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HYDRAULIC RESISTANCE OF GRASS MEDIA ON SHALLOW OVERLAND FLOW

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ABSTRACT

Simulated dense vegetation with random blade arrangements and different blade flexibilities were used to determine the hydraulic properties of flow of small, non-submerging depths. With the water flowing among the randomly patterned vegetation blades, drag resistance becomes the dominant force that retards the flow. An equation of flow was established based on the momentum balance in the system. Experimental results were used to determine the coefficient of blade resistance, R_D, and plotted in terms of blade width and flow depth Reynolds number respectively.

Descriptors: Grass Waterways, Hydraulic Resistance, Drag, Flow Properties

Indentifiers: Grass Waterways, Turbulent Flow Hydraulics

HYDRAULIC RESISTANCE OF GRASS MEDIA ON SHALLOW OVERLAND FLOW

I. INTRODUCTION

The effects of vegetation on the flow characteristics of water through open channels has long been of interest to hydraulicians. The presence of vegetation in open channels acts to retard the flow of water by causing a loss of energy through turbulence. Various flow models have been employed to estimate and explain this type of hydraulic resistance. Due to the variety of conditions which may be present with flow through vegetation, much of the work has been empirical in nature. The combination of large flow depth variation over various kinds of vegetation adds to the problem of estimating hydraulic resistance in vegetation covered open channels. The depth of flow is to a large extent dependent on the density, height and flexibility of the vegetative elements. This report will explain the hydraulic resistance of vegetative in terms of the drag upon the individual elements and will attempt to advance the concepts of various other researchers in this area.

Review of Related Research

There are two major formulas for computing discharge in open channels as it relates to the resistance factor of the channel. The first was developed by Chezy in 1775:

$$V = C(RS)^{1/2} \quad (1)$$

where:

V = velocity of flow,

S = slope of channel,

R = hydraulic radius of the channel, and

C = coefficient of roughness.

One of the most widely used empirical equations, especially in the United States, relating the mean channel velocity to hydraulic resistance and other parameters of the channel is known as Manning's Formula:

$$V = \frac{(1.486)}{n} (R^{2/3}) \ (S_e^{1/2}) \quad \text{for British Technical Units} \qquad (2)$$

or:

$$V = \frac{1}{n} (R^{2/3}) \ (S_e^{1/2}) \qquad \text{for SI Units} \qquad (3)$$

where:

V = mean flow velocity in channel, LT^{-1};

S_e = slope of energy line;

R = hydraulic radius, L; and

n = Manning's roughness term, $L^{1/6}$.

For fixed boundary streams as well as most alluvial channels, the value of Manning's roughness term can be selected from established tables and charts. Ree and Palmer (1) have presented Manning's 'n' value for many types of vegetative channel linings. They found that when vegetation is submerged, values of 'n' vary with the product of average velocity, V, and hydraulic radius, R, and generally decrease as flow depth increases. When flow is such that the vegetation is non-submerged the value of 'n' was found to increase with depth but no relation is believed to exist between 'n' and 'VR'.

A number of studies have attempted to determine the retardance of flow for different artificial roughness elements. Sayne (2), in an effort to establish roughness standards for wide, open channels, discussed the results of early experiments by Kenlegan, Nikuradse and Einstein. This approach, however, was found inadequate when describing certain other types of roughness, especially where the important boundary characteristics were relative spacings in addition to relative size of the roughness elements. Rowobari, Rice and Garton (3) sought to determine the relationship of Manning's resistance coefficient, n, to size of rough elements, pattern of arrangement, density of spacing, slope, and discharge in a smooth artificial channel using dimensional analysis and gradually varied flow. Round aluminum pegs served as roughness elements. They found that an increase in either density or size of roughness elements increased the resistance coefficient. However, they concluded that sufficient data was not available to present conclusive results on the individual effects of size and density because not enough roughness elements were studied.

Einstein and Bank (4) studied the effect of composite roughness in a channel using concrete blocks and pegs. They proposed that the shear resistance contributed by dissimilar sources of roughness, $\tau_o = \tau_s + \tau_r$ with its magnitude proportional to the mean flow velocity square. Using rigid wires to simulate vegetative cover Fenzl and Davis (5) tried to explain resistance in in terms of soil roughness, τ_r. Based upon the assumption proposed by Einstein and Bank, they established a dimensionless equation to describe the total resistance to flow per unit area of bed with:

$$\tau_o = f_1 \rho V^2 + f_2 \left(\frac{Vb}{\nu}, \frac{V^2h^4}{J}, \frac{y_n}{h}, \frac{b}{h}, \beta\right) Nbh\rho V^2, \qquad (4)$$

with:

ρ = density of fluid, FT^2L^{-4};

V = mean velocity, LT^{-1};

$f_1, f_2, \ldots f_i$ = a function;

b = diameter of wires, L;

ν = kinematic viscosity of fluid, L^2T^{-1}

h = height of elements, L;

y_n = normal depth of water, L;

β = parameters of profile shape of plant unit;

J = measure of flexible rigidity, L^6T^{-2}; and

N = number of elements.

If isolated roughness flow is present Fenzl and Davis defined the function f_2 as a drag coefficient, C_d. Under such a condition the resistance varies directly as the density of the vegetation.

Through their experimental work they found that the assumption of $\tau_o = \tau_s + \tau_r$ is a valid one. They further concluded:

1. For very small depths of flow ($y \leq y_1 \leq h$) in a channel with vegetative roughness elements of height, h, soil roughness is the predominant source of hydraulic resis-

tance. Under these conditions, resistance decreases with increasing depth of flow.

2. At some greater depth of flow ($y_2 \leq y_1 \leq h$), resistance becomes essentially independent of small changes in soil roughness and increases with increasing depth of flow.

3. There is a range in depth of flow ($y_1 \leq y \leq y_2$), within which resistance is influenced by both soil and vegetation roughness. The values of y_1 and y_2 are dependent on the nature of the soil roughness, the population density of the vegetation elements, and the velocity of flow. Other important factors may be shape and rigidity of vegetation.

Fenzl (6) represented a drag coefficient, C_d, which varied with Reynold's number and relative depth of flow as:

$$C_d = f_3 \left(\frac{Vb\rho}{\mu}, \frac{R''}{b}\right) = \frac{(\tau_o - \tau_r)}{NbR''\rho V^2/2} \qquad (5)$$

with R" = hydraulic radius of bed and wires, L.

He noticed in his experimental work that as water depth increases, the relationship between the drag coefficient of the wires and relative depth, h/R", was logarithmic. Further he found that when the wires were partially submerged ($h/R'' \leq 1.0$), the hydraulic resistance varied directly with the depth of flow with other factors being held constant. For totally submerged flow, the drag coefficient of the wires varied inversely with the relative depth, apparently as a logrithmic function of h/R", for h/R" < 0.8, and a power function for h/R" > 0.8.

In his experiments on alfalfa Fenzl found the following:

1. The resistance caused by the soil decreased rapidly with depth of flow in proportion to the resistance of the grass alone.
2. For the long-cut alfalfa resistance was found to vary primarily with depth of flow and the shape of the plants.
3. A drag coefficient calculated for the clipped grass was found to vary with the relative submergence of the plants.

To limit the scope of the solution Fenzl considered only subcritical flow and found that the resistance parameter, $\tau_o/\rho V^2$, to be dependent on no less than four dimensionless ratios, namely: the measure of the relative roughness of the soil, k_s/y; the relative submergence of the vegetation, h/y; measure of the plant form; and Reynold's number $Vb\rho/\mu$. With reference to his work Fenzl concluded that it is possible to develop prediction equations for hydraulic resistance in terms of parameters which are measures of the physical characteristics of the flow system.

Looking at velocity profiles Kouwen (7) indicated that flow field should be separated into two areas: the flow outside the vegetation cover and flow inside it. He further indicated that a logarithmic profile was suitable to describe flow outside vegetation. Mathematically this velocity profile, U(y), can be expressed as:

$$\frac{U(y)}{U_*} = \frac{1}{\kappa} \ln \frac{y}{y'} \qquad (6)$$

where:

κ = Von Karman's turbulence coefficient;

y'= intercept on y axis where U(y) = 0, L; and

y = distance from channel bed.

Rouse (8) indicated that y' is probably dependent on:

$$y' = f_4\left(\frac{\nu}{\sqrt{\tau_o/\rho}}, h\right) \tag{7}$$

with ν being the kinematic viscosity of fluid.

Since the shear velocity, U_*, equals $\sqrt{\tau_o/\rho}$ Kouwen expressed $U(y)/U_*$ as the dimensionless function:

$$\frac{U(y)}{U_*} = f_5\left(\frac{h}{(EI/U_*^{\,2})^{1/4}}, h/y_n\right) \tag{8}$$

where:

E = modulus of elasticity of material making up roughness element, FL^{-2}; and

I = second moment of area of its corss section, L^4.

Kouwen referred to the ratio y_n/h as the relative roughness and considered it to be a pertinent parameter in the evaluation of the retardance coefficient. He further indicated that 'n' is primarily a function of the relative roughness and that n vs. VR is not satisfactory for artificial grasses.

From the two regions of flow Kouwen and Unny (7, 9) arrived at the expression:

$$\frac{U(y)}{U_*} = C_1 + C_2 \ln y_n/h \tag{9}$$

They also approximated the relative roughness term by A/A_b with

A and A_b being the total flow area and the area blocked by the vegetation respectively. The final equation took the form:

$$\frac{U(y)}{U_*} = C_1 + C_2 \ln A/A_b \qquad (10)$$

They found that the constant C_1 was dependent on the density of the vegetation and considered the constant C_2 to be a function of vegetation stiffness.

Phelps (10), working with a turf surface, looked at hydraulic resistance in terms of Darcy's roughness coefficient f. Izzard (11, 12) has concluded that f varied inversely with the Reynold's number, Re. Izzard also found that for steep slopes and Reynold's number, Re, between 200 and 2,000 the relationship between f and Re could be represented in form:

$$f \cdot Re = \text{constant}$$

Phelps using dimensionless analysis arrived at this dimensionless equation:

$$f = f_6(y_n/d;\ Re)$$

with d = nominal length dimension representing size of flow passage, L.

Based on his belief that (f · Re) is not a constant in laminar flow range but a function of R_e with its value decreasing as Re increases, he came up with the formula:

$$f \cdot Re = \frac{16{y_n}^2}{d^2} \cdot \frac{2g}{\nu} \cdot \frac{S_d}{g/y_n} \qquad (11)$$

with S being the energy gradient.

Further examination by Gourlay (13) of velocity profile indicated that for $So \leq .05$ there are three distinct layers of flow:

1. A layer of virtually constant low velocity near the bed.
2. A layer of rapidly increasing velocity within the upper grass layer.
3. A layer of less rapidly increasing velocity above the grass. He further indicated that the discontinuity between layers two and three occurred at top of grass and that all grass bending occurred in layer two. The velocity in the bottom layer was found, in general, to be proportional to shear velocity, U_*. When the $S_o \geq .05$, layers two and three merge together forming a two layer appearance.

In regard to hydraulic resistance Gourlay indicated that on steep slopes the slope is a parameter in defining the retardance to flow. He believed that this was a gravitational effect due to the fact that grass will tend to bend downhill due to its weight. Ree and Palmer in their plots of n versus VR did not have slope as a parameter.

In a later paper Kouwen and Unny (14) verified the logarithmic formula for velocity profile but they found large variation in Von Karman's turbulence coefficient. They also defined a local friction factor, f_k, as:

$$\sqrt{8/f_k} = U_k/U_* \tag{12}$$

where:

U_k = average velocity on top of grass, LT^{-1}; and

U_* = local shear velocity, LT^{-1}.

In evaluating the local friction factor, f_k, Kouwan and Unny found a constant value for flow with erect vegetation and another for it being prone. The former has a value of friction factor, for cases studied on artificial grasses, more than five times greater than that with prone vegetation (1.4 to .25). They also found that f_k and Manning's n were primarily a function of relative roughtness, y_n/h, for the flow with erect vegetation while for prone cases f_k appeared to be a function of Reynold's number, Re.

Kouwen and Unny defined a dimensionless parameter $(mEI/\rho U_*^2)^{1/4}/h$ which relates the amount of bending to the boundary shear. Their resulting relationship takes the following form:

$$\frac{k}{h} = \frac{3.57}{h} \left(\frac{mEI}{\rho U_*^2}\right)^{1/4} - .286 \qquad (13)$$

where:

h = height of roughness element, L;

k = deflected height of roughness element, L; and

m = number of roughness elements per unit area of channel bed.

For flow through tall vegetations, Li and Shen (15) studied the effect of pattern arrangement on the drag coefficient, C_d. They indicated that the best estimate for C_d of an individual cylinder is 1.2 provided that:

1. no aeration exists behind the cylinder;
2. there is no blockage effect; and
3. the flow is subcritical.

However, this local drag coefficient for a single cylinder could be different in a multiple cylinder arrangement.

The recent work by Thompson and Roberson (16) advanced the concept of the three zones of velocity distribution. The zones defined are:

1. A viscous sublayer of height δ' occurring adjacent to channel bottom.
2. A zone below the top of the roughness elements of height, k, and above the viscous sublayer which is considered to be influenced by intensive turbulence mixing.
3. A zone above the top of the roughness elements which is considered free of local wave effects.

The velocity distribution in the viscous sublayer, $U(\delta')$, was approximated by:

$$\frac{U(\delta')}{U_*} = \frac{U_* y}{\nu} \tag{14}$$

The local shear stress, τ_s', at δ' was found to be:

$$\tau_s' = \frac{\mu U\delta'}{\delta'} \tag{15}$$

where:

$U\delta'$ = velocity at limit of viscous sublayer.

Thompson and Roberson defined roughness element concentration on the boundary, λ, as:

$$\lambda = NA_e/A_t \tag{16}$$

where:

N = number of elements;

A_e = base area of one element, L^2; and

A_t = total boundary area, L^2.

They then obtained the average shear stress per unit area of boundary as:

$$\tau_s'' = \tau_s' \ (1 - T\lambda) \tag{17}$$

where T is a dimensionless factor defined as ratio of sum of areas occupied by element base and zone of separation to base area occupied by elements. The value of T was determined by Thompson and Roberson to have a range of 2.0 to 3.0.

They also calculated drag resistance for discrete resistance elements by the finite difference equation.

$$\frac{\Delta\tau_r}{\tau_0} = \frac{\lambda C_d}{2A_e} \left(\frac{U(y)}{U_*}\right)^2 \Delta A_p \tag{18}$$

where A_p is the projected area of the resistance element.

Most recently, Chen (17) published laboratory study results on flow resistance in broad shallow channels lined with Kentucky Bluegrass and Hybrid Bermuda grass. Data anlayses were carried out based on Darcy-Weisbach friction energy loss relationship and concluded that the friction coefficient, f, increases, generally, with the bed slope and decreases with decreasing Reynolds number.

The presented conclusion is a very significant one for this work represents the first of such an extended effort to evaluate systematically in laboratory the flow resistance of real grass media in channels of various slopes. This conclusion also clears any possible doubt on the fact that slope of the channel bed is a factor affecting the resistance coefficient to shallow flow through grass media and that such effect is not a result of using artificial vegetation as Gourlay, Kouwen and others might be suspected of.

Although much work has been done in an attempt of detemining the resistance factor of vegetation, the effort can be catagorized into two different approaches. The first group of works centered around using real vegetation as experimental media to collect data for developing empirical results which engineers could use under similar conditions. The leading researchers in this area are Ree and Palmer and their work has long been recognized and widely used in engineering design of irrigation channels and vegetative covered waterways.

The second school of attempt, shared by investigators such as Fenzl, Kouwen, Unny, Izzard, Phillips, Li, Shen, Thompson, Roberson, and Chen aimed at developing a rational explanation of the existance of vegetation resistance to flow. They sought to confirm their theory by conducting experiments in laboratory flumes using rigid cylinders or flexible strips (except Chen) arranged in fixed patterns to simulate the vegetation under concern. Their published results have been extremely useful in helping understand the basic mechanics of flow through vegetations.

In this study, a new attempt is made to closely simulate grass media by using flexible blades with different degrees of stiffness arranged in random patterns. This was done by embedding these strips in molden paraffin. The experimental results are used to calibrate the analytical equations derived based on fundamental fluid mechanics principles.

Scope of the Present Study

As shown in the literature review some work has been done on hydraulic resistance due to the presence of vegetation either in field conditions or with simulated vegetation with defined patterns. However, very little work has been done in examining the sediment filtering efficiency of the vegetation.

At the present time many users prefer to view resistance in terms of the 'n' vs. 'VR' plots provided by Ree and Palmer. For totally submerged flow of real grass media this approximation of 'n' is valid. When overland flow of shallow depth or flow of shallow depth or flow through relatively stiff grass media is present, Ree and Palmer's experimental results may not be applicable in describing the resistance to flow, for they did not intent to have their result being applied under this condition. It was therefore the intent of this study to relate the hydraulic resistance imposed by randomly arranged short dense vegetation in terms of the drag produced by the grass blades. The approach of using drag was attempted by

Thompson and Roberson, and applied to tall loose vegetations with fixed pattern by Li and Shen.

The flow equations developed in this study, based on considerations of fundamental principles involved in open channel hydraulics and fluid mechanics, are to be used in the evaluation of the sediment trapping efficiency through vegetative filters, as the second phase of a continuous research effort. In order to be able to describe the process of sediment trapping in channels covered with real or artificial vegetation, better understanding of the hydraulic properties, such as profiles of flow velocity within the vegetative cover as well as above it, is very essential. For this reason, an attempt is made in this research report to provide a thorough description of the behavior of the flow in vegetated channels, in addition to the determination of the flow resistance factor of such a channel.

II. ANALYTICAL ANALYSIS

The analysis of the hydraulic resistance will be divided into two flow areas: the flow through the vegetative media and the flow above it. The velocity distribution above the vegetation will be assumed to follow a logarithmic profile (7, 9) and the flow through the vegetation to satisfy continuity equation and laminar flow equation near the boundary region. The hydraulic resistance will then be explained in terms of the shear and drag forces imposed on the flow by the contacting boundary and the blades of the simulated grass.

Velocity Profiles of Non-submerged Flow

In examining the flow resistance in the non-submerged case three assumptions are made:

1. Velocity profile is uniform in the horizontal plane through the gap between the simulated grass blades.
2. Viscous shear is the dominating force in the lower region near the bed.
3. The effect of curvelinear motion as evidenced by water weaving around individual blades is implicitly included in the coefficient of drag and needs not be considered separately.

Figure 1 gives the representation of the assumed velocity profile for flow within the artificial vegetation. The laminar flow equation is applied between the bottom and $y = \delta$ where δ

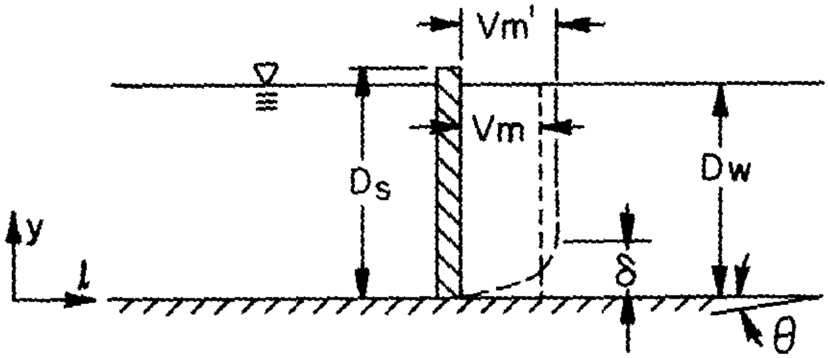

Fig. 1 Anticipated velocity profile for non-submerged flow conditions

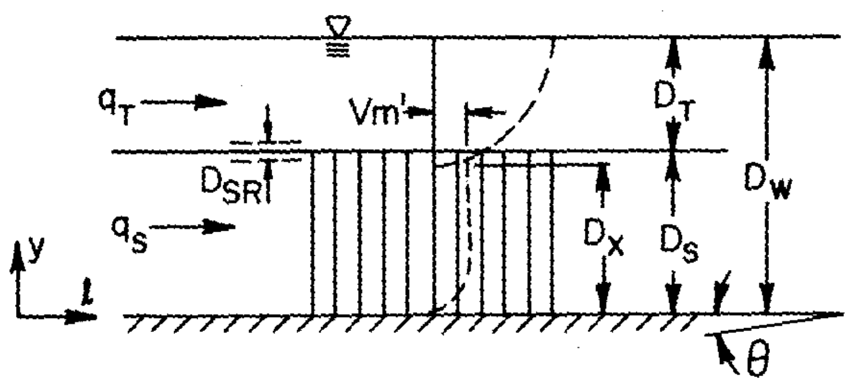

Fig. 2 Anticipated velocity profile for submerged flow conditions

is the boundary layer thickness. Since $v(y) = 0$ at $y = 0$ the laminar flow equation is:

$$v(y) = (\gamma \text{ Sin } \theta) \left(\frac{y^2}{2\mu}\right) + \frac{Ay}{\mu} \qquad (0 \leq y \leq \delta) \tag{19}$$

where:

γ = specific weight of water, FL^{-3};

θ = angle of a flume from horizontal;

y = distance from bottom of flume, L;

μ = dynamic viscosity of water, FTL^{-2}; and

A = constant of integration.

From $\delta < y < D_w$ the velocity is assumed to equal Vm' such that:

$$v(y) = Vm' \qquad (\delta \leq y \leq D_w) \tag{20}$$

From assumed velocity profile, the following relationships holds:

$$v(y)\Big|_{y=\delta} = Vm' \tag{21}$$

Substitution of Eq. 21 into Eq. 19 and solving for A gives:

$$A = \frac{Vm'\mu}{\delta} - \frac{\gamma \text{ Sin } \theta \ \delta}{2} \tag{22}$$

By substituting Eq. 22 back into Eq. 19 and letting Sin $\theta = -S_o$, for small θ, the laminar flow equation becomes:

$$v(y) = \frac{\gamma S_o}{2\mu} (\delta y - y^2) + \frac{Vm'y}{\delta} \qquad (0 \leq y \leq \delta) \tag{23}$$

where S_o is the slope of the flume.

If the boundary layer thickness is known the velocity at any point within the boundary layer thickness can be found. In a laminar Newtonian fluid flow, the viscous shear, τ, is proportional to the velocity gradient at the point of concern. Application of Newton's Law of viscosity and the definition of boundary layer thickness leads to the conclusion that shear at the distance of boundary layer thickness from the wall vanishes. Mathematically this can be expressed as:

$$\tau\Big|_{y=\delta} = \mu\frac{dv(y)}{dy}\Big|_{y=\delta} = 0 \qquad (24)$$

Differentiation of Eq. 23 and solving Eq. 24 for boundary layer thickness, δ, yields:

$$\delta = \pm\sqrt{2\mu Vm'/\gamma\ S_o} \qquad (25)$$

with positive root being adopted based on physical significance.

The value for Vm' can be found by first integrating the velocity equation with respect to y which gives the flowrate, q_s, per unit width of flume:

$$q_s = \int_0^\delta v(y)\ dy + \int_\delta^{D_w} Vm'dy$$

$$= Vm'D_w - \frac{1}{3}\sqrt{\frac{2\mu}{\delta S_o}}\ Vm'^{3/2} \qquad (26)$$

By substituting continuity relationship, $q_s = VmD_w$, into Equation 26 a general expression for Vm' becomes:

$$Vm' = \frac{3VmD_w}{3D_w - \sqrt{2\mu Vm'/\gamma\ S_o}} \qquad (27)$$

where:

Vm = mean velocity within vegetation, LT^{-1}.

Equation 27 can then be solved by using trial and error technique for Vm'.

Velocity Profile for Submerged Flow

In representing the velocity profile above the artificial grasses the following assumptions are made:

1. v(y) equation derived in previous section for flow between blades still holds true.
2. Universal velocity equation is applicable for flow above vegetation blades.

For turbulent flow the universal velocity equation is:

$$U(y) = \frac{1}{k} U_*(\ln \frac{Y - D_x}{D_{sr}}) \tag{28}$$

Where U_* is the shear velocity; D_{sr} is the irregularity of the vegetation blade length; k is the universal constant which is taken as 0.4 for water flow; and D_x is defined as the depth measured from the channel bed (y = 0) to the point in the flow where the logrithmic velocity profile initiates. This depth is expected to be slightly smaller than the average height of the simulated grass blades, D_s. Figure 2 gives a representation of the flow profile for the submerged case.

To satisfy the boundary condition at the tip of the blades the velocity should be equal to Vm', or:

$$Vm' = \frac{1}{k} U_*(\ln \frac{D_s - D_x}{D_{sr}}) \tag{29}$$

Solving Eq. 29 for D_x yields:

$$D_x = D_s - e^{[\frac{k\ Vm'}{U_*} + \ln(D_{sr})]} \tag{30}$$

By substituting the above equation into Eq. 28 the velocity profile for water flow above the vegetation is obtained as:

$$U(y) = \frac{1}{k} U_* \{Ln \frac{y - D_s + e^\sigma}{D_{sr}}\} \quad (31)$$

with

$$\sigma = \frac{k\ Vm'}{U_*} + ln(D_{sr}) \quad (32)$$

When integrated over a range of y from D_s to D_w the result will give the discharge through the part of the flow area above the grass media. This can be mathematically expressed as:

$$q_t = \int_{D_s}^{D_w} U(y)\ dy \quad (33)$$

By substituting Eq. 31 into Eq. 33 and carrying out the integration for the discharge above the grass media it yields:

$$q_t = \frac{1}{k} U_* \{(D_t + e^\sigma)\ Ln(D_t + e^\sigma) - \sigma e^\sigma - D_t - D_t\ ln(D_{sr})\} \quad (34)$$

where:

D_t = depth of water above vegetative cover.

Hydraulic Resistance Analysis

A. Basic Equation. The hydraulic resistance due to vegetative channels can be derived by using the momentum equation. Figure 3 gives a representation of different forces acting on the flow element. The basic equation for submerged flow is:

$$W\ S_o = (F_d + F_b + F_{ws}) + (F_{wt}) \quad (35)$$

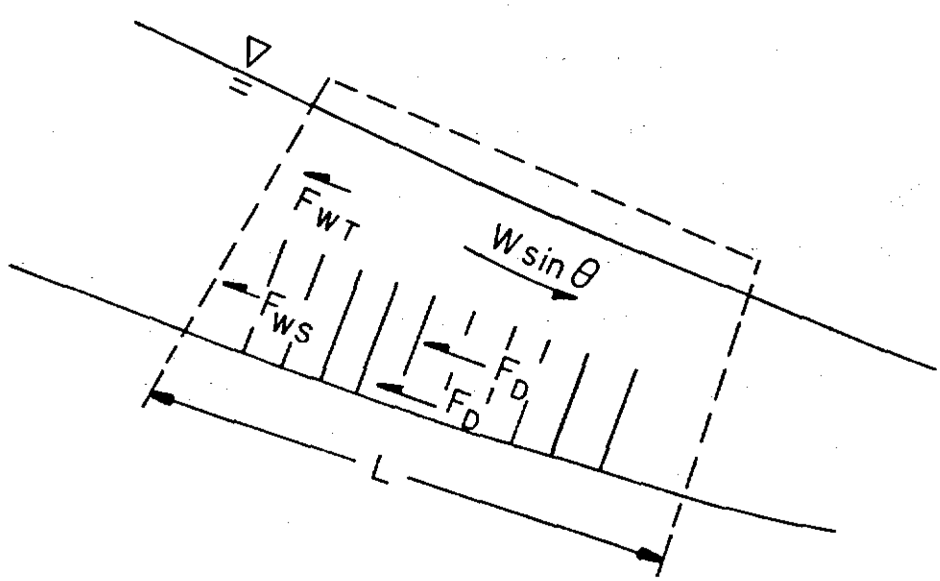

Fig. 3 Schematics of forces acting on a flow element

where:

W = weight of water in control volume, F;

F_d = drag force due to grass, F;

F_b = force due to bed shear, F;

F_{ws}= force due to wall shears within vegetation, F;

F_{wt}= force due to wall shears above vegetation, F;

W = weight of water in control volume $(\forall_w - \forall_s)\gamma$, F;

$\forall_w$ = volume of water in L, L^3;

L = length of section under consideration, L; and

$\forall_s$ = volume of blades in V_w, L^3.

The hydraulic resistance for nonsubmerged case can be derived from Equation 35 as the term F_{wt} vanishes.

B. Drag Force. The drag force resisting the flow due to the blades can be expressed as:

$$F_d = N_b \rho A_s R_d \frac{Vm'^2}{2} \tag{36}$$

where:

N_b = number of blades in $\forall_w$;

A_s = cross sectional area blocked by vegetation, L^2; and

R_d = drag coefficient for blades.

C. Bottom Shear Force. The resisting force due to the shear along the bed is:

$$F_b = \tau_b (A_b' - A_p) \tag{37}$$

where:

τ_b = bed shear,

A_b' = bed area, and

A_p = projectional area of blades on bed.

The expression for the bottom shear, τ_b, is derived from Eq. 23 using $\tau_b\big|_{y=0} = \mu\frac{dv(y)}{dy}$ or:

$$\tau_b = \frac{\gamma S_o \delta}{2} + \frac{Vm'\mu}{\delta} = 2\sqrt{\mu\gamma S_o Vm'/2} \tag{38}$$

The final expression for the resisting force due to bottom shear then becomes:

$$F_b = 2\sqrt{\mu\gamma S_o Vm'/2}\ (A_b' - A_p) \tag{39}$$

D. <u>Wall Shear</u>. The resisting force due to sidewall shear within the begetative cover is given by:

$$F_{ws} = 2\tau_{ws} D_t L \tag{40}$$

where:

τ_{ws} = wall shear within vegetation, FL^{-2}.

For the sidewall shear within the vegetation the following assumptions are made.

1. Laminar flow is present.
2. The vertical velocity distribution is uniform.
3. The shear due to bottom is negligible.

Figure 4 gives the forces acting on a volume element of fluid. By summing forces and setting them equal to zero:

$$p\delta h\delta y - (p + \frac{dp}{d\ell}\,\delta\ell)\ \delta h\delta y - \tau\delta y\delta\ell + (\tau + \frac{\partial\tau}{\partial h}\,\delta h)\,\delta y\delta\ell + \gamma\delta\ell\delta h\delta y \sin\theta = 0 \tag{41}$$

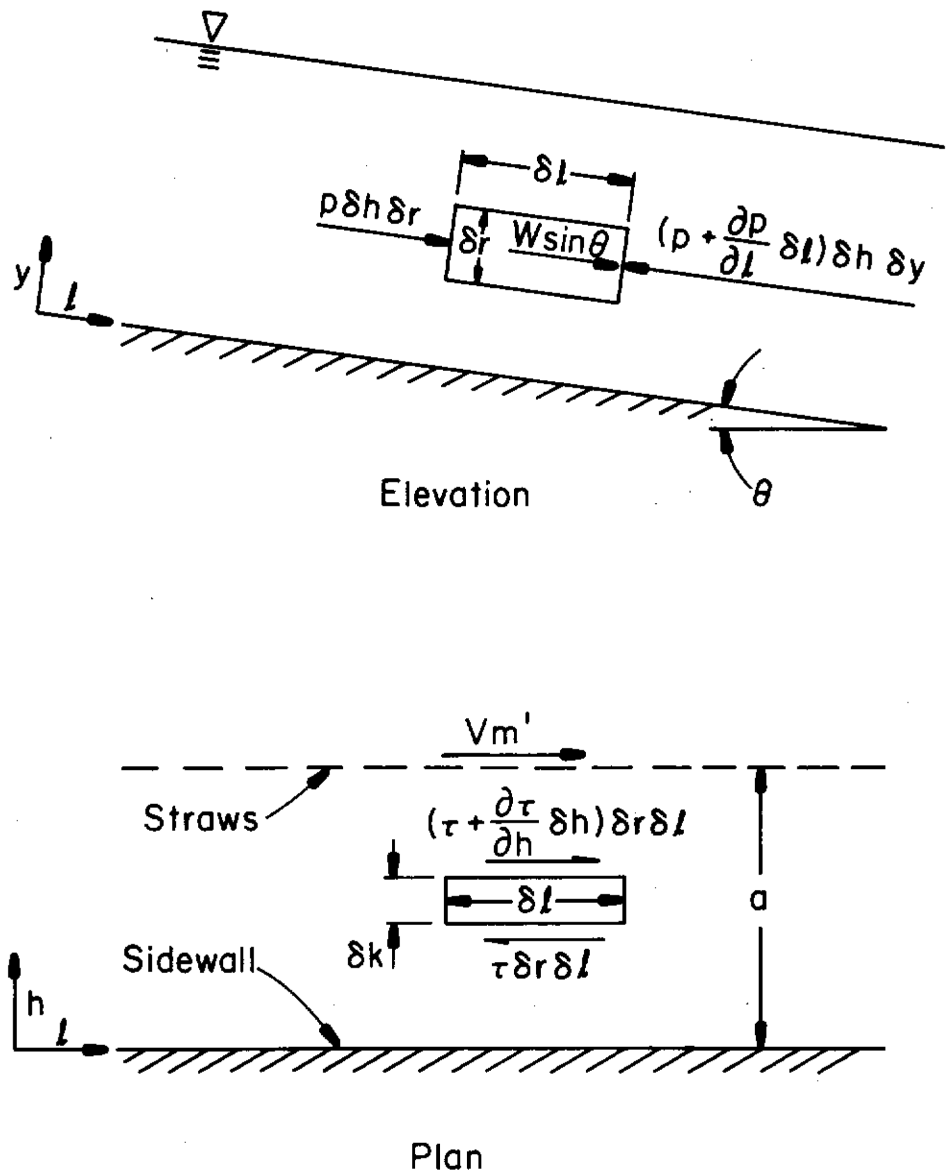

Fig. 4 Schematics of forces acting on an elemental volume of fluid near the channel wall

where:

p = hydrostatic pressure, FL^{-2}; and

h = distance from sidewall, L.

Integrating Eq. 41 and setting $\tau = \mu \, dV/dh$:

$$\tau = h[\frac{\partial}{\partial \ell} (p + \gamma y)] + B = \mu \frac{dV}{dh} \tag{42}$$

Solving equation 42 for velocity distribution in horizontal direction results in:

$$V(h) = \frac{Vm'h}{a} + \frac{1}{2\mu} [h^2 - ah] [\frac{\partial}{\partial \ell} (p + \gamma y)] \tag{43}$$

where:

a = distance from sidewall to first row of vegetation blades next to the wall.

Since $\frac{\partial}{\partial \ell} (p + \gamma y) \approx - \gamma S_o$, the shear expression, τ, becomes:

$$\tau = \frac{Vm'\mu}{a} - \frac{\gamma S_o}{2} (2h - a) \tag{44}$$

At the wall $h = 0$ which, when substituted back into Eq. 44 gives the wall shear expression:

$$\tau_{ws} = \frac{Vm'\mu}{a} + \frac{a}{2} \gamma S_o \tag{45}$$

For flow above the grass media the resisting sidewall force is:

$$F_{wt} = 2\tau_{wt} D_t L \tag{46}$$

where:

τ_{wt} = sidewall shear above vegetation, FL^{-2}

For expressing the sidewall shear above the vegetation an expression relating shear to Manning's n is used (19):

$$\tau_{wt} = \frac{.45\ \gamma\ n_w{}^2 V_t{}^2}{R_t{}^{1/3}} \tag{47}$$

where:

n_w = Manning's n value for the wall,

V_t = mean velocity in the region above the blades, and

R_t = hydraulic radius in region above blades.

The velocity in the region above the vegetation, V_t, equals the flow rate above the blades per unit width of flume divided by the water depth above the vegetation, D_t. By applying the continuity equation the resulting expression for q_t is:

$$q_t = \frac{Q - q_s B_{op}}{W_c} = \frac{Q}{W_c}\ [Vm'D_s - 1/3\ \sqrt{2\mu/\gamma S_o}Vm'^{3/2}] \tag{48}$$

where:

w_c = width of the channel; L,

B_{op} = cross sectional open flow width beneath the vegetation, L; and,

Q = total discharge in the channel, L^3T^{-1}.

E. Final Form of Drag Equation. By substituting the force expressions back into the basic drag equation and considering a 1 foot length of flume (L = 1'), the final form of drag equation for submerged flow is:

$$(A_b' - A_p)\ D_s \gamma S_o + D_t W_c \gamma S_o = N_b\ \rho\ A_s R_d\ \frac{Vm'^2}{2} +$$

$$2\sqrt{\mu\gamma S_o Vm'/2}\ (A_b' - A_p) + 2\ [\frac{Vm'\mu}{a} + \frac{a}{2}\ \gamma S_o]\ D_s +$$

$$2[\ \frac{.45\ n_w{}^2\ q_t{}^2}{R_t{}^{1/3} D_t}\ ] \tag{49}$$

For the case of non-submerged flow the last term does not apply and the expression for the drag coefficient of the vegetation becomes:

$$R_d = \frac{(A_b' - A_p)\ \gamma S_o - \tau_b\ (A_b' - A_p) - 2\tau_{ws} D_w}{N_b \rho A_s Vm'^2/2} \tag{50}$$

III. EXPERIMENTAL FACILITIES AND PROCEDURES

The experimental apparatus consisted of a 16-foot (4.88m) long rectangular flume which was 0.481 feet (0.147m) wide by 1.5 feet (0.457m) deep. At one end was a reservoir 4 feet (1.22m) high by 1 foot (0.304m) long with a 1 inch (25.4mm) sluice gate opening connected to the reservoir and the main flume. Water was supplied into the reservoir from a constant head pit through a 3 inch (76mm) pipe. Figure 5 is the schematic drawing of the facility.

One wall of the flume was build of 1/2 inch (12.7mm) plexiglass for visual observation while the other wall was made of 1.2 inch (12.7mm) plywood. Two pieces of planed 2 inch by 6 inch (51mm x 152mm) lumber was used for the bottom of the flume. The bottom was lined with 1-1/2 inch (38.1mm) thick modeling clay upon which units of the artificial vegetation was fixed. The flume rested on a 6 inch (152mm) I beam which was supported by a hinged platform at one end and a screw jack at the other. The jack could be adjusted to give slopes from 0% to 9.0%. Figure 6 is a general arrangement of the laboratory setup.

Three types of artificial grasses were used. Polypropylene coffee sticks with dimension of 5-1/4 inch (133mm) by 1/4 inch (6.4mm) by 1/16 inch (1/6mm) were used as one type. The other two types of artificial grasses were cut out of acetate films

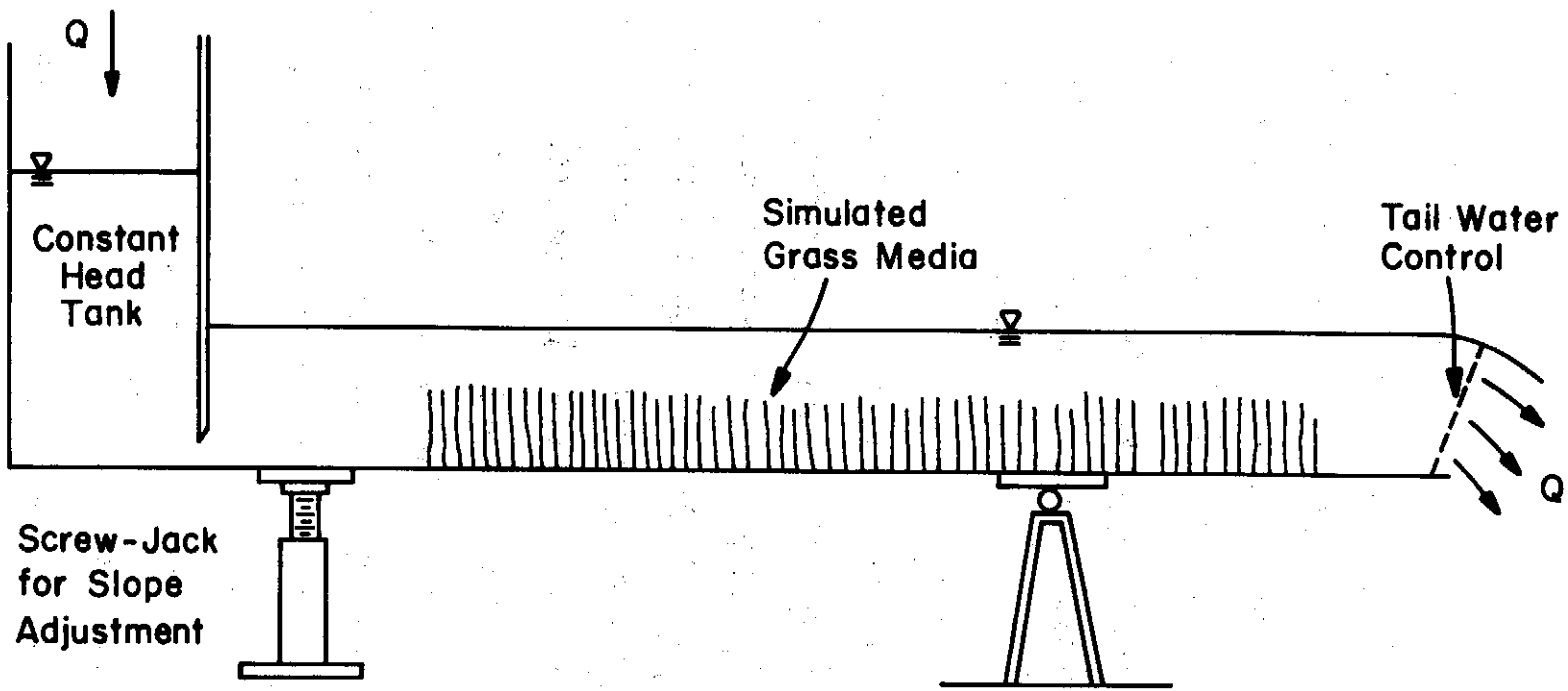

Fig. 5 Schematic drawing of the experimental flume

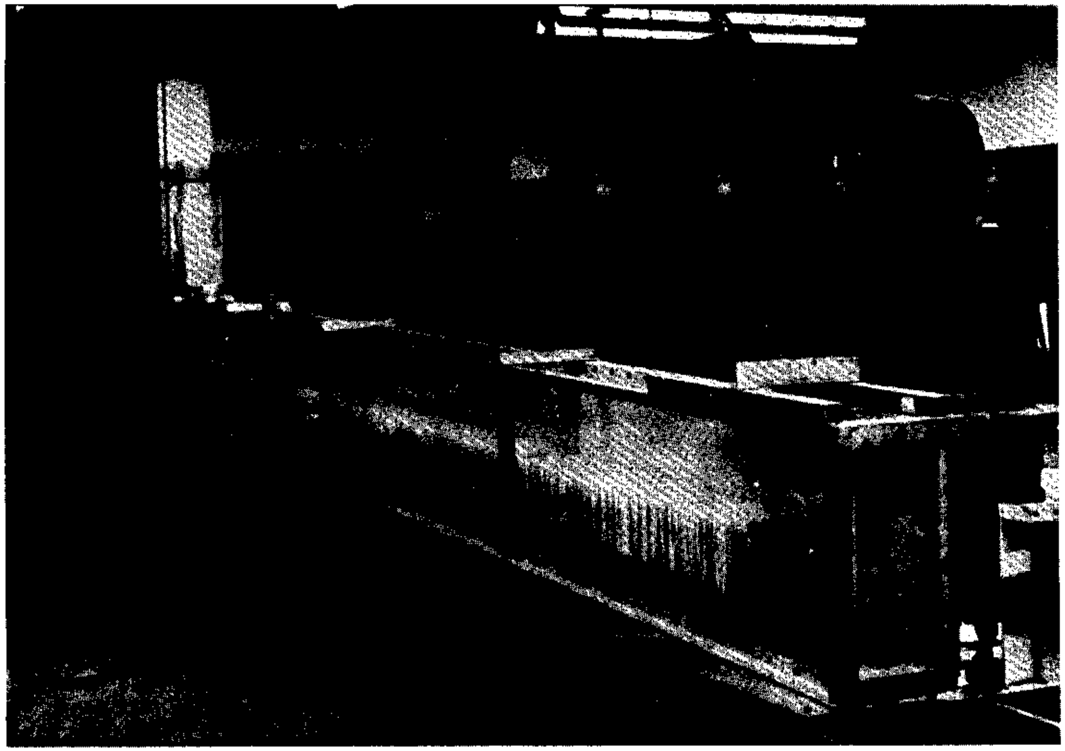

Fig. 6 General arrangement of the laboratory flume

of 0.0008 feet (0.24mm) and 0.0003 feet (0.09mm) in thickness. The individual blades were embedded in paraffin by first heating the paraffin to a liquid state and pouring it into a 5-3/4 inch (146mm) by 4 inch (102mm) rectangular mold. The blades were placed in the hot paraffin by means of fixing two wire mesh over the mold and randomly dropping in the blades. The paraffin with the embedded artificial grasses was then cooled and fixed upon the modeling clay with screws.

The independent variables in the experiments were slope, discharge, grass density and grass stiffness. The dependent variables were water depth. The experiment was divided into A, B, C and D series. Series A was with the stiffest media (polypropylene sticks) used with a density of 8.5 blades/inch^2 (131.7 blades/dm^2). Series B was with the stiffest media with 15.5 blades/inch^2 (240 blades/dm^2). Series C and D were with different stiffnesses and 8.5 straws/inch^2 (131.7 blades/dm^2) density. For each series, the flow resistance measurements were made first and consisted of taking water depth measurements with an electronic point gauge for various slopes and flow rates. In the series C and D experiments non-submerged flow was done first then submerged flow followed repeating non-submerged conditions. The reason for repeating was to observe the effect of bending of the artificial vegetation.

IV. DISCUSSION OF RESULTS

In presenting the results of this study the data will first be viewed in terms of n vs. VR plots as suggested by Ree and Palmer. The ratio of the average velocity to shear velocity vs. the natural log of the ratio of total flow area to the area blocked by vegetation (V/U_* vs. $\ln A/A_b$) as proposed by Unny and Kouwen are also presented for a possible comparison. The data will then be analyzed in terms of the drag imposed on the flow by the grass blades. The variation of drag coefficient, R_d, with the Reynold's number will be presented. Before the results are presented an explanation of the method of solution for pertinent variables will be given.

Solution to Various Parameters

A. Mean Velocity. In computing the mean velocity within the vegetation, a correction had to be made due to the velocity distribution in the gap between the blades and sidewall. The velocity distribution in the horizontal direction is given by Eq. 43 as:

$$V(h') = \frac{Vm'h'}{a} + \frac{\gamma S_o}{2\mu} (ah' - h'^2) \qquad (51)$$

where:

a = distance between first row of blade and sidewall, L; and,

h'= variable distance from sidewall, L.

To find the unit flow rate, q_a, in the gap between the sidewall and the blades, a, the above equation is integrated with respect to h':

$$q_a = \int_0^a V(h')\, dh' = \frac{Vmh'^2}{2a} + \frac{\gamma S_o}{2\mu}\left[\frac{ah'^2}{2} - \frac{h'^3}{3}\right]\Bigg|_0^a$$

$$= \frac{Vma}{2} + \frac{\gamma S_o a^3}{12\mu} \qquad (52)$$

The flow within the grass, q_s', is given by:

$$q_s' = Vm(N' - 1)\ (g_p) \qquad (53)$$

where:

N' = average number of blades in a single row across the flume, and

g_p = average gap distance between two adjacent blades in a row, L.

The total flow below the top of grass, Q_s, equals to q_s' plus $2q_a$ or:

$$Q_s = Vm(N' - 1)\ g_p D_w + (Vma + \frac{\gamma S_o a^3}{6\mu})D_w \qquad (54)$$

where:

Q_s = total discharge within vegetation, L^3T^{-1}

Solving EQ. 54 for Vm results in:

$$Vm = \frac{Q_s - \frac{a^3}{6\mu}\gamma S_o\ D_w}{\{[(N' - 1)\ g_p + a]\ D_w\}} \qquad (55)$$

B. <u>Average Gap Width</u>. In arriving at an expression for determining the average gap between blades (flow opening), g_p, for randomly arranged blades four different blade orientations as shown in Figure 7 were considered. The average projected width of a blade, L_{avg}, is:

$$L_{avg} = (W_s + T_s + L_3 + L_4)/4 \tag{57}$$

where:

W_s = blade width, L;

T_s = blade thickness, L; and

$L_3 = L_4 + (W_s) \sin 45°$, L.

The number of blades per linear foot equals $(\frac{1}{L_{avg} + g_p})$ and this expression for gap width is given by:

$$D_{sg} = (\frac{1}{L_{avg} + g})^2 \tag{58}$$

where:

D_{sg} = number of blaeds per unit area,

or solving for gap width, g_p:

$$g_p = \frac{1}{\sqrt{D_{sg}}} - L_{avg} \tag{59}$$

<u>'n' vs. 'VR' Plots</u>

Ree and Palmer, in working with grass channels, arrived at a means of expressing hydraulic resistance. They proposed that Manning's n, value be plotted against VR which gives a smooth curve for submerged conditions. In Figures 8 through 11 the n vs. VR curves for authors' data is plotted for various stiffnesses and densities of grass. In the n vs. VR plots only the downsloping part of the curve which represent submerged flow conditions, is readily apparent following a definitive pattern. For the non-submerged flow case the only conclusion

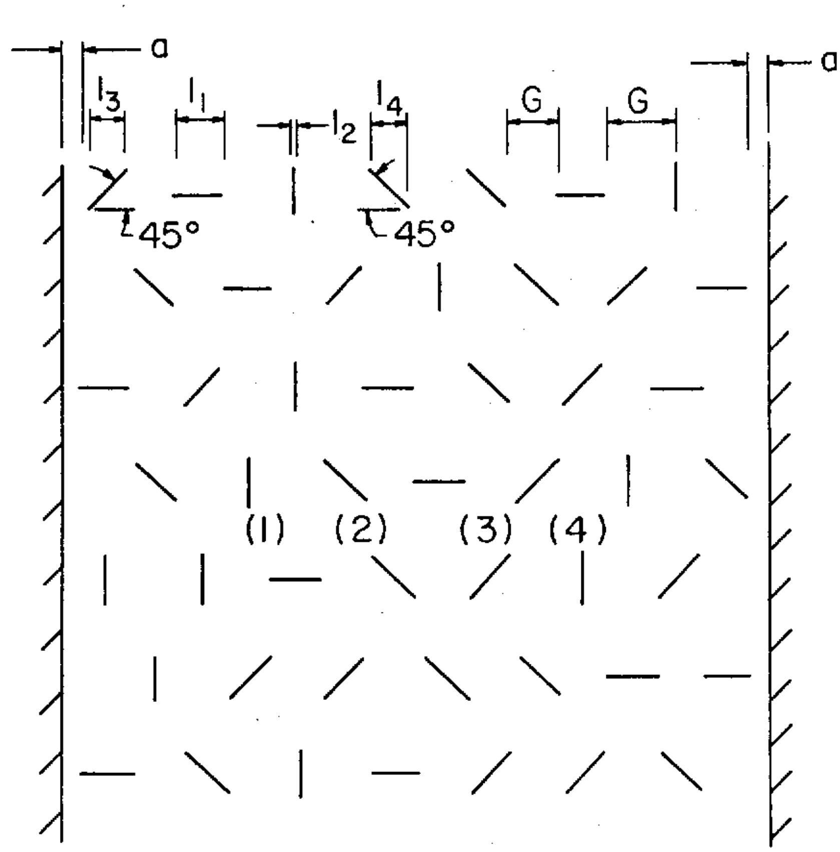

Fig. 7 Four representative vegetation blade orientations

that can be drawn is that the Manning's n increases as depth increases. This is just the opposite of what occurs for the submerged flow case.

In examining the constructed plots one can notice the dependency of the curve on the bed slope. The Manning's n vs. VR plots by Ree and Palmer were originally believed to be independent of slope. However, Gourlay and Chen in their experiments with artificial and real grasses respectively noticed the dependency of n vs. VR curves on slope. If comparison is made of the extent of dependency of curves on slope, it is seen that for the stiffest simulated vegetation used there is a great difference. However, for the least stiff vegetation the variation between the curves is small. The least stiff grasses used closely approximate the flexibility of real grasses. Therefore, this leads the author to believe that in real grass experiments with large flows, such as those conducted by Ree and Palmer, the n vs. VR dependency on slope is small and for the most part negligible.

U/U_* vs. $\ln A/A_b$

Kouwen and Unny in analyzing their data arrived at a representation of the velocity profile as:

$$\frac{U(y)}{U_*} = C_1 + C_2 \ln \frac{y_n}{h} \qquad (60)$$

Equation 60 is in the same form as Eq. 28 derived in the section on Analytical Analysis of this report. Kouwen and Unny approximated y_n/h by the ratio of total flow area to area blocked by vegetation and plotted $U(y)U_*$ vs. $\ln A/A_b$.

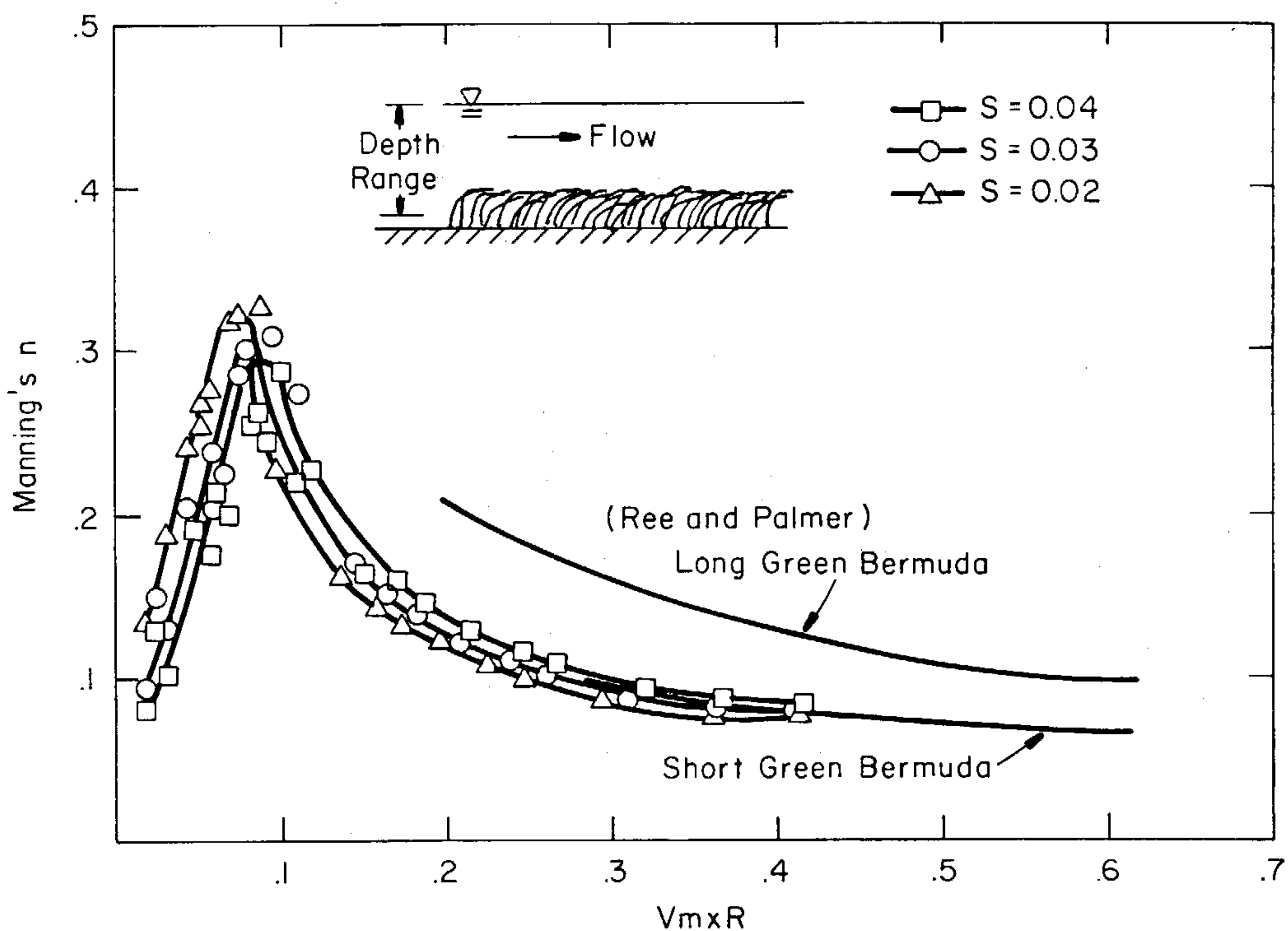

Fig. 8 Manning's n vs V_mR curves for highly flexible simulated grass with population of 1224 blades/ft^2

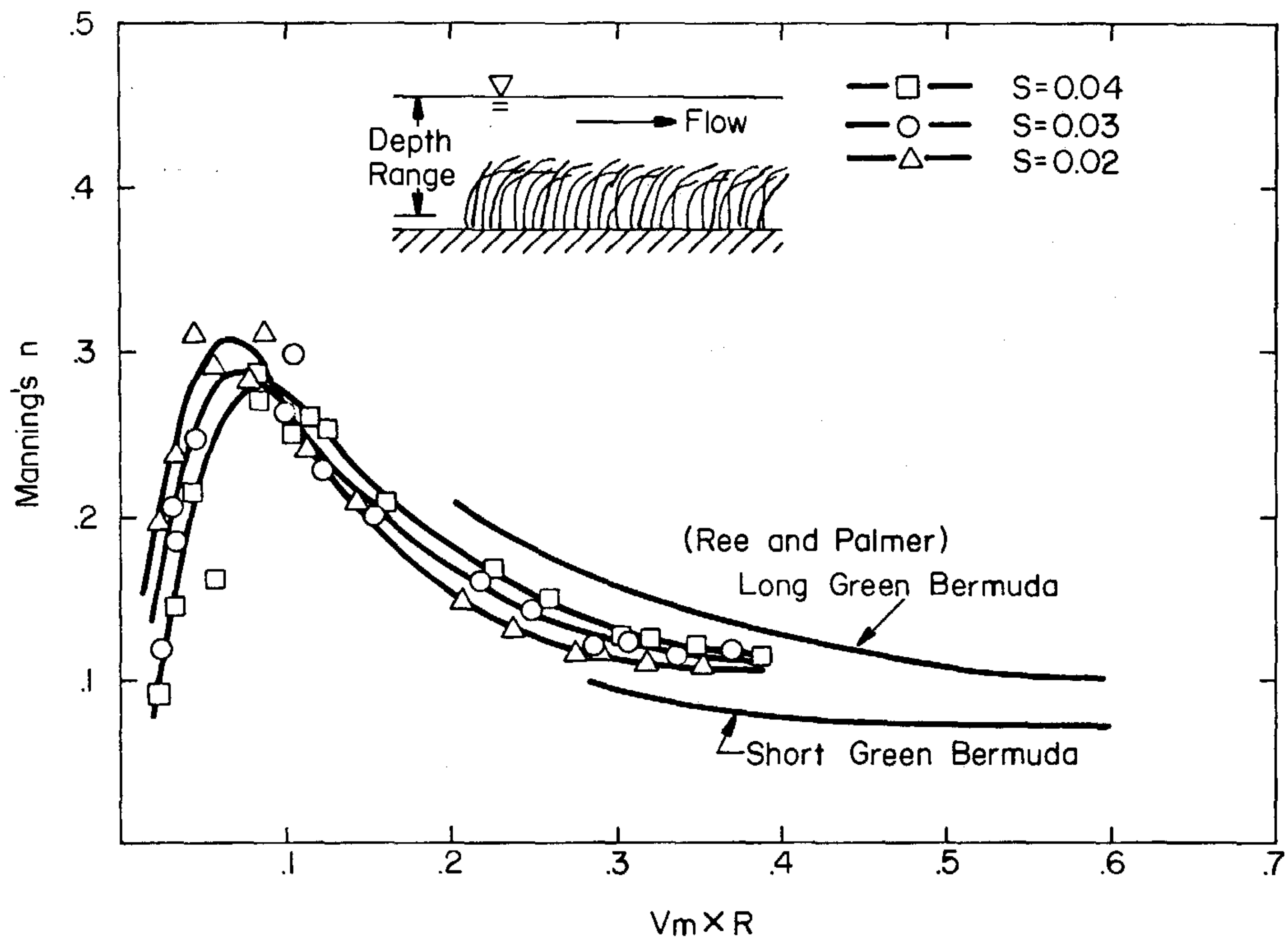

Fig. 9 Manning's n vs V_mR curves for medium stiff simulated grass with population of 1224 blades/ft^2

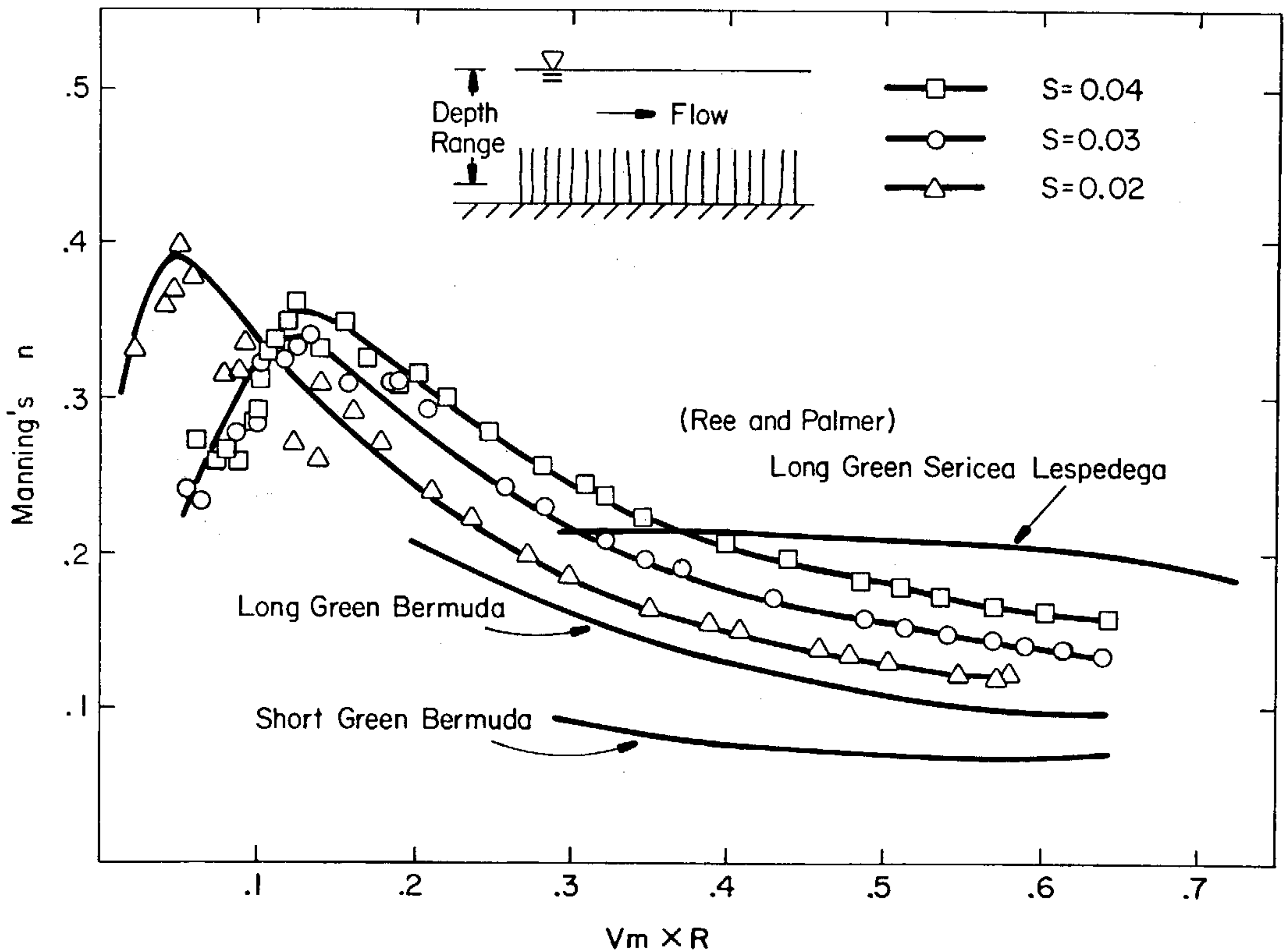

Fig. 10 Manning's n vs V_mR curves for stiff simulated grass with population of 1224 blades/ft^2

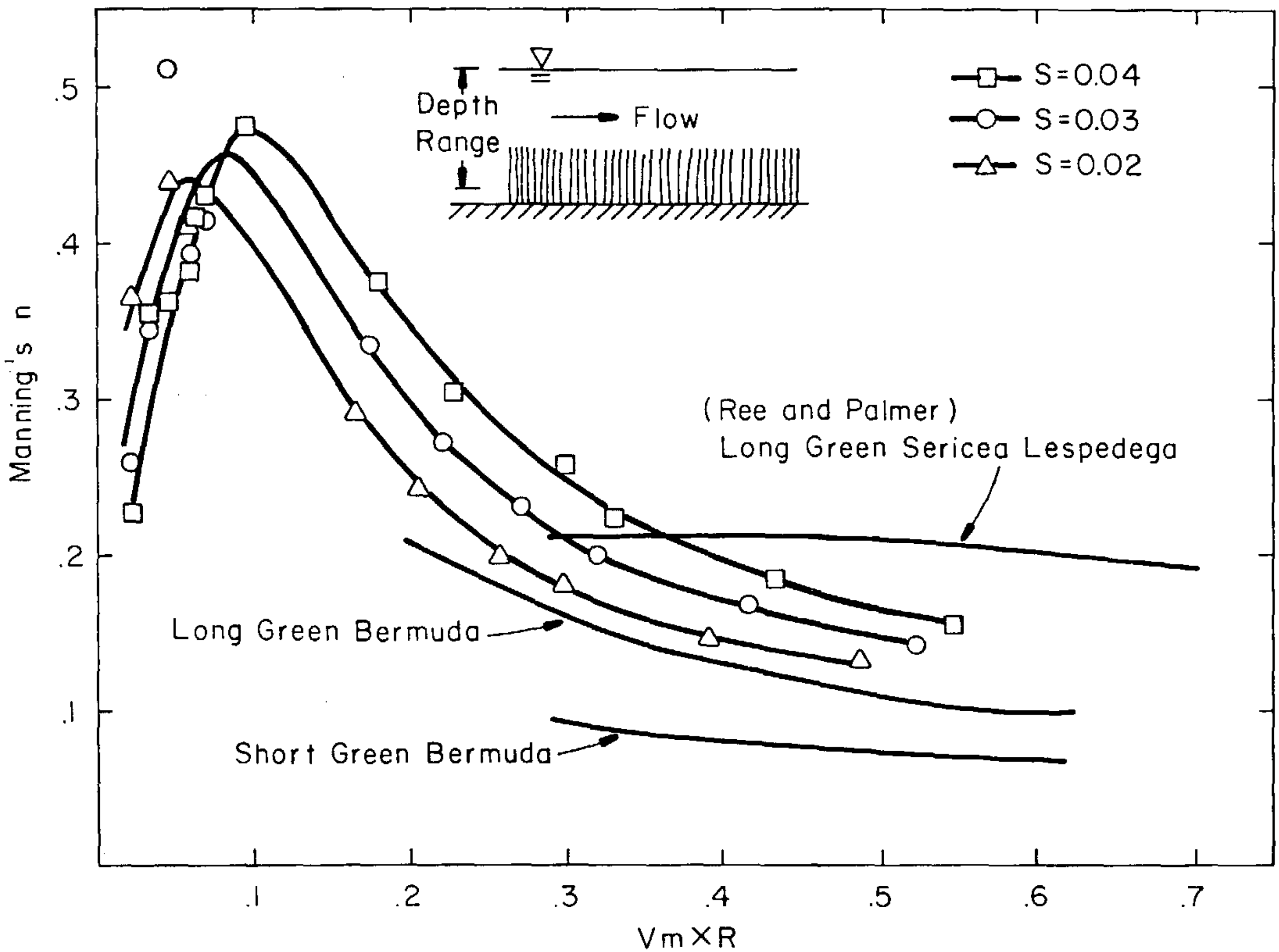

Fig. 11 Manning's n vs V_mR curves for stiff simulated grass with population of 2232 blades/ft^2

In analyzing the data taken in this study, V/U_* is plotted against ln A/A_b where the shear velocity, U_*, is calculated from:

$$U_* = \sqrt{gR'S_o} \tag{60}$$

Figures 12 and 13 show these plots. For the stiffest vegetation a straight line can be drawn through the points. This indicates that the velocity in the flow area above the blades may be represented by the logarithmic flow formula. However, in the plots for the medium and least stiff simulated grass there is a scatter of points. This occurrence agrees with Kouwen and Unny who found that A/A_b approximates y_n/h only for the case when the vegetation is erect. However, the use of the logarithmic flow formula is still believed to be a good approximation of the velocity profile in the case of prone vegetation. Table 1 is part of the analytical results of the data based on this analysis.

Hydraulic Resistance

A. Non-submerged. For the condition where the water depth is below the top of the vegetation, the drag resistance to flow due to the presence of vegetation can be calculated from the reduced form of equation 50:

$$R_d = \frac{(A_b' - A_p)\gamma S_o - 2\sqrt{\mu\gamma S_o Vm'/2}\ (A_b' - A_p) - 2D_w(\frac{Vm'\mu}{a} + \frac{a}{2}\gamma S_o)}{N_b\ \rho\ A_s\ Vm'^2/2} \tag{61}$$

All the parameters in the right-hand side of Eq. 61 are measurable or constant quantities except for Vm'. By solving Eq. 55 for the mean velocity below the top of the vegetation, Vm, the value for Vm' can be solved by use of Eq. 27.

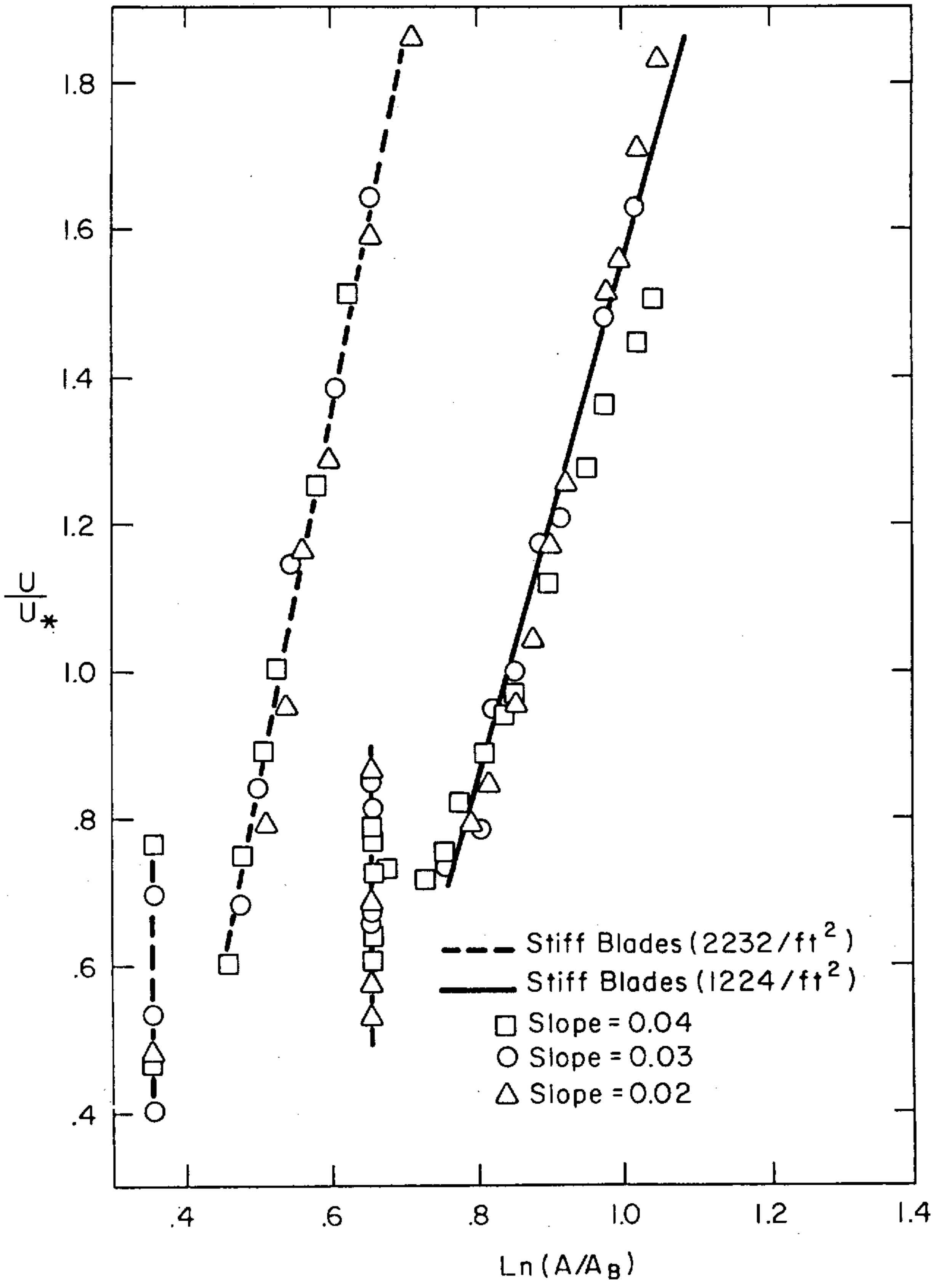

Fig. 12 Plots of U/U_* vs $Ln(A/A_B)$ for stiff simulated grass of different populations

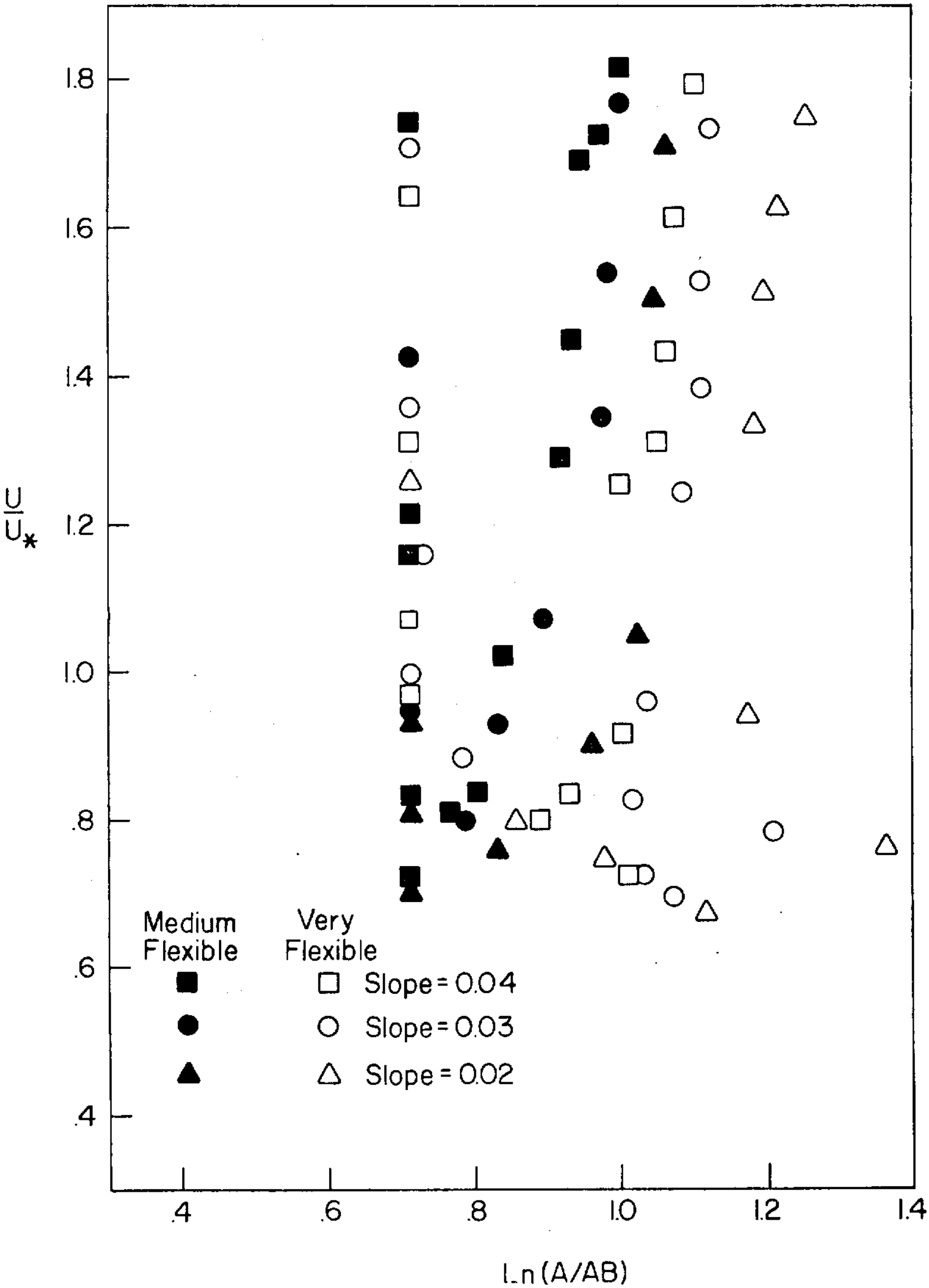

Fig. 13 Plots of U/U_* vs $Ln(A/A_B)$ for flexible grass blades

TABLE 1: Analytical Results of Data Using Kouwen and Unny Approach

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0308	0.1860	0.3249	0.0601	0.2968	0.4879	0.6659	0.6582
0.0374	0.2050	0.3615	0.0736	0.2844	0.5120	0.7061	0.6582
0.0403	0.2170	0.3686	0.0794	0.2897	0.5267	0.6999	0.6582
0.0437	0.2240	0.3879	0.0862	0.2810	0.5349	0.7252	0.6582
0.0441	0.2270	0.3863	0.0870	0.2847	0.5385	0.7174	0.6582
0.0482	0.2520	0.3804	0.0951	0.3100	0.5675	0.6704	0.6582
0.0499	0.2610	0.3799	0.0984	0.3178	0.5775	0.6579	0.6582
0.0511	0.2750	0.3688	0.1007	0.3390	0.5929	0.6221	0.6582
0.0536	0.2920	0.3640	0.1055	0.3576	0.6110	0.5957	0.6582
0.0557	0.3020	0.3657	0.1096	0.3640	0.6213	0.5885	0.6582
0.0574	0.3080	0.3695	0.1130	0.3649	0.6275	0.5889	0.6582
0.0595	0.3220	0.3660	0.1170	0.3796	0.6416	0.5705	0.6582
0.0624	0.3380	0.3657	0.1227	0.3923	0.6573	0.5564	0.6582
0.0694	0.3440	0.4028	0.1374	0.3602	0.6628	0.6077	0.6582
0.0773	0.3780	0.4086	0.1531	0.3780	0.6947	0.5883	0.6582
0.0844	0.3840	0.4412	0.1677	0.3536	0.6998	0.6304	0.6582
0.1356	0.4390	0.5743	0.2484	0.2960	0.7464	0.7694	0.7714
0.1588	0.4540	0.6327	0.2824	0.2743	0.7582	0.8346	0.8050
0.1784	0.4660	0.6782	0.3101	0.2601	0.7674	0.8837	0.8311
0.1879	0.4710	0.7012	0.3237	0.2532	0.7711	0.9093	0.8418
0.2037	0.4760	0.7462	0.3475	0.2393	0.7744	0.9636	0.8523
0.2428	0.4960	0.8287	0.4006	0.2209	0.7890	1.0502	0.8935
0.2744	0.5130	0.8852	0.4413	0.2111	0.8014	1.1046	0.9272
0.3085	0.5230	0.9641	0.4881	0.1958	0.8075	1.1938	0.9465
0.3285	0.5320	0.9983	0.5132	0.1910	0.8137	1.2269	0.9636
0.3480	0.5370	1.0419	0.5394	0.1839	0.8166	1.2759	0.9729
0.3738	0.5450	1.0929	0.5727	0.1767	0.8215	1.3303	0.9877
0.4037	0.5610	1.1277	0.6071	0.1744	0.8327	1.3543	1.0166
0.4374	0.5730	1.1821	0.6480	0.1684	0.8403	1.4069	1.0378

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0368	0.2340	0.3110	0.0723	0.3379	0.5119	0.6077	0.6582
0.0399	0.2450	0.3232	0.0786	0.3353	0.5237	0.6171	0.6582

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

0.0071	0.0860	0.2749	0.0235	0.2099	0.3320	0.8280	0.3578
0.0116	0.1510	0.2576	0.0387	0.3262	0.4400	0.5854	0.3578
0.0162	0.1880	0.2887	0.0540	0.3366	0.4908	0.5883	0.3578
0.0204	0.2240	0.3047	0.0679	0.3584	0.5356	0.5689	0.3578
0.0218	0.2450	0.2964	0.0727	0.3885	0.5602	0.5327	0.3578
0.0241	0.2660	0.3037	0.0803	0.4032	0.5837	0.5203	0.3578
0.0326	0.3390	0.3228	0.1088	0.4458	0.6587	0.4901	0.3578
0.1135	0.4530	0.6345	0.2825	0.2731	0.7573	0.8378	0.5024
0.1383	0.4620	0.7357	0.3327	0.2380	0.7631	0.9641	0.5221
0.1971	0.4880	0.9214	0.4362	0.1959	0.7809	1.1799	0.5769
0.2644	0.5090	1.1258	0.5499	0.1637	0.7932	1.4192	0.6190

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

0.0071	0.0940	0.2517	0.0235	0.2276	0.3247	0.7751	0.3578
0.0116	0.1560	0.2498	0.0388	0.3215	0.4183	0.5971	0.3578
0.0158	0.1980	0.2673	0.0527	0.3520	0.4712	0.5674	0.3578
0.0204	0.2340	0.2921	0.0679	0.3600	0.5120	0.5704	0.3578
0.0210	0.2500	0.2816	0.0700	0.3903	0.5293	0.5320	0.3578
0.0241	0.2760	0.2931	0.0804	0.4005	0.5561	0.5271	0.3578
0.0326	0.3590	0.3051	0.1089	0.4583	0.6341	0.4812	0.3578

SLOPE OF FLUME = C.C3C0FT/FT
DENSITY CF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
C.C071	C.1C40	0.2277	C.0236	0.2492	0.3162	0.7200	0.3578
0.0116	0.1670	0.2336	0.C388	C.3330	C.4007	0.5830	0.3578
0.0156	C.25C0	C.2087	0.0520	0.4882	C.4904	0.4254	0.3578
0.0204	0.2550	0.2682	0.C680	C.3844	0.4949	0.5420	0.3578
C.C241	C.2920	0.2774	C.0805	0.4067	0.5295	0.5239	0.3578
0.1135	0.4620	0.6041	C.2736	C.2513	C.6615	C.9133	0.5221
C.1383	0.4710	0.7021	0.3226	0.2183	0.6662	1.0540	0.5414
C.1971	0.5010	0.8686	C.42C4	C.1827	0.6838	1.2703	0.6031
0.2644	0.5260	1.0498	0.5273	0.1549	0.6966	1.5070	0.6518

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

C.0071	C.12C0	0.1974	0.0236	0.2887	C.3102	0.6366	0.3578
0.0156	0.2500	0.2092	0.0521	0.4443	0.4476	0.4674	0.3578
C.C204	0.2710	0.2528	0.0681	0.3877	0.4656	0.5428	0.3578
0.0241	0.3230	C.2510	C.C806	0.4389	C.5084	0.4937	0.3578

SLOPE OF FLUME = C.0200FT/FT
DENSITY OF SIMULATED GRASS = 2232.C0CCBLADES PER SQ. FCOT
HEIGHT OF SIMULATEC GRASS = 0.3920FT

C.0075	0.1560	0.1608	0.0250	0.3777	0.3164	0.5084	0.3578
0.0154	0.2710	C.19C7	0.C514	0.4599	0.4168	0.4577	0.3578
0.0200	C.3070	0.2188	0.0668	0.4355	0.4434	0.4934	0.3578
C.1383	C.4960	0.6230	0.3004	0.2074	0.5572	1.1181	0.5931
0.1971	0.5250	0.7855	0.3961	C.1695	0.5699	1.3784	0.6499
0.2644	C.5560	0.9381	0.4947	0.1462	0.5828	1.6097	0.7073

SLOPE OF FLUME = 0.0150FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0075	0.1820	0.1381	0.0250	0.4222	0.2960	0.4667	0.3578
0.0154	0.2920	0.1774	0.0515	0.4499	0.3746	0.4737	0.3578

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

0.0368	0.2660	0.2778	0.0734	0.3482	0.4611	0.6024	0.6582
0.0399	0.2970	0.2693	0.0795	0.3866	0.4873	0.5527	0.6582

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

0.0279	0.1820	0.3057	0.0552	0.2691	0.4178	0.7316	0.6582
0.0316	0.1930	0.3285	0.0629	0.2603	0.4301	0.7637	0.6582
0.0391	0.2330	0.3370	0.0779	0.2876	0.4725	0.7133	0.6582
0.0428	0.2600	0.3306	0.0853	0.3155	0.4992	0.6623	0.6582
0.0495	0.2840	0.3509	0.0988	0.3151	0.5215	0.6728	0.6582
0.0511	0.3120	0.3289	0.1018	0.3581	0.5468	0.6014	0.6582
0.0578	0.3380	0.3440	0.1153	0.3610	0.5690	0.6045	0.6582
0.0615	0.3560	0.3480	0.1228	0.3694	0.5839	0.5959	0.6582
0.0661	0.3760	0.3543	0.1320	0.3762	0.6000	0.5905	0.6582
0.0769	0.3920	0.3979	0.1543	0.3440	0.6121	0.6501	0.6582
0.1655	0.4730	0.6129	0.2841	0.2515	0.6691	0.9159	0.8460
0.1925	0.4850	0.6826	0.3233	0.2291	0.6764	1.0093	0.8711
0.2104	0.4910	0.7305	0.3493	0.2155	0.6796	1.0748	0.8834
0.2299	0.5050	0.7613	0.3738	0.2104	0.6887	1.1055	0.9115

0.2707	0.5180	0.8592	0.4303	0.1889	0.6955	1.2355	0.9369
0.3177	0.5360	0.9539	0.4913	0.1734	0.7054	1.3523	0.9711
0.3385	0.5440	0.9925	0.5176	0.1680	0.7098	1.3983	0.9859
0.3601	0.5510	1.0346	0.5450	0.1622	0.7133	1.4505	0.9987
0.3805	0.5590	1.0686	0.5697	0.1584	0.7177	1.4890	1.0131
0.4008	0.5670	1.1011	0.5941	0.1549	0.7220	1.5252	1.0273
0.4229	0.5740	1.1397	0.6209	0.1506	0.7254	1.5711	1.0396
0.4449	0.5810	1.1769	0.6472	0.1468	0.7289	1.6147	1.0517
0.0368	0.2550	0.2869	0.0727	0.3592	0.4947	0.5800	0.6582
0.0399	0.2710	0.2933	0.0790	0.3658	0.5099	0.5752	0.6582

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0116	0.1510	0.1505	0.0226	0.3952	0.3113	0.4833	0.6582
0.0208	0.2260	0.1823	0.0410	0.4265	0.3807	0.4789	0.6582
0.0233	0.2460	0.1880	0.0460	0.4376	0.3971	0.4734	0.6582
0.0254	0.2710	0.1857	0.0501	0.4724	0.4168	0.4456	0.6582
0.0295	0.2880	0.2048	0.0587	0.4460	0.4295	0.4767	0.6582
0.0391	0.3070	0.2578	0.0786	0.3692	0.4430	0.5819	0.6582
0.0428	0.3260	0.2665	0.0862	0.3716	0.4564	0.5838	0.6582
0.0449	0.3470	0.2623	0.0903	0.3937	0.4709	0.5569	0.6582
0.0599	0.3650	0.3363	0.1214	0.3168	0.4821	0.6975	0.6582
0.0678	0.3840	0.3629	0.1376	0.3034	0.4942	0.7343	0.6582
0.1863	0.5070	0.6127	0.3022	0.2141	0.5636	1.0872	0.9154
0.2241	0.5210	0.7047	0.3548	0.1887	0.5694	1.2375	0.9427
0.2532	0.5380	0.7558	0.3915	0.1793	0.5775	1.3087	0.9748
0.2707	0.5480	0.7845	0.4130	0.1746	0.5822	1.3475	0.9932
0.3106	0.5610	0.8675	0.4644	0.1597	0.5871	1.4776	1.0166
0.3281	0.5690	0.8963	0.4854	0.1558	0.5906	1.5176	1.0308
0.3497	0.5760	0.9374	0.5122	0.1498	0.5932	1.5804	1.0430
0.3871	0.5890	1.0028	0.5570	0.1416	0.5981	1.6767	1.0654
0.4075	0.5960	1.0368	0.5809	0.1378	0.6007	1.7260	1.0772
0.4191	0.6090	1.0323	0.5912	0.1404	0.6073	1.6997	1.0987
0.0368	0.2860	0.2607	0.0740	0.3482	0.4275	0.6097	0.6582
0.0399	0.3230	0.2498	0.0801	0.3942	0.4545	0.5497	0.6582

SLOPE OF FLUME = 0.0150FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0075	0.1250	0.1172	0.0146	0.3874	0.2454	0.4778	0.6582
0.0096	0.1340	0.1418	0.0189	0.3353	0.2539	0.5584	0.6582
0.0121	0.1650	0.1455	0.0239	0.3754	0.2818	0.5162	0.6582
0.0146	0.1890	0.1538	0.0290	0.3885	0.3015	0.5102	0.6582
0.0179	0.2170	0.1654	0.0357	0.3962	0.3230	0.5120	0.6582
0.0200	0.2410	0.1663	0.0399	0.4226	0.3404	0.4885	0.6582
0.0249	0.2760	0.1824	0.0501	0.4213	0.3641	0.5011	0.6582
0.0304	0.3140	0.1959	0.0611	0.4275	0.3882	0.5045	0.6582
0.0353	0.3370	0.2134	0.0714	0.4111	0.4020	0.5308	0.6582
0.0387	0.3510	0.2247	0.0783	0.4010	0.4102	0.5478	0.6582
0.0432	0.3770	0.2344	0.0877	0.4030	0.4250	0.5515	0.6582
0.2345	0.5550	0.6662	0.3556	0.1798	0.5077	1.3120	1.0059
0.2495	0.5610	0.6968	0.3749	0.1728	0.5098	1.3669	1.0166
0.2823	0.5740	0.7609	0.4164	0.1600	0.5141	1.4802	1.0396
0.2956	0.5790	0.7862	0.4329	0.1555	0.5157	1.5246	1.0482
0.3102	0.5890	0.8035	0.4493	0.1537	0.5197	1.5462	1.0654
0.3285	0.5950	0.8379	0.4716	0.1481	0.5214	1.6070	1.0755
0.3426	0.6040	0.8544	0.4873	0.1465	0.5249	1.6277	1.0905
0.3580	0.6120	0.8753	0.5048	0.1441	0.5278	1.6584	1.1037
0.3751	0.6190	0.9015	0.5244	0.1407	0.5301	1.7008	1.1150
0.3909	0.6270	0.9218	0.5419	0.1386	0.5329	1.7297	1.1279
0.0368	0.3130	0.2405	0.0747	0.3469	0.3872	0.6212	0.6582
0.0399	0.3540	0.2303	0.0809	0.3935	0.4119	0.5590	0.6582

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0129	0.0570	0.4274	0.0241	0.1023	0.2697	1.5850	0.7084
0.0177	0.0890	0.3714	0.0328	0.1587	0.3373	1.1012	0.7084
0.0239	0.1350	0.3279	0.0440	0.2375	0.4157	0.7888	0.7084
0.0295	0.1300	0.4294	0.0553	0.1765	0.4072	1.0543	0.7084
0.0416	0.2110	0.3684	0.0771	0.2845	0.5193	0.7093	0.7084
0.0447	0.2340	0.3436	0.0799	0.3270	0.5471	0.6280	0.8119
0.0547	0.2450	0.3875	0.0942	0.2987	0.5595	0.6927	0.8578
0.0628	0.2660	0.3873	0.1022	0.3156	0.5829	0.6644	0.9401
0.0707	0.2760	0.4107	0.1124	0.3049	0.5936	0.6920	0.9770
0.0936	0.2860	0.5138	0.1451	0.2490	0.6032	0.8518	1.0125
0.1393	0.3090	0.6792	0.2059	0.1975	0.6249	1.0868	1.0899
0.1622	0.3140	0.7718	0.2368	0.1752	0.6286	1.2278	1.1060
0.1933	0.3180	0.9031	0.2789	0.1503	0.6307	1.4320	1.1186
0.2079	0.3260	0.9361	0.2958	0.1473	0.6380	1.4672	1.1435
0.2308	0.3350	0.9986	0.3233	0.1403	0.6457	1.5465	1.1707
0.2640	0.3500	1.0729	0.3614	0.1341	0.6587	1.6288	1.2145

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

0.0139	0.0630	0.4212	0.0263	0.1038	0.2651	1.5887	0.7084
0.0177	0.1020	0.3240	0.0328	0.1865	0.3379	0.9589	0.7084
0.0239	0.1460	0.3047	0.0442	0.2519	0.4044	0.7536	0.7084
0.0295	0.1460	0.3828	0.0554	0.2002	0.4038	0.9479	0.7084
0.0395	0.2110	0.3524	0.0738	0.2782	0.4857	0.7254	0.7084
0.0447	0.2370	0.3358	0.0790	0.3155	0.5149	0.6522	0.8246
0.0547	0.2550	0.3619	0.0915	0.3073	0.5339	0.6778	0.8978
0.0628	0.2810	0.3545	0.0988	0.3346	0.5605	0.6325	0.9949
0.0707	0.2790	0.4037	0.1116	0.2922	0.5581	0.7234	0.9878

0.0936	0.2860	0.5138	0.1449	0.2327	0.5638	0.9112	1.0125
0.1393	C.3180	C.6506	0.2028	C.1965	0.5928	1.0976	1.1186
0.1622	0.3220	0.7435	0.2337	C.1728	0.5952	1.2493	1.1311
C.1933	0.3260	C.87C5	0.2752	0.1482	0.5969	1.4585	1.1435
0.2079	0.3340	0.9035	0.2921	0.1449	0.6036	1.4968	1.1677
C.23C8	0.3420	0.9692	0.3197	0.1369	0.6097	1.5897	1.1914
0.2640	0.3660	1.0074	0.3548	0.1376	0.6300	1.5990	1.2592

SLCPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000ELACES PER SQ. FOOT
HEIGHT OF SIMULATEC GRASS = 0.2110FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0129	0.0730	0.3347	0.0242	0.1336	C.2645	1.2656	0.7084
0.0177	0.1150	0.2882	0.0329	0.2103	0.3322	0.8675	0.7084
0.0239	0.1640	0.2722	C.0444	C.2822	0.3968	0.6859	0.7084
0.0295	0.1670	0.3351	0.0555	0.2316	C.4000	0.8378	0.7084
0.0378	C.2110	0.3403	0.0712	0.2666	0.4496	0.7569	0.7084
0.0447	0.2530	0.2998	0.0753	C.3419	C.4927	0.6085	0.8899
0.0547	C.2710	0.3272	0.0880	0.3277	0.5096	0.6421	0.9587
0.0628	0.3020	0.3169	0.0950	0.3637	0.5381	0.5890	1.0670
C.0707	0.2840	0.3925	0.1103	0.2814	0.5211	0.7532	1.0055
0.0936	0.3020	0.4723	C.1407	0.2431	0.5364	0.8804	1.0670
0.1393	0.3280	0.6216	0.1997	0.1942	0.5571	1.1157	1.1496
C.1622	C.3310	0.7141	0.2304	0.1696	0.5583	1.2790	1.1587
0.1933	0.3370	0.8295	0.2707	0.1471	0.5615	1.4773	1.1766
0.2C79	0.3500	C.8448	0.2861	0.1480	0.5719	1.4771	1.2145
0.2308	0.3550	0.9190	0.3142	0.1369	C.5747	1.5992	1.2287
C.2640	0.3830	0.9460	0.3484	0.1398	0.5964	1.5861	1.3046

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0129	0.0890	0.2742	0.0242	0.1700	0.2667	1.0281	0.7084
0.0177	0.1300	0.2562	0.0331	0.2344	0.3225	0.7944	0.7084
0.0239	0.1880	0.2384	0.0446	0.3222	0.3879	0.6145	0.7084
0.0295	0.2030	0.2755	0.0555	0.2933	0.4028	0.6838	0.7084
0.0324	0.2110	0.2923	0.0612	0.2835	0.4106	0.7119	0.7084
0.0447	0.2660	0.2757	0.0728	0.3508	0.4611	0.5980	0.9401
0.0547	0.2970	0.2832	0.0835	0.3676	0.4872	0.5812	1.0503
0.0628	0.3280	0.2802	0.0912	0.3970	0.5120	0.5472	1.1496
0.0707	0.2990	0.3623	0.1072	0.2879	0.4880	0.7424	1.0570
0.0936	0.3180	0.4370	0.1370	0.2482	0.5024	0.8697	1.1186
0.1393	0.3390	0.5925	0.1965	0.1900	0.5166	1.1468	1.1826
0.1622	0.3420	0.6811	0.2266	0.1657	0.5176	1.3159	1.1914
0.1933	0.3500	0.7857	0.2658	0.1452	0.5219	1.5055	1.2145
0.2079	0.3630	0.8024	0.2812	0.1456	0.5312	1.5106	1.2510
0.2308	0.3720	0.8608	0.3079	0.1376	0.5366	1.6040	1.2755
0.2640	0.3910	0.9197	0.3444	0.1327	0.5490	1.6751	1.3253

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

0.0129	0.1150	0.2117	0.0242	0.2339	0.2714	0.7801	0.7084
0.0177	0.1560	0.2141	0.0332	0.2833	0.3161	0.6775	0.7084
0.0229	0.2110	0.2042	0.0429	0.3635	0.3677	0.5554	0.7084
0.0239	0.2190	0.2077	0.0452	0.3663	0.3745	0.5546	0.7456
0.0295	0.2400	0.2169	0.0518	0.3727	0.3920	0.5533	0.8372
0.0447	0.2840	0.2482	0.0700	0.3641	0.4262	0.5824	1.0055
0.0547	0.3230	0.2496	0.0800	0.3946	0.4545	0.5491	1.1342

0.0628	0.3650	0.2405	0.0872	0.4444	0.4832	0.4977	1.2565
0.0707	0.3230	0.3226	0.1031	0.3045	0.4537	0.7111	1.1342
0.0936	0.3440	0.3897	0.1322	0.2623	0.4674	0.8336	1.1972
0.1393	0.3520	0.5614	0.1929	0.1836	0.4704	1.1935	1.2202
0.1622	0.3570	0.6407	0.2221	0.1618	0.4725	1.3561	1.2343
0.1933	0.3700	0.7266	0.2594	0.1456	0.4795	1.5154	1.2701
0.2079	0.3850	0.7396	0.2745	0.1467	0.4889	1.5129	1.3098
0.2308	0.3920	0.8010	0.3012	0.1367	0.4921	1.6277	1.3278
0.2640	0.4120	0.8570	0.3372	0.1317	0.5034	1.7025	1.3776

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	CW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0094	0.0420	0.4161	0.0173	0.0858	0.2315	1.7973	0.7173
0.0129	0.0680	0.3493	0.0236	0.1411	0.2949	1.1845	0.7173
0.0166	0.0700	0.4460	0.0309	0.1124	0.2988	1.4930	0.7173
0.0229	0.1220	0.3451	0.0418	0.2109	0.3950	0.8735	0.7173
0.0301	0.1380	0.4261	0.0583	0.1851	0.4196	1.0155	0.7188
0.0322	0.1610	0.3437	0.0550	0.2547	0.4538	0.7574	0.8729
0.0364	0.1670	0.3647	0.0605	0.2459	0.4621	0.7894	0.9095
0.0491	0.2140	0.3343	0.0711	0.3166	0.5233	0.6389	1.1575
0.0530	0.2240	0.3382	0.0753	0.3227	0.5353	0.6318	1.2032
0.0561	0.2230	0.3604	0.0798	0.3018	0.5340	0.6750	1.1987
0.0669	0.2590	0.3491	0.0898	0.3443	0.5756	0.6066	1.3484
0.0680	0.2310	0.4152	0.0950	0.2679	0.5430	0.7646	1.2340
0.0782	0.2500	0.4278	0.1059	0.2740	0.5648	0.7574	1.3130
0.0973	0.2390	0.5665	0.1334	0.2001	0.5508	1.0285	1.2680
0.1133	0.2520	0.6133	0.1520	0.1912	0.5651	1.0853	1.3210
0.1266	0.2550	0.6744	0.1688	0.1750	0.5677	1.1879	1.3328
0.1455	0.2580	0.7630	0.1924	0.1555	0.5699	1.3386	1.3445
0.1705	0.2650	0.8621	0.2223	0.1397	0.5763	1.4960	1.3713
0.1871	0.2680	0.9321	0.2422	0.1298	0.5785	1.6111	1.3825
0.2297	0.2740	1.1112	0.2924	0.1098	0.5822	1.9085	1.4047

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0094	0.0470	0.3725	0.0174	0.0967	0.2292	1.6253	0.7173
0.0129	0.0760	0.3132	0.0236	0.1586	0.2917	1.0736	0.7173
0.0166	0.0780	0.4010	0.0310	0.1258	0.2951	1.3590	0.7173
0.0229	0.1300	0.3259	0.0421	0.2179	0.3814	0.8544	0.7173
0.0260	0.1380	0.3673	0.0503	0.2010	0.3927	0.9353	0.7188
0.0301	0.1510	0.3600	0.0539	0.2178	0.4109	0.8761	0.8088
0.0322	0.1690	0.3167	0.0532	0.2671	0.4350	0.7281	0.9214
0.0364	0.1770	0.3315	0.0583	0.2631	0.4450	0.7449	0.9677
0.0491	0.2240	0.3130	0.0697	0.3262	0.5008	0.6250	1.2032
0.0530	0.2380	0.3105	0.0734	0.3424	0.5162	0.6014	1.2638
0.0561	0.2320	0.3407	0.0785	0.3065	0.5094	0.6688	1.2383
0.0669	0.2730	0.3254	0.0882	0.3579	0.5528	0.5886	1.4010
0.0680	0.2400	0.3935	0.0936	0.2711	0.5177	0.7602	1.2722
0.0782	0.2840	0.3607	0.1016	0.3313	0.5635	0.6401	1.4405
0.0973	0.2490	0.5353	0.1314	0.2035	0.5259	1.0180	1.3090
0.1133	0.2570	0.5971	0.1508	0.1860	0.5335	1.1192	1.3406
0.1266	0.2610	0.6535	0.1672	0.1715	0.5370	1.2170	1.3561
0.1455	0.2620	0.7473	0.1911	0.1499	0.5368	1.3921	1.3599
0.1705	0.2700	0.8408	0.2205	0.1355	0.5436	1.5467	1.3900
0.1871	0.2720	0.9139	0.2405	0.1249	0.5446	1.6781	1.3973
0.2297	0.2800	1.0798	0.2897	0.1071	0.5499	1.9638	1.4263

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0094	0.0520	0.3380	0.0174	0.1055	0.2232	1.5142	0.7173
0.0129	0.0830	0.2884	0.0238	0.1691	0.2822	1.0219	0.7173
0.0166	0.0890	0.3520	0.0311	0.1449	0.2919	1.2057	0.7173
0.0229	0.1380	0.3233	0.0443	0.2115	0.3637	0.8888	0.7188
0.0301	0.1670	0.3022	0.0501	0.2571	0.4002	0.7551	0.9095
0.0322	0.1880	0.2669	0.0499	0.3153	0.4249	0.6281	1.0280
0.0364	0.1930	0.2893	0.0555	0.2958	0.4304	0.6723	1.0542
0.0491	0.2420	0.2808	0.0675	0.3545	0.4820	0.5825	1.2805
0.0530	0.2570	0.2794	0.0714	0.3708	0.4967	0.5625	1.3406
0.0561	0.2430	0.3194	0.0770	0.3122	0.4827	0.6617	1.2846
0.0669	0.2900	0.3005	0.0866	0.3735	0.5275	0.5698	1.4614
0.0680	0.2480	0.3761	0.0924	0.2684	0.4871	0.7722	1.3050
0.0782	0.2950	0.3432	0.1004	0.3304	0.5316	0.6457	1.4785
0.0973	0.2610	0.5022	0.1291	0.2072	0.4984	1.0077	1.3561
0.1133	0.2670	0.5672	0.1487	0.1859	0.5033	1.1271	1.3788
0.1266	0.2690	0.6276	0.1653	0.1685	0.5044	1.2441	1.3862
0.1455	0.2710	0.7143	0.1887	0.1483	0.5051	1.4140	1.3937
0.1705	0.2790	0.8051	0.2178	0.1337	0.5112	1.5748	1.4227
0.1871	0.2810	0.8754	0.2375	0.1232	0.5120	1.7097	1.4299
0.2297	0.2890	1.0360	0.2862	0.1054	0.5166	2.0055	1.4580

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0094	0.0600	0.2937	0.0175	0.1220	0.2189	1.3416	0.7173
0.0129	0.0940	0.2559	0.0239	0.1891	0.2742	0.9331	0.7173
0.0166	0.0990	0.3180	0.0312	0.1572	0.2811	1.1314	0.7173
0.0208	0.1380	0.2939	0.0402	0.2124	0.3320	0.8851	0.7188
0.0229	0.1590	0.2493	0.0394	0.2755	0.3567	0.6988	0.8604
0.0301	0.1850	0.2560	0.0471	0.2967	0.3847	0.6655	1.0119
0.0322	0.2010	0.2409	0.0482	0.3334	0.4011	0.6007	1.0948
0.0364	0.2110	0.2531	0.0531	0.3277	0.4109	0.6160	1.1434
0.0491	0.2620	0.2519	0.0656	0.3803	0.4579	0.5503	1.3599
0.0530	0.2740	0.2564	0.0698	0.3849	0.4682	0.5477	1.4047
0.0561	0.2560	0.2974	0.0755	0.3169	0.4522	0.6577	1.3367
0.0669	0.3120	0.2735	0.0848	0.3933	0.4994	0.5477	1.5345
0.0680	0.2600	0.3527	0.0908	0.2695	0.4552	0.7749	1.3522
0.0782	0.3190	0.3105	0.0982	0.3513	0.5046	0.6153	1.5567
0.0973	0.2740	0.4706	0.1269	0.2084	0.4660	1.0099	1.4047
0.1133	0.2760	0.5428	0.1469	0.1811	0.4668	1.1628	1.4119
0.1266	0.2800	0.5951	0.1630	0.1665	0.4695	1.2676	1.4263
0.1455	0.2880	0.6593	0.1850	0.1528	0.4753	1.3871	1.4545
0.1705	0.2900	0.7653	0.2148	0.1316	0.4753	1.6101	1.4614
0.1871	0.2960	0.8180	0.2335	0.1245	0.4794	1.7063	1.4819
0.2297	0.3000	0.9870	0.2822	0.1033	0.4797	2.0575	1.4953

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VAVG	VR	N	S.VEL.	V/U*	LN(A/AB)
0.0094	0.0760	0.2317	0.0175	0.1621	0.2205	1.0505	0.7173
0.0129	0.1120	0.2155	0.0240	0.2257	0.2678	0.8049	0.7173
0.0166	0.1300	0.2414	0.0312	0.2224	0.2884	0.8372	0.7173
0.0187	0.1380	0.2645	0.0362	0.2111	0.2970	0.8906	0.7188
0.0229	0.1820	0.1993	0.0361	0.3375	0.3415	0.5836	0.9955
0.0301	0.2080	0.2142	0.0443	0.3432	0.3650	0.5869	1.1291
0.0322	0.2190	0.2124	0.0462	0.3582	0.3745	0.5670	1.1806
0.0364	0.2340	0.2182	0.0508	0.3643	0.3871	0.5637	1.2469
0.0491	0.2860	0.2243	0.0638	0.4051	0.4279	0.5242	1.4475
0.0530	0.2980	0.2298	0.0680	0.4064	0.4367	0.5261	1.4886
0.0561	0.2790	0.2651	0.0734	0.3367	0.4222	0.6278	1.4227
0.0669	0.3370	0.2482	0.0830	0.4082	0.4642	0.5346	1.6116
0.0680	0.2850	0.3122	0.0881	0.2896	0.4263	0.7324	1.4440
0.0782	0.3430	0.2835	0.0964	0.3612	0.4680	0.6058	1.6293
0.0973	0.2870	0.4428	0.1250	0.2042	0.4263	1.0386	1.4510
0.1133	0.2910	0.5064	0.1443	0.1797	0.4285	1.1819	1.4649
0.1266	0.2970	0.5511	0.1599	0.1671	0.4322	1.2750	1.4853
0.1455	0.3080	0.6045	0.1812	0.1557	0.4394	1.3758	1.5216
0.1705	0.3120	0.6965	0.2102	0.1357	0.4408	1.5802	1.5345
0.1871	0.3160	0.7522	0.2289	0.1264	0.4427	1.6992	1.5473
0.2297	0.3230	0.8983	0.2761	0.1066	0.4449	2.0189	1.5692

In arriving at a relationship which indicates how the drag coefficient, R_d, varies over various flow rates, plots of the drag coefficient vs. the Reynold's number based on the mean characteristic dimension of blade were prepared. The characteristic length used to find the Reynolds' number is taken as being equal to the average projectional width of blades, L_{avg}, or:

$$Re_1 = \frac{Vm' \; L_{avg}}{\nu} \tag{62}$$

To assure that the laminar flow assumption was correct a Reynold's number based on the gap width where water flows between the blades, g_p, was used:

$$Re_f = \frac{Vm' g_p}{\nu} \tag{63}$$

If the value obtained for Re_f for a given flow rate is found to be less than 2000 the assumption of laminar flow is considered valid. Table 2 shows the values of the pertinent parameters under various non-submerged flow conditions. Since the values of Re_f are less than 2000 it is concluded that the laminar flow assumption is justified.

Figure 14 is the plot of R_d vs. Re_1 for various vegetation stiffnesses and population densities used. This plot indicates that for a given Re_1, R_d is dependent on slope and density but independent of grass stiffness. By plotting $\frac{R_d}{\gamma S_o}$ against Re_1 as shown in Fig. 15, it is seen that only two curved are formed. This demonstrates the fact that for a given Re_1, $\frac{R_d}{\gamma S_o}$ is dependent only on the vegetative density. Furthermore, if the number of

TABLE 2: Values of the Pertinent Parameters Under Various Non-submerged Conditions

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0305	0.1860	0.3263	0.0024	1.1761	277.4128	443.108	412.663	5568.801	0.471
0.0374	0.2050	0.3630	0.0025	0.9502	224.1366	492.891	459.025	6927.203	0.381
0.0403	0.2170	0.3700	0.0025	0.9144	215.6732	502.438	467.916	7366.832	0.366
0.0437	0.2240	0.3894	0.0026	0.8255	194.7086	528.780	492.448	8003.156	0.331
0.0441	0.2270	0.3878	0.0026	0.8324	196.3419	526.547	490.369	8076.105	0.333
0.0482	0.2520	0.3817	0.0025	0.8592	202.6663	518.313	482.700	8825.324	0.344
0.0499	0.2610	0.3811	0.0025	0.8616	203.2387	517.524	481.966	9126.613	0.345
0.0511	0.2750	0.3700	0.0025	0.9148	215.7755	502.335	467.820	9333.926	0.367
0.0536	0.2920	0.3650	0.0025	0.9399	221.7018	495.628	461.574	9778.605	0.377
0.0557	0.3020	0.3667	0.0025	0.9313	219.6691	497.840	463.634	10158.621	0.373
0.0574	0.3080	0.3705	0.0025	0.9120	215.1177	503.094	468.527	10469.805	0.365
0.0595	0.3220	0.3670	0.0025	0.9299	219.3329	498.252	464.017	10840.344	0.373
0.0624	0.3380	0.3666	0.0025	0.9315	219.7253	497.813	463.609	11368.984	0.373
0.0694	0.3440	0.4038	0.0026	0.7678	181.1031	548.294	510.621	12744.121	0.308
0.0773	0.3780	0.4096	0.0026	0.7462	176.0177	556.141	517.929	14204.137	0.299
0.0844	0.3840	0.4422	0.0027	0.6401	150.9848	600.422	559.167	15578.516	0.256

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

0.0368	0.2340	0.3121	0.0025	1.1245	303.1343	423.771	394.655	6700.168	0.515
0.0399	0.2450	0.3243	0.0025	1.0419	280.8662	440.277	410.026	7288.363	0.477

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

0.0071	0.0860	0.2773	0.0022	0.8121	349.3208	376.561	161.990	2188.123	0.325
0.0116	0.1510	0.2589	0.0021	0.9328	401.2212	351.489	151.204	3586.140	0.374
0.0162	0.1880	0.2859	0.0022	0.7434	319.7363	393.567	169.305	4999.359	0.298
0.0204	0.2240	0.3057	0.0023	0.6681	287.3594	415.142	178.587	6283.230	0.268
0.0218	0.2450	0.2993	0.0023	0.6972	299.8770	406.446	174.846	6728.324	0.279
0.0241	0.2660	0.3046	0.0023	0.6733	289.5901	413.583	177.916	7433.328	0.270
0.0326	0.3390	0.3236	0.0023	0.5965	256.5566	439.336	188.995	10063.172	0.239

TABLE 2: Continued

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0071	0.0940	0.2537	0.0022	0.8486	417.1602	344.425	148.166	2187.563	0.389
0.0116	0.1560	0.2510	0.0022	0.8677	426.5547	340.793	146.603	3592.141	0.397
0.0158	0.1980	0.2684	0.0023	0.7586	372.9238	364.414	156.765	4875.277	0.347
0.0204	0.2340	0.2931	0.0024	0.6361	312.6648	397.905	171.172	6291.191	0.291
0.0210	0.2500	0.2825	0.0023	0.6847	336.5864	383.557	165.000	6479.000	0.314
0.0241	0.2760	0.2940	0.0024	0.6322	310.7671	399.141	171.704	7443.449	0.289
0.0326	0.3590	0.3058	0.0024	0.5840	287.0581	415.233	178.626	10072.223	0.267

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0071	0.1040	0.2293	0.0023	0.8899	510.3296	311.407	133.962	2188.266	0.475
0.0116	0.1670	0.2346	0.0023	0.8501	487.5107	318.603	137.058	3595.051	0.454
0.0156	0.2500	0.2093	0.0022	1.0701	613.7051	284.137	122.231	4799.613	0.572
0.0204	0.2550	0.2691	0.0025	0.6463	370.6580	365.371	157.176	6295.238	0.345
0.0241	0.2920	0.2782	0.0025	0.6047	346.8210	377.742	162.498	7452.746	0.323

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0071	0.1200	0.1988	0.0023	0.9878	679.7966	269.908	116.110	2188.448	0.633
0.0156	0.2500	0.2099	0.0024	0.8857	609.5637	284.971	122.589	4813.695	0.568
0.0204	0.2710	0.2536	0.0026	0.6062	417.1565	344.293	148.109	6304.277	0.389
0.0241	0.3230	0.2517	0.0026	0.6154	423.5300	341.729	147.006	7458.004	0.394

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0075	0.1560	0.1616	0.0023	1.1943	1027.3875	219.464	94.410	2313.269	0.957
0.0154	0.2710	0.1913	0.0025	0.8520	732.9734	259.804	111.763	4757.227	0.683
0.0200	0.3070	0.2194	0.0027	0.6475	557.0244	297.892	128.148	6179.250	0.519

TABLE 2: Continued

SLOPE OF FLUME = 0.0150FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0075	0.1820	0.1388	0.0025	1.2152	1393.8623	188.440	81.064	2317.304	1.298
0.0154	0.2920	0.1780	0.0028	0.7375	845.8623	241.723	103.985	4769.129	0.788

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0368	0.2660	0.2787	0.0027	1.0068	379.9539	378.440	352.438	6801.699	0.645
0.0399	0.2970	0.2701	0.0027	1.0717	404.4707	366.790	341.589	7360.594	0.687

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0279	0.1820	0.3072	0.0026	0.9949	312.8806	417.062	388.406	5128.730	0.531
0.0316	0.1930	0.3301	0.0027	0.8616	270.9758	448.164	417.371	5844.301	0.460
0.0391	0.2330	0.3384	0.0028	0.8196	257.7705	459.420	427.853	7232.758	0.438
0.0428	0.2600	0.3317	0.0027	0.8529	268.2329	450.382	419.437	7912.117	0.456
0.0495	0.2840	0.3521	0.0028	0.7572	238.1372	478.061	445.214	9173.602	0.404
0.0511	0.3120	0.3298	0.0027	0.8629	271.3816	447.836	417.065	9440.867	0.461
0.0578	0.3380	0.3449	0.0028	0.7889	248.1100	468.309	436.132	10695.172	0.421
0.0615	0.3560	0.3489	0.0028	0.7711	242.5134	473.739	441.189	11395.340	0.412
0.0661	0.3760	0.3552	0.0028	0.7439	233.9509	482.321	449.181	12253.566	0.397
0.0769	0.3920	0.3989	0.0030	0.5895	185.4069	541.679	504.461	14347.180	0.315

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0116	0.1510	0.1512	0.0023	2.7378	1291.5537	205.300	191.194	2094.612	2.194
0.0208	0.2260	0.1830	0.0025	1.8700	882.1914	248.477	231.405	3794.314	1.498
0.0233	0.2460	0.1886	0.0025	1.7594	829.9797	256.109	238.512	4256.949	1.410
0.0254	0.2710	0.1863	0.0025	1.8039	851.0034	252.899	235.522	4630.781	1.445
0.0295	0.2880	0.2054	0.0026	1.4837	699.9265	278.840	259.681	5426.074	1.189
0.0391	0.3070	0.2586	0.0030	0.9352	441.1885	351.127	327.001	7283.504	0.749
0.0428	0.3260	0.2673	0.0030	0.8755	413.0085	362.943	338.006	7994.563	0.702
0.0449	0.3470	0.2630	0.0030	0.9041	426.5173	357.153	332.613	8373.789	0.724
0.0599	0.3650	0.3373	0.0034	0.5492	259.0862	458.050	426.578	11296.512	0.440
0.0678	0.3840	0.3640	0.0035	0.4715	222.4156	494.254	460.295	12823.906	0.378

TABLE 2: Continued

SLOPE OF FLUME = 0.0150FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMF	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0075	0.1250	0.1179	0.0023	3.3740	2122.2512	160.104	149.104	1352.232	3.605
0.0096	0.1340	0.1426	0.0025	2.3045	1449.5427	193.654	180.348	1753.351	2.462
0.0121	0.1650	0.1462	0.0026	2.1953	1380.8628	198.457	184.821	2212.523	2.345
0.0146	0.1890	0.1546	0.0026	1.9647	1235.8123	209.888	195.467	2680.325	2.099
0.0179	0.2170	0.1661	0.0027	1.7017	1070.3767	225.507	210.012	3306.415	1.818
0.0200	0.2410	0.1669	0.0027	1.6848	1059.7454	226.625	211.054	3690.311	1.800
0.0249	0.2760	0.1831	0.0029	1.3997	880.3831	248.576	231.497	4635.613	1.495
0.0304	0.3140	0.1965	0.0030	1.2151	764.2896	266.785	248.455	5660.180	1.298
0.0353	0.3370	0.2141	0.0031	1.0234	643.7366	290.682	270.710	6618.910	1.093
0.0387	0.3510	0.2254	0.0032	0.9229	580.5015	306.019	284.993	7257.613	0.986
0.0432	0.3770	0.2351	0.0033	0.8483	533.5876	319.216	297.283	8131.379	0.906

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

0.0129	0.0570	0.4343	0.0027	0.7602	179.3061	560.823	578.081	2271.186	0.305
0.0177	0.0890	0.3751	0.0025	1.0214	240.9334	484.299	499.202	3062.357	0.409
0.0239	0.1350	0.3298	0.0024	1.3217	311.7456	425.839	438.943	4084.431	0.530
0.0295	0.1300	0.4323	0.0027	0.7684	181.2375	558.221	575.398	5155.863	0.308
0.0416	0.2110	0.3698	0.0025	1.0509	247.8851	477.555	492.250	7159.090	0.421

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

0.0139	0.0630	0.4277	0.0029	0.6859	184.8856	552.344	569.341	2472.307	0.314
0.0177	0.1020	0.3267	0.0025	1.1777	317.4661	421.860	434.841	3057.177	0.539
0.0239	0.1460	0.3064	0.0024	1.3393	361.0366	395.611	407.784	4103.672	0.613
0.0295	0.1460	0.3852	0.0027	0.8471	228.3533	497.441	512.748	5159.957	0.388
0.0395	0.2110	0.3538	0.0026	1.0046	270.8120	456.874	470.933	6849.059	0.460

TABLE 2: Continued

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0129	0.0730	0.3390	0.0028	0.9363	294.4624	437.709	451.178	2270.181	0.500
0.0177	0.1150	0.2903	0.0026	1.2779	401.9033	374.886	386.422	3063.016	0.683
0.0239	0.1640	0.2735	0.0025	1.4402	452.9438	353.212	364.080	4115.578	0.769
0.0295	0.1670	0.3369	0.0028	0.9488	298.3831	435.083	448.471	5162.266	0.507
0.0378	0.2110	0.3418	0.0028	0.9223	290.0728	441.373	454.955	6616.672	0.493

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0129	0.0890	0.2772	0.0027	1.1685	441.0093	357.920	368.934	2263.227	0.749
0.0177	0.1300	0.2579	0.0026	1.3496	509.3533	333.057	343.305	3076.193	0.865
0.0239	0.1880	0.2394	0.0025	1.5666	591.2188	309.176	318.689	4129.664	1.004
0.0295	0.2030	0.2767	0.0027	1.1730	442.6956	357.249	368.241	5152.500	0.752
0.0324	0.2110	0.2935	0.0028	1.0419	393.2061	379.054	390.719	5682.453	0.668

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0129	0.1150	0.2134	0.0027	1.5772	744.0208	275.523	284.001	2251.165	1.264
0.0177	0.1560	0.2154	0.0027	1.5485	730.4851	278.137	286.696	3082.726	1.241
0.0229	0.2110	0.2051	0.0026	1.7090	806.2334	264.841	272.990	3970.265	1.369

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0094	0.0420	0.4251	0.0027	0.8110	191.2966	544.021	570.661	1637.915	0.325
0.0129	0.0680	0.3534	0.0024	1.1756	277.3005	452.296	474.444	2204.739	0.471
0.0166	0.0700	0.4521	0.0028	0.7188	169.5469	578.644	606.979	2903.591	0.288
0.0229	0.1220	0.3474	0.0024	1.2190	287.5383	444.652	466.426	3888.716	0.488

TABLE 2: Continued

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	CW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0094	0.0470	0.3797	0.0027	0.8899	239.8875	486.001	509.800	1637.425	0.407
0.0129	0.0760	0.3165	0.0025	1.2829	345.8313	405.119	424.957	2207.101	0.587
0.0166	0.0780	0.4059	0.0028	0.7801	210.3008	519.484	544.922	2904.641	0.357
0.0229	0.1300	0.3280	0.0025	1.1962	322.4661	419.725	440.279	3911.424	0.548

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	CW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0094	0.0520	0.3442	0.0028	0.9291	292.2053	440.570	462.144	1642.268	0.496
0.0129	0.0830	0.2915	0.0026	1.2979	408.1978	373.091	391.361	2219.825	0.693
0.0166	0.0890	0.3558	0.0028	0.8705	273.7632	455.323	477.619	2904.929	0.465

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	CW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0094	0.0600	0.2983	0.0028	1.0298	388.6631	381.778	400.473	1642.057	0.660
0.0129	0.0940	0.2584	0.0026	1.3769	519.6462	330.667	346.859	2228.150	0.883
0.0166	0.0990	0.3211	0.0029	0.8898	335.7998	410.990	431.115	2916.705	0.570

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	CW	VMP	BLT	RD	N*RD/GM*S	RE1	REF	RE2	RD/GM*S
0.0094	0.0760	0.2346	0.0028	1.3345	629.5491	300.259	314.962	1635.819	1.069
0.0129	0.1120	0.2172	0.0027	1.5566	734.3328	278.009	291.623	2232.048	1.247
0.0166	0.1300	0.2432	0.0029	1.2425	586.1428	311.227	326.467	2900.324	0.996

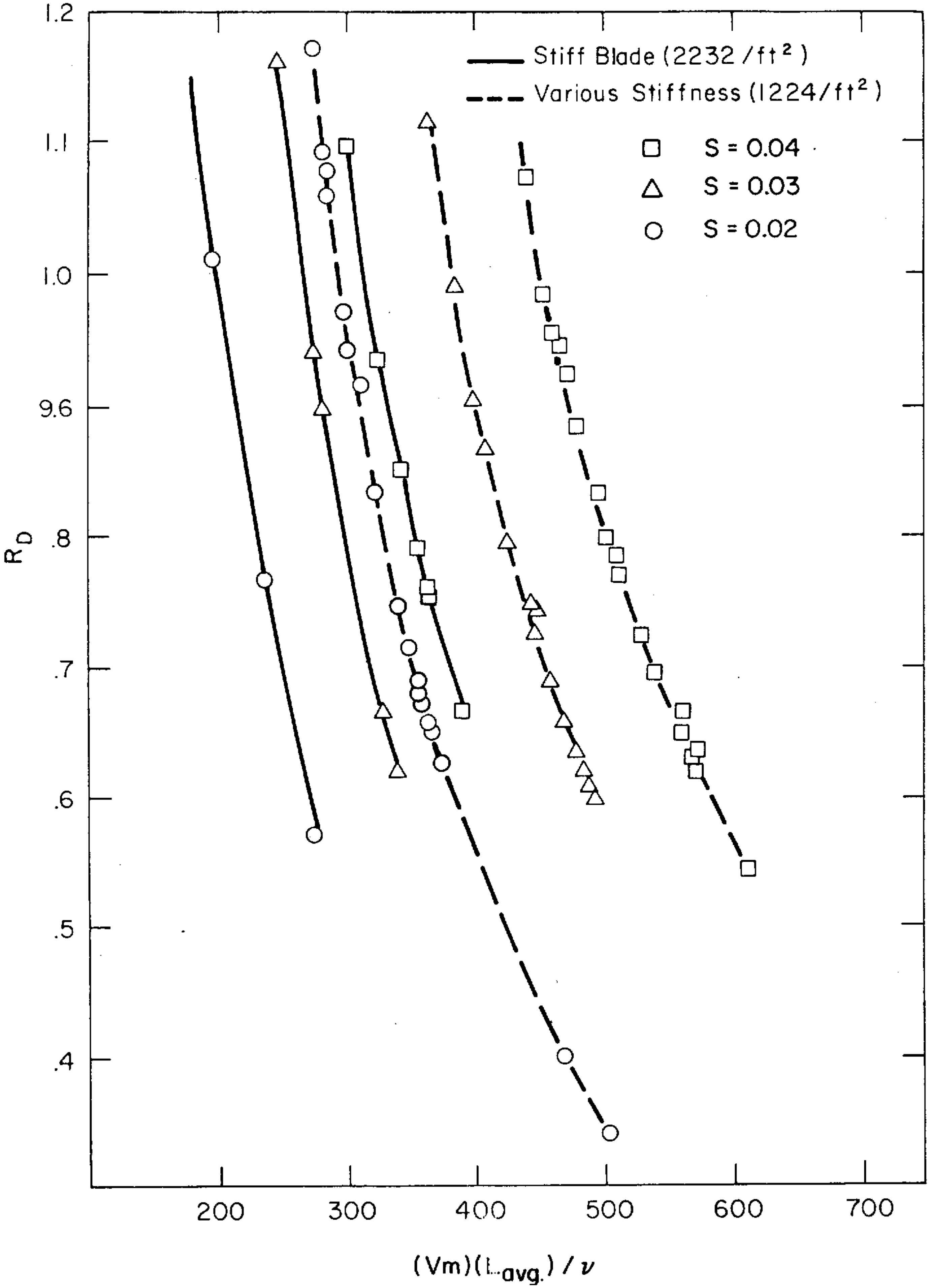

Fig. 14 R_D vs R_1 curves for different simulated grass . . . .

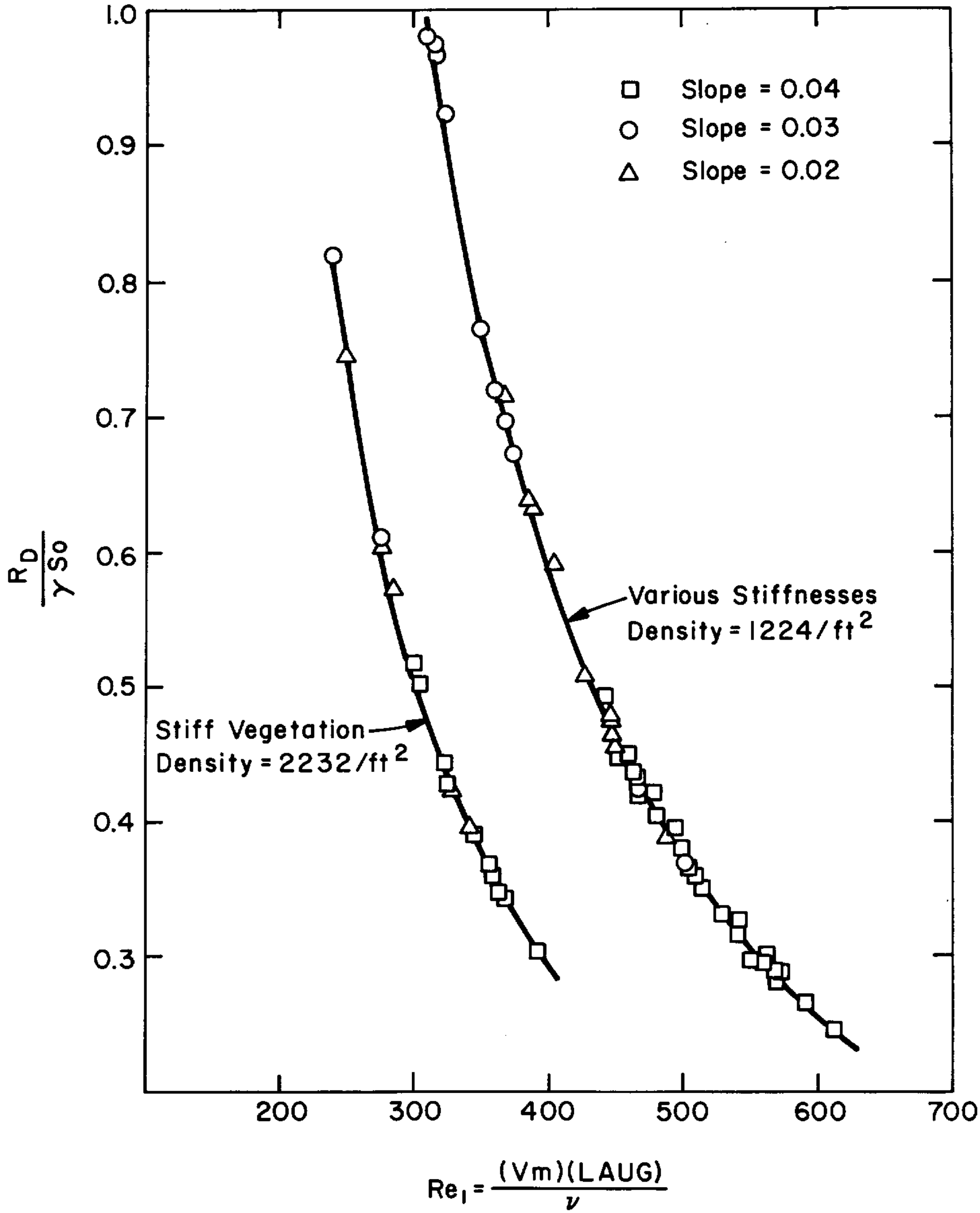

Fig. 15 Plot of R_D/S_0 vs blade Reynolds numer R_{el} for various simulated grass

blades in one foot length of flume, N_b, is multiplied by $\frac{R_d}{\gamma S_o}$ and plotted against Re_1 as in Fig. 16, only one curve results to represent the total drag resistance in the section.

B. Submerged Flow. For the submerged flow case, Eq. 49 is the applicable drag equation. The major assumption in the submerged flow analysis is that the curve of the $\frac{N_b C_d}{\gamma S_o}$ vs. Re_1 plot for non-submerged flow (Fig. 16) remains valid in the submerged condition. In order to obtain a mathematical expression of the curve represents of $\frac{N_b R_d}{\gamma S_o}$ vs. Re_1 linear regression technique was used. The following equation formed

$$\ln(N_b R_d/\gamma S_o) = \ln K + x \ln(Re_1) \tag{64}$$

can be used to describe the straight line. When the linear regression method was employed to determine the constants K and x, the following ecpression is obtained as:

$$\frac{N_b R_d}{\gamma S_o} = 2.05\ (10)^7\ (Re_1)^{-1.848} \tag{65}$$

Solving equation 65 for R_d gives:

$$R_d = \frac{\gamma S_o [2.05\ (10)^7\ [\frac{Vm'\ L_{avg}}{\nu}]^{-1.848}}{N_b} \tag{66}$$

By substituting the drag coefficient equation into the drag equation, Eq. 49, Vm' can then be solved for by trial and error procedure.

An expression in the form of Eq. 47 is used to calculate a Manning's n value for that portion of flow above the vegetation,

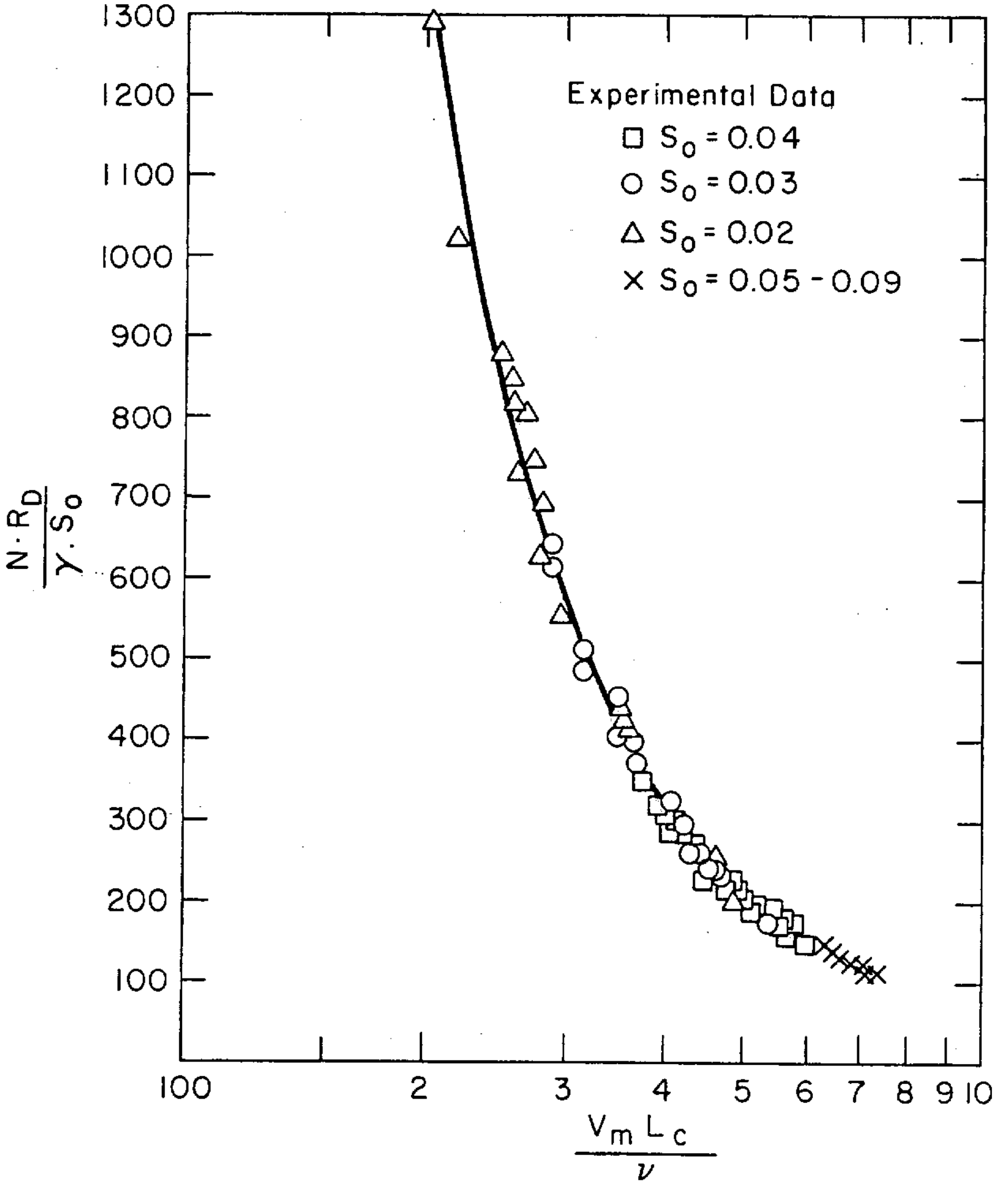

Fig. 16 Plot of $NR_D/\gamma S_0$ vs blade Reynolds number R_{el} for various simulated grass

nt:

$$\tau_{wt} = \frac{.45\gamma\, n_t^{\,2}\, V_t^{\,2}}{R_t^{\,1/3}} \tag{67}$$

where:

τ_{wt} = shear due to sidewall above the blades, FL^{-2}.

The shear due to the top of blades, τ_{ts}, is calculated from the shear velocity term, U_*, in Eq. 34 as being:

$$U_* = \sqrt{\tau_{ts}/\rho} \tag{68}$$

The force due to τ_{ts}, is not included in the drag equation because for erect vegetation this resistance is internal and is therefore included as part of the drag resistance. Table 3 gives the pertinent parameter values for the two densities of the stiff vegetation.

In the medium and least stiff simulated vegetation experiments, it was noted that the blades bent down to form a wavy bed. For this condition it is believed that two separate and distinct flow areas are formed. Thus the shear term, τ_{ts}, is no longer an internal shear and must be included in the drag equation. The form of the drag equation for flexible media becomes:

$$W\, S_o = (F_d + F_{ws} + F_b) + (F_{wt} + F_{ts}) \tag{69}$$

where:

F_{ts} = Force due to shear at top of blades = $\tau_{ts}\, W_c$

The exact value of the shear term due to wavy flexible bed is

TABLE 3: Values of the Pertinent Parameters Under Submerged Flow Conditions

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.1356	0.4390	0.5550	0.0031	0.6578	0.4579	0.0205	0.0650	701.80	2836.20
0.1588	0.4540	0.5650	0.0031	0.8438	0.4579	0.0223	0.0910	714.44	4799.69
0.1784	0.4660	0.5730	0.0031	0.9507	0.4579	0.0220	0.1010	724.56	6454.40
0.1879	0.4710	0.5760	0.0031	1.0044	0.4579	0.0219	0.1060	728.35	7279.95
0.2037	0.4760	0.5790	0.0031	1.1260	0.4579	0.0221	0.1200	732.15	8677.72
0.2428	0.4960	0.5910	0.0032	1.2636	0.4579	0.0211	0.1290	747.32	12056.24
0.2744	0.5130	0.6030	0.0032	1.3286	0.4579	0.0206	0.1320	762.50	14748.14
0.3065	0.5230	0.6050	0.0032	1.4802	0.4579	0.0203	0.1450	768.82	17789.84
0.3285	0.5320	0.6140	0.0032	1.5196	0.4579	0.0200	0.1470	776.40	19517.27
0.3480	0.5370	0.6160	0.0032	1.5993	0.4579	0.0201	0.1550	778.93	21275.61
0.3738	0.5450	0.6210	0.0032	1.6781	0.4579	0.0197	0.1600	785.26	23554.37
0.4037	0.5610	0.6310	0.0033	1.6852	0.4579	0.0193	0.1570	797.90	26128.24
0.4374	0.5730	0.6380	0.0033	1.7523	0.4579	0.0190	0.1610	806.75	29097.25

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.1135	0.4530	0.5420	0.0030	0.8159	0.2511	0.0223	0.0880	316.58	4566.19
0.1383	0.4620	0.5470	0.0030	1.0561	0.2511	0.0229	0.1170	319.50	6782.03
0.1971	0.4880	0.5630	0.0031	1.3633	0.2511	0.0220	0.1450	328.85	12007.41
0.2644	0.5090	0.5740	0.0031	1.6833	0.2511	0.0210	0.1710	335.27	18068.68

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.1135	0.4620	0.5480	0.0035	0.7013	0.1883	0.0201	0.0680	320.09	4503.91
0.1383	0.4710	0.5530	0.0035	0.9272	0.1883	0.0217	0.0970	323.01	6719.79
0.1971	0.5010	0.5720	0.0036	1.1913	0.1883	0.0209	0.1200	334.11	11912.98
0.2644	0.5260	0.5870	0.0036	1.4586	0.1883	0.0203	0.1430	342.87	17931.25

TABLE 3: Continued

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.1383	0.4960	0.5700	0.0044	0.6855	0.1255	0.0181	0.0600	332.94	6540.96
0.1971	0.5250	0.5880	0.0045	0.9626	0.1255	0.0194	0.0900	343.45	11745.13
0.2644	0.5560	0.6070	0.0045	1.1778	0.1255	0.0190	0.1080	354.55	17720.56

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

0.1655	0.4730	0.5780	0.0036	0.6984	0.3434	0.0193	0.0650	730.88	5189.61
0.1925	0.4850	0.5850	0.0036	0.8847	0.3434	0.0206	0.0880	739.73	7548.32
0.2104	0.4910	0.5890	0.0036	1.0041	0.3434	0.0208	0.1010	744.79	9119.58
0.2299	0.5050	0.5980	0.0037	1.0376	0.3434	0.0204	0.1020	756.17	10757.14
0.2707	0.5180	0.6050	0.0037	1.2435	0.3434	0.0203	0.1220	765.02	14374.70
0.3177	0.5360	0.6150	0.0037	1.4013	0.3434	0.0200	0.1350	777.67	18512.69
0.3385	0.5440	0.6200	0.0037	1.4581	0.3434	0.0196	0.1380	783.99	20333.73
0.3601	0.5510	0.6240	0.0038	1.5252	0.3434	0.0196	0.1440	789.05	22248.33
0.3805	0.5590	0.6290	0.0038	1.5685	0.3434	0.0193	0.1460	795.37	24031.23
0.4008	0.5670	0.6330	0.0038	1.6089	0.3434	0.0192	0.1490	800.43	25831.41
0.4229	0.5740	0.6370	0.0038	1.6640	0.3434	0.0190	0.1530	805.49	27784.14
0.4449	0.5810	0.6410	0.0038	1.7150	0.3434	0.0188	0.1560	810.55	29736.89
0.0368	0.2550	0.2879	0.0025	1.3286	1.1328	0.0206	0.1320	364.08	14748.14
0.0399	0.2710	0.2943	0.0026	1.4802	1.0843	0.0203	0.1450	372.09	17789.84

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

0.1863	0.5070	0.6000	0.0045	0.6374	0.2289	0.0149	0.0460	758.70	6724.51
0.2241	0.5210	0.6080	0.0045	0.8499	0.2289	0.0188	0.0770	768.82	10057.94
0.2532	0.5380	0.6200	0.0046	0.9348	0.2289	0.0188	0.0850	783.99	12521.32
0.2707	0.5480	0.6250	0.0046	0.9808	0.2289	0.0188	0.0890	790.31	14037.29
0.3106	0.5610	0.6320	0.0046	1.1338	0.2289	0.0188	0.1030	799.17	17578.71
0.3281	0.5690	0.6360	0.0046	1.1769	0.2289	0.0187	0.1060	804.22	19111.91
0.3497	0.5760	0.6400	0.0047	1.2456	0.2289	0.0186	0.1120	809.28	21026.59
0.3871	0.5890	0.6470	0.0047	1.3467	0.2289	0.0185	0.1200	818.13	24339.14
0.4075	0.5960	0.6510	0.0047	1.3967	0.2289	0.0184	0.1240	823.19	26139.37
0.4191	0.6090	0.6600	0.0047	1.3589	0.2289	0.0181	0.1190	834.57	27052.34
0.0368	0.2860	0.2616	0.0030	1.6640	0.9141	0.0190	0.1530	330.75	27784.14
0.0399	0.3230	0.2505	0.0029	1.7150	0.9964	0.0188	0.1560	316.81	29736.89

TABLE 3: Continued

SLOPE OF FLUME = 0.0150FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.2345	0.5550	0.6300	0.0053	0.7114	0.1717	0.0160	0.0550	796.64	10638.95
0.2495	0.5610	0.6320	0.0053	0.7725	0.1717	0.0169	0.0630	799.17	11977.79
0.2823	0.5740	0.6400	0.0054	0.8896	0.1717	0.0177	0.0760	809.28	14853.60
0.2956	0.5790	0.6430	0.0054	0.9339	0.1717	0.0177	0.0800	813.08	16022.64
0.3102	0.5890	0.6500	0.0054	0.9537	0.1717	0.0176	0.0810	821.93	17237.21
0.3285	0.5950	0.6520	0.0054	1.0138	0.1717	0.0178	0.0870	824.46	18881.23
0.3426	0.6040	0.6570	0.0054	1.0330	0.1717	0.0176	0.0880	830.78	20092.12
0.3580	0.6120	0.6620	0.0055	1.0611	0.1717	0.0176	0.0900	837.10	21417.45
0.3751	0.6190	0.6660	0.0055	1.1002	0.1717	0.0175	0.0930	842.16	22912.57
0.3909	0.6270	0.6710	0.0055	1.1260	0.1717	0.0175	0.0950	848.48	24276.05
0.0368	0.3130	0.2414	0.0033	1.7150	0.8045	0.0188	0.1560	305.19	29736.89
0.0399	0.3540	0.2309	0.0032	1.3286	0.8790	0.0206	0.1320	292.01	14748.14

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.0447	0.2340	0.3698	0.0025	0.2349	0.9733	0.0841	-0.0954	492.25	495.73
0.0547	0.2450	0.3698	0.0025	0.4524	0.9733	0.1394	-0.3045	492.25	1411.25
0.0628	0.2660	0.3698	0.0025	0.4271	0.9733	0.7313	-1.5083	492.25	2155.11
0.0707	0.2760	0.3696	0.0025	0.4829	0.9733	1.5401	3.5917	492.25	2879.90
0.0936	0.2860	0.3698	0.0025	0.7235	0.9733	0.4207	1.4698	492.25	4977.98
0.1393	0.3090	0.3698	0.0025	1.0204	0.9733	0.1784	0.8790	492.25	9174.12
0.1622	0.3140	0.3698	0.0025	1.1929	0.9733	0.1611	0.9281	492.25	11272.19
0.1933	0.3180	0.3698	0.0025	1.4397	0.9733	0.1500	1.0429	492.25	14133.21
0.2079	0.3260	0.3698	0.0025	1.4661	0.9733	0.1327	0.9393	492.25	15468.33
0.2308	0.3350	0.3698	0.0025	1.5441	0.9733	0.1184	0.8828	492.25	17566.41
0.2640	0.3500	0.3698	0.0025	1.6168	0.9733	0.1018	0.7946	492.25	20618.16

TABLE 3: Continued

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	CW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.0447	0.2370	0.3538	0.0026	0.2738	0.9242	0.0960	-0.1270	470.93	653.10
0.0547	0.2550	0.3528	0.0026	0.3886	0.9242	0.2462	-0.4620	470.93	1568.62
0.0628	0.2810	0.3538	0.0026	0.3601	0.9242	0.6477	1.1262	470.93	2312.48
0.0707	0.2790	0.3538	0.0026	0.4869	0.9242	0.8375	1.9690	470.93	3037.27
0.0936	0.2860	0.3538	0.0026	0.7463	0.9242	0.4207	1.5163	470.93	5135.35
0.1393	0.3180	0.3538	0.0026	0.9506	0.9242	0.1500	0.6886	470.93	9331.49
0.1622	0.3220	0.3538	0.0026	1.1224	0.9242	0.1407	0.7623	470.93	11429.55
0.1933	0.3260	0.3538	0.0026	1.3545	0.9242	0.1327	0.8678	470.93	14290.57
0.2079	0.3340	0.3538	0.0026	1.3847	0.9242	0.1198	0.8009	470.93	15625.71
0.2308	0.3420	0.3538	0.0026	1.4747	0.9242	0.1098	0.7817	470.93	17723.79
0.2640	0.3660	0.3538	0.0026	1.4610	0.9242	0.0898	0.6333	470.93	20775.53

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

0.0447	0.2530	0.3418	0.0028	0.2003	0.8444	0.2163	-0.2092	454.95	771.79
0.0547	0.2710	0.3418	0.0028	0.3065	0.8444	3.1548	-4.6697	454.95	1687.32
0.0628	0.3020	0.3418	0.0028	0.2912	0.8444	0.2123	0.2985	454.95	2431.17
0.0707	0.2640	0.3418	0.0028	0.4712	0.8444	0.4877	1.1097	454.95	3155.97
0.0936	0.3020	0.3418	0.0028	0.6293	0.8444	0.2123	0.6450	454.95	5254.04
0.1393	0.3280	0.3418	0.0028	0.8804	0.8444	0.1291	0.5489	454.95	9450.18
0.1622	0.3310	0.3418	0.0028	1.0490	0.8444	0.1242	0.6292	454.95	11548.25
0.1933	0.3370	0.3418	0.0028	1.2465	0.8444	0.1157	0.6967	454.95	14409.26
0.2079	0.3500	0.3418	0.0028	1.2346	0.8444	0.1018	0.6068	454.95	15744.40
0.2308	0.3550	0.3418	0.0028	1.3506	0.8444	0.0975	0.6362	454.95	17842.47
0.2640	0.3830	0.3418	0.0028	1.3241	0.8444	0.0807	0.5158	454.95	20894.22

TABLE 3: Continued

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.0447	0.2660	0.2935	0.0028	0.2462	0.9322	0.7313	-0.8694	390.72	1242.20
0.0547	0.2970	0.2935	0.0028	0.2735	0.9322	0.2482	0.3278	390.72	2157.72
0.0628	0.3280	0.2935	0.0028	0.2703	0.9322	0.1291	0.1685	390.72	2901.58
0.0707	0.2990	0.2935	0.0028	0.4492	0.9322	0.2322	0.5037	390.72	3626.37
0.0936	0.3180	0.2935	0.0028	0.5831	0.9322	0.1500	0.4224	390.72	5724.45
0.1393	0.3390	0.2935	0.0028	0.8448	0.9322	0.1133	0.4620	390.72	9920.59
0.1622	0.3420	0.2935	0.0028	1.0000	0.9322	0.1098	0.5301	390.72	12018.66
0.1933	0.3500	0.2935	0.0028	1.1668	0.9322	0.1018	0.5735	390.72	14879.68
0.2079	0.3630	0.2935	0.0028	1.1628	0.9322	0.0917	0.5149	390.72	16214.81
0.2308	0.3720	0.2935	0.0028	1.2398	0.9322	0.0862	0.5162	390.72	18312.89
0.2640	0.3910	0.2935	0.0028	1.2937	0.9322	0.0772	0.4826	390.72	21364.64

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

0.0239	0.2190	0.2051	0.0026	0.2657	1.4467	0.0406	-0.0521	272.99	195.01
0.0295	0.2400	0.2051	0.0026	0.2669	1.4467	0.1100	-0.1417	272.99	709.99
0.0447	0.2840	0.2051	0.0026	0.3139	1.4467	0.4877	0.7392	272.99	2102.35
0.0547	0.3230	0.2051	0.0026	0.2937	1.4467	0.1385	0.1965	272.99	3017.87
0.0628	0.3650	0.2051	0.0026	0.2663	1.4467	0.0904	0.1162	272.99	3761.73
0.0707	0.3230	0.2051	0.0026	0.4366	1.4467	0.1385	0.2921	272.99	4486.52
0.0936	0.3440	0.2051	0.0026	0.5396	1.4467	0.1076	0.2804	272.99	6584.59
0.1393	0.3520	0.2051	0.0026	0.8334	1.4467	0.1000	0.4025	272.99	10780.74
0.1622	0.3570	0.2051	0.0026	0.9615	1.4467	0.0960	0.4457	272.99	12878.81
0.1933	0.3700	0.2051	0.0026	1.0790	1.4467	0.0874	0.4551	272.99	15739.82
0.2079	0.3850	0.2051	0.0026	1.0696	1.4467	0.0798	0.4120	272.99	17074.96
0.2308	0.3920	0.2051	0.0026	1.1546	1.4467	0.0768	0.4285	272.99	19173.03
0.2640	0.4120	0.2051	0.0026	1.2052	1.4467	0.0700	0.4076	272.99	22224.79

TABLE 3: Continued

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

C	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.0301	0.1380	0.3474	0.0024	29.6177	1.1105	0.0185	-2.6436	466.43	543.37
0.0322	0.1610	0.3474	0.0024	0.3449	1.1105	0.3041	0.5066	466.43	734.11
0.0364	0.1670	0.3474	0.0024	0.4164	1.1105	0.1649	0.3316	466.43	1115.57
0.0491	0.2140	0.3474	0.0024	0.3260	1.1105	0.0567	0.0892	466.43	2279.05
0.0530	0.2240	0.3474	0.0024	0.3340	1.1105	0.0523	0.0843	466.43	2641.45
0.0561	0.2230	0.3474	0.0024	0.3745	1.1105	0.0527	0.0952	466.43	2927.55
0.0669	0.2590	0.3474	0.0024	0.3525	1.1105	0.0430	0.0732	466.43	3919.36
0.0680	0.2310	0.3474	0.0024	0.4695	1.1105	0.0498	0.1129	466.43	4014.73
0.0782	0.2500	0.3474	0.0024	0.4808	1.1105	0.0448	0.1040	466.43	4949.33
0.0973	0.2390	0.3474	0.0024	0.7221	1.1105	0.0475	0.1655	466.43	6704.07
0.1133	0.2520	0.3474	0.0024	0.7801	1.1105	0.0444	0.1672	466.43	8172.73
0.1266	0.2550	0.3474	0.0024	0.8736	1.1105	0.0438	0.1847	466.43	9393.43
0.1455	0.2580	0.3474	0.0024	1.0092	1.1105	0.0432	0.2105	466.43	11129.10
0.1705	0.2650	0.3474	0.0024	1.1498	1.1105	0.0420	0.2330	466.43	13417.91
0.1871	0.2680	0.3474	0.0024	1.2511	1.1105	0.0415	0.2506	466.43	14943.79
0.2297	0.2740	0.3474	0.0024	1.5089	1.1105	0.0406	0.2955	466.43	18853.84

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

0.0260	0.1380	0.3280	0.0025	15.6677	1.0810	0.0185	-1.3985	440.28	287.44
0.0301	0.1510	0.3280	0.0025	0.5524	1.0810	0.2841	-0.7577	440.28	668.91
0.0322	0.1690	0.3280	0.0025	0.3003	1.0810	0.1457	0.2113	440.28	859.65
0.0364	0.1770	0.3280	0.0025	0.3451	1.0810	0.1039	0.1732	440.28	1241.11
0.0491	0.2240	0.3280	0.0025	0.3041	1.0810	0.0523	0.0767	440.28	2404.59
0.0530	0.2380	0.3280	0.0025	0.3010	1.0810	0.0477	0.0694	440.28	2766.99
0.0561	0.2320	0.3280	0.0025	0.3533	1.0810	0.0495	0.0844	440.28	3053.09
0.0669	0.2730	0.3280	0.0025	0.3261	1.0810	0.0407	0.0641	440.28	4044.90
0.0680	0.2400	0.3280	0.0025	0.4416	1.0810	0.0472	0.1006	440.28	4140.27
0.0782	0.2840	0.3280	0.0025	0.3784	1.0810	0.0392	0.0716	440.28	5074.87
0.0973	0.2490	0.3280	0.0025	0.6694	1.0810	0.0450	0.1456	440.28	6829.61
0.1133	0.2570	0.3280	0.0025	0.7588	1.0810	0.0434	0.1590	440.28	8298.26
0.1266	0.2610	0.3280	0.0025	0.8422	1.0810	0.0427	0.1735	440.28	9518.96
0.1455	0.2620	0.3280	0.0025	0.9877	1.0810	0.0425	0.2026	440.28	11254.64
0.1705	0.2700	0.3280	0.0025	1.1167	1.0810	0.0412	0.2219	440.28	13543.43
0.1871	0.2720	0.3280	0.0025	1.2240	1.0810	0.0409	0.2415	440.28	15069.32
0.2297	0.2800	0.3280	0.0025	1.4548	1.0810	0.0397	0.2790	440.28	18979.36

TABLE 3: Continued

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.0229	0.1380	0.3558	0.0028	-9.4285	0.7972	0.0185	0.8416	477.62	-172.98
0.0301	0.1670	0.3558	0.0028	0.1846	0.7972	0.1649	0.1470	477.62	494.59
0.0322	0.1880	0.3558	0.0028	0.1488	0.7972	0.0793	0.0570	477.62	685.33
0.0364	0.1930	0.3558	0.0028	0.2107	0.7972	0.0727	0.0740	477.62	1066.79
0.0491	0.2420	0.3558	0.0028	0.2333	0.7972	0.0467	0.0526	477.62	2230.27
0.0530	0.2570	0.3558	0.0028	0.2371	0.7972	0.0434	0.0497	477.62	2592.67
0.0561	0.2430	0.3558	0.0028	0.2983	0.7972	0.0464	0.0669	477.62	2878.77
0.0669	0.2900	0.3558	0.0028	0.2772	0.7972	0.0385	0.0515	477.62	3870.58
0.0680	0.2480	0.3558	0.0028	0.3923	0.7972	0.0453	0.0857	477.62	3965.95
0.0782	0.2950	0.3558	0.0028	0.3398	0.7972	0.0379	0.0622	477.62	4900.55
0.0973	0.2610	0.3558	0.0028	0.5888	0.7972	0.0427	0.1213	477.62	6655.29
0.1133	0.2670	0.3558	0.0028	0.6854	0.7972	0.0416	0.1378	477.62	8123.94
0.1266	0.2690	0.3558	0.0028	0.7763	0.7972	0.0413	0.1549	477.62	9344.64
0.1455	0.2710	0.3558	0.0028	0.9067	0.7972	0.0410	0.1795	477.62	11080.32
0.1705	0.2790	0.3558	0.0028	1.0320	0.7972	0.0399	0.1986	477.62	13369.13
0.1871	0.2810	0.3558	0.0028	1.1338	0.7972	0.0396	0.2167	477.62	14895.00
0.2297	0.2890	0.3558	0.0028	1.3557	0.7972	0.0386	0.2526	477.62	18805.04

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.0208	0.1380	0.3211	0.0029	-7.7088	0.8028	0.0185	0.6881	431.12	-141.43
0.0229	0.1590	0.3211	0.0029	0.0254	0.8028	0.4546	0.0557	431.12	49.31
0.0301	0.1850	0.3211	0.0029	0.1655	0.8028	0.0843	0.0674	431.12	716.88
0.0322	0.2010	0.3211	0.0029	0.1565	0.8028	0.0650	0.0491	431.12	907.61
0.0364	0.2110	0.3211	0.0029	0.1920	0.8028	0.0583	0.0540	431.12	1289.08
0.0491	0.2620	0.3211	0.0029	0.2152	0.8028	0.0425	0.0441	431.12	2452.56
0.0530	0.2740	0.3211	0.0029	0.2253	0.8028	0.0406	0.0441	431.12	2814.95
0.0561	0.2560	0.3211	0.0029	0.2860	0.8028	0.0436	0.0602	431.12	3101.05
0.0669	0.3120	0.3211	0.0029	0.2561	0.8028	0.0362	0.0448	431.12	4092.87
0.0680	0.2600	0.3211	0.0029	0.3736	0.8028	0.0428	0.0773	431.12	4188.23
0.0782	0.3190	0.3211	0.0029	0.3082	0.8028	0.0356	0.0530	431.12	5122.83
0.0973	0.2740	0.3211	0.0029	0.5504	0.8028	0.0406	0.1078	431.12	6877.57
0.1133	0.2760	0.3211	0.0029	0.6583	0.8028	0.0403	0.1280	431.12	8346.23
0.1266	0.2800	0.3211	0.0029	0.7333	0.8028	0.0397	0.1407	431.12	9566.93
0.1455	0.2880	0.3211	0.0029	0.8202	0.8028	0.0387	0.1533	431.12	11302.61
0.1705	0.2900	0.3211	0.0029	0.9734	0.8028	0.0385	0.1808	431.12	13591.41
0.1871	0.2960	0.3211	0.0029	1.0416	0.8028	0.0378	0.1901	431.12	15117.28
0.2297	0.3000	0.3211	0.0029	1.2787	0.8028	0.0374	0.2307	431.12	19027.33

TABLE 3: Continued

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	BLT	VMT	RD	NT	U*	REF	RET
0.0187	0.1380	0.2432	0.0029	8.9690	1.0736	0.0185	-0.8006	326.47	164.55
0.0229	0.1820	0.2432	0.0029	0.1347	1.0736	0.0903	0.0587	326.47	546.01
0.0301	0.2080	0.2432	0.0029	0.1884	1.0736	0.0600	0.0546	326.47	1213.58
0.0322	0.2190	0.2432	0.0029	0.1865	1.0736	0.0543	0.0494	326.47	1404.32
0.0364	0.2340	0.2432	0.0029	0.2023	1.0736	0.0489	0.0478	326.47	1785.79
0.0491	0.2860	0.2432	0.0029	0.2169	1.0736	0.0389	0.0408	326.47	2949.26
0.0530	0.2980	0.2432	0.0029	0.2253	1.0736	0.0376	0.0409	326.47	3311.66
0.0561	0.2790	0.2432	0.0029	0.2777	1.0736	0.0399	0.0535	326.47	3597.76
0.0669	0.3370	0.2432	0.0029	0.2511	1.0736	0.0342	0.0415	326.47	4589.57
0.0680	0.2850	0.2432	0.0029	0.3469	1.0736	0.0391	0.0655	326.47	4684.94
0.0782	0.3430	0.2432	0.0029	0.2985	1.0736	0.0338	0.0487	326.47	5619.54
0.0973	0.2870	0.2432	0.0029	0.5387	1.0736	0.0388	0.1010	326.47	7374.29
0.1133	0.2910	0.2432	0.0029	0.6292	1.0736	0.0384	0.1165	326.47	8842.94
0.1266	0.2970	0.2432	0.0029	0.6890	1.0736	0.0377	0.1254	326.47	10063.64
0.1455	0.3080	0.2432	0.0029	0.7557	1.0736	0.0366	0.1334	326.47	11799.32
0.1705	0.3120	0.2432	0.0029	0.8815	1.0736	0.0362	0.1541	326.47	14088.12
0.1871	0.3160	0.2432	0.0029	0.9551	1.0736	0.0358	0.1653	326.47	15614.00
0.2297	0.3230	0.2432	0.0029	1.1491	1.0736	0.0353	0.1956	326.47	19524.04

difficult to determine and is considered beyond the scope of the present study. However, some computed results based on uncontested assumptions that logarithmic velocity holds true for flow above the mean height of the bent-down vegetation and velocity between the blades is not affected by the presence of flow above the vegetative part, are also presented in Table 4 only for the completeness of the presentation.

TABLE 4: Determination of Flow Velocity Profile and Shear Velocity at Top of Vegetation

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	QS	QT	DX	VMAX	TTS	RET	RE2
0.1356	0.4390	0.5550	0.1046	0.0309	0.3622	0.7088	0.0082	2836.20	22352.72
0.1568	0.4540	0.5650	0.1065	0.0523	0.3803	0.9830	0.0160	4799.69	23533.00
0.1784	0.4660	0.5730	0.1080	0.0704	0.3825	1.1223	0.0198	6454.40	24497.03
0.1879	0.4710	0.5760	0.1086	0.0794	0.3834	1.1907	0.0218	7279.95	24889.51
0.2037	0.4760	0.5790	0.1092	0.0946	0.3852	1.3585	0.0279	8677.72	25284.74
0.2428	0.4960	0.5910	0.1114	0.1314	0.3859	1.5228	0.0322	12056.24	26893.18
0.2744	0.5130	0.6030	0.1137	0.1608	0.3859	1.6055	0.0337	14748.14	28379.69
0.3085	0.5230	0.6080	0.1146	0.1939	0.3868	1.7888	0.0407	17789.84	29172.80
0.3285	0.5320	0.6140	0.1157	0.2127	0.3868	1.8369	0.0418	19517.27	29967.67
0.3480	0.5370	0.6160	0.1161	0.2319	0.3872	1.9489	0.0465	21275.61	30347.85
0.3738	0.5450	0.6210	0.1171	0.2567	0.3874	2.0322	0.0496	23554.37	31049.96
0.4037	0.5610	0.6310	0.1189	0.2848	0.3871	2.0326	0.0477	26128.24	32476.20
0.4374	0.5730	0.6380	0.1203	0.3172	0.3872	2.1110	0.0502	29097.25	33538.86

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	QS	QT	DX	VMAX	TTS	RET	RE2
0.1135	0.4530	0.5420	0.0637	0.0498	0.3805	0.9469	0.0150	4566.19	22525.29
0.1383	0.4620	0.5470	0.0643	0.0739	0.3856	1.2740	0.0265	6782.03	23184.74
0.1971	0.4880	0.5630	0.0662	0.1309	0.3874	1.6790	0.0407	12007.41	25205.84
0.2644	0.5090	0.5740	0.0675	0.1969	0.3882	2.0580	0.0566	18068.68	26804.19

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	QS	QT	DX	VMAX	TTS	RET	RE2
0.1135	0.4620	0.5480	0.0644	0.0491	0.3674	0.7769	0.0090	4503.91	23227.13
0.1383	0.4710	0.5530	0.0650	0.0732	0.3824	1.0923	0.0182	6719.79	23895.66
0.1971	0.5010	0.5720	0.0672	0.1299	0.3854	1.4311	0.0279	11912.98	26290.98
0.2644	0.5260	0.5870	0.0690	0.1955	0.3869	1.7715	0.0396	17931.25	28326.75

TABLE 4: Continued

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 2232.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMF	CS	QT	CX	VMAX	TTS	RET	RE2
0.1383	0.4960	0.5700	0.0670	0.0713	0.3482	0.7524	0.0070	6540.96	25937.59
0.1971	0.5250	0.5860	0.0691	0.1280	0.3786	1.1264	0.0157	11745.13	28321.07
0.2644	0.5560	0.6070	0.0713	0.1932	0.3827	1.3973	0.0226	17720.56	30962.53

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMF	CS	QT	CX	VMAX	TTS	RET	RE2
0.1655	0.4730	0.5780	0.1089	0.0566	0.3576	0.7748	0.0082	5189.61	25081.98
0.1925	0.4850	0.5850	0.1102	0.0823	0.3780	1.0325	0.0150	7548.32	26029.79
0.2104	0.4910	0.5890	0.1110	0.0994	0.3819	1.1899	0.0198	9119.58	26531.98
0.2299	0.5050	0.5980	0.1127	0.1173	0.3818	1.2327	0.0201	10757.14	27705.47
0.2707	0.5180	0.6050	0.1140	0.1567	0.3849	1.4980	0.0288	14374.70	28751.34
0.3177	0.5360	0.6150	0.1159	0.2018	0.3859	1.6980	0.0353	18512.69	30242.17
0.3385	0.5440	0.6200	0.1168	0.2216	0.3861	1.7534	0.0369	20333.73	30943.09
0.3601	0.5510	0.6240	0.1176	0.2425	0.3865	1.8444	0.0402	22248.33	31543.45
0.3805	0.5590	0.6290	0.1185	0.2619	0.3865	1.8872	0.0413	24031.23	32257.85
0.4008	0.5670	0.6330	0.1193	0.2816	0.3866	1.9426	0.0430	25831.41	32927.57
0.4229	0.5740	0.6370	0.1200	0.3028	0.3868	2.0090	0.0453	27784.14	33544.73
0.4449	0.5810	0.6410	0.1208	0.3241	0.3869	2.0625	0.0471	29736.89	34167.03
0.0368	0.2550	0.2879	0.1137	0.1608	0.3859	1.6055	0.0337	14748.14	6735.77
0.0399	0.2710	0.2943	0.1146	0.1939	0.3868	1.7888	0.0407	17789.84	7315.91

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMF	CS	QT	CX	VMAX	TTS	RET	RE2
0.1863	0.5070	0.6000	0.1130	0.0733	0.2112	0.6566	0.0041	6724.51	27908.23
0.2241	0.5210	0.6080	0.1145	0.1096	0.3689	0.9711	0.0115	10057.94	29061.25
0.2532	0.5380	0.6200	0.1167	0.1365	0.3739	1.0882	0.0140	12521.32	30601.80
0.2707	0.5480	0.6250	0.1177	0.1530	0.3757	1.1501	0.0153	14037.29	31421.98
0.3106	0.5610	0.6320	0.1190	0.1916	0.3806	1.3430	0.0205	17578.71	32527.67
0.3281	0.5690	0.6360	0.1197	0.2083	0.3812	1.3927	0.0218	19111.91	33200.32
0.3497	0.5760	0.6400	0.1205	0.2292	0.3824	1.4801	0.0243	21026.59	33820.15
0.3871	0.5890	0.6470	0.1218	0.2653	0.3835	1.6036	0.0279	24339.14	34961.70
0.4075	0.5960	0.6510	0.1226	0.2849	0.3840	1.6668	0.0298	26139.37	35595.92
0.4191	0.6090	0.6600	0.1243	0.2949	0.3830	1.6186	0.0274	27052.34	36875.20
0.0368	0.2860	0.2616	0.1200	0.3028	0.3868	2.0090	0.0453	27784.14	6863.02
0.0399	0.3230	0.2505	0.1208	0.3241	0.3869	2.0625	0.0471	29736.89	7424.18

TABLE 4: Continued

SLOPE OF FLUME = 0.0150FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.3920FT

Q	DW	VMP	CS	CT	DX	VMAX	TTS	RET	RE2
0.2345	0.5550	0.6300	0.1185	0.1160	0.2963	0.7667	0.0059	10638.95	32077.95
0.2495	0.5610	0.6320	0.1189	0.1306	0.3378	0.8549	0.0077	11977.79	32527.67
0.2823	0.5740	0.6400	0.1204	0.1619	0.3635	1.0202	0.0112	14853.60	33702.72
0.2956	0.5790	0.6430	0.1210	0.1746	0.3676	1.0743	0.0124	16022.64	34155.65
0.3102	0.5890	0.6500	0.1223	0.1879	0.3677	1.0975	0.0127	17237.21	35123.82
0.3285	0.5950	0.6520	0.1227	0.2058	0.3724	1.1801	0.0147	18881.23	35590.79
0.3426	0.6040	0.6570	0.1236	0.2190	0.3726	1.2022	0.0150	20092.12	36406.20
0.3580	0.6120	0.6620	0.1246	0.2335	0.3734	1.2364	0.0157	21417.45	37169.13
0.3751	0.6190	0.6660	0.1253	0.2497	0.3748	1.2830	0.0167	22912.57	37821.42
0.3909	0.6270	0.6710	0.1262	0.2646	0.3755	1.3176	0.0175	24276.05	38597.85
0.0368	0.3130	0.2414	0.1208	0.3241	0.3869	2.0625	0.0471	29736.89	6930.58
0.0399	0.3540	0.2309	0.1137	0.1608	0.3859	1.6055	0.0337	14748.14	7499.96

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	CS	CT	DX	VMAX	TTS	RET	RE2
0.0447	0.2340	0.3698	0.0393	0.0054	0.2110	-0.0036	0.0176	495.73	7939.46
0.0547	0.2450	0.3698	0.0393	0.0154	0.2110	-0.3089	0.1796	1411.25	8312.69
0.0628	0.2660	0.3698	0.0393	0.0235	0.2110	-3.3436	4.4052	2155.11	9025.20
0.0707	0.2760	0.3698	0.0393	0.0314	0.2110	9.4621	24.9795	2879.90	9364.50
0.0936	0.2860	0.3698	0.0393	0.0543	0.2110	4.3980	4.1834	4977.98	9703.79
0.1393	0.3090	0.3698	0.0393	0.1000	0.2110	3.2178	1.4960	9174.12	10484.16
0.1622	0.3140	0.3698	0.0393	0.1229	0.2110	3.5131	1.6679	11272.19	10653.82
0.1933	0.3180	0.3698	0.0393	0.1541	0.2110	4.0469	2.1059	14133.21	10789.53
0.2079	0.3260	0.3698	0.0393	0.1686	0.2110	3.8145	1.7086	15468.33	11060.96
0.2308	0.3350	0.3698	0.0393	0.1915	0.2110	3.7511	1.5090	17566.41	11366.33
0.2640	0.3500	0.3698	0.0393	0.2247	0.2110	3.6034	1.2227	20618.16	11875.27

TABLE 4: Continued

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	QS	QT	DX	VMAX	TTS	RET	RE2
0.0447	0.2370	0.3538	0.0376	0.0071	0.2110	-0.0436	0.0312	653.10	7693.02
0.0547	0.2550	0.3538	0.0376	0.0171	0.2110	-0.7665	0.4134	1568.62	8277.30
0.0628	0.2810	0.3538	0.0376	0.0252	0.2110	3.1756	2.4561	2312.48	9121.26
0.0707	0.2790	0.3538	0.0376	0.0331	0.2110	5.4093	7.5071	3037.27	9056.34
0.0936	0.2860	0.3538	0.0376	0.0560	0.2110	4.5371	4.4520	5135.35	9283.56
0.1393	0.3180	0.3538	0.0376	0.1017	0.2110	2.6720	0.9181	9331.49	10322.28
0.1622	0.3220	0.3538	0.0376	0.1246	0.2110	3.0281	1.1253	11429.55	10452.12
0.1933	0.3260	0.3538	0.0376	0.1558	0.2110	3.5240	1.4583	14290.57	10581.96
0.2079	0.3340	0.3538	0.0376	0.1703	0.2110	3.3870	1.2421	15625.71	10841.64
0.2308	0.3420	0.3538	0.0376	0.1932	0.2110	3.4291	1.1833	17723.79	11101.32
0.2640	0.3660	0.3538	0.0376	0.2265	0.2110	3.0442	0.7766	20775.53	11880.36

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	QS	QT	DX	VMAX	TTS	RET	RE2
0.0447	0.2530	0.3418	0.0363	0.0084	0.2110	-0.3228	0.0848	771.79	7933.74
0.0547	0.2710	0.3418	0.0363	0.0184	0.2110	-11.3678	42.2260	1687.32	8498.20
0.0628	0.3020	0.3418	0.0363	0.0265	0.2110	1.0374	0.1725	2431.17	9470.31
0.0707	0.2840	0.3418	0.0363	0.0344	0.2110	3.2455	2.3846	3155.97	8905.86
0.0936	0.3020	0.3418	0.0363	0.0573	0.2110	2.2419	0.8057	5254.04	9470.31
0.1393	0.3280	0.3418	0.0363	0.1030	0.2110	2.2527	0.5834	9450.18	10285.64
0.1622	0.3310	0.3418	0.0363	0.1259	0.2110	2.6219	0.7665	11548.25	10379.71
0.1933	0.3370	0.3418	0.0363	0.1571	0.2110	2.9882	0.9399	14409.26	10567.86
0.2079	0.3500	0.3418	0.0363	0.1716	0.2110	2.7516	0.7130	15744.40	10975.53
0.2308	0.3550	0.3418	0.0363	0.1945	0.2110	2.9410	0.7836	17842.47	11132.32
0.2640	0.3830	0.3418	0.0363	0.2277	0.2110	2.6135	0.5151	20894.22	12010.36

TABLE 4: Continued

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

Q	DW	VMP	QS	QT	DX	VMAX	TTS	RET	RE2
0.0447	0.2660	0.2935	0.0312	0.0135	0.2110	-1.9273	1.4636	1242.20	7163.66
0.0547	0.2970	0.2935	0.0312	0.0235	0.2110	1.0929	0.2080	2157.72	7998.53
0.0628	0.3280	0.2935	0.0312	0.0316	0.2110	0.6917	0.0550	2901.58	8833.39
0.0707	0.2990	0.2935	0.0312	0.0395	0.2110	1.7083	0.4912	3626.37	8052.38
0.0936	0.3180	0.2935	0.0312	0.0624	0.2110	1.6391	0.3455	5724.45	8564.07
0.1393	0.3390	0.2935	0.0312	0.1081	0.2110	1.9998	0.4133	9920.59	9129.63
0.1622	0.3420	0.2935	0.0312	0.1310	0.2110	2.3253	0.5441	12018.66	9210.42
0.1933	0.3500	0.2935	0.0312	0.1622	0.2110	2.6005	0.6368	14879.68	9425.87
0.2079	0.3630	0.2935	0.0312	0.1767	0.2110	2.4501	0.5134	16214.81	9775.98
0.2308	0.3720	0.2935	0.0312	0.1996	0.2110	2.5302	0.5159	18312.89	10018.35
0.2640	0.3910	0.2935	0.0312	0.2329	0.2110	2.5002	0.4510	21364.64	10530.05

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.2110FT

0.0239	0.2190	0.2051	0.0218	0.0021	0.2110	0.1355	0.0052	195.01	4120.80
0.0295	0.2400	0.2051	0.0218	0.0077	0.2110	-0.0874	0.0389	709.99	4515.94
0.0447	0.2840	0.2051	0.0218	0.0229	0.2110	2.1620	1.0582	2102.35	5343.86
0.0547	0.3230	0.2051	0.0218	0.0329	0.2110	0.7849	0.0748	3017.87	6077.70
0.0628	0.3650	0.2051	0.0218	0.0410	0.2110	0.5568	0.0262	3761.73	6867.99
0.0707	0.3230	0.2051	0.0218	0.0489	0.2110	1.1669	0.1652	4486.52	6077.70
0.0936	0.3440	0.2051	0.0218	0.0718	0.2110	1.2407	0.1523	6584.59	6472.84
0.1393	0.3520	0.2051	0.0218	0.1175	0.2110	1.8397	0.3138	10780.74	6623.38
0.1622	0.3570	0.2051	0.0218	0.1404	0.2110	2.0756	0.3846	12878.81	6717.46
0.1933	0.3700	0.2051	0.0218	0.1716	0.2110	2.2169	0.4011	15739.82	6962.07
0.2079	0.3850	0.2051	0.0218	0.1861	0.2110	2.0997	0.3287	17074.96	7244.32
0.2308	0.3920	0.2051	0.0218	0.2090	0.2110	2.2258	0.3555	19173.03	7376.04
0.2640	0.4120	0.2051	0.0218	0.2423	0.2110	2.2243	0.3217	22224.79	7752.36

TABLE 4: Continued

SLOPE OF FLUME = 0.0400FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	QS	CT	DX	VMAX	TTS	RET	RE2
0.0301	0.1380	0.3474	0.0242	0.0059	0.1378	23.0086	13.5330	543.37	4398.71
0.0322	0.1610	0.3474	0.0242	0.0080	0.1378	1.6113	0.4969	734.11	5131.83
0.0364	0.1670	0.3474	0.0242	0.0122	0.1378	1.2454	0.2129	1115.57	5323.08
0.0491	0.2140	0.3474	0.0242	0.0248	0.1378	0.5491	0.0154	2279.05	6821.19
0.0530	0.2240	0.3474	0.0242	0.0288	0.1378	0.5448	0.0138	2641.45	7139.93
0.0561	0.2230	0.3474	0.0242	0.0319	0.1378	0.6126	0.0176	2927.55	7108.06
0.0669	0.2590	0.3474	0.0242	0.0427	0.1378	0.5355	0.0104	3919.36	8255.55
0.0680	0.2310	0.3474	0.0242	0.0438	0.1378	0.7519	0.0247	4014.73	7363.05
0.0782	0.2500	0.3474	0.0242	0.0539	0.1378	0.7409	0.0210	4949.33	7968.68
0.0973	0.2390	0.3474	0.0242	0.0731	0.1378	1.1358	0.0530	6704.07	7618.05
0.1133	0.2520	0.3474	0.0242	0.0891	0.1378	1.1981	0.0541	8172.73	8032.43
0.1266	0.2550	0.3474	0.0242	0.1024	0.1378	1.3353	0.0661	9393.43	8128.05
0.1455	0.2580	0.3474	0.0242	0.1213	0.1378	1.5356	0.0858	11129.10	8223.67
0.1705	0.2650	0.3474	0.0242	0.1463	0.1378	1.7323	0.1051	13417.91	8446.80
0.1871	0.2680	0.3474	0.0242	0.1629	0.1378	1.8774	0.1216	14943.79	8542.42
0.2297	0.2740	0.3474	0.0242	0.2055	0.1378	2.2477	0.1691	18853.84	8733.67

SLOPE OF FLUME = 0.0350FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	QS	CT	DX	VMAX	TTS	RET	RE2
0.0260	0.1380	0.3280	0.0229	0.0031	0.1378	12.1715	3.7871	287.44	4152.13
0.0301	0.1510	0.3280	0.0229	0.0073	0.1378	-1.3420	1.1118	668.91	4543.27
0.0322	0.1690	0.3280	0.0229	0.0094	0.1378	0.8285	0.0864	859.65	5084.85
0.0364	0.1770	0.3280	0.0229	0.0135	0.1378	0.7782	0.0581	1241.11	5325.55
0.0491	0.2240	0.3280	0.0229	0.0262	0.1378	0.4959	0.0114	2404.59	6739.68
0.0530	0.2380	0.3280	0.0229	0.0302	0.1378	0.4744	0.0093	2766.99	7160.91
0.0561	0.2320	0.3280	0.0229	0.0333	0.1378	0.5644	0.0138	3053.09	6980.39
0.0669	0.2730	0.3280	0.0229	0.0441	0.1378	0.4864	0.0080	4044.90	8213.98
0.0680	0.2400	0.3280	0.0229	0.0451	0.1378	0.6932	0.0196	4140.27	7221.09
0.0782	0.2840	0.3280	0.0229	0.0553	0.1378	0.5574	0.0099	5074.87	8544.95
0.0973	0.2490	0.3280	0.0229	0.0744	0.1378	1.0334	0.0410	6829.61	7491.88
0.1133	0.2570	0.3280	0.0229	0.0905	0.1378	1.1563	0.0490	8298.26	7732.58
0.1266	0.2610	0.3280	0.0229	0.1038	0.1378	1.2758	0.0583	9518.96	7852.93
0.1455	0.2620	0.3280	0.0229	0.1227	0.1378	1.4942	0.0795	11254.64	7883.02
0.1705	0.2700	0.3280	0.0229	0.1476	0.1378	1.6715	0.0954	13543.43	8123.72
0.1871	0.2720	0.3280	0.0229	0.1643	0.1378	1.8276	0.1129	15069.32	8183.90
0.2297	0.2800	0.3280	0.0229	0.2069	0.1378	2.1524	0.1508	18979.36	8424.60

TABLE 4: Continued

SLOPE OF FLUME = 0.0300FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	QS	CT	CX	VMAX	TTS	RET	RE2
0.0229	0.1380	0.3558	0.0248	-0.0019	0.1378	-7.3246	1.3714	-172.98	4504.27
0.0301	0.1670	0.3558	0.0248	0.0054	0.1378	0.5521	0.0418	494.59	5450.82
0.0322	0.1880	0.3556	0.0248	0.0075	0.1378	0.2913	0.0063	685.33	6136.25
0.0364	0.1930	0.3558	0.0248	0.0116	0.1378	0.3956	0.0106	1066.79	6299.45
0.0491	0.2420	0.3558	0.0248	0.0243	0.1378	0.3648	0.0054	2230.27	7898.80
0.0530	0.2570	0.3558	0.0248	0.0283	0.1378	0.3613	0.0048	2592.67	8388.39
0.0561	0.2430	0.3558	0.0248	0.0314	0.1378	0.4655	0.0087	2878.77	7931.43
0.0669	0.2900	0.3558	0.0248	0.0422	0.1378	0.4059	0.0051	3870.58	9465.50
0.0680	0.2480	0.3558	0.0248	0.0432	0.1378	0.6066	0.0142	3965.95	8094.63
0.0782	0.2950	0.3558	0.0248	0.0534	0.1378	0.4953	0.0075	4900.55	9628.70
0.0973	0.2610	0.3558	0.0248	0.0725	0.1378	0.8920	0.0285	6655.29	8518.95
0.1133	0.2670	0.3558	0.0248	0.0886	0.1378	1.0299	0.0368	8123.94	8714.78
0.1266	0.2690	0.3558	0.0248	0.1019	0.1378	1.1636	0.0465	9344.64	8780.06
0.1455	0.2710	0.3558	0.0248	0.1208	0.1378	1.3556	0.0624	11080.32	8845.34
0.1705	0.2790	0.3558	0.0248	0.1457	0.1378	1.5286	0.0764	13369.13	9106.46
0.1871	0.2810	0.3558	0.0248	0.1624	0.1378	1.6756	0.0910	14895.00	9171.74
0.2297	0.2890	0.3558	0.0248	0.2050	0.1378	1.9871	0.1235	18805.04	9432.86

SLOPE OF FLUME = 0.0250FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	QS	CT	CX	VMAX	TTS	RET	RE2
0.0208	0.1380	0.3211	0.0223	-0.0015	0.1378	-5.9886	0.9168	-141.43	4065.71
0.0229	0.1590	0.3211	0.0223	0.0005	0.1378	0.1645	0.0060	49.31	4684.40
0.0301	0.1850	0.3211	0.0223	0.0078	0.1378	0.3340	0.0088	716.88	5450.41
0.0322	0.2010	0.3211	0.0223	0.0099	0.1378	0.2794	0.0047	907.61	5921.79
0.0364	0.2110	0.3211	0.0223	0.0141	0.1378	0.3270	0.0057	1289.08	6216.41
0.0491	0.2620	0.3211	0.0223	0.0267	0.1378	0.3256	0.0038	2452.56	7718.95
0.0530	0.2740	0.3211	0.0223	0.0307	0.1378	0.3356	0.0038	2814.95	8072.50
0.0561	0.2560	0.3211	0.0223	0.0338	0.1378	0.4364	0.0070	3101.05	7542.18
0.0669	0.3120	0.3211	0.0223	0.0446	0.1378	0.3680	0.0039	4092.87	9192.04
0.0680	0.2600	0.3211	0.0223	0.0457	0.1378	0.5668	0.0116	4188.23	7660.03
0.0782	0.3190	0.3211	0.0223	0.0558	0.1378	0.4405	0.0054	5122.83	9398.27
0.0973	0.2740	0.3211	0.0223	0.0750	0.1378	0.8199	0.0225	6877.57	8072.50
0.1133	0.2760	0.3211	0.0223	0.0910	0.1378	0.9783	0.0317	8346.23	8131.42
0.1266	0.2800	0.3211	0.0223	0.1043	0.1378	1.0850	0.0383	9566.93	8249.27
0.1455	0.2880	0.3211	0.0223	0.1232	0.1378	1.2035	0.0455	11302.61	8484.95
0.1705	0.2900	0.3211	0.0223	0.1481	0.1378	1.4254	0.0633	13591.41	8543.88
0.1871	0.2960	0.3211	0.0223	0.1648	0.1378	1.5167	0.0700	15117.28	8720.65
0.2297	0.3000	0.3211	0.0223	0.2074	0.1378	1.8554	0.1031	19027.33	8838.50

TABLE 4: Continued

SLOPE OF FLUME = 0.0200FT/FT
DENSITY OF SIMULATED GRASS = 1224.0000BLADES PER SQ. FOOT
HEIGHT OF SIMULATED GRASS = 0.1378FT

Q	DW	VMP	QS	QT	DX	VMAX	TTS	RET	RE2
0.0187	0.1380	0.2432	0.0169	0.0018	0.1378	6.9676	1.2410	164.55	3078.80
0.0229	0.1820	0.2432	0.0169	0.0060	0.1378	0.2815	0.0067	546.01	4060.45
0.0301	0.2080	0.2432	0.0169	0.0132	0.1378	0.3250	0.0058	1213.58	4640.52
0.0322	0.2190	0.2432	0.0169	0.0153	0.1378	0.3121	0.0047	1404.32	4885.93
0.0364	0.2340	0.2432	0.0169	0.0195	0.1378	0.3217	0.0044	1785.79	5220.58
0.0491	0.2860	0.2432	0.0169	0.0321	0.1378	0.3189	0.0032	2949.26	6380.71
0.0530	0.2980	0.2432	0.0169	0.0361	0.1378	0.3275	0.0032	3311.66	6648.43
0.0561	0.2790	0.2432	0.0169	0.0392	0.1378	0.4114	0.0055	3597.76	6224.54
0.0669	0.3370	0.2432	0.0169	0.0500	0.1378	0.3548	0.0033	4589.57	7518.53
0.0680	0.2850	0.2432	0.0169	0.0511	0.1378	0.5106	0.0083	4684.94	6358.40
0.0782	0.3430	0.2432	0.0169	0.0613	0.1378	0.4202	0.0046	5619.54	7652.39
0.0973	0.2870	0.2432	0.0169	0.0804	0.1378	0.7913	0.0198	7374.29	6403.02
0.1133	0.2910	0.2432	0.0169	0.0964	0.1378	0.9205	0.0263	8842.94	6492.26
0.1266	0.2970	0.2432	0.0169	0.1097	0.1378	1.0025	0.0304	10063.64	6626.12
0.1455	0.3080	0.2432	0.0169	0.1286	0.1378	1.0893	0.0345	11799.32	6871.54
0.1705	0.3120	0.2432	0.0169	0.1536	0.1378	1.2667	0.0460	14088.12	6960.78
0.1871	0.3160	0.2432	0.0169	0.1702	0.1378	1.3683	0.0529	15614.00	7050.02
0.2297	0.3230	0.2432	0.0169	0.2128	0.1378	1.6381	0.0741	19524.04	7206.18

V. CONCLUSIONS

The prediction of the hydraulic resistance to flow due to various vegetation is a complex problem. Through this study some progress has been made toward a better understanding of hydraulic properties of flow through dense vegetative covers.

A close review of the experimental data plotted in terms of n vs. VR as proposed by Ree and Palmer revealed that these relationships vary with the bed slope in the region of low VR values. The dependency of these curves on the bed slope, however, is more pronounced as stiffness of the vegetation blade increases and for real grasses this dependency is believed to be not very apparent.

By examining the data through the V/V_s vs. ln A/A_b plots as suggested by Kouwen and Unny, the same conclusion was reached that the universal velocity equation is applicable for flow above stiff vegetation. However for flexible vegetative media the universal velocity equation may be applicable only when the vegetation blades do not oscillate with moving water.

In advancing the concept of using drag force as a means of explaining the hydraulic resistance it was found that the coefficient of drag, R_d, of the vegetation blade varies continuously with the blade Reynolds number to form smooth curve for each vegetation density and slope. When $\frac{N_b R_d}{\gamma S_o}$ was plotted against the Reynolds number a single smooth curve representing various blade stiffnesses, population densities and channel slopes was obtained.

In analyzing flow retardance for submerged conditions based on momentum equation it was found that different approaches are needed for describing various force components for different blade stiffnesses. For flexible vegetative cover a wavy bed is formed by the bending of blades which separates the flow regime into two distinct regions thus a shear force due to top of blades is present. This force in the case of erect stiff vegetation is included as part of the drag resistance.

NOTATIONS

A	=	total flow area, L^2;
A_b	=	flow area blocked by vegetation, L^2;
A_b'	=	bed area, L^2;
A_e	=	base area of one element, L^2;
A_p	=	projectional area of blades on bed, L^2;
A_s	=	cross sectioned area blocked by vegetation, L^2;
A_t	=	total boundary area, L^2;
a	=	distance from sidewall to blade, L;
B	=	constant of integration;
B_{op}	=	cross sectional open flow beneath vegetation, L^2;
b	=	diameter of wires, L;
C_1	=	constant dependent on density of vegetation;
C_2	=	constant dependent on vegetation stiffness;
D_s	=	average height of simulated grass blades, L;
D_{sg}	=	number of blades per unit area;
D_{sn}	=	measure of blade unevennwaa, L;
D_t	=	depth of water above top of grass-s;
D_w	=	flow depth, L;
D_x	=	depth from channel bed to point where logrithmic profile begins, L;
E	=	modulus of elasticity, F/L^2;
F_b	=	force due to bottom shear, F;
F_d	=	drag force due to grass, F;

F_{ts} = force due to shear at top of blades;

F_{ws} = force due to wall shear within vegetation, F;

F_{wt} = force due to wall shear above vegetation, F;

f = Darcy's roughness coefficient;

f_k = local friction factor;

g_p = average gap distance between two adjacent blades in a row, L;

h = height of elements, L;

h' = distance from sidewalk, L;

I = second moment of area, L^4;

J = measure of flexible rigidity;

k = universal constant for turbulent flow;

k_s = measure of soil roughness, L;

L = length of section under consideration;

L_{avg} = average projected width of a blade, L;

L_3, L_4 = W_s sin 45°, L;

N = number of elements;

N' = average number of blades in a single row across flume;

N_b = number of blades in $\forall w$;

n = Manning's roughness term, $L^{1/6}$;

n_t = Manning's in value for the portion of flow above vegetation, $L^{1/6}$;

n_w = Manning's in value for the wall, $L^{1/16}$;

p = hydrostatic pressure, F/L^2;

Q = total discharge, L^3/T;

Q_s = total discharge below vegetation, L^3/T;

q_a = flow rate in gap between wall and first blade line, L^3/T;

q_s = flow rate below the vegetation per unit width of flume, L^3/T;

q_s' = flow rate per unit width within grass, L^3/T;

q_t = discharge over the top of the blades per unit width of the flume, L^3/T;

R' = hydraulic radius of flume corrected for narrowness of flume, L;

R" = hydraulic radius of bed and wores, L;

R = hydraulic radius, L;

R_d = drag coefficient for blades;

Re = Reynolds' number;

R_s = spacing hydraulic radius, L;

R_t = hydraulic radius in region about grass, L;

S_e = slope of energy line;

S_o = slope of flume;

S_s = spare between simulated vegetation, L;

T = dimensionless factor defined as ratio of sum of areas occupied by element base and zone of separation to base area occupied by elements.

T_s = blade thickness, L;

U_k = average velocity at top of grass, L/T;

U(y) = velocity at depth y, L/T;

U_* = shear velocity, L/T;

$U(\delta')$= velocity in viscous sublayer, L/T;

U_δ' = velocity at limit of viscous sublayer, L/T;

$\forall_s$ = volume of blades in $\forall w$, L^3;

$\forall_w$ = volume of water in L, L^3

V = mean flow velocity in channel, L/T;

Vm = mean velocity within vegetation, L/T;

Vm' = assumed velocity from δ to D_w, L/T;

V_t = mean velocity in the regions above the vegetation, L/T;

$V(h')$ = velocity distribution in horizontal, L/T;

$V(y)$ = velocity at depth y for non-submerged case, L/T;

W = weight of water in control volume

W_c = channel width, L;

W_s = blade width, L;

Y_n = normal depthof water, L;

y = distance from bed, L;

y' = intercept on y axis where $U(y) = 0$, L;

β = parameter of profile shape of plant unit;

δ = boundary layer thickness, L;

δ' = viscous sublayer height, L;

γ = specific weight of water, F/L^3;

λ = parameter = $\frac{k\ V_m'}{U_*} + Ln(D_{sr})$;

θ = angle of flume from horizontal;

ρ = density of fluid, $F - T^2/L^4$;

τ = viscous shear;

τ_b = bed shear;

τ_o = total shear resistance to flow, F/L^2;

τ_r = vegetative roughness shear, F/L^2;

τ_s = soil roughness shear, F/L^2;

τ_s' = local shear stress, F/L^2;

τ_s'' = average shear stress per unit area of boundary, T/L^2;

τ_{ts} = shear due to tips of blades, F/L^2;

τ_{ws} = wall shear within vegetation, F/L^2;

τ_{wt} = wall shear above vegetation, F/L^2;

μ = dynamic viscosity, $F\ T/L^2$;

ν = kinetic viscosity of fluid, L^2/T.

APPENDIX I

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APPENDIX II

COMPUTER PROGRAM
USED IN THE ANALYSIS

YOUR NEW FORTRAN STATEMENTS, WITH NUMBERS RE-ORDERED, ARE AS FOLLOWS

```
      INTEGER CASE
      REAL LAVG,N1,N2,NC,NT,MU,NU,NSTR
      DIMENSION FQ(40),FDW(40),FVAVG(40),FVM(40),FVR(40),FSV(40),FVRT(40
     (),FNC(40),FVMP(40),FCD(40),FSNCGS(40),FRE1(40),FREF(40),FUSTAR(40)
     (,FNT(40),FCT(40),FVMT(40),FART(40),FRSTR(40),FNSTR(40),FSVSTR(40),
     (FVRSTR(40),FVRTS(40),FDX(40),FBLT(40),FVMAX(40),FTTS(40),FQS(40),
     (FRET(40),FRE2(40),FCDGSO(40)
C
C   THIS PROGRAM ANALIZES THE RESULTS GETHERED DURING THE EXPEREMENTS
C        CONDUCTED ON FLOW THROUGH VEGETATION COVERED FLUME
C
C
   10 READ(5,1030)SO,DSG,HSG,CASE
      IF(SO.LE.0.0)GOTO430
C
C   DEFINE CONSTANTS
C
      I=0
      J=0
      RHO=1.9364
      MU=.00002112
      NU=.0000109
      GM=62.4
      N1=.01
      N2=.014
      WC=.481
      ACC=0.001
      ACCY=0.00001
      TTS=0.0
      ACY=0.001
      RK=20500000.
      DW1=0.0
      IF(CASE.EQ.1)GOTO30
      IF(CASE.EQ.2)GOTO20
      WRITE (6,1000)
 1000 FORMAT ('1 DATA IS FOR LEAST STIFF SIMULATED GRASS WITH :')
      TS=.0003
      DS=.1378
      DSR=.0065
      GOTO40
```

```
   20 WRITE (6,1010)
 1010 FORMAT('1 DATA IS FOR MEDIUM STIFF SIMULATED GRASS WITH :')
      TS=.0008
      DS=.211
      DSR=.02266
      GOTO40
   30 WRITE (6,1020)
 1020 FORMAT('1 DATA IS FOR STIFFEST SIMULATED GRASS WITH :')
      TS=.0037
      DS=.392
      DSR=0.00098
C
C  COMPUTE WIDTH BLOCKED BY BLADES WITH AVG. PROJECTED WIDTH= .0148/STRA
C
   40 LAVG=((.666+(TS*12.))/4.)/12.
      GAP=(((1./DSG)**.5)/12.)-LAVG
      STRW=(.481/(LAVG+GAP))
      A=GAP/2.
      WB=STRW*LAVG
C
C  COMPUTES AVG. NUMBER OF BLADES,SN, IN ONE FOOT LENGTH OF THE FLUME
C
      SN=69.264*DSG
C
C  READ IN DATA
C
   50 READ(5,1050)Q,DW
      IF(Q.LE.0.0)GOTO340
      GPF=Q/WC
C
C  COMPUTE AREA,AB, BLOCKED BY VEGETATION
C  FOR NON-SUBMERGED FLOW GO TO 90
C
      SOP=STRW*GAP
      IF (DW.GT.DS) GO TO 60
      GOTO180
   60 AB=DS*WB
      DT=DW-DS
      VAVG=Q/(((.481-WB)*DS)+(DT*.481))
      RT=0.5*WC
      AC=WC
      AP=(1.59307*DSG*TS)
```

```
      VW=WC*DS
      VS=1.59307*DSG*DS*TS
      RNT=(DT/RT**(1./3.))*.45*(N1*N1+N2*N2)
      TV=2.5*(DT*ALOG(DT/DSR)-DT)
      IF ((CASE.GT.1).AND.(DW.GT.DS)) VMP=VMP1
      IF ((CASE.GT.1).AND.(DW.GT.DS)) GO TO 230
      TBV=RHO*WC/TV/TV
      PAD=DS*GM*SO*LAVG*RHO/2.
      BLC=(2.*MU/(GM*SO))**.5
      BWR=BOP/WC
C
C   COMPUTE CONSTANTS IN MOMENTUM EQUATION
C
      X0=((WC-AP)*DS+DT*WC-A*DS)*GM*SO-RNT*(Q/WC/DT)**2.-TBV*(Q/WC)**2.
      X1=2.*DS*MU/A-RNT*2.*BWR*Q*DS/WC/DT/DT-TBV*2*Q*(BWR*DS+DT)/WC
      X2=RNT*(BWR*DS/DT)**2.+((BWR*DS)**2+DT*DT+2*DT*BWR*DS)*TBV
      X3=RNT*(BWR*BLC/DT/3.)**2.+(BLC*BWR/3)**2*TBV
      X4=PAD*RK*(LAVG/NU)**(-1.848)
      X5=(WC-AP)*(2.*MU*GM*SO)**.5
      IF (CASE.GT.1) X5=2.*X5
      X6=RNT*BLC*BWR*Q*2./WC/DT/DT/3.+2*TBV*BLC*BWR*Q/3/WC
      X7=-RNT*BLC*BWR*BWR*DS*2./DT/DT/3.-TBV*BLC*BWR*(BWR*DS+DT)*2/3
C
C   VARIABLE INCREAMENT METHOD TO FIND VMP
C   STATEMENTS 301,401 AND 501 ARE FOR (N*CD/GM/SO)=CONT.VALUE OF 108
C
      VMP=.1
      DVMP=.01
   70 IF(VMP.GE.0.5229) GOTO80
      RES=X0-X1*VMP-X2*VMP*VMP-X3*(VMP**3)-X4*(VMP**.152)-X5*(VMP**.5)-X
     (6*(VMP**1.5)-X7*(VMP**2.5)
      GOTO90
   80 RES=X0-X1*VMP-X2*VMP*VMP-X3*(VMP**3)-108*PAD*VMP**2-X5*(VMP**.5)-X
     (6*(VMP**1.5)-X7*(VMP**2.5)
   90 IF(ABS(RES).LT.ACC)GOTO230
      IF(RES.LT.0.0) GOTO100
      VMP=VMP+DVMP
      GOTO70
  100 VMP=VMP-DVMP
      DDVMP=0.001
  110 VMP=VMP+DDVMP
      IF(VMP.GE.0.5229) GOTO120
```

-101-

```
      RES=X0-X1*VMP-X2*VMP*VMP-X3*(VMP**3)-X4*(VMP**.152)-X5*(VMP**.5)-X
     (6*(VMP**1.5)-X7*(VMP**2.5)
      GOTO130
  120 RES=X0-X1*VMP-X2*VMP*VMP-X3*(VMP**3)-108*PAD*VMP**2-X5*(VMP**.5)-X
     (6*(VMP**1.5)-X7*(VMP**2.5)
  130 IF(ABS(RES).LT.ACC)GOTO230
      IF(RES.LT.0.0) GOTO140
      GOTO110
  140 VMP=VMP-DDVMP
      DDDVMP=0.0001
  150 VMP=VMP+DDDVMP
      IF(VMP.GE.0.5229) GOTO160
      RES=X0-X1*VMP-X2*VMP*VMP-X3*(VMP**3)-X4*(VMP**.152)-X5*(VMP**.5)-X
     (6*(VMP**1.5)-X7*(VMP**2.5)
      GOTO170
  160 RES=X0-X1*VMP-X2*VMP*VMP-X3*(VMP**3)-108*PAD*VMP**2-X5*(VMP**.5)-X
     (6*(VMP**1.5)-X7*(VMP**2.5)
  170 IF(ABS(RES).LT.ACC)GOTO230
C
C    SAFETY VALVE
      IF(RES.LT.0.0) WRITE(6,1040)Q,DW
      IF(RES.LT.0.0) GOTO50
      GO TO 150
C
C   COMPUTE MEAN VELOCITY,VM, FOR NON-SUBMERGED CASE
C
  180 AB=DW*WB
      DCONS=((((((DSG*144.)**.5)*.481)-1.)*GAP)+A)*DW
      VM=((Q-((A**3.)*62.4*SO*DW/(6.*MU)))/DCONS)
      VMDW=VM*DW
      DVMP=VM
      VMP=VM+DVMP
      CONS=(2.*MU/62.4/SO)**.5/3.
  190 DVMP=.5*DVMP
      VMPDW=(DW-(VMP**.5)*CONS)*VMP
      IF(ABS(VMPDW-VMDW).GT.ACCY)GOTO200
      GO TO 230
  200 IF(VMPDW.GT.VMDW)GOTO210
      GOTO220
  210 VMP=VMP-DVMP
      GOTO190
  220 VMP=VMP+DVMP
```

```
      GOTO190
C
C  DETERMINE SHEAR VELOCITY U* AND ZERO DISPLACEMENT DISTANCE DX
C
  230 BLT=(VMP*2.*MU/62.4/SO)**.5
      BDT=(BLT/2.)-(((62.4*SO*(BLT**3.))/(12.*MU*VMP)))
      IF (DW.LE.DS) GOTO 320
      RE1=VMP*LAVG/NU
      CD=(GM*SO*RK*(RE1**(-1.848)))/SN
      IF (VMP.GE.0.5229) CD=108*GM*SO/SN
      VMP1=VMP
      QS=VMP*DS-((VMP**1.5)*((2.*MU/62.4/SO)**.5))/3.
      IF (CASE.GT.1) QS=QS-((VMP**1.5)*((2.*MU/62.4/SO)**.5))/3.
      QT=(Q/WC)-QS*BCP/WC
      VM=Q/(WC*DT+BCP*QS)
      VMT=QT/DT
      RET=VMT*DT/NU
      IF (CASE.GT.1) GO TO 290
      VSTAR=0.005
      DVSR=0.01
  240 VSTAR=VSTAR+DVSR
      EEP=VMP/2.5/VSTAR+ALOG(DSR)
      QTINT=VSTAR*2.5*((DT+EXP(EEP))*ALOG(DT+EXP(EEP))-DT-EEP*EXP(EEP)-D
     (T*ALOG(DSR))
      IF(VSTAR.GT.2.) GOTO 50
C
C   SAFETY VALVE
      IF (ABS(QTINT-QT).LT.ACY) GOTO300
      IF(QTINT.GT.QT) GO TO 250
      GOTO240
  250 VSTAR=VSTAR-DVSR
      DVSR1=0.001
  260 VSTAR=VSTAR+DVSR1
      EEP=VMP/2.5/VSTAR+ALOG(DSR)
      QTINT=VSTAR*2.5*((DT+EXP(EEP))*ALOG(DT+EXP(EEP))-DT-EEP*EXP(EEP)-D
     (T*ALOG(DSR))
      IF(VSTAR.GT.2.) GOTO 50
C
C   SAFETY VALVE
      IF (ABS(QTINT-QT).LT.ACY) GOTO300
      IF(QTINT.GT.QT) GO TO 270
      GO TO 260
```

```
  270 VSTAR=VSTAR-DVSR1
      DVSR2=0.0001
  280 VSTAR=VSTAR+DVSR2
      EEP=VMP/2.5/VSTAR+ALOG(DSR)
      QTINT=VSTAR*2.5*((DT+EXP(EEP))*ALOG(DT+EXP(EEP))-DT-EEP*EXP(EEP)-D
     (T*ALOG(DSR))
C
C
C    SAFETY VALVE
      IF (QTINT.GT.QT) WRITE (6,1060)Q,DW
      IF (QTINT.GT.QT) GO TO 50
      IF(VSTAR.GT.2.) GOTO 50
      IF (ABS(QTINT-QT).LT.ACY) GOTO300
      GO TO 280
  290 VSTAR=(Q-BOP*(VMP*DS-2*SQRT(2*MU/GM/SO)*(VMP)**(3./2.)/3))/WC/TV
  300 USTAR=VSTAR
      TTS=USTAR**2*RHO
      IF (CASE.GT.1) VMAX=2.5*VSTAR*ALOG(DT/DSR)
      DX=DS
      IF (CASE.GT.1) GO TO 310
      DX=DS-EXP(EEP)
      IF (DX.LT.0.) WRITE (6,1070)Q,DW
      IF (DX.LT.0.0) GO TO 50
      VMAX=2.5*VSTAR*ALOG((DW-DX)/DSR)
  310 NT=(((RT**(1./3.))*TTS)/(.45*GM*VMT*VMT))**.5
      QSCH=QS*BOP
      QTCH=QT*WC
C
C   COMPUTES THE VALUES OF SHEAR RESISTANCE FOR THE WALL AND BOTTOM
C
  320 TB=(MU*VMP*62.4*SO)**.5
      TW=(MU*VMP/A)+(A*62.4*SO/2.)
      VAVG=VM
C
C    COMPUTE VALUES FOR KOUWAN AND REE-PALMER PLOTS
C
      R=((DW*.481)-2.*DW*((VAVG*.012/(1.486*(SO**.5)))**(3./2.)))/.481
      NC=(1.486/VAVG)*(R**(2./3.))*(SO**.5)
      SV=((32.2*R*SO)**.5)
      VRT=VAVG/SV
      AR=DW*.481
      ART=ALOG(AR/AB)
```

```
      VR=VAVG*R
C
C   USE HYDRAULIC RADIUS BETWEEN BLADES X NUMBER OF BLADE PER UNIT WIDTH
C   OF CHANNEL, SPFW, AS PARAMETER
C
      SPFW=(DSG*144.)**0.5
      RSTR=DW*GAP/(GAP+2*DW)*SPFW
      IF (DW.GT.DS) RSTR=DW*GAP/(GAP+2*DS)*SPFW
      NSTR=1.486*(RSTR)**(2./3.)*SO**0.5/VAVG
      SVSTR=(32.2*RSTR*SO)**0.5
      VRTSTR=VAVG/SVSTR
      VRSTR=VAVG*RSTR
      IF(DW.GT.DS)GOTO330
C
C  COMPUTE CD FOR NON-SUBMERGED CASE
C
      VW=.481*DW
      VS=(1.59307*DSG*DW*TS)
      V=VW-VS
      AP=1.59307*DSG*TS
      DX=0.0
      CD=((V*62.4*SO)-TB*(.481-AP)-(2*TW*DW))/(SN*.9675*LAVG*DW*VM*VM)
      VMP1=VMP
C
C  COMPUTES REYNOLDS NUMBER USING FIRST THE BLADE WIDTH AND THEN THE WAT
C  AS THE CHARACTERISTIC LENGTH
C
  330 RE1=VMP*LAVG/NU
      RE2=VMP*DW/NU
      REF=VMP*GAP/NU
C
C COMPUTES A VALUE FOR  CD/(GAMMA*SLOPE)
C
      CDGSO=CD/(GM*SO)
      SNCGS=(SN*CD)/(GM*SO)
      I=I+1
      FQ(I)=QPF
      FDW(I)=DW
      FART(I)=ART
      FVM(I)=VM
      FVAVG(I)=VAVG
      FVR(I)=VR
```

```
      FSV(I)=SV
      FVRT(I)=VRT
      FNC(I)=NC
      FVMP(I)=VMP
      FCD(I)=CD
      FSNCGS(I)=SNCGS
      FCDGSD(I)=CDGSD
      FRE1(I)=RE1
      FREF(I)=REF
      FRE2(I)=RE2
      FVRSTR(I)=VRSTR
      FSVSTR(I)=SVSTR
      FNSTR(I)=NSTR
      FVRTS(I)=VRTSTR
      FBLT(I)=BLT
      IF(DW.LE.DS)GOTO50
      FTTS(I)=TTS
      FDX(I)=DX
      FVMAX(I)=VMAX
      FRET(I)=RET
      FUSTAR(I)=USTAR
      FNT(I)=NT
      FQT(I)=QT
      FQS(I)=QS*BOP/WC
      FVMT(I)=VMT
      GOTO50
  340 K=I
      I=0
      DSGF=DSG*144
      WRITE (6,1080) SD
      WRITE (6,1090) DSGF
      WRITE (6,1170) DS
      WRITE(6,1100)
  350 I=I+1
      WRITE(6,1110)FD(I),FDW(I),FVAVC(I),FVR(I),FNC(I),FSV(I),FVRT(I),FA
     (RT(I)
      IF (I.GE.K) GO TO 360
      GOTO350
  360 I=0
      WRITE (6,1080) SD
      WRITE (6,1090) DSGF
      WRITE (6,1170) DS
```

```
      WRITE (6,1100)
  370 I=I+1
      WRITE (6,1110)FQ(I),FDW(I),FVAVG(I),FVRSTR(I),FNSTR(I),FSVSTR(I),
     ( FVRTS(I),FART(I)
      IF(I.GE.K)GOTO380
      GO TO 370
  380 I=1
      WRITE (6,1080) SO
      WRITE (6,1090) DSGF
      WRITE (6,1170) DS
      WRITE(6,1120)
  390 IF(FDW(I).GT.DS)GOTO400
      WRITE(6,1130)FQ(I),FDW(I),FVMP(I),FBLT(I),FCD(I),FSNCGS(I),FRE1(I)
     (,FREF(I),FRE2(I),FCDGSO(I)
      I=I+1
      IF(I.GT.K)GOTO010
      GOTO390
  400 JJ=I
      WRITE (6,1080) SO
      WRITE (6,1090) DSGF
      WRITE (6,1170) DS
      WRITE(6,1140)
  410 WRITE(6,1150)FQ(I),FDW(I),FVMP(I),FBLT(I),FVMT(I),FCD(I),FNT(I),
     ( FUSTAR(I),FREF(I),FRET(I)
      I=I+1
      IF(I.LE.K)GOTO410
      WRITE (6,1080) SO
      WRITE (6,1090) DSGF
      WRITE (6,1170) DS
      WRITE(6,1160)
      I=JJ-1
  420 I=I+1
      WRITE(6,1150)FQ(I),FDW(I),FVMP(I),FQS(I),FOT(I),FDX(I),FVMAX(I),
     ( FTTS(I),FRE1(I),FRE2(I)
      IF (I.LT.K) GOTO 420
      GOTO010
 1030 FORMAT(3F10.4,I5)
 1040 FORMAT (/' FOR Q=',F6.4,'DW=',F6.4,'VMP CANNOT BE FOUND'/)
 1050 FORMAT(2F10.4)
 1060 FORMAT (/' FOR Q=',F6.4,'DW=',F6.4,'TURBULENT FLOW PROFILE IS NOT
     (ESTABLISHED'/)
 1070 FORMAT (/' FOR Q=',F6.4,'DW=',F6.4,'DX HAS A NEGATIVE VALUE'/)
```

```
1080 FORMAT('1  SLOPE OF FLUME                          =',F10.4,'FT/FT')
1090 FORMAT('   DENSITY OF SIMULATED GRASS              =',F10.4,'BLADES PER SQ. F
    (OOT')
1100 FORMAT(//'             Q          DW        VAVG        VR          N
    (   S.VEL.     V/U*    LN(A/AB)'//)
1110 FORMAT(3X,6F10.4)
1120 FORMAT(//'             Q         DW         VMP        BLT         RD     N
    (*RD/GM*S     RE1        REF          RE2     RD/GM*S'//)
1130 FORMAT(3X,6F10.4,4F10.3)
1140 FORMAT(//'             Q          DW        VMP         BLT         VMT
    (    RD          NT        U*          REF         RFT'//)
1150 FORMAT(3X,8F10.4,2F10.2)
1160 FORMAT(//'             Q          DW        VMP         QS          QT
    (   DX         VMAX        TTS         RET         RE2'//)
1170 FORMAT('   HEIGHT OF SIMULATED GRASS    =',F10.4,'FT')
 430 CONTINUE
     STOP
     END
```

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05/24/77 TIME= 09.59.16