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Investigations of Hydraulic Conductivity for the Mathematical Modelling of Wave Action through Porous Structures

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Abstract— *The mathematical treatment of wave interaction with porous coastal structures has only been possible under several simplifying assumptions. Some of the assumptions have been necessary due to the absence of quantitative expressions to identify and describe certain complex interactions between wave motion and porous coastal structures. Limited information on permeability coefficients, including the influence of geometry and porosity, the use of such coefficients determined under steady flow conditions to describe the flow under time dependent conditions and the lack of information on acceleration effects have been established. This paper describes the results of two experimental programmes. The first on steady flow permeability coefficients covering a wide range of experimental media. The second on forces acting on porous media under steady uniform flow and uni-directional accelerated flow conditions, the latter being a specific form of unsteady flow.*

Keywords: Hydraulic conductivity, Permeability coefficients, Drag forces, Inertia force

1 Wave action on porous coastal structures

When a progressive wave collides with a porous structure, reflection and transmission of the wave take place on and across the interface. The resultant flow is often non-Darcy and may be single or two phase. Two phase flow may occur due to external and internal wave breaking. These flow conditions in combination generate a complicated flow system which will influence the effective conductivity of the structure, reducing wave transmission and increasing reflection. During this process the constituent elements of the structure are subjected to unsteady wave forces.

The mathematical treatment of the subject has only been possible under several simplifying assumptions. Some of these have been necessary due to the absence of quantitative expressions to identify and describe certain complex interactions between wave motion and porous coastal structures. Limited information on permeability coefficients, including the influence of geometry and porosity, the use of such coefficients determined under steady flow conditions to describe flow under time-dependent conditions, limited knowledge on acceleration effects, interface losses, air entrainment due to internal and external wave breaking are some of them. It is in this context that results from experimental investigations of such complex interactions can be used effectively to understand the physics of the phenomena and to modify and refine the mathematical treatment of the subject.

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2 The objective of the paper

The objective of this paper is to describe the results of two experimental investigations on the hydraulic performance of porous media.

The first investigation refers to the hydraulic conductivity of a range of porous media leading to an assessment of the influence of geometry and porosity on steady flow permeability coefficients. This study necessitated the careful selection of experimental media which allowed specific parameters to be varied in a systematic manner.

The second investigation refers to the forces acting on porous media under steady uniform flow and uni-directional accelerated flow conditions, the latter being a specific form of unsteady flow.

3 Experimental media and techniques

3.1 Selection of experimental media

Prior to the selection of porous media for experimental investigation, it was necessary to identify the governing parameters which are characteristic of any given porous medium. On the basis that a porous medium consists of an assembly of packed elements (packed either randomly or in a pre-determined manner), the following governing parameters can be used for classification.

1. Overall porosity (three dimensional porosity)
2. Shape (geometry) of the void
3. Size of the void
4. Characteristic dimension of the void
5. Tortuosity
6. Properties of the leading interface (two dimensional porosity, shape, roughness)

The influence of the geometry of both the constituent elements and the resulting voids matrix on its hydraulic behaviour can be investigated experimentally by the proper selection of experimental media. The experimental media selected for the study included porous structures consisting of porous hollow block armour units, cylindrical and spherical lattice structures and randomly packed spheres and stones. The physical properties of the media are presented in Table 1.

3.2 Flow resistance equations

Several investigations have been made in different disciplines in order to establish resistance equations for the description of non-linear flow through porous media. Hannoura and Barends [1] and Anderson [2] review most of the formulations of the equations and the respective coefficients by different authors. There are still differences of opinions on the formulations of these coefficients.

From amongst these relationships many authors have supported the Forchheimer [3] relation for steady non-Darcy flows on the basis of experimental evidence. This relationship is expressed as

$$I = au + bu^2 \qquad (1)$$

where I is the magnitude of the hydraulic gradient, u is the bulk or macroscopic velocity and a,b are laminar and turbulent flow coefficients dependent on governing parameters which are characteristic of any given porous medium

In this formula the laminar and turbulent terms are expressed separately which permits the determination of their relative influence by evaluating the ratio of the respective terms given by

$$\frac{I_T}{I_L} = \frac{b}{a}u \qquad (2)$$

The Exponential form and Friction factor-Reynolds number correlations have also been used extensively to describe steady non-Darcy flows.

The hydraulic gradient-velocity relationship for unsteady non-Darcy flow is usually described by an extended Forchheimer equation which contains a coefficient, 'c' to account for acceleration effects.

$$I = au + bu^2 + c\frac{\partial u}{\partial t} \qquad (3)$$

In porous media the unsteady flow problem is very complex. Accelerating flow can cause a change in the expected flow regime for a particular Reynold's number and may cause a delay in the onset of turbulence in coarse porous media. Any change in the flow regime will affect the flow resistance. In a porous medium the virtual mass of a particle is restricted by the presence of neighbouring particles. The limitation on wake growth due to limited pore volume downstream of each grain will influence the effective virtual mass of the particles. In addition, most porous media experience some distortion under an applied force. Therefore, during the acceleration phase the grains of the media may experience an acceleration albeit small.

3.3 Experimental techniques

The objective of steady flow tests is to determine the laminar and turbulent flow permeability coefficients under steady flow conditions. On each occasion the experimental medium was assembled in a horizontal flume and for a given discharge, the difference in the levels of the water surface upstream and downstream of the test structure was noted. The experimental medium which was in the form of a rectangular block was of width 30 cm, length 30 cm and height 40 cm. This method ensures the presence of free surface conditions in contrast to flow with closed boundaries as observed in permeameters which have been used extensively for steady flow permeability tests. Experimental values were obtained at very close intervals of velocity over a wide range whose limits were determined by the practical limitations of the experimental set up.

Most of the previous investigations on unsteady flow through porous media have been conducted using vertical U-tube oscillators or horizontal pulsating channels. In this context it was considered relevant and compatible to conduct an experimental programme to assess the performance of porous media under uni-directional accelerated flow conditions. This was justified in the light of considerable scatter observed in the results of previous investigations. It is noted that tests under constant acceleration have an advantage with the immediate consequence being that the equations characterizing the motion may be logically reduced to a workable form dependent only on a few variables. For comparison it was necessary to conduct experiments under constant velocity conditions as well. It was also considered relevant to study the force field under such conditions in preference to permeability characteristics.

The objective of the constant velocity and acceleration tests was to investigate the force field, drag and inertia forces under varying flow conditions. This test series posed several conceptual problems in adopting a suitable experimental technique. The main difficulty lies in imposing a constant acceleration on a volume of fluid while being able to measure its magnitude. Sarpkaya and Garrison [4] performed one of the few tests of this type on a cylindrical member inside a vertical tank of rectangular cross-section.

However, the problem was viewed from a frame of reference in which the body is moved under constant velocity and acceleration in initially still water. It is noted that the flow past a stationary object is hydrodynamically equivalent to the same object moved in the otherwise still fluid as long as the fluid is incompressible. However, the forces experienced by the object differ due to the presence of a pressure gradient in the fluid on the one hand and to the inertia of the object itself on the other. In the case of a moving fluid, the object experiences an extra force which is equal to the displaced mass of the fluid times the acceleration, due to the pressure field necessary to accelerate the fluid. Consequently it is only necessary to study the case of relative motion and either of the two techniques could be adopted.

In the present study, which was limited to porous hollow block armour units, a pack of model units was accelerated in initially still water inside a wide flume. A carriage moving on rails was designed for this purpose. The model units were assembled to form a cubic pack of twenty seven units and the horizontal force acting on the centre unit was measured, together with the velocity time profile of the motion. By incorporating a dual facility to repeat the tests under different values of constant velocity it was possible to compare the imposed forces in the two states of flow, namely, constant acceleration and constant velocity.

In any experimental technique relating to moving objects, vibrations are likely to develop which could distort results. From the initial stages of this experimental program, it was apparent that the carriage motion introduced vibrations which prevented a simple analysis of the force data. Modifications were made to the apparatus to reduce vibrations and care was exercised in adopting data reduction methods depending on the relative influence of vibrations.

There have been several investigations based on this technique where objects have been moved in a prescribed motion. Although this type of study can be performed within a well-defined flow environment on structural elements such as cylindrical members, similar studies cannot be extended easily to porous media because they generate a much more complex flow environment not amenable to simple analysis. In this context it is recognised that it is not possible to extend arguments valid for single bodies to study the behaviour of porous media under the same conditions of flow.

4 Measurement of flow coefficients under steady flow

4.1 Method of analysis

The two equations for the hydraulic gradient-velocity relationship considered for analyses were the Forchheimer form given in (1) and the Exponential form

$$I = cu^m \qquad (4)$$

In addition to (1) and (4), a Friction factor-Reynolds number relationship of the form

$$I = c_l \frac{l}{d}\frac{u^2}{2g} \qquad (5)$$

in which

$$c_l = \frac{c_2}{Re} + c_3 \qquad (6)$$

where

$$Re = \frac{ud}{\nu} \qquad (7)$$

in which d is the characteristic dimension, was also examined.

The respective coefficients in these equations were determined by using linear regression analysis based on a least squares technique. The goodness of fit is represented by the linear correlation coefficient.

4.2 Discussion of results

Table 1 presents a summary of the results from steady flow tests. In addition to the respective equations, the table also illustrates the relevant physical properties, maximum and minimum values of mean velocity and the value of velocity at which the laminar and turbulent terms in the Forchheimer equations are equal in magnitude ($u = a/b$).

From the results it is evident that both the Forchheimer and the Exponential form of the resistance equation can be used for hydraulic gradient-velocity relationship for steady flow through porous media. This conclusion is strengthened by the fact that results have been obtained covering a wide range of porous media having very different geometric and packing characteristics. On all occasions the linear correlation coefficient of fitness exceeded 0.95. In the case of the exponential form, the exponent of the velocity term varies between 1.2 and 1.6 for the porous media used in this study. Both equations more or less coincide with each other for lower values of velocity and significant deviations are observed only for higher values.

In order to compare the performance of different structures, the structures consisting of hollow block units and cylindrical lattices are classified into one group. Randomly packed spheres and rounded stones are classified into a second group. This allows a differentiation between structures having a well defined porous matrix and those having a randomly oriented porous matrix. The Forchcheimer relationship for the first group is presented in Figure 1.

Figure 1 clearly illustrates the efficiency of structures consisting of hollow block units compared with cylindrical lattice structures. This figure also illustrates that as the characteristic dimension of the cylindrical lattice structure increases, the hydraulic gradient for a given velocity decreases. This is also reflected in the Forchheimer equation in that as the diameter increases the turbulent flow coefficient 'b' decreases. In the case of randomly packed media, it was observed that the curve for rounded stones lies between those corresponding to the spheres. The hydraulic gradient for the larger diameter spheres is less than that for the smaller diameter spheres. For randomly packed media, the hydraulic gradient decreases for increase in porosity.

A study of the parameter I_T / I_L can be used to investigate the onset of turbulence based on the ratio of turbulent and laminar components of the hydraulic gradient. For example in the case of cylindrical lattice structures, as the diameter is increased the value of velocity corresponding to the onset of turbulence is increased. The values of the velocity at which the laminar and turbulent terms become equal to each other for the 15 mm, 20 mm and 30 mm structures are 0.20, 0.51 and 0.85 m/sec respectively. These results indicate the importance of the dimension of the void in relation to the onset of turbulence. This trend is also observed for the assembly of spheres.

With reference to the governing parameters required to define a porous matrix it is observed that for the three cylindrical lattice structures, all geometric parameters except the dimensions of the void (d) are constant. Using the above property it can be assumed that 'b' is proportional to a certain index (m) of the dimension of the void (i.e. $b \propto d^m$). From regression analysis on the three sets of values of 'b' and 'd' it was found that m equals -1.983 with a correlation coefficient of 0.96. It is noted that lattice structures of this nature provide an excellent opportunity of varying a single geometric parameter at a time while maintaining all other parameters constant.

The results from this experimental programme illustrate the sensitivity of the flow coefficients in the resistance equation to changes in the characteristic dimension of the void and the interface properties. An overall view of the results clearly indicates the importance of the hydraulic parameters 'a' and 'b' in the Forchheimer equation and of the geometric parameters in characterising different porous media.

There have been several recent investigations on the permeability of rockfill. Most of these investigations have been conducted to establish hydraulic gradient-velocity relationships for the mathematical modelling of wave action through porous structures. Following the detailed analysis of Shih [5] of permeability measurements carried out at Hydraulics Research, Wallingford and the inspection of data collected at Aalborg University, Burcharth and Christensen [6] suggest that there might be several distinct flow regimes possible in rubble material and that the transition from a laminar flow pattern to a turbulent flow pattern would be described by a Reynolds number. Further it is proposed that a plot of I/u against u would be of the form such that the extreme portions of the graph represent laminar and turbulent flow while a transition region modelled by the Forchheimer equation lies between these two extremes.

The Forchheimer equation has been used in the analysis of permeability data for many years and up to date there has been no significant evidence to suggest that it is not applicable over the whole range of possible flow rates. Burcharth and Christensen [6] support that view, in the context that within the accuracy of the experiments no deviation from the Forchheimer equation could be found. However, it may well be that the range of Reynolds numbers tested for a single a sample might not be large enough to demonstrate a deviation from the Forchheimer equation. If that may be the case it is suggested that caution be exercised in the scaling up of the laboratory tests to larger prototype material.

5 Measurement of forces under constant velocity and constant acceleration

5.1 Method of analysis

The forces acting on a hollow block armour unit under constant velocity conditions corresponding to that of steady flow can be expressed by,

$$F = b' u^{m'} \qquad (8)$$

in which b' is the drag coefficient under steady flow and m is the index of velocity (≈ 2.0)

The forces under constant acceleration can be represented by

$$F = bu^2 + c\dot{u} \qquad (9)$$

in which b is the drag coefficient under constant acceleration, c is the acceleration coefficient and $\dot{u}$ is the value of constant acceleration

If the force, velocity and acceleration are known, the coefficients in (9) can be determined by the method of least squares. In this method the objective is to correlate the measured force with the theoretical force and the respective coefficients are determined for the best fit values of the predicted and observed forces for the selected time period.

A residual force is defined as

$$R(t) = F_t(t) - F_m(t) \qquad (10)$$

in which F_t is the theoretical force given by (9). F_m is the measured force.

The coefficients are then determined such that the value of the function $\int R^2 dt$ is a minimum.

The measured force data from constant acceleration tests $F_m(t)$ were subjected to a multi-point smoothing procedure in order to compute thc smoothed force $F_s(t)$. The force coefficients 'b' and 'c' in (9) were determined from this force timehistory. A frequency analysis was performed on the residual force

$$F_r(t) = F_m(t) - F_s(t) \qquad (11)$$

to obtain information on the frequencies present in the recorded signal.

For each porous armour block tested, the following graphs were made use of in the final analyses of results.

(a) variation of measured force (F_m) versus time
(b) variation of smoothed force (F_s) versus time
(c) spectral analysis of the residual force (F_r)
(d) variation of the measured force (F_m) versus velocity together with the fitted curve
(e) velocity-time plot for the motion
(f) force versus velocity plots for constant velocity tests together with the fitted curve

5.2 Discussion of results

The results from constant acceleration and constant velocity tests are summarised in Tables 2 and 3. For each armour unit, tests were performed for two values of constant acceleration. The lower value of constant acceleration lies in the range 0.15-0.24 m/sec^2 and the higher value lies in the range 0.35-0.47 m/sec^2. Measurements of drag force under constant velocity, $F_{DF}(CV)$, were obtained by performing tests at constant velocity for at least four different values. In the presentation of results the unit 'gm force' was used for force measurements. This has been adopted because of the comparatively small values of force measured in this study (1 gm force = 980.665 x 10^{-5} N).

Figure 2 illustrates the force-velocity relationship obtained under both constant velocity and constant acceleration for the Cob armour unit. The curves clearly indicate that as the value of acceleration increases from zero the measured forces increase. Several experimental runs also confirmed the consistency and repeatability of the results.

If ΔF_{TF} is defined as the difference between the total force under constant acceleration and constant velocity, at any given velocity, with reference to (9) and (8),

$$\Delta F_{TF} = bu^2 + c\dot{u} - b'u^m \qquad (12)$$

From Figure 2, the value of ΔF_{TF} increases with increasing velocity, particularly for the higher value of acceleration.

Since the inertia force component due to constant acceleration is assumed to be constant, the above observation is due to the increase in the drag force component. In effect the drag force corresponding to a given instantaneous velocity within a flow with constant acceleration differs from that for the same constant velocity in a flow with zero acceleration; the former is greater than the latter. From the two values of constant acceleration which were used in this investigation, it is evident that as the value of acceleration increases the corresponding increase in the drag force is greater.

This aspect is further illustrated in Figure 3 for Cob units in which both the difference in total force ΔF_{TF} given in (12) and drag force ΔF_{DF} are plotted against velocity.

$$\Delta F_{DF} = bu^2 - b'u^m \qquad (13)$$

$$\Delta F_{TF} = \Delta F_{DF} + c\dot{u} \qquad (14)$$

The figure refers to the lower and higher values of acceleration. These curves represent the relative magnitude of two force components. The first is the difference between the drag force in steady flow and that in an unsteady flow domain. The second is the constant inertia force. Together these two components constitute the difference in total force, ΔF_{TF}. From these two plots it is evident that the influence of the acceleration component is comparatively small.

The study reveals that the total force under constant acceleration can be expressed as

$$F_{TF}(CA) = F_{DF}(CA) + F_{IF}(CA) \qquad (15)$$

in which

$$F_{DF}(CA) = F_{DF}(CV) + \Delta F_{DF}(CA) \qquad (16)$$

where $F_{TF}(CA)$ is the total force under constant acceleration, $F_{DF}(CA)$ is the drag force under constant acceleration, $F_{IF}(CA)$ is the inertia force under constant acceleration, $F_{DF}(CV)$ is the drag force under constant velocity,

$\Delta F_{DF}(CA)$ is the difference in drag force under constant acceleration and constant velocity

The relative magnitude of the drag force under constant velocity, $F_{DF}(CV)$, and the total force under constant acceleration, $F_{TF}(CA)$, were presented in Figure 2.

From this study it is observed that the difference in drag force identified by $\Delta F_{DF}(CA)$ can be quite significant. At constant acceleration, $\Delta F_{DF}(CA)$ increases with increasing velocity. At a given velocity $\Delta F_{DF}(CA)$ increases with increasing acceleration (Figure 3), an aspect observed by comparing the results from both lower and higher values of acceleration.

The constant inertia force, $F_{IF}(CA)$, due to constant acceleration, is small in comparison with the increase in drag force. In this study it was observed that its magnitude did not always increase with an increase in the magnitude of acceleration. Only two values of constant acceleration were used for this study and as a consequence it is not possible to comment on this aspect.

Van Gent [7] reported the results of permeability tests performed on rockfill and spheres using an oscillating water tunnel as the experimental apparatus. It was observed that the term $au + bu|u|$ for oscillatory flow conditions was larger than for stationary flow, with the difference caused by a larger value of *'b'* (turbulent contribution) rather than by a larger value of *'a'* (laminar contribution). The contribution of the inertial resistance was much smaller than the quadratic turbulent friction. These observations for unsteady oscillatory flow conditions are consistent with the findings reported in this paper.

6 Concluding remarks

The paper has described the results of two experimental programmes which illustrate different aspects of fluid-structure interaction directly related to the modelling of wave-structure interaction of porous costal structures. The results provide an understanding on critical issues relating to flow through porous media and focus attention on the current practice of using steady flow permeability coefficients in the modelling of wave-structure interaction.

The results of steady flow permeability tests established that both the Forchheimer and Exponential forms of resistance equation ((1) and (4)) can be used for the hydraulic gradient-velocity relationship. Use of the Forchheimer form is recommended because it permits the investigation of the onset of turbulence based on the ratio between turbulent and laminar components of the hydraulic gradient as given in (2). The results also illustrated the sensitivity of the flow coefficients in the resistance equations to changes in the characteristic dimension of the void and interface properties. This information is directly applicable when estimating resistance coefficients for mathematical simulation of flow through porous media. The variability of the respective flow coefficients, when using different experimental apparatus, was evident from a comparison with previous investigations. Studies over a wide range of porous media demonstrated that it was not possible to develop a general formula which accommodates all the variables involved.

Results from constant acceleration and velocity tests on a moving porous block identified the relative importance of the drag force and inertia force coefficients under constant acceleration. The drag force corresponding to a given instantaneous velocity within a flow with constant acceleration differed from that for the same constant velocity in a flow with zero acceleration; the former was greater than the latter. As the acceleration increased the corresponding increase in the drag force was greater. In comparison with the significant increase in the drag force, the influence of the inertia force under constant acceleration conditions was small.

Table 1: Results from steady flow permeability tests

Porous media	Properties P = Porosity D = Characteristic dimension	Maximum and minimum velocities measured (m/s)		Fitted curves $I = au+bu^2$ $I_L = au,\ I_T = bu^2$ $I = au^m$	Velocity (u^*) at which $I_L = I_T$ $u^* = a/b$ (m/s)	Fitted curves $I = c_f(1/d)(u^2/2g)$ $c_f = (c_2/Re)+c_3$
		v_{min}	v_{max}			
Rectangular block of SHED units	$P = 0.614$ $D = 21.54$ mm	0.049	0.255	$I = 0.703u+5.802u^2$ $I = 4.43u^{1.538}$	0.121	$c_f = (5743.9/Re)+2.452$
Rectangular block of COB units	$P = 0.627$ $D = 19.00$ mm	0.048	0.236	$I = 0.917u+6.407\ u^2$ $I = 4.872u^{1.496}$	0.143	$c_f = (5826.9/Re)+2.384$
Rectangular block of HOBO units	$P = 0.803$ $D = 20.00$ mm	0.050	0.230	$I = 1.05u+7.188\ u^2$ $I = 5.394u^{1.484}$	0.146	$c_f = (7396.9/Re)+2.821$
Rectangular block of HOBO units	$P = 0.823$ $D = 25.00$ mm	0.078	0.261	$I = 0.566u+4.68\ u^2$ $I = 3.894u^{1.588}$	0.121	$c_f = (6320.4/Re)+2.297$
Cylindrical lattice structure	$P = 0.607$ $D = 15.00$ mm	0.015	0.311	$I = 0.612u+3.05\ u^2$ $I = 2.176u^{1.352}$	0.200	$c_f = (2422.4/Re)+0.910$
Cylindrical lattice structure	$P = 0.627$ $D = 20.00$ mm	0.048	0.331	$I = 0.682u+1.338\ u^2$ $I = 1.497u^{1.274}$	0.510	$c_f = (4801.3/Re)+0.522$
Cylindrical lattice structure	$P = 0.627$ $D = 30.00$ mm	0.055	0.370	$I = 0.642u+0.751\ u^2$ $I = 1.143u^{1.226}$	0.855	$c_f =$ (10169.3/Re)+0.437
Randomly packed spheres	$P = 0.350$ $D = 19.00$ mm	0.040	0.173	$I = 1.707u+14.632\ u^2$ $I = 9.460u^{1.465}$	0.117	$c_f =$ (10843.1/Re)+5.522
Randomly packed spheres	$P = 0.394$ $D = 25.00$ mm	0.031	0.197	$I = 1.454u+11.558\ u^2$ $I = 7.406u^{1.441}$	0.126	$c_f =$ (15994.2/Re)+5.687
Randomly packed spheres	$P = 0.362$ $D = 34.80$ mm	0.022	0.184	$I = 1.120u+14.085\ u^2$ $I = 8.606u^{1.518}$	0.080	$c_f =$ (23868.9/Re)+9.652

Table 2: Results from unidirectional constant acceleration tests

	LV and HV refer to lower and higher values of acceleration in m/s^2		Force-velocity relationship $F = bu^2 + c\dot{u}$ (gm force) (1 gm force = 980.665×10^{-5} N)			$u^* = (c\dot{u}/b)^{1/2}$ (m/s) (u^* is the velocity at which the drag force component equals the acceleration component)
			b	c	$c\dot{u}$	
COB units	LV	0.226	33.23	3.82	0.87	0.161
	HV	0.354	41.00	5.39	1.91	0.216
SHED units	LV	0.238	31.00	3.69	0.88	0.168
	HV	0.379	42.01	0.88	0.33	0.089
		0.373	42.99	0.21	0.08	0.043
HOBO units	LV	0.151	31.53	8.99	1.36	0.207
	HV	0.429	38.29	5.46	2.34	0.247
		0.414	37.98	2.25	0.93	0.156

Table 3: Results from constant velocity tests

	Range of constant velocity and mean force		Fitted curve $F = b'u^m$ r = correlation coefficient			Fitted curve $F = bu^2$	
	Velocity (m/s)	Mean force (gm force)	b'	m	r	b	r
COB units	0.25-1.50	2.50-70.03	31.17	1.84	0.995	32.76	0.872
SHED units	0.25-2.25	2.06-140.00	30.47	1.91	0.998	30.76	0.850
HOBO units	0.42-2.31	4.64-130.31	29.95	1.89	0.979	30.75	0.863

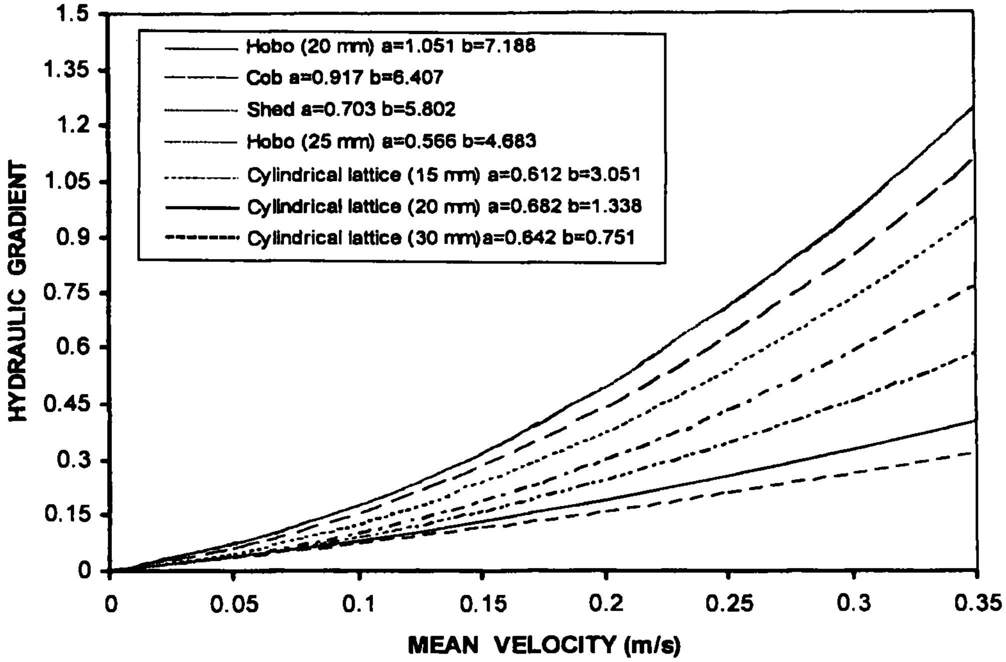

Figure 1: Hydraulic Gradient vs mean velocity

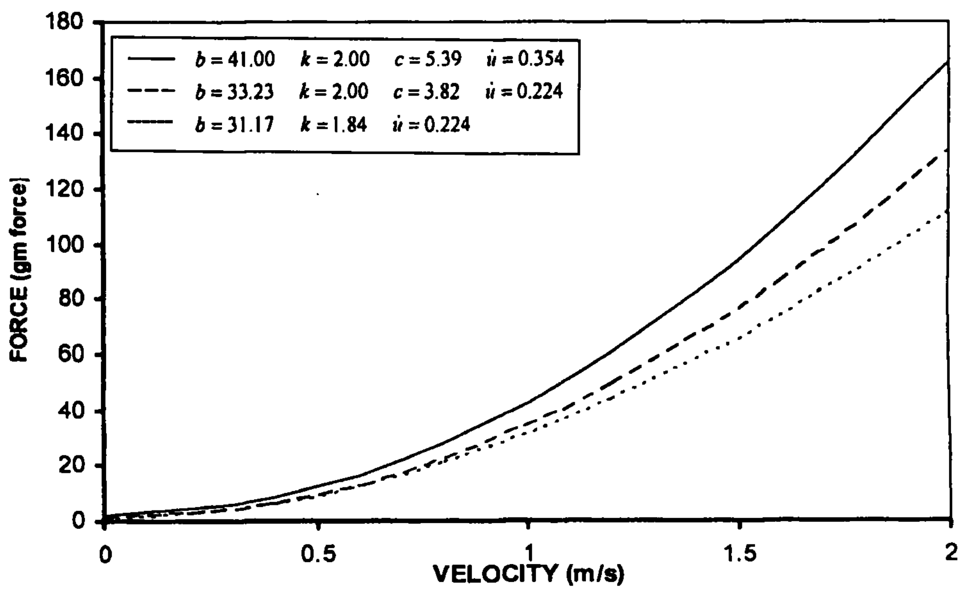

Figure 2: Force vs velocity for Cob units

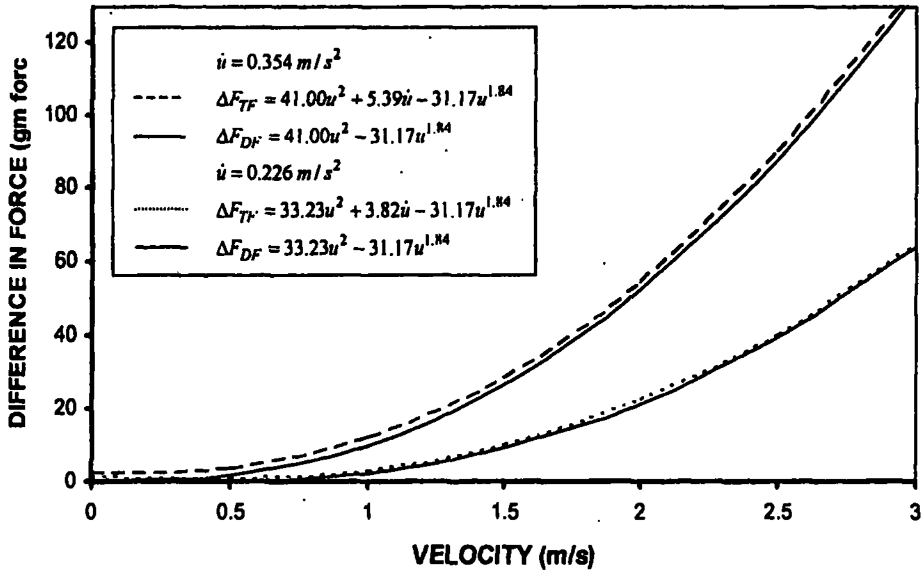

Figure 3: Difference in force and velocity

References

1. Hannoura, A. and Barends, F., *Non-Darcy flow: A state of the art*, Flow and transport in porous media, Editors: Verruijt, A. Barends, F., Balkema, A.A. Rotterdam, The Netherlands, 1981.
2. Anderson, O.H., *Flow in porous media with special reference to breakwater structures*, PhD thesis, Hydraulic and Coastal Engineering Laboratory, Aalborg University, Aalborg, Denmark, 1994.
3. Forchheimer, P., *Wasserbewegung durch Boden*, Zeit. Ver. deutsch. Ing., 45, 1901.
4. Sarpkaya, T. and Garrison, C.J., *Vortex formation and resistance in unsteady flow*, Journal of Applied Mechanics, Vol. 30, Series E. No. 1, 1963.
5. Shih, R.W.H., *Permeability characteristics of rubble material-New formulae*, Proc. 22nd Conf. on Coastal Engineering, Delft, The Netherlands. Available as HR published paper No. 38, HR Wallingford, UK, 1990.
6. Burcharth, H. and Christensen, C., *On stationary and non-stationary porous flow in coarse granular materials*, MAST G6 Project I\, University of Aalborg, Denmark, 1991.
7. Van Gent, M.R.A., *Permeability measurements for the modelling of wave action on and in porous structures*, Proc. of Conf. on Coastal Dynamics '94, ASCE, 1994.

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