HYDRAULIC BEHAVIOUR OF POROUS COASTAL STRUCTURES

PART (I) REVIEW OF STEADY AND UNSTEADY FLOW THROUGH POROUS MEDIA

by
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1.0 Introduction

The objectives of this paper are to identify the important aspects of flow through porous media and its application to coastal structures. In doing so it is possible to identify two areas of interest, namely, steady flow and unsteady flow, and in each area a broad classification could be made under the sections, theoretical developments and experimental work.

The primary objective of discriminating between steady and unsteady flow is to differentiate between work on steady, Darcy and non-Darcy flow regimes and that on wave action through porous media (unsteady flow).

Unsteady flow conditions also include unidirectional accelerated flow and oscillatory (or reversing) flow which is established in U-tube oscillators and in pulsating water tunnels. Investigations relating to these two conditions and steady flow regimes could be classified into one group where most of the work has been performed from a strictly hydraulics point of view. This paper will primarily focus attention on topics relating to this group. Part(ii) of this paper will discuss wave action on porous coastal structures.

2.0 Flow through porous media

2.1 Flow regimes in porous media

Problems involving flow of fluids through porous media have traditionally been solved on the assumptions of Darcy's equation relating head loss and velocity (Darcy 1856), given by -

$$u = -k\frac{\partial H}{\partial s} = ki \qquad (1)$$

where

u = discharge velocity (also identified as bulk or macroscopic velocity)

k = coefficient of permeability in the 's' direction, dependent on properties of the fluid and the medium.

H = total fluid head

s = distance measured in the direction of the resultant velocity at the point under consideration

i = the negative total head gradient $\left(= -\frac{\partial H}{\partial s}\right)$.

It should be observed that in a medium of porosity 'n' the discharge per unit area in a particular direction is given by

$$u = nu_p \qquad (2)$$

where u_p is the actual mean velocity of the pore fluid.

Darcy's law represents a linear relationship between head loss and velocity and it satisfactorily describes the flow conditions, provided the velocities are small. It has been realized that this law fails to hold for high flow velocities for which more general flow equations must be used to describe the flow correctly. Any deviation from Darcy's law represents non-Darcian flows, for which a fundamental approach could be adopted by seeking the physical causes underlying the deviations from linearity.

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The deviation from Darcy's law at high flow rates has been attributed to both inertial effects and the onset of turbulence. There has, however, been a wide range of values of Reynolds number reported for the upper limit of validity of the law. Scheidegger (1974) quotes values ranging from 0.1 to 75. It should be noted that there exists no unique definition for Reynolds number and various forms have been used by different investigators.

Saturated flow in porous media may be characterized by one of the following flow regimes.

Microseepage : when non-Newtonian flow is observed at extremely small velocities.

Darcy flow : laminar Newtonian flow characterized by stable streamlines in the pores; a regime in which viscous forces dominate and inertial effects are negligible. The head loss is directly proportional to the first power of the velocity.

Non-linear laminar flow: which could be identified as a steady inertial regime in which both viscous and inertial terms influence the flow. Stable streamlines are present in the pores. The head loss deviates from a linear relationship with velocity.

Turbulent transitional flow: in this regime some of the streamlines in the pores become unstable and inertial effects emerge to play a dominant role with viscous effects being less prominent. The head loss gradually becomes proportional to the square of the velocity.

Fully turbulent regime: where inertial effects govern the flow with negligible viscous effects. Stable streamlines no longer exist in the pores and the head loss varies approximately with the square of the velocity.

Apart from porosity another important parameter in relation to flow through porous media is tortuosity. This is defined as the ratio of the length of the flow channel for a fluid particle to the length of the porous medium.

2.2 Classification of steady non-Darcy flow 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. Scheidegger (1974) presents detailed information on the research on the subject and Hannoura and Barends (1981) review the work on the same subject in a way that is more beneficial in relation to coastal hydraulics.

In non-Darcy flows the main problem is to establish a relationship between two measurable parameters namely the pressure head gradient and the velocity of the pore fluid. Several representations have emerged which can be categorised under any of the following formulae.

(i) The Forchheimer form $I = au + c_0 u^{m_0} + bu^2$ (3)

(ii) The general form $I = au + c_0 u^{m_0} + bu^2$ (4)

(iii) The exponential form $I = c_1 u^{m_1}$ (5)

(iv) Friction factor - Reynolds number correlations such as

$$\lambda = \frac{c_2}{R_e m_2 n^{m_3}} \qquad (6)$$

where

I = magnitude of the hydraulic gradient
u = bulk or macroscopic velocity
R_e = Reynolds number
n = porosity

$a, b, c_0, c_1, c_2, m_0, m_1, m_2, m_3$ are constants for a particular medium, fluid and flow regime.

λ = friction factor, for which several definitions similar to eq. 6 have been presented by different investigators.

From amongst these relationships many authors have supported the Forchheimer (1901) relation (eq.3) on the basis of experimental evidence. Theoretical developments supporting the validity of this equation have been presented by Ahmed and Sunanda (1969) and McCorquodale (1970).

Experimental and analytical investigations of flow through idealized media show that 'a' and 'b' are not strictly constants and depend on the Reynolds number of the flow. However, for all practical purposes it can be assumed that 'a' and 'b' remain constant over a range of Reynolds number. The importance of this formula is that laminar and turbulent terms are expressed separately which permits the determination of their relative influence by evaluating the ratio of respective terms given by

$$\frac{I_T}{I_L} = \frac{b}{a} u \qquad (7)$$

In some cases, the Forchheimer equation has been modified by the inclusion of a third term proportional to velocity-cubed in order to obtain a better fit to experimental values.

The general form of the equation (eq. 4) contains an additional term $c_0 u^{m_0}$, not present in the Forchheimer equation. m_0 is assumed to have a value of approximately 1.5. In general it can be stated that this term accounts for a transitional term intermediate between fully laminar and fully turbulent flow. Although this equation is presented as an improvement on the Forchheimer equation, Nasser and McCorquodale (1974) quote Ng(1969) who found that in the Reynolds number range 600-4000, the Forchheimer equation gave correlation with his experimental values equally as good as did the three term general formula.

The high-velocity flow phenomena occurring in porous media can be expressed in mathematical terms in several ways. Without attempting to understand the physics of the phenomena, one can simply fit, heuristically, curves or equation to the experimental data so as to obtain a correlation. The exponential relation (eq. 5) belongs to this category. This equation is completely empirical and has not been given a theoretical basis by its numerous users.

Friction factor - Reynolds number correlations and other relationships based on similar concepts have been presented by various authors and an excellent review of such formulae is given by Scheidegger (1974). Unfortunately, all such correlations are subject to limitations as the Reynolds number and friction factor depend significantly upon the definition of a general characteristic length associated with the porous medium. It should be noted that in most cases the characteristic length in a random porous matrix is not really defined either geometrically or by detailed statistical reasoning. Hence it is evident that results obtained under these conditions must be regarded as subject to a major shortcoming in that a length parameter is employed for which no universal definition exists.

There have also been attempts to establish correlations between the flow variables involving the porosity and particle diameter, without their being represented by the friction factor and Reynolds number. Similarly some authors have introduced the shape of particles and related parameters as factors influencing fluid flow.

An interesting result of experimental evidence noted by Scheidegger (1974) is that the critical Reynolds number above which turbulence is believed to occur is much lower for porous media, varying from 0.1 to 75, than for straight tubes for which it is approximately 2000. It was concluded that deviation from Darcy's law at high velocities is primarily due to the emergence of inertia effects in laminar flow owing to the curvature of the flow channel and not due to the onset of turbulence. Only at very high Reynolds numbers will true turbulence occur and this causes the second change in the flow regime observed experimentally.

It is evident that the critical Reynolds number for the emergence of inertia effects is very much influenced by the curvature of the flow channels and therefore it must be expected that there exists no such parameter as a universal Reynolds number for a porous medium at which non-linearity would set in. Depending on the curvature of the channels, the critical Reynolds number will vary from one flow channel to another even if the cross-sections are identical or if the flow channels are assembled together to form a porous medium of identical porosity and tortuosity. This discussion illustrates that there is no proper physical basis for assuming that flow behaviour and therefore friction factors should be the same for identical Reynolds numbers, unless very careful consideration is given to the definition of variables associated with such numbers as well as the inclusion of curvature in a definite form.

2.3 Unsteady flow in porous media

The influence of unsteady flow in porous media on the non-Darcy hydraulic conductivity has often been assumed to be negligible, an assumption which may be valid in the case of low Reynolds number flow through highly compacted fine porous media.

Polubarinova-Kochina (1962) generalized the Forchheimer relation to include a time dependent term, $c\frac{\partial u}{\partial t}$, so that the hydraulic gradient for unsteady non-Darcy flows could be expressed as

$$I = au + bu^2 + c\,\frac{\partial u}{\partial t} \qquad (8)$$

Many investigators have not considered the influence of this additional term and consequently very little research has been carried out on either acceleration effects or air entrainment.

3.0 Hydraulic gradient-velocity relationships for steady non-Darcy flow in porous media

Engelund (1953) proposed that the hydraulic gradient I of flow through homogeneous sand can be written as $I = au + bu^2$ and developed this equation to the form:

$$i_I - \alpha_0 \frac{(1-n)^3}{n^2}\,\frac{\gamma}{gd^2}\,u + \beta_0\,\frac{(1-n)}{n^3}\,\frac{1}{gd}\,u^2 \qquad (9)$$

in which α_0 and β_0 are constants depending upon the shape of the grains.

n = porosity
γ = kinematic viscosity
d = grain size
g = gravitational constant

It was found from experiments and a literature review, that the values of the constants given in Table 1 were valid.

All the measurements on which Engelund based his recommendations were obtained in sand, where the flow, although turbulent, corresponds to a much smaller Reynolds number than that which would be observed in a rubble mound structure. LeMehaute (1957) as part of a detailed study on wave transmission through permeable structures developed the following expression.

$$I = \frac{c}{n^5}\frac{1}{d}\frac{u^2}{2g} \quad (10)$$

in which

$$c = \frac{c_2}{(ud/\gamma)} + c_3 \quad (11)$$

Values of $c_2 = 28.0$ and $c_3 = 0.20$ were recommended. It is observed that the equations of both Engelund (1953) and LeMehaute (1957) are of identical form except for the coefficient and the influence of porosity.

Ward (1964) developed an equation for both laminar and turbulent flow in porous media, based on a dimensional analysis, to express the pressure gradient. All experiments were represented on a plot of the friction factor (f_k) for the porous media versus the Reynolds number (R_k), in which the characteristic length in both cases is the square root of the permeability ($\sqrt{k}$) of the porous medium. Fig. 1a. indicates a smooth transition from laminar to turbulent flow.

This method of presentation was also adopted by Sollitt and Cross (1972) who performed tests on gravel. Their plot is shown in Fig. 1b. In comparison with Ward (1964) who presented a single curve for different media consisting of glass beads, ion exchange resin, sand, gravel and granular activated carbon, Sollitt and Cross (1972) presented three different curves, on the basis of different diameters of stones.

Arbhabhirama and Dinoy (1973) used the same parameters to analyse results on sand, angular gravel and large gravel. However the plot presented is different and is modelled on the pipe friction diagram known as the Moody diagram. This plot is illustrated in Fig. 1c.

Results of tests performed on cylindrical lattice structures by Kondo and Toma (1972) are presented in Fig. 1d. By using structures of different diameter within a limited flow range the results show a linear relationship on the log scale.

Kamel (1969) and Keulegan (1973) based their analyses on similar parameters and the results of the latter are given in Fig. 1e. This is another example where results from different media have been represented by a single curve.

Extensive and well-documented studies on the hydraulic conductivity of crushed rock and river gravel have also been presented by Dudgeon (1966) and McCorquodale, Hannoura and Nasser (1978). Gupta (1985) discussed the use of angularity of aggregate particles as a measure of their shape and hydraulic resistance.

One of the most extensive investigations in this field was conducted at Hydraulics Research, Wallingford, U.K., as a part of a major research programme on wave action on porous coastal structures. Allsop and Shih (1988) and Shih (1990) outline the important findings from this study. A permeameter having a diameter 0.6m was used to study the performance, under steady flow conditions, of materials with size varying from 2mm to 61mm. Both single size and wide graded samples were tested. Shih (1990) proposed new formulae for the permeability of rubble materials. In effect the existing formulae which were originally developed by Engelund for sand were updated with the inclusion of appropriate modifications resulting from detailed statistical analysis of experimental data. Table 2 summarises the principal findings of this study.

4.0 Time dependent flow in porous media

4.1 Effects of unsteady flow

In comparison with the vast amount of information available on the hydraulic gradient -velocity relationship for steady flow conditions, very few investigations have been performed under unsteady flow conditions.

In porous media, the unsteady flow problem is very complex. Accelerating flow can cause a change in the expected flow regime for a particular Reynolds number and may cause a delay in the onset of turbulence in coarse porous media. Any change in 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. Pioneering experimental work in this field was performed by Keulegan (1968) in a study of the damping effects of wave screeens. Keulegan used an oscillatory flow tank to study the coefficients of resistance of wire mesh screens.

Shuto and Hashimoto (1978) used similar apparatus to study the hydraulic resistance of artificial concrete blocks. Theoretical analyses and experimental work involving both steady and unsteady flow were used to clarify the mechanism by which wave energy is absorbed by block structures. Three kinds of armour units namely the tetrapod, hollow tetrahedron and the hexaleg were investigated. From these tests it was concluded that resistance coefficients obtained under steady flow and oscillatory flow show almost no difference for periods of oscillation greater than 3.4 secs. It was also recommended that, for the armour units investigated, it is advisable to use units heavier than 500gm and that experiments should be carried out with Reynolds numbers greater than 1000.

The most significant contribution in this field has been made by Hannoura and McCorquodale (1978a) who considered inertia effects in relation to materials such as crushed rock, a common construction material for breakwaters. Both steady and accelerated flow tests were performed in essentially the same apparatus with modifications to suit both test conditions. Details of the apparatus are given in Fig. 2a.

Hannoura and McCorquodale (1978a) adopted a semi-empirical representation of one dimensional unsteady flow in porous media expressed in the form

$$I = (a + b|u|)u + \frac{(1+c)}{g}\frac{du}{dt} \qquad (12)$$

where

a,b = steady flow coefficients
$c = (1-n)C_n/n$ = acceleration coefficient
C_n = inertia coefficient
n = porosity

However in determining 'c', it was assumed that the steady flow coefficients 'a' and 'b' were valid for unsteady flow conditions.

Figs. 2b and 2c illustrate the results of this work. During this initial period the total resistance to the flow through the porous media was found to be as much as three times the corresponding steady flow resistance. The value of 'c' varied from negative to approximately +6, with the most significant positive results occurring for the largest rock size. Fig. 2c is a further comparison between the steady and unsteady flow resistance, indicating the influence of the accelerating head (initial difference in the water level in the U-tube oscillator). It shows that flow resistance approaches the steady flow resistance as the acceleration head decreases.

In general it is observed that a comparatively large scatter is present in the experimental results. The duration of each test was very short and made accurate measurements of the virtual mass effect very difficult. Due to the physics of the flow regime, the steady flow drag coefficients may not be applicable to unsteady flow conditions. Possible distortions of the porous matrix will have an influence by reducing the effect of acceleration because some of the applied force is used to accelerate the grains. The authors concluded that a statistical analysis yielded evidence of the existence of a virtual mass effect in porous media for the 4.4cm rock but the scatter was too great to comment on the smaller sized materials.

Burcharth and Thompson (1983) investigated a similar problem from a different view point. The objectives of this study were to explain some of the differences in the hydraulic stability of slender and bulky armour units and to examine scale effects that might be present in rubble mound breakwater models of different sizes. Horizontal beds of Dolosse and stones which represent two extremities in the variety of units were subjected to sinusoidal oscillatory flows parallel to the cover layer. The test results revealed that no significant differences exist between the hydraulics stability of Dolosse and rocks of the same weight Furthermore, units of different sizes showed the same stability and no viscous scale effects was observed.

Hettiarachchi (1987) conducted an experimental programme to assess the performance of hollow block porous armour units under constant velocity and unidirectional accelerated flow conditions. This investigation was considered relevant and compatible with previous studies relating to specific unsteady flow conditions. It was also justified in the light of considerable scatter observed in the results of previous studies. Tests under constant acceleration have an advantage with the immediate consequence being that the equations characterising the motion may be logically reduced to a workable form dependent only on a few variables. Results from this study 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 was small.

4.2 Air entrainment studies

The phenomenon of air entrainment due to wave - breakwater interaction has received very little attention. Few investigators have dealt with the problem of air entrainment in waves. Fuhrboter (1970) investigated the effect of air entrainment in waves in the breaking zone and found that the effect of aeration cannot be neglected.

The hydraulic conductivity of a porous structure such as a rubble mound breakwater has been shown to affect the wave reflection, transmission and run-up. However, with short period or breaking waves, air may be entrained in the flow within the porous structure, thus reducing the wave transmission and increasing reflection. Although saturated flow in a porous structure can be classified in detail, a similar classification does not exist for two-phase flow in porous media.

McCorquodale, Nasser and Hannoura (1977) investigated this phenomenon and observations were made on air-water flow in wave absorbers consisting of crushed rock. The flow tests were performed in an apparatus consisting of a closed-loop of 10.16cm diameter pipe having a recirculating flow system together with a removable test section. The loop included an air diffuser capable of injecting air bubbles into the flow. Both co-current and counter-current air flows were investigated. All experiments were conducted under steady flow conditions. Details of the apparatus are given in Fig. 3a. Some of their results are presented in Figs. 3b and 3c. They show typical results for co-current and counter-current flow of air water mixture in crushed rock. The counter-current flows were found to be very unstable for high values of discharge. The reduction in the conductivity was found to be much greater for counter-current flow due to the blockage provided by the entrained air.

Subsequently Hannoura and McCorquodale (1978b) performed further tests on counter-current flow. In particular, conceptual models and semi-empirical equations were proposed to describe the nature of the flow and the hydraulic conductivity of air-water flow through coarse porous media. The flows in the tests were primarily on a vertical axis.

5.0 Concluding Remarks

5.1 From this review it is evident that although the velocity-hydraulic gradient relationship for flow of fluids through porous media has been investigated by many researchers, no general agreement has yet been reached as to its form. The main reasons for the appearance of a number of conflicting equations for their relationship could be attributed to the following,

(i) Practical difficulties of covering an extensive range of flow conditions for a particular porous medium. The experimental arrangements used were best suited only to a limited flow range in which they performed well with minimum experimental errors.

(ii) Frequently large scatter of experimental results and the limited number of readings for a given experiment.

(iii) Use of different governing equations and various parameters for the analyses of experimental data. Some authors presented equations for individual materials, for example, a particular type of stone of given diameter, while others preferred a general equation for all data covering a wide range of materials.

5.2 For reasons identified in Section 5.1 it is difficult to perform a detailed comparative study of existing data either by using the data in its present form or by normalizing it to a set of common parameters. The variability of the respective flow coefficients when using different experimental apparatus was also evident from the review. Studies over a wide range of porous media demonstrated the difficulties associated in developing a general formula which accommodates all the variables involved.

5.3 Steady flow permeability coefficients play an important role in the mathematical modelling of wave reflection and transmission through porous media. These steady flow coefficients are assumed to be valid under time dependent conditions and have been incorporated into the majority of mathematical formulations. The review also identified 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.

5.4 This review established that both the Forchheimer and Exponential forms of resistance equations (eqs. 3 and 5) can be used for the hydraulic gradient-velocity relationship. Use of the Forchheimer form is recommended because it permits the investigation of the on-set of turbulence based on the ratio between turbulent and laminar components of the hydraulic gradient (eq. 7).

Of the many formulae developed, those of Engelund (1953) and Le Mehaute (1957) have been used widely for modelling purposes. The formulae developed by Shih (1990) after detailed experimental and statistical analysis are recommended for computational work and mathematical modelling.

5.5 Steady flow permeability tests over an extensive flow domain covering a wide range of materials of interest are required to obtain a better understanding of the hydraulic gradient-velocity relationship for materials used for the construction of coastal structures. It is recommended that these tests be performed in at least three different permeameters to study the variability of the coefficients when using different experimental apparatus. Steady flow tests should be supplemented with unsteady flow tests or cyclic flow tests to obtain a better understanding of inertia effects.

The overall effects of air entrainment should be investigated in detail for a wide range of flow conditions.

6.0 References

AHMED, N. & SUNADA, D.K. (1969) Non-linear flow in porous media. Journal of the hydraulics division, ASCE. Vol. 95, HY6, pp 1847-1857.

ALLSOP, N.W.H. & SHIH, R.W.K. (1988) Permeability of Rubble Mound Coastal Structures to Wave Action: Laboratory and numerical modelling. Proc. 2nd Int. Symposium on Wave Research and Coastal Engineering, University of Hannover, Germany.

ARBHABHIRAMA, A. & DINOY, A.A. (1973) Friction-factor and Reynolds number in porous media flow. Journal of the hydraulics division, ASCE, Vol. 99, HY6, pp. 901-911.

BURCHARTH, H.F. & THOMPSON, A.C. (1983) Stability of armour units in oscillatory flow. Proc. ASCE Conf. Coastal Structures '83, Virginia, U.S.A.

DARCY, H. (1856) Les fontaines publiques de la ville de Dijon, Dalmont, Paris.

DUDGEON, C.R. (1966) An experimental study of the flow of water through coarse granular media. La Houille Blanche. 7. pp. 785-801.

ENGELUND, F. (1953) On the laminar and turbulent flow of groundwater through homogeneous sand. Trans. Danish Acad. Tech. Sci. No. 3.

FORCHHEIMER, P. (1901) Wasserbewegung durch Boden. Zeit. Ver. deutsch. Ing. 45.

FUHRBOTER, A. (1970) Air entrainment and energy dissipation in breakers. Proc. 12th Conf. on Coastal Engineering. Washington D.C., U.S.A. Chapter 24, pp. 391-398.

HANNOURA, A.A. & McCORQUODALE, J.A. (1978a) Virtual mass of coarse granular media. Journal of the waterways port coastal and ocean division. ASCE. Vol. 104, WW2, pp. 191-200.

HANNOURA, A.A. & McCORQUODALE, J.A. (1978b) Air-water flow in coarse granular media. Journal of the hydraulics division. ASCE. Vol. 104, HY7, pp. 1001-1010.

HANNOURA, A.A. & BARENDS, F. (1981) Non-Darcy flow: A state of the art. Flow and transport in porous media. Editors. Verruijit, A. Barends, F. Balkema, A.A., Rotterdam, The Netherlands.

KAMEL, A.M. (1969) Water wave transmission through and reflection by pervious coastal structures. US Army Engineer Waterways Experiment Station. Res. report. H-69-1.

KEULEGAN, G.H. (1968) Wave damping effect of screens. US Army Engineer. Waterways Experiment Station. CE. Vicksburg, Missisipi. Res. report. No. 2-12.

KEULEGAN, G.H. (1973) Wave transmission through rock structures. Hydraulic model investigation. US Army Engineer Waterways Experiment Station. Hydraulics Laboratory, Vicksburg, Missisipi. Res. report. H-73-1, 75.

KONDO, H. & TOMA, S. (1972) Reflection and transmission for a porous structure. Proc. 13th Conf. on Coastal Engineering, Vancouver, Canada. Chapter 104, pp. 1847-1865.

LEMEHAUTE, B. (1957) Permeabilite des digues en enrochements aux ondes gravite periodiques. (The perviousness of rockfill breakwaters to periodic gravity waves) La Houille Blanche. No. 6, 1957, pp. 903-916 and Nos. 2,3, 1958.

McCORQUODALE, J.A., NASSER, M.S. & HANNOURA, A.A. (1977) The effect of entrained air on wave action on a porous structure. Proc. 6th Canadian congress of Applied Mechanics, Vancouver, Canada. pp. 541-542.

McCORQUODALE, J.A., HANNOURA,A.A. & NASSER, M.S. (1978) Hydraulic conductivity of rockfill. Journal of Hydraulic Research. Vol. 16 No.2, pp. 123-137.

POLUBARINOVA-KOCHINA, P.Y. (1962) Theory of the motion of groundwater. Princeton University Press, Princeton, New Jersey.

SCHEIDEGGER, A.E. (1974) The physics of flow through porous media. University of Toronto Press.

SHIH, R.W.K. (1990) Permeability Characteristics of Rubble Material-New Formulae. Proc. 22nd Int. Conference on Coastal Engineering, Delft, Netherlands.

SHUTO, N. & HASHIMOTO, H. (1970) Hydraulic resistance of artificial concrete blocks. Proc. 12th Conf. on Coastal Engineering, Washington D.C., U.S.A. Chapter 97, pp. 1857-1599.

SOLLITT, C.K. & CROSS, R.H. (1972) Wave transmission through permeable breakwaters. Proc. 13th Conf. on Coastal Engineering, Vancouver, Canada. Chapter 103, pp. 1827-1846.

WARD, J.C. (1964) Turbulent flow in porous media. Journal of the hydraulics division. ASCE. Vol. 90, HY5, pp. 1-12.

	Laminar coefficient α_0	Turbulent coefficient β_0
uniform, spherical particles.	≈ 780	≈ 1.8
uniform, rounded sand grains	≈ 1000	≈ 2.8
irregular, angular grains	up to 1500 or more	up to 3.6 or more

TABLE 1 FLOW COEFFICIENTS FOR ENGELUND'S (1953) EQUATION

The permeability relationship for single size materials is given by $i = au + bu^2$, where i = hydraulic gradient, u = superficial velocity and

$$a = [\alpha_1 + \alpha_2 (\frac{g}{\upsilon^2})^{2/3} D_{15}^2] \frac{(1-n^3)}{n^2} \frac{\upsilon}{g} \frac{1}{D_{15}^2}$$

$$b = \{\beta_1 + \beta_2 \exp[\beta_3 (\frac{g}{\upsilon^2})^{1/3} D_{15}]\} \frac{(1-n)}{n^3} \frac{1}{gD_{15}}$$

where

n = porosity
α_1 = 1683.71, α_2 = 3.12 x 10^{-3}
β_1 = 1.72, β_2 = 1.57, β_3 = −5.10 x 10^{-3}
υ = kinematic viscosity of water = 1.14 x 10^{-6} m^2/s
g = gravitational acceleration = 9.81 m/s^2

The permeability relationship for wide graded materials is given by $i = au + bu^2$, where i = hydraulic gradient, u = superficial velocity and

$$a = [\alpha_1 + \alpha_2 (\frac{g}{\upsilon^2})^{2/3} D_*^2] \frac{(1-n^3)}{n^2} \frac{\upsilon}{g} \frac{1}{D_*^2}$$

$$b = \{\beta_1 + \beta_2 \exp[\beta_3 (\frac{g}{\upsilon^2})^{1/3} D_*]\} \frac{(1-n)}{n^3} \frac{1}{gD_*}$$

$$D_* = D_{15} (\frac{D_{15}}{D_{50}})^{-1.11} (\frac{D_{50}}{D_{85}})^{0.52}$$

where

n = porosity
α_1 = 1683.71, α_2 = 3.12 x 10^{-3}
β_1 = 1.72, β_2 = 1.57, β_3 = −5.10 x 10^{-3}
υ = kinematic viscosity of water = 1.14 x 10^{-6} m^2/s
g = gravitational acceleration = 9.81 m/s^2

TABLE 2 HYDRAULIC GRADIENT - VELOCITY RELATIONSHIPS FOR RUBBLE MATERIAL (Shih 1990)

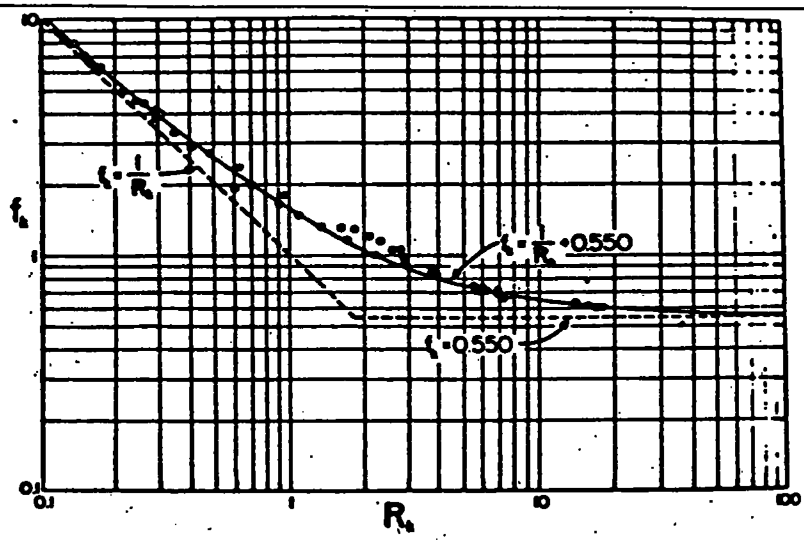

Fig. 1.a Friction factor vs Reynolds number (Ward 1964)

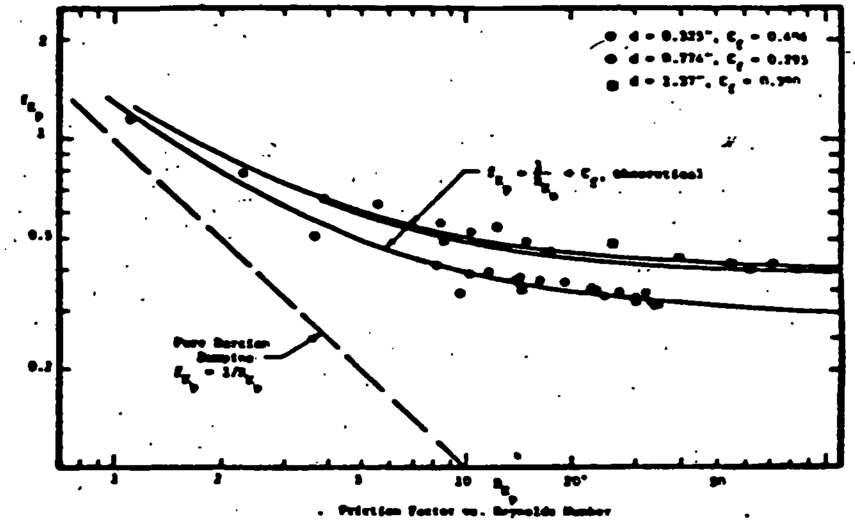

Fig. 1.b Friction factor vs Reynolds number (Sollitt and Cross 1972)

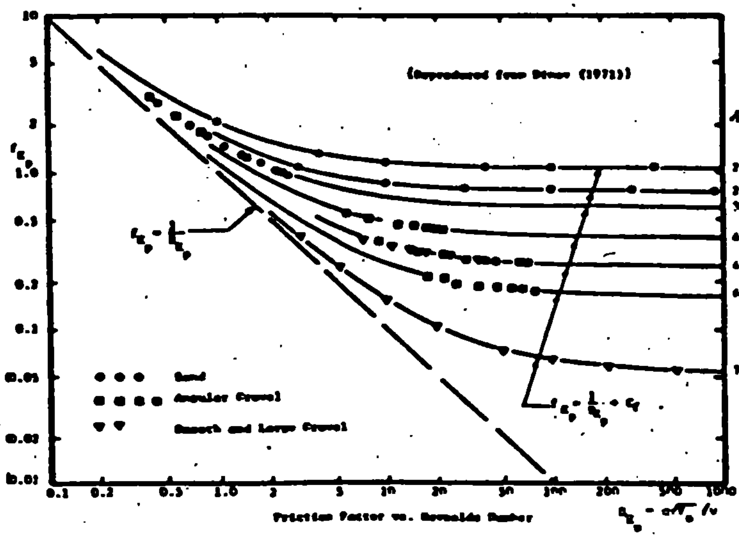

Fig. 1.c Friction factor vs Reynolds number (Arbhabhirama and Dinoy 1973)

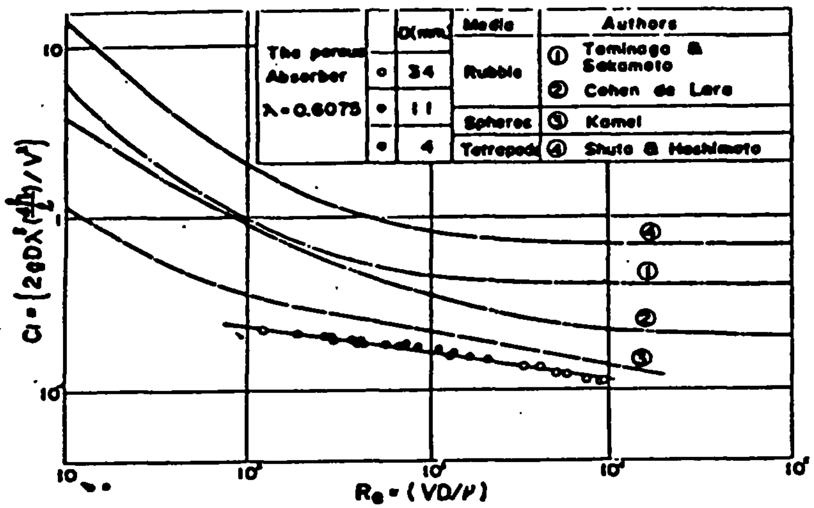

Fig. 1.d Friction factor vs Reynolds number (Kondo and Toma 1972)

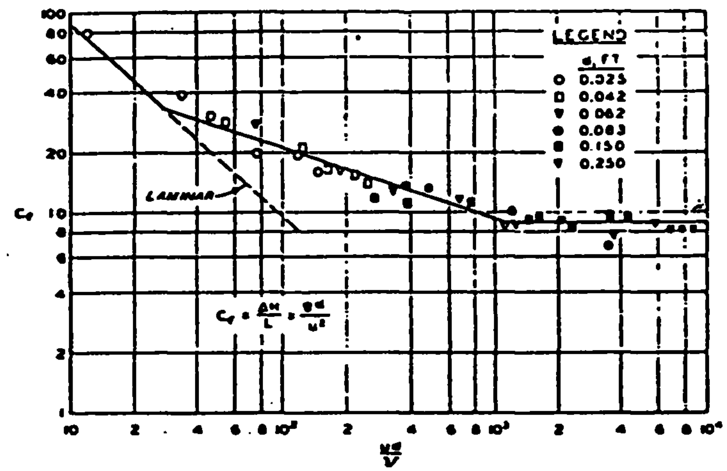

Fig. 1.e Friction factor vs Reynolds number (Keulegan 1973)

FIG. 1 VARIATION OF FRICTION FACTOR WITH REYNOLDS NUMBER

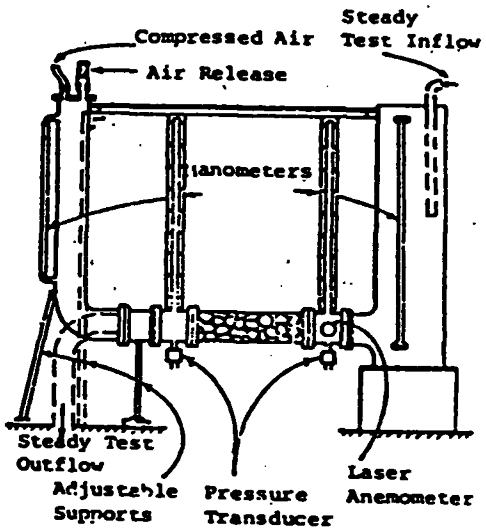

Fig. 2.a Experimental apparatus

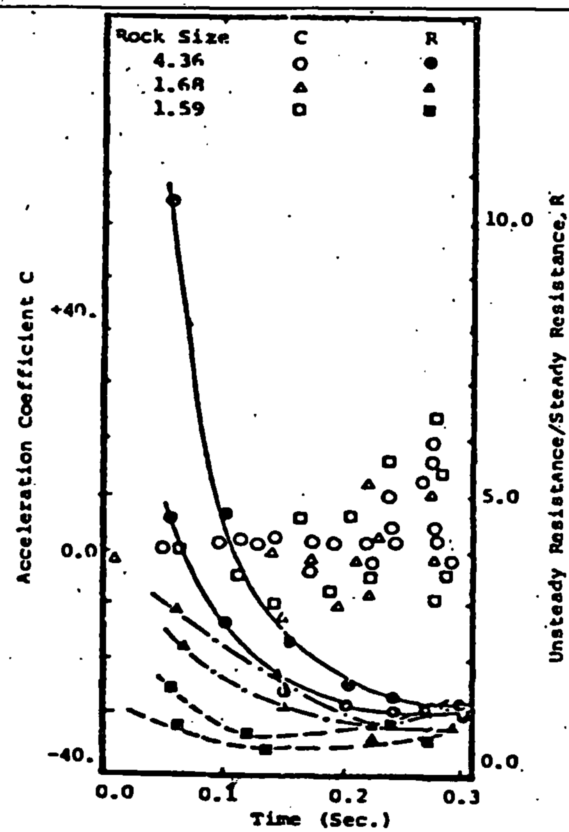

Fig. 2.b Acceleration coefficient vs time

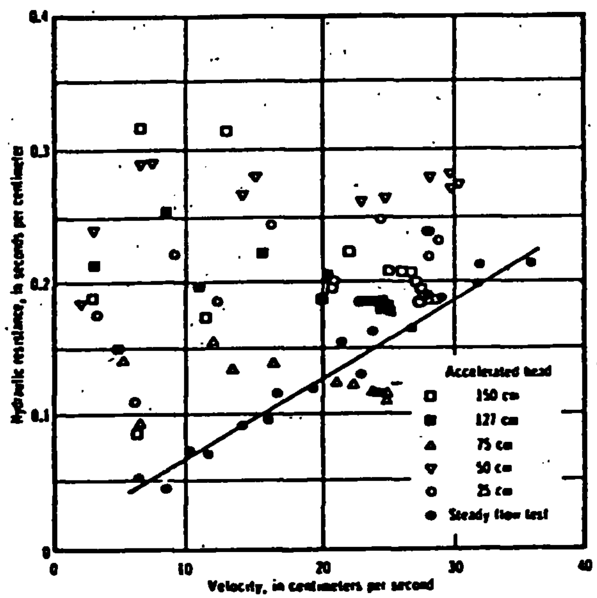

Fig. 2.c Hydraulic resistance vs velocity

FIG. 2 EFFECTS OF UNSTEADY FLOW

(Hannoura and McCorquodale 1978a)

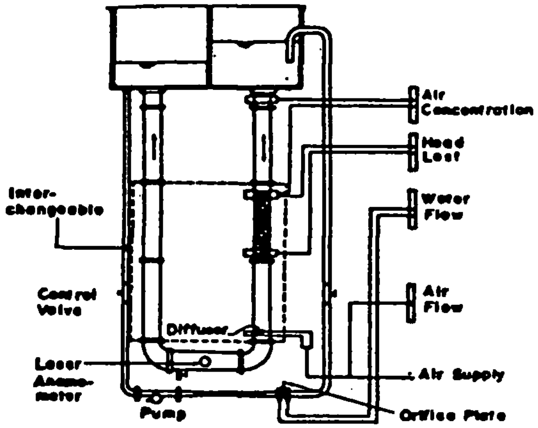

Fig. 3.a Experimental apparatus

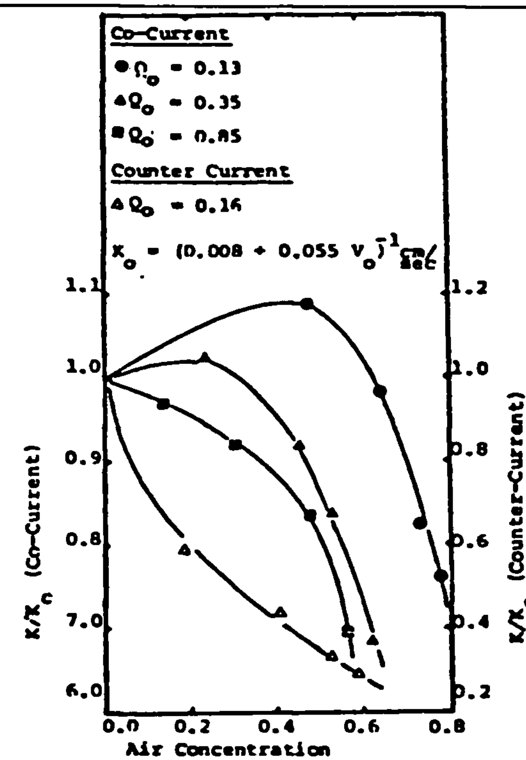

Fig. 3.b Effect of air concentration on conductivity

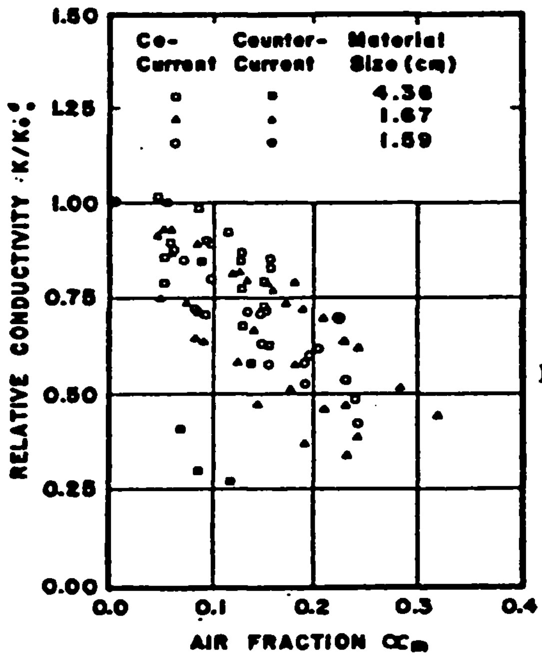

Fig. 3.c Relative conductivity vs air fraction

FIG. 3 EFFECTS OF AIR ENTRAINMENT

(Hannoura and McCorquodale 1978b)