Experimental Investigation of Flow through Porous Media & its Characteristics

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HYDRAULICS & FLOOD CONTROL ENGINEERING

Ву

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DEPARTMENT OF CIVIL ENGINEERING
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JULY 2016

BONAFIDE CERTIFICATE

This is to certify that the Project report entitled "Experimental Investigation of Flow through Porous Media & its Characteristics" is a record of the bonafide dissertation work carried out by me, Rajat Kumar, towards the partial fulfilment of requirements for the award of degree of Master of Technology in HYDRAULICS & FLOOD CONTROL ENGINEERING.

Also, I do hereby state that I have not submitted the matter embodied in any other University/Institute for the award of any degree as per my knowledge and belief.

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This is to certify that the above made statements made by the candidate are correct to the best of my knowledge.

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ABSTRACT

"EXPERIMENTAL INVESTIGATIONS ON FLOW THROUGH POROUS MEDIA WITH AN EMPHASIS ON CHARACTERISTIC PARAMETERS"

Water is capricious. It rains too little or too much, in the right or wrong season, it always moves too slow or too fast, but it does also secret itself. It puts itself in reserve. It results in flood or drought. Its movement through the soil strata is indeed complex. With the gradual dwindling of surface sources, the role of subsurface sources is gaining momentum. Therefore, any aspect relating to movement of water through the porous strata is still fascinating and is welcome.

The subject of seepage flow appears conceptually simple; upon deeper and more detailed examination, the character of flow of a fluid element through the tortuous passages of a granular medium assumes an almost indescribable complexity. A steadily increasing interest has been created during the past century to study the laws governing the flow of fluids through beds of granular media. As a result of this, coupled with ever increasing demand for information brought about by the advances in technical sciences, numerous theoretical studies, modeling approaches, laboratory and field tests and mathematical models have been developed to establish the true relationship between different variables. Further, examination of literature, which is scattered over different publications, indicates a little agreement between the results of different researchers and hence equations thus obtained are of limited use. The subject is further complicated as different investigators adopted various methods of

expressing the results of their research. In addition, majority of the approaches are found to lack describing complete range of seepage flow.

Objectives of the present investigation are

- ✓ to verify and ascertain the reliability of the present experimental
 investigation with that of the past study.
- ✓ to obtain the relationship between velocity of flow and the
 corresponding hydraulic gradient covering a very wide range of
 velocity on a numerous sizes of porous media (which was hitherto
 not attempted).
- to express pre-Darcian, Darcian, post-Darcian and Forchhelmer coefficients as functions of the size of the media.
- ✓ to apply the corrections for porosity effect, wall effect and tortuosity
 effect to make the findings more realistic and applicable on the field.

In order to achieve these objectives, experimental program had been planned and carried out. Results and findings of the study are presented in six chapters.

The FIRST Chapter is a general one and describes the nature and significance of seepage flow. A brief description of macro and microscopic nature of seepage flow is presented. Objectives of the study are stated. It concludes with scope of the present work.

A review of relevant past work on seepage flow with an emphasis on various forms of linear and non-linear equations is presented in SECOND

Chapter. It is done to illustrate the methods of attack and then to develop line of reasoning. Earlier studies on the effect of media properties such as porosity, tortuosity, shape and size of the particle on the relationship between resistance to flow and flow regime are recollected and reviewed. Wall effect, a factor which takes into account the constraints in the laboratory while using a permeameter and tortuosity effect, a factor which takes into account the actual path followed by the fluid particle are also subjected review.

The THIRD Chapter describes various characteristics of the porous media. The experimental setup, i.e., permeameter, and the experimentation techniques are explained. Steps involved in the determination of media properties such as size, porosity, and hydraulic parameters such as velocity and hydraulic gradient are briefly enunciated in this chapter. In order to cover as wide as possible the range of seepage flow, ten sizes of gravel, flve sizes of river sand and three sizes of glass spheres are used as solid media and water is used as fluid medium. Further, special steps taken to modify and improve the permeameter to cover a wide range of values of velocities and the corresponding hydraulic gradients for all the media used in the study are also explained in this chapter.

Analysis of experimental data is presented in the FOURTH Chapter.

First of all, the trend of present investigation is ascertained by comparing it with that of earlier works. A new form of relationship between velocity of flow and the corresponding hydraulic gradient covering a wide range of velocity is developed for all sizes and shapes of the media used. Expressions relating

Pre-Darcian, Darcian, Post-Darcian and Forchheimer coefficients as functions of the size of the media are developed. These relationships are then represented in the form of graphs.

FIFTH Chapter presents a similar analysis of the experimental data, incorporating the correction for porosity, wall and tortuosity effects to those relationships obtained in the earlier chapter. This will enable the application of the findings a more realistic and field oriented.

SIXTH Chapter sets forth the conclusions and the important findings of this investigation. A few suggestions are made as a scope for further study.

It is hoped that this thesis may serve to clarify some of the basic ideas concerning seepage flow, with gravel, river sand and glass spheres as media and provides a greater insight into the mechanism and behavior of flow through porous media and thus contribute to an extension of our knowledge in this field.

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CHAPTER - I

Introduction



CHAPTER - I

INTRODUCTION

1.1 INTRODUCTION

Water plays a vital part in all forms of life on the earth from simplest living organisms to the most complete human systems of any country. The resources of water are plenty of which ground water is one, the study of which was regarded as "occult" science until recently. In view of the significant contribution made by ground water resources to water supply, any fact contributing to a greater understanding of the problems relating to ground water flow, either directly or indirectly, is of prime concern.

The subject of seepage flow is one, which at first eight appears conceptually simple; however, the character of flow of a fluid filament through the tortuous passages of a granular medium is very similar to what is shown in Fig.1.1. (Kovacs (1981), Fand (1987))

Any study of the flow of fluids through porous media must first of all intuitively clarify what is meant by a porous medium.

A porous medium is defined as a solid body containing void spaces, distributed more or less frequent through the medium. In either regular or random manner. In a porous medium, pores may be interconnected or non-interconnected, but at least a part of the pore system must be interconnected to make fluid flow possible through the medium. This pore space is termed as the effective pore space of the medium. Pores vary in shape, size and magnitude and provide curvilinear paths for the fluid to flow.

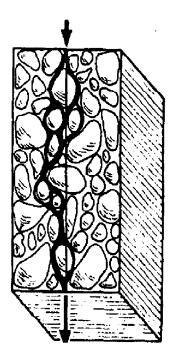


Fig. 1.1 : Actual and average directions of flow of a fluid through a porous medium

In order to have a proper insight into the subject of seepage flow, first of all, two size scales, namely macroscopic and microscopic scales, have to be distinguished to describe the flow phenomenon.

The macroscopic scale is large when compared to particle or pore size. On this scale, flow of fluid through the medium is described as a continuous phenomenon in space. In this scale, no distinction is made between the solid and fluid constituents of the system. Macro pressure gradients are thought of as the pressure drop between any two points in a statistically homogeneous medium. The macro velocity is based on the total cross sectional area of the system. It is obviously less than the true pore velocity.

The microscopic scale, on the contrary, is a scale commensurate with the particle or pore size of the medium, but still large as compared with molecular dimensions. On this scale, true fluid velocities are described. The microscopic velocity is the basic dynamic dependent variable giving rise to shear stresses and inertial effects. In general, macro variables are first determined experimentally and then related to corresponding micro components, to analyze and express the results of research.

1.2 FUNDAMENTAL CHARACTERISTICS OF SEEPAGE FLOW

The resistance that a packing of rigid particles offers to the flow of a fluid is obviously bound up with the shape and dimensions of the flow channels in the packing. Various forms of equations have been proposed based on a simple model which seeks to replace the actual pore channels which cannot be treated by rigorous hydrodynamics. The complex network of flow channels discloses the difficulty in making a useful and direct physical measurement of the pore size. Factors which influence the pore size and structure are (a) mean particle size, (b) porosity of the packing, (c) shape and surface roughness of individual particles, and (d) size distribution of particles in the packing. In laboratory experimental work, an effect will also be caused by wall of the permeameter inducing a more open packing in its immediate vicinity. (Scheiddeger (1960), Kovacs (1981), Muskat (1982))

As in the case of flow through pipes, resistance in seepage flow also depends upon basic dynamic variable, micro velocity, and on physical properties of the fluid, namely, its viscosity and density. The nature of all the seepage flow problems is that there is a regime where the laws of viscous

fluid motion operate with a gradual transition to regimes where turbulence becomes a dominating force.

When liquids are used in experiments, there is a possibility of dissolved air coming out of solution and getting lodged in some of the pore throats. This reduces the effective permeability and alters flow characteristics of the system.

In general, transport of a fluid is influenced by various forces, such as molecular forces, electro-viscous forces, viscous forces and Inertial forces. Size of media used in the present study ranges from 1.4 mm to 20 mm gravel, 1.7 mm to 6.7 mm river sand and 16.7 mm to 35 mm glass spheres. Further, since water is the fluid medium, forces of interest are only those arising from viscosity and inertia which occur commonly in any type of seepage flow. Their relative magnitudes with respect to each other decide the regime of flow.

The fundamental relation required is the one that would relate head loss across the bed and corresponding macro flow rate, expressed in terms of structural properties of granular medium. Various formulae and correlations, which have been proposed merely, relate these basic variables.

1.3 IMPORTANCE OF SEEPAGE FLOW

1.3.1 General

Ever since Darcy described his experiments in 1856, the subject of seepage flow has been subjected to continuous exploitation in both theoretical and experimental aspects. (Carman (1937), Rose (1945), Collins

(1951), Todd (1959), Scheiddeger (1960), Harr (1962), Bear (1969), Kovacs (1981), Muskat (1982), Verruijit (1982), Fand (1987), Shih(1990), Van Gent (1995), Hall et al., (1995), the author Thiruvengedam and his guide Pradeep kumar (1997), Wang et al., (1999), Venkatraman and Rama Mohan Rao (2000), Legrand (2002), Murali et al., (2004)). Examination of the literature referred to here, indicates little agreement between results of different works. In addition, the subject is further complicated as different investigators adopted various modes of expressing the results of their research.

Theory of seepage describes the laws governing flow of fluids in porous media. It meets the requirements of practice by providing methods for the computation of seepage through structures of various kinds during their planning, erection and operation. Computation of seepage plays an extremely important part in the design of hydraulic structures. Problem of seepage control in hydraulic structures determines the final design and dimensions of the structures. Study of diffusion and flow of fluids through materials such as bricks and porous earthenware has long been a problem in the ceramic industry. A number of studies on the flow of a gas through moulding sand have been reported. Extraction of water from artesian basins by deep wells is a problem in the flow of liquids through porous rocks or sands. Scientific treatment of problems of irrigation, soil erosion and sub surface drainage with tiles is still open to further development. Thus, the importance of seepage flow analysis lies in developing preventive measures against ill effects of seepage flow.

1.3.2 Flow through a Permeameter

In general, in the experimentation on seepage flow, cylindrical permeameters are used because of ease in their operation and simple mathematical treatment. From a review of the past work, it is clear that considerable amount of literature (Dudgeon (1966), Ahmed and Sunada (1969), Arabhabirama and Dinoy (1973), Subramanya and Madhav (1978). Pradeep kumar and Venkatraman (1995), Murali et al., (2004)) is available on flow through media of different varieties. However, it is common practice to solve these problems using Darcy's law which is expressed as

$$V_b = \frac{Q}{A} = -k \frac{\partial h}{\partial x} = -ki \tag{1.1}$$

where

V_b = Bulk velocity of flow

Q = Discharge

A = Area of flow

k = Darcy's coefficient of permeability

$$\frac{\partial h}{\partial x}$$
 = i = Hydraulic gradient

It is generally accepted that Darcy's law is valid for low velocities. In many of flow situations velocity of flow is high. In such situations, the linear relationship between V_b and I no longer holds good and exhibit non-linear relationship (Polubarinova-Kochina 1952), Van Gent (1992), Burcharth and Andersen (1995), Hall et al.,(1995)). Further, all the experimental data obtained from the permeameter have to consider the effect of wall of the

permeameter, as flow situations near the boundary are different from those away from the wall.

1.4 SCOPE OF THE PRESENT WORK

A steadily increasing interest has been created during the past century to study the laws governing the flow of fluids through beds of granular media. As a result of this, coupled with ever increasing demand for information brought about by the advances in technical sciences, numerous theoretical studies, modeling approaches, laboratory and field tests and mathematical models have been developed to establish the true relationship between different variables. Further, examination of literature, which is scattered over different publications, indicates a little agreement between the results of different researchers and hence equations thus obtained are of limited use. The subject is further complicated as different investigators adopted various methods of expressing the results of their research. In addition, majority of the approaches are found to lack describing complete range of seepage flow.

Objectives of the present investigation are

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 velocity on a numerous sizes of porous media (which was hitherto
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to apply the corrections for porosity effect, wall effect and tortuosity effect to make the findings more realistic and applicable on the field.

In order to achieve these objectives, experimental program had been planned and carried out. Results and findings of the study are presented in six chapters.

The FIRST Chapter is a general one and describes the nature and significance of seepage flow. A brief description of macro and microscopic nature of seepage flow is presented. Objectives of the study are stated. It concludes with scope of the present work.

A review of relevant past work on seepage flow with an emphasis on various forms of linear and non-linear equations is presented in SECOND Chapter. It is done to illustrate the methods of attack and then to develop line of reasoning. Earlier studies on the effect of media properties such as porosity, tortuosity, shape and size of the particle on the relationship between resistance to flow and flow regime are recollected and reviewed. Wall effect, a factor which takes into account the constraints in the laboratory while using a permeameter and tortuosity effect, a factor which takes into account the actual path followed by the fluid particle are also subjected review.

The THIRD Chapter describes various characteristics of the porous media. The experimental setup, i.e., permeameter, and the experimentation

techniques are explained. Steps involved in the determination of media properties such as size, porosity, and hydraulic parameters such as velocity and hydraulic gradient are briefly enunciated in this chapter. In order to cover as wide as possible the range of seepage flow, ten sizes of gravel, five sizes of river sand and three sizes of glass spheres are used as solid media and water is used as fluid medium. Further, special steps taken to modify and improve the permeameter to cover a wide range of values of velocities and the corresponding hydraulic gradients for all the media used in the study are also explained in this chapter.

Analysis of experimental data is presented in the FOURTH Chapter. First of all, the trend of present investigation is ascertained by comparing it with that of earlier works. A new form of relationship between velocity of flow and the corresponding hydraulic gradient covering a wide range of velocity is developed for all sizes and shapes of the media used. Expressions relating Pre-Darcian, Darcian, Post-Darcian and Forchheimer coefficients as functions of the size of the media are developed. These relationships are then represented in the form of graphs.

FIFTH Chapter presents a similar analysis of the experimental data, incorporating the correction for porosity, wall and tortuosity effects to those relationships obtained in the earlier chapter. This will enable the application of the findings a more realistic and field oriented.

SIXTH Chapter sets forth the conclusions and the important findings of this investigation. A few suggestions are made as a scope for further study.

It is hoped that this thesis may serve to clarify some of the basic ideas concerning seepage flow, with gravel, river sand and glass spheres as media and provides a greater insight into the mechanism and behavior of flow through porous media and thus contribute to an extension of our knowledge in this field.



CHAPTER - II

Review of Past Work



CHAPTER - II

REVIEW OF PAST WORK

2.1 INTRODUCTION

Since the pioneering experiments of Darcy (1856) on the flow of water through filter sands, a succession of important analytical treatments coupled with experimental support have appeared on the subject of porous media flow, there by, subjecting it to continuous exploitation in various aspects by different investigators. A brief and relevant review of the past work related to seepage flow is presented in this chapter.

2.2 PAST WORK ON GROUNDWATER FLOW IN NUTSHELL

It was in 19th century, groundwater hydrology began as a quantitative science. Flow of water through porous structure was demonstrated first by French Civil Engineer, Henry Darcy. He postulated a mathematical law that governs the flow of ground water, which later becomes most widely referred and used law, as Darcy's law.

Dupuit (1863), based on Darcy's Law, derived an equation for the rate of flow of water to a well. Thiem (1906) modified Dupuit's equation to calculate hydraulic properties of an equifer by means of a pump test.

Later part of the 19th Century saw the development of a more comprehensive understanding of the relationship of ground water to the geological formations in which it occurs. Chamberlin (1885) published the first hydrogeologic report, "The Requisite and Qualifying Conditions of Artesian Wells" in 1885. It provided a theoretical basis for the scientific study of the occurrence of ground water prompting an explosion of activity in the evaluation of ground water resources in the United States.

King (1892) wrote "Principles and Conditions of the Movement of Groundwater" which introduced a number of concepts related to the movement of ground water due to gravity and presented water level contour maps. He was the first to observe that in humid areas water table was a subdued reflection of surface topography.

As early as 1901, Forchheimer was the first to realize that Darcy's law was not universally valid for flow through porous media. It was stated that at higher Reynolds number, linear relationship between hydraulic gradient and velocity of flow breaks down.

Theis (1935) proposed an equation describing the decline of the piezometric (potentiometric) surface in a fully confined aquifer due to the withdrawal of water from a well. This work formed the basis to quantify the flow of water to wells in confined or semi confined aquifers. Formation of a

regional cone of depression and its impact on the dynamic equilibrium of the aquifer was also described.

Hubbert (1940) in his book, "The Theory of Ground Water Motion", proposed a theoretical foundation for Darcy equation. It was demonstrated that Darcy's law for groundwater flow is analogous to Ohm's law for the flow of electricity.

Jacob (1940) devised a graphical method of interpreting aquifer test data for a pumping well in a fully confined aquifer.

Ergun (1952) proposed a modified form of Forchheimer's expression to describe flow through packed columns made of spheres, cylinders, round sand and coarse materials.

Hantush and Jacob (1955) solved the problem of quantifying nonsteady flow to a well in a leaky or semi-confined aquifer.

Ahmed and Sunada (1969) derived expressions for Forchhelmer coefficients from Navier Stokes equation and established that these coefficients are not strictly constants as was hitherto assumed and found to depend on Reynolds Number of flow.

Nasser (1970) made use of this form of expression to study radial non-Darcy flow through crushed rock.

Arbhabirama and Dinoy (1973) suggested the use of square root of intrinsic permeability as characteristic length to define friction factor and Reynolds Number. A graph similar to Moody diagram of pipe flow was presented for porous media flow.

Volker (1975) presented the results of an experimental study using screened gravel as media packed in converging boundaries, simulating flow to a well. The partial differential equation with suitable boundary values was solved using finite difference method.

Subramanya and Maday (1978) have reported extensive studies on linear and non linear flow, through porous media and have brought out an elaborate report on the various problems encountered in seepage flow.

Somerton and Wood (1988) investigated effect of wall of the permeameter on the resistance and the viscous effects were accounted for by incorporating the Brinkman's extension term (1947) in the momentum equation. The wall zone is assumed to extend from the inner side of the wall to one-radius of the particle used as media.

Nield (1991) analyzed the ability of the Brinkman-Forchheimer equation to adequately model flow in a porous medium and at a porous-medium and clear-fluid interface. It was demonstrated that certain terms in the equation require modification, and that there was a difficulty when using this equation to deal with a stress boundary condition.

Sohvas (1992) reported the results on the relation between shape of particles and soil permeability.

macroscopic equations using the extended Darcy-Forchheimer model. The second method considers the microscopic balance equations. In both cases, time and volume averaging operators are applied in a different order.

Karakas and Kavvs (2000) derived a conservation equation for the random ground water flow seepage velocity under general conditions of hydraulic stochastic functions.

Fourar and Henormand (2001) presented a new model for describing two-phase flow at high velocities in porous media and fractures. It was based on the generalization of the single-phase Forchhelmer's equation by introducing a multiplying factor for the superficial velocity during two-phase flow. This factor was assumed to depend on the saturation and field properties but not on the flow regime.

Macedo et al., (2001) studied the influence of turbulent effects on a fluid flow through a porous medium by numerically solving the set of Reynolds – averaged Navier-Stokes equations. A good agreement with the Forchheimer's equation is observed.

Buddhima and Sujeewa (2002) proposed an explicit solution for the critical hydraulic gradient required to move a base particle with in a pore channel. The theoretical model was tested in the laboratory using five gravel filters and a cohesionless base soil consisting of very fine river sand.

Imam Wahyudi et al., (2002) reported results of a study conducted to examine several sands with a large spread of particles size in order to validate the modeling of both Darcy's and Forchheimer's law parameters.

Tortuosity values calculated from pressure drop experiments were found to be within range of values found in the literature.

Payne and Song (2002) established exponential decay bounds for solutions of the Forchheimer equations in semi-infinite pipe flow through a porous medium when homogeneous initial and lateral surface boundary conditions are applied.

Legrand (2002) analyzed and compared experimentally the capillary model based on the square root of permeability as characteristic length, considering the effect of the pore diameter and the tortuosity.

Brown et al., (2003) presented a review and progress of post Darcy work in the conference held as a remembrance of 200th birth anniversary of Darcy.

Murali et al., (2004) brought out the limitations of not specifying the range of applicability of equations relating linear and nonlinear parameters with the size of the medium.

Mehmet Emin Birpinar and Zekai Sen (2004) developed an analytical solution for radial groundwater flow towards a fully penetrating well in a leaky aquifer. The results are presented as a set of type curves for a leaky aquifer with non-Darcian groundwater flow.

Reddy and Rao (2004) studied the effect of convergence of stream lines on the linear and non-linear parameters of Forchheimer's equation.

Fourar and Henormand (2004) examined 3D effect on flows at high velocities through homogeneous porous media. Results of numerical

simulations of a steady incompressible Newtonian fluid flowing through a 2D and a 3D periodic porous media performed at various Reynolds numbers are presented. The flow patterns were described and pressure and shear stress at the fluid / solid interface were analyzed.

Xiao-Hong Wang and Zhi-Feng Liu (2004) studied the scaling relations for the fluid permeability and the inertial parameter in the Forchhelmer equation based on solving the Navier-Stokes equations in the two-dimensional percolation porous media for 500 different configurations.

Note: In addition to the above references, relevant past work is cited while discussing various concepts such as methods of approach, governing equations, porosity, wall and tortuosity effects.

2.3 THE CONCEPTS

2.3.1 Methods of Approach

Aim of all the investigators on seepage flow had been to relate flow resistance to its behaviour in terms of measurable properties of the fluid and the medium. Three methods of approach to achieve this objective have been described. They are

- i) Correlation based on pipe flow analogy,
- ii) Correlation based on flow characteristics of the medium.
- iii) Correlation based on drag on the individual particle.

Pipe flow analogy consists in relating micro flow properties of granular medium to those of flow through a pipe by replacing linear dimensions of the latter with the corresponding hydraulic equivalents of medium.

In the second approach, flow characteristics, rather than structural parameters of granular medium are considered. One or two overall flow parameters are determined from experiments and are then used to predict flow pattern in all regimes of flow. For example, Darcy's law, Forchheimer equation etc. A detailed discussion is presented in Sec. 2.3.6.

In the third approach, two non-dimensional numbers to quantify resistance to flow and flow behaviour when a fluid flows through the coarse granular media are derived by the use of dimensional analysis. These numbers are Resistance Coefficient λ and Reynolds Number Re respectively and are given by

$$\lambda = \frac{\text{Id}_{p}g}{V^{2}} \frac{1}{G_{1}(Z), G_{2}(\hat{\mathbf{f}}), G_{3}(D/d), G_{4}(\mathbf{r}_{0}), G_{5}(\mathbf{s})}$$
(2.1)

and

$$Re = \frac{\rho v d_p}{\mu} G_2(f)$$
 (2.2)

Where

G₁(z) = Function expressing effects of shape of the particle on resistance,

G₂(f) = Function expressing effect of porosity on resistance,

 $G_3(D/d)$ = Function expressing effect of wall on resistance,

 $G_4(r_o)$ = Function expressing effect of surface roughness on resistance,

 $G_5(s)$ = Function expressing particle size distribution,

Relationship between these two variables is obtained from experiments for different fluids and media. These two parameters, in general, are also used to characterize the flow pattern in a granular medium,

which is generally classified based on the relative influence of viscous and inertial forces and the term *regime* is often used to identify the flow behaviour. When the former predominates, regime is referred to as *laminar regime*, and the *turbulent regime* indicates the predominance of inertial forces. Further, intermediate range is divided into steady inertial and turbulent transitional regimes.

Analysis of the experimental data of the various investigators (Wright (1969), Subramanya and Madhav (1978), Kovacs (1981)) discloses that the behaviour of flow through porous media may be analyzed by classifying the flow regimes into five categories as illustrated in Fig. 2.1. They are (i) Micro seepage, (ii) Darcy regime, (iii) Non linear laminar regime, (iv) Turbulent transitional regime and (v) Fully turbulent regime.

As the thesis is not concerned with micro seepage flow in which velocities are extremely small – of the order of 10⁻⁵ cm/sec – and flow may become non Newtonian, it is not discussed here any more.

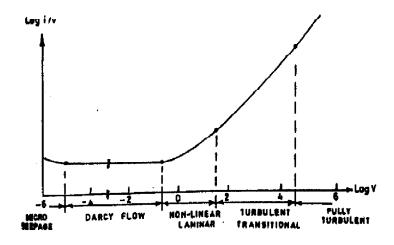


Fig. 2.1 Flow regimes in porous media

In the Darcian zone, flow is represented by Darcy's law. In this zone, micro velocity is stationary and head loss is proportional to velocity of flow. Maximum velocity occurs nearly in the centre of each flow passage. Viscous forces are very large as compared with inertial forces in this regime. Effect of surface forces is not felt.

In non linear laminar regime, although both viscous and inertial forces influence the motion, effect of inertial forces gradually increases and causes the flow to deviate from linear relationship as expressed by Darcy's law. Micro velocity is stationary and flow is still laminar in this regime. Stationary vortices are formed at the upper end of the regime.

In turbulent transitional regime micro velocity fluctuates with a regular frequency and head loss becomes more dependent on square of the velocity. Inertial actions predominate and vortices are shed at regular intervals from individual grains. Turbulence may begin in stages as the velocity of flow is increased.

In fully turbulent regime, flow is turbulent and micro velocity fluctuates randomly about an average value. Head loss is more or less dependent on square of the velocity.

Flow through porous medium is stochastic in nature. It is not possible to predict with any accuracy the limit of a particular regime although the change from one regime to another regime is gradual and not abrupt as observed in the case of flow through straight open channels or flow in pipes. However, Reynolds number has been generally accepted as a parameter to

classify the flow regimes, and Kovacs (1969) and Wright (1968 and 1969) have suggested numerical limits of Reynolds number for various zones, which are given in Table 2.1.

Table 2.1: Limits of Reynolds number for various regimes

Si. No.		Range of Reynolds Number		
	Regime	Wright	Kovacs	
	, , , ,	$R_{o} = \frac{0.6 \text{ V dp}}{v \text{ (1-f)}}$	$R_{\bullet} = \frac{V d_k}{v}$	
1	Darcy regime	1-5	< 10	
2	Non linear laminar	90 – 120	10 – 100	
3	Turbulent transition	800	100 – 1000	
4	Fully turbulent	> 800	> 1000	

where

V = Velocity of flow

d = Volume diameter of the particle

 d_k = Size of the particle as defined by Kovacs and $\frac{d(1-f) \alpha_s}{4f}$

f = Porosity

υ = Kinematic viscosity

α_s = Shape factor of the particle

Proper definitions of the characteristic length and characteristic pore velocity are the primary requirements to analyze seepage flow problems. Further, it requires the consideration of porosity, wall and tortuosity effects on the analysis of the data and hence in developing relationships among different variables.

2.3.2 Characteristic Length Dimension

Size of the pore is an important parameter in the study of seepage flow. However, it cannot be determined directly, since the pore system forms a very complicated surface and geometrically difficult to describe. Therefore, size of the particle has been chosen as the characteristic length parameter in defining seepage flow characteristics. Volume diameter, which is the diameter of a sphere having the same volume, is used to denote the size of the particle. (Scheidegger (1960) and Kovacs (1981)).

Hydraulic radius, defined as the ratio of void ratio (e) to specific surface (S) of pore space is used as characteristic length in the study of seepage flow problems. (Scheidegger (1960) and Kovacs (1981))

In addition to volume diameter and hydraulic radius, square root of intrinsic permeability is also found in the literature. But, as it cannot be determined directly, it is of limited use. (Arbhabirama and Dinoy (1973), Venkataraman and Rama Mohan Rao (2000)).

2.3.3 Porosity Effect

Another important parameter influencing flow phenomenon is the porosity, which depends upon the degree of packing. A certain percentage variation in porosity of the medium brings about a much larger change in resistance to flow than what would be caused by an equal change of percentage in any other parameter. It exercises greatest influence of all the functions on the flow resistance. Porosity is the main parameter linking micro

and macro velocities, pore size and particle size of any particular assemblage of similarly shaped particles.

The basic assumptions in defining a porosity function are:

- no pores are sealed off,
- ii) pores are distributed at random.
- iii) pores are reasonably uniform in size,
- iv) medium is of moderate porosity,
- v) slip phenomenon is absent.

In order to consider the effect of porosity and transform macro values to micro values correction for porosity is required. The correction has two components; namely, (i) the correction to be applied for velocity and (ii) the correction to be applied to the size of the particle. Therefore, porosity enters the governing equation through the *characteristic pore velocity* and *characteristic length*. Hence, complete porosity function will be the product of that part entering via micro velocity and that part entering via pore dimension.

It is seen from past work as quoted by Wright (1968) that the formulae purporting to represent the influence of porosity in the resistance equation are numerous. However, it is observed that, majority of the formulae were proved to be applicable over a limited range of porosity only. There is a large variation of this function with the regime of flow, and some of them lack analytical foundation, and majority of the functions do not reflect the effect of shape of the particles, which also affects the resistance.

Macro velocity is corrected for porosity to obtain micro velocity as

$$V_{v} = \frac{V_{b}}{f} \tag{2.3}$$

and the size of the pore is obtained from size of the particle as

$$d_{por} = \frac{d_p f}{(1-f)} \tag{2.4}$$

where V_v = Micro velocity of flow

V_b = Macro velocity of flow

 d_{por} = Size of the pore

d_p = Size of the particle (volume diameter)

f = Porosity of the medium.

This function gives reliable results for values of porosity between 30% and 70%. Further, Carman (1937) also adopts, a porosity function of the same form as suggested by Rose, which gave consistent results in the range of 0.3 < f < 0.5, which is the common range occurring in the field.

2.3.4 Wall Effect

It is not possible to reproduce identical conditions in the laboratory as those that exist in the field. Permeameters used in laboratory are of different shapes and finite sizes. Results of any experimental study cannot be applied directly to field conditions. They require correction, called wall effect, to take care of influence of the permeameter boundary.

Total surface area of contact near the wall of a permeameter is larger and hence the resistance offered by the container wall to flow is significant. Further, in laminar regime, where energy loss is primarily due to shearing forces, overall resistance may considerably be affected because of presence of a finite boundary.

Flow paths in the immediate vicinity of the wall, where particles are loosely packed, are less tortuous and hence velocities are high. Studies on velocity distribution across a packed bed through which a fluid is flowing disclose that effect of wall on resistance-flow pattern relationship needs to be considered.

Rose and Rizk (1949) plotted the ratio, (resistance of finite bed / resistance of infinite bed) against the parameter (D/d_p), where D is the size of the permeameter and d_p is the size of the particle, along with the data of many other investigators and observed for Reynolds numbers less than 400 the magnitude of wall correction is greater than unity; and for Reynolds numbers greater than 400 the factor is less than unity. Finally, they opined that the effect of wall can be neglected when the ratio of size of the permeameter to the size of the media is greater than 50.

According to Dudgeon (1966 and 1967), the marked dependence of velocity on porosity causes a much higher than average flow rate to occur near the wall. Error in taking mean velocity to represent one dimensional velocity can be estimated from porosity-permeability data and measurements of local porosity in the wall zone, compared with the overall average porosity. Dudgeon estimated the effect experimentally, by measuring flow through inner zone and wall zone separately in a specially designed permeameter and proposed wall correction factors as listed in Table 2.2.

Table 2.2: Wall correction factors (Proposed by Dudgeon)

Regime	Wall correction factors		
Lea Aurita	Estimated	Measured	
Linear regime	1.06	1.10	
Non-linear regime	1.06	1.07	

Nasser (1970) adopted a wall correction factor, proposed by Mc Corquodale and NG (1969 and 1970), which was obtained on the basis of studies conducted by Dudgeon (1967). It is a function of the area of cross section of the permeameter and size of the particle. However, Nasser's work does not indicate as to how the wall effect has to be considered when the flow is radial.

2.3.5 Tortuosity Effect

Tortuosity (τ) is one of the fundamental geometrical properties of the porous medium. It was introduced to account for the fact that the pores are not straight in a real porous medium. Length of the most probable path is longer than the overall length of the porous medium. Tortuosity is defined as the length of the actual flow path of particle divided by the overall (average) path of fluid particle through the porous medium i.e. sinuosity of actual flow path in the porous medium. Hence, tortuosity (τ) takes the value greater than one. Values of $\tau < 1$ are not physically correct.

It is thus, a dimensionless textural constant related to the shape and orientation of the pores. Therefore, tortuosity is a macroscopic measure of both the sinuousness of the flow path and variation of pore size along the flow path. Tortuosity is expressed mathematically as

$$\tau = \frac{I_e}{L} \tag{2.5}$$

where I_e = Actual fluid flow path through porous medium,

L = Average path of fluid particle through porous medium.

According to Carman (1937) hydraulic gradient which is a representative of driving force in the porous medium may be corrected for tortuosity effect as:

$$\left(\frac{\nabla h_r}{L}\right) = \frac{\nabla h_r}{l_n} \times \frac{l_n}{L} \tag{2.6}$$

$$i_{th} = i_{ect} \tau$$
 (2.7)

$$i_{\text{act}} = \frac{i_{\text{th}}}{\tau} \tag{2.8}$$

Comiti and Renaud (1989) proposed an equation for pore velocity based on the presentation of the porous medium by a bundle of identical tortuous pores, as

$$V_{\nu} = \frac{Vb}{f}\tau \tag{2.9}$$

Kopenen et al., (1997) discussed the concept of tortuosity of fluid flow in porous media. A clear correlation between the average tortuosity of the flow paths and the porosity of the substance was established, and the findings were presented in the form of a graph between porosity (ϕ) and tortuosity (τ) .

2.3.6 Governing Equations – General Remarks

Some of the relevant works concerning various forms of equations employed in seepage flow are reviewed in this section. Each approach is better understood when its performance is compared with those of others.

Darcy (1856) was the first to relate superficial velocity and hydraulic gradient by means of an experimentally determined coefficient, called the Darcy Coefficient or Coefficient of permeability, (k) and is given by

$$V_{b} = ki \tag{2.10}$$

Darcy's law is applicable when flow is laminar. Till the beginning of this century, this equation was used irrespective of the flow regime. However, the validity of this equation became questionable for flows with high Reynolds numbers.

it was recognized that there was an upper limit to the validity of this law in terms of velocity. Maximum diameter of the uniform sand in which the laminar flow occurs is found to be around half a millimeter.

Experiments for the determination of Reynolds number at which the Darcy's law is expected to break down have been reviewed by many investigators. It is evident from the review of these investigations, that there is no agreement on the value of Reynolds number, at which Darcy's law would no longer be valid. Todd (1959) and Scheidegger (1960) quote the range as from 1.0 to 10 and 0.1 to 75 respectively. This wide variation in the

range of Reynolds number is due in part to the actual indeterminacy of the effects of size, shape and distribution of particles and porosity effect.

Forchheimer (1901), based on the results of experiments on a sand model for well flow and studying the transient pressure change in porous media by the diffusion equation, based on adding terms of a high order in the equation, was the first to propose an equation covering linear and post-linear ranges in a quadratic form as,

$$i = a_t V + b_t V^2 \tag{2.11}$$

in which \mathbf{a}_t and \mathbf{b}_t are constants determined by properties of the fluid and porous medium and are known as Darcy and non-Darcy parameters. It is obvious from the above equation that $\mathbf{a}_t V$ represents the rate of energy loss in the linear regime and $\mathbf{b}_t V^2$ for fully developed turbulent regime. As mentioned in Scheidegger (1960), equation (2.11) was later refined by Forchheimer himself (1901), by adding a third term to make equation fit experimental data better as

$$i = a_t V + b_t V^2 + c_t V^3$$
 (2.12)

In order to take into account the effect of transitional conditions of seepage flow, the two term Forchheimer equation was modified as (Rose (1951))

$$i = a_1 V + b_1 V^2 + c_1 V^{1.5}$$
 (2.13)

Forchheimer equation has been further generalized to contain a time dependent term after Polubarinova-Kochina (1952), as

$$j = \mathbf{a}_t \mathbf{V} + \mathbf{b}_t \mathbf{V}^2 + \mathbf{c}_t \frac{\mathrm{d} \mathbf{v}}{\mathrm{d} \mathbf{f}}$$
 2.14)

For steady flow conditions, Eq.(2.14) reduces to Eq. (2.11). Further, Eqs. (2.12) and (2.13) seem to be the more representative ones containing linear, turbulent and transitional regimes. However, according to McCorquodale (1969) these equations were 'only slightly' better than the two-term Forchheimer equation. In general, Eq. (2.11) is used in computations because of its simplicity.

Widely used forms of hydraulic gradient-velocity of flow relationships are summarized in Table 2.3.

Nature and factors influencing **a**_f and **b**_f of Forchheimer equation have become the subject of investigation. Ahmed and Sunada (1969) derived expressions for **a**_f and **b**_f from Navier-Stokes equations as

$$a_r = \frac{\mu}{\rho g k_a} \tag{2.15}$$

and

$$b_{i} = \frac{1}{g\sqrt{ck_{o}}}$$
 (2.16)

where

 μ = Dynamic viscosity of the fluid

p = Density of the fluid

 $k_0 = Intrinsic permeability = cd_0^2$

d_p = Size of the particle

c = Media constant

g = Acceleration due to gravity

Table 2.3: Different Forms of Non-Linear Equations

SI. No.	Equation	Proposed by		Remarks	
1.	$i = \mathbf{a_f} \vee + \mathbf{b_f} \vee^2$	Forchheimer	(1901)	Empirical	
2.	$I = \mathbf{a}_f \mathbf{V} + \mathbf{b}_f \mathbf{V}^2 + \mathbf{c}_f \mathbf{V}^3$	Forchheimer	(1901)	Empirical	
3	i = pV ^j	Missbach	(1931)	Empirical	
4	$V_p = c r^{\beta} i^n$	Willkins	(1955)	Sami-empirical	

it was established that \mathbf{a}_f and \mathbf{b}_f are not constants and are dependent on Reynolds number of flow. Curtis and Lawson (1970) expressed doubts on the possibility of obtaining a *single-generalized curve* relating friction factor and Reynolds number presented by Ahmed and Sunada as they neglected turbulent fluctuations in the derivation. It was pointed out that the expressions for \mathbf{a}_f and \mathbf{b}_f are similar to those proposed by Irmay (1959). They suggested the use of an exponential form of equation.

Ranganadha Rao and Suresh (1970) observed that the practical usefulness of the equations proposed by Ahmed and Sunada based on Forchheimer equation is limited, because the intrinsic permeability in the equations cannot be determined directly. They noted that there is a large difference in the values of \mathbf{a}_f and \mathbf{b}_f obtained for media of approximately the same size used by various investigators. They attributed this large difference to neglecting the effects of porosity, shape, orientation of the particle and tortuosity in the equations for \mathbf{a}_f and \mathbf{b}_f .

Commenting on Ahmed and Sunada's study, Todd (1970) opined that ar term involving turbulent characteristics in porous media should have been considered in the expressions for ar and br. Mavis (1971) suggested that Ahmed and Sunada could have stated the limits of applicability of their work and the antecedent conditions on the values of intrinsic permeability.

Another heuristic correlation between i and V is (Scheidegger (1960) and Subramanya and Madav (1978))

$$i = pV^{1.8}$$
 (2.17)

Exponent 1.8 is not well established.

Wide use of an equation of the form,

$$i = pV^i (2.18)$$

is also found in literature. (Scheidegger (1960) and Subramanya and Madhav (1978)). In this equation, p is a coefficient determined by the properties of the medium and the fluid and j is an exponent lying between 1 and 2. j equals 1 for laminar flow and tends to 2 as the flow regime approaches turbulent flow conditions. A glance at the nature of p indicates that this single parameter accounts for the effects of various properties of the medium, namely, size, shape, surface area, tortuosity and porosity and properties of the fluid, that is, density and viscosity. Conclusions from such equations may be misleading or confusing.

Willkins (1955) while investigating the permeability properties of a wide range of gravel and glass spheres, derived the equation of the form:

$$V_{n} = c \mu^{\alpha} r^{\beta} i^{n} \qquad (2.19)$$

where

 V_p = Seepage velocity,

r = Hydraulic mean radius

Void ratio
Surface area per unit volume

 c, α and $\beta = constants$

n = i/j = Constant

 μ = Dynamic viscosity of the fluid

It is obvious that Eq. (2.19) is an improved form of Eq. (2.18) as majority of the media properties are given separate identify in Eq. (2.19).

Parkin (1963) used this form of equation to study the hydraulic and stability problems of inbuilt spillway dams.

2.4 CONCLUDING REMARKS

Various regimes of flow that occur in a seepage flow have been reviewed. The concepts such as characteristic length dimension, characteristic pore velocity the wall effect and tortuosity effect have been discussed along with the past work carried on them. A detailed study on various forms of governing equations including the drawbacks is also presented in this chapter.



CHAPTER - III

Porous Medium and Experimentation



CHAPTER - III

POROUS MEDIUM AND EXPERIMENTATION

3.1 INTRODUCTION

Details of permeameter used, properties of media needed to analyze flow behaviour and procedures adopted in the experimentation are described in this chapter.

In order to achieve the stated objectives, specially conceived permeameter has been fabricated. The details are presented in Sec. 3.3 to 3.5

Steps involved in determining various geometric and hydraulic properties such as porosity, volume diameter of the media, velocity of flow and hydraulic gradient, needed in the analysis of the experimental data, are described in Secs. 3.3 to 3.5.

3.2 PERMEAMETER

Figure 3.1 shows the dimensional details of the permeameter used in the present study and Plates 3.1, 3.2 and 3.3 present different views along with manometer board and flow regulating arrangement of the setup.

It consists of a vertical circular G.I. column of 6200 mm high and 150 mm diameter. A cursory look at the works carried out by the earlier investigators reveals that for computing hydraulic gradient a single length of travel with one set of head loss readings from two manometers, one at the

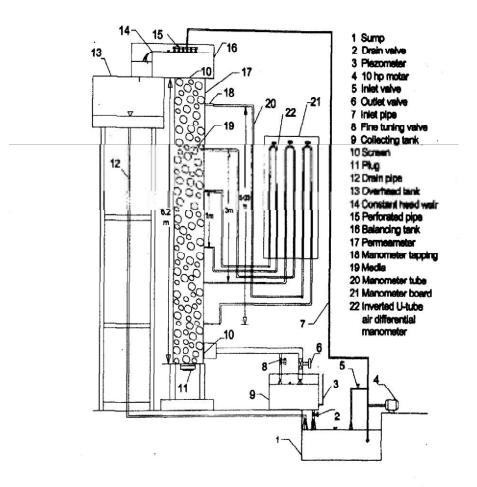


Fig. 3.1 Experimental setup (Permeameter)

beginning and the other at the end of test section, was used. In the present study three different lengths of travel (1000 mm, 3007 mm, 5032 mm), with three sets of plezometric tapping points, enabling to compute three numbers of hydraulic gradient are used. This is done to avoid error due to non-uniformity in packing, if any, of the porous medium. The details of computation are presented in later sections. Proper care is exercised to file away all the burns and projections at the tapping points. The short copper tubes attached to these holes are connected to a manometer board by polythene tubes as shown in Plate 3.2. The manometric heads are measured to an accuracy of \pm 0.25 mm.

The fluid medium used in these experiments is water, which is supplied from an over head tank to the header tank of size 2 m x 0.5 m x 0.6 m located at the entrance to the permeameter. A perforated horizontal pipe is fixed at the end of the delivery pipe to ensure that water is filled into the tank without any turbulence and does not fall in the form of a thick jet at one point near the inlet of the permeameter. Further, a 3.5 mm thick aluminum screen with 85% perforations placed at the entry of permeameter facilitated relatively turbulent-free entry of water into the permeameter. A similar screen at the exit end of permeameter allowed the retention of media in the permeameter. The water level is maintained constant in the header tank during each run.

Two valves of 75 mm diameter are fitted at the supply point and discharge end of the permeameter to regulate the flow through the

permeameter. Further, at the discharge end, a bye pass valve is provided to facilitate fine regulation of flow and to maintain steady conditions. Discharge was determined by volumetric method.

Before taking the piezometric readings, it is ensured that all the entrapped air is removed as follows:

- The material is saturated with water by increasing progressively the water level in the porous media with a very low flow rate.
- Water is, then, circulated at its maximum flow rate for several hours to flush potential air bubbles from the system.
- Piezometers are also flushed thoroughly.
- Experiments are then conducted only if the pressure homogeneity in the bed is verified.
- Repeated measurements with both low and high rates of flow are carried out. When, at a given flow rate, measurements are proved to be constant, the system is considered as correctly de-aired and the actual test is begun.

As the water level in the piezometer fluctuates, three pairs of maximum and minimum readings are taken and average of these readings is taken as the piezometric head loss. During every run, temperature of the outflow is noted at regular intervals, from which viscosity is determined.

3.3 DETERMINATION OF MEDIA PARAMETERS

A porous medium is characterized by a variety of properties like size or diameter and porosity. Experimental procedures to determine these properties are explained herein. Gravel, river sand and glass spheres are selected as the media for the investigation.

The material is sieved through sieves of different sizes to separate the gravel into sizes of 1.4 mm, 2.15 mm, 3.8 mm, 5.8 mm, 7.8 mm, 9 mm, 12.3 mm, 14.6 mm, 17.5 mm and 20.0 mm, river sand into sizes of 1.7 mm, 2.4 mm, 3.3 mm, 4.2 mm, 6.7 mm, and glass spheres of 16. 7 mm, 20 mm, 35mm.

3.3.1 Size of the Particle

In the case of regular shaped particles, like spheres, diameter is used as size of the particle in computations. This is determined to an accuracy of 0.01 mm using a caliper. For every size, around 200 glass spheres are selected and diameter of each particle is determined by the calipers. To avoid the error in handling, the glass spheres are kept on a plane surface, without rolling, and the size is noted. Then average of these readings yields the size of that particle.

Similar steps are repeated for all the three sizes of glass spheres. A deviation of 3% to 16% was observed from the dimensions specified by the manufacturer of the glass spheres.

Crux of the analysis of data lies in a proper definition of characteristic size of an irregular shaped particle. In the present analysis volume diameter is used since majority of the investigators in the past have used only this definition. This would facilitate comparison of the results with those of others.

Volume diameter of a non-spherical particle is determined by following the procedure described below:

A sample of 400 to 500 particles is chosen at random from each material size. Such a large sample will reduce the error in determining the size of the particle. Each particle is drowned in the graduated cylinder containing predetermined volume of water. The difference in water levels before and after drowning indicates the volume of the particle. Sometimes, a bunch of 10, 15 or 50 particles are drowned at the same time, care being taken to see that no water splashes and the volume of all the particles is noted from which the volume of a single particle is deduced. All these steps are repeated for all sizes of the media.

Volume diameter, which is defined as the equivalent diameter of a sphere having same volume, was then computed for each particle. For the case of bunch of particles, volume diameter is

$$d = 3 \sqrt{\frac{6 \times \text{Volume of bunch of particles}}{N}}$$
 (3.1)

where

N = Number of particles

Mean of the above values is taken as volume diameter of the medium, which in turn is considered as 'size' of the medium.

3.3.2 Porosity

Dry porosity, which here afterwards is referred to as porosity, is determined as described below:

Permeameter is cleaned, dried and then filled with the medium of known size up to the top. Outlet valves are closed and the permeameter is slowly filled until water level reaches the lowest piezometer. A measured quantity of water is then poured till water reaches top piezometer. This measured volume of water indicates the volume of voids between top and bottom piezometers. From geometry, volume of the permeameter enclosed between these two plezometers is computed. Porosity is then computed as,

Similar steps are repeated for all sizes of the media before starting the experiment. Details of media properties are presented in Table 3.1.

3.4 EXPERIMENTAL PROCEDURE

Experimental procedure and the details of measurements taken are explained in the following paragraphs.

Permeameter is filled with the medium, under gravity, ensuring even packing by varying height of fall uniformly. Water is then allowed to flow through the permeameter under a constant head for a period of 1 to 1.5 hours at maximum possible rate so that all the particles are reoriented and

Table 3.1 Characteristics of Media Used in the Study

SI. No.	Description of the media	Volume Diameter (mm)	Porosity (%)
1	Gravel	1.4	48.0
2	Gravei	2.15	58.5
3	Gravel	3.8	30.0
- 4	Gravel	5.8	49.0
5	Graval	7.8	51.0
6	Gravel	9.0	46.0
7	Graval	12.3	46.5
8	Gravel	14.6	44.0
9	Gravel	17,5	42.0
10	Gravel	20.0	43.0

no further reorientation takes place during experimentation. It is then dealred as described earlier. Once the flow attains steady state conditions, discharge and the corresponding head loss readings are noted in both the configurations. Temperature of the outflow is recorded for every run. Data obtained from tests are presented in Appendix-A. (Tables -A1 to A18).

3.5 DETERMINATION OF HYDRAULIC PARAMETERS

3.5.1 Velocity of Flow

Velocity of flow is the basic dynamic dependent variable which controls the entire analysis. Bulk velocity of flow V_b is obtained as

$$V_b = \frac{Q}{A} \tag{3.3}$$

where Q is the rate of flow and A is the area of cross section of the permeameter. Then, pore velocity $V_{\mathfrak{p}}$ is obtained as

$$V_p = \frac{V}{f} \tag{3.4}$$

3.5.2 Hydraulic Gradient

Hydraulic gradient is obtained simply by dividing the difference in piezometric heads between any two points with the length of travel between them; that is,

$$i = \frac{h_i}{L} \tag{3.5}$$

where

h_f = Difference in piezometric heads between any two points

L = Length of travel between them.

Values of i for three sets of piezometers are determined from piezometric readings and corresponding lengths of travel. Average of these values is considered in the analysis of data.

3.6 Concluding Remarks

The construction details of permeameter—used in the present study and different steps involved in determining various physical properties of the media used are described in this chapter. It also enunciates the procedures adopted in computing velocity of flow and the hydraulic gradient for further use in the analysis of experimental data.



CHAPTER - IV Analysis of Experimental Data

CHAPTER - IV

ANALYSIS OF EXPERIMENTAL DATA

4.1 INTRODUCTION

This chapter presents the analysis of experimental data obtained from the present study and those of others, keeping in view the stated objectives.

4.2 ASCERTAINING THE RELIABILITY OF TREND OF PRESENT EXPERIMENTAL INVESTIGATION

It may be noted that in order to make use of the findings of any experimental investigation, it is first of all necessary to ascertain the reliability of trend of the investigation under consideration by comparing it with that of the past, if any.

Right from 1856, when Darcy showed that the treatment of seepage flow concepts is no more abstract, it can be tackled through experiments also, a lot of experimental investigations have been added to the 'past work' on seepage flow.

Darcy initiated experimentation on seepage flow with 2 sets of media. The first set consisted of four sizes of Soan river sand (both unwashed and washed type ranging from 0.58-0.77 mm, 0.13-1.0 mm, 1 mm and 0.12-2.0 mm packed to 38% porosity) and the second set is of 0.17 mm of gravel packed to 38% porosity. The discharge during experimentation ranged from 2.13 to 29.4 lpm creating a corresponding range of head loss of 1.11 to

13.93 m. A graph was then plotted with velocity of flow (m/s) as ordinate and hydraulic gradient as abscissa. While the 'velocity of flow' (V_b) represents the energy possessed by a moving fluid, 'hydraulic gradient' (i) indicates the rate of energy lost by the fluid to overcome resistance to flow. The V_b-1 experimental data points corresponding to four sizes of Sona river sand, represented by series1, series2, series3 and series4 are shown in Fig.4.1. (Reproduced from Darcy's original work). Also shown are the experimental data points corresponding to Set 2 in the same figure. It may be observed from Fig.4.1 that in the range of experiments conducted,

- (i) V_b and 'i' bear a definite linear relation depicted by a straight line with a positive slope,
- (ii) the relationship for different sizes are:

$$V_b = 2.85E - 4 i$$
 (Series 1) (4.1)

$$V_b = 1.66 E - 4 i \text{ (Series 2)}$$
 (4.2)

$$V_b = 2.15 E-4 i$$
 (Series 3) (4.3)

$$V_b = 2.15 E-4 i$$
 (Series 4) (4.4)

$$V_b = 2.71 E-4 i$$
 (Set 2) (4.5)

All the above five equations are compared with standard form of Darcy's equation i.e.

$$V_b = k i ag{4.6}$$

where k is the coefficient of permeability, a parameter which represents the ability of the soil matrix to conduct a fluid flow through it. In short, 'k' represents the ease with which a fluid can flow through a soil.

In the present study, as stated earlier, the velocity of flow, hydraulic gradient and sizes of the media used varied over a very wide range. As the scope of the present section of this chapter is to ascertain the reliability of the trend of present experimentation, those experimental data points falling in the range pertaining to that of Fig.4.1 were segregated and a similar graphical analysis was made.

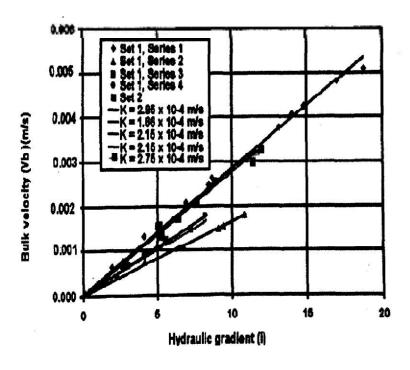


Fig. 4.1 Variation of hydraulic gradient with bulk velocity (Darcy's graph reproduced)

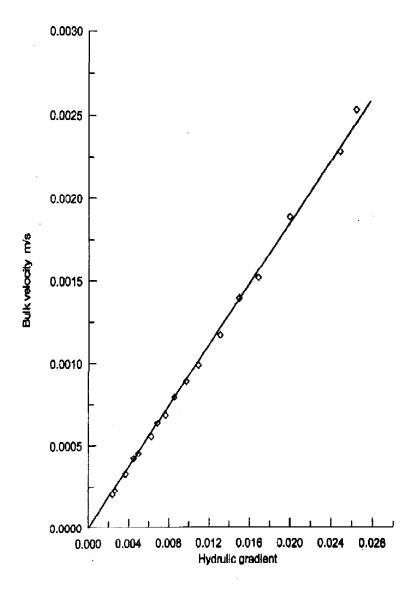


Fig. 4.2 Variation of hydraulic gradient with bulk velocity for 1.4 mm size of gravel

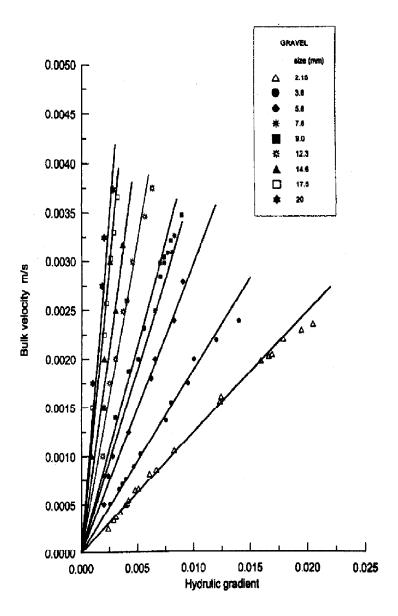


Fig. 4.3 Variation of hydraulic gradient with bulk velocity for remaining nine sizes of gravel

It was already mentioned that 10 sizes of gravel were used in the present study. In order to be lucid and to avoid possible confusion, the experimental data points (i- V_b) corresponding to any one size of gravel were alone shown separately. This will enable a clear comparison of the trends of present study with that represented in Fig. 4.1.

Figure 4.2 shows the variation of 'i' with V_b for the data pertaining to 1.4 mm gravel packed to 48% porosity. It is obvious that all the points are found to align along a straight line with a positive slope. On regression analysis the equation obtained is as:

$$V_b = 0.093 i$$
 (1.4 mm) (4.7)

Experimental data points (i and V_b) of the remaining nine sizes of gravel i.e 2.15 mm, 3.8 mm, 5.8 mm, 7.8 mm, 9.0 mm,12.3 mm, 14.6 mm, 17.5 mm and 20.0 mm gravel are depicted in Fig.4.3. They are also found to lie along different straight lines with different positive slopes. Accordingly, the relationships are expressed as:

$V_b = 0.125 i$	(2.15 mm)	(4.8)
V _b = 0.19 i	(3.8 mm)	(4.9)
$V_b = 0.28 i$	(5.8 mm)	(4.10)
$V_b = 0.381$	(7.8 mm)	(4.11)
V _b = 0.43 i	(9.0 mm)	(4.12)
V _b = 0.65 i	(12.3 mm)	(4.13)
V _b = 0.85 i	(14.6 mm)	(4.14)
$V_b = 1.20 i$ (17.5 mm)		(4.15)
V _b = 1.40 i	(20.0 mm)	(4.16)

- (i) Similar trends are observed in all the cases,
- (ii) Linear relationship between V_b and 'i' is found to be valid.
- (iii) Coefficients appearing in the equations are in conformity with the earlier findings. That is, as the size of media increases there is an obvious increase in the fluid conveying capacity (hydraulic conductivity) of media.

Finally, as the trends of variation of 'i' with V_b for the data used in present study agree well with that of Darcy's data, the reliability of experimentation is ascertained.

CONCLUDING REMARKS

The trend of present of experimental investigation is established by comparing with Darcy's work. The relationship between and i/Vb & Vb is analyzed and it is established that at lower velocity of Row, the relationship between i/V_b and Vb is depicted by a line with a negative slope. It is not a single straight line with a positive slope.



CHAPTER - V Analysis of Experimental Data After Applying Corrections

CHAPTER - V

ANALYSIS OF EXPERIMENTAL DATA AFTER APPLYING CORRECTIONS

5.1 INTRODUCTION

This chapter presents the analysis of experimental data obtained from the present study and those of others after taking due care for corrections for porosity effect, wall effect and tortuosity effect.

5.2 ORRECTIONS FOR POROSITY, WALL AND TORTUOSITY EFFECTS

It is observed that a certain percentage variation in porosity of the medium brings about a much larger change in resistance to flow than what would be caused by an equal change of percentage in any other parameter. It exercises greatest influence of all the functions on the flow resistance. Porosity is the main parameter linking bulk and pore velocities, pore size and particle size of any particular assemblage of similarly shaped particles. In order to consider the effect of porosity and transform macro values to micro values correction for porosity is required. The correction has two components; namely, (i) the correction to be applied for velocity and (ii) the correction to be applied to the size of the particle. Therefore, porosity enters the governing equation through the characteristic pore velocity and characteristic length. Hence, complete porosity function will be the product of that part entering via pore velocity and that part entering via pore dimension.

Correction for porosity accounts for pore velocity of flow and size of the pore, which is the actual flow channel of the media. Velocity of flow corrected for porosity, pore velocity, $V_{\rm p}$, is obtained from the bulk velocity as

$$V_{p} = \frac{V_{p}}{f} \tag{5.1}$$

and size of the pore is obtained from size of the particle as

$$d_{por} = \frac{d_p f}{(1-f)} \tag{5.2}$$

It is not possible to reproduce identical conditions in the laboratory as those that exist in the field. Permeameters used in laboratory are of different shapes and finite sizes. Results of any experimental study cannot be applied directly to field conditions. They require correction, called wall effect, to take care of influence of the permeameter boundary. Flow paths in the immediate vicinity of the wall, where particles are loosely packed, are less tortuous and hence velocities are high. Studies on velocity distribution across a packed bed through which a fluid is flowing discloses that effect of wall on resistance-flow pattern relationship needs to be considered. Correction factor for wall effect is computed using equation proposed by Dudgeon (1967) as

$$C_{w} = \left[\frac{(D+4.83t)}{D^{2}} \right]^{-1}$$
 (5.3)

As stated in section 2.3.5, Tortuosity (τ) is one of the fundamental geometrical properties of the porous medium. It was introduced to account for the fact that the pores are not straight in a real porous medium. Length of

the most probable path is longer than the overall length of the porous medium. Tortuosity is defined as the length of the actual flow path of particle divided by the overall (average) path of fluid particle through the porous medium i.e sinuosity of actual flow path in the porous medium. Hence, tortuosity (τ) takes the value greater than one. Values of $\tau < 1$ are not physically correct. It is thus, a dimensionless textural constant related to the shape and orientation of the pores. Therefore, tortuosity is a macroscopic measure of both the sinuosness of the flow path and variation of pore size along the flow path.

Correction factor for tortuosity effect is determined from the results of study of Kopenon et al (1997). For the known porosity of the medium, corresponding tortuosity correction factor is obtained and then applied to both velocity of flow and hydraulic gradient as:

(i) Velocity corrected for tortuosity:

$$V_{tc} = V_b \tau \tag{5.4}$$

where

 $\tau = tortuosity$

(ii) Hydraulic gradient corrected for tortuosity

$$t_{c} = \frac{i}{\tau} \tag{5.5}$$

Finally, velocity of flow is corrected for porosity, wall and tortuosity effects as

$$V_{c} = (V_{b}/f) C_{w} \tau \tag{5.6}$$

Using Eqs. 5.5 and 5.6 corrected values of hydraulic gradient (i_c) and velocity of flow (V_c) are obtained.

A graph, plotted as shown in Fig.5.1, depicts the relationship between i_c / V_c and V_c for the gravel of size 1.4 mm. This is similar to Fig. 4.14 pertaining to same size of gravel, with I / V_b and V_b values not subjected any correction. It may be observed that, except a relative shift in magnitudes of i_c / V_c for different values of V_c , there is a striking similarity in the trends depicting the relationship between i_0/V_c and V_c as shown in Fig.5.1 and that represented in Fig.4.14. Similarly, Fig. 5.2 shows the variation of i_o/V_c with V_c pertaining to remaining nine sizes of gravel, i.e., 2.15 mm, 3.8 mm, 5.8 mm, 7.8 mm, 9 mm, 12.3 mm, 14.6 mm, 17.5 mm and 20 mm packed to

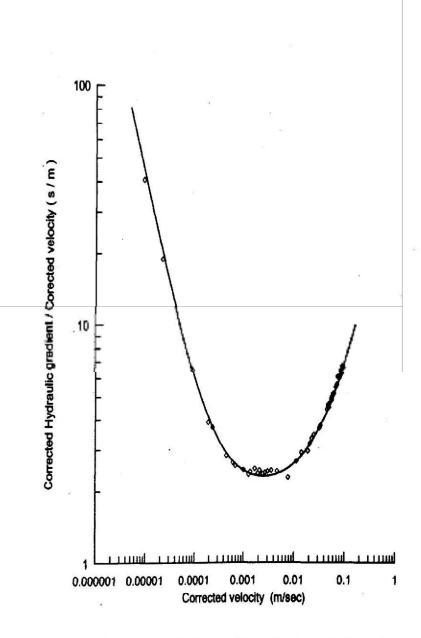


Fig. 5.1 Variation of corrected hydraulic gradient / corrected velocity with corrected velocity for 1.4 mm gravel

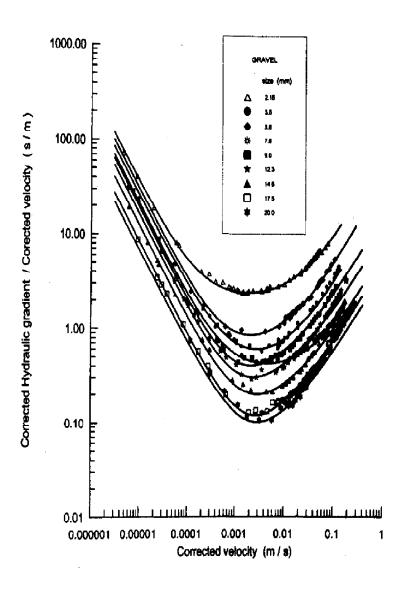


Fig. 5.2 Variation of corrected hydraulic gradient / corrected velocity with corrected velocity for remaining nine sizes of gravel

On comparison of corresponding figures, that is, comparing Fig.5.1 with Fig.4.14. Fig.5.2 with Fig.4.15, Fig.5.3 with Fig.4.16, Fig.5.4 with Fig.4.17 and Fig.5.5 with Fig.4.18 respectively, it may be observed that even after application of corrections for porosity, wall and tortuosity effects:

- ➤ That the trend line depicting the variation of ic/V_c with Vc is not a single rising line with only positive slope and a simple extrapolation of straight lines joining i/V_c and V_c in the reverse direction for complete range of velocity of flow to calculate Darcy and non-Darcy parameters is no more correct.
- ➤ At lower velocity of flow, the line segment representing variation of ic/V_c with V_c has a negative slope. Equations relating Darcy parameter and non-Darcy parameter with size of the medium without specifying the limits of velocity are no more reliable.

Like earlier observation, in this case also it can be concluded that the equations representing the relationship between Darcy and non-Darcy parameter with the size of the medium are of limited use. Therefore, it is necessary to analyze the relationship between i_c and V_c in a systematic manner giving due weightage to the nature of variation of i_c / V_c with V_c considering wall, porosity and tortuosity effects, to make the findings more realistic.

Figure 5.7 shows the variation of i_c with V_c for the remaining nine sizes ie. 2.15 mm, 3.8 mm, 5.8 mm, 7.8 mm, 9 mm, 12.3 mm, 14.6 mm, 17.5 mm and 20.0 mm of gravel. On similar lines, the $(i_c - V_c)$ data pertaining to 1.7 mm river sand packed to 34% shown in Fig.5.8. The Fig. 5.9 depicts the variation of i_c with V_c for the remaining four sizes of river sand of 2.4 mm, 3.3 mm, 4.2 mm and 6.7 mm, packed to 36.9%, 35.6% and 34%. The $(i_c - V_c)$ data for all the three sizes of glass spheres of 16.7 mm, 20.0 mm and 35 mm packed with 59%, 56%, and 54% are plotted as shown in Fig. 5.10.

For any sample, irrespective of size and shape, even after taking into account the effects of porosity, wall and tortuosity,

- > it is seen that i_c, which is a measure of energy loss in the medium, increases as velocity of flow is increased, which is in agreement with earlier findings.
- it may also be noted from all the figures, that there is a systematic and regular orientation of i_c Vs V_c lines of different sizes. While the i_c -V_c line of small size medium is found to have a steeper slope and higher i_c value, that of large size medium has a flatter slope and smaller i_c values for given flow rate of flow. This infers the rate of increase of total resistance is higher for small size samples as compared with that of large size.

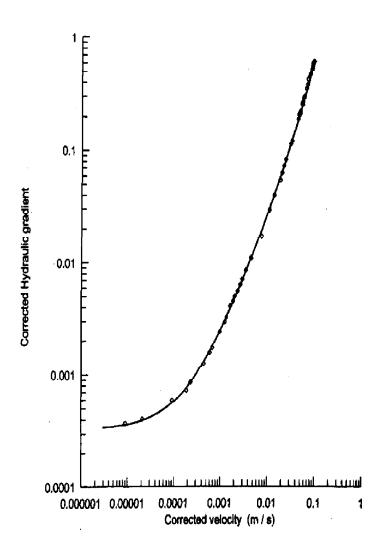


Fig. 5.6 Variation of corrected hydraulic gradient with corrected velocity for 1.4 mm gravel

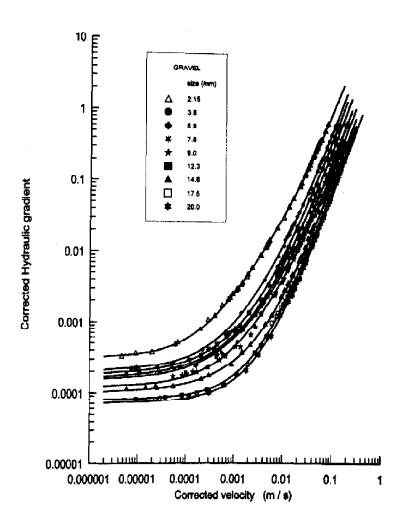
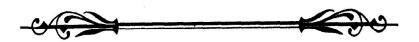


Fig. 5.7 Variation of corrected hydraulic gradient with corrected velocity for remaining nine sizes of gravel



APPENDIX - B

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