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VELOCITY PROFILE AND FRICTION FACTOR FOR FLOW OVER A PERMEABLE BOUNDARY: A LITERATURE REVIEW.

P. Engel

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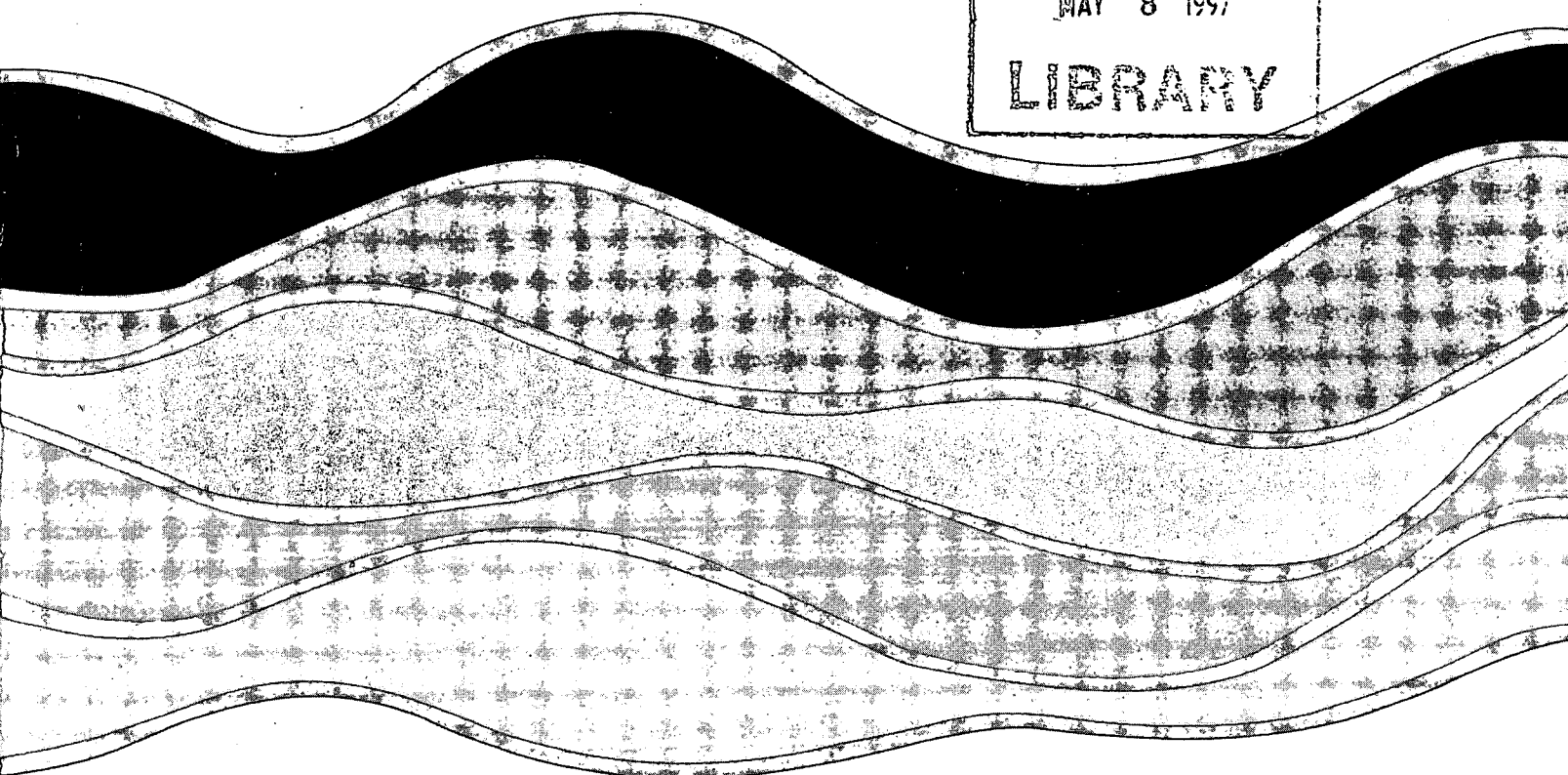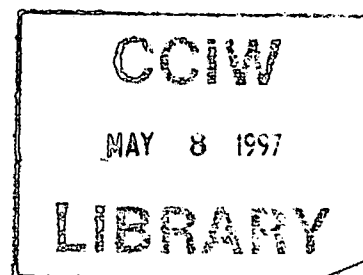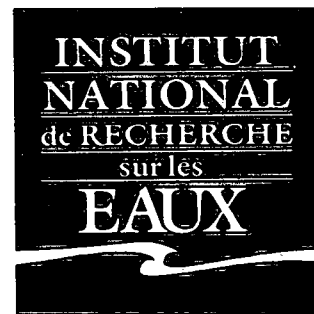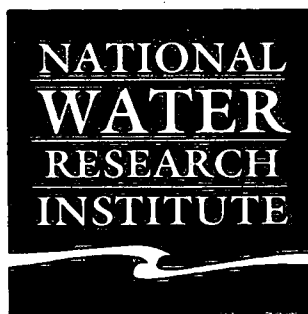
VELOCITY PROFILE AND FRICTION FACTOR FOR FLOW OVER

A PERMEABLE BOUNDARY: A LITERATURE REVIEW

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MANAGEMENT PERSPECTIVE

Effective aquatic ecosystem protection requires better understanding of flow characteristics near the stream bed. Natural streams have beds formed by permeable materials and yet, very little is known about the interaction of the pervious bed and the turbulent flow over it. The porosity of the bed allows fine suspended sediments and contaminants carried by the open channel flow, to be stored and concentrated there depending on the existing hydraulic conditions. The intrusion of sediment fines into the gravel bed greatly restricts transport of dissolved oxygen into and through the bed substrate and reduces the ability of interstitial water flow to sustain substrate organisms and remove metabolic waste. These factors have significant implications for maintaining river habitat functions and point to the importance of continuing research on physical river processes.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Pour protéger efficacement les écosystèmes aquatiques, il faut mieux comprendre les caractéristiques d'écoulement près du lit du cours d'eau. Les lits des cours d'eau naturels sont formés de matières perméables; pourtant, on connaît très peu les interactions entre la couche perméable et l'écoulement turbulent au-dessus. À cause de sa porosité, cette couche peut stocker et concentrer plus ou moins, selon les conditions hydrauliques qui prévalent, les sédiments et contaminants fins en suspension transportés par le courant. L'introduction de sédiments fins dans le lit de gravier réduit grandement le transport de l'oxygène dissous à l'intérieur de ce lit et réduit la capacité de l'eau interstitielle de supporter des organismes et d'éliminer les déchets métaboliques. Ces facteurs ont des répercussions importantes sur le maintien des fonctions d'habitat d'un cours d'eau et soulignent l'importance de continuer les recherches sur les processus physiques qui interviennent dans les cours d'eau.

ABSTRACT

An extensive literature review was conducted. It was found that available information dealing with the topic of this report was quite limited. Sixteen articles were selected for final review. The results showed that there is an urgent need for carefully conducted experiments to determine the basic characteristics of the vertical velocity profile for flows near the permeable boundary. In particular, it is necessary to conclusively determine if the von Karman constant remains constant at 0.4 or if it decreases as the permeability of the boundary increases. Five research suggestions are presented.

RÉSUMÉ

Après une recherche approfondie dans la littérature, on a observé qu'il y a très peu d'information sur le sujet qui nous occupe. On a choisi seize articles que l'on a soumis à un examen plus complet. Les résultats ont montré qu'il est urgent d'effectuer des expériences sérieuses pour déterminer les caractéristiques fondamentales du profil vertical des vitesses dans le cas des écoulements qui s'effectuent à la limite de la couche perméable. Il est notamment nécessaire de déterminer de façon concluante si la constante de Karman reste à 0,4 ou si elle diminue avec l'augmentation de la perméabilité à la limite de la couche perméable. On propose cinq projets de recherche.

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1.0 INTRODUCTION

Natural streams have beds formed by permeable materials and yet, very little is known about the interaction of the pervious bed and the turbulent flow over it in comparison with the very large number of studies on turbulent flow over impervious smooth and rough boundaries. Usually, the pervious bed is considered to be equivalent to an impervious boundary of the same texture, thereby ignoring the effects of the permeability on the flow. In reality, the part of the flow that moves through the porous bed and the flow above it, interact in a complex manner so that the basic assumptions commonly used for solid, impervious boundaries are no longer applicable when considering processes at the stream bed.

The ability to adequately describe the effects of the permeable bed on the flow process is very important in determining contaminant pathways and providing effective aquatic ecosystem protection. The porosity of the bed not only allows flow to pass through the permeable medium but also facilitates the exchange of mass, momentum and energy between the main turbulent stream and the seepage flow. As a result, fine suspended sediments and contaminants carried by the open channel flow, can be passed into the porous medium, stored and concentrated there depending on the existing hydraulic conditions (Einstein, 1968; Bencala, 1984; Savant et al, 1987). The intrusion of sediment fines into the gravel bed greatly restricts transport of dissolved oxygen into and through the bed substrate and reduces the ability of interstitial water flow to remove metabolic waste (Mendoza and Zhou, 1993). The formation of streambed biofilms, which are a prominent element in removing contaminants from the flow, is affected by flow conditions near the bed (Lau, 1995). Clearly, flow processes in the vicinity of the permeable bed have significant implications for maintaining river habitat functions with emphasis on fish spawning beds and water quality.

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The review is focused on the vertical velocity profile and friction factor for flows over porous boundaries. The literature on these topics is quite limited in comparison to corresponding literature on solid impermeable boundaries. After extensive search of available literature, sixteen articles were selected for inclusion in this report. The review covers experimental and theoretical investigation and combinations of both. It is indicated in the reviews whether the articles contain data. Based on the review of the sixteen articles, five research suggestions are proposed.

2.0 LITERATURE REVIEWED

2.1 BEAVERS AND JOSEPH (1967)

Reference:	Boundary Conditions at a Naturally Permeable Wall.
Year of Publication:	1967
Authors:	Beavers, G.S. and D.D. Joseph.
Published in:	Journal of Fluid Mechanics, Vol. 30, Part 1, pp. 197-207
Data:	Figures.

REVIEW

In this paper experiments giving the mass efflux of a Poiseulle flow over a naturally permeable block are reported. The block was inserted into an open rectangular channel in a manner that permitted separate measurement of the flow through the block and the main flow above the block. A simple theory based on replacing the effect of the boundary layer with a slip velocity proportional to the exterior velocity gradient of the laminar flow is proposed.

Predicted flow rates agree well with measured flow rates for mean velocity Reynolds numbers up to about 800. The data presented indicate that the rectilinear flow of a viscous fluid over the surface of a permeable material induces a boundary layer region within the material. The effects of this boundary layer can be such as to greatly alter the nature of the tangential motion near the porous surface. In addition to the permeability of the boundary, the resultant slip velocity was found to be dependent on the structural characteristics of the porous medium.

Flow of a Newtonian fluid over a porous medium presents great difficulties in obtaining appropriate boundary conditions at the permeable surface due to the complex interaction between the internal and external flow fields. This paper makes an important contribution because it presents a means to overcome the problem for laminar flows. Currently, there is no known methodology for calculating the slip velocity at the interface between a turbulent flow and a porous bed. More experiments are required to provide the necessary information for river flows.

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2.2 CHU AND GELHAR (1972)

Reference: Turbulent Pipe Flow with Granular Permeable Boundaries.
Year of Publication: 1972
Authors: Chu, Y. and L. W. Gelhar
Published in: Report No. 148, R.M. Parsons Laboratory, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Mass.
Data: Tables and Figures.

REVIEW

In this report the effects of boundary permeability on turbulent shear flow are investigated theoretically and experimentally. Experiments were conducted with six pipes of different sizes, boundary permeabilities and geometric properties of the porous layer.

Experimental results show, similar to findings of others, that the friction factor increases as the Reynolds number increases. Comparisons are made with the shape of the friction factor diagram of Lovera and Kennedy (1969). Although, the dynamics of the plane bed sediment transport studied by Lovera and Kennedy may be different, both boundaries can be said to have been permeable. The dependence of the friction factor on Reynolds number is interpreted to mean that the characteristics of the classical fully rough turbulent flow regime are not found in turbulent permeable boundary flow. This was attributed to the turbulent fluctuations which offset the effect of friction reducing slip velocity at the bed surface resulting in a net increase of resistance which depends on the Reynolds number. A better insight into the behaviour of the friction factor was obtained by noting that the total friction factor could be separated into a boundary roughness component and an induced stress component. The roughness component decreases with Reynolds number in the classical way and the induced stress component increases with Reynolds number. The net effect is the increase of the total friction factor with Reynolds number. The friction factor was also found to increase with increasing boundary permeability. The total friction factor was found to decrease with the

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dimensionless variable $\frac{D}{\sqrt{K}}$ (D = pipe diameter and K = the intrinsic permeability of the porous boundary) which was due to an increase in K.

Results showed that in order to have a logarithmic velocity distribution near the wall, a depression of the y ordinate by a small amount Δy (Figure 1) was required. The method to determine the value of Δy without imposing any restrictions on κ is by no means unique. Since κ is a universal characteristic of turbulent flows with impervious boundaries and is independent of Reynolds number, it was deemed appropriate to assume that κ is constant for a given permeable boundary. As a result, it was necessary to have Δy vary. It was found that Δy increased slightly with Reynolds number. The value of κ for the granular, permeable boundary was found to be 0.27 which is in close agreement with results from Munoz and Gelhar (1968).

2.3 GUPTA and PAUDYAL (1985)

Reference: Characteristics of Free Surface Flow Over Gravel Bed.
Year of Publication: 1985
Authors: Gupta A.D. and Paudyal G.N.
Published in: Journal of Irrigation and Drainage Engineering, Vol 111, No.4, pp. 299-318
Data: Tables and Figures.

REVIEW

The aim of this paper is the experimental evaluation of the major characteristics of shallow free surface flow over a permeable bed of gravel. The principal objectives of the experiments were to investigate the effects of the permeable bed on the vertical velocity distribution and the boundary resistance. Experiments were conducted in three stages. The first stage was directed towards determining the permeability of the bed material, specific gravity, grain size distribution and porosity. The second stage consisted of the flume tests of flows over the permeable bed. The third stage was designed for comparison with an equivalent impermeable bed having the same gravel roughness.

The velocity profile for flow over the permeable bed was analyzed using the Prandtl-von Karman logarithmic velocity distribution by depressing the virtual zero plane below the nominal surface by a small distance Δy (Figure 1). This distance is estimated from the analysis of the measured velocity distributions. The general form of velocity distribution is given as

$$\frac{u}{U_*} = \frac{1}{\kappa}\ln\left(\frac{y + \Delta y}{k_s}\right) + A \tag{1}$$

where U_* = shear velocity, u = point velocity, κ = the von Karman constant, k_s = the equivalent grain size roughness and A = a dimensionless value determined by experiment. The value of k_s was taken to be equal to D_{50} (D_{50} = the median diameter of the uniform granular boundary). The parameters A, κ and Δy were estimated by using non-linear regression. For the D_{50} of 9.8 mm

used it was found that $\Delta y = 0.32$, $A = 8.21$ and $\kappa = 0.28$ which is similar to that found by Chu and Gelhar (1972) and significantly less than the value of 0.4 traditionally known to be approximately valid for impermeable surfaces.

The friction factor was determined as

$$f = \frac{8gRS_f}{V^2} \tag{2}$$

where g = acceleration due to gravity, R = hydraulic radius, S_f = the friction slope and f = the Darcy-Weisbach friction factor. Results showed that the friction factor for permeable beds increases with the Reynolds number. By considering V_o as the slip velocity at the bed surface (Figure 1), the equation for the friction factor can be written as

$$f = 8\left[\frac{1}{\kappa}\ln\left(\frac{h + \Delta y}{ek_s}\right) + \frac{V_o}{U_*}\right]^{-2} \tag{3}$$

where e = the base of natural logarithms, V_o = the slip velocity at the porous surface and h = the depth of flow. The relationship indicates that the slip velocity is a significant parameter in determining the boundary resistance. The slip velocity is the result of the presence of water in the pore spaces and decreases the friction. The momentum exchange between the porous bed and the flow above it increases the flow resistance. Experimental evidence shows that the net effect is an increase in the friction factor and this increase is dependent on the Reynolds number (Figure 2). Reasonable agreement was found between measured and computed friction factors.

A dimensional analysis is presented based on the general functional relationship for the friction factor f given as

$$f = \phi(V, h, R, D_{50}, d_b, K, g, \rho, \mu) \tag{4}$$

where ϕ denotes a function, d_b = the thickness of the porous bed, ρ = the density of water and μ = the dynamic viscosity of water. Equation (4) appears to be over specified and results in unecessary

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redundancy in the dimensional analysis. A more rigorous and parsimonious relationship can be written as

$$f = \phi(h, D_{50}, U_*, K, d_b, \rho, \nu) \tag{5}$$

where $\nu = $ the kinematic viscosity. Dimensional analysis based on equation (5) results in

$$f = \phi_1\left(\frac{U_* D_{50}}{\nu}, \frac{h}{D_{50}}, \frac{\sqrt{K}}{D_{50}}, \frac{d_b}{D_{50}}\right) \tag{6}$$

where ϕ_1 denotes another function. Further experimental work based on equation (6) should be undertaken with systematic testing of different beds with varying permeability, porosity, thickness and particle size.

2.4 GUPTA and UTAINRAT (1988)

Reference:	Experiments on Resistance to Flow in Channels with Permeable Beds.
Year of Publication:	1988
Authors:	Gupta A.D. and Utainrat W.
Published in:	Proceedings of the 6th Congress, Asian and Pacific Regional Division, IAHR,Kyoto, Japan, 20-22 July, pp. 441-448.
Data:	Tables and Figures.

REVIEW

This paper is an extension of the work conducted by Gupta and Paudyal (1985) which was limited to a porous boundary of one median grain size. New experiments were conducted using four permeable beds of different median grain size. The main objectives of the experiments were to investigate the effect of the permeable bed on the velocity distribution above the bed as well as the boundary resistance. Experiments were conducted in two stages. The permeability of the bed material and other physical properties such as specific gravity, grain size distribution and porosity of the bed were determined in the first stage. The second stage was the flume tests involving experiments with flows over the four permeable beds.

Similar to the work by Gupta and Pardyal (1985), the data was analyzed using the velocity distribution

$$\frac{u}{U_*} = \frac{1}{\kappa} \ln \left(\frac{y + \Delta y}{k_s} \right) + A \tag{1}$$

Parameters A, κ and Δy were estimated by applying non-linear regression analysis to the measured velocity distributions. The value of the von Karman constant was found to decrease as the permeability of the bed increased. There was a decrease in κ but no consistent dependence of A and Δy on permeability. The decrease in κ was interpreted to mean a change in the dissipation of the mean flow energy. In other words, with an increase in permeability of the bed, the momentum

exchange near the bed becomes more active which results in reduction of the κ values. A reduction in th κ values implies an increase in the velocity gradient of the velocity profile. The observed gradient increase may be the direct result of applying the non-linear regression over the full depth of the flow instead of the wall region only. Zippe and Graf (1983) found that when velocity profiles were analysed using the logarithmic distribution in the inner region (wall region) and Cole's wake law in the outer region, differences in the effects of permeable and impermeable boundaries could be demonstrated by using the traditional value of $\kappa = 0.4$ in the wall region. This further demonstrates the need for more extensive data in the region near the porous bed in order to facilitate the proper data analysis.

Analysis of the data further showed that, for a given Reynolds Number $R_e = \frac{Uh}{\nu}$, the Darcy-Weisbach friction factor for a permeable bed increases as the permeability increases. For the four permeable beds tested, power relationships between f and the relative roughness $\frac{D_{50}}{h}$ were developed. These relationships were expressed as

$$f = a\left(\frac{D_{50}}{h}\right)^b \tag{7}$$

where a and b are empirical coefficients. The highest correlation was found for the two beds having the largest permeability. Values of a were found to decrease slightly as permeability increased but there was no clear relationship between b and permeability.

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2.5 IWASA AND AYA (1987)

Reference:	Mass transport in the flow over permeable boundaries.
Year of Publication:	1982
Authors:	Iwasa Y and Aya S.
Published in:	Proceedings of XXII Congress, IAHR, Lausanne, 31 Aug.-4 Sep., 1987. pp. 263-268.
Data:	None.

REVIEW

This paper deals with the convective velocity and the dispersion coefficient of tracer clouds in the flow over permeable boundaries. The study consisted of experimental visualization and mathematical modelling.

The flow visualization with dye solutions in a laboratory flume covered with sand was made to demonstrate the interaction between the open channel flow and the flow in the permeable bed as a prelude to mathematical modelling. The permeable boundary was classified into layers A, B and C. The most upper layer A was rapidly penetrated by a rhodamine B solution inserted into the upper flow. The dye concentration in the A layer rapidly diminished once the inflow of the dye was stopped. The dye penetrated layer B very slowly but the bottom layer C was not penetrated at all. This was interpreted to mean that the main interaction between the flow and the permeable boundary occurs in the A layer which is referred to as the mixing layer.

The mathematical model was designed to deal with the flow observed in layer A to simulate the depth-wise mass and momentum transfer existing between the two flows. Towards this end, a model similar to longitudinal mixing in open channel flows with dead zones was used. The results showed that the convective velocity and the dispersion coefficient are strongly dependent on the ratio of the thickness of the mixing layer to the depth of the stream flow. It was concluded that more study

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on the effect of thickness of the mixing layer as well as deposition of fine suspended sediments on gravel beds is required.

2.6 LOVERA AND KENNEDY (1969)

Reference:	Friction Factors for Flat Bed Flows in Sand Channels.
Year of Publication:	1969
Authors:	Lovera, F. and J.F. Kennedy.
Published in:	Journal of the Hydraulics Division, ASCE, Vol. 95, No. HY4, pp. 1227-1234.
Data:	Tables and Figures.

REVIEW

The purpose of this paper is to is to examine the relationship between the friction factor and the other parameters for sand bed channel flows which were known or could reasonably be assumed to have been in the flat-bed regime and to have had active transport of bed material. To this end, available data for both natural streams and laboratory channels were examined. The friction factors thus obtained were presented in the same format as the familiar Moody pipe friction diagram. The results showed that the friction factor of the flat bed flow did not follow the same trend as observations made on rough impervious boundaries. For a flow over the flat bed of constant relative depth, the friction factor increased continuously with the flow Reynolds number. This trend is similar to that found by Gupta and Paudyal (1985) and others for flows over rigid permeable beds.

This paper is noteworthy because analysis of a wide range of data shows the effect of the porous bed. It is interesting to note that this effect was not recognized to be the reason for the drastic departure from the traditional shape of the friction factor diagram.

2.7 MENDOZA and ZHOU (1993)

Reference: Effect of Porous Bed on Turbulent Stream Flow Above Bed.
Year of Publication: 1993
Authors: Mendoza C. and Zhou D.
Published in: Journal of Hydraulic Engineering, ASCE, Vol 118, No. 9, pp. 1222-1240.
Data: Tables and Figures

REVIEW

This work introduces a theoretical analysis of the effect of a plane porous bed on the turbulent shear flow above it. The flow in the channel is assumed to be steady, uniform, fully developed and two dimensional. The effect of the pervious boundary on the main flow is taken as the perturbation of an equivalent turbulent flow over an impervious bed of the same surface texture. The turbulence field is regarded as stationary and statistically homogeneous in planes parallel to the channel bottom. The interaction of the external and internal flows occurs through the transfer of momentum and energy at the interface. The hydrodynamics of the perturbations are described with equations obtained by subtracting the Navier-Stokes equations governing the unperturbed turbulent flow from that governing the perturbed flow. This resulted in a velocity distribution given by

$$\frac{u}{U_*} = \frac{1}{\kappa}\ln\left[\frac{y + z_1}{z_1}\right] + \frac{V_o}{U_*} \tag{8}$$

where z_1 = a linear scale which must be determined experimentally. The value of z_1 was approximated by comparing equation (8) with the velocity distribution obtained by Zagni and Smith (1976) resulting in

$$z_1 = D_{50}\exp\left[\kappa\left(\frac{V_o}{U_*} - 9.09\right)\right] \tag{9}$$

The resulting velocity distribution was found to agree very well for $y \geq 0$ with experimental data from Zippe and Graf (1983) and Nakagawa and Nezu (1980).

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Using this velocity distribution it was found that, for a given flow condition, the von Karman constant κ decreased as the permeability of the boundary increased. This was taken as confirmation of similar results obtained by Gupta and Paudyal (1985), Munoz-Goma and Gelhar (1968), Chu and Gelhar (1972) and Gupta and Utainrat(1988) based on the use of the logarithmic distribution (law of the wall) over the full flow depth. This agreement suggests that the author's new equation has similar properties to the universal logarithmic distribution and does not provide any new information. In fact, Zippe and Graf (1983) have shown that good results are obtained when κ is kept constant at 0.4 when the logarithmic velocity distribution is used in the wall region (inner region) and the wake law is used in the flow above the wall region. This suggests that more work is required in interpretation of velocity measurements. More measurements in the wall region are required to permit a proper fit of the velocity distribution.

The equation for the friction factor was determined to be

$$f = 8\left[\frac{1}{\kappa}\ln\left(\frac{h}{ez_1}\right) + \frac{V_o}{U_*}\right]^{-2} \tag{10}$$

This equation is quite similar in form to that given by Gupta and Paudyal (1985). The difference is in the term $\frac{h}{z_1}$ which has been found valid for permeable and impermeable boundaries indicating that z_1 must somehow depend on boundary permeability. By differentiating equation (10) and introducing the average velocity over the flow depth h, the authors arrived at the relationship

$$\frac{1}{8}\frac{df}{dh} = \left(\frac{U}{U_*}\right)^{-3}\frac{V_o}{U_*}\frac{1}{h} \tag{11}$$

where U = the average velocity in the vertical. Equation (11) shows that a change in either energy slope or flow depth (through U_*) will result in a change of f with Reynolds number. This is due to the presence of the slip velocity V_o and the fact that the turbulence in the flow will not die out

at the porous surface. Using the Manning equation and the Reynolds number $Re = \frac{Uh}{\nu}$, it was further shown that

when $V_o > \frac{1}{3}U$

$$\frac{d^2 f}{d[\ln(Re)]^2} > 0 \tag{12}$$

and when $V_o < \frac{1}{3}U$

$$\frac{d^2 f}{d[\ln(Re)]^2} < 0 \tag{13}$$

Equations (12) and (13) confirm the tendencies depicted by experimental data plotted as shown in Figure 2 and are a criterion for the curvature of the f curves on a semilog plot.

2.8 MUNOZ-GOMA AND GELHAR (1968)

Reference: Turbulent Pipe Flow with Rough and Porous Walls.
Year of Publication: 1968
Authors: Munoz-Goma, R.J. and L. W. Gelhar
Published in: Report No. 109, Hydro Dynamics Laboratory, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Mass.
Data: Tables and Figures.

REVIEW

The material of interest in this report is the experimental evaluation of the major characteristics of turbulent flow along porous boundaries. Experiments were conducted with air flow in two circular pipes of 25.4 cm diameter, using 3.2 mm spherical roughness elements in one of them and a 30.5 mm thick porous lining in the other. The Reynolds number based on pipe diameter and average velocity ranged from 10^5 to 5×10^5.

The rough impervious pipe behaved in every respect in accordance with the classical experiments of Nikuradse for particulate roughness. The most notable difference found in the porous pipe was the very high friction factor and its continuous increase with Reynolds number throughout the range of the experiments. A speculative explanation for this variation of f is given with reference to the modified Darcy equation (Ward, 1964) which is given by

$$\frac{1}{\rho}\frac{dp}{dx} = \frac{\nu q}{K} + 0.550\frac{q^2}{\sqrt{K}} \qquad\qquad 14$$

where p = the pressure in the pipe, x is the streamwise distance and q = the specific discharge in the direction x. A similar expression was proposed by Rumer and Drinker (1966). For low rates of flow, the linear term, dependent on viscosity, is dominant over the quadratic term. As the Reynolds number increases, the influence of the linear term gradually diminishes and eventually, the equation becomes independent of viscosity. This gradual change in the form of equation (14)

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for the turbulent motion within the porous medium should be reflected in the characteristics of the pipe flow. It is considered to be conceivable that the increase in the pipe friction factor with Reynolds number may reflect this change of flow regime in the porous medium. If this is the case, the friction factor will become constant only when equation (14) is practically independent of the viscosity at sufficiently high permeability Reynolds numbers for the porous medium. Further work on this premise is recommended.

Most noteworthy within the scope of this review is the result that the κ and the thickness of the flow for which the log-law is valid, seem to vary as a function of the displacement Δy of the origin from the wall. In order to plot the data in terms of the law of the wall parameters, some decision must be made with regard to the value of Δy. There is an inherent ambiguity in this process, because it is not known in advance how far away from the wall the semi-logarithmic law should extend. Therefore, the determination of the best location for the effective origin and the resulting slope $\frac{1}{\kappa}$ of the semi-logarithmic straight line will be affected by the thickness of the zone where a good fit to the data is required. The presence of both κ and Δy allows for the arbitrary determination of one of them. The acceptance of κ as a universal constant having a value of 0.4, results in the depression of the origin Δy decreasing slightly with Reynolds number. A constant value of Δy results in a value of κ less than 0.4. Further experiments are required to extend these findings over a wider range of flow conditions and boundary permeability.

2.9 NAKAGAWA AND NEZU (1980)

Reference: Turbulent Behaviors of Open Channel Flows with Permeable Beds.
Year of Publication: 1980
Authors: Nakagawa, H. and I. Nezu.
Published in: International Conference on Water Resources Development, Taipei, Taiwan, Republic of China, May 12-14, pp. 661-670.
Data: Tables and Figures.

REVIEW

In this paper, open channel flow over a permeable bed with and without transpiration (flow into or out of the porous bed) is examined. Flow without transpiration only is pertinent to the present review. Experiments were conducted in three phases. In the first phase, flow was over a rough, solid bed, impermeable bed as a reference. The second phase used a dense permeable bed consisting of three layers of uniformly sized glass beads. In the third phase, the same glass beads were used to form a loose bed consisting of five layers of the glass beads. Porosity and permeability of the beds were obtained by standard methods. Three different flow conditions were used for each phase.

In determining the mean flow characteristics of the open channel flow special attention was given to the determination of the shear velocity U_*. Emphasis is placed on the fact that the log law should not be used here because results from other investigators have reported that κ is not necessarily equal to the well known value of 0.4. This difficulty was avoided by using a Reynolds - stress method. The Reynolds stresses were measured with a dual sensor hot - film anamometer. Having determined U_*, the velocity defect law was used to determine κ and the slip velocity V_o. The results showed that the von Karman constant κ does tend to decrease as the permeability increased.

Another important contribution of this paper is the introduction of induced stress. As a result of the dynamic interaction between the open channel flow and the seepage flow, the seepage flow is

agitated and as a result, an additional shear stress will be induced in the main flow. The balance of the stresses is given by

$$\tau_o = \tau_o' + \tau_i \tag{15}$$

where τ_o = the total shear stress at the bed, τ_o' = the shear stress generated by the wall roughness and τ_i = the shear stress induced by the seepage flow on the open channel flow above the porous bed. The induced shear stress was experimentally determined as

$$\frac{\tau_i}{\tau_o} = \frac{\tau_o - \tau_o'}{\tau_o} \tag{16}$$

Results showed that the ratio $\frac{\tau_i}{\tau_o}$ increased with permeability of the bed and accounted for up to 14% of the total shear stress for the conditions tested. The results also showed that $\frac{\tau_i}{\tau_o}$ increased with Reynolds number. Addittional experiments should be conducted to define these flow characteristics over a wider range of bed conditions and main flow conditions.

2.10 NAKAGAWA AND TSUIMOTO (1984)

Reference: Interaction Between Flow Over a Granular Permeable Bed and Seepage
Flow - A Theoretical Analysis.
Year of Publication: 1988
Authors: Nakagawa, H. and T. Tsuimoto.
Published in: Journal of Hydroscience and Hydraulic Engineering, Vol. 2, No. 2, pp
1-10.
Data: Tables and Figures.

REVIEW

In this paper, the authors address the problem of slip velocity and transpiration velocity (flow in or out of the porous bed) on the structure of the open channel flow by means of theoretical analysis. A general equation for the velocity distribution above the porous bed was derived. For the case of flow with transpiration, the shear stress at the bed was expressed as

$$\tau_o = -\rho\overline{uv} + \nu\frac{\delta U}{\delta y} - \rho v_o U \tag{17}$$

where τ_o = the bed shear stress, ρ = the density of the fluid, u = streamwise velocity fluctuations, v = the vertical velocity fluctuations, ν = kinematic viscosity, v_o = the vertical transpiration velocity, U = the depth averaged flow velocity of the free surface flow and y = the vertical ordinate referenced to the surface of the porous bed. Applying the mixing length theory given as

$$-\overline{uv} = (\kappa y)^2 \left(\frac{dU}{dy}\right)^2 \tag{18}$$

and combining equations (17) and (18), making appropriate terms dimensionless and integrating, the authors arrived at the following general equation for the vertical velocity distribution with transpiration:

$$\frac{u}{U_*} = \frac{\pi_{vo}}{4\kappa^2}\ln^2\frac{y}{k_s} + \frac{1}{\kappa}\left[\left(\frac{\pi_{vo}}{2}\right)D_r + \sqrt{1 + \pi_{vo}\pi_P}\right]\ln\left(\frac{y}{k_s}\right) + \left[\frac{\pi_{vo}D_r}{4} + \sqrt{1 + \pi_{vo}\pi_P}\right]D_r + \pi_P \tag{19}$$

where $\pi_{vo} = \frac{v_o}{U_*}$, $\pi_P = \frac{V_o}{U_*}$ and D_r = a constant. The terms containing v_o account for the effect of the transpiration flow. Equation (19) was used by the authors to show that κ decreases when transpiration is into the free surface flow and increases when transpiration is into the porous bed. When there is no transpiration, then $\pi_{vo} = 0$ and equation (19) reduces to

$$\frac{u}{U_*} = \frac{1}{\kappa}\ln\left(\frac{y}{k_s}\right) + D_r \tag{20}$$

Even though there is no transpiration, the porous medium still contains water and this must have an effect on the free surface flow. Such effect is not evident in equation (20). Indeed, equation (20) is equivalent to the conventional formula developed for rough, solid, impermeable boundaries. The value of D_r depends on the choice of the location of $y = 0$. Equation (20) does not reflect the depression of the $y = 0$ position, normally designated as Δy, which has been experimentally determined by Zagni and Smith (1976), Gupta and Paudyal (1985) and others. The presence of the slip velocity V_o certainly requires that the theoretical value of zero velocity must be below the surface of the porous bed. The fact that Δy is not present in equations (19) and (20) indicates that they do not represent fully the physical processes that govern the free surface flow over a permeable bed. Further work is required to obtain a more encompassing relationship for the vertical velocity distribution governing such flows.

2.11 NAKAGAWA, TSUIMOTO AND SHIMIZU (1988)

Reference: Velocity Profile of Flow Over Rough Permeable Bed.
Year of Publication: 1988
Authors: Nakagawa, H. Tsuimoto, T. and Shimizu, Y.
Published in: Proceedings of the 6th Congress, Asian and Pacific Regional Division, IAHR,Kyuoto, Japan, 20-22 July, pp. 449-456.
Data: Tables and Figures.

REVIEW

In this paper, results of studies of shallow flows over rough permeable beds, such as are found in gravel bed streams, are presented. The topic is treated both theoretically and experimentally. Two flumes with adjustable slope; 8 m long and 0.21 m wide and 8 m long and 0.3 m wide were used. In the first flume porous beds of one to three layers consisting of glass marbles having a diameter of 29.7 mm were placed and velocity profiles were measured with a micro propeller current meter. In the second flume, one and six layers of glass beads with diameter of 12.5 mm were used and velocity profiles were measured using two - component Laser Doppler Anemometer operated in the forward scattering mode. Physical properties of these beds, such as porosity and permeability were determined. The shear velocity was determined from $\tau = \sqrt{ghS}$ ($S =$ the water surface slope of uniform flow).

Results showed that the vertical velocity profile could be divided into three regions, namely, the roughness sublayer, inertial layer and the wake region. The velocity profile was characterizd by the thickness of the roughness sublayer designated as d_R and the slip velocity V_o. The dimensionless roughness sublayer thickness $\frac{d_R}{D_{50}}$, is virtually independent of Reynolds number and energy slope but decreases as the thickness of the porous bed layer increases. The dimensionless velocity $\frac{V_o}{U_*}$ was found to be independent of Reynolds number but decreased as thickness of the porous bed and energy slope increased. The latter suggests that the flow resistance varies with the thickness of the

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porous bed layer which is attributed to the fact that the momentum exchange between the main flow and the seepage flow becomes more active for a thicker porous bed. Based on a consideration of the eddy kinematic viscosity, a theoretical equation for the velocity profile from the bed to the free surface was developed. Good agreement with the experimental data was found. Fundamental to the success of this equation is the proper determination of the thickness of the roughness sublayer.

2.12 RICHARDSON AND PARR (1991)

Reference: Friction Factor and Free-Surface Flow Over Porous Media.
Year of Publication: 1993
Authors: Richardson C.P. and Parr A.D.
Published in: Journal of Hydraulic Engineering, ASCE, Vol. 117, No. 11, pp. 1496-1512.
Data: Tables and Figures.

REVIEW

This paper examines frictional resistance for steady free-surface flow over a porous bed of uniformly sized glass beads. The results described herein grew out of an effort by Richardson and Parr (1988) to associate momentum transfer with simultaneous mass transfer of chemical solutes from interstitum under varied hydraulic conditions during simulated agricultural runoff. Boundary resistance experiments were conducted at zero slope in a 4.88 m long and 0.152 m wide plexiglass flume. Water was passed at various flow rates down the flume and across a 1.22 m long by 2.54 cm deep recessed test section which was impermeable at the bottom and contained 2.54 cm of randomly dumped uniformly sized glass beads. Five different porous boundaries, each consisting of a particular median size were used. The five sizes ranged between 0.11 mm to 3.00 mm. The flow was non-uniform with longitudinal varying depth and velocity. The Darcy - Weisbach friction factor was computed from reach-averaged values of hydraulic radius, energy slope and mean flow velocity. Both laminar and turbulent flow conditions were examined. This paper addresses flows pertinent to overland flow and therefore deals with a lower range of turbulent flow and fully rough turbulent flow is not considered.

A subsurface injection of blue dye into the porous bed composed of 1.03 mm glass beads, showed evidence of subsurface streamwise migration and spreading with time under laminar flow conditions. This behaviour indicated the presence of a thin layer of streamwise convective velocity immediately

below the surface of the bed. This bed surface exhibited a decreased frictional resistance under laminar flow conditions.

Experimental results further showed that two frictional mechanisms due to the porous bed are at work. For laminar flows, velocity slip at the bed surface occurs and this reduces frictional resistance. In turbulent flow, momentum exchange between the free surface flow and the porous bed because of turbulent fluctuations, increases frictional resistence. As the permeability increases, both mechanisms become more active. In laminar flows velocity slip effects dominate. As flow becomes more turbulent, velocity slip becomes less important and the importance of turbulence eddy penetration into the porous bed increases.

The authors conclude that, from an engineering design point of view, there is a need for development of empirical design relationships that specifically address the interactive nature of channel flow bounded by porous media. This requires additional experimentation. Mathematical modelling may provide insight into and direction for this experimental approach.

2.13 Ruff and Gelhar (1972)

Reference: Turbulent Shear Flow in Porous Boundary.
Year of Publication: 1972
Authors: Ruff J.F. and Gelhar L.W.
Published in: Journal of Engineering Mechanichs Division, ASCE, Vol 98, No.EM4, pp. 975-991.
Data: Figures.

REVIEW

It has been observed that there is a significant lateral transport of momentum into the porous boundary through turbulent action. The aim of this paper is to develop a quantitative description of that process within the realm of the theory for turbulent shear flow. The study is based on the premise that the flow in the porous boundary should exhibit characteristics of both the porous medium flow and the turbulent shear flow above it.

The paper sets out to provide some basic experimental information about porous boundary flow, by investigating velocity distributions in the boundary of a polyurethane lined pipe. This study is concerned primarily with the flow in a porous boundary when the boundary is exposed to an external turbulent shear flow. The primary focus of the investigation is the development of a method of measuring the seepage velocities in the porous boundary. Mathematical models based on different eddy viscosity assumptions are developed in an effort to describe the mean velocity distribution in the porous boundary of the pipe.

Measurements were performed in a 3 cm thick urethane foam lining a 30 cm ID pipe which was part of an open circuit air flow system. Two methods of observing the mean velocity in the porous boundary were developed using hot wire anamometers and helium gas as a tracer. The helium tracer technique was based on the use of miniature hot wire anamometer probes as helium sensors. Observations of the travel time of the peak concentration between two probes were used to

determine the seepage velocities. The data were reduced manually and by cross correlation. In the shearing zone, seepage velocities were determined directly from the hot wire anemometer observations. Measurements performed by both the tracer and the direct hot wire anemometer methods were required to determine the vertical velocity distribution over the entire porous boundary.

From the mean velocity and turbulence measurements it was shown that significant lateral momentum transfer and turbulence occurs in the porous boundary and that this effect is confined to a very thin layer. Unfortunately, this depth of penetration was not compared with the boundary thickness and the permeabilty. It was observed that a finite velocity exists at the surface of the porous boundary. This slip velocity was found to decrease approximately exponentially over the shear zone and a constant pressure gradient flow was found to exist over the remaining thickness of the porous boundary.

Three mathematical models were developed, two assuming constant eddy viscosity and the third using an eddy viscosity proportional to the velocity. Because of the scatter in the experimental results no definitive comparisons could be made.

2.14 TSUJIMOTO AND SHIMIZU (1986)

Reference: Flow in Porous Medium of Loose Structure Accompanied with Free Surface

Year of Publication: 1986

Authors: Tsujimoto T. and Shimizu Y.

Published in: Memoirs, Faculty of Technology, Kanazawa University, Vol 19, No. 2 pp. 11-20.

Data: Tables and Figures.

REVIEW

In this paper mathematical modelling is used to examine the effect of the stream flow over the porous bed on the seepage flow within the bed. The theotrical results are confirmed with flume experiments.

The Navier-Stokes equation is applied to the flow in the porous medium after separating the flow velocity and pressure into their averages and perturbations respectively. A non-Darcy law, as given by Ward (1964), was used to describe the flow resistance in the porous medium. Based on this, the propagation of pressure fluctuation at the interfacial boundary, brought about by the free surface flow into the porous medium, has been analyzed. It was found that an apparent Reynolds stress due to the fluctuating seepage flow velocity is induced even inside the porous medium. This plays a role in the momentum exchange between the free surface flow and the flow in the porous medium. A seepage flow velocity profile was developed by assuming a characteristic mixing length in the porous medium. This allowed the additional discharge due to the extra seepage induced by the free surface flow to be evaluated. Under some conditions, depending on the structure and composition of the porous medium and the characteristics of the pressure fluctuations imposed by the turbulence of the free surface flow, a siginificant induced seepage velocity component is brought about.

The experiments were conducted in a rectangular flume 8 m long and 33 cm wide. The porous medium was made up of four layers of glass beads, having a diameter of 1.75 cm. The porosity of

this layer was 0.346. The measurements of the free surface velocity were made with a propeller type current meter having a propeller diameter of 3mm. The seepage flow velocity profile was measured by a tracer method using salt water and density probes. The three probes were set at the same height at intervals of 10 cm in the porous medium and an inlet of salt water was also set at the same height just upstream of the first probe. The salt water was injected into the porous medium from the inlet instantaneously and the time difference between the density peaks recorded was measured. The velocity was then estimated from this travelling time and distance between the probes. It was observed that the velocity of the free surface flow connects with the seepage flow velocity at the boundary very smoothly and without discontinuity. More sophisticated instrumentation is required to obtain more precise results.

2.15 ZAGNI and SMITH (1976)

REVIEW

This paper presents an experimental investigation into the extent of the interchange between the flow in the channel and the upper layer of the bed and the effect of the permeable bed on the velocity profile and boundary resistance. Tests were conducted in a rectangular flume using permeable beds that were log-normally graded in order to reveal the effect of the shape of grain size distributions. A total of 20 different grain size distributions were used. Five different values of D_{50} were used, each with four geometrical standard deviations ($\sigma_g = \frac{D_{84}}{D_{16}}$). The five median grain sizes were 2.1 mm, 4.0 mm, 7.1 mm, 11.0 mm and 17.0 mm. Each grainsize was used with four values of $\sigma_g = 1.0, 1.25, 1.50$ and 1.75. For each of the 20 distributions, five preset water surface slopes were used to obtain the desired series of uniform, tranquil flows.

To examine the effect on velocity profiles the traditional logarithmic distribution was used with the origin depressed by an amount Δy, given as

$$\frac{u}{U_*} = \frac{1}{\kappa}\ln\left(\frac{y + \Delta y}{D_{50}}\right) + A \tag{1}$$

Velocity profiles were plotted as $\frac{u}{U_*}$ vrs. $\frac{(y+\Delta y)}{D_{50}}$. Using an optimization process, different values of $\frac{\Delta y}{D_{50}}$ were tried until values of A, for values of $\kappa = 0.40$, which gave the best linear fit with correlation coefficients greater tham 0.95, were determined. Results showed that $\frac{\Delta y}{D_{50}} \approx 0.68$ for all cases. The zero velocity plane approaches the nominal bed surface as the grading becomes wider (σ_g increases for a given D_{50}) and thus permeability decreases. For gravel beds with small median

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diameter and large values of σ_g, Δy would be negligible and bed behaviour would be similar to an impermeable boundary. Alternatively, with larger median diameters and narrow grading, the effect could be significant, especially in the case of shallow flows.

Friction factors were determined from the test data and values of the equivalent sand roughness k_s were computed from equation

$$\frac{1}{\sqrt{f}} = 2.03\log 12.27\frac{R}{k_s} \tag{21}$$

where $R =$ the hydraulic radius. Using the values of k_s thus determined a regression equation was developed which can be expressed as

$$\frac{k_s}{D_{65}} = 4.47\left(\frac{\sqrt{K}}{D_{65}}\right)^{\frac{1}{2}} \tag{22}$$

where $D_{65} =$ the particle size for which 65% are finer. For an impermeable bed the authors have taken $k_s \approx D_{65}$. This means that the bed will approach impermeability as $\frac{\sqrt{K}}{D_{65}} \to 0.05$. This observation is not compatible with experimental findings reported by the authors. For a bed material composed of uniform spheres it was reported that

$$\frac{\sqrt{K}}{D_{50}} = 0.0027 \tag{23}$$

This is much lower than the value of 0.05 at which the bed may be considered impermeable according to equation (22). Combining equations (21) and (22) one obtains

$$\frac{1}{\sqrt{f}} = 2.03\log\left[2.74\frac{R}{D_{65}}\left(\frac{D_{65}}{\sqrt{K}}\right)^{\frac{1}{2}}\right] \tag{24}$$

It can be seen from equation (24) that flow resistance in the fully rough turbulent flow regime increases as the permeability increases. However, numerical values need to be confirmed.

2.16 ZIPPE and GRAF (1983)

Reference: Turbulent Boundary Layer Flow Over Permeable and Non-Permeable
                          Rough Surfaces.
Year of Publication: 1983
Authors: Zippe H.J. and Graf W.H.
Published in: Journal of Hydraulic Research, IAHR, Vol. 21, No. 1, pp. 51-65
Data: Tables and Graphs.

REVIEW

This paper is an experimental investigation in which flow over a permeable rough surface is compared with flow over a non-permeable, rough and smooth surfaces. The experiments were conducted in a wind tunnel using two permeable beds of different relative thickness. The authors give a noteworthy description of the flow over non-permeable and permeable boundaries. In the first case the non-slip condition is maintained at the surface. In the second case the flow is free to enter and leave the permeable boundary and the non-slip condition is found somewhere within this boundary. Conservation of mass is always maintained or no mass transfer across the permeable boundary is possible. This type of flow must be distinguished from flow with "non-zero mass transfer" obtained by injection into or suction from the flow across the permeable boundary.

The comparison of flows over porous and non-porous surfaces requires very accurate determination of the respective velocity profiles. Velocity profiles and their turbulent fluctuations were measured with a constant-temperature hotfilm-anemometer. The universal velocity defect law was applied to obtain the shear velocity and the law of the wall was used to obtain the reference level for the flow depth. Velocity profiles were measured at carefully determined positions. The experimental set-up made it possible to measure each velocity profile several times. The average velocity profiles so obtained were used to calculate shear velocity U_*, resistance copefficient c_f and the reference plane for the velocity probe. It is particularly noteworthy that the law of the wall was used to detemine the reference plane and the velocity defect law was used to detemine the shear velocity U_*.

Results from the experiments showed that the velocity defect law is valid for both permeable and non-permeable surfaces. The roughness height y' (defined as the distance from the wall at which the velocity is zero) is expressed as $\frac{y'}{k_s}$ (k_s =Nikuradse sand-grain roughness). This ratio was confirmed to be close to the value of $\frac{1}{30}$ for impermeable surfaces but was found to increase with Reynolds number for permeable beds and have a dependency on the relative thickness of the permeable bed given as $\frac{D_{50}}{d_B}$ (d_B = the thickness of the porous bed). For non-permeable surfaces the resistance coefficient c_f was found to be independent of the Reynolds number. For rough, permeable surfaces c_f increases with Reynolds number and is dependent on the relative thickness of the bed. The data are limited and more measurements are required to extend the range of the present results.

3.0 SUMMARY AND CONCLUSIONS

Review of available literature has shown that information on open channel flow over permeable beds is quite limited in comparison to that for flows over rigid impermeable beds. In many cases flows over permeable beds have been treated the same as flows over impermeable beds. This may not be too serious if the main concern is with average flows passing downstream or prediction of flood stages or in general, processes which deal with depth averaged quantities. Consideration of permeability is important when processes at the bed are being considered. As a result of the turbulence in the flow above the porous bed, there will be significant momentum transfer and mass transport from the stream through the porous interface. This can be expected to have important implication in tracing contaminant pathways, initiation if sediment transport, development and sustainability of biofilms on the bed particles, friction factor and shape of the velocity profile. This report has concentrated on the effect of boundary permeability on friction factor and vertical velocity profile.

3.1 Research Suggestion No. 1

There is general agreement that the friction factor increases as Reynolds number increases in the fully rough turbulent flow regime. In contrast to this, for the same flow conditions, the friction factor for a rigid, impermeable boundary is known to be constant. The difference is attributable to the effect of the turbulence. It has been shown that the friction factor may be written as

$$f = f_o + f_i \tag{25}$$

where f_o = the friction factor due to the boundary roughness and f_i = the friction factor component due to the shear stress induced on the main flow by the sepage flow in the permeable bed. The

flow resistance attributable to the permeability effect is then given by

$$f_i = f - f_o \qquad (26)$$

Experimental data indicate that f_i increases as the Reynolds number increases. More experiments are needed to determine this f_i over a wider range of bed and flow conditions

3.2 Research Suggestion No. 2

The review shows that the logarithmic vertical velocity profile is affected primarily in two ways, namely, the depression of the vertical distance ordinate Δy (Figure 1) and the slope of the semi-logarithmic linear equation in the region of the flow in which the log-law is valid. The latter is reflected by a change in the value of the von Karman constant κ. In fact, it can be said that the presence of both κ and Δy allows for the arbitrary determination of one of them. Some investigations have shown that κ decreases as permeability increases. Others have concluded that κ should be equal to the tradidional value of 0.4, which results in uncertainties of the values of Δy. Comprehensive experiments need to be conducted to determine values of both κ and Δy over a wide range of bed and flow conditions.

3.3 Reseach Suggestion No. 3

The effect of the permeable bed is dependent on the depth of the permeable layer. For a given flow condition over a bed of given permeability, there is a maximum depth below the bed surface, say d_p, (Figure 1) to which the turbulence fluctuations of the free surface flow can be felt. This depth may be called the zone of influence. Experiments need to be conducted to determine the maximum depth d_p of the permeable bed where the influence of turbulence can be felt. Values of such maximum values of d_p should be defined over a practical range of flow conditions and bed

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permeability. A complete mathematical solution requires a coupling of the seepage flow and the free surface flow within the layer of depth d_p.

3.4 Research Suggestion No. 4

Seepage flow is a common occurrence in rivers and canals. Seepage through the bed alters the flow configuration near the bed. In particular, the effects of seepage flow are dependent on the sublayer thickness d_p of the bed and the wake pattern behind the bed particles (Watters and Rao, 1971). In addition the seepage flow modifies the velocity profile near the bed and increases the shear stress at the bed. Experiments on the initiation of sediment transport are usually conducted on carefully prepared, smooth porous beds and one would expect that permeability effects are implicitly included in the experimental results. However, the induced shear stress at the bed due to the momentum exchange between the free surface flow and the porous bed has been found to be dependent on the thickness of the bed. As a result of this variability in the induced stress, the critical shear stress may not be the same for identical stream flow conditions. This may partly explain the considerable scatter in the plotted data on the Shields diagram for large Reynolds numbers (Yalin and Karahan, 1979). Experiments should be conducted to examine this effect.

3.5 Research Suggestion No. 5

Benthic biofilms play a major role in the metabolic conversion and partial removal of biodegradable material in rivers and streams. Biofilm growth is affected by flow conditions in the stream. Higher velocity and turbulence can increase growth by increasing the transport rate of nutrients from the bulk fluid to the film surface but, at the same time, sloughing of the film may increase because of the higher shear stress (Lau, 1995). Biofilms would appear to particularly vulnerable to the interface dynamics between the main flow turbulence and the seepage flow in the permeable bed.

The increase in shear stress at the bed as a result of the momentum exchange between main flow and seepage flow should be an important consideration in the study of biofilms in the laboratory. The shear stress induced at the bed, because of its pemeability, is dependent on the thickness of the porous bed. It is therefore important to know how many particle diameters of bed thickness are required to correctly model stream bed conditions in the laboratory. Experiments should be conducted with biofilm growth on different bed thicknesses to determine the effect of bed thickness required for a given permeability.

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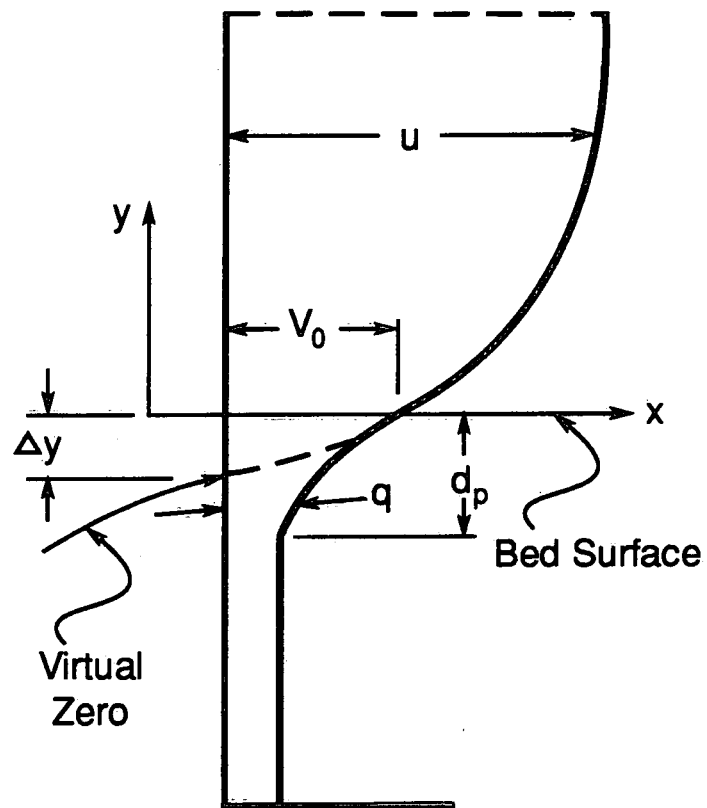
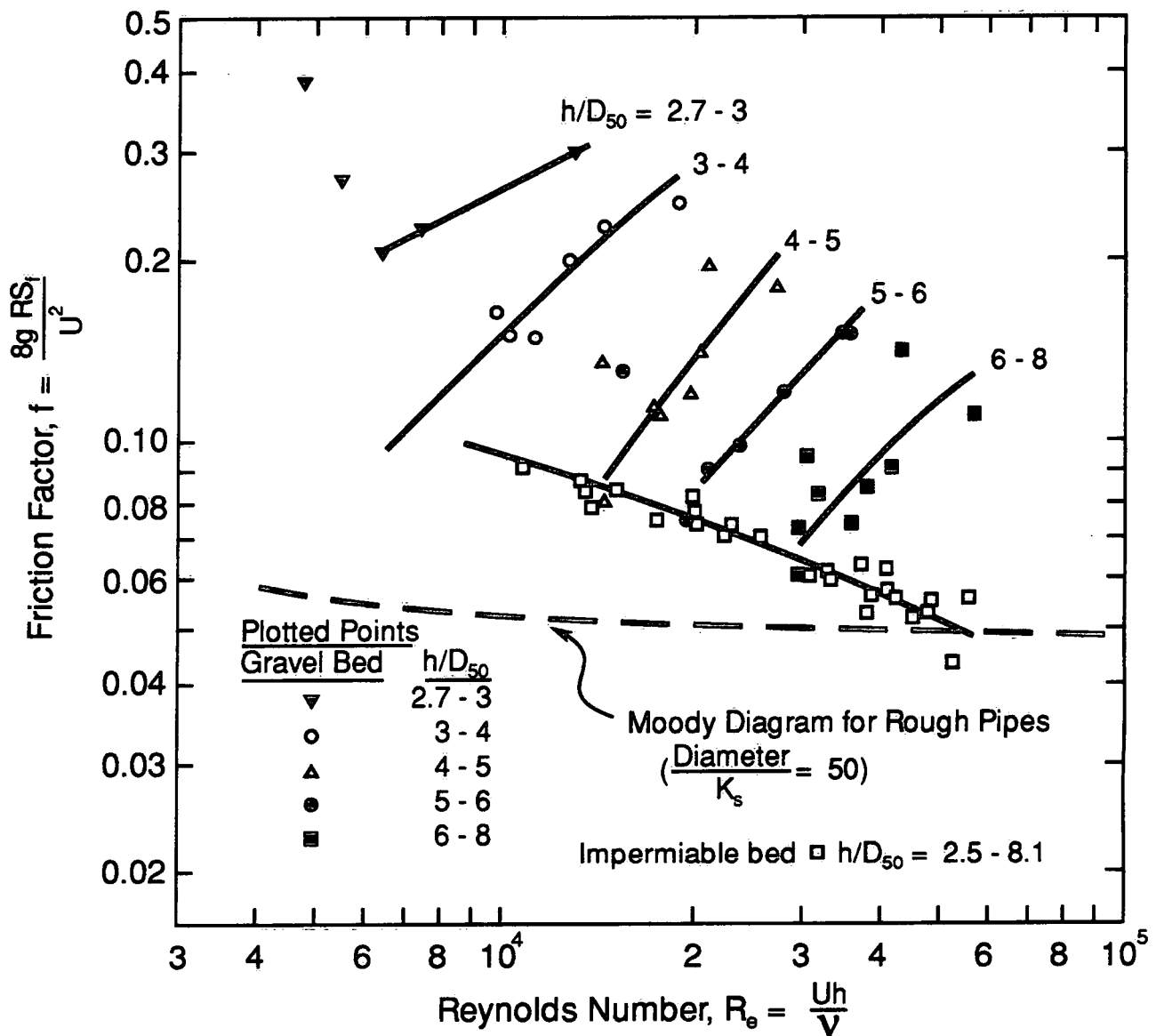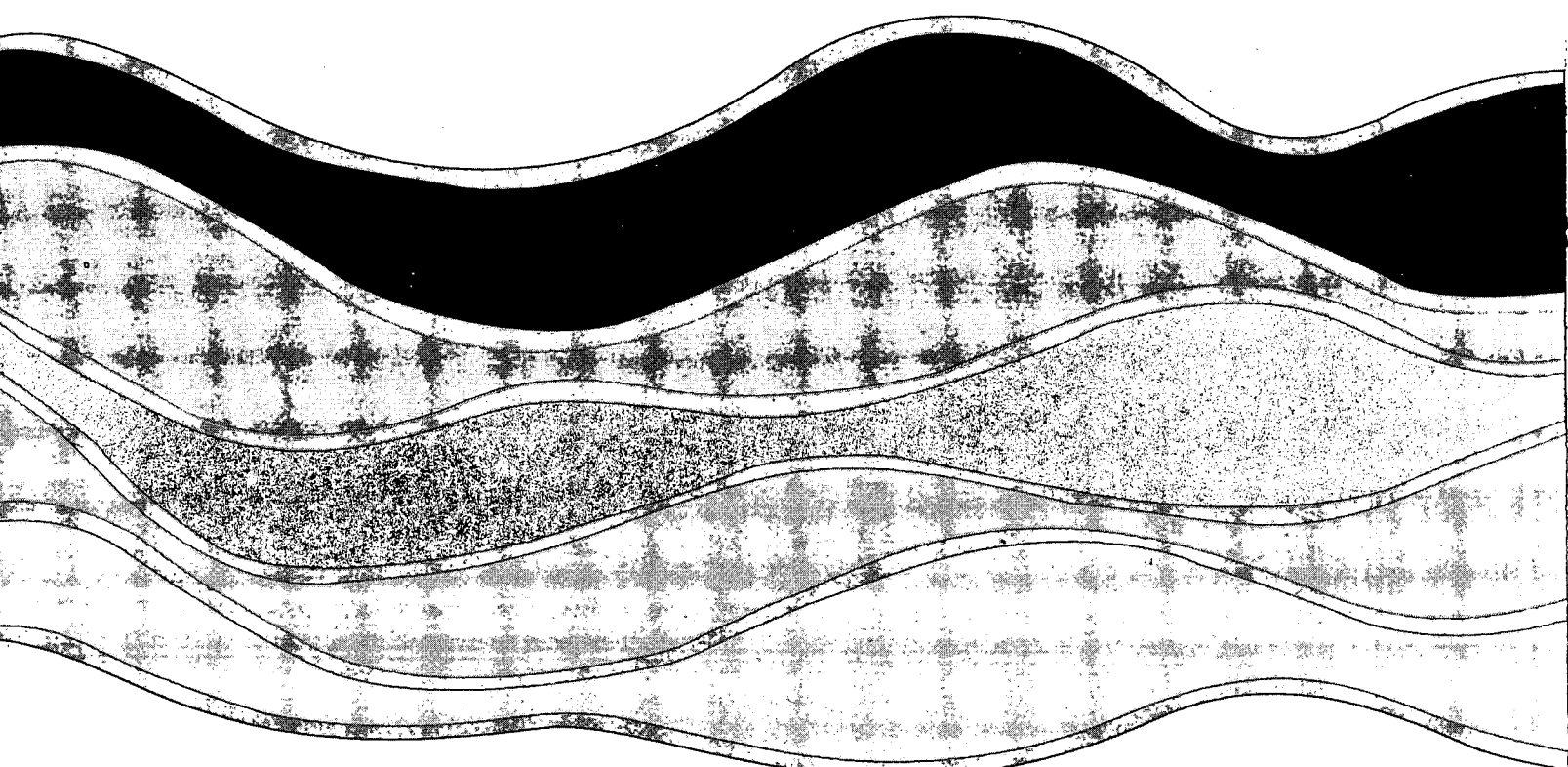Figure 1. Velocity profile for flow over permeable bed.

Figure 2. Friction Factor and Reynolds Number for
Flow over Permeable Gravel Bed and
Impermeable Bed. (Gupta and Paudyal, 1985)

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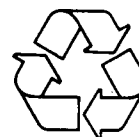P.O. BOX 5050, BURLINGTON, ONTARIO L7R 4A6

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