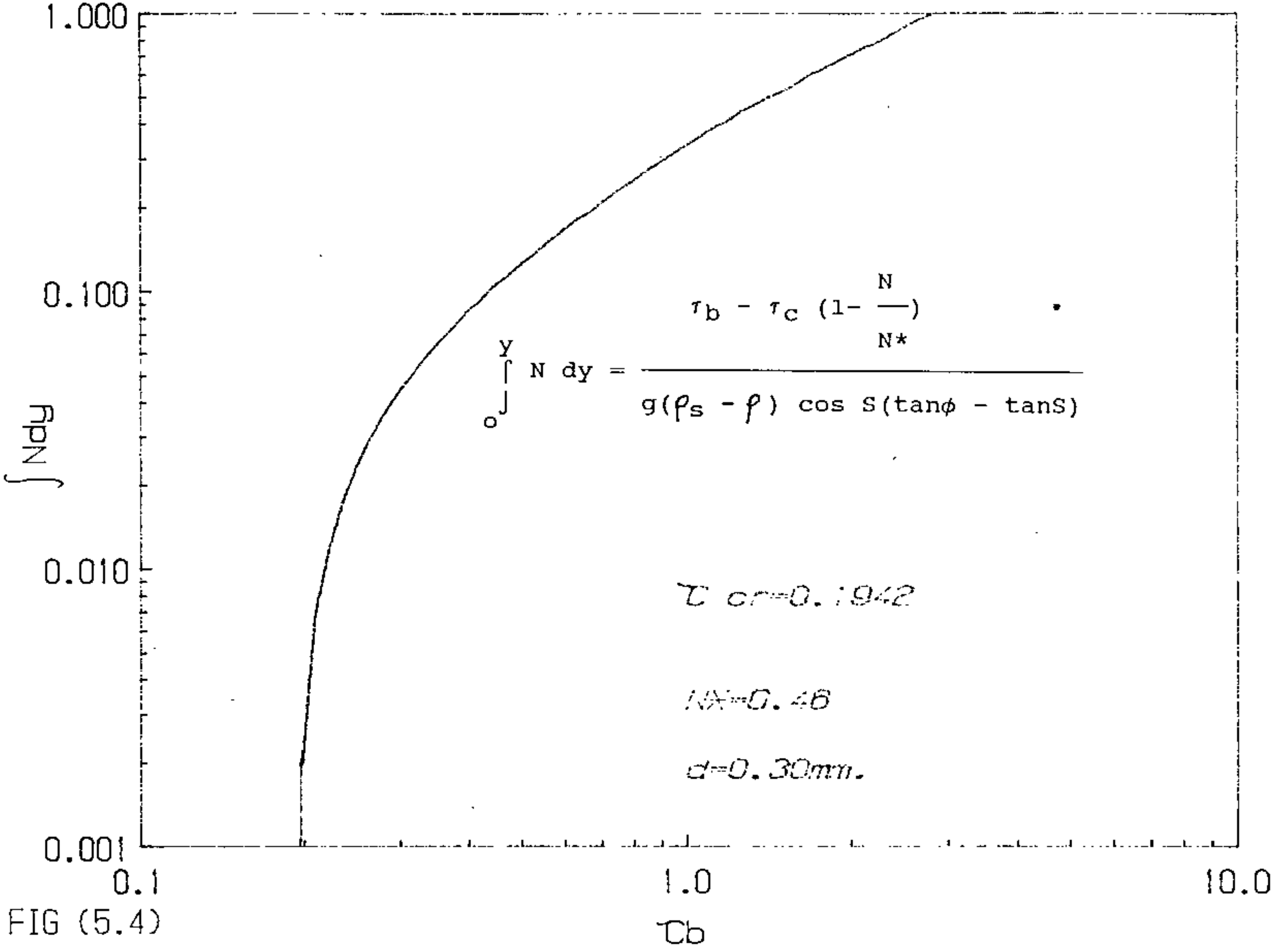

1.000
0.100
0.010
0.001
0.1
1.0
10.0
$\int N dy$
τ_b
$\int_o^y N\,dy = \dfrac{\tau_b - \tau_c\,(1 - \dfrac{N}{N^*})}{g(\rho_s - \rho)\,\cos S\,(\tan\phi - \tan S)}$
τ_{cr}=0.1942
N*=0.46
d=0.30mm.

FIG (5.4)

5.3 VELOCITY DISTRIBUTION

Velocity distribution along a vertical axis at the mid-width of the channel was measured. Velocity profiles of all experiments are found in Figs(5.8). The velocity profiles are plotted on semi-log paper with velocity in m/sec as the normal scale abscissa and the distance from the bed as the ordinate which is logarithmic in scale. The velocity distribution shows that the relation between V and log y is linear.

The theoretical formulation of the flow resistance may be based on dimensional analysis involving the proper physical and geometrical factors which affect the flow resistance. The variables used in dimensional analysis are chosen so as to represent all parameters involved in the problem. The variables include the velocity V, the depth y, the shear stress τ_b, the wall displacement y_o', the density ρ, viscosity ν and the gravitational acceleration g.

The general functional relationship for those variables is given in the form :

$$\phi_1(V, y, \tau_b, y_o', \rho, \nu, g)=0 \qquad ....(5.8)$$

Selecting V, y and ρ as repeated variables, the Π-theorem yields four Π-terms among which the following relationships exist.

$$\phi_2\left[\frac{V}{\sqrt{\tau_b/\rho}}, \frac{Vy}{\nu}, \frac{V}{\sqrt{g\,y}}, \frac{y}{y_o'}\right]=0 \quad ....(5.9)$$

or $$\frac{V}{V_*} = \phi_3(Re, Fe, \frac{y}{y_o}) \qquad ......(5.10)$$

where V_* = shear velocity = $\sqrt{\tau_b/\rho}$

Re = Reynolds number = $\frac{Vy}{\nu}$

Fe = Froude number = $\frac{V}{\sqrt{g\,y}}$

Rouse(5) revealed that the importance of Froude number appears only when appreciable surface waves or disturbances are present. Also *Powell*(d) disclosed that gravity starts to affect the flow resistance when Froude number exceeds 2.49. In the present experiments the values of Froude number are less than 1.0 . Accordingly when gravity does not affect the flow resistance, equation (5.10) may be reduced to

$$\frac{V}{V_*} = \phi_4(Re, \frac{y}{y_o'}) \qquad ....(5.11)$$

In the present experiments the range of Reynolds number is between 2.3×10^4 and 14.4×10^4 thus the flow is turbulent. As for the values of the particle Reynolds number $Re_* = u_* d/\nu$, defining the lower limit for rough flow, the range in the present work was between 9.1 and 26.79 . This range deviates completely from Nikuradse upper extreme value of transitional state for flat bed where Re_* is given equal to 67. However *Khalil*⁽⁴⁾ verified that the lower limit for rough flow over rippled beds for $v_* d/\nu$ may be as low as 10 showing that the grain size d has a little importance in standing as a geometric parameter for a rippled surface and it may be more convenient to substitute d with an equivalent sand roughness, d_s function of the ripple height h, ripple length λ and grain size d. No attempt was made in the present work to find the functional relation between d_s and h, λ, d.

Accordingly the flow in the present work could be safely considered as turbulent rough flow. For a hydrodynamically rough surface, i.e. the height of the roughness elements is large enough relative to the thickness of the laminar sublayer, viscous effects are negligible and Re in equation (5.11) may be eliminated reducing the equation to

$$\frac{V}{V_*} = \phi_s\left(\frac{Y}{Y_o'}\right) \qquad \text{........(5.12)}$$

Upon plotting $\frac{V}{V_*}$ versus $\log \frac{Y}{Y_o'}$ Figs(5.5, 5.6, 5.7) the data of each experiment gave a straight line with a slope $k \leq 0.4$. k is the von Karman turbulent constant, a measure of the convective path or mixing length.

In open channel flow without sediments the conventional value of the turbulent constant k is 0.4. This value was ascertained by taking the velocity distribution on a flat bed with no suspended sediment load, as shown in Fig (5.7) where h/λ =0.0, C_{av} =0.0, k =0.4.

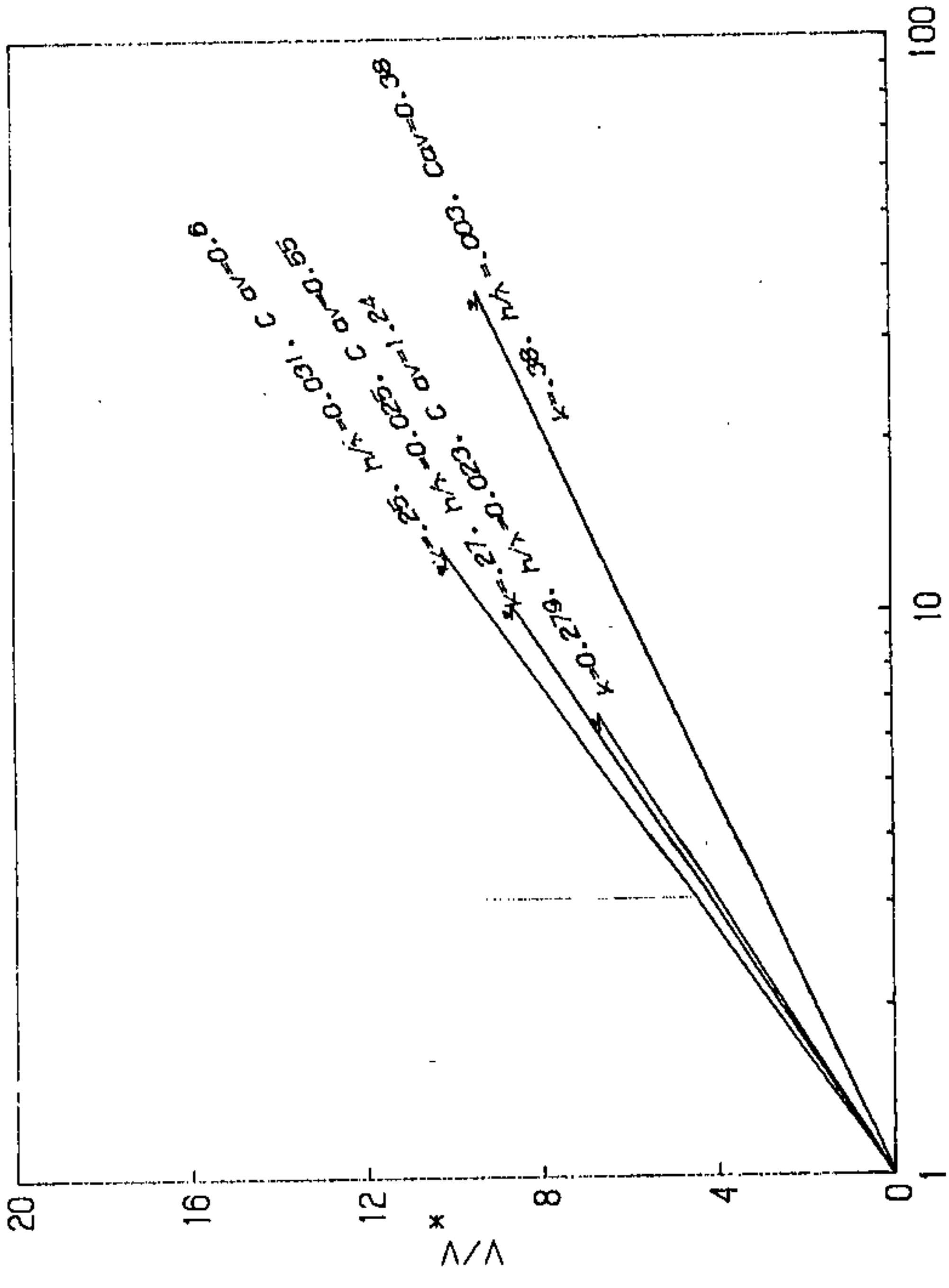


FIG (5.5) Exp.16. 20. 21. 23.

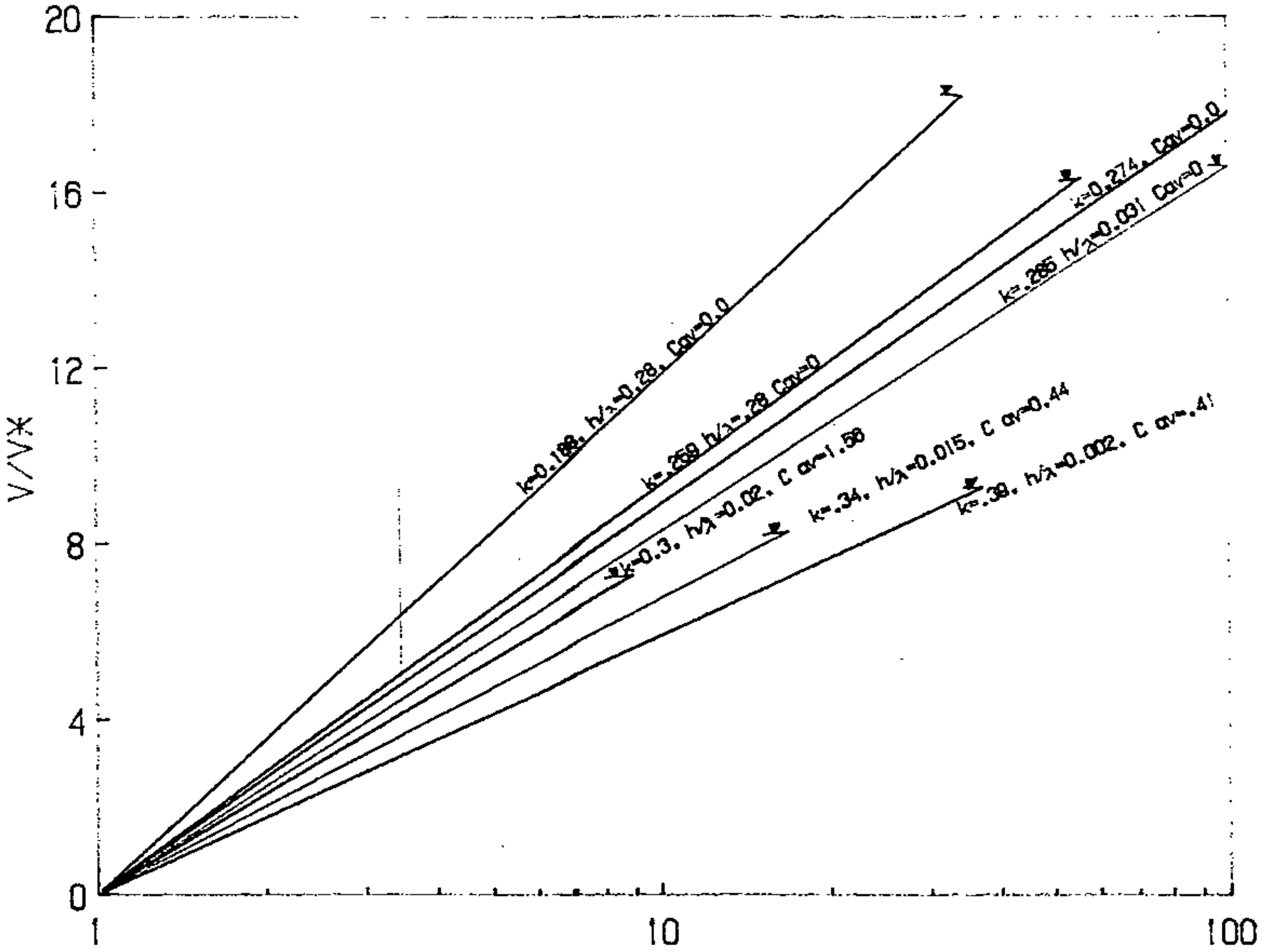


FIG (5.6) EXP 2, 5, 9, 10, 15, 17, 22

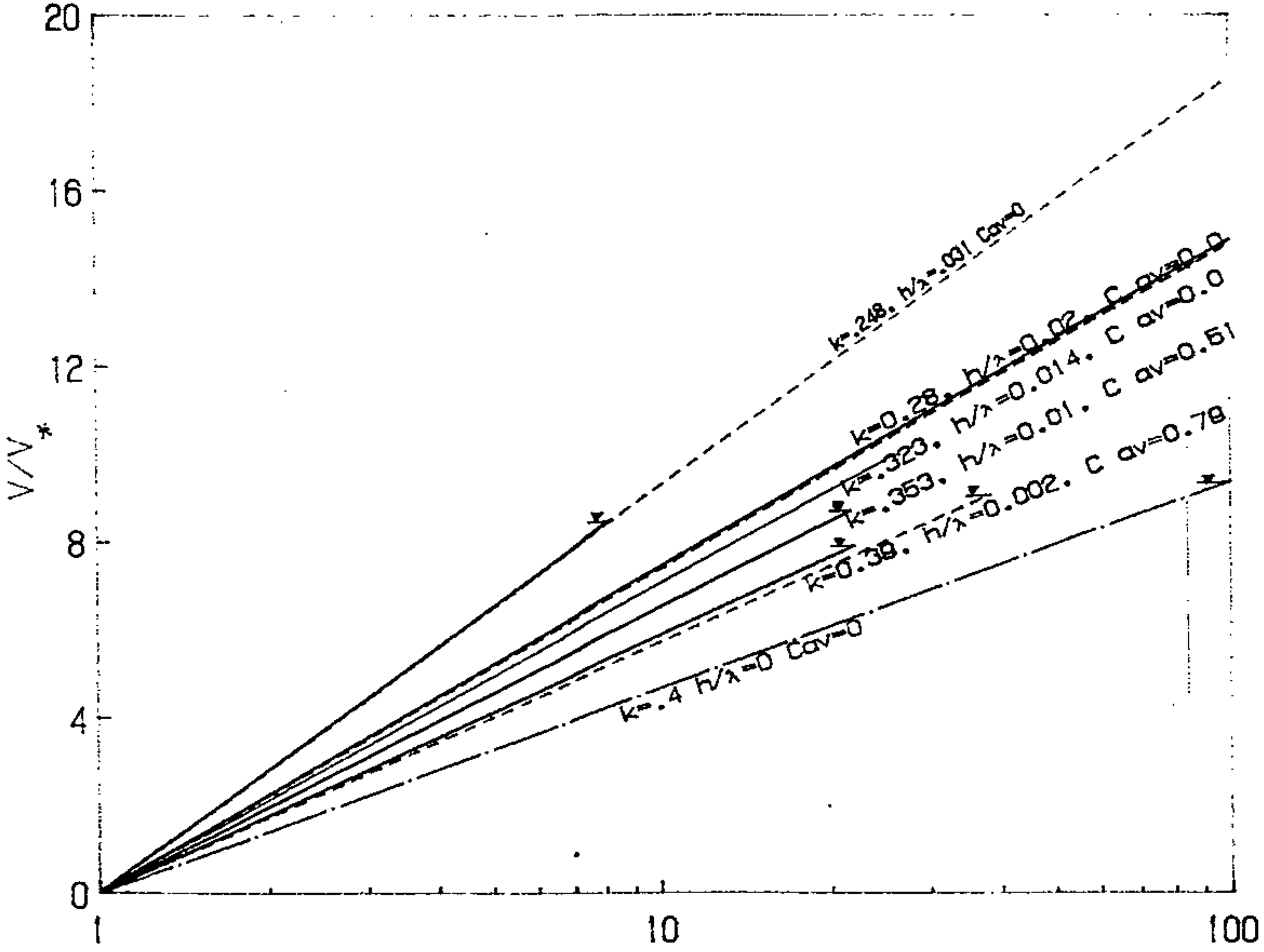


FIG (5.7) EXP 1.6.7.8.11.12.13.14

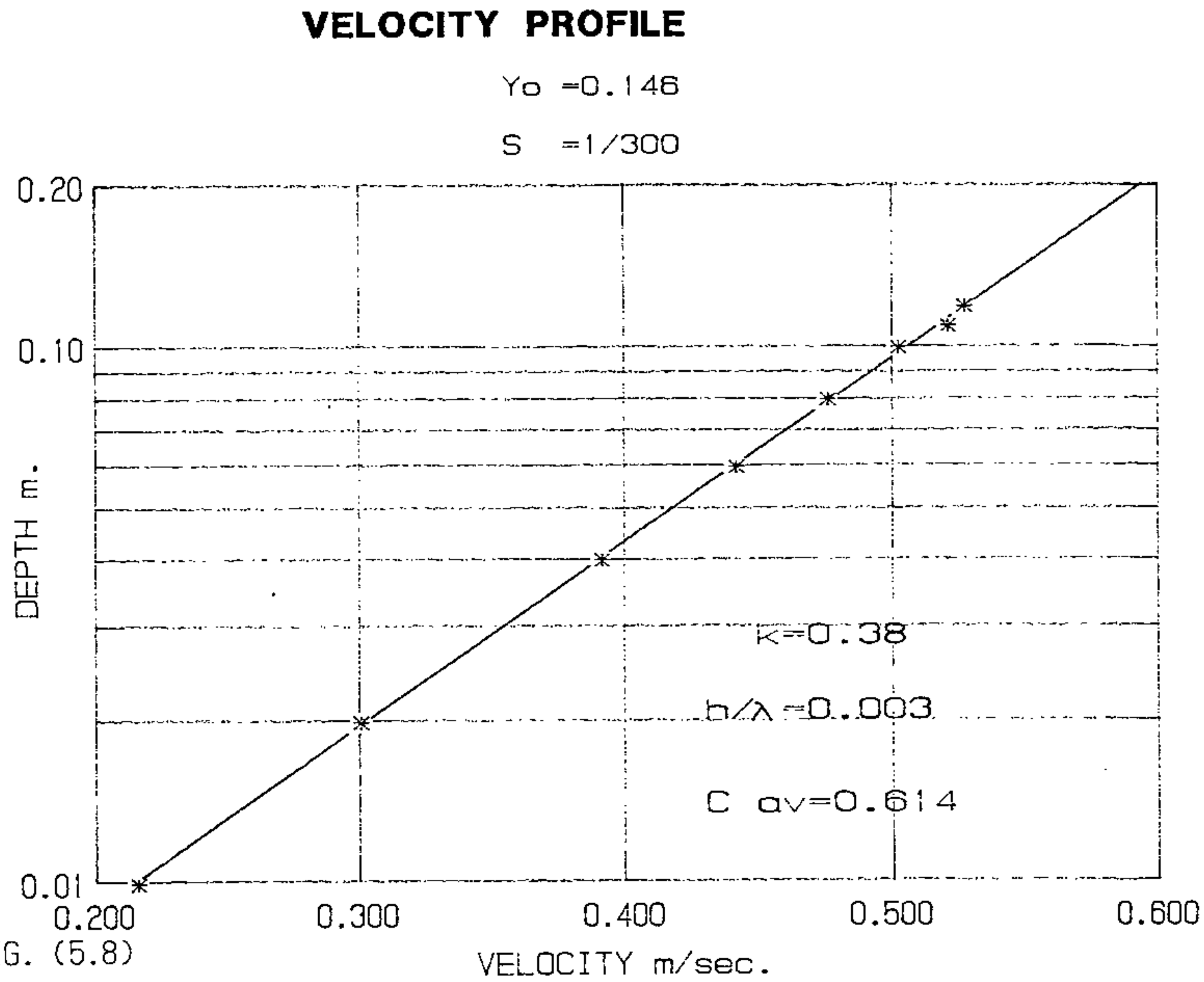
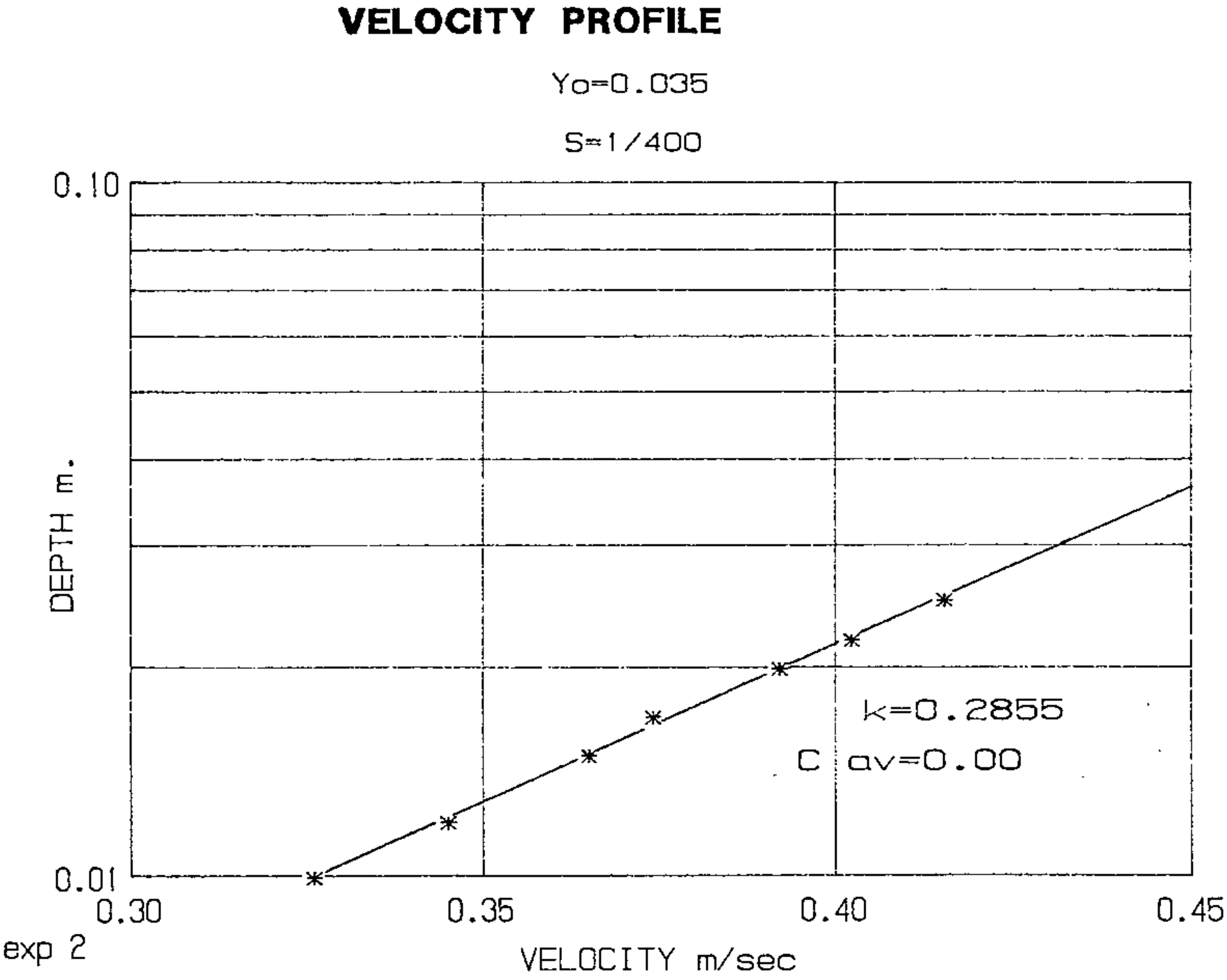

VELOCITY PROFILE
Yo =0.146
S =1/300
0.20
0.10
0.01
DEPTH m.
k=0.38
h/λ =0.003
C av=0.614
0.200
0.300
0.400
0.500
0.600
VELOCITY m/sec.

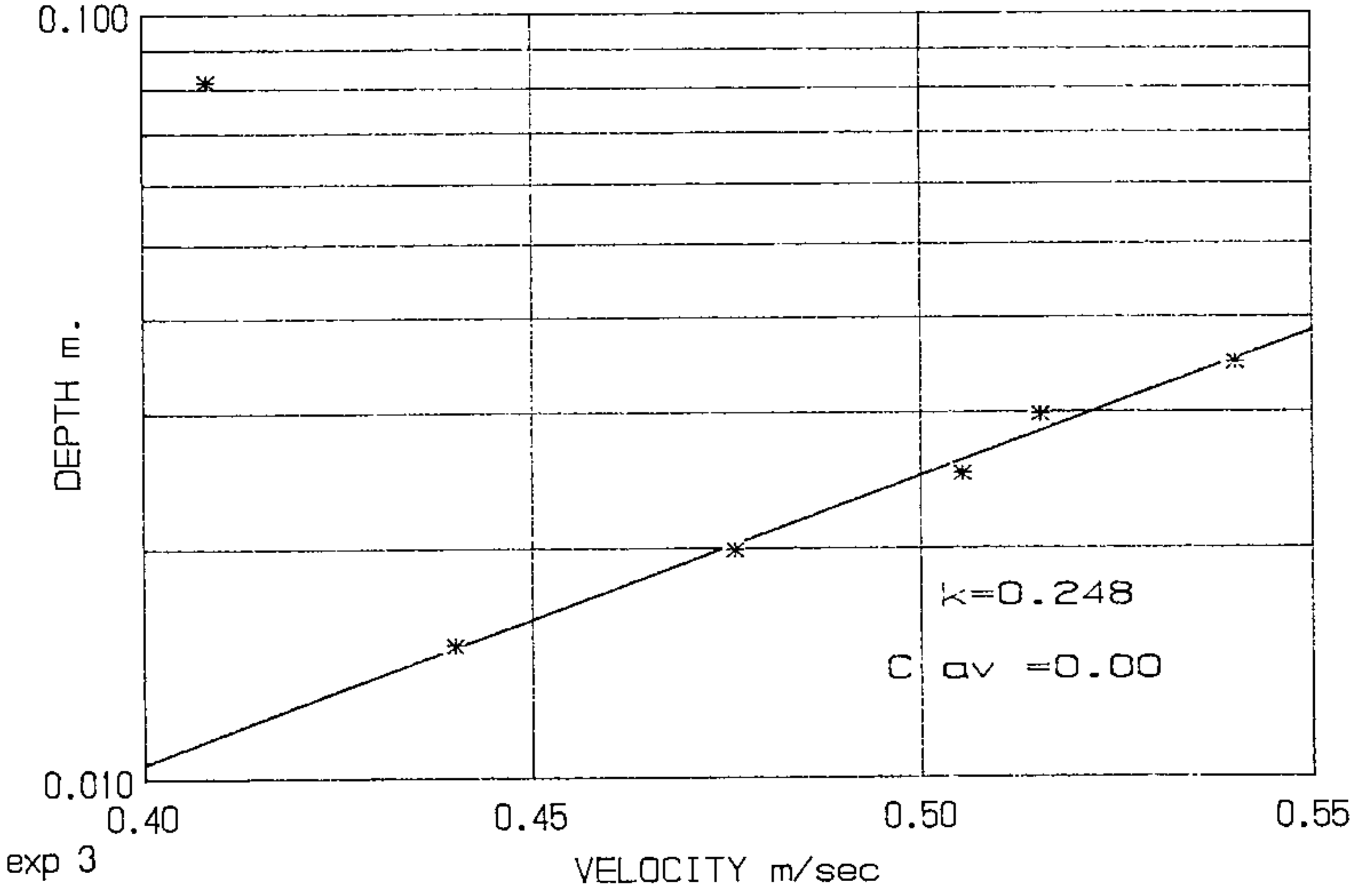
FIG. (5.8)


VELOCITY PROFILE
Yo=0.035
S=1/400
0.10
DEPTH m.
0.01
0.30
0.35
0.40
0.45
exp 2
VELOCITY m/sec
k=0.2855
C av=0.00

VELOCITY PROFILE

Yo=0.04

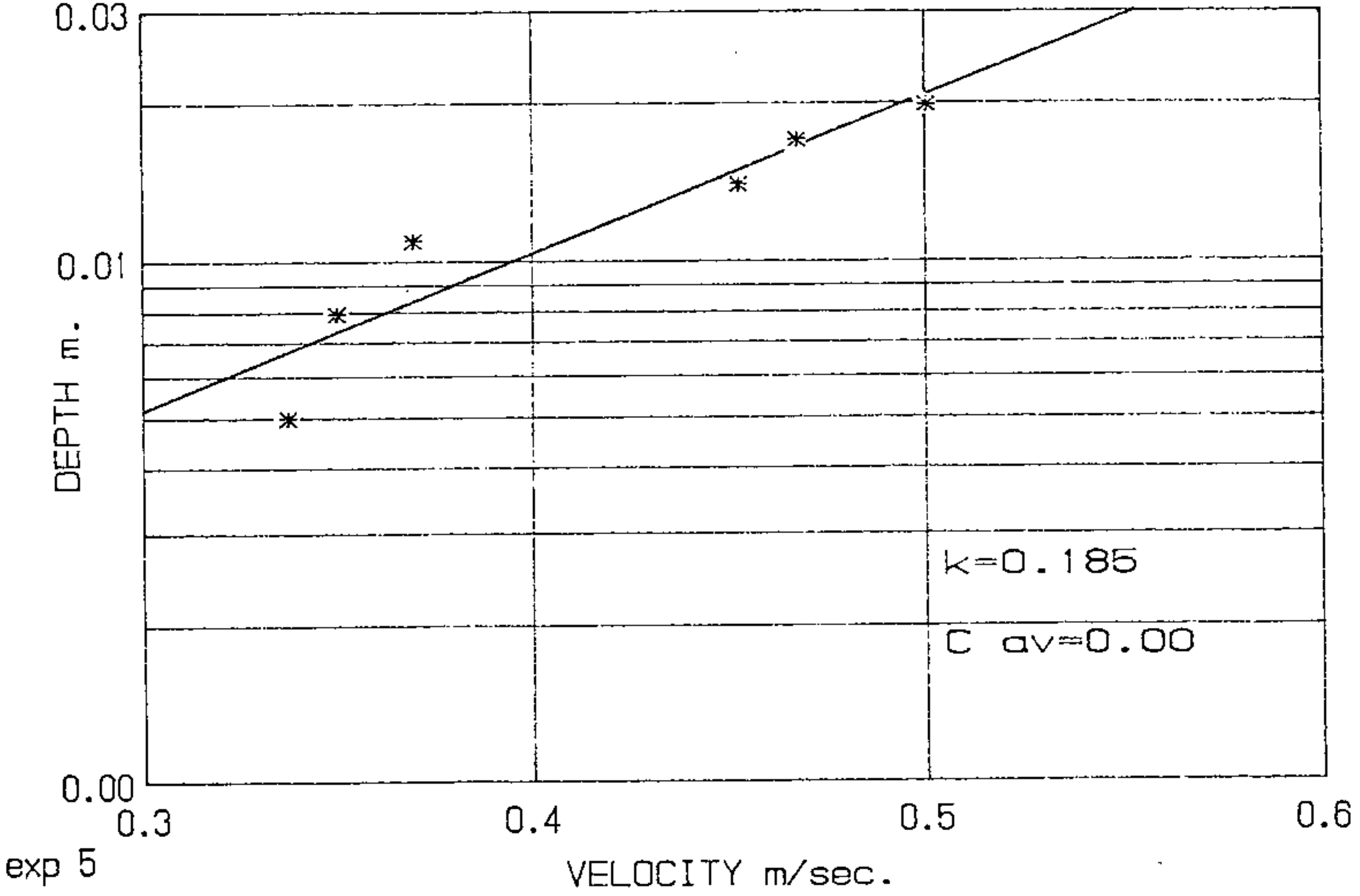
S =1/400

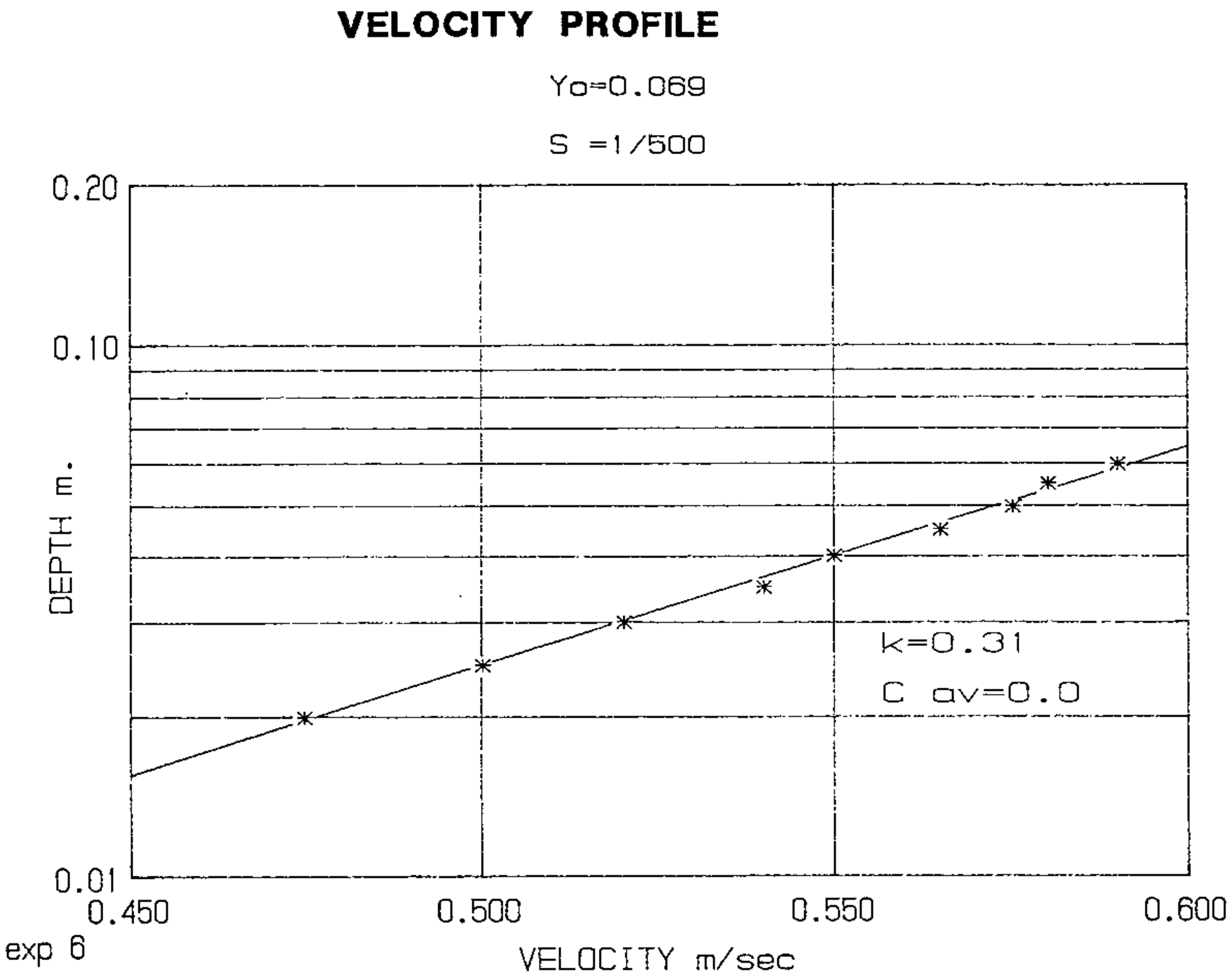


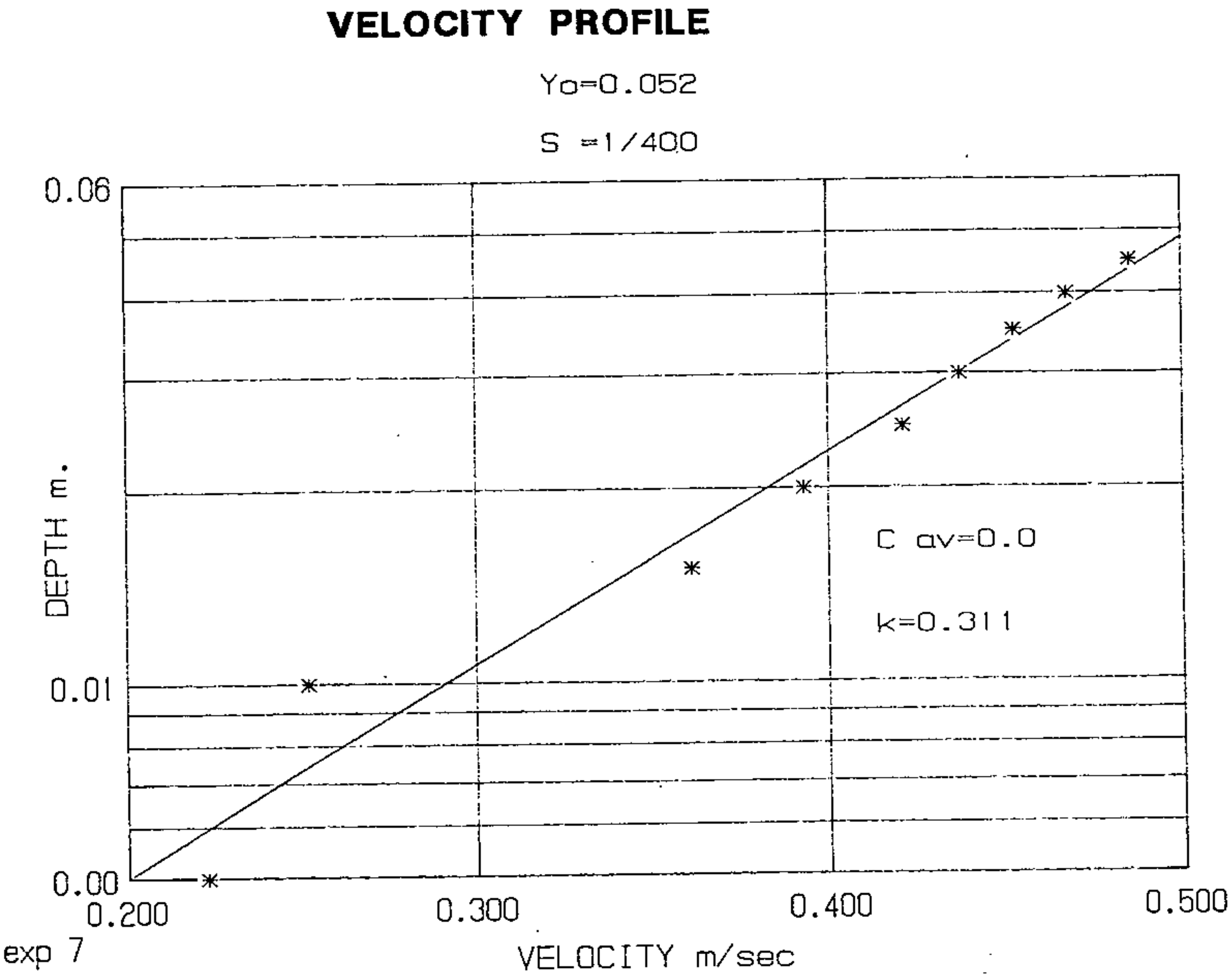
VELOCITY PROFILE

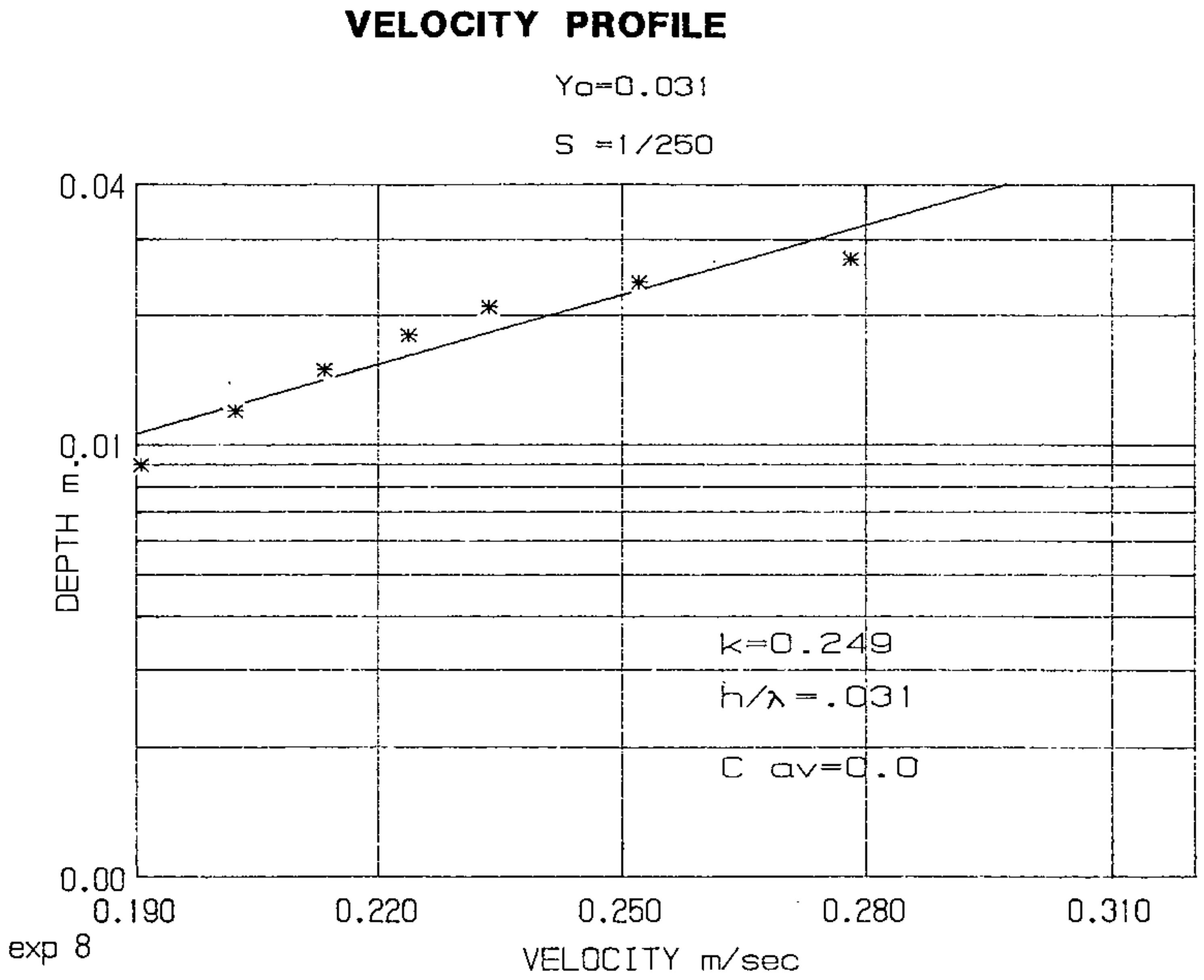
Yo=0.032

S =1/300




VELOCITY PROFILE
Yo=0.069
S =1/500
0.20
0.10
0.01
DEPTH m.
k=0.31
C av=0.0
0.450
0.500
0.550
0.600
exp 6
VELOCITY m/sec

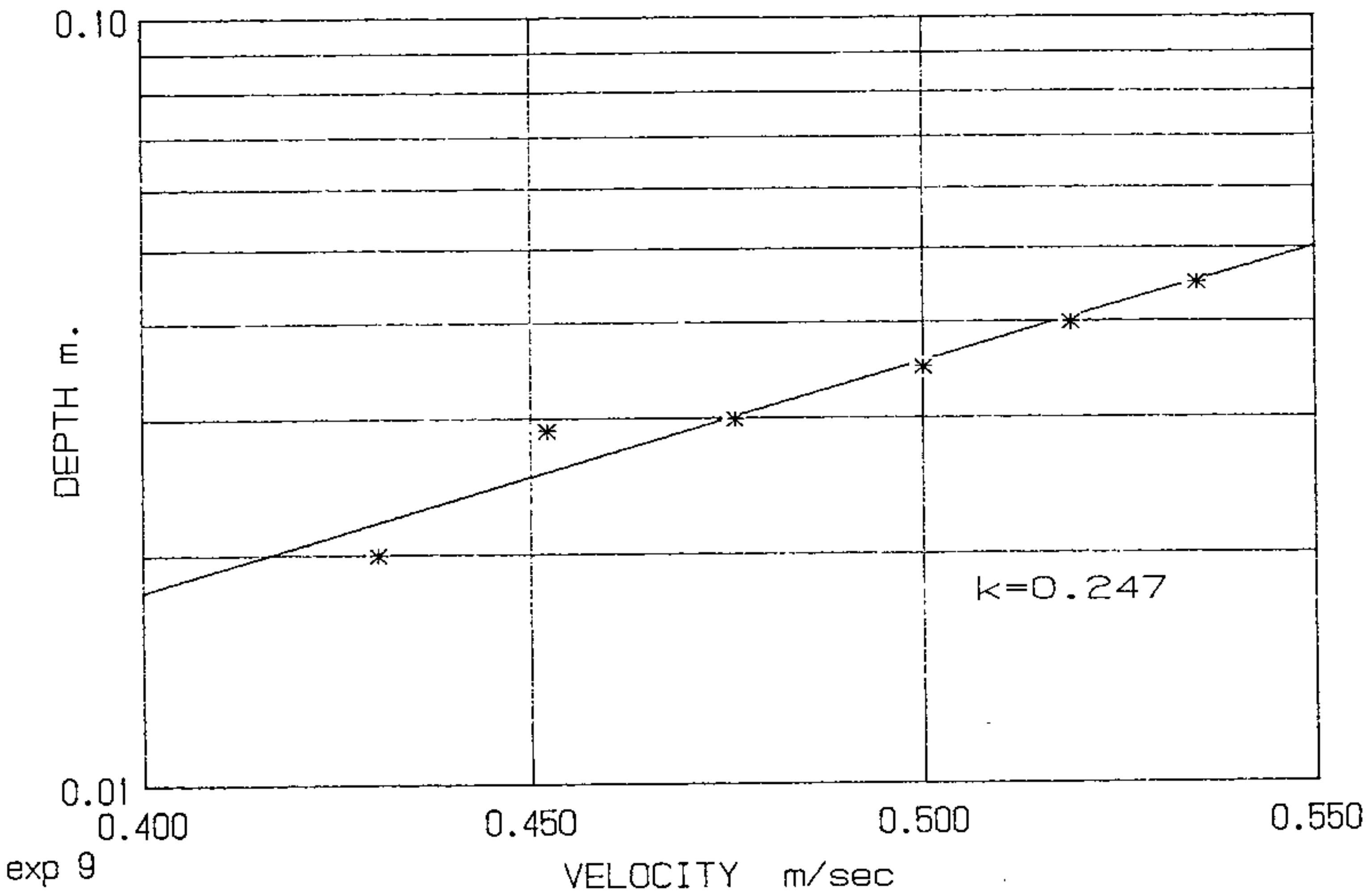

VELOCITY PROFILE
Yo=0.052
S =1/400
C av=0.0
k=0.311
0.06
0.01
0.00
DEPTH m.
0.200
0.300
0.400
0.500
VELOCITY m/sec
exp 7


VELOCITY PROFILE
Yo=0.031
S =1/250
0.04
0.01
0.00
DEPTH m.
k=0.249
h/λ=.031
C av=0.0
0.190
0.220
0.250
0.280
0.310
exp 8
VELOCITY m/sec

VELOCITY PROFILE

Yo=0.058

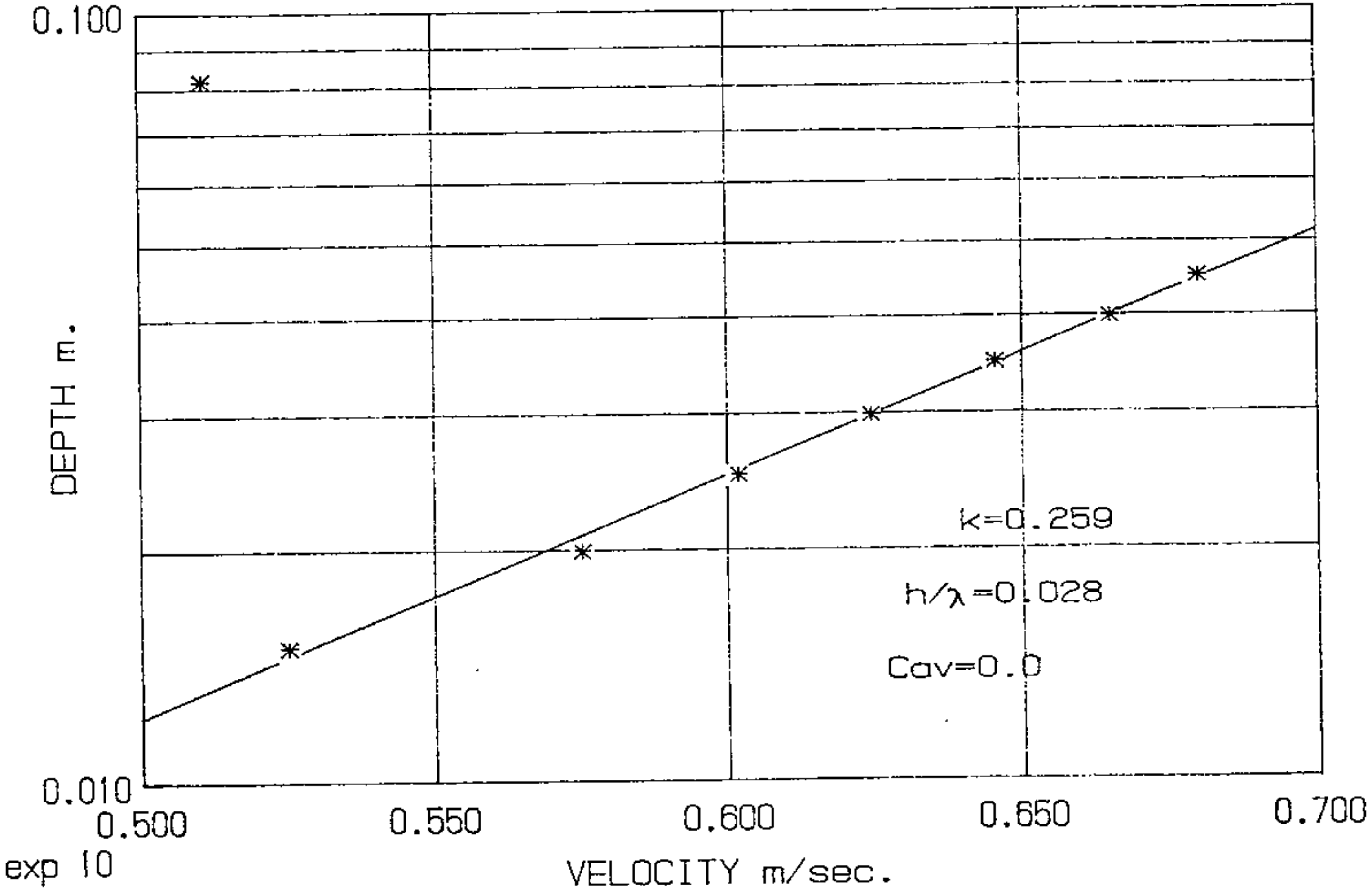
S =1/400



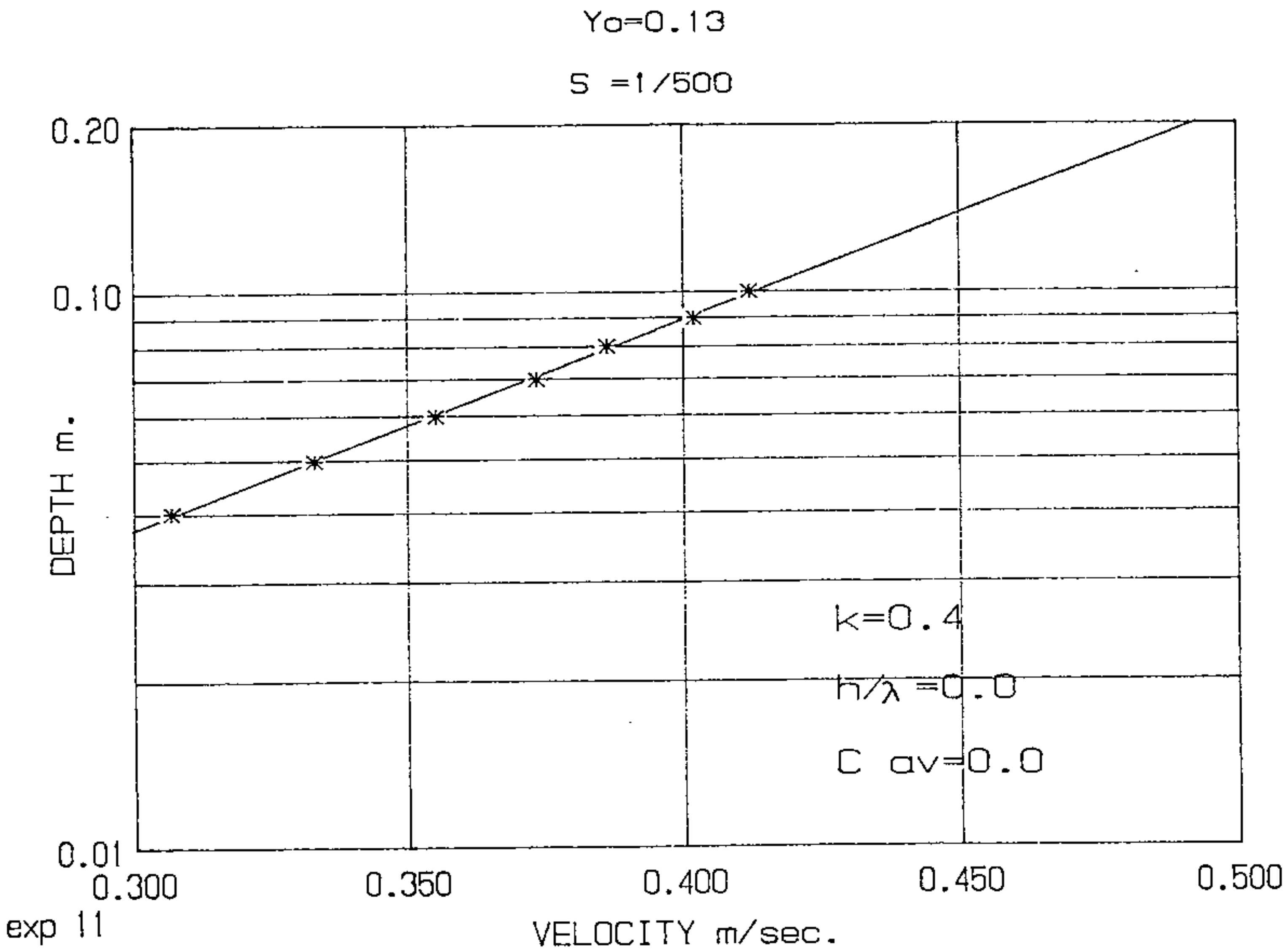
VELOCITY PROFILE

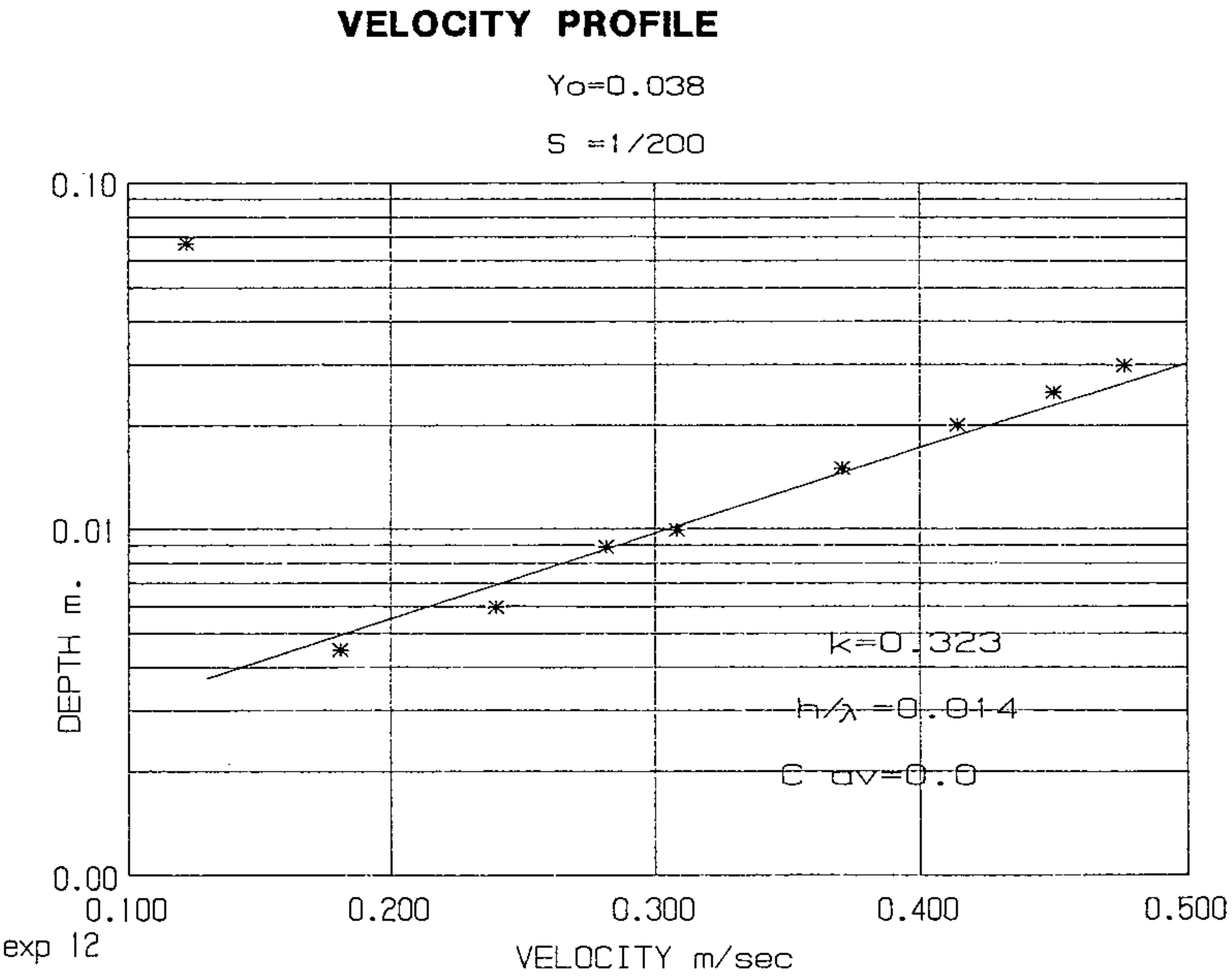
Yo=0.054

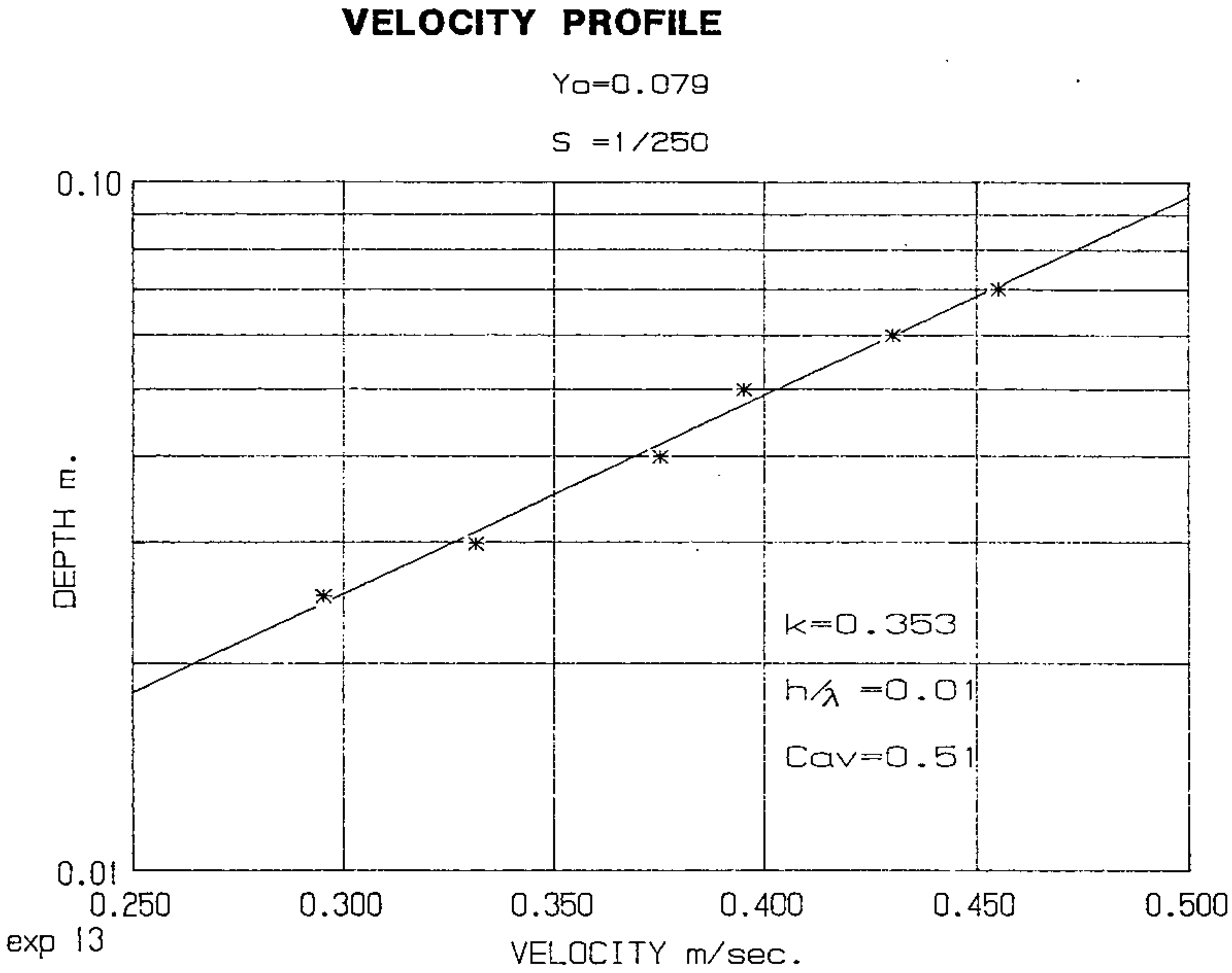
S =1/350



VELOCITY PROFILE



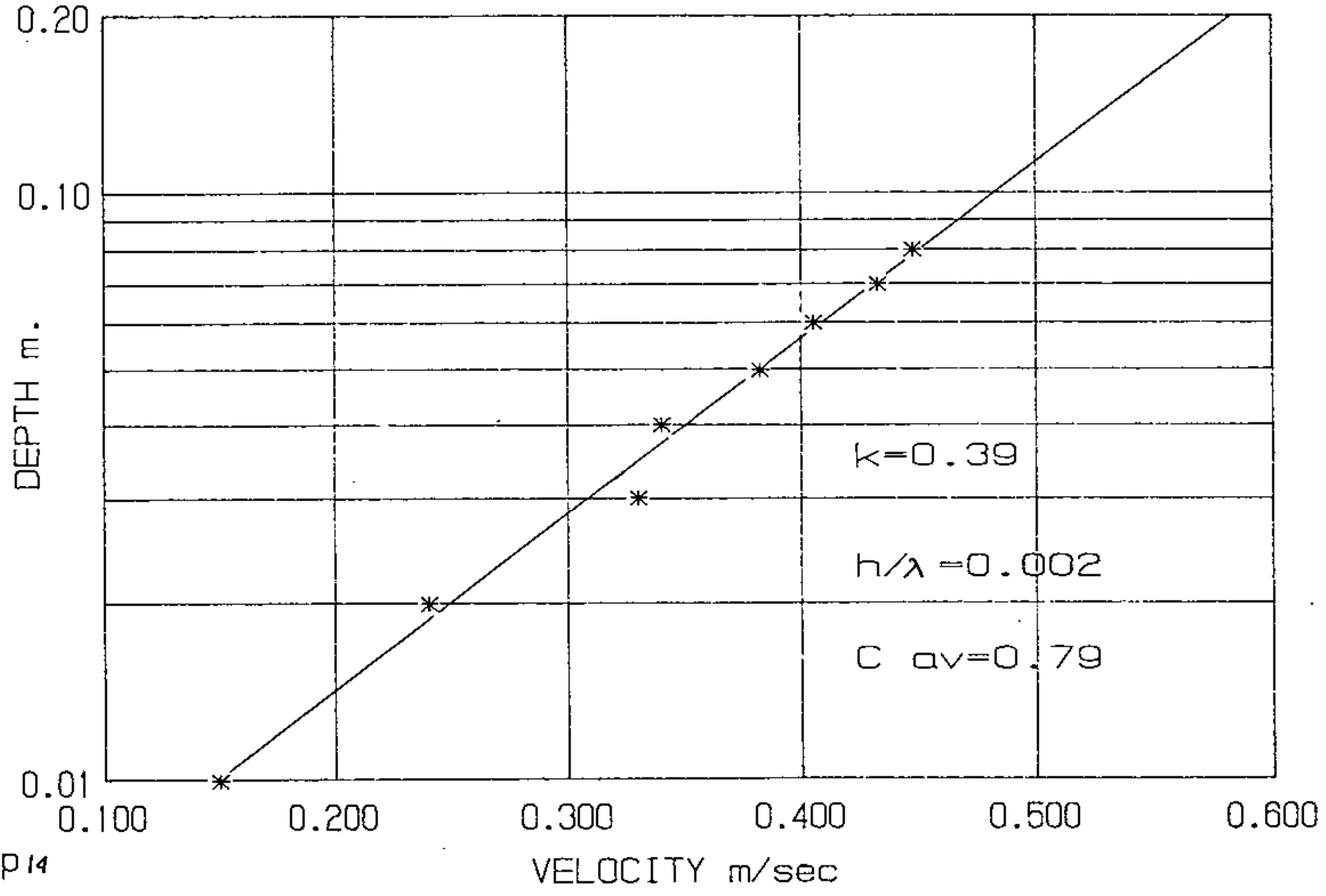

VELOCITY PROFILE
Yo=0.038
S =1/200
0.10
0.01
0.00
DEPTH m.
0.100
0.200
0.300
0.400
0.500
exp 12
VELOCITY m/sec
k=0.323
h/λ =0.014
C av=0.0


VELOCITY PROFILE
Yo=0.079
S =1/250
0.10
DEPTH m.
0.01
0.250
0.300
0.350
0.400
0.450
0.500
VELOCITY m/sec.
k=0.353
h/λ =0.01
Cav=0.51
exp 13

VELOCITY PROFILE

Yo=0.086

S=1/250

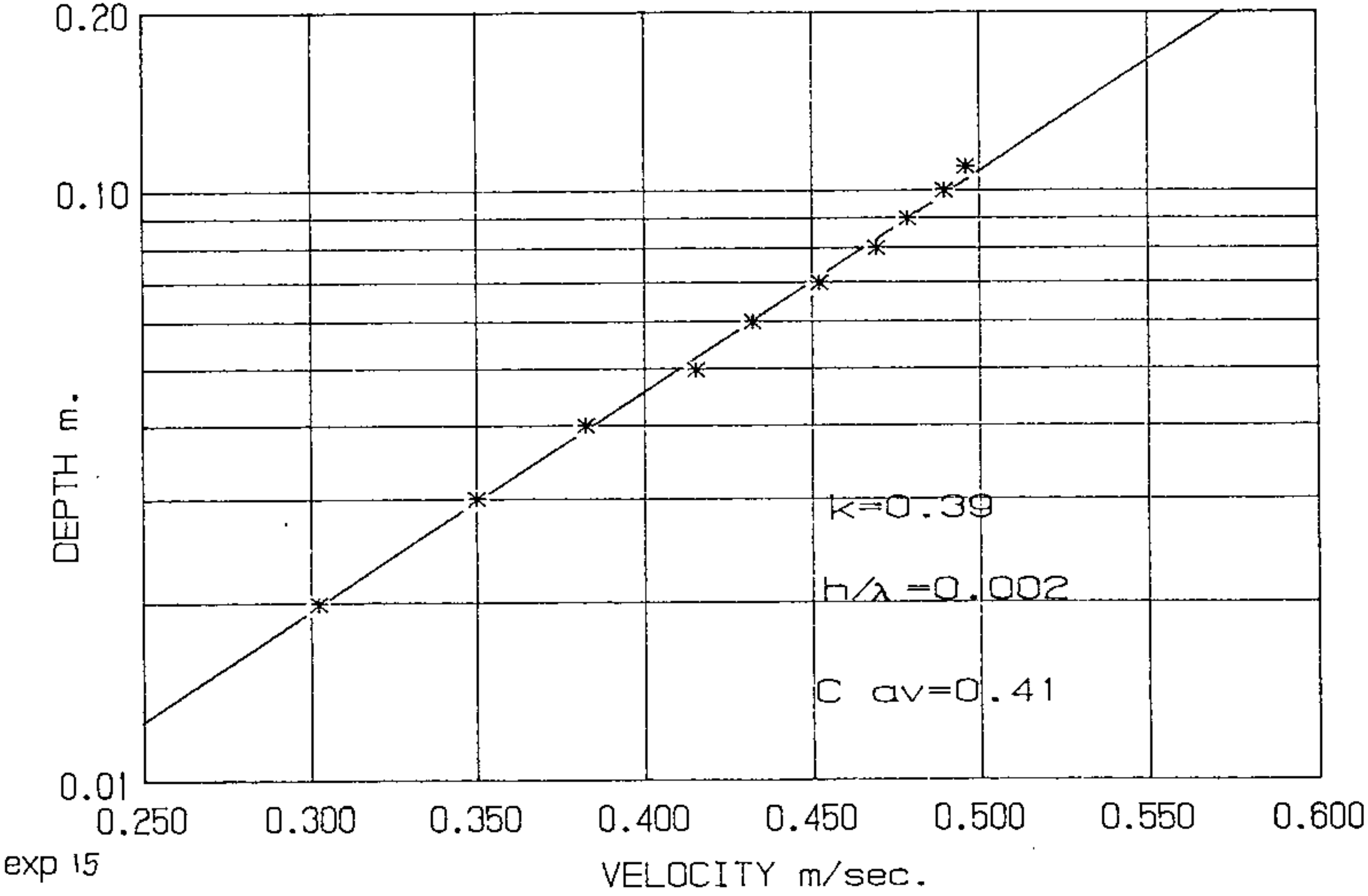


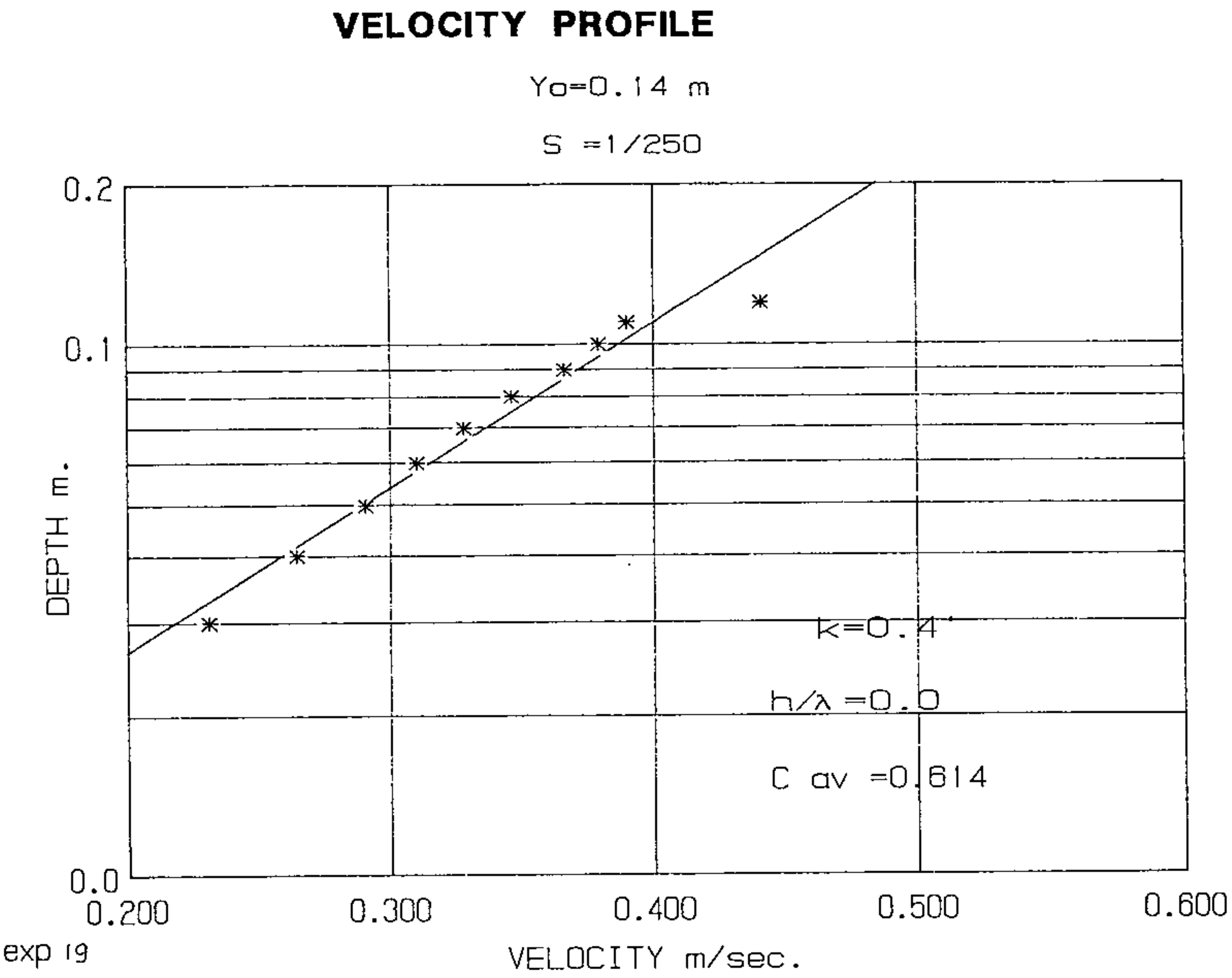
exp 14

VELOCITY PROFILE

Yo =0.123

S =1/300

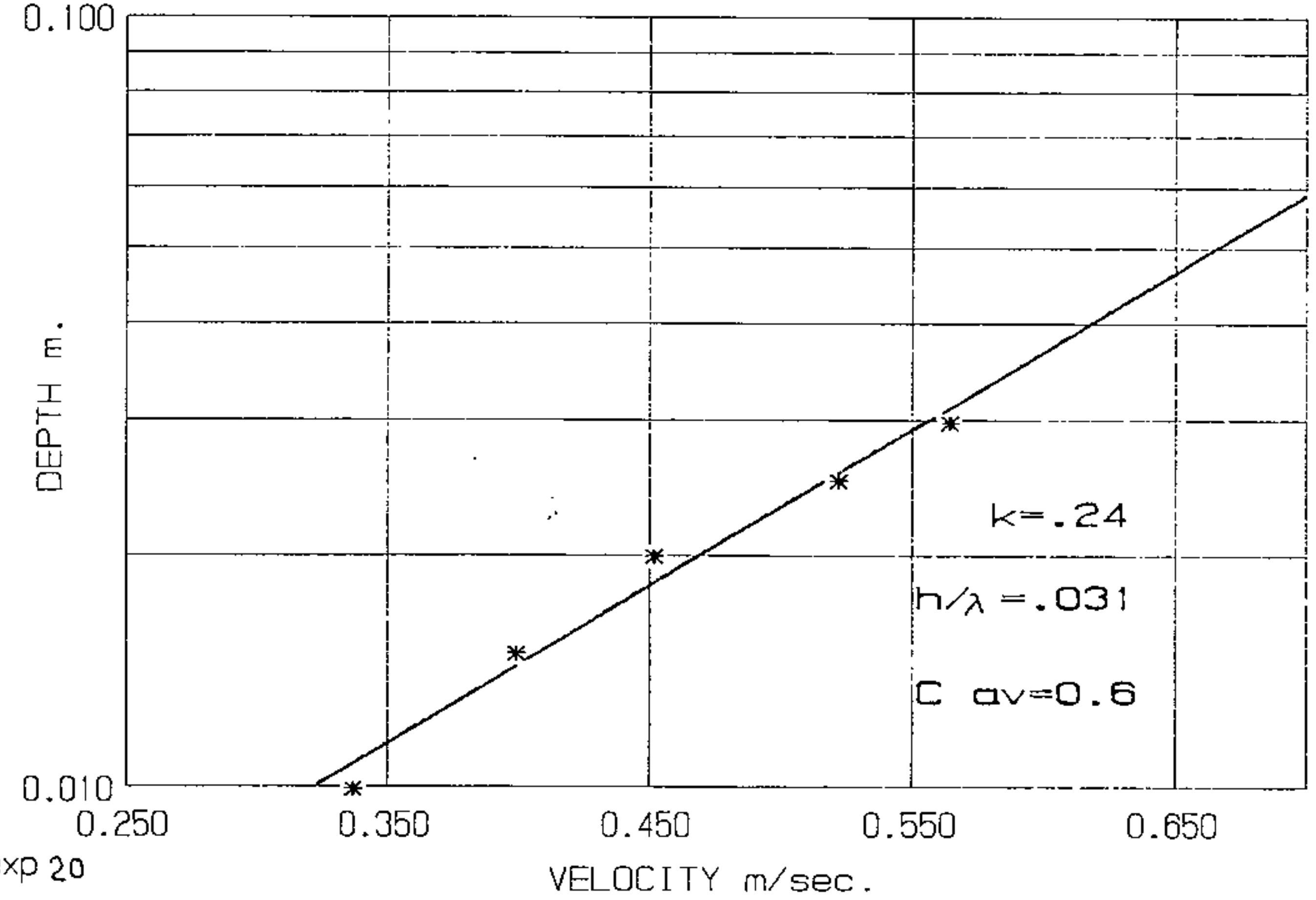



VELOCITY PROFILE
Yo=0.14 m
S =1/250
0.2
0.1
0.0
DEPTH m.
0.200
0.300
0.400
0.500
0.600
VELOCITY m/sec.
k=0.4
h/λ =0.0
C av =0.614
exp 19

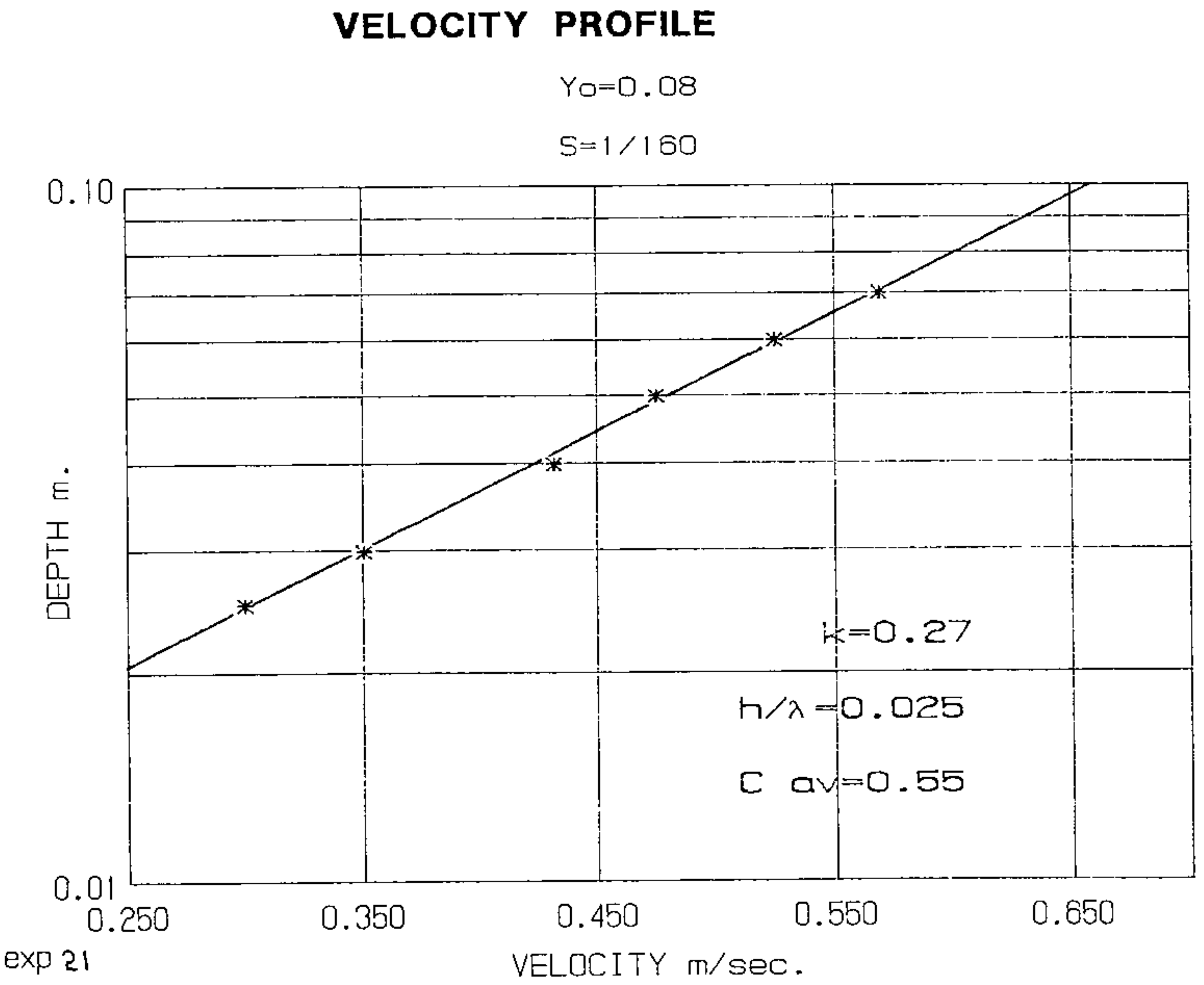
VELOCITY PROFILE

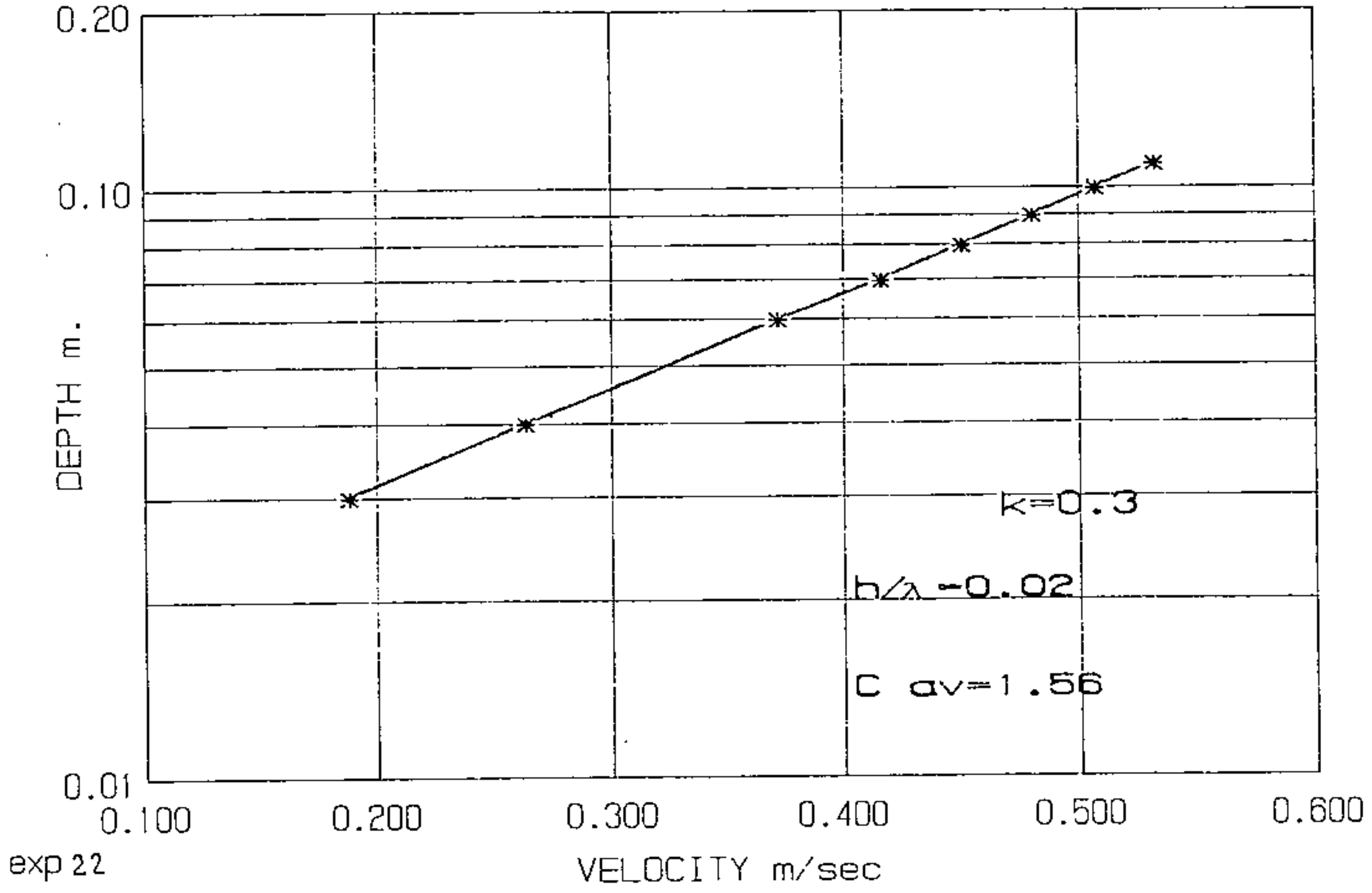
Yo=0.039

S=1/100



exp 20


VELOCITY PROFILE
Yo=0.08
S=1/160
0.10
0.01
DEPTH m.
k=0.27
h/λ =0.025
C av=0.55
0.250
0.350
0.450
0.550
0.650
VELOCITY m/sec.
exp 21



VELOCITY PROFILE

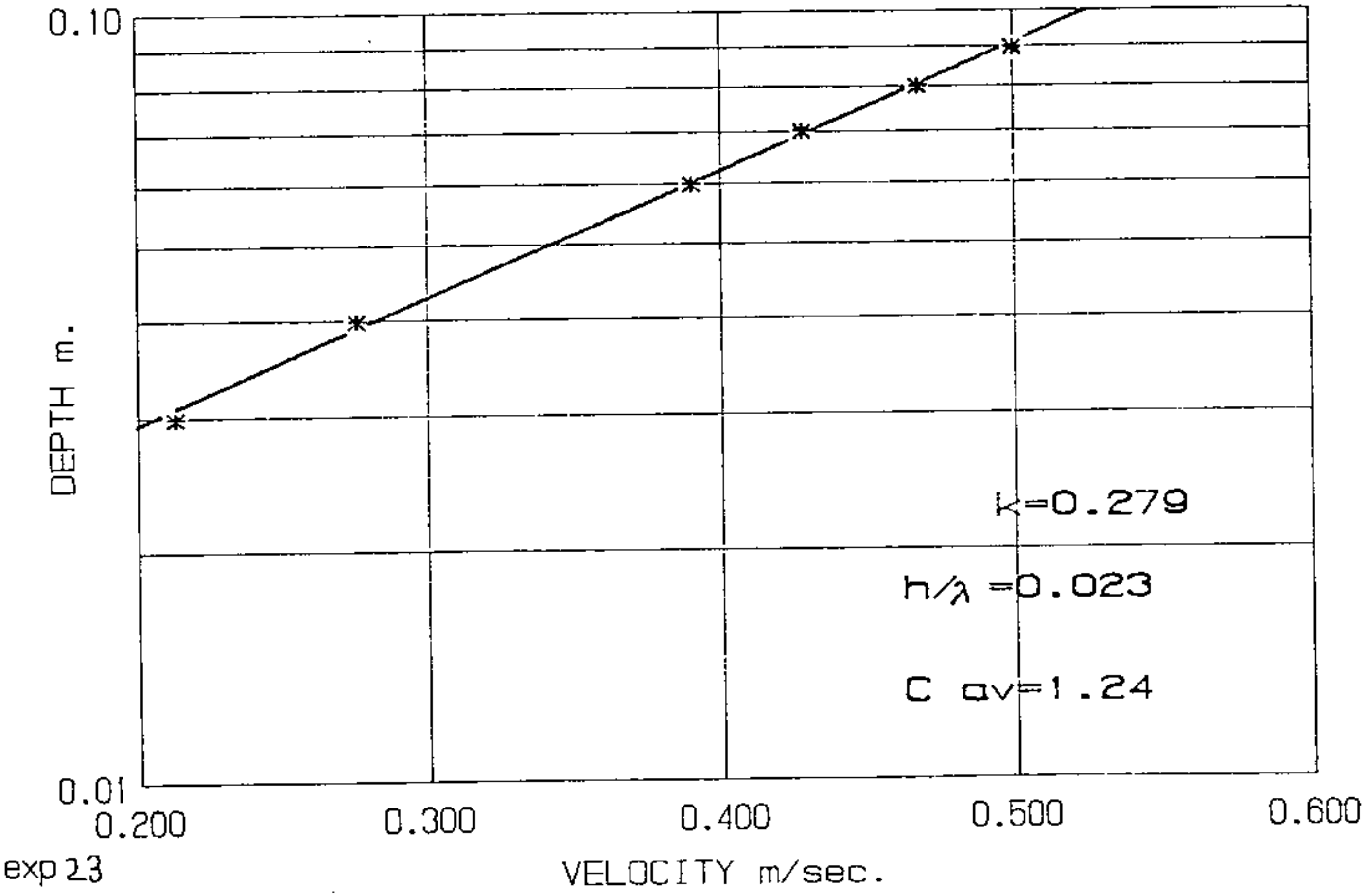
Yo= 0.132

S=1/200

VELOCITY PROFILE

Yo=0.100

S=1/160



For channels with rippled beds and/or with suspended load, the value of k was found to be different from 0.4. In the present experimental work the range of values of k was from 0.188 to 0.4. It appears that the flow is resisted not only by the textural roughnesses, but also by the raised features of the bed. Also there is the complicated effect of the sediment in transport.

In the present study the influence of bed ripples on the channel roughness cannot be separated from the effect of suspended load. A survey for each rippled pattern was performed in order to obtain the average mean of ripple height, h, and ripple lenght, λ, and then the average mean of ripple steepness h/λ.

The height of the ripple is governed by the grain size and flow conditionts but since the height determines the flow pattern down-stream it also determines the length of ripple.

Yalin(12)(1972) by dimensional reasoning relates the steepness of bed forms as

$$h/\lambda = f\left(\frac{\theta}{\theta_c} , Re_* , \frac{y_o}{d} \right)$$

where θ is the dimensionless shear stress.

A plot γ data for ripple steepness h/λ is shown in Fig(5.9) where the ripple steepness is plotted versus Re_*. It shows that ripple steepness increases to a certain maximum value and then decreases with increasing Re_*. Actually plots of this kind are deceptive, nevertheless they are valuable as indicators of the trend.

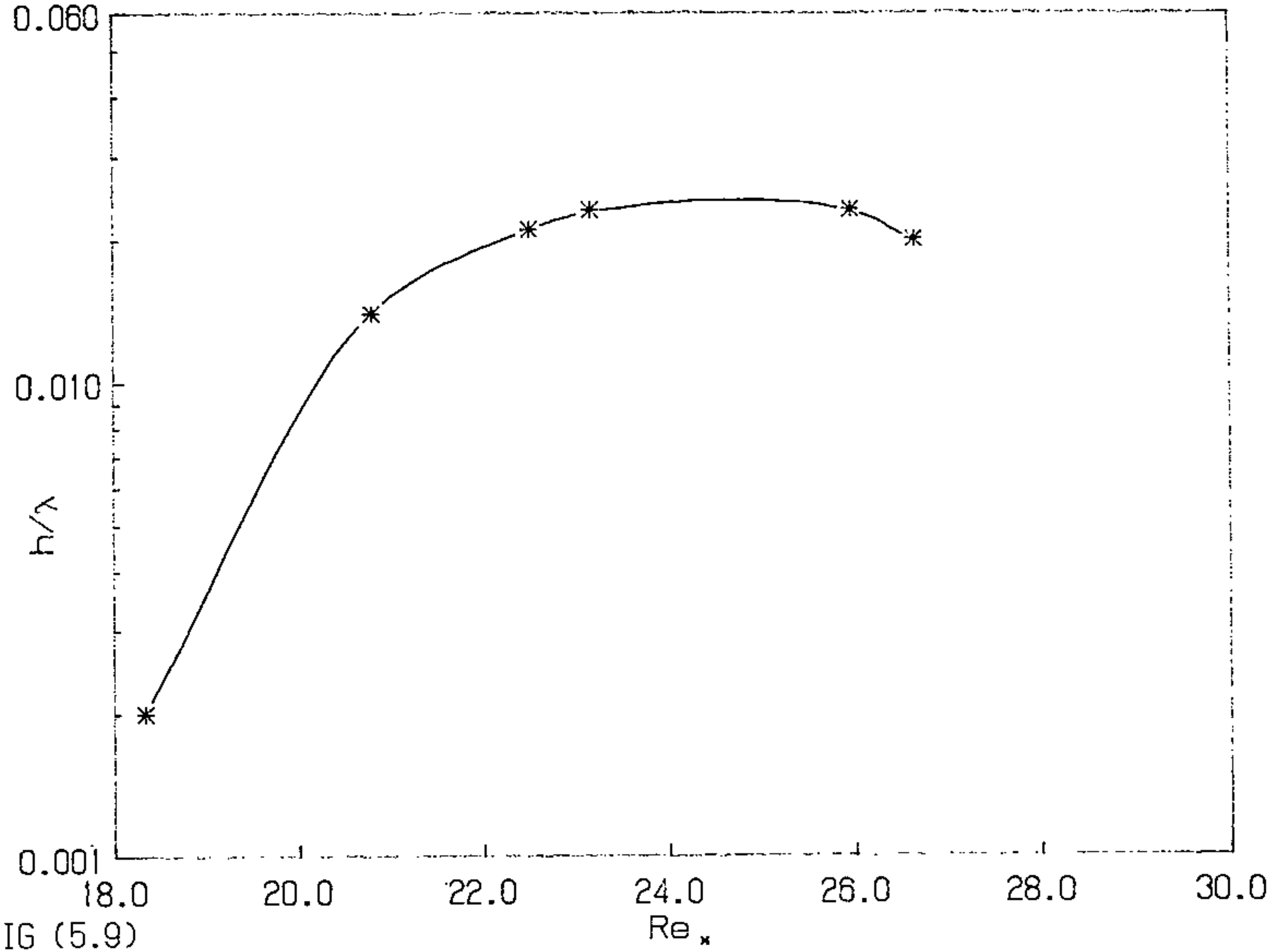


FIG (5.9)

The values of k and h/λ are given in Table (5.2) and represented graphically in Fig(5.10). It appears that the turbulent coefficient retains a constant value so long as h/λ is constant irrespective of the value of suspended load.

Table (5.2)

k	0.4	0.39	0.38	0.352	0.34	0.323	0.3
h/λ	0.00	0.002	0.003	0.01	0.015	0.014	0.02
k	0.29	0.279	0.27	0.259	0.25	0.249	
h/λ	0.021	0.023	0.025	0.028	0.031	0.031	

Flow on a rippled bed is basically different from flat bed flow, being accelerated and decelerated it could greatly influence the growth and diffusion of turbulence and therefore could react upon the values of the turbulent coefficient.

From publications by *Vanoni and others*(7), it was claimed that the suspended load may have a considerable effect on the flow resistance by damping the turbulence or by interfering with its production. But actually in their studies they did not separate the effect of the bed formations.

In the present study, experimental data shown in Figs (5.5,5.6,5.7) give evidence that the concentration of suspended load has little if any effect on the value of k. The value of the turbulent constant is less than 0.4 even when the concenrtation of suspended load is zero. Sediment motion is responsible for the formation of bed configurations, and the various bed forms are created. The change of the values of k due to these bed forms is much more pronounced than that due to suspended load.

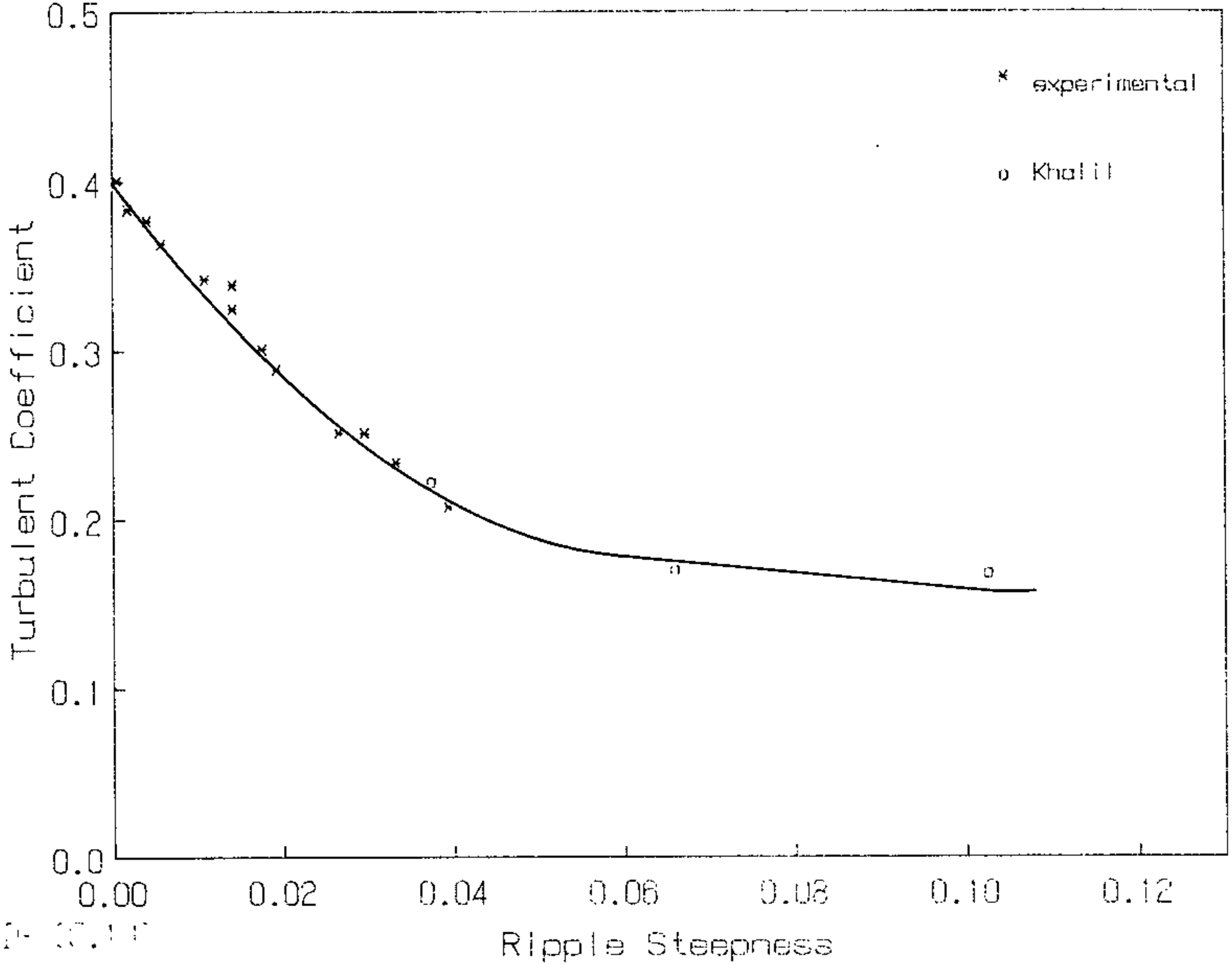

Turbulent Coefficient
0.0
0.1
0.2
0.3
0.4
0.5
Ripple Steepness
0.00
0.02
0.04
0.06
0.08
0.10
0.12
* experimental
o Khalil

Fig. [illegible]

The transport of suspended load alone seems to add slightly to the flow resistance that it can be disregarded. This conclusion is in agreement with results obtained by *Vanoni and Nomicos*(8), *Sayer and Albertson*(9), and *Khalil*(4).

5.4 INCIPIENT SUSPENSION

If and when the entire motion of the solid particles is such that they are surrounded by fluid, they are said to move in suspension. Owing to the weight of the particles, there is a tendency for settling, which however is counter balanced by the irregular motion of the fluid particles, i.e. the turbulent velocity components. Thus the hydraulic conditions of a stream determine if and when a particular grain size will be set in suspension.

From the present experiments it was noted that for low shear stresses ($\tau_b < 2N/m^2$) no suspension was observed. Also, it was observed that for a single grain layer in motion no suspension occurs. Actually the criteria for the incipient suspension may be better described by the value of w/u_*. The mode of transport may be indicated by the value of w/u_*, for $6 > w/u_* > 2$, the mode of transport is bed-load, $2 > w/u_* > 0.6$ saltation occurs and $0.85 > w/u_* > 0$ sediment is transported in suspension.

Also if $1 <$ number of moving layers < 2 then saltation occurs and suspended load may be detected at depths close to the bed. When the number of moving layers exceeds two, then suspended load may be found at any depth.

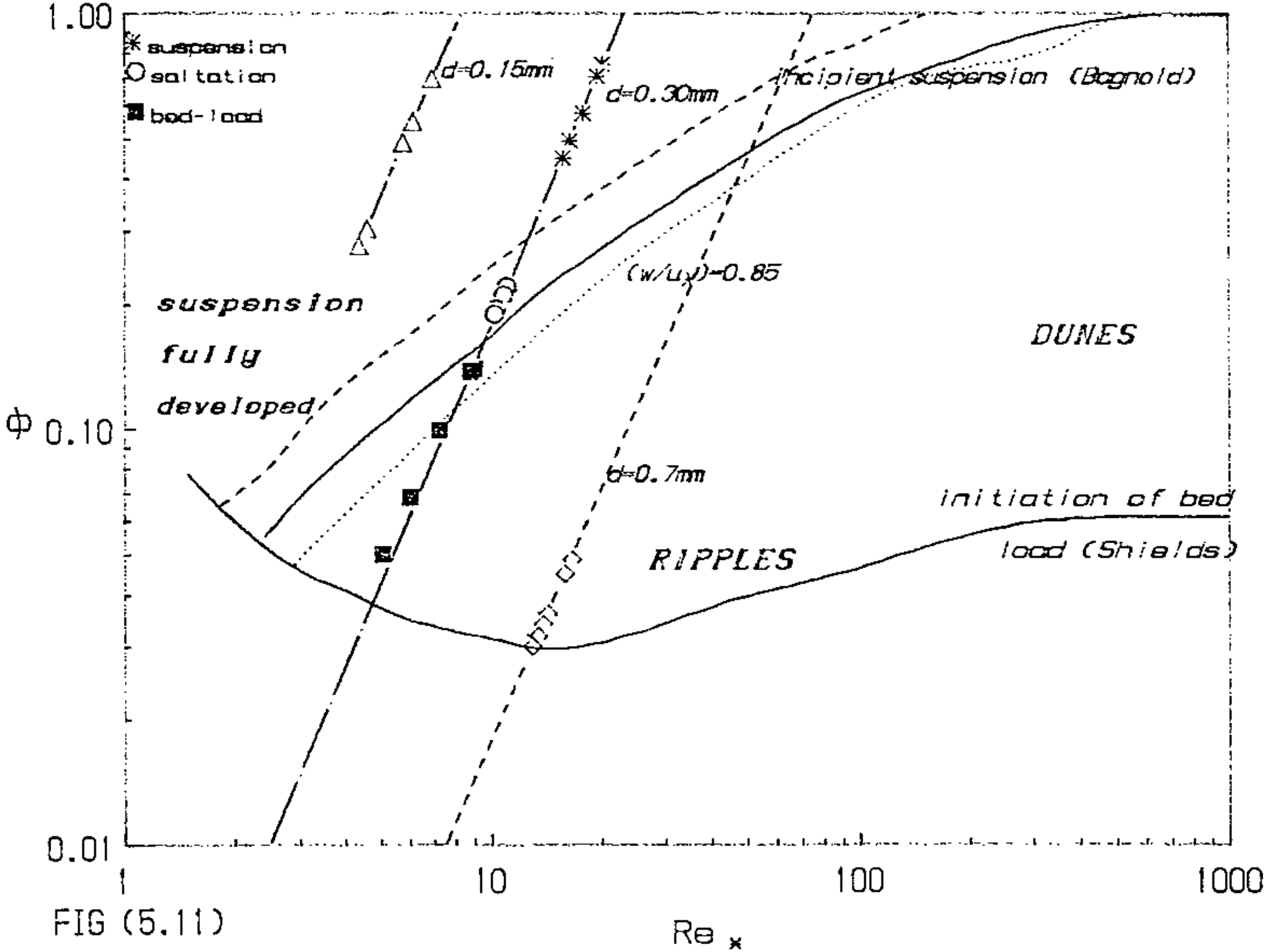
According to *Bagnold*(10) grains are set into suspension when $\theta = 0.4\frac{w^2}{gd}$.

The above criteria of the incipient suspension together with Shields values of θ for the incipient bed movement are shown graphically in Fig (5.11).

On the same graph the experimental values for grain size 0.3 mm diameter used in the present work are plotted. Also experimental values for grains of 0.7 mm diameter, studied by Khalil are plotted, in addition to those for grain size 0.15 mm

Observations and measurements agree as shown with the criteria of suspension given earlier.

It is noted that finer grains are set into suspension at lower values of u_*. Fine grains with diameters less than 0.15 mm are set into suspension at u_* marginally greater that u_{*c} required for the initiation of motion.



* suspension
○ saltation
■ bed-load
d=0.15mm
d=0.30mm
incipient suspension (Bagnold)
(w/u*)=0.85
suspension
fully
developed
DUNES
d=0.7mm
initiation of bed
load (Shields)
RIPPLES
Φ
1.00
0.10
0.01
1
10
100
1000
Re *

FIG (5.11)

5.5 VERTICAL DISTRIBUTION OF SUSPENDED LOAD

The turbulence intensity, and thus diffusivity vary with the distance from the bottom.

Thoretically the concentration distribution of suspended load is given by

$$\frac{C}{C_a} = \left[\frac{y_o - y}{y} \cdot \frac{a}{y_o - a}\right]^{z} \qquad \cdots\cdots(5.13)$$

The vertical concentration distribution according to equation (5.13) is shown graphically in Figs (5.12 & 5.13).

Theexperimental results are given for each value of z.

It is noted that the concentration is smaller farther away from the bed than close to it. From a mathematical point of view, at the bed where y=0, the concentration becomes C = ∞, which is impossible. That suspension does not exist close to the bed is physically sound; particles close to the bed are not embedded in water any more, but indeed form part of the bed-load.

For low values, of z, the distribution is uniform, where-as for large z values, little sediment will be found close to the surface of the channel. The particle size, expressed as the setling velocity is directly responsible for this kind of distribution.

The experimental values when plotted as $\frac{y - a}{y_o - a}$ versus $\frac{C}{C_a}$ for constant values of z agree satisfactorily with the theoretical relations, as seen from Figs (5.12 & 5.13).

Vertical Distribution of Suspended Load

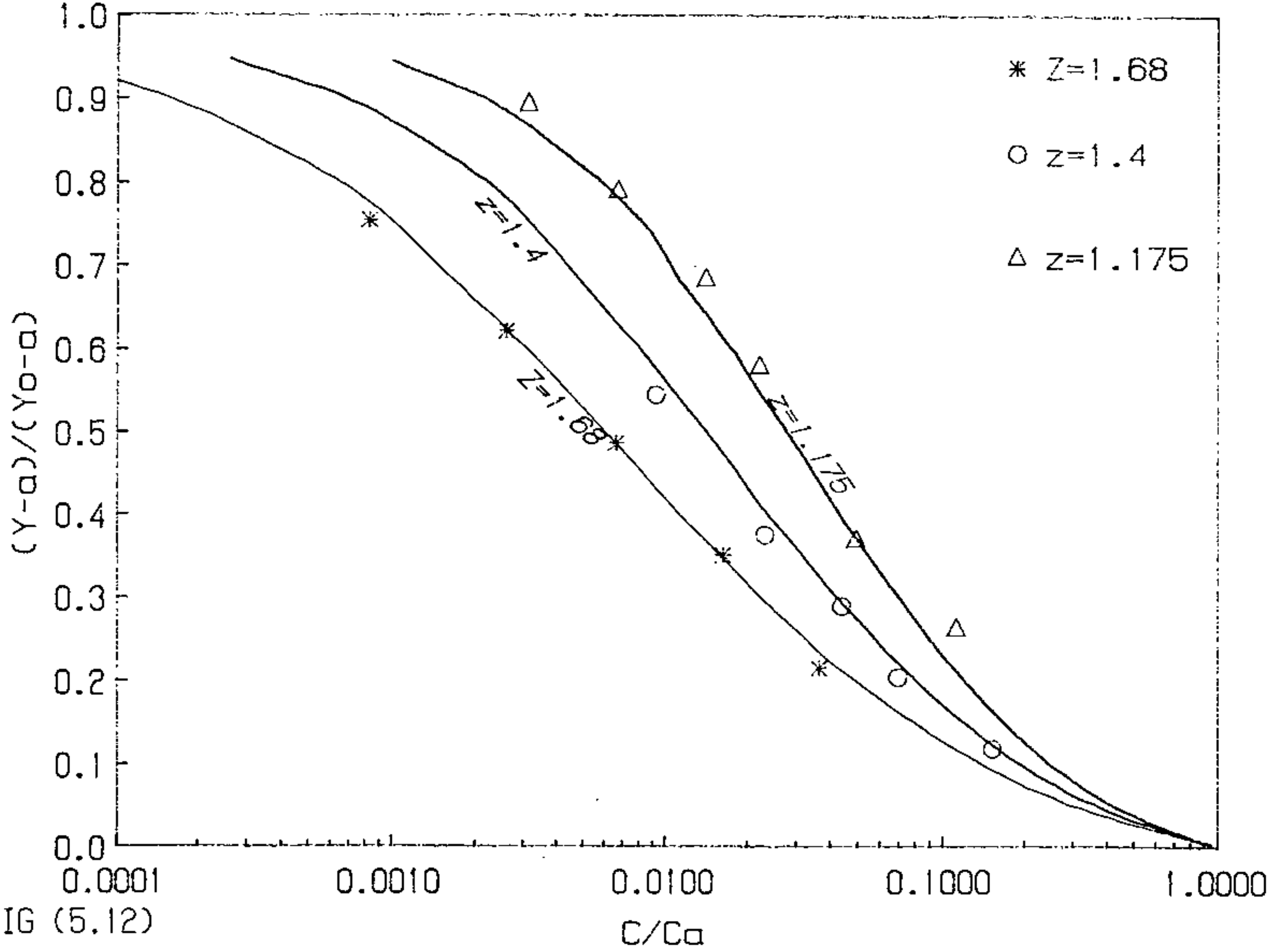


FIG (5.12)

Vertical Distribution of Suspended Load

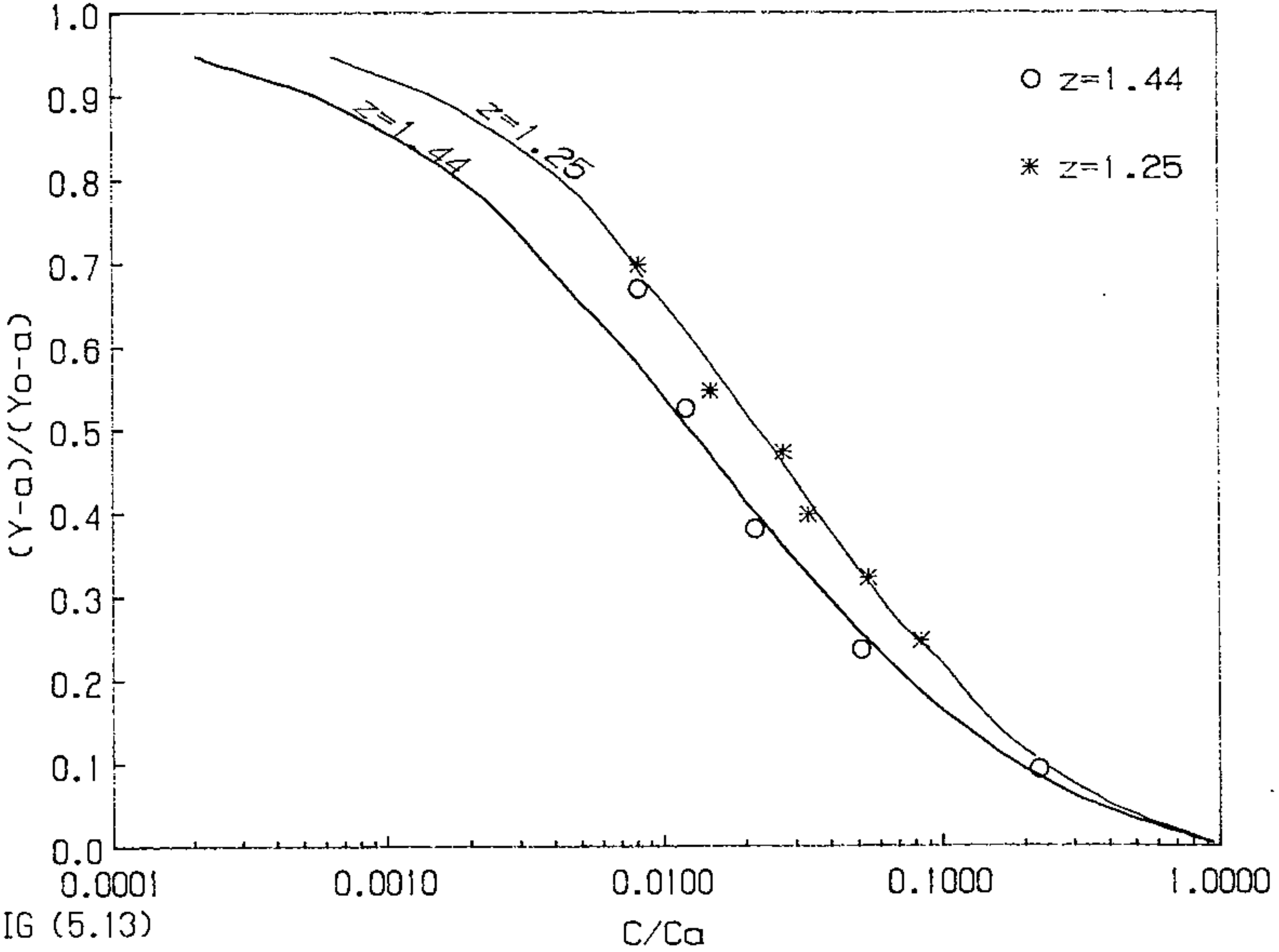


FIG (5.13)

The exponent z in the concentration distribution relationship is calculated from the slope of $\log\left[\frac{y_0 - y}{y_0 - a} \cdot \frac{a}{y}\right]$ versus $\log \frac{C}{C_a}$, as shown in Figs (5.14) to (5.23).

Where $z = \omega / \beta k u_*$, is a function of the shear velocity, the turbulent constant, the grain size represented by the fall velocity which in turn is affected by the concentration of solid particles, and another factor β to account for the diffusivity of solid particles on the momentum transfer coefficient.

The relationship between the diffusivity of solid particles and the one of linear momentum is proportional and not necessarily identical. Some knowledge could be gained if we knew how willingly a solid particle followed its liquid environment.

From previous studies, for sediment in water it is not at all clear when β is equal to, smaller than or larger than unity.

In the present work β was found to vary from 1.0 to 1.40. The lower value is for low concentrations while the upper value seems to be a limit for the grain size used in the present experimental work. The relation between β and the average concentration is shown in Fig (5.24).

According to *Ismail*(12), the sediment transfer coefficient ϵ_s was found to be equal to 1.5 times the momentum transfer coefficient, ϵ_m, for 0.10 mm particles, and to 1.3 ϵ_m for the 0.16 mm sand.

The present work revealed a certain relationship between β and the turbulent constant k. The experimental values when plotted on logarithmic scales gave a straight line relationship as shown in Fig (5.25) in the form

$$k = m\,\beta^{n} \quad , \qquad \qquad .....(5.14)$$

where the value of m and n are found to be 2.45 and (-1.093) respectively.

With the aid of equation (5.14) an initial guess of the value of β may be achieved and used in finding the value of z in the concentration distribution relationship given in equation (5.13). The concentration distribution at various levels may be then estimated using equation (5.13) and the average concentration may thus be determined. The value of β is then checked using Fig (5.24). If β is different from the initial guess value then it should be changed until the correct value of β is attained by succssesive iterations and thus the correct value of z is determined.

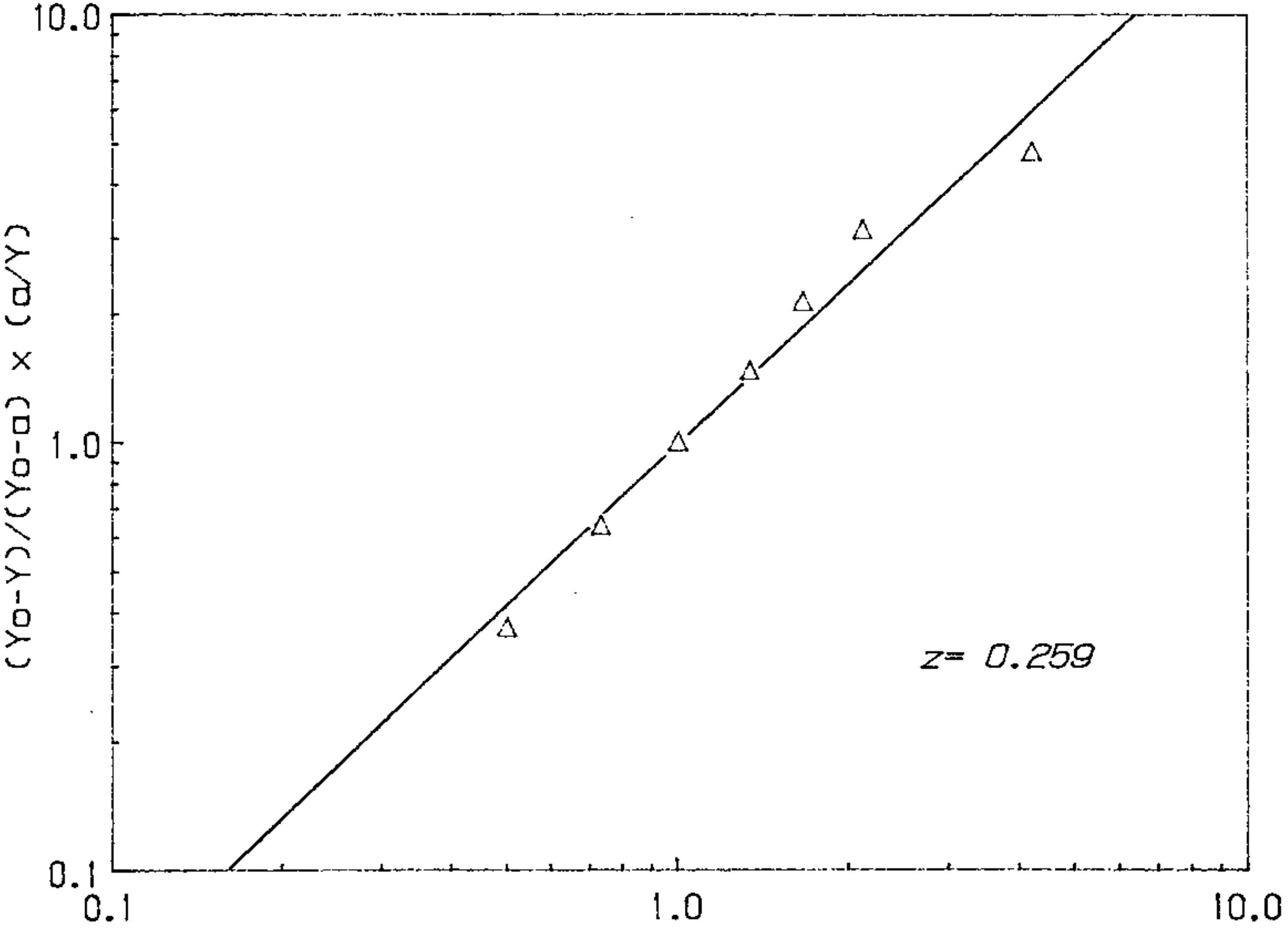


FIG. (5.14) exp 10

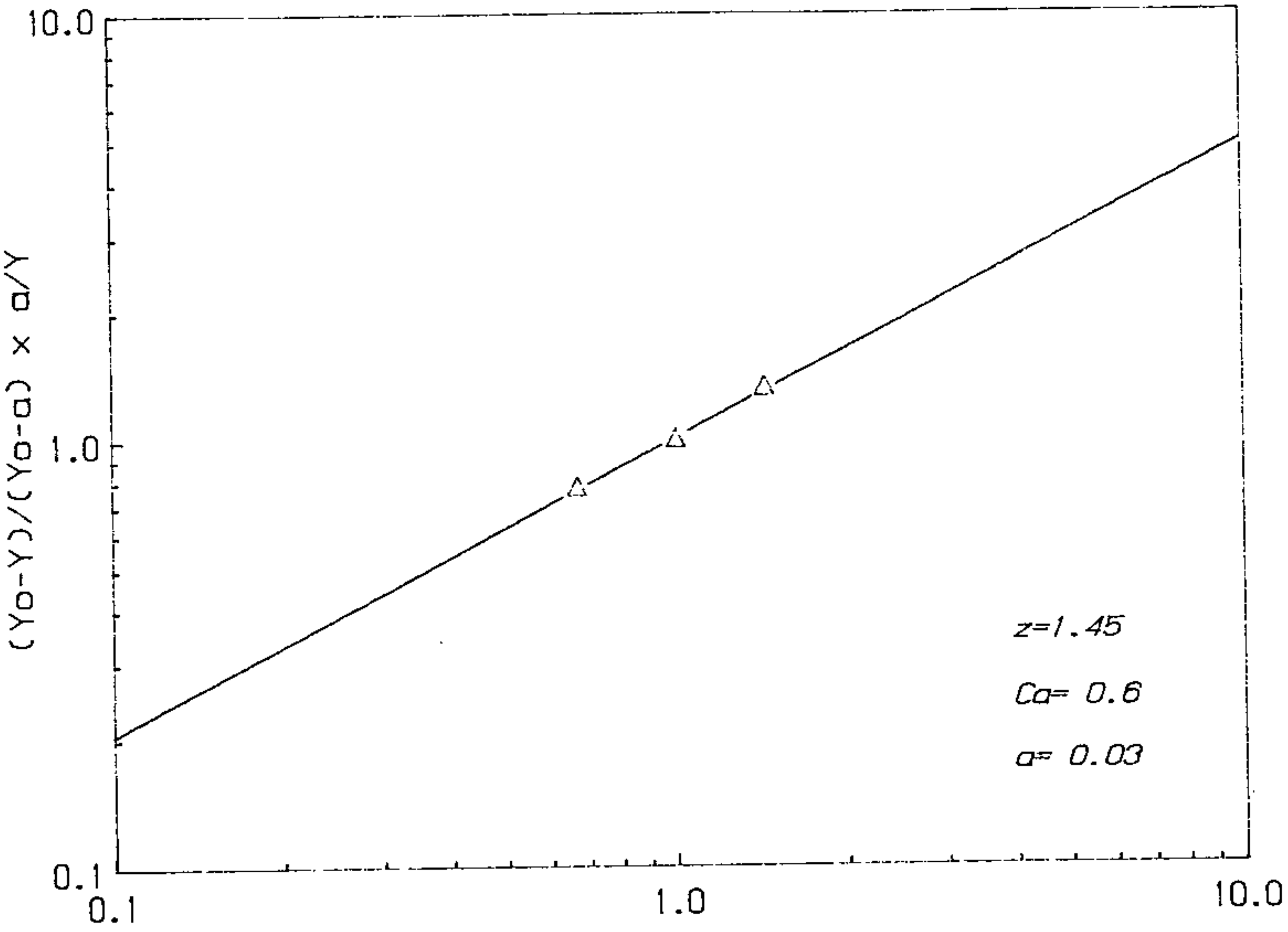


FIG. (5.15) exp 13

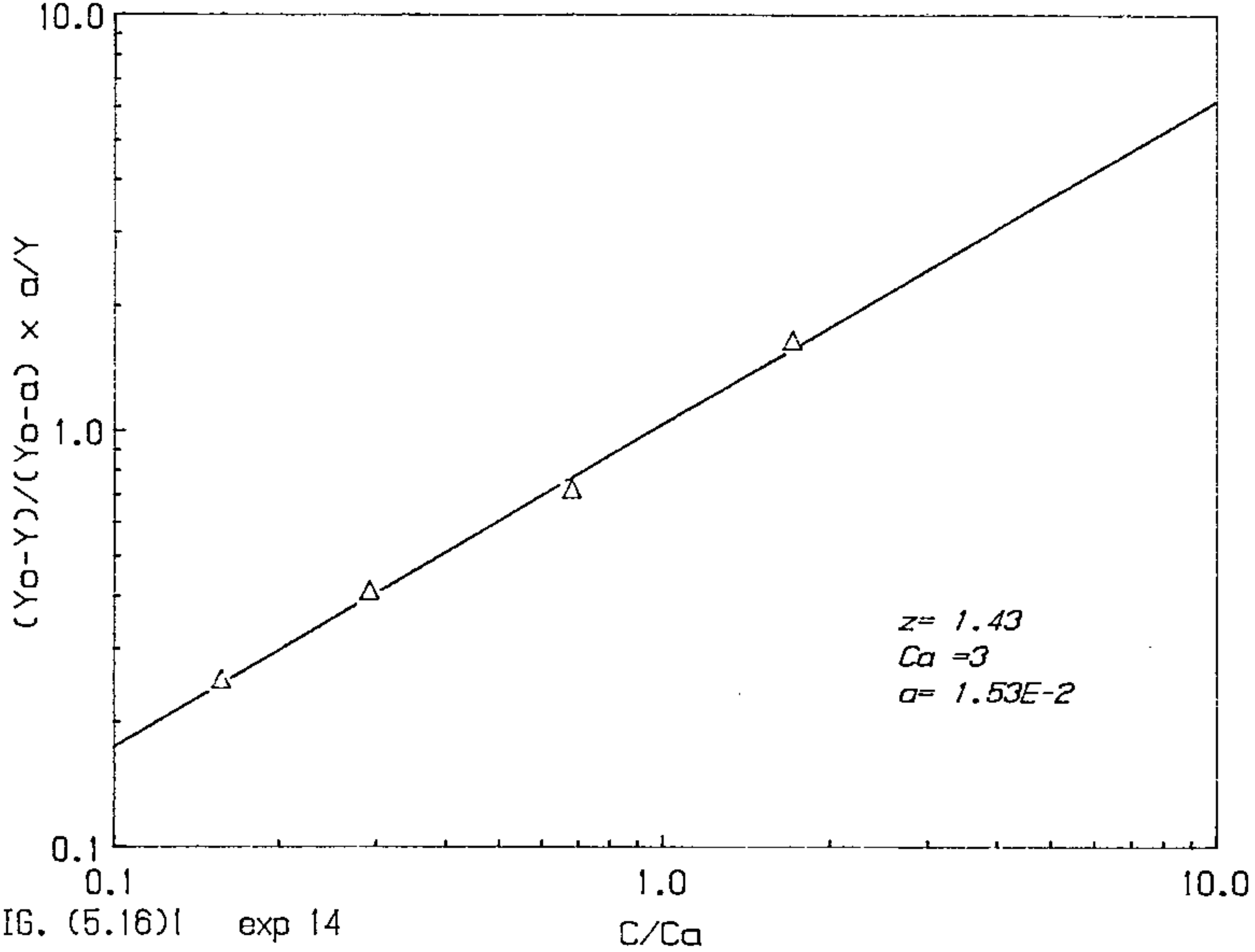


FIG. (5.16)I exp 14

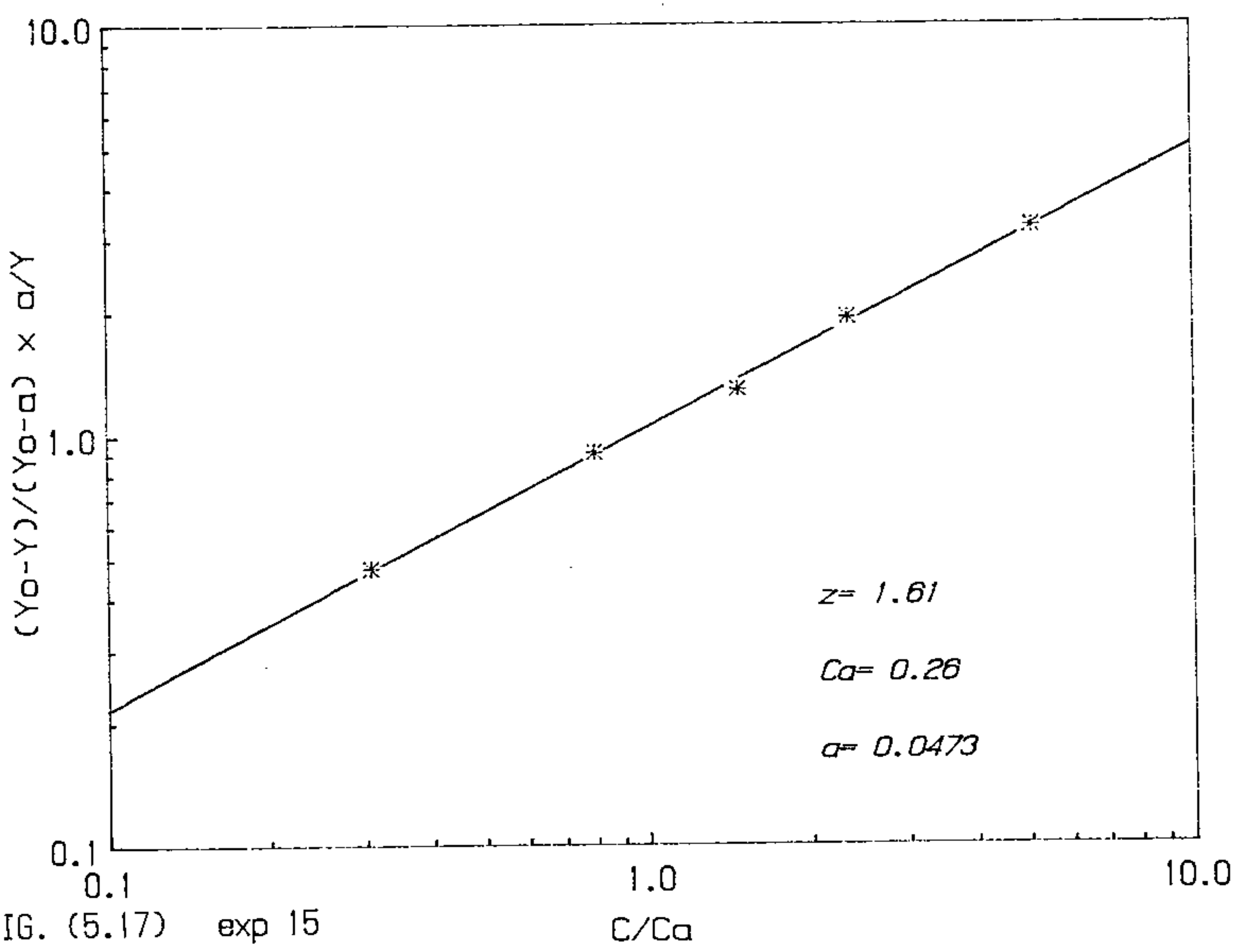


FIG. (5.17) exp 15

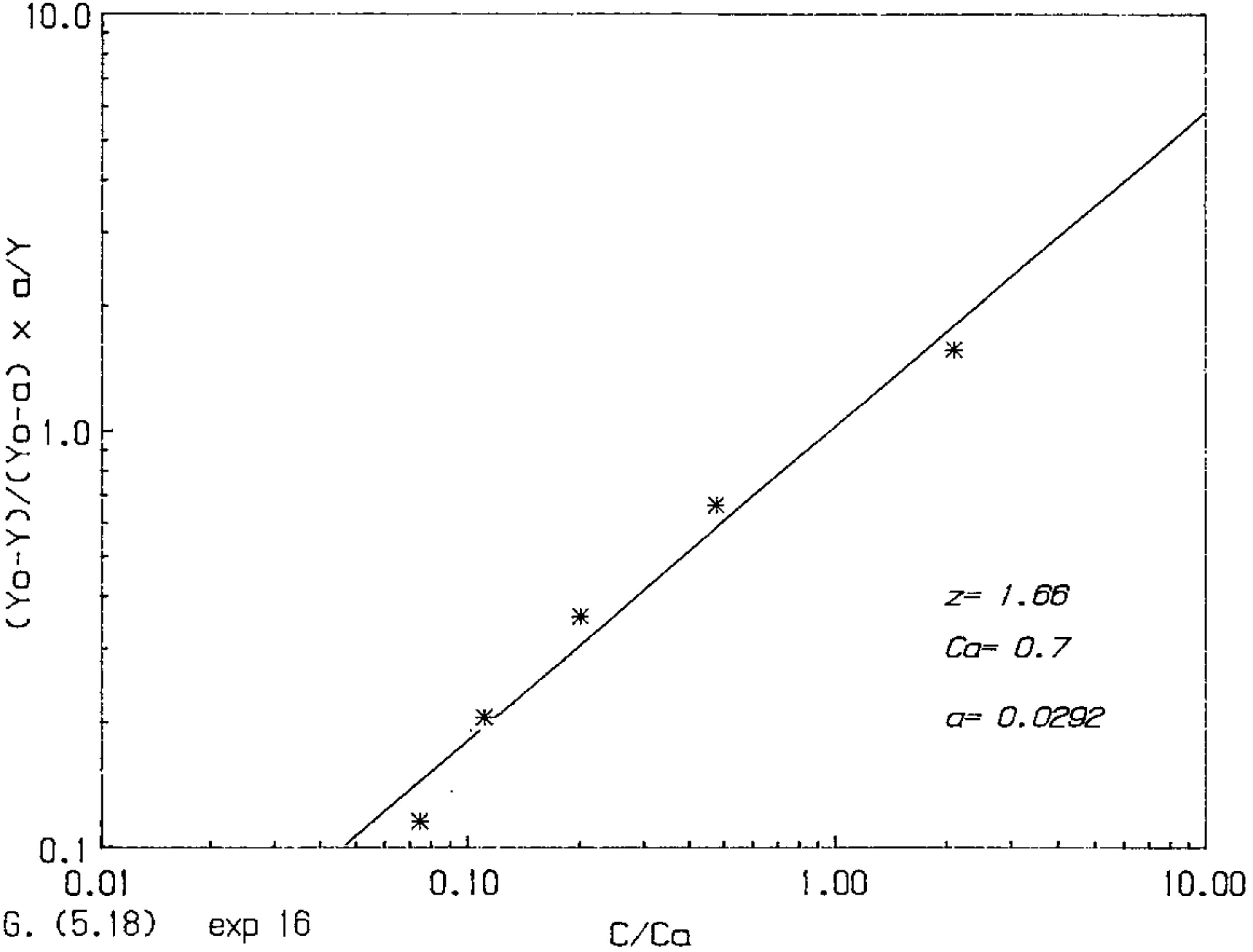


FIG. (5.18) exp 16

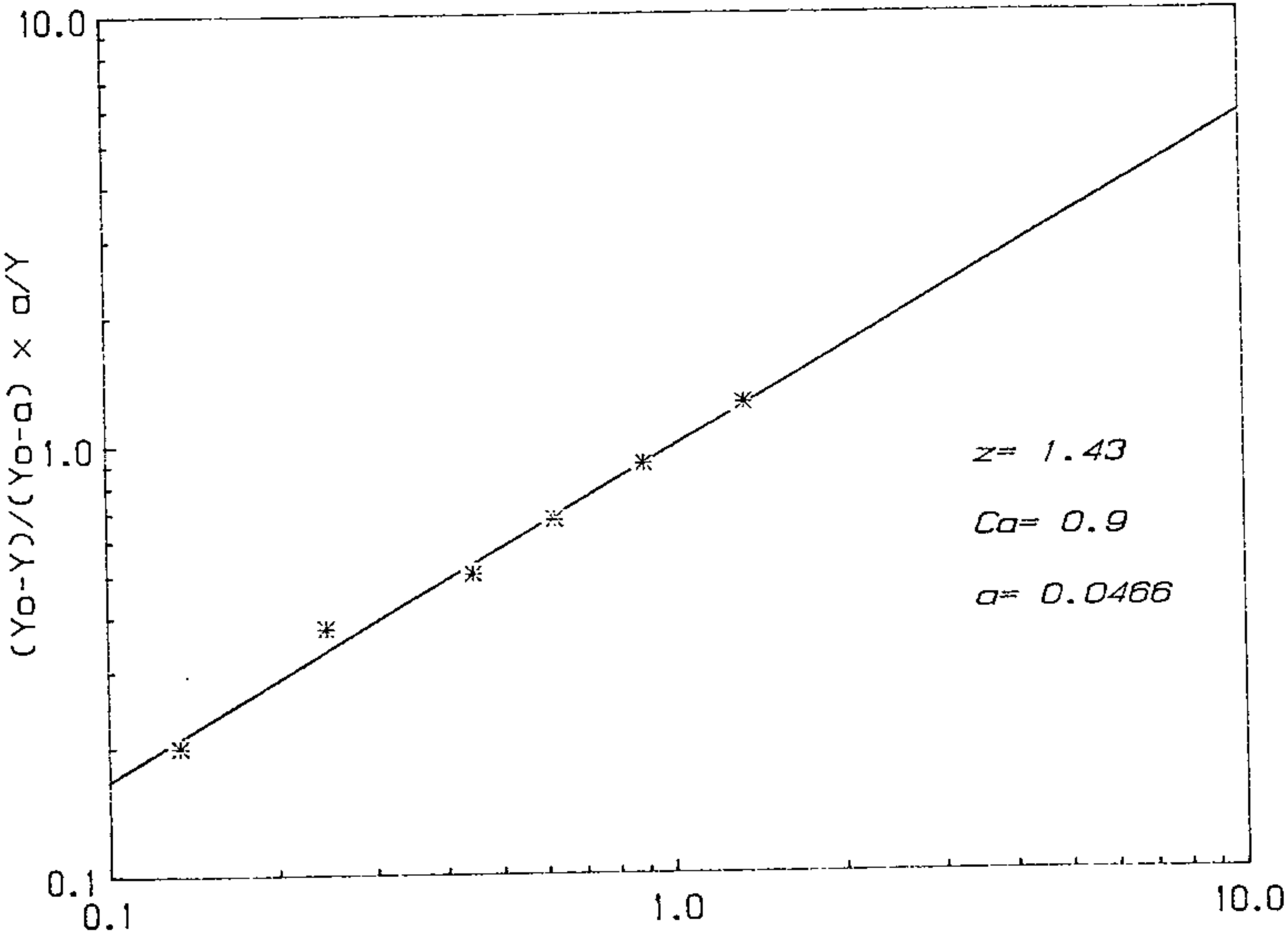


FIG. (5.19) exp 19

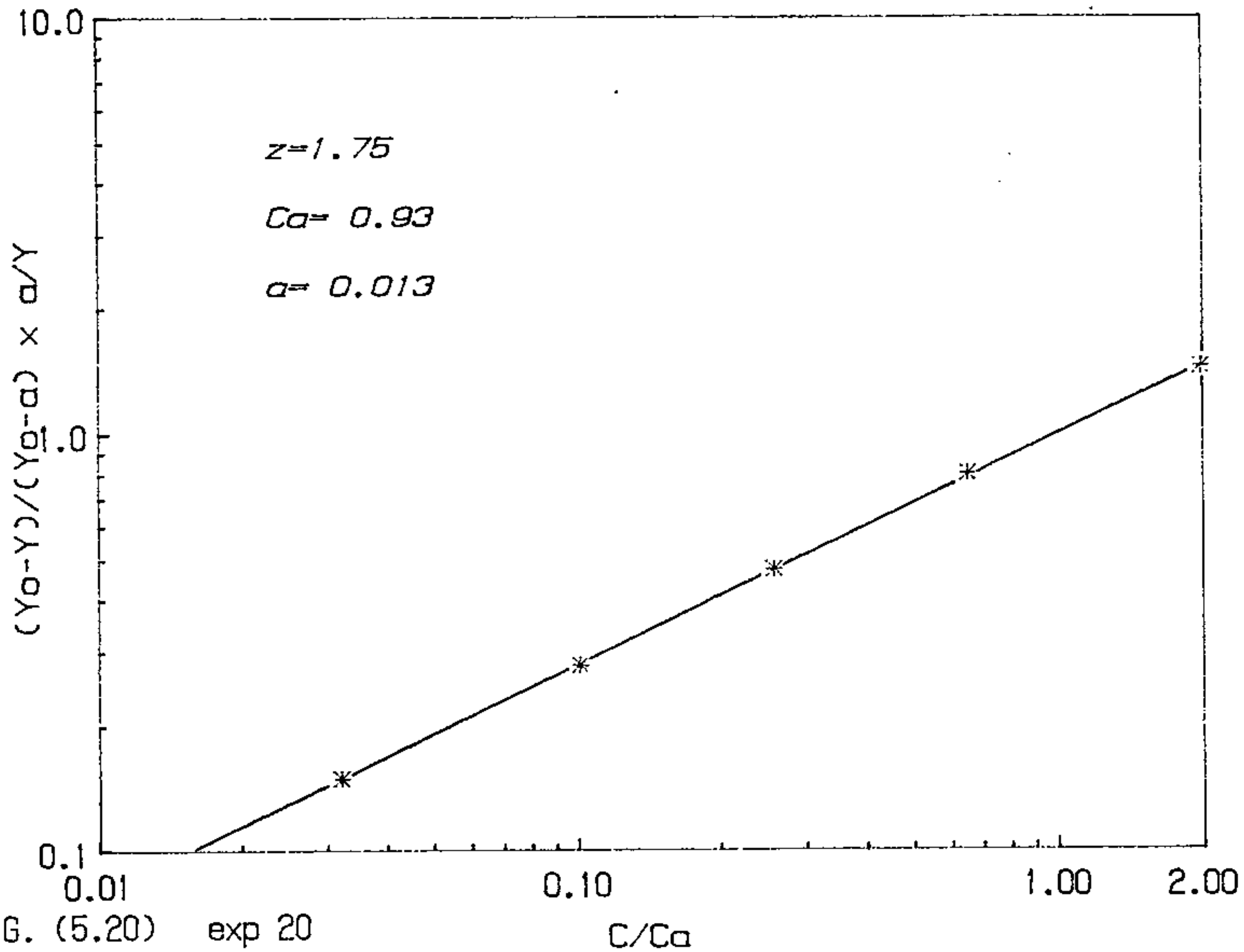


FIG. (5.20) exp 20

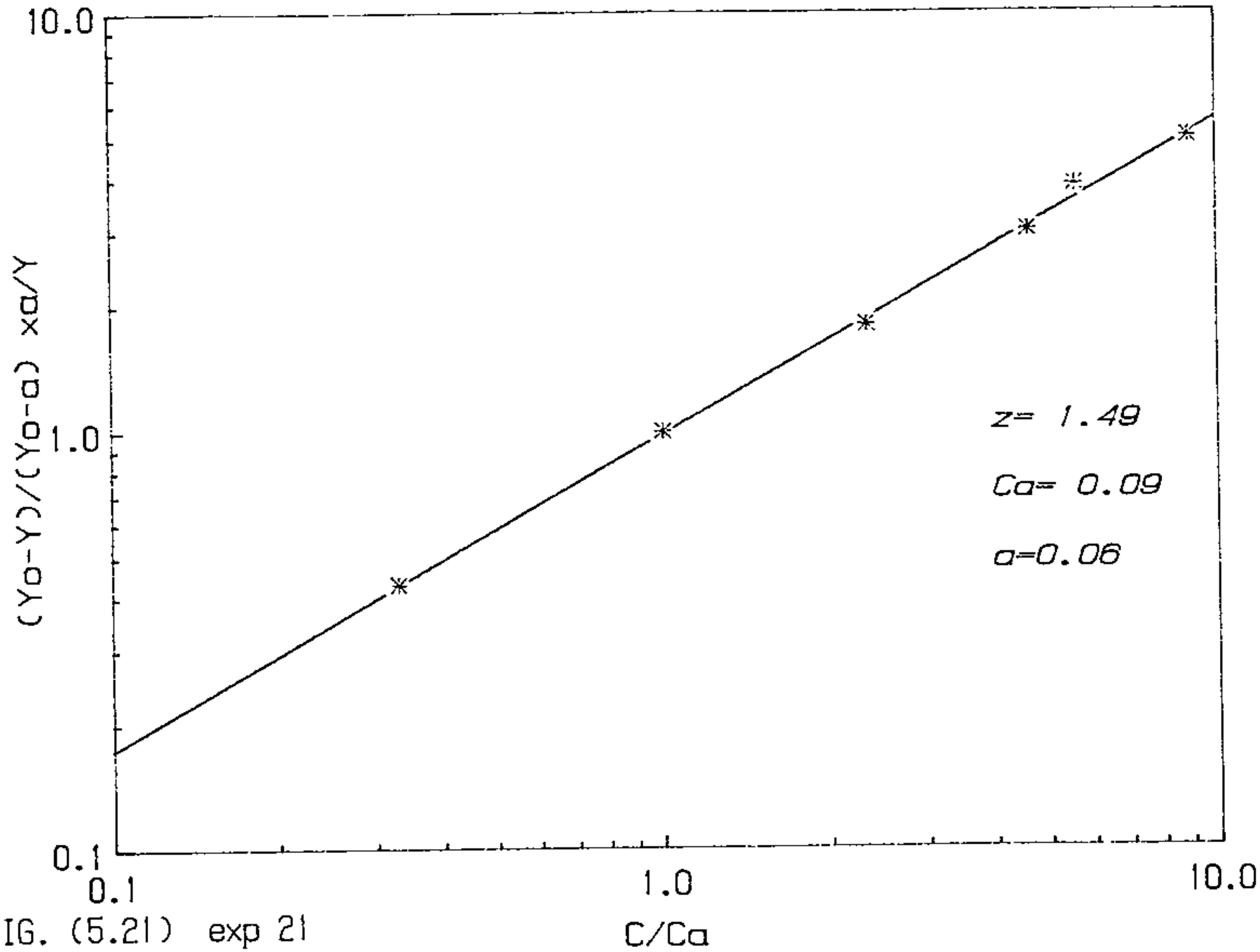


FIG. (5.21) exp 21

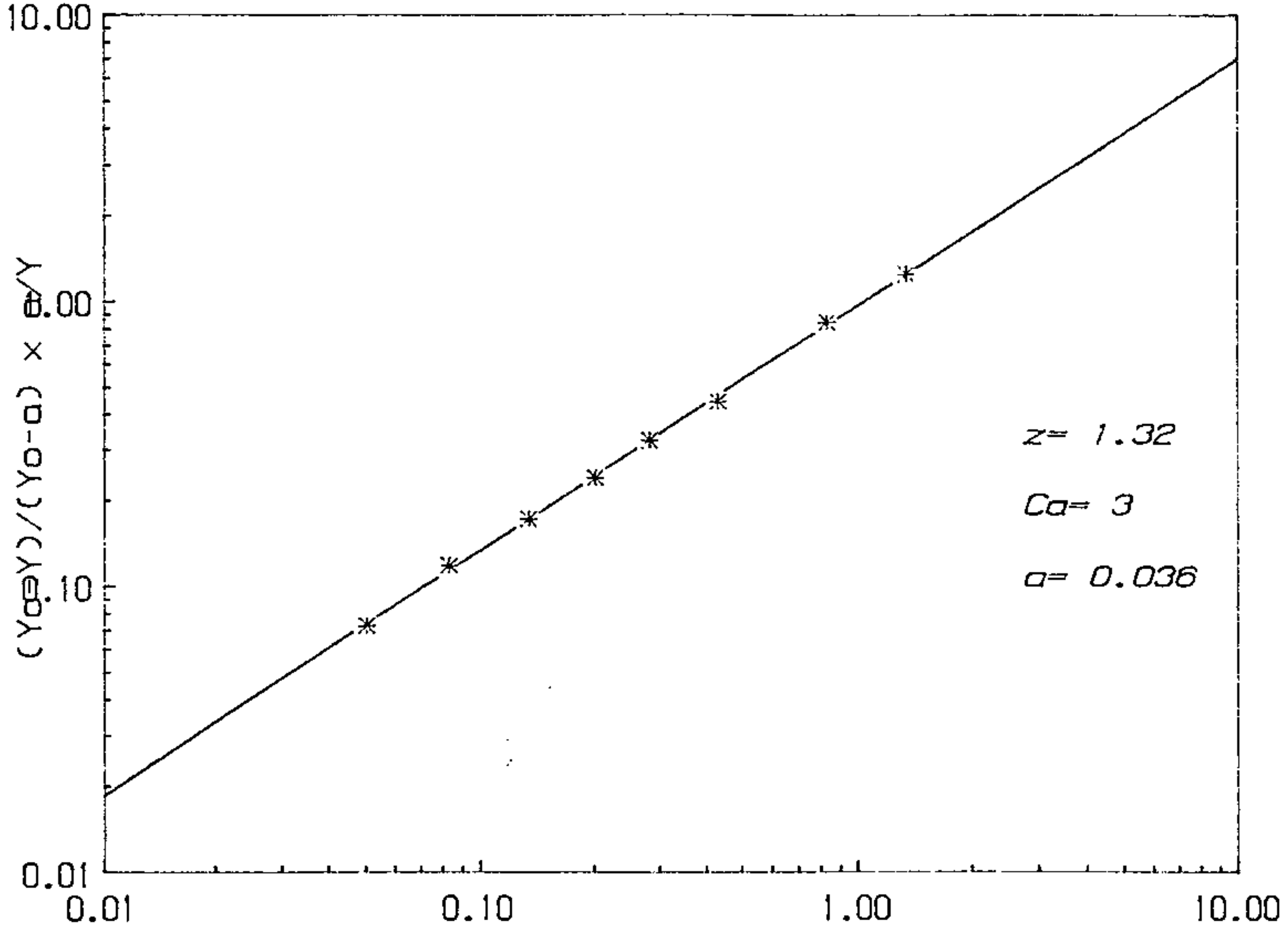


FIG. (5.22) exp 22

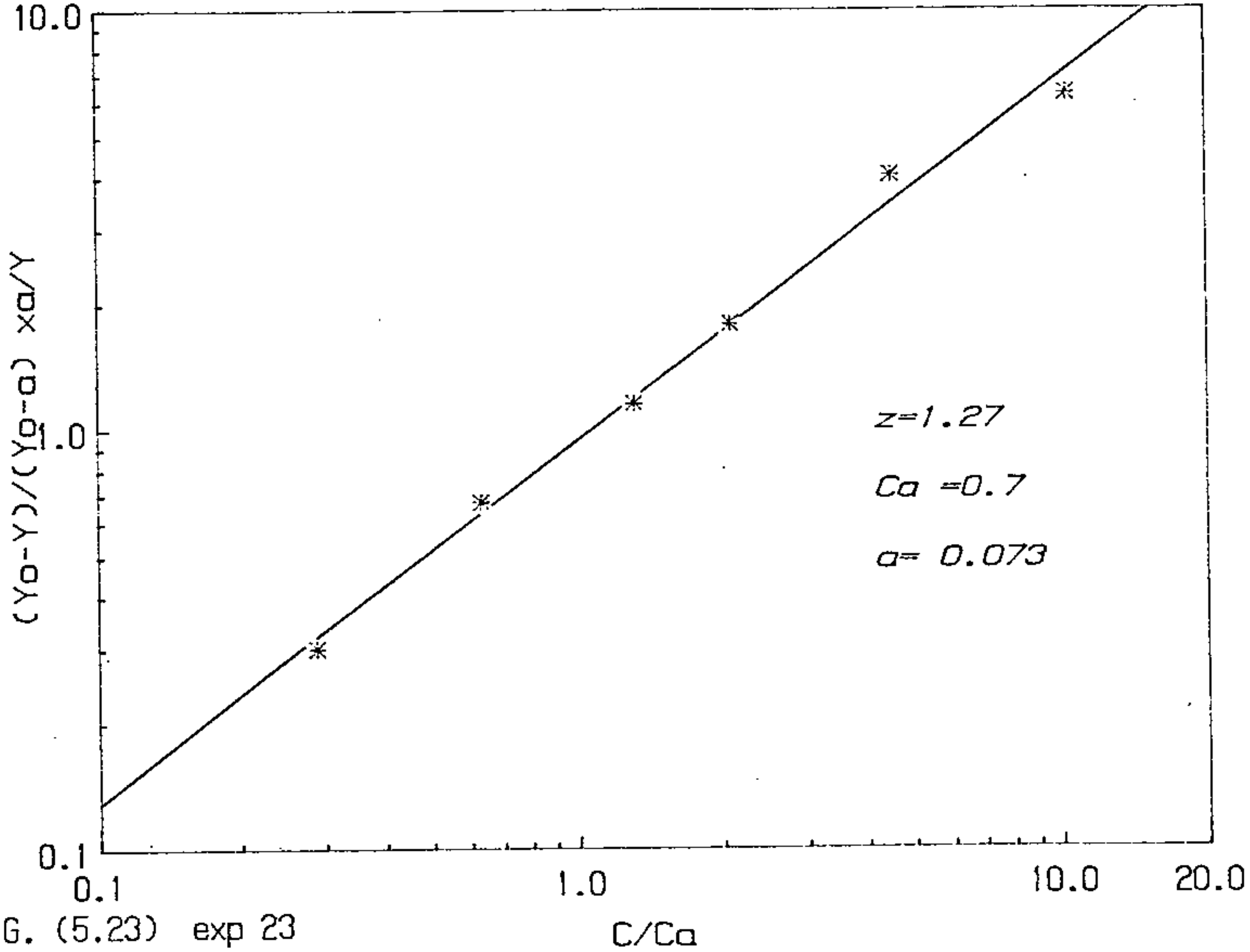


FIG. (5.23) exp 23

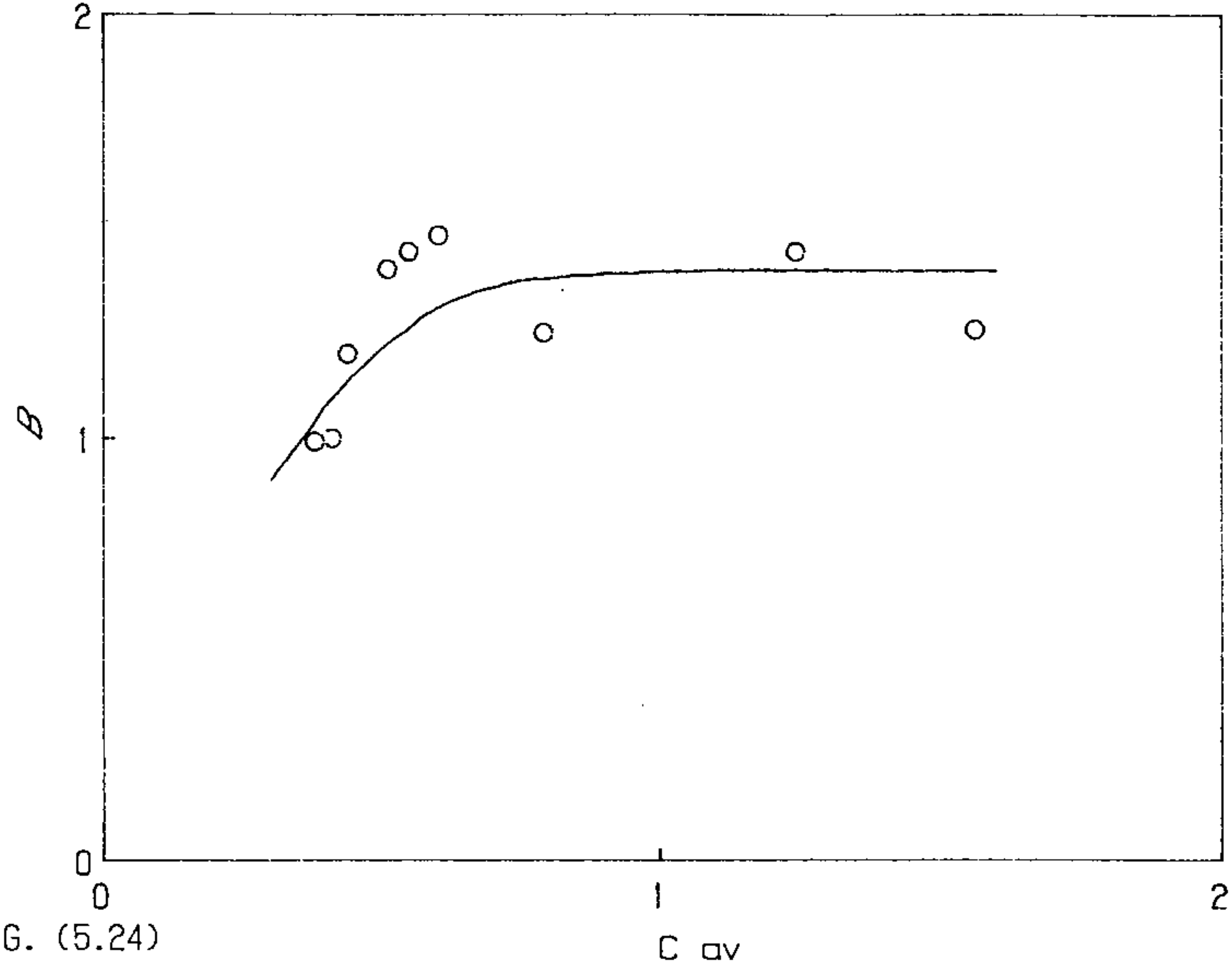


FIG. (5.24)

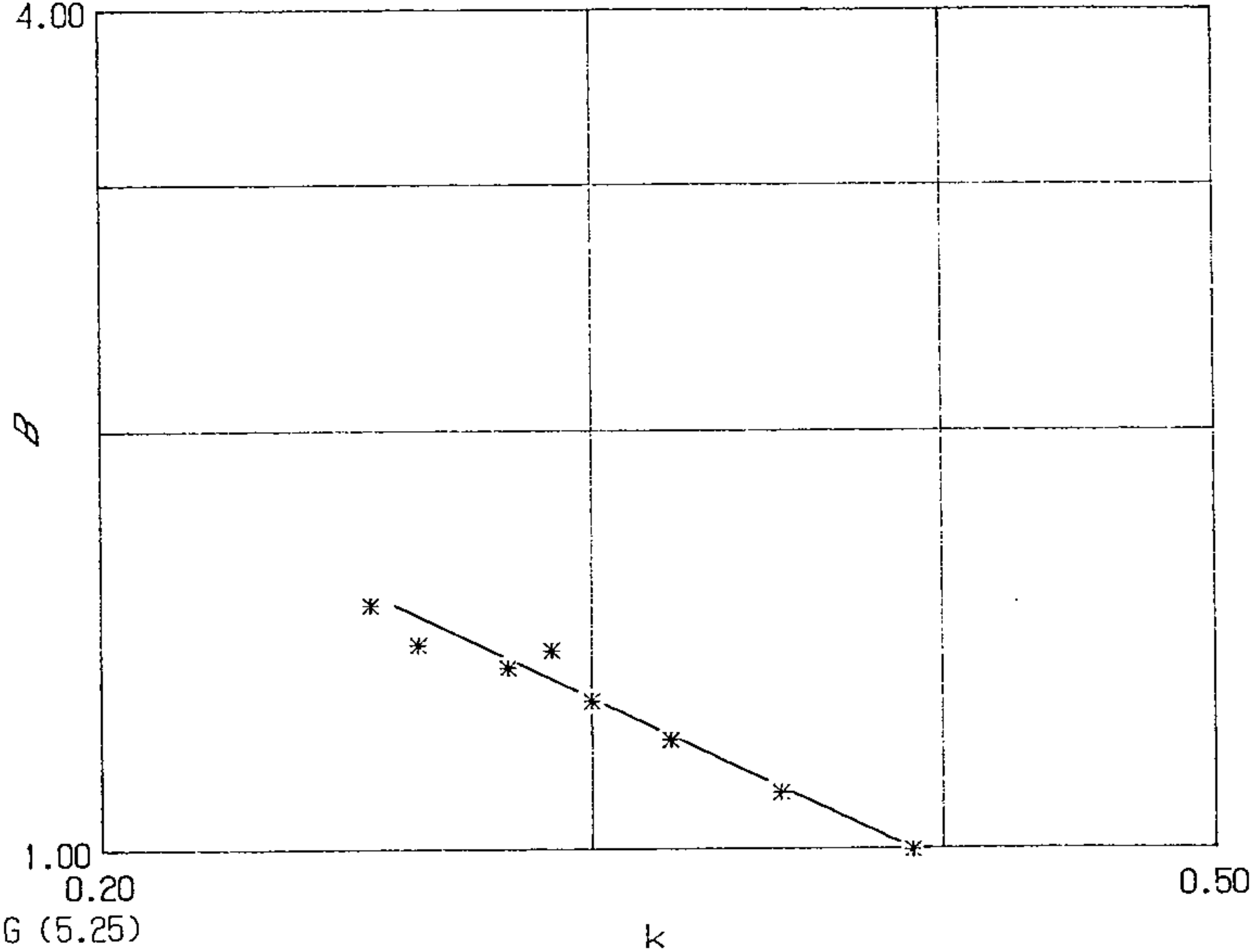


FIG (5.25)

5.6 SUSPENDED LOAD CONCENTRATION AT LEVEL a= y'/2

The bed-load concentration at a= half the hypothetical thickness of the bed layer in motion was previously discussed and considered to be a constant value equal to 759 gm/liter, on submerged weight basis.

The concentration distribution of suspended load follows equation (5.13). This equation was used to find the concentration of suspended load at a. Considering b as an arbitrary level, C_b is the concentration of suspended load at that level, y_o is the normal depth of water. The required concentration C_a was found from

$$\frac{C_a}{C_b} = \left[\frac{y_o - a}{y_o - b} \cdot \frac{b}{a} \right]^z$$

Upon evaluating C_a using the above, the following results were attained

Table 5.3

Test	s	β	$(a - \frac{y'}{2})10^4$	Suspended load concentration at (a)	Bed-load concentration at a	% Deviation
13	1.45	1.40	3.54	744	759	-1.9
14	1.43	1.25	3.85	767	759	+1.1
15	1.61	1.00	4.55	776	759	+2.2
16	1.66	0.99	5.39	760	759	+0.24
17	1.52	1.20	4.54	757	759	-0.26
18	1.67	1.22	5.31	760	759	+0.24
19	1.43	0.98	6.19	771	759	+1.6
20	1.75	1.48	4.218	744	759	-1.9
21	1.49	1.40	5.62	742	759	-2.2
22	1.32	1.26	7.43	748	759	-1.4
23	1.27	1.44	7.059	756	759	-0.46

It is clear from table (5.3), that the deviations of the values of suspended load concentration and bed-load concentration both calculated at the mid depth of the moving layer, are within the acceptable experimental allowances. Thus it can be concluded with great certainty that at this hypothetical level both concentrations are the same, which means that the bed-load concentration may be used to estimate the suspended load concentration at any depth. A step by step procedure is illustrated for the computation of the bed-load, the suspended load in order to determine the total load.

5.7 SUSPENDED LOAD RATE OF TRANSPORT

The most famous suspended load equations were discussed in chapter II. The experimental work was analyzed using Lane and Kalinske, Einstein, Brooks approaches, in addition to the present approach.
The results are tabulated below.

Table 5.4 SUSPENDED LOAD RATES gm/m-sec (submerged wt.)

Test No.	Lane and Kalinske	Einstein	Brooks	Present Approach	Experimental
13	6.8	153	5	5.2	6
14	46.7	260	17	17.17	20
15	38.4	176	16.95	17.15	15
16	24.3	434	23	23.74	22
17	84	271	31.7	32.68	43
18	66	384	28.2	29.12	28
19	96	353	60	62	60
20	37.5	262	60.8	63.18	50
21	92	334	78	80.9	80
22	194	662	160	162	180
23	200	983	218	232	220

Graphical representation of table (5.4) is given in Fig (5.26) which shows that the present approach gives the best fit for the data collected in the present experimental work. Brooks approach gives values very close to the experimental results because actual values of k and z are used. The deviation may be due to the fact that the lower limit used by Brooks is 2d (twice the grain diameter, while in the present approach the lower limit is the mid depth of the moving layer. Nevertheless Brooks approach offers no means for finding the values of k and z, and his estimates would not be so close if the experimentally estemated values of z and k were not used.While in the present approach k and z may be evaluated without field measurements.

As for Lane and Kalinske method the deviation of the calculated values from the measured ones are due to the use of a constant value for k, the von Karman constant in addition to considering the value of $\epsilon_s=\epsilon_{av}=y_o u_*/15$ as constants in the concentration function introduced by them. In addition the Manning coefficient n, is not defined for movable beds.

It is clear that Einstein's approach shows maximum deviations from the experimental data.

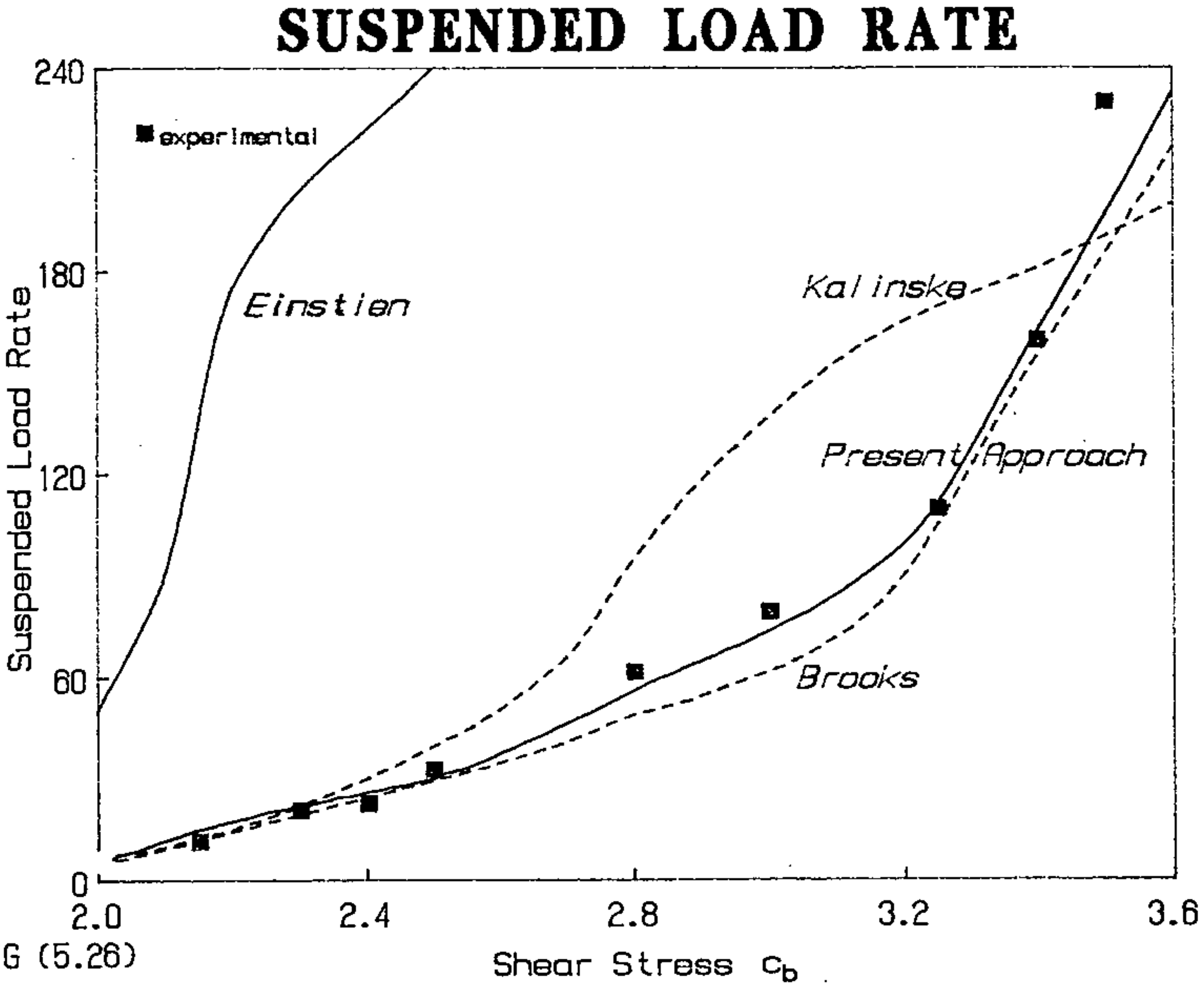

SUSPENDED LOAD RATE
experimental
Einstien
Kal inske
Present Approach
Brooks
Suspended Load Rate
240
180
120
60
0
2.0
2.4
2.8
3.2
3.6
Shear Stress c_b

FIG (5.26)

5.8 TOTAL LOAD TRANSPORT RATE

The total load is the sum of suspended load and bed-load. In the present work wash load was negligible, thus it was not included in the calculations.

The experimental total load was compared with theoretical values emerging from the use of the present approach, Laursen, Kalinske, and Einsteins methods. Table (5.5) gives the results of the computations which are also represented in Fig (5.27).

Table 5.5 Total Load Rates

Test No.	Experimental	Present approach	Einstein	Laursen	Kalinske
1	10.1	8.23	11.03	7.76	18.7
2	10.3	8.76	11.73	7.8	19.8
3	10.7	9.65	14.8	13.6	20.95
4	12.1	11.06	15.9	11.76	21.067
5	12.2	11.1	19.66	13.53	22.6
6	14.0	12.85	25.87	27.33	24.6
7	14.6	13.9	31.04	20	26.37
8	15.3	14.48	34.5	20.27	27.4
9	16.2	14.96	41.39	29	27.7
10	14.1	14.3	37.94	34.9	27.4
11	46.1	41.35	103.48	49	46.72
12	57.1	46.98	68.98	71.3	39.63
13	68.3	62.18	285	267.5	101.64
14	93.1	81.88	450	400	104.49
15	100	100.3	298	125.4	103.44
16	127	131.2	675	185	97.84
17	133	151.4	438	158	131.88
18	131	134	565	202.5	118.8
19	187	194	629	291.7	181.17
20	130	141	486	200.8	112.12
21	186	195.2	629	328.4	147.04
22	332	335	1000	468	190.53
23	373	393.2	1300	497.1	294.91

The curves indicate that the sediment discharge increases rapidly with increasing shear stress. The total load prediction shows radical disagreement between Einstein and others' results. The disagreement becomes more pronounced at higher values of total transport rates than at lower ones. Laursen and Kalinske approaches indicate values closer to the

TOTAL LOAD RATES

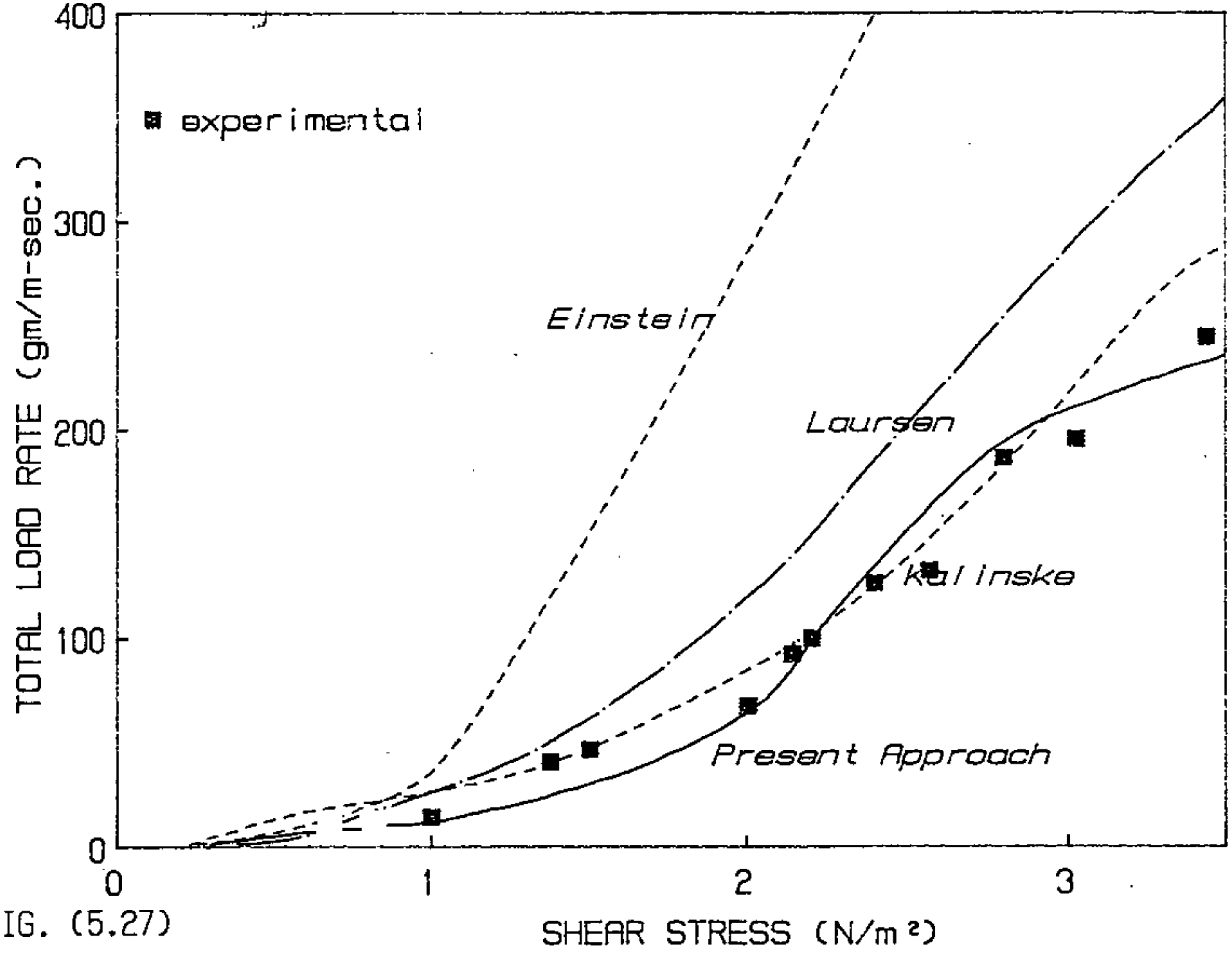


FIG. (5.27)

experimental values actually measured in the laboratory. However it is important to remeber that the conditions to which any formula is applied should correspond to those on which the development of the formula was based. Appreciable variation can be expected with variation of grading and shape of sediments.

As for the present approach, experimental results show the least deviations from the values predicted by the mechanistic reasoning.

The following step wise procedure is recommended for the computation of bed-load, suspended load and total load, using the present approach, for known values of S, y_n and V_m

1- Calculate τ_b; bed shear stress. Detailed method of calculation is given in Appendix B.

2- Find the shear velocity related to bed shear stress; $u_* = \sqrt{\tau_b/\rho}$

3- Compute Re_*; particle Reynolds number = $u_* d/\nu$.

4- From the relation of Re_* versus h/λ shown in Fig (5.9) find the value of the ripple steepness h/λ.

5- Read the value of k from Fig (5.10).

6- Compute the value of β as explained in article 5.6

7- Calculate the value of z from $z = w/u_*\beta k$.

8- Find the mid thickness $(y'/2)$, of the moving layer as explained in article 5.2

9- Using the concentration distribution relation

$$\frac{C}{C_{y'/2}} = \left[\frac{y_n - y}{y_n - y'/2}\;\frac{y'/2}{y}\right]^z$$

with $C_{y'/z}$ know =759 gm /l submerged weight, the concentration distribution profile may be found.

10-Find $\int_{y'/z}^{y_o} C\, u\, dy$ to get the suspended load rate. Graphical integration may be used or any one of the methods discussed in chapter II.

11-Find the value of the bed-load rate as explained in chapter III and outlined in Appendix C, (C.5).

12-The sum of the suspended load rate and bed-load rate gives the total load rate.

The above step by step approach was used to analyze the experimental data, as shown in table (5.6).

Experimental values when compared to theoretical values obtained using the above procedure gave deviations within the acceptable experimental error (max=13%, min=0%).

The comparison supports the soundness of the approach.

Test No.	13	14	15	16	17	18	19	20	21	22	23
Y_n	0.079	0.086	0.123	0.146	0.081	0.120	0.140	0.039	0.08	0.132	0.1
1/s	250	250	300	300	200	250	250	100	160	200	160
τ_b	3.309	3.38	3.912	4.64	3.90	4.568	5.323	3.749	4.834	6.388	6.07
U_*	0.055	0.0575	0.0625	0.0681	0.0624	0.675	0.0729	0.0612	0.0693	0.0799	0.07
Re_*	18.33	19.17	20.83	22.70	20.79	22.50	24.30	20.40	23.16	26.63	25.96
h/	0.001	0.005	0.0145	0.2	0.014	0.02	0.024	0.012	0.021	0.019	0.02
k	0.39	0.37	0.315	0.29	0.32	0.3	0.275	0.35	0.285	0.29	0.3
β	1.00	1.06	1.26	1.31	1.22	1.3	1.4	1.1	1.35	1.31	1.3
z	1.8	1.7	1.612	1.6	1.6	1.6	1.425	1.7	1.495	1.317	1.3
$a \times 10^4$	3.54	3.85	4.55	5.39	4.54	5.31	6.19	4.218	5.62	7.43	7.05
C_{md}	0.04	0.08	0.0917	0.097	0.19	0.13	0.337	0.351	0.463	0.83	1.22
f_b	0.223	0.258	0.186	0.194	0.255	0.167	0.46	0.1819	0.2809	0.505	0.63
V_m	0.33	0.44	0.45	0.498	0.531	0.535	0.577	0.618	0.658	0.709	0.75
q	0.026	0.037	0.055	0.072	0.043	0.064	0.08	0.024	0.053	0.093	0.07
KV/U_*	2.34	2.8	2.3	2.3	2.7	2.37	2.2	3.5	2.7	2.57	2.91
Suspended load rate	5.2	17.17	17.15	23.74	32.68	29.12	62.00	63.18	80.97	162.00	232.4
Bed-load rate	56.98	64.71	83.16	107.47	82.77	104.87	131.94	78.1	114.27	173.6	160.82
Theor. Total rate	62.18	81.88	100.31	131.21	151.45	134.00	194.00	141.28	195.24	335.6	393.22
exp. Total rate	68.3	93.1	100.3	127.1	133.1	131.00	187.00	130.00	186.00	332.00	373.00
% Deviation	+8.9	+12	--	-3	-13	-2	-3.8	-8	-4.9	-1.	-5.4

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CHAPTER VI

CONCLUSIONS

Within the extent of this research concerning the bed-load, suspended load and total load the following main conclusions may be drawn.

1 - A mechanistic approach for the determination of bed-load, suspended load and total load is developed.

2 - The proposed concept when examined for bed-load showed that

a - The measured rates of bed-load are in good agreement with the computed value when introducing a coefficient = 0.63, which is the ratio between bed-load transport for rippled beds and that for flat beds.

b - The maximum concentration of the bed-load is 759 gm/l on submerged weight basis corresponding to a volume concentration of 0.46.

3 - Velocity profiles for rippled beds follow a logarithmic law in the form :

$$\frac{V}{V_*} = \frac{1}{k} \ln \frac{y}{y_o}$$

the value of the turbulent coefficient is not a constant value but decreases with the increase of ripple steepness. The transport of suspended load seems to add slighty to the flow resistance that it can be disregarded.

4 - If there is less than one grain layer in motion, bed-load occurs, if 1 < number of moving layers < 2, then saltation, if more than two grain layers are set in motion, then suspension occurs.
This criteria was found satisfactory to define the different phases of sediment transport.

5 - The Vertical distribution of suspended load was found to follow the logarithmic law,

$$\frac{C}{C_a} = \left[\frac{y_o - y}{y_o - a} \cdot \frac{a}{y} \right]^z$$

The exponent z varies with the variation of the sediment transfer coefficient and the turbulent constant. Graphical relations were set to relate the different variables and to enable the engineer to determine the value of z with certainty.

6 - The value of β relating the sediment transfer coefficient ϵ_s to the momentum transfer coefficient was found to vary with the suspended sediment concentration from 1.0 at low concentrations to a constant value of 1.4 for average concentration $\geq$ 1 gm/liter.

7 - The suspended load concentration when extrapolated to the mid-depth of the hypothetical moving layer of

bed-load, was found to be equal to the maximum concentration of 0.46. This evidence provides a correlation between the bed-load concentration and the suspended load distribution and makes it possible to determine the suspended load rate without measuring the concentration at a reference level.

8 - A step by step procedure was developed for evaluating the total load, using the mechanistic approach.

9 - Total load transport rate was evaluated using different methods in addition to the present approach. The experimental values were in good agreement with the proposed method.

10 - According to the present study, the mechanistic approach proved to be a successful approach in the determination of the bed-load, suspended load and total load knowing few hydraulic parameters namely the slope, the normal depth and the mean velocity of the flow.

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APPENDIX (A)

SUMMARY OF EXPERIMENTAL RESULTS

THE RESULTS OF ALL EXPERIMENTAL MEASUREMENTS AND CALCULATIONS ARE LISTED IN TABULAR FORM . THE ENTRIES OF EACH COLUMN ARE GIVEN BELOW .

(1) Test number .

(2) Normal depth of flow in (m) .

(3) 1/ channel slope .

(4) Mean shear stress $\tau_o=\rho gRS$ in (N/m^2) .

(5) Shear velocity $u_*=(\tau_o/\rho)^{1/2}$ in (m/sec) .

(6) Mean velocity of flow at 0.386 y_n in (m/sec) .

(7) Hydraulic radius R=Area /Wetted perimeter in (m) .

(8) Reynolds number $Re = 4\ V_m R/\nu$.

(9) Friction factor of the bed calculated as explained in Appendix (B) .

(10) Bed shear stress τ_b calculated as explained in Appendix (B) .

(11) Corrected shear velocity $u_*=(\tau_b/\rho)^{1/2}$ in (m/sec) .

(12) Turbulent coeffient determined from the velocity profile plotted on semilog scale as Log y Vs. V for each run . $k=2.3\ u_* J$, where J is the slope of the profile d(Log y)/dv.

(13) The volume concentration of grains per unit volume of space .

(14) Number of moving layers $= \int_{o}^{y} N \, dy \, / \, N_* K$.

(15) Fall velocity /shear velocity .

(16) Dimentionles shear velocity .

(17) Particle Reynolds number$= u'_* d/\nu$.

(18) Bed-load rate as determined by Schoklitsch, summarized in Appendix (C), C.1.

(19) Bed-load rate as determined by Kalinske, summerized in Appendix (C), C.2.

(20) Bed-load rate as determined by Meyer-Peter, summarized in Appendix (C), C.3.

(21) Bed-load rate as determined by Einstein, summarized in Appendix (C), C.4.

(22) Bed-load rate as determined by Khalil, summarized in Appendix (C), C.5.

(23) Measured bed-load rate based on submerged weight per unit width per unit time.

(24) The suspended sediment concentration distribution exponent as estimated from the slope of the log-log graph of the measured concentration profiles; $\log C / Ca$ Vs. $\log \dfrac{y_n - y}{y_n - a} \cdot \dfrac{a}{y}$

(25) Sediment load transfer coefficient calculated from $z = \omega / \beta u_* k$.

(26) Mid depth of the assumed hypothetical moving layer.

(27) Suspended load concentration estimatated using

$$\frac{C}{C_{y'/z}} = \left(\frac{y_n - y}{y_n - y'/z} \cdot \frac{y'/z}{y} \right)$$

(28) Bed-load concentration based on 0.46 volume concentration in (g/L), submerged weight.

(29) Deviation (Exp -Theo)/Exp x 100%.

(30) Bed forms steepness, a measure of bed forms height/wave lenght.

(31) Suspended load concentration at mid depth of the flow.

(32) Suspended load average concentration; concentration of suspended load in gm/l divided by the depth of flow.

1	2	3	4	5	6
Test	Y_n	1/S	τ_o	U_* average	V_m
1	0.045	500	0.679	0.02606	0.418
2	0.035	400	0.6959	0.02638	0.358
3	0.04	400	0.774	0.0278	0.449
4	0.038	350	0.8198	0.0291	0.41
5	0.032	300	0.8624	0.02936	0.42
6	0.069	500	0.9274	0.03045	0.51
7	0.052	400	0.997	0.03077	0.395
8	0.031	250	1.008	0.03175	0.303
9	0.058	400	1.025	0.032	0.44
10	0.054	350	1.075	0.03273	0.58
11	0.13	500	1.366	0.0369	0.338
12	0.039	200	1.518	0.0376	0.37
13	0.079	250	2.03	0.0451	0.33
14	0.086	250	2.14	0.0463	0.44
15	0.123	300	2.209	0.0470	0.45
16	0.146	300	2.419	0.0490	0.498
17	0.081	200	2.579	0.0908	0.531
18	0.120	250	2.61	0.051	0.535
19	0.140	250	2.80	0.0533	0.577
20	0.039	100	3.02	0.055	0.618
21	0.08	160	3.198	0.0565	0.658
22	0.132	200	3.44	0.0586	0.709
23	0.10	160	3.678	0.0605	0.757

1	7	8	9	10	11	12
Test	R	$R_{e}x10^{-4}$	f_b	τ_b	U_*	k
1	0.0346	6.43	0.0339	0.74	0.0272	0.2515
2	0.0283	12.6	0.0483	0.774	0.0278	0.2855
3	0.0315	6.30	0.0331	0.834	0.0288	0.248
4	0.0255	4.64	0.0427	0.928	0.0304	0.24
5	0.02637	4.90	0.0422	0.93	0.0305	0.188
6	0.04726	10.7	0.0324	1.056	0.325	0.31
7	0.03861	6.78	0.058	1.138	0.0337	0.311
8	0.02569	2.32	0.2296	1.182	0.03439	0.249
9	0.04182	8.18	0.0505	1.222	0.03495	0.247
10	0.3823	9.85	0.0278	1.168	0.03419	0.259
11	0.0696	10.5	0.1720	2.456	0.0495	0.400
12	0.0309	5.08	0.156	2.669	0.0516	0.323
13	0.0517	7.58	0.223	3.046	0.055	0.353
14	0.0546	7.77	0.258	3.309	0.0575	0.39
15	0.0675	12.3	0.186	3.912	0.0625	0.39
16	0.07398	14.4	0.194	4.64	0.0681	0.38
17	0.05259	8.18	0.255	3.90	0.0624	0.34
18	0.666	13.8	0.167	4.568	0.0675	0.29
19	0.0724	9.78	0.46	5.323	0.0729	0.41
20	0.0309	5.58	0.1819	3.749	0.0612	0.25
21	0.0521	8.59	0.2809	4.834	0.0695	0.27
22	0.0702	9.92	0.5053	6.388	0.0799	0.3
23	0.06	7.36	0.6375	6.070	0.0779	0.279

1	13	14	15	16	17
Test	N	No. of moving layers	w/u_*	θ	R_{e*}
1	0.22	0.498	1.47	0.152	9.06
2	0.24	0.529	1.438	0.159	9.27
3	0.269	0.584	1.388	0.1717	9.6
4	0.308	0.670	1.315	0.1911	10.13
5	0.309	0.672	1.311	0.1915	10.17
6	0.36	0.787	1.23	0.2174	10.83
7	0.396	0.861	1.186	0.234	11.23
8	0.415	0.902	1.163	0.243	11.46
9	0.432	0.938	1.144	0.2516	11.65
10	0.409	0.889	1.169	0.2405	11.39
11	0.876	1.904	0.808	0.5057	16.50
12	0.95	2.065	0.775	0.549	17.20
13	1.08	2.36	0.727	0.627	18.33
14	1.18	2.57	0.696	0.681	19.17
15	1.396	3.034	0.640	0.806	20.83
16	1.655	3.59	9.587	0.955	22.70
17	1.391	3.02	0.641	0.803	26.79
18	1.63	3.54	0.592	0.94	22.50
19	1.899	4.13	0.548	1.096	24.30
20	1.293	2.81	0.653	0.772	20.40
21	1.725	3.75	0.575	0.995	23.16
22	2.278	4.95	0.501	1.315	26.63
23	2.165	4.70	0.513	1.25	25.96

	18	19	20	21	22	23
Test	Schoklitsch	Kalinske	Meyer-Peter	Einstein	Khalil	Measured
1	2.00	18.7	5.23	11.03	8.23	10.1
2	1.78	19.8	5.7	11.73	8.76	10.3
3	2.83	20.95	6.91	14.8	9.65	10.7
4	3.1	21.067	9.02	15.9	11.06	12.1
5	3.3	22.6	9.04	19.66	11.1	12.2
6	4.3	24.6	11.64	25.87	12.85	14.0
7	3.33	26.37	13.27	31.04	13.9	14.6
8	3.13	27.4	14.9	34.5	14.48	15.3
9	4.3	27.7	15.5	41.39	14.96	16.2
10	6.72	27.4	15.21	37.94	14.3	14.1
11	5.5	46.72	34.9	103.48	41.35	46.1
12	7.1	39.63	22.96	68.98	46.84	57.1
13	9.47	40.84	65.3	131.34	56.98	66.3
14	10.06	57.79	72.29	189.7	64.71	75.1
15	14.34	65.04	65.03	121.89	83.16	85.3
16	18.39	73.54	157.9	241.4	107.47	105.1
17	22.79	47.88	106.4	167.3	82.77	84.2
18	24.51	52.79	181.5	181.3	104.87	103.0
19	16.0	85.17	221.7	275.95	131.98	127.0
20	23.6	74.62	67.46	224.2	78.1	80.1
21	39.9	55.04	198.5	295.3	114.27	108.0
22	22.23	96.53	285.5	345.0	173.60	152.0
23	20.68	94.91	236.9	327.7	160.82	148.0

1 Test	24 Z	25 ß	26 $a \times 10^4$	27 Suspended load concentration at a	28 Bed load concentration at a	29 % deviation
13	1.45	1.40	3.54	744	759	-1.9
14	1.43	1.25	3.85	767	759	+1.1
15	1.61	1.00	4.55	776	759	+2.2
16	1.66	0.99	5.39	760	759	+0.24
17	1.52	1.20	4.54	757	759	-0.26
18	1.67	1.22	5.31	760	759	+0.24
19	1.43	0.98	6.19	771	759	+1.6
20	1.75	1.48	4.218	774	759	-1.9
21	1.49	1.40	5.62	742	759	-2.2
22	1.32	1.26	7.43	748	759	-1.4
23	1.27	1.44	7.059	756	759	-0.46

1	12	30	31	32
Test	K	h/λ	C_{md}	C_{av}
13	0.353	0.01	0.3	0.51
14	0.39	0.002	0.36	0.79
15	0.39	0.002	0.125	0.41
16	0.38	0.003	0.96	0.38
17	0.34	0.015	0.3	0.44
18	0.79	0.021	—	—
19	0.40	—	0.4	0.614
20	0.25	0.031	0.26	0.6
21	0.0.27	0.025	0.42	0.55
22	0.3	0.02	0.96	1.56
23	0.279	0.023	1.26	1.24

Test No.	13	14	15	16	17	18	19	20	21	22	23
y_n	0.079	0.086	0.123	0.146	0.081	0.120	0.140	0.039	0.08	0.132	0.1
1/s	250	250	300	300	200	250	250	100	160	200	160
τ_b	3.309	3.38	3.912	4.64	3.90	4.568	5.323	3.749	4.834	6.388	6.07
U_*	0.055	0.0575	0.0625	0.0681	0.0624	0.675	0.0729	0.0612	0.0693	0.0799	0.07
Re_*	18.33	19.17	20.83	22.70	20.79	22.50	24.30	20.40	23.16	26.63	25.96
h/λ	0.001	0.005	0.0145	0.2	0.014	0.02	0.024	0.012	0.021	0.019	0.02
k	0.39	0.37	0.315	0.29	0.32	0.3	0.275	0.35	0.285	0.29	0.3
β	1.00	1.06	1.26	1.31	1.22	1.3	1.4	1.1	1.35	1.31	1.3
z	1.8	1.7	1.612	1.6	1.6	1.6	1.425	1.7	1.495	1.317	1.3
$ax10^4$	3.54	3.85	4.55	5.39	4.54	5.31	6.19	4.218	5.62	7.43	7.05
C_{md}	0.04	0.08	0.0917	0.097	0.19	0.13	0.337	0.351	0.463	0.83	1.22
f_b	0.223	0.258	0.186	0.194	0.255	0.167	0.46	0.1819	0.2809	0.505	0.63
V_m	0.33	0.44	0.45	0.498	0.531	0.535	0.577	0.618	0.658	0.709	0.75
q	0.026	0.037	0.055	0.072	0.043	0.064	0.08	0.024	0.053	0.093	0.07
KV/U_*	2.34	2.8	2.3	2.3	2.7	2.37	2.2	3.5	2.7	2.57	2.91
Suspended load rate	5.2	17.17	17.15	23.74	32.68	29.12	62.00	63.18	80.97	162.00	232.4
Bed-load rate	56.98	64.71	83.16	107.47	82.77	104.87	131.94	78.1	114.27	173.6	160.82
Theor. Total rate	62.18	81.88	100.31	131.21	151.45	134.00	194.00	141.28	195.24	335.6	393.22
exp. Total rate	68.3	93.1	100.3	127.1	133.1	131.00	187.00	130.00	186.00	332.00	373.00
% Deviation	+8.9	+12	--	-3	-13	-2	-3.8	-8	-4.9	-1.	-5.4

APPENDIX (B)

SIDE WALLS CORRECTION PROCEDURE

In flume studies, the roughness factor for the sides usually differs from the roughness factor of the bed, and the frictional forces are also not uniformly distributed over the cross section. Failure to disclose the distribution of friction over the cross section may lead to inconsistent results and incorrect conclusions. It is therefore, always necessary to correct the flume data in such a way as to eliminate the effect of the sides and to represent them as if the flume is wide.

The method used here to correct for side walls effect was proposed by *Khalil in 1969*, and is applicable for experimental flumes of any section.

The mean tangential shear stress τ_m, for a parallel flow of a steady mean velocity V_m in an open flume having a slope S and a hydraulic radius R is given by:

$$\tau_m=\rho\ g\ R\ S \qquad ....(B.1)$$

From Darcy relation

$$\tau_m=f_m x\frac{1}{8}\rho\ V_m^2 \qquad ....(B.2)$$

where f_m is the mean value of the friction factor for the flume section.

Considering the rectangular section shown in sketch, and denoting the average shear stress on the wall by τ_m , and the average shear on the bed by τ_b , the total shear force per unit length is made up of the forces acting on the different parts of the boundary, that is:

$$\tau_m(2d+b) = \tau_v x2d + \tau_b b \qquad \text{......(B.3)}$$

but by defintion;

$$f = \tau \,/\, \frac{1}{8}\rho\, V^2 \qquad \text{......(B.4)}$$

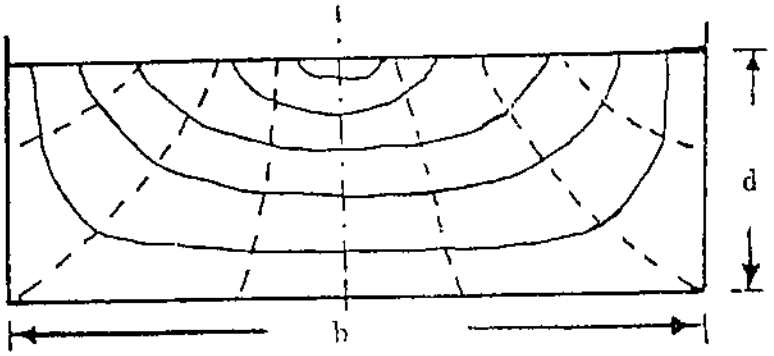


Fig (B.1)

Since the cross section can be divided into sub-areas each having the same mean velocity and restricted only by the shear at the wetted perimeter, (i.e. dividing lines are lines of zero shear), and since the pressure gradient is the same for the different sub-areas, then for a rectangular cross section equation(B.3) may be written in the form :

$$f_m(2d+b) = f_v x2d + f_b b \qquad \text{.....(B.5)}$$

or

$$f_b = f_m + \frac{2d}{b}(f_m - f_v) \qquad \text{.....(B.6)}$$

f_m is defined by measurable quantities such as velocity or discharge, slope and hydraulic radius.

For turbulent rough flow, the ratio of f_b to f_v depends on their relative roughness, and for channels with sides which are smooth, such a ratio depends on the Reynolds number Re. Reynolds number associated with the different sub-areas are;

$$Re_m = \frac{4\ R_m V_m}{\nu}$$

$$Re = \frac{4\ R_b V_b}{\nu}$$

and $$Re = \frac{4\ R_v V_v}{\nu}$$

the subscripts m, b and v, refer to mean, bed and wall respectively.

For the same velocity :

$$\frac{Re_m}{R_m} = \frac{Re_b}{R_b} = \frac{Re_v}{R_v} \qquad \text{......(B.7)}$$

and since the subareas have the same pressure gradient, then from equation(B.4) it follows that :

$$\frac{R_m}{f_m} = \frac{R_b}{f_b} = \frac{R_v}{f_v} \qquad \text{......(B.8)}$$

by substituting in equation (B.7) we have :

$$\frac{Re_m}{f_m} = \frac{Re_b}{f_b} = \frac{Re_v}{f_v} \qquad \text{......(B.9)}$$

Since Re_m and f_m are known quantities, the ratio Re_v/f_v may then be evaluated. For known values of Re_m/f_m , f_v is obtainable from ;

$$f = 0.398\left(\frac{f}{Re}\right)^{1/5} \qquad \text{......(B.10)}$$

By substituting in equation (B.6) , the bed friction factor may be determined.

Recourse is then made to introduce a velocity factor α, such that

$$\alpha = V_v/V_m \qquad \text{......(B.11)}$$

α is supposed to depend on the ratio of bed friction factor to wall friction factor and also on the ratio b/d.

The consideration of velocity factor, enhances equations (B.6) and (B.9) to the following forms :

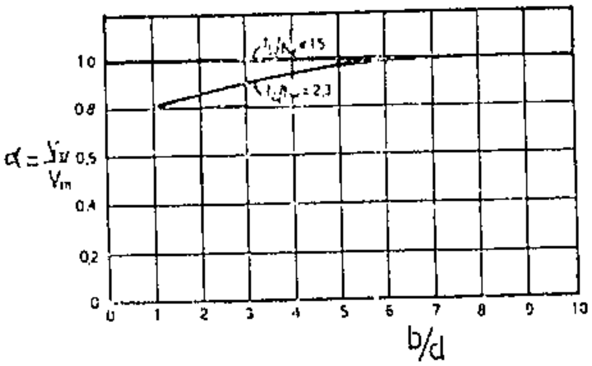
$$f_b = f_m + \frac{2d}{b}(f_m - \alpha^2 f_m) \qquad \text{......(B.12)}$$

and

$$\frac{Re_m}{f_m} = \frac{Re_b}{f_b} = \frac{Re_v}{f_v}\,\frac{1}{\alpha^2} \qquad \text{........(B.13)}$$

the value of α is obtained graphically.

The sequence of calculations may be summarized as follow :



1- $\tau_m = \rho\ g\ R\ S$

2- $f_m = \frac{\tau_m \times 8}{\rho\ V_m^2}$

3- $Re_m = \frac{4\ V_m R}{\nu}$

4- $\frac{Re_m}{f_m} = \frac{Re_v}{f_v} = \frac{Re}{f}$

5- $f = 0.316\left(\frac{R_*}{f}\right)^{1/5}$

6- $f_b = f_m + \frac{2d}{b}(f_m - f_v)$

7- Using Fig(B.2) find α .

8- $f_b = f_m + \frac{2d}{b}(f_m - \alpha^2 f_m)$

APPENDIX (C)

SUMMARY OF BED-LOAD EQUATIONS.

WITH A NUMERICAL EXAMPLE

C.1 SCHOKLITSCH

Test No 13

$q = V_m x\ y_n$

$= 0.33x0.079 = 0.026$

$q_c = 0.6\ d^{3/2}/S^{7/6} = 0.6\ x(o.3\ x\ 10^{-3})^{3/2} x\ 250^{7/6}$

$= 1.956\ x\ 10^{-3}$

$g_s = 2500\ S^{3/2}(q - q_c) x\ 1000\ x\ \frac{1.65}{2.65}$

$= 9.468\ \ g_m/m\text{-}sec$ (sub. weight)

C.2 KALINSKE

Test No 17

$\tau_c/\tau = 0.194\ /\ 2.579 = 0.0753$

$u'_* = 0.0624$ m/sec

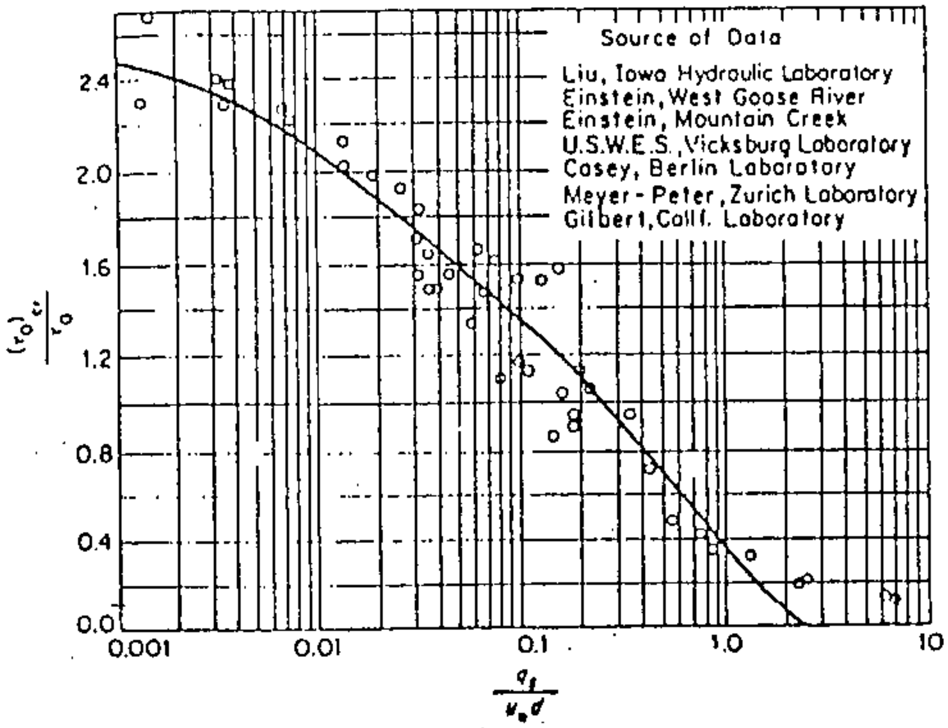
$f(\tau_c/\tau) =$ from fig(C.1)

$= 1.55$

$q_s = u'_*\ d\ f(\tau_c/\tau)$

$= 0.0624\ x\ 1.55\ x\ 0.3x10^{-3} x\ 1000\ x\ 1650$

$= 47.87\ g_m/m\text{-}sec$ (sub. weight)



Fig(C.1) Kalinske's equation [After Kalinske (1947).]

C.3 MEYER-PETER

Test No. 18

$$R_h' = \tau b/\rho g S = \frac{4.568 \times 250}{9.81 \times 1000} = 0.1164$$

$$(K'/K) = 0.9$$

$$\frac{\gamma \ R_h' (K'/K)^{2/3} S}{d\ (\gamma_s - \gamma)} - 0.047 = \frac{0.25 \sqrt[3]{\rho}}{d\ (\gamma_s - \gamma)} \quad g_s'^{\,2/3}$$

$g_s' = 181.5$ gm/m-sec (sub.weight)

C. 4 EINSTEIN

Test No. 15

$$\psi = \frac{\rho_s - \rho}{\rho} \cdot \frac{d}{SR} = \frac{1.65 \times 0.3\times 10^{-3} \times 300}{0.0675} = 2.2$$

$$\delta = \frac{11.6\ \nu}{u'_*} = \frac{11.6 \times 0.9\times 10^{-6}}{0.0625} \text{X } 1000 = 0.167 \text{ mm}$$

$K_s = 0.3$ mm

$K_s / \delta = 1.796$

$x = 1.6$

$\Delta = K_s / x = 0.1875$

$X = 1.39\ \delta = 0.232$

$Y = 0.8$

$\beta_x = \log\ (10.6\ x/\Delta) = 1.117$

$\beta = \log(10.6) = 1.025$

$(\ \beta/\beta_x)^2 = 1.187$

$\xi = 1$

$\psi_x = \xi\ Y\ (\beta/\beta_x)^2\ \psi$

$= 2.08$

$\phi_* = 3.5$ from Fig(2.4)

$$\phi_* = \frac{g'_s}{\gamma_s} \sqrt{\frac{\rho}{\rho_s - \rho} \quad \frac{1}{g\ d^3}}$$

$$\phi_* = \frac{g'_s}{1650} \text{ x } \sqrt{\frac{1}{1.65} \quad \frac{1}{9.8\ [0.3\times 10^{-3}]^3}}$$

$g'_s = 121.89$ gm/m-sec (sub.weight)

C.5 KHALIL

Test No. 10

$N = 0.409$ i.e less than one grain layer in motion

$$g'_* = \frac{\tau_b - \tau_c(1-N/N_*)}{\tan\phi} \times 0.892 \times 8.57 \times U'_* \times 0.63 \left[1 - .6(N/N_*)^{9/7}\right]$$

$\tau_b = 1.168$ column (10)

$\tau_c = 0.194$ from shields diagram

$N_* = 0.46$

$U'_* = 0.03419$

$$g'_* = \left[1.168 - 0.194(1 - 0.409)/\ 0.46\right] \times \frac{0.892 \times 8.57}{\tan 30} \times 0.03419 \times 0.63 \times \left[1 - 0.6\left(\frac{0.0409}{0.46}\right)^{9/7}\right] \times \frac{1000}{9.8}$$

$= 14.3$ gm/m-sec (sub.weight)

Test No. 20 ; $\int_0^y N\,dy > N_* K$

$$g'_* = \frac{\tau_b}{\tan\phi} \times 0.892 \times 8.57 \times 0.4 \times 0.63\, u'_*$$

$\tau_b = 3.749$ column (10)

$u_* = 0.0612$

$$g'_* = \frac{3.749}{\tan 30} \times 0.892 \times 8.57 \times 0.4 \times 0.63 \times 0.0612 \times \frac{1000}{9.8}$$

$= 78.1$ gm/m-sec (sub.weight)

الملخص

مدخل ميكانيكي لمعدل الحمل الكلي الرسوبي

نقل الحمل الرسوبي في القنوات المكشوفة يعتبر مشكلة جذبت أنظار العديد من المهندسين والمهتمين لارتباطها الوثيق بتهذيب الأنهار وتصميم مشاريع الري وبسبب مداخلاتها في تصميم الموانئ وتغيير مجاري الأنهار بالإضافة الى مشاكل النحر والترسيب.

وقد استفاض الباحثون فيها شرحا وتحليلا محاولين جاهدين التوصل الى ايجاد المعادلات التي تربط معدل الحمل الكلي الرسوبي بمتغيرات معدل السريان وخصائص المواد الرسوبية.

يقسم الحمل الرسوبي الى قسمين:

١. حمل النقل القاعي وهو الجزء الذي تكون فيه مركبة الوزن المغمور العامودية في وضع اتزان مع القوى المماسة المؤثرة على الحبيبات.

٢. حمل النقل المعلق وهو ذلك الجزء الذي يكون فيه الوزن في اتزان مع القوى الناشئة عن المركبة العامودية لفعل الإضطراب للمائع.

يقدم هذا البحث مدخلا ميكانيكيا لتقدير معدل الحمل الكلي الرسوبي ويعرض الإختبارات اللازمة لتقدير مدى اتفاقه مع القياسات المخبرية. كذلك يوجد العلاقات التي تربط ما بين حمل النقل القاعي وحمل النقل المعلق كما يتطرق البحث الى العلاقة بين ثابت الاضطراب ومقياس التموجات ومدى تأثير حمل النقل المعلق على ثابت الاضطراب. هذا الى جانب العلاقة بين معامل نقل المواد الرسوبية ومعامل نقل كمية التحرك. بالاضافة الى وضع معيار لتحديد بداية التعلق.

وتحتوي الرسالة على ستة فصول بالاضافة الى الملخص والمراجع والملاحق.

١. **الفصل الأول :** مقدمـــة.

٢. **الفصل الثاني:** يشمل عرضا موجزا لاهم النظريات والأبحاث والإختبارات والمعادلات التجريبية والنظرية الخاصة بهذا الموضوع مع بيان أهم ما توصل اليه الباحثون من نتائج .

٣. **الفصل الثالث :** وفيه عرض تفصيلي للمدخل الميكانيكي لمعدل الحمل الكلي الرسوبي .

٤. **الفصل الرابـع:** وهو خاص ببرنامج التجارب العملية التي أجريت في هذا البحث ويشمل شرحا وافيا للأجهزة والأدوات والمواد المستخدمة وطريقة العمل مدعمه بالرسوبات التوضيحية والصور الفوتوغرافية.

٥. **الفصل الخامس :** ويحوي تحليلا تفصليا شاملا لنتائج التجارب ضمن المدخل المقدم ومقارنات مع نظريات الآخرين مدعما بالجداول والرسومات البيانية التوضيحية.

٦. **الفصل السادس :** وفيه ملخص لأهم النتائج التي تم التوصل اليها استنادا الى القياسات المخبرية والتي يمكن ايجازها فيما يلي:

١. تم عرض مدخل ميكانيكي لمعدل الحمل الكلي الرسوبي.
٢. عند فحص المدخل تبين أن :

أ. القياسات المخبرية تتفق تماما مع المدخل عند ادخال معامل = ٠ر٦٣ وهو النسبة بين حمل النقل القاعي على سطح متموج وحمل النقل القاعي على سطح مستو.

ب. أقصى تركيز ممكن للحمل القاعي هو ٧٥٩ غم/لتر على اساس الوزن المغمور وهذا يعادل تركيزا حجميا = ٠ر٤٦ .

٣. أثبتت التجارب المخبرية أن ثابت الاضطراب يقل عن قيمته المعروفة ٤ر٠ ويتناقص مع زيادة مقياس التموجات وأن تأثير الحمل المعلق على ثابت الاضطراب غير مؤكد.

٤. تم وضع معيار لتحديد طرق النقل المختلفة يعتمد على عدد الطبقات للحمل القاعي بافتراض انضغاطها لاقصى تركيز.

٥. بالنسبة للأس الخاص بتوزيع تركيز الحمل المعلق في الاتجاه الرأسي فقد وضعت علاقات بيانية يستطيع من خلالها المهتم حساب قيمته بدقة.

٦. أوضحت النتائج أن قيمة العامل الذي يربط بين معامل نقل المواد الرسوبية ومعامل نقل كمية التحرك يعتمد على متوسط تركيز الحمل المعلق اذا كان التركيز لا يتعدى ١ غم/لتر ثم يصل الى قيمة ثابتة = ٤ر١ بالنسبة لحبيبات الرمل ذات القطر ٣ر٠ مم.

٧. وجد أن تركيز الحمل القاعي وامتداد تركيز الحمل المعلق متساويان عند منتصف سماكة الطبقة القاعية المتحركة، وبهذا تم الربط بين الحمل القاعي والحمل المعلق مما يمكن من حساب الحمل المعلق دون اللجوء لقياس تركيز الحمل المعلق عند نقطة مرجع.

٨. إستنادا الى ما ورد فقد تم وضع طريقة تمكننا من حساب الحمل القاعي الرسوبي والحمل المعلق لايجاد الحمل الكلي الرسوبي بمعرفة متغيرات السريان من عمق وميل وسرعة متوسطة بالاضافة لمعرفة خصائص المواد الرسوبية.

"بسم الله الرحمن الرحيم"

"مدخل ميكانيكي لمعدل الحمل الكلي الرسوبي"

رسالة ماجستير مقدمه من

المهندسة حنان محمد سعيد شعبان المغربي

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