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METHODS OF COMPUTING BEDLOAD FROM DUNE PROFILES

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by

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MANAGEMENT PERSPECTIVE

Measurement of the sediment transported by dune movement in large rivers cannot be obtained with reasonable engineering tolerances by conventional bedload samplers. This report presents two methods of determining bedload which are dedicated to hydrographic survey systems capable of obtaining bed profiles using echo sounders on a rapidly moving boat, the horizontal control of which can be maintained with telemetric slave units on shore or geo-synchronous satellites. The results are used as a basis for the preparation of an ISO Draft International Standard for the computation of bedload. The work was done in collaboration with the Water Survey of Canada Division of the Integrated Monitoring Branch.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Les mesures de sédiments transportés par le mouvement des dunes dans les grands cours d'eau ne peuvent être obtenues avec des tolérances d'ingénierie raisonnables à l'aide d'échantillonneurs ordinaires de charges de fond. Ce rapport présente deux méthodes permettant de déterminer la charge de fond, destinée à des systèmes de relevés hydrographiques capables de produire des profils des lits à l'aide d'écosondeurs montés dans un bateau se déplaçant rapidement, et dont le contrôle horizontal peut être maintenu à l'aide d'unités télémétriques asservies sur la plage, ou de satellites géosynchrones. Les résultats doivent servir de base pour la préparation d'une Norme provisoire internationale ISO pour le calcul des charges de fond. Le travail a été fait en collaboration avec la Division des relevés hydrographiques du Canada de la Direction générale de la surveillance intégrée.

ABSTRACT

Using theoretical and dimensional analysis two methods of measuring bedload in large rivers have been examined. Both methods require the same data gathering procedure in the field and differ only in the way these data are processed. Both methods provide similar results with accuracies of about ±30%. Results have shown that profiling procedures are dependent on the flow conditions in the river. Guidelines for hydrographic surveys have been presented.

RÉSUMÉ

À l'aide de l'analyse théorique et dimensionnelle, deux méthodes de mesure de la charge de fond dans les grands cours d'eau ont été examinées. Ces deux méthodes nécessitent la même méthode de cueillette des données sur le terrain et leur seule différence est la façon de traiter les données. Ces deux méthodes fournissent des résultats semblables avec des exactitudes d'environ ±30%. Les résultats ont montré que les méthodes de préparation des profils dépendent des conditions d'écoulement du cours d'eau. On présente également des lignes directrices pour les relevés hydrographiques.

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INTRODUCTION

The total sediment load in a river is composed of suspended as well as bedload transport. Whereas the suspended load can often be determined with sufficient accuracy by direct measurement, this is not the case for bedload. Although bedload is not normally a major component of the total sediment load, it must nevertheless be taken into consideration when an artificial change such as a diversion, dredging, impoundment or training of a river is contemplated.

Direct methods of bedload measurement such as the use of bedload samplers and tracers are not satisfactory when the bed is composed of migrating dunes. The volume of sediment retained in the samplers is highly variable because it is dependent on the placement of the sampler relative to the longitudinal profile of the dunes. Tracers are susceptible to being buried for long periods of time, thereby resulting in measurements which are sporadic and inconclusive.

Bedload discharge, resulting from the propagation of dunes can, however, be determined by dune tracking. Hydrographic survey systems are available which make it possible to obtain bed profiles using echo sounders on a rapidly moving boat, the horizontal control of which can be maintained with telemetric slave units on shore (Figure 1) or geo-synchronous satellites. Surveys can be made quickly with sufficient precision and when applied at a suitable frequency over a given traverse will provide the necessary spatial and temporal data.

In this report two methods of utilizing the hydrographic data are examined using theoretical and dimensional analysis and existing experimental results presented by Engel and Wiebe (1979), Engel and Lau (1980) and Engel (1981). The results are used as a basis for the preparation of a Draft International Standard (DIS) for the computation of bedload through the ISO Technical Committee 113, Subcommittee 6 (ISO/TC113/SC6). The work was done in collaboration with the Water Survey of Canada Division, Integrated Monitoring Branch.

THE ABSOLUTE DEPARTURE METHOD

During the time in which two successive profile measurements are taken over the same dune track (traverse), there has been a transport of bedload through the downstream migration of the bed forms. It has been shown by Crickmore (1970) and Engel and Lau, 1980) that the volumetric bedload transport at a given point along a bed form can be expressed as

$$q_s = U_w(\eta - \eta_o) \tag{1}$$

where q_s = the volumetric transport rate per unit width at a given point including the voids, U_w = the speed of dune migration, η = the bed elevation at any given point and η_o = the bed elevation of the point of flow reattachment on the back of the dune which is taken to be the point of zero transport (Figure 2). The transport over a full bed form is then given by

$$\bar{q_s} = \frac{U_w}{\Lambda}\int_0^{\Lambda}(\eta - \eta_o)dx \tag{2}$$

which can be written as

$$\bar{q_s} = U_w\overline{(\eta - \eta_o)} \tag{3}$$

where $\bar{q_s}$ = the average volumetric transport rate per unit width over the bed form, Λ = the dune length, x = the abscissa along the bed form and $\overline{(\eta - \eta_o)}$ = the shaded area of the bed form cross-section in Figure 2. The values of η, $\bar{\eta}$ and U_w can be obtained from profile records. However, the value of η_o is not normally known and a means of determining this value must be found before equation (3) can be used. The elevation η_o is some distance above the elevation of the lowest point in the trough on the lee-side of the dunes (Figure 2). This can be expressed by writing

$$\eta_o = \eta_t + \alpha\Delta \tag{4}$$

in which η_t = the elevation of the dune trough, α = a coefficient and Δ = the height of the dunes from trough to crest. Combining equations (3) and (4)

$$\bar{q_s} = U_w\overline{[(\eta - \eta_t) - \alpha\Delta]} \tag{5}$$

If one assumes that dunes are triangular in shape, then

$$\overline{(\eta - \eta_t)} = \frac{1}{2}\Delta \tag{6}$$

Combining equations (5) and (6) and rearranging one obtains

$$\bar{q_s} = U_w\Delta(0.5 - \alpha) \tag{7}$$

A typical river bed profile record consists of a series of dunes and therefore, the average transport rate is computed from average values of U_w and Δ for the whole length of record which can be expressed as

$$\bar{q}_{s\ell} = \bar{U}_w\bar{\Delta}(0.5 - \alpha) \tag{8}$$

where $\bar{q}_{s\ell}$ = the average volumetric transport rate computed from the full profile record, $\bar{U}_w$ = the average migration speed and $\bar{\Delta}$ = the average height of all the dunes in the profile record.

Equation (8) is very simple in form but values of dune heights are difficult to determine. A more convenient parameter is the absolute value of the departure of the bed elevations from the mean level given by

$$\epsilon = \mid \eta - \bar{\eta} \mid \tag{9}$$

where ϵ = the absolute departure of bed elevations about the mean bed elevation and $\bar{\eta}$ = the mean bed elevation. The average value of ϵ is computed from

$$\bar{\epsilon} = \frac{1}{n}\sum_{i=1}^{n} \mid (\eta_i - \bar{\eta}) \mid \tag{10}$$

where n = the number of bed elevations in the record. For triangular bed forms $\bar{\epsilon} = \frac{1}{4}\bar{\Delta}$ and therefore, equation (8) can be written

$$\bar{q}_{s\ell} = 4(0.5 - \alpha)\bar{\epsilon}\bar{U}_w = K\bar{\epsilon}\bar{U}_w \quad (11)$$

Results from measurements of the length of flow separations by Engel (1981) have shown that α is a function of $\frac{D_{50}}{\Delta}$ and $\frac{\Delta}{\Lambda}$ and therefore K can be expressed as

$$K = f\left(\frac{D_{50}}{\Delta}, \frac{\Delta}{\Lambda}\right) \quad (12)$$

where D_{50} = the median diameter of sediment particles and f denotes a function. Equation (12) is plotted with K as a function of $\frac{\Delta}{\Lambda}$ and $\frac{D_{50}}{\Delta}$ as a parameter in Figure 3. The curves show that for values of $\frac{\Delta}{\Lambda} > 0.05$, K is independent of $\frac{D_{50}}{\Delta}$. For $\frac{\Delta}{\Lambda} < 0.05$, $\frac{D_{50}}{\Delta}$ becomes increasingly important as $\frac{\Delta}{\Lambda}$ decreases. For a given value of $\frac{\Delta}{\Lambda} < 0.05$, K increases as $\frac{D_{50}}{\Delta}$ increases. Measurements by Jonys (1973), for a large number of bed forms and a limited range of flow conditions, have shown that $\alpha \approx 0.17$. This would result in a value of $K = 1.32$. Examination of Figure 3 shows that this corresponds to a dune steepness of approximately 0.06. For dunes with $\frac{\Delta}{\Lambda} < 0.06$, $K > 1.32$.

It is more convenient to express the bedload as submerged weight per unit width. This can be accomplished by modifying Equation (11) to give

$$G_{s\ell} = K\gamma_s(1 - p)\bar{\epsilon}\bar{U}_w \quad (13)$$

where $G_{s\ell}$ = the submerged weight per unit width. Data from experiments by Engel and Lau (1980) were compared with results obtained using equation (13) and these are given in Figure 4. The agreement between computed and measured bedload is quite good. The scatter is considered to be due to the uncertainty in the determination of $\bar{\epsilon}$, U_w, α and the measurement of the bedload discharge. This method provides bedload data with an accuracy of about ±30% (Engel and Lau, 1980).

THE VOLUMETRIC METHOD

If one super-imposes two successive profiles, taken a time t apart, on a fixed set of coordinates, then the second profile is displaced with respect to the first, as shown in Figure 5a. At any given point along the super-imposed profiles, one can compute elevation differences δ_η which are positive in the regions of deposition and negative in the regions of scour. For steady state conditions, the average sum of the negative elevation differences should be equal to the sum of the positive elevation differences. The volume of bedload over one dune length is given by either the areas of scour or deposition. This can be readily computed by dividing the shaded areas of deposition into thin slices of width δx and height $\frac{1}{2}(\delta\eta_i + \delta\eta_{i+1}) = \bar{\delta\eta}_i$, in which i = the ith point in the profile. The volume of bedload per unit width, including the voids, for one dune is then given by

$$V = \delta x \sum_{i=1}^{n_1} |\ \bar{\delta\eta}_i\ | \quad (14)$$

where n_1 = the number of slices in one dune length. Since successive profiles were taken a time t apart, then the transport rate $q_s(t)$ per unit width at time t can be expressed as

$$q_s(t) = \frac{\delta x}{t}\sum_{i=1}^{n_1} \mid \bar{\delta\eta_i} \mid \tag{15}$$

where $q_s(t)$ = the volume transport rate per unit width. Theoretically, if the dune profiles consists of identical dunes, one needs to look at only one dune. However, in practice there is considerable variability in dune shapes along the profile. Equation (15) is therefore applied to a series of m dunes and then divided by m to give

$$q_s(t) = \frac{1}{m}\frac{\delta x}{t}\sum_{i=1}^{n} \mid \bar{\delta\eta_i} \mid \tag{16}$$

where m = the number of dunes in the bed profile and n = the total number of slices in the total bed profile. Once again it is more convenient to use the submerged weight per unit width and thus equation (16) can be modified to give

$$G_s(t) = \frac{\gamma_s(1-p)}{m}\frac{\delta x}{t}\sum_{i=1}^{n} \mid \bar{\delta\eta_i} \mid \tag{17}$$

Equation (17) provides the bedload transport rate only at a single time t. In order to obtain the average transport rate, the distribution of $G_s(t)$ must be known. The analytical considerations can be simplified by considering idealized triangular dune shapes (Engel and Wiebe, 1979). Two successive profiles extending over two dunes are shown in Figure 5b. Considering the area ABED, the volume of sediment per unit width may be expressed as

$$V = \ell\Delta - \frac{\ell^2\Delta}{\Lambda} \tag{18}$$

where ℓ = the relative longitudinal displacement (lag) between successive profiles in time t. The volume transport rate can be computed from the quotient $\frac{V}{t}$ which can be written as

$$q_s(t) = \frac{\ell\Delta}{t} - \frac{\ell^2\Delta}{\Lambda t} \tag{19}$$

Introducing the dune migration speed $U_w = \frac{\ell}{t}$ and a time scale $t_* = \frac{\Lambda}{U_w}$, which is the required time for one complete bed form to pass a given point, equation (19) can be non-dimensionalized to give

$$\frac{q_s(t)}{\Delta U_w} = (1 - \frac{t}{t_*}) \tag{20}$$

Equation (20) shows that, for a given dune geometry and migration speed, $q_s(t)$ is a linear function of t as shown in Figure 6. The average value of $q_s(t)$ would then occur at $\frac{t}{t_*} = 0.5$ which results in

$$\bar{q_s} = \frac{1}{2}\Delta U_w \tag{21}$$

where $\bar{q}_s$ = the average bedload transport. Comparison of equations (7) and (21) shows that both result in the same transport rate if $\alpha = 0$. If it is accepted that $\alpha > 0$ is valid, then the bedload transport in equation (21) needs to be corrected by a coefficient given by

$$K_\alpha = \frac{(0.5 - \alpha)}{0.5} \tag{22}$$

where K_α is a dimensionless coefficient in which α is also a function of $\frac{D_{50}}{\Delta}$ and $\frac{\Delta}{\Lambda}$ as shown in Figure 7 based on data from Engel (1981).

It can be seen from Figure 6 that, for a given Δ and U_w, if one has a measurement of $q_s(t)$, or equivalently $G_s(t)$ at some time interval $0 \le \frac{t}{t_*} \le 1.0$, the average value of the bedload discharge during the passing of a dune, can be calculated by utilizing the triangular shape of the bedload distribution. A typical plot of $G_s(t)$ as a function of $\frac{t}{t_*}$ is shown schematically in Figure 8. $G_s(t)$ is computed for a particular value of $\frac{t}{t_*} < 0.5$ and plotted as $G_s(t)$ versus $\frac{t}{t_*}$. The coefficient K_α is implicitly included in the measurement of $G_s(t)$. The bedload discharge distribution can then be constructed by drawing a straight line through the plotted point, intersecting the $\frac{t}{t_*}$ axis at $\frac{t}{t_*} = 1.0$ and extending the line to intersect the $G_s(t)$ axis at $\frac{t}{t_*} = 0$. The average bedload discharge per unit width is then the value of $G_s(t)$ at $\frac{t}{t_*} = 0.5$ which can be computed from the relationship

$$\bar{G}_s = \frac{G_s(t_1)}{1 - \frac{2t_1}{t_*}} \tag{23}$$

where $\bar{G}_s$ = the average submerged weight per unit weight of bedload.

Data from experiments by Engel and Wiebe (1979), compared with results obtained using equation (23), are given in Figure 9. The agreement between computed and measured bedload is similar to that obtained in Figure 4. The scatter is considered to be due to the uncertainty in the determination of $\bar{\delta\eta}_i$ and the measurement of the bedload discharge. Accuracies obtainable with this method is about ±30% (Engel and Wiebe, 1979).

DETERMINATION OF DUNE MIGRATION SPEED

The rate of profiling from a moving boat is much faster than the rate of bed form propagation downstream and therefore, each point on a bed profile may be considered to be an instantaneous record of the stream bed taken at some time t_j. As a result, the time interval between successive profiles can be expressed as

$$t_\ell = t_{j+1} - t_j \tag{24}$$

where t_ℓ = the elapsed average time between the measurement of two successive bed profiles on the same traverse line, t_{j+1} = the starting time for the measurement of the $(j+1)$th profile and t_j = the starting time for the measurement of the jth profile. The time increment t_ℓ must be chosen so that the advancement of the bed forms during this period is not large enough to permit sufficient profile shape distortion, thereby preventing an adequate measurement of dune displacement. Alternatively, t_ℓ must not be so short as to render too small a bed form displacement for reasonable measurement.

When the jth and $(j+1)$th profile, referenced to a common reference axis, are superimposed there is a relative, downstream displacement of the $(j+1)$th profile with respect to the jth profile.

Because of the irregularity of the dune shapes, it is difficult and impractical to determine such profile displacements by visual inspection. The most direct method to compute the average profile displacement is cross-correlation between two successive profiles. The $(j+1)$th profile is displaced along the abscissa of the reference axis towards its original position in small increments of the total displacement. For each such displacement, the cross-correlation coefficient is computed according to the relationship

$$R(\ell) = \frac{1}{n-2}\sum_{i=1}^{n} \eta(x_i)_j \eta(x_i+\ell)_{j+1} \tag{25}$$

where $R(\ell)$ = the cross-correlation coefficient at spatial lag ℓ between the $(j+1)$th and jth profile and n = the number of data points. The value of ℓ which provides the largest value of $R(\ell)$ is taken as the average spatial lag between the two the bed forms. The average dune migration speed is then simply computed from the relationship

$$\bar{U}_w = \frac{\bar{\ell}}{t_\ell} \tag{26}$$

where $\bar{\ell}$ = the average spatial lag between the two successive profiles.

TRAVERSING RETURN PERIOD

The effectiveness of the two methods of computing the bed load depends on how much time can pass before the bed profiles become too much distorted to yield data with sufficient precision to compute $\sum \bar{\delta} n_i$ and $\bar{U}_w$. Therefore survey methods are restricted by the maximum permissible value of t_ℓ which may be termed the return period t_r. This means that the survey of each traverse must be repeated in a time $t_\ell \leq t_r$. This time limit influences the number of dune tracks or traverses in a grid that can be surveyed repeatedly to obtain the required spatial and temporal data.

The number of traverses depends on the length of each traverse, the distance between adjacent traverses, the speed of the survey vessel upstream, downstream and across from one traverse to the next. The total distance traveled by the survey boat over N traverses is $L_t + 2(N-1)L_t$ where L_t = the length of each traverse in the survey grid and N = the number of traverses in the grid. If one considers a traversing speed of V_t, taken as the average speed of the survey boat upstream and downstream, the total traversing time can be given as

$$t_t = \frac{(2N-1)L_t}{V_t} \tag{27}$$

In addition to the traveling times along the traversing lines there is the time required to position the boat at the beginning of each new traverse line. Taking this time to be t_p, then the return period t_r is given by

$$t_r = \frac{(2N-1)L_t}{V_t} + t_p \tag{28}$$

The return period should be less than the time t_* for a complete dune length to pass a given point along the traverse. This can be expressed by writing

$$t_r = K_t t_* \tag{29}$$

in which K_t = a coefficient with a value less than 1.0.

The coefficient K_t can be formulated using dimensional analysis by noting that

$$\frac{U_w}{u_*} = f_w(X, Y, Z) \tag{30}$$

and

$$\frac{\Lambda}{D_{50}} = f_\Lambda(X, Y, Z) \tag{31}$$

in which $X = \frac{u_* D_{50}}{\nu}$, $Y = \frac{\rho u_*^2}{\gamma_s D_{50}}$, $Z = \frac{h}{D_{50}}$, u_* = the shear velocity, h = the flow depth, ρ = the density of the fluid, ν = the kinematic viscosity of the fluid, γ_s = the submerged unit weight of the sediment and f_w and f_Λ denote dimensionless functions. It has been shown that $t_* = \frac{\Lambda}{U_w}$ and therefore, dividing equation (30) into equation (31) results in

$$\frac{t_* u_*}{D_{50}} = f_t(X, Y, Z) \tag{32}$$

where f_t denotes another dimensionless function. It can be argued further that the return period can be expressed as

$$\frac{t_r u_*}{D_{50}} = f_r(X, Y, Z) \tag{33}$$

where f_r is another dimensionless function. Combining equations (32) and (33) results in

$$\frac{t_r}{t_*} = K_t = f_K(X, Y, Z) \tag{34}$$

where f_K = another dimensionless function.

Engel (1978) conducted a series of experiments in a large sediment flume. For each particular flow condition a series of bed profiles were recorded sequentially along the centre-line of the flume a time t_ℓ apart. In each case, profiles were taken in pairs, using profiles 1&2, 1&3...1&N etc, to compute the maximum cross-correlation coefficient $R(\ell)$ in accordance with equation (25) designated as R_{max}. The magnitude of R_{max}, is indicative of the amount of distortion the dunes have undergone during their movement downstream in the time elapsed between the taking of two successive profiles. If the bedforms were to remain completely in tact, then $R_{max} = 1.0$. Normally, $R_{max} < 1.0$ depending on the length of the time interval $0 < t_\ell < t_r$ between each pair of profiles. Values of R_{max} are plotted as a function of $\frac{t_r}{t_*}$ in Figure 10 for four different values of Y. The plot clearly shows that R_{max} decreases as $\frac{t_r}{t_*}$ increases. The results also show that, for a given value of R_{max}, the relative return period $\frac{t_r}{t_*}$ does not depend significantly on the flow intensity given by the mobility number Y over the the range of flow conditions tested. The experimental results indicate that $K_t \leq 0.5$ but are not comprehensive enough to draw general conclusions. Therefore, for each bedload measurement, the value of K_t must be determined on site.

CONCLUSIONS

Using theoretical and dimensional analysis two methods of measuring bedload in large rivers have been examined and the following conclusions obtained:

Both methods require the same data gathering procedure in the field and differ only in the way these data are analyzed. Both methods provide similar results with accuracies of about ±30%.

The bedload transport takes place above a plane passing through the point of flow reattachment on the back of the dunes. This position has been found to depend the bedform steepness $\frac{\Delta}{\Lambda}$ and the relative sediment size $\frac{D_{50}}{\Delta}$.

The accuracy of the bedload determination depends on the frequency with which the same profiles are measured. The maximum time interval t_r between measurement of the same profile (return period) should be such that $\frac{t_r}{t_*} \leq 0.5$.

The return period should be expected to be dependent on the relative depth Z but appears to be independent of the flow intensity represented by the mobility number Y.

The value of the return period coefficient K_t must be determined on site.

ACKNOWLEDGEMENT

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APPENDIX II. NOTATION

The following symbols are used in this paper

D_{50} = the median sand grain diameter;
f = a function;
$G_s(t)$ = the submerged unit weight per unit width at time t;
$G_{s\ell}$ = the submerged weight of the bedload for the full profile record;
$\bar{G}_s$ = the average submerged weight per unit width of bedload;
h = depth of flow;
i = a counter;
j = a counter;
K = a coefficient;
K_α = a coefficient;
K_t = a coefficient;
ℓ = the spatial lag between two successive profiles on the same traverse;
$\bar{\ell}$ = the average spatial lag between two successive profiles on the same traverse;
L_t = the length of each traverse line in a survey grid;
m = the number of dunes a bed profile;
N = the number of traverse lines in a survey grid;
n_1 = the number of positive values of $\bar{\delta}_i$ for a single dune;
p = porosity of the sediment;
$q_s(t)$ = the volumetric transport rate per unit width at time t;
q_s = the volumetric transport rate per unit width at a point including the voids;
$\bar{q}_s$ = the average volumetric transport rate per unit width over the a single dune;
$\bar{q}_{s\ell}$ = the average volumetric transport rate per unit width from the full profile record;
$R(\ell)$ = the cross correlation coefficient at lag ℓ;
t = time between two successive surveys of the same traverse;
t_* = the time for a complete dune to pass a given point;
t_t = the total time spent in traveling along N traverse lines;
t_r = the return period;
t_p the total time required to position the boat for N traverse lines;
t_ℓ = the elapsed average time between two successive profiles on the same traverse line;
U_w = the speed of dune migration;
$\bar{U}_w$ = the average dune speed;
u_* = the shear velocity.
V_t = the average velocity boat velocity along a traverse line;
V = the volume per unit width including the voids of the sediment;
x = the abscissa along the bed profile;

α = a coefficient;
γ_s = the submerged unit weight of the sediment;
Δ = the height of a dune from trough to crest;
$\bar{\Delta}$ = the average dune height from a full profile record;
δx = a fixed interval of x;
$\delta\eta_i$ = ith difference $(\eta_i - \eta_t)$;
$\bar{\epsilon}$ = the average absolute departure of bed elevations about the mean bed elevation;

ϵ = the absolute departure about the mean bed elevation;
η = the bed elevation at any given point;
η_o = the bed elevation at the point of flow reattachment on the back of a dune;
η_t = the elevation of the lowest point in the dune trough;
$\bar{\eta}$ = the mean bed elevation;
η_i = the ith bed elevation;
Λ = the dune length from crest to crest;

$X = \frac{u_* D_{50}}{\nu}$;
$Y = \frac{\rho u_*^2}{\gamma_s D_{50}}$;
$Z = \frac{h}{D_{50}}$;

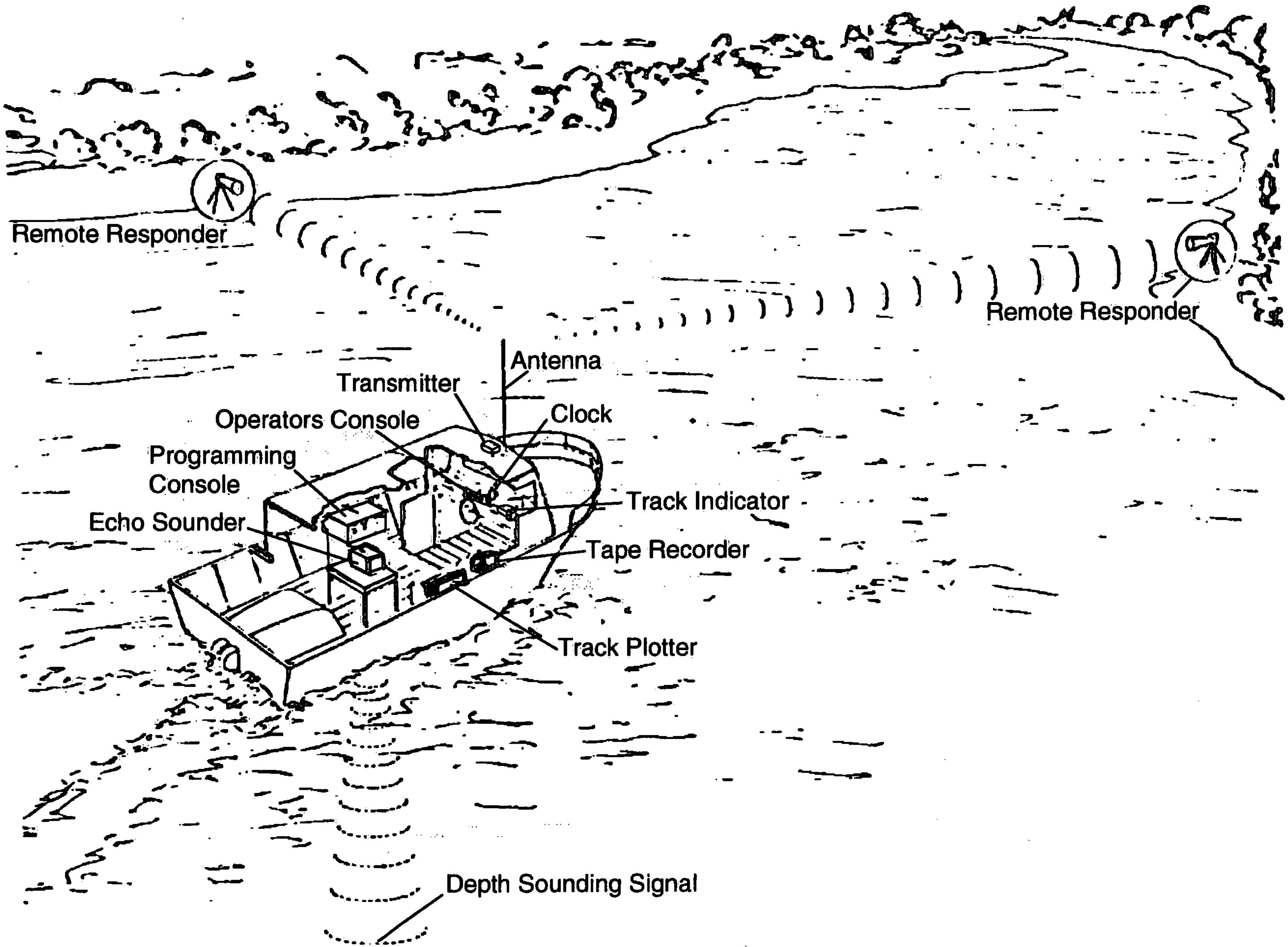

FIGURE 1 DATA COLLECTING HYDROGRAPHIC SURVEY BOAT

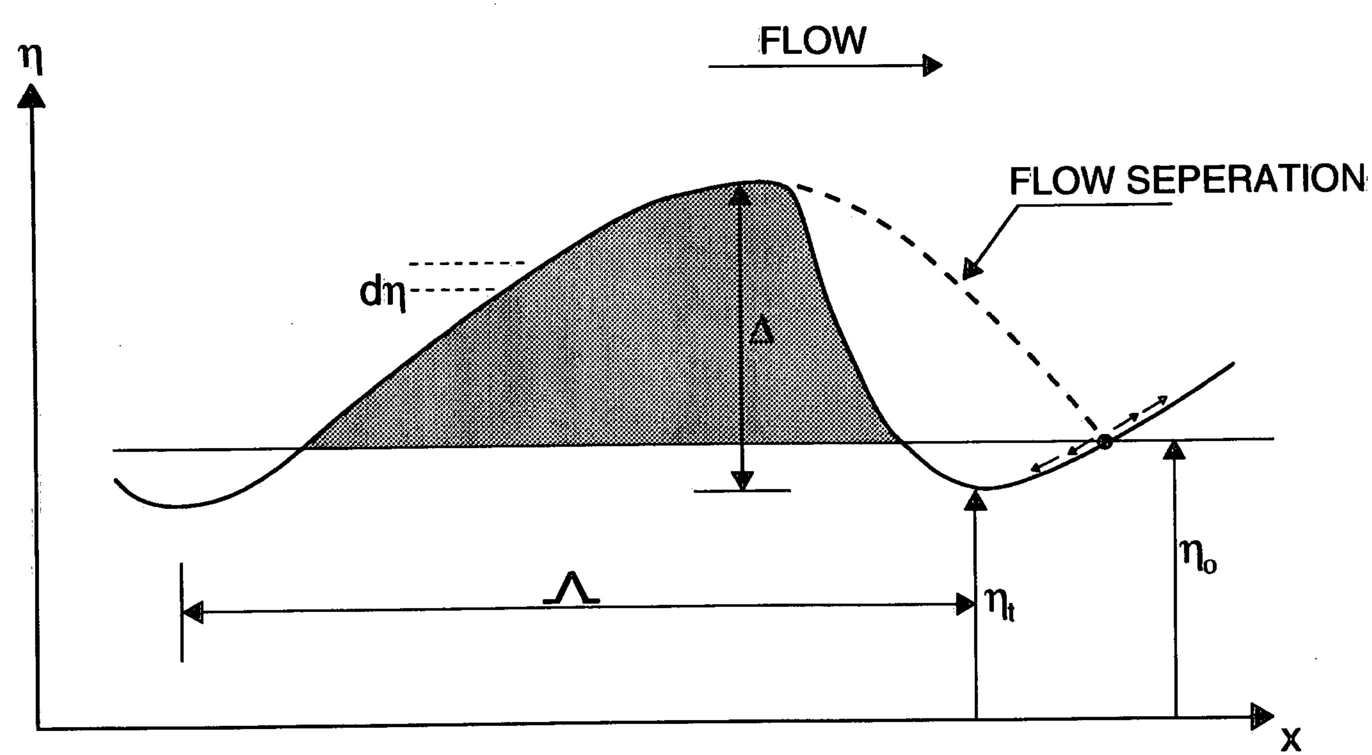

FIGURE 2 DUNE PROFILE DEFINITION SKETCH

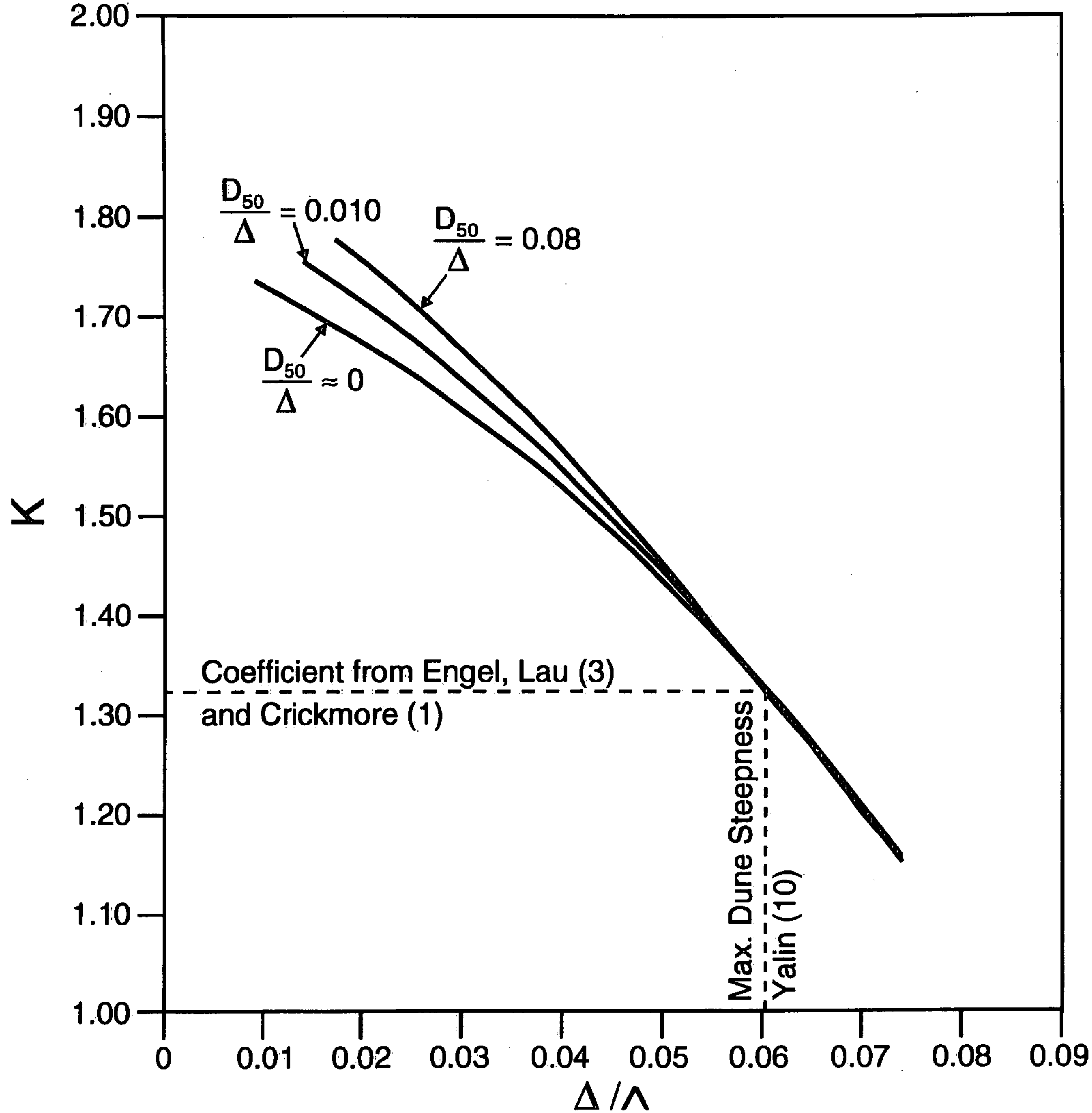

FIGURE 3 BED LOAD DISCHARGE COEFFICIENT

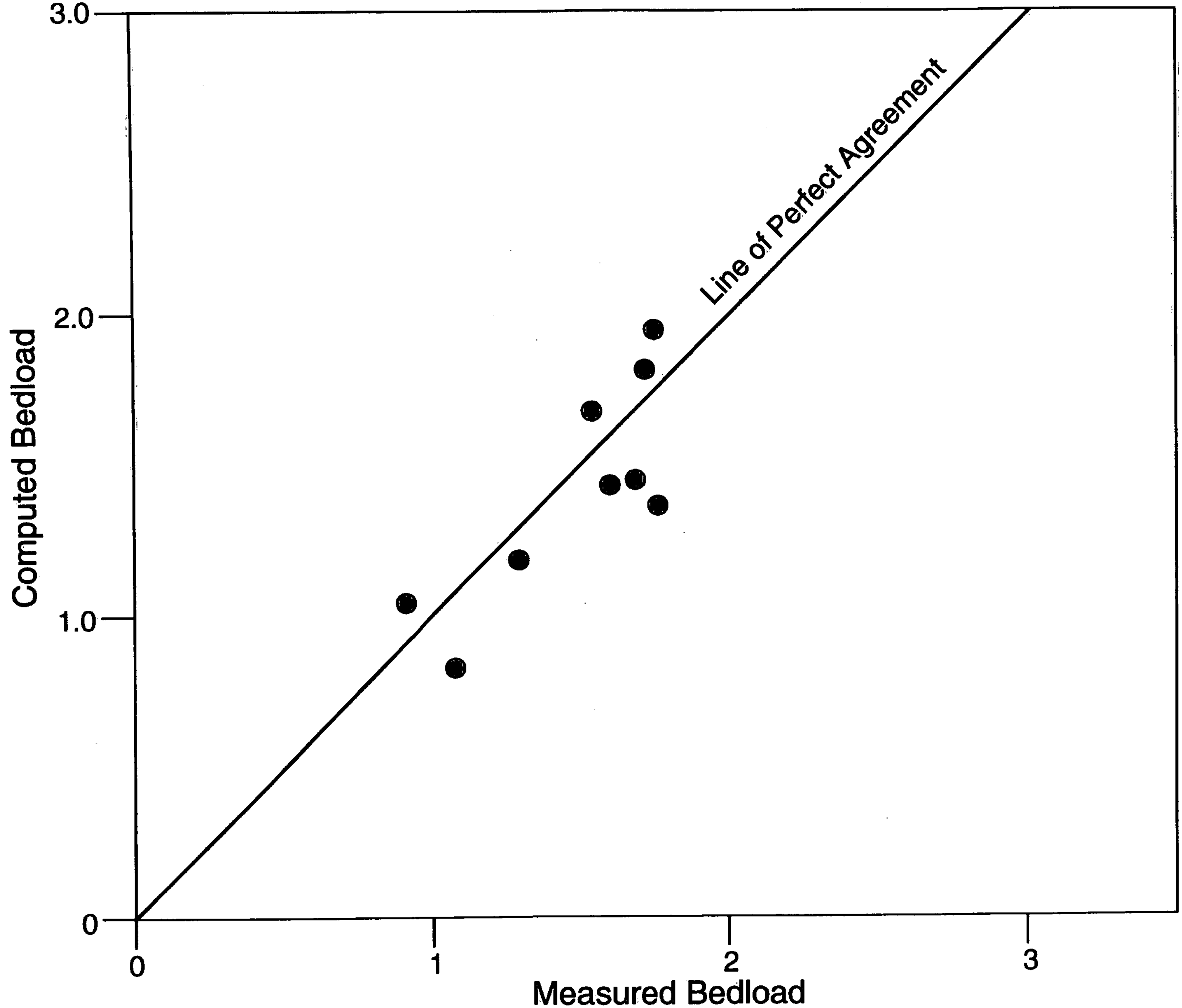

FIGURE 4 COMPARISON OF COMPUTED AND MEASURED BEDLOAD

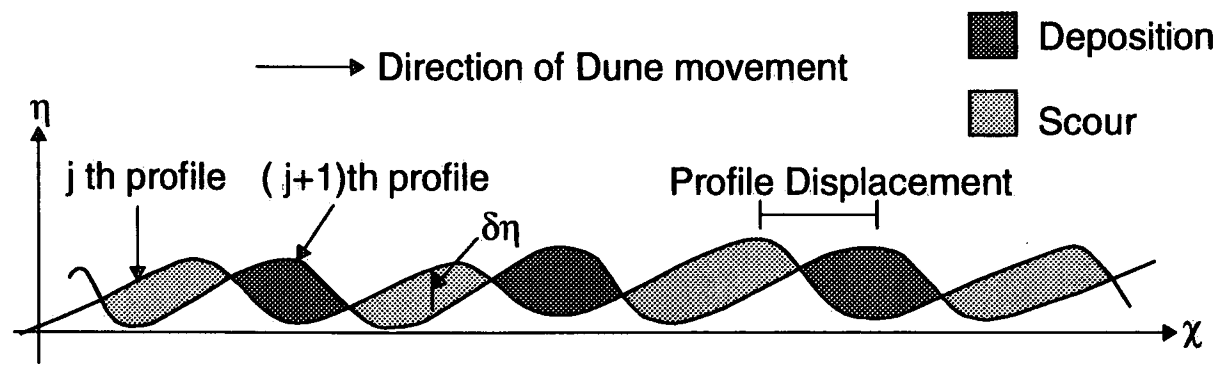

FIGURE 5a TWO DUNE PROFILES A TIME "t" APART SUPER IMPOSED

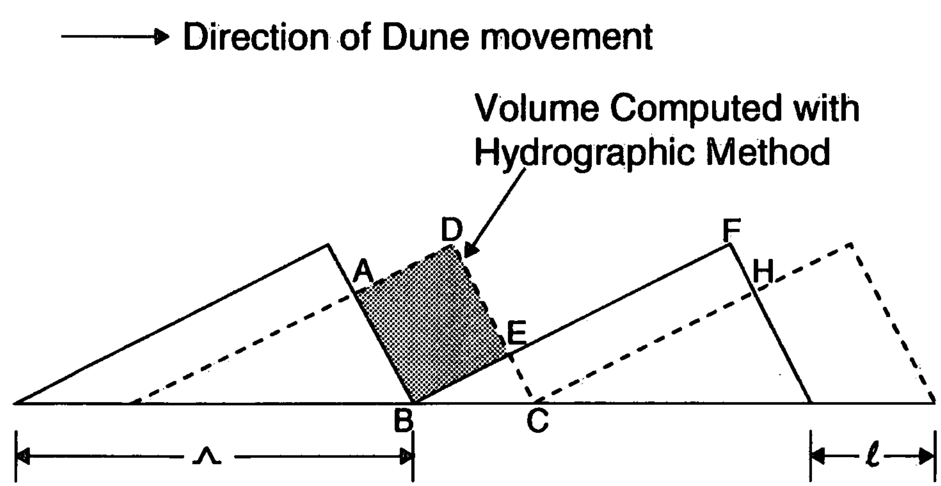

FIGURE 5b TWO IDEALIZED TRANGULAR PROFILES A TIME "t" APART SUPER IMPOSED

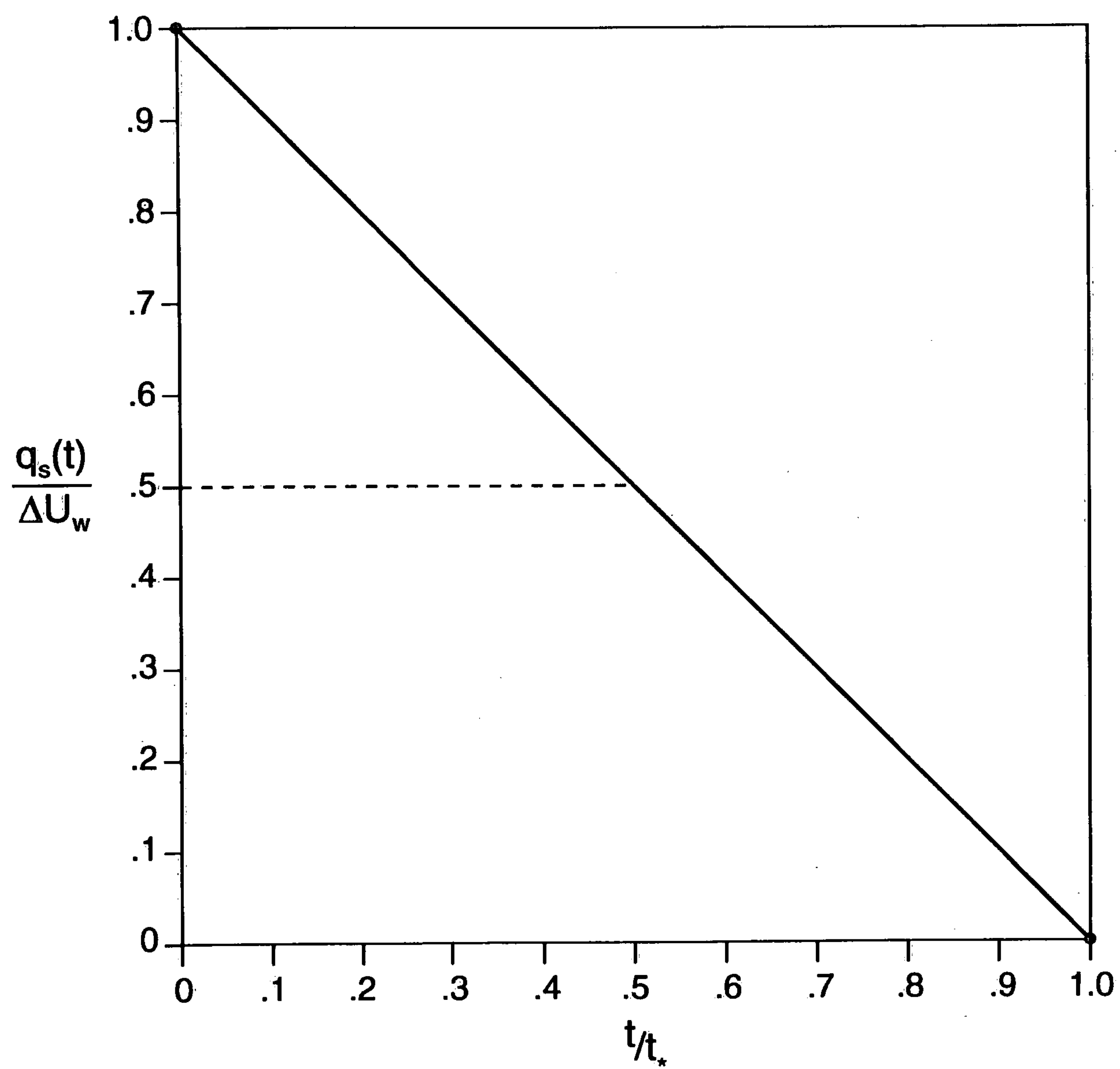

FIGURE 6 BED LOAD DISCHARGE DISTRIBUTION

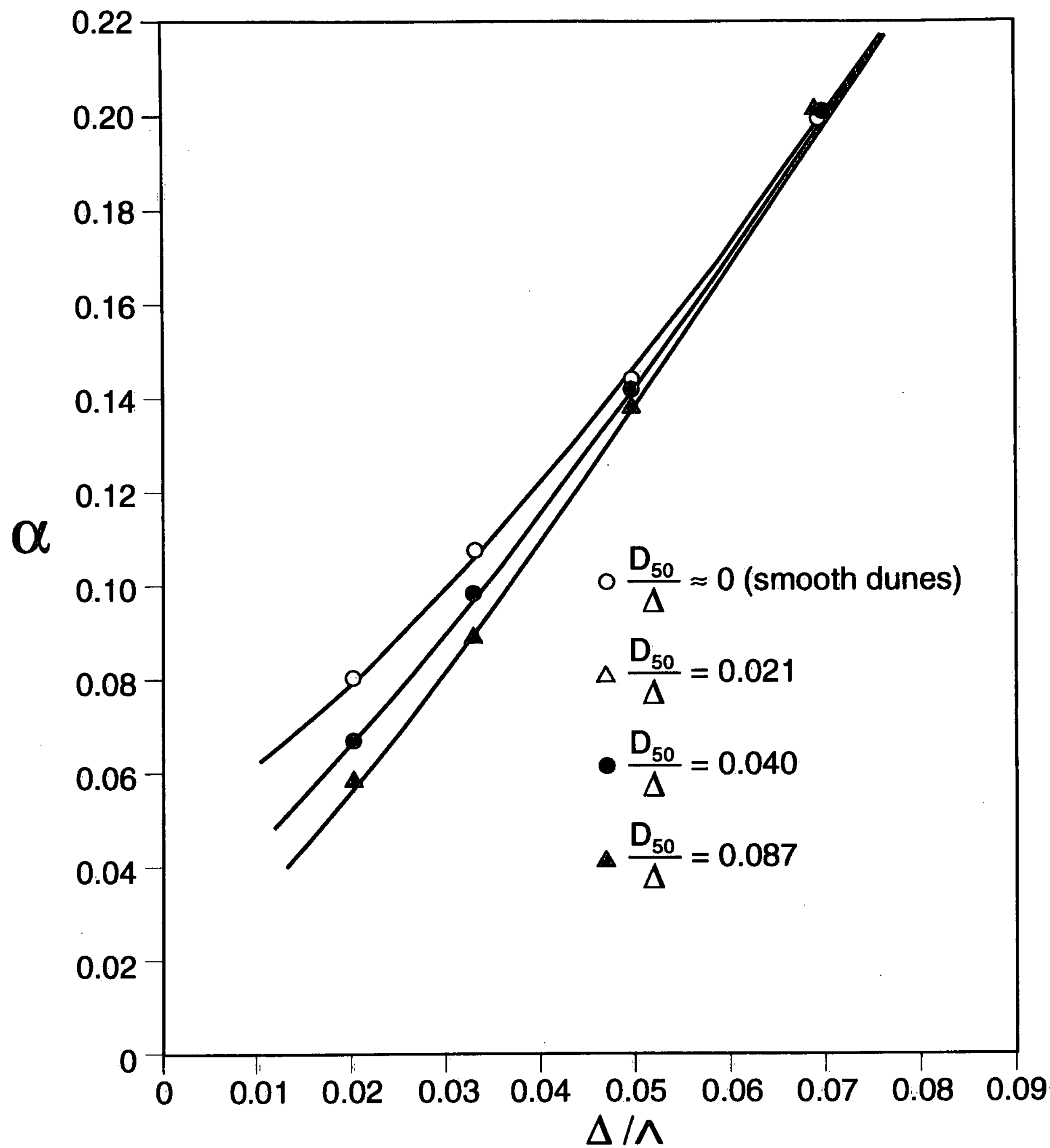

FIGURE 7 VARIATION OF α WITH DUNE STEEPNESS

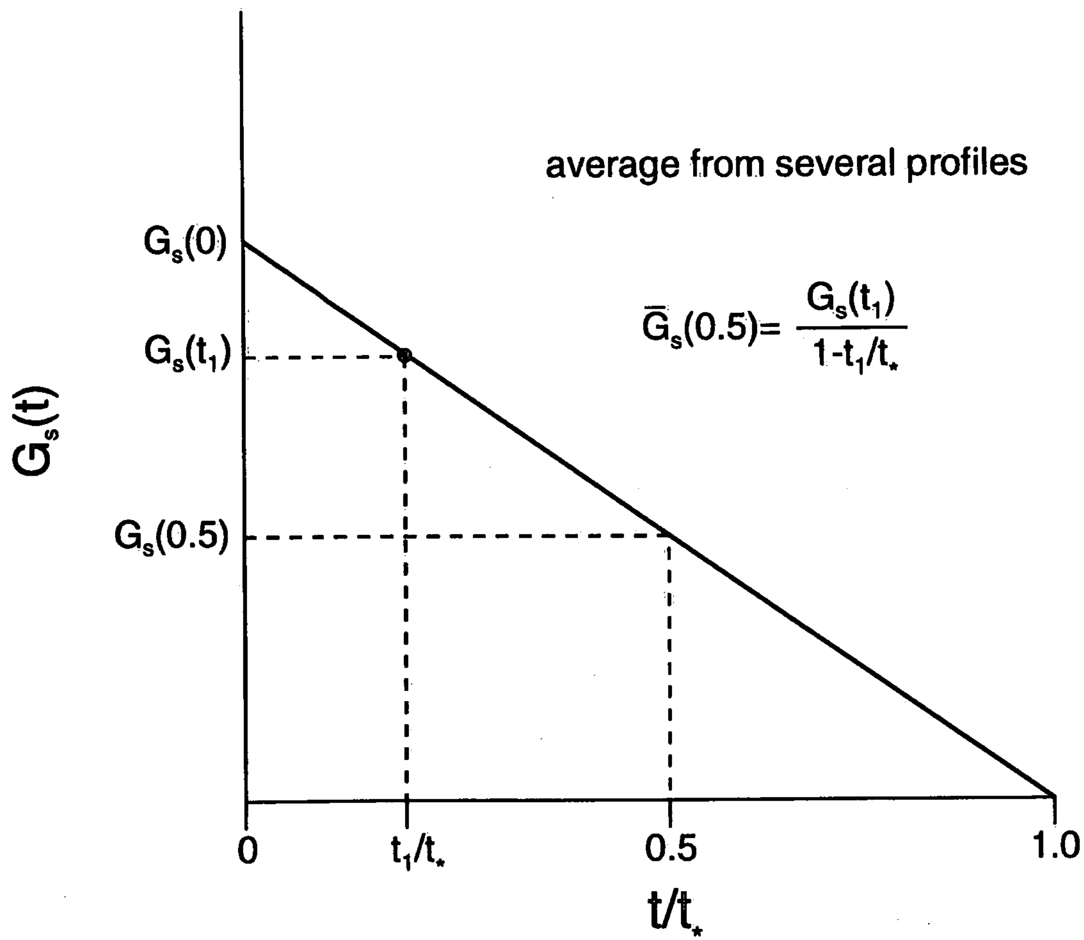

FIGURE 8 DISTRIBUTION USING ONE AVERAGE VALUE OF $G_s(t)$ vs. t/t_*

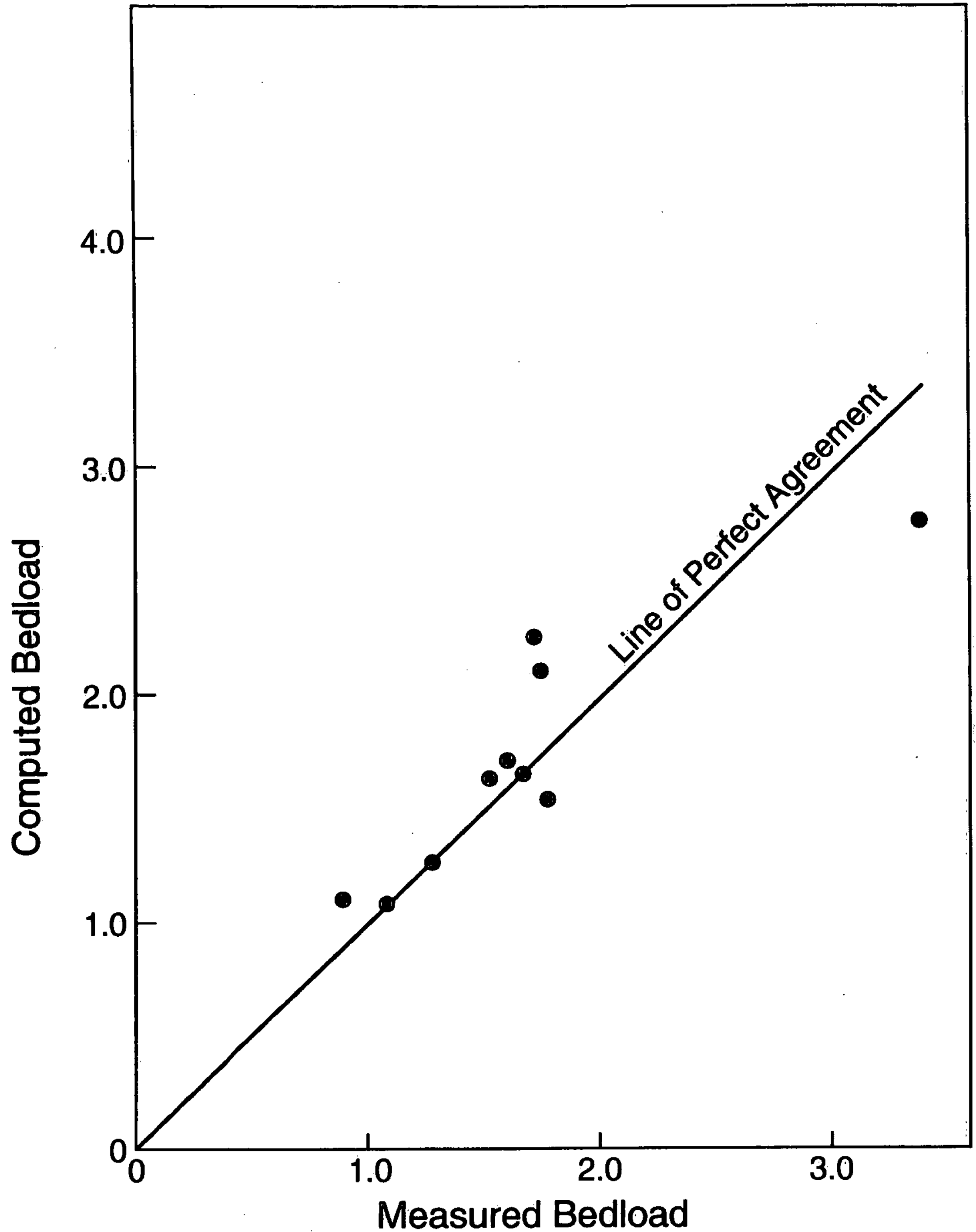

FIGURE 9 COMPARISON OF COMPUTED AND MEASURED BEDLOAD FOR VOLUMETRIC METHOD

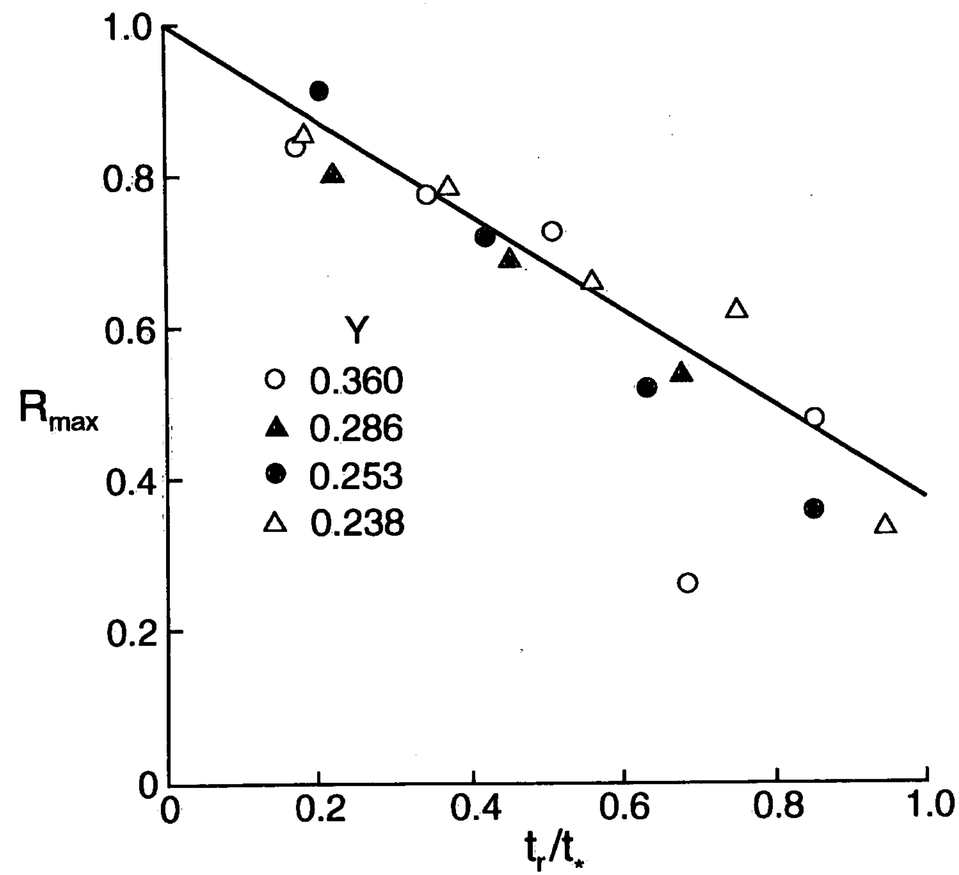

FIGURE 10 VARIATION OF Rmax WITH RELATIVE RETURN PERIOD

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