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 CORRECTIONS 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, \( V_p \), is obtained from the bulk velocity as

\[
V_p = \frac{V}{f} \quad (5.1)
\]

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

\[
d_{\text{por}} = \frac{d_p f}{(1 - f)} \quad (5.2)
\]

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

\[
C_w = \left[ \frac{(D + 4.83\delta)}{D^2} \right]^{-1} \quad (5.3)
\]

As stated in section 2.3.5, Tortuosity (\( \tau \)) 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 ($\tau$) 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:

$$V_{tc} = V_b \tau \quad (5.4)$$

where

$$\tau = \text{tortuosity}$$

(ii) Hydraulic gradient corrected for tortuosity

$$t_c = \frac{i}{\tau} \quad (5.5)$$

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

$$V_c = (V_0 f ) C_w \tau \quad (5.6)$$
Using Eqs. 5.5 and 5.6 corrected values of hydraulic gradient ($l_c$) and velocity of flow ($V_c$) are obtained.

A graph, plotted as shown in Fig.5.1, depicts the relationship between $l_c / V_c$ 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 $l / V_b$ and $V_b$ values not subjected any correction. It may be observed that, except a relative shift in magnitudes of $l_c / V_c$ for different values of $V_c$, there is a striking similarity in the trends depicting the relationship between $l/V_c$ and $V_c$ as shown in Fig.5.1 and that represented in Fig.4.14. Similarly, Fig. 5.2 shows the variation of $l/V_c$ 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 58.5%, 30%, 49%, 51%, 46%, 46.5%, 44%, 42% and 43% respectively. The corresponding figure representing variation of $l/V_b$ with $V_b$ (without corrections) is Fig.4.15. The same inference can be drawn on comparison of Figs. 5.2 and 4.15 with each other. On similar lines, the graphs with corrected values of hydraulic gradient and velocity of flow for 1.7 mm river sand and other four sizes of river sand i.e., 2.4 mm, 3.3 mm, 4.2 mm, and 6.7 mm are presented in Figs. 5.3 and 5.4 respectively. The corresponding figures before application of corrections are Figs 4.16 and 4.17. Figure 5.5 pertains to the trend of variation between $l_c/V_c$ and $V_c$ for three sizes of glass spheres. However, the corresponding figure in the earlier phase of analysis is Fig.4.18 for the three sizes of glass spheres.
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
Fig. 5.3 Variation of corrected hydraulic gradient / corrected velocity with corrected velocity for 1.7 mm river sand
Fig. 5.4 Variation of corrected hydraulic gradient / corrected velocity with corrected velocity for remaining four sizes of river sand.
Fig. 5.5 Variation of corrected hydraulic gradient / corrected velocity with corrected velocity for three sizes glass sphere
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 $Ic/Vc$ with $Vc$ is not a single rising line with only positive slope and a simple extrapolation of straight lines joining $Ic/Vc$ and $Vc$ 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 $Ic/Vc$ with $Vc$ 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 $Ic$ and $Vc$ in a systematic manner giving due weightage to the nature of variation of $Ic/Vc$ with $Vc$ considering wall, porosity and tortuosity effects, to make the findings more realistic.
5.3 REANALYSIS OF 'NEW APPROACH' RELATING HYDRAULIC GRADIENT - VELOCITY RELATIONSHIP AFTER APPLYING CORRECTIONS

It may be recollected from Second Chapter that literature on porous media flow containing corrections for porosity, wall and tortuosity effects is very scant and rare and also is found to suffer from the drawbacks such as:

- Different forms of expressions were used to account for these effects and the results of research were expressed in various methods.
- Majority of the approaches are found to lack describing complete range of seepage flow. That is, the range of experimentation by an individual investigator is very limited.
- Hence, little agreement among the results of different researchers even after applying correction and hence equations thus obtained are of limited use.

In this section the details of reanalysis of 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 is presented.

For the complete range of experimentation, the values of $i_c$ and $V_c$ pertaining to 1.4 mm size gravel are plotted as shown in Fig.5.6. While the values of $V_c$ varied from 0.000009 m/s to 0.15 m/s, the corresponding $i_c$ values varied from 0.00037 to 0.79. It may be observed that, except a relative shift in magnitudes of $i_c$ for different values of $V_c$, there is a striking
similarity in the trends depicting the relationship between $i_c$ and $V_c$ as shown in Fig. 5.6 and with that of as depicted in Fig. 4.20. In this case also, it may be found that all the points align along a single line with a relatively flatter slope at lower velocities, with a gradual increase in steepness with the increase in velocity. This is also in accordance with the well established experiments on pipe flow by Froude and Hazen and Poiseuille.

For this case also, i.e., after applying corrections for porosity, wall and tortuosity effects, from the mathematical analysis it was determined that a four-term polynomial covering pre-Darcian, Darcian, post-Darcian and Forchheimer range is found to express the relationship between $i_c$ and $V_c$ in the fittest way.

The equation proposed is

$$i_c = a_c V_c^{0.5} + b_c V_c^1 + c_c V_c^{1.5} + d_c V_c^2$$

where

- $i_c = \text{corrected hydraulic gradient}$
- $V_c = \text{corrected velocity of flow}$
- $a_c = \text{corrected Pre-Darcian coefficient}$
- $b_c = \text{corrected Darcian coefficient}$
- $c_c = \text{corrected Post-Darcian coefficient}$
- $d_c = \text{corrected Forchheimer coefficient}$
Figure 5.7 shows the variation of $i_c$ with $V_c$ for the remaining nine sizes 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 20.0 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
Fig. 5.8 Variation of corrected hydraulic gradient with corrected velocity for 1.7 mm river sand
Fig. 5.9 Variation of corrected hydraulic gradient with corrected velocity for remaining four sizes of river sand
Fig. 5.10 Variation of corrected hydraulic gradient with corrected velocity for three sizes glass sphere
As explained earlier even after applying corrections for flows at low velocities, position of point of separation is fixed and is located usually far downstream on the surface of the material of the media. The wake formed is small and stable. Size of the wake increases as the velocities increases, due to increased inertial effects. As a result, resistance offered to flow is quite large at higher velocities.

The point of separation is not fixed in the case of rounded bodies and depends upon the flow regime and the size of the wake. In the case of coarse granular media, the wake developed on the downstream side of the particles is very wide and pressure on the downstream side is lesser than that on the upstream side, resulting in a large pressure drag along with a considerable amount of skin drag.

Finally, the equations relating \( i_c \) and \( V_c \) for different media are:

1. For gravel:

\[
i_c = 0.012 V_c^{0.5} + 0.9 V_c + 6 V_c^{1.5} + 50 V_c^6 \]  
\[ (1.4 \text{ mm}) \quad (5.8) \]

\[
i_c = 0.01 V_c^{0.5} + 0.8 V_c + 5 V_c^{1.5} + 43 V_c^5 \]  
\[ (2.15 \text{ mm}) \quad (5.9) \]

\[
i_c = 0.008 V_c^{0.5} + 0.6 V_c + 4 V_c^{1.5} + 38 V_c^4 \]  
\[ (3.8 \text{ mm}) \quad (5.10) \]

\[
i_c = 0.008 V_c^{0.5} + 0.4 V_c + 3 V_c^{1.5} + 30 V_c^3 \]  
\[ (5.8 \text{ mm}) \quad (5.11) \]

\[
i_c = 0.005 V_c^{0.5} + 0.28 V_c + 2 V_c^{1.5} + 22 V_c^2 \]  
\[ (7.8 \text{ mm}) \quad (5.12) \]

\[
i_c = 0.004 V_c^{0.5} + 0.28 V_c + 1.5 V_c^{1.5} + 20 V_c^2 \]  
\[ (9.0 \text{ mm}) \quad (5.13) \]

\[
i_c = 0.003 V_c^{0.5} + 0.14 V_c + 0.065 V_c^{1.5} + V_c^2 \]  
\[ (12.3 \text{ mm}) \quad (5.14) \]
\[ i_c = 0.002 V_e^{0.5} + 0.07 V_c + 0.5 V_c^{1.5} + 7.5 V_c^2 \] (14.6 mm) \hfill (5.15)

\[ i_c = 0.0015 V_e^{0.5} + 0.05 V_c + 0.4 V_c^{1.5} + 0.4 V_c^2 \] (17.5 mm) \hfill (5.16)

\[ i_c = 0.0008 V_e^{0.5} + 0.04 V_c + 0.3 V_c^{1.5} + 5 V_c^2 \] (20.0 mm) \hfill (5.17)

ii For river sand:

\[ i_c = 0.0055 V_e^{0.5} + 1 V_c + 4 V_c^{1.5} + 13 V_c^2 \] (1.7 mm) \hfill (5.18)

\[ i_c = 0.004 V_e^{0.5} + 0.8 V_c + 3 V_c^{1.5} + 10 V_c^2 \] (2.4 mm) \hfill (5.19)

\[ i_c = 0.002 V_e^{0.5} + 0.6 V_c + 2 V_c^{1.5} + 8 V_c^2 \] (3.3 mm) \hfill (5.20)

\[ i_c = 0.0012 V_e^{0.5} + 0.5 V_c + 1.5 V_c^{1.5} + 6.5 V_c^2 \] (4.2 mm) \hfill (5.21)

\[ i_c = 0.0005 V_e^{0.5} + 0.3 V_c + 0.7 V_c^{1.5} + 4 V_c^2 \] (6.7 mm) \hfill (5.22)

iii For Glass spheres:

\[ i_c = 0.30012 V_e^{0.5} + 0.04 V_c + 1.2 V_c^{1.5} + 10 V_c^2 \] (16.7 mm) \hfill (5.23)

\[ i_c = 0.0001 V_e^{0.5} + 0.02 V_c + 1 V_c^{1.5} + 7 V_c^2 \] (20.0 mm) \hfill (5.24)

\[ i_c = 0.00005 V_e^{0.5} + 0.0019 V_c + 0.32 V_c^{1.5} + 2.5 V_c^2 \] (35.0 mm) \hfill (5.25)

Using these equations, for a known size of media used in the present study, for a known rate of flow corresponding resistance to flow can be determined. In this case also, it immediately strikes to mind that this work up to this stage suffers from a serious limitation on the range of its applicability.

As is done in Chapter 4, a glance at the equations 5.8 to 5.17 pertaining to gravel, or Eqs. 5.18 to 5.22 pertaining to river sand or Eqs. 5.23 to 5.25 for glass spheres infer that there is a definite relationship between
the coefficients appearing in equations and the corresponding sizes of media.

For example, consider the ten sizes of gravel media used in the present study along with their coefficients.

The sizes of gravel media used are 1.4 mm, 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. The corresponding pre-Darcian coefficients are 0.012, 0.01, 0.008, 0.006, 0.005, 0.004, 0.003, 0.002, 0.0015, and 0.0008. It may be observed that as the size of the media increases, values of the coefficients decrease. That is, as size of the media increases, these coefficients are found to decrease.

Similarly, comparing the ten sizes of gravel with the corresponding values of Darcian coefficients, the same inference can be drawn.

Similar is the case with the post Darcian and Forchheimer coefficients when compared with the corresponding sizes of gravel.

A glance at the values of the four coefficients along with the corresponding sizes for the case of river sand and glass spheres also indicate the similar trend of relationship among them.

Table 5.1 lists the corrected values of the pre-Darcy, Darcy, post-Darcy and Forchheimer coefficients along with size of the media used in the present study.

122
Table 5.1 Corrected Values of Pre-Darcy, Darcy, Post-Darcy, and Forchheimer coefficients of media used in the present study

<table>
<thead>
<tr>
<th>Size</th>
<th>$a_c$</th>
<th>$b_c$</th>
<th>$c_c$</th>
<th>$d_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0014</td>
<td>0.012</td>
<td>0.9</td>
<td>6</td>
<td>50</td>
</tr>
<tr>
<td>0.00215</td>
<td>0.01</td>
<td>0.8</td>
<td>5</td>
<td>43</td>
</tr>
<tr>
<td>0.0038</td>
<td>0.008</td>
<td>0.6</td>
<td>4</td>
<td>38</td>
</tr>
<tr>
<td>0.0058</td>
<td>0.006</td>
<td>0.4</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>0.0078</td>
<td>0.005</td>
<td>0.28</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>0.009</td>
<td>0.004</td>
<td>0.26</td>
<td>1.5</td>
<td>20</td>
</tr>
<tr>
<td>0.0123</td>
<td>0.003</td>
<td>0.14</td>
<td>0.65</td>
<td>14</td>
</tr>
<tr>
<td>0.0146</td>
<td>0.002</td>
<td>0.07</td>
<td>0.5</td>
<td>7.5</td>
</tr>
<tr>
<td>0.0175</td>
<td>0.0015</td>
<td>0.05</td>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>0.02</td>
<td>0.0008</td>
<td>0.04</td>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>River Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0017</td>
<td>0.0055</td>
<td>1</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>0.0024</td>
<td>0.004</td>
<td>0.8</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>0.0023</td>
<td>0.002</td>
<td>0.6</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>0.0042</td>
<td>0.0012</td>
<td>0.5</td>
<td>1.5</td>
<td>605</td>
</tr>
<tr>
<td>0.0067</td>
<td>0.0005</td>
<td>0.3</td>
<td>0.3</td>
<td>4</td>
</tr>
<tr>
<td>Glass sphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0167</td>
<td>0.00012</td>
<td>0.04</td>
<td>1.2</td>
<td>10</td>
</tr>
<tr>
<td>0.02</td>
<td>0.0001</td>
<td>0.02</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>0.035</td>
<td>0.000051</td>
<td>0.0019</td>
<td>0.32</td>
<td>2.5</td>
</tr>
</tbody>
</table>
In the range of experiments conducted, the value of pre-Darcy coefficient \( a_c \) for gravel varies from 0.0008 to 0.012 (s/m)\(^{0.5} \), for river sand it is from 0.0005 to 0.0055 (s/m)\(^{0.5} \) and for glass spheres it varies from 0.000051 to 0.00012 (s/m)\(^{0.5} \). The Darcy coefficient \( b_c \) for gravel lies between 0.04 and 0.9 (s/m) and that of river sand falls between 0.3 and 1 and for glass spheres it is between 0.000051 to 0.00012 (s/m). The post Darcy coefficient \( c_c \) for gravel varies from 0.3 to 6 (s/m)\(^{1.5} \) for river sand it is from 0.7 to 4 (s/m)\(^{1.5} \) and for glass sphere 0.0019 to 0.04 (s/m)\(^{1.5} \). Forchheimer coefficient \( d_c \) for gravel is 5 to 50 (s/m)\(^2 \) and for river sand 4 to 13 (s/m)\(^2 \) and for glass sphere is 2.5 to 10 (s/m)\(^2 \).

For present study pre-Darcy coefficient \( a_c \) is plotted as the ordinate while the size of the particle, \( d_p \), is plotted as the abscissa for gravel, as shown in Fig. 5.11. It is found that all points lie along a curve. However, it may be noted that due to non-availability of \( a_c - d_p \) data of other investigators, they could not be shown in Fig. 5.11. The equation for \( a_c \) in terms of \( d_p \) is obtained by inverse modeling as

\[
a_c = 0.013 \exp (-132 d_p) \quad (5.26)
\]

Similarly, the variation of Darcy parameter \( b_c \) for gravel with size of media \( d_p \) for the data obtained in the present study are plotted in Fig. 5.12. In this case also the data points of the present investigation aligned on a curve and as those of others are not available they could not be shown. The equation for \( b_c \) as a function of size of the media, based on inverse modeling obtained as:

\[
b_c = 1.144 \exp (-175 d_p) \quad (5.27)
\]

124
Fig. 5.11 Variation of corrected pre-Darcy coefficient with size of gravel
Fig. 5.12 Variation of corrected Darcy coefficient with size of gravel
Fig. 5.13 Variation of corrected post-Darcy coefficient with size of gravel
Fig. 5.14 Variation of corrected Forchheimer coefficient with size of gravel
Fig. 5.15 Variation of corrected pre-Darcy coefficient with size of river sand
Fig. 5.16 Variation of corrected Darcy coefficient with size of river sand
Fig. 5.17 Variation of corrected post-Darcy coefficient with size of river sand
Fig. 5.18 Variation of corrected Forchheimer coefficient with size of river sand
Fig. 5.19 Variation of corrected pre-Darcy coefficient with size of glass sphere
Fig. 5.20 Variation of corrected Darcy coefficient with size of glass sphere
Fig. 5.21 Variation of corrected post-Darcy coefficient with size of glass sphere
Fig. 5.22 Variation of corrected Forchheimer coefficient with size of glass sphere
Relationship between post-Darcy parameter \( 'c_c' \) (on y-axis) and size of particle (on x-axis) of gravel is depicted in Fig. 5.13. In this case also the data points of the present investigation aligned on a curve and as those of others are not available they could not be shown. The equation for \( 'c_c' \) as a function of size of the media, based on inverse modeling obtained as:

\[
c_c = 7.24 \exp(-170 \, d_p)
\]  

(5.28)

The variation of Forchheimer coefficient \( 'd_d' \) with size \( d_p \) of gravel for the data obtained in the present study is plotted in Fig. 5.14. In this case also the points are found to align along a curve. The equation relating \( d_c \) and \( d_p \) is obtained as:

\[
d_c = 59.7 \exp(-128 \, d_p)
\]  

(5.29)

Similarly, the variations of pre-Darcy coefficients, Darcy coefficients, post-Darcy and Forchheimer coefficients with size of river sand and glass spheres are plotted as shown in Figs 5.15 to 5.22. In all these cases also corresponding data points are found to align along a curve.

The equations obtained are:

For river sand

\[
a_c = 0.01143 \exp(-486 \, d_p)
\]  

(5.30)

\[
b_c = 1.4 \exp(-238.5 \, d_p)
\]  

(5.31)

\[
c_c = 6.7 \exp(-345 \, d_p)
\]  

(5.32)

\[
d_c = 17.7 \exp(-228.7 \, d_p)
\]  

(5.33)
For glass spheres

\[ a_c = 0.00025 \exp (-46.18 d_p) \]  

(5.34)

\[ b_c = 0.57 \exp (-163 d_p) \]  

(5.35)

\[ c_c = 4.12 \exp (-73 d_p) \]  

(5.36)

\[ d_c = 32.45 \exp (-73.56 d_p) \]  

(5.37)

Therefore, using Eqs. (5.26) to (5.37) for a known size of the medium, either for coarse media or round particles, for the given rate of flow corresponding head loss can be determined, as \(a_c\), \(b_c\), \(c_c\) and \(d_c\) are the measures of energy loss.

5.4 CONCLUDING REMARKS

The relationship between \(i/V_c\) and \(V_c\) is reanalyzed and it is established that even after corrections for porosity, wall and tortuosity effects, the same trend of relationship is found to exist. That is, at lower velocity of flow, the relationship between \(i/V_c\) and \(V_c\) is depicted by a line with a negative slope. It is not a single straight line with a positive slope. The limitation of application of Forchheimer equation is thus established. A four term equation is found to relate hydraulic gradient and velocity of flow in a better way, covering complete range of experimentation. Equations were then proposed relating pre-Darcian, Darcian, post-Darcian and Forchheimer coefficients with the size of the media. Using these equations, which are more realistic and field applicable as they reflect the effects of corrections for porosity, wall and tortuosity, for a known size of the medium, either for coarse media or round particles, for the given rate of flow corresponding head loss can be determined, as \(a_c\), \(b_c\), \(c_c\) and \(d_c\) are the measures of energy lost during fluid flow through the media.