CHAPTER VI

Conclusions
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CONCLUSIONS

6.1 GENERAL REMARKS

The conclusions drawn from the present work are presented in Sec. 6.2. Possible areas in which further work may be taken up are given in Sec. 6.3.

6.2 CONCLUSIONS

The study of the laws governing flow through porous media has become basic for many scientific and engineering applications. The scope of hydromechanics in porous media allows the investigation to be carried out in two phases, namely,

i) Study of the properties of porous media and of fluids and

ii) Study of the interactions between driving and resisting forces and the relationships among these forces, fluid and solid media characteristics.

Based on these observations, experimental studies to analyze the flow behaviour through porous media consisting of gravel, river sand and glass spheres packed in a permeameter have been conducted. The media used are gravel of sizes 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, 20 mm, river sand of size 1.7 mm, 2.4 mm, 3.3 mm, 4.2 mm, and 6.7 mm and glass spheres of size 16.7 mm, 20 mm, 35 mm.
The permeameter used in the present study consists of a G.I. column of 6.2 m high and 0.152 m internal diameter. This size of permeameter facilitated very wide range of experimental data on hydraulic gradient and velocity of flow.

A cursory look at the works carried out by the previous investigators reveals that for computing hydraulic gradient a single length of travel was used. In the present study to avoid error due to non-uniformity in packing, three different lengths of travel have been chosen.

The reliability of trend of present experimentation was ascertained by comparing with that of Darcy. For this purpose, graphs depicting the trend of variation of $i$ with $V_b$ for present data of all the media used with that of Darcy's data were compared and coefficient of permeability is obtained for 18 sizes of media.

(i) Gravel

<table>
<thead>
<tr>
<th>$V_b$</th>
<th>$i$</th>
<th>(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.093</td>
<td>l</td>
<td>1.4</td>
</tr>
<tr>
<td>0.125</td>
<td>l</td>
<td>2.15</td>
</tr>
<tr>
<td>0.19</td>
<td>l</td>
<td>3.8</td>
</tr>
<tr>
<td>0.28</td>
<td>l</td>
<td>5.8</td>
</tr>
<tr>
<td>0.38</td>
<td>l</td>
<td>7.8</td>
</tr>
<tr>
<td>0.43</td>
<td>l</td>
<td>9.0</td>
</tr>
<tr>
<td>0.65</td>
<td>l</td>
<td>12.3</td>
</tr>
<tr>
<td>0.85</td>
<td>l</td>
<td>14.6</td>
</tr>
<tr>
<td>1.20</td>
<td>l</td>
<td>17.5</td>
</tr>
<tr>
<td>1.40</td>
<td>l</td>
<td>20.0</td>
</tr>
</tbody>
</table>
(ii) River sand

\[ V_b = 0.05 \ i \quad (1.7 \ mm) \]
\[ V_b = 0.08 \ i \quad (2.4 \ mm) \]
\[ V_b = 0.10 \ i \quad (3.3 \ mm) \]
\[ V_b = 0.15 \ i \quad (4.2 \ mm) \]
\[ V_b = 0.25 \ i \quad (6.7 \ mm) \]

(iii) Glass sphere

\[ V_b = 2.5 \ i \quad (16.7 \ mm) \]
\[ V_b = 3.0 \ i \quad (20.0 \ mm) \]
\[ V_b = 3.5 \ i \quad (35.0 \ mm) \]

The limitations in the applicability of Forchheimer's equation to porous media flow were brought out. For this purpose, graphs showing the variation of \( i/V_b \) with \( V_b \) for the experimental data, which did not consider the lower limits of velocity, were plotted. The procedure of computing Darcy and non-Darcy parameters from these graphs were discussed. The limitation, such as simple extrapolation in the reverse direction without verifying the nature of variation of \( i/V_b \) with \( V_b \) was brought out.

In the next stage, actual nature of variation of \( i/V_b \) with \( V_b \) for complete range of experimentation of the present study is illustrated with graphs drawn between \( i/V_b \) and \( V_b \). The trend of variation is found to be along a line with a negative slope to certain range of velocity and after that the data points are found to fall along a line with a positive slope. It is, therefore, established beyond doubt that the nature of variation of \( i/V_b \) with \( V_b \) is no more along a single line with a positive slope. Therefore, the equations for
Darcy and non-Darcy parameters in terms of size were proved to be of limited applicability.

In the further stage of analysis, instead of continuing the analysis on the existing form of equations, an attempt is made to propose a new form of polynomial relating \( i \) with \( V_b \) covering complete range of experimentation. It is found from mathematical analysis that a four term equation is found to express the relationship between \( i \) and \( V_b \). The proposed equation is of the form

\[
i = a V^{0.5} + b V + c V^{1.5} + d V^2
\]

where

\( i \) = hydraulic gradient,

\( a \) = pre-Darcian coefficient

\( b \) = Darcian coefficient

\( c \) = post-Darcian coefficient

\( d \) = Forchheimer coefficient

The four term equations relating \( i \) with \( V_b \) for all the sizes of used in the present study for the complete range of experimentation were proposed.

They are:

For gravel

\[
i = 0.0115 V_b^{0.5} + 7 V_b^{1.0} + 33 V_b^{1.5} + 510 V_b^{2.0}
\]

(1.4 mm)

\[
i = 0.011 V_b^{0.5} + 5.7 V_b^{1.0} + 23 V_b^{1.5} + 460 V_b^{2.0}
\]

(2.15 mm)

\[
i = 0.0105 V_b^{0.5} + 3.5 V_b^{1.0} + 18 V_b^{1.5} + 400 V_b^{2.0}
\]

(3.8 mm)
i = 0.0095 V_b^{0.5} + 2.5 V_b^{1.0} + 14 V_b^{1.5} + 350 V_b^{2.0} (5.8 mm)

i = 0.0087 V_b^{0.5} + 1.6 V_b^{1.0} + 8.3 V_b^{1.5} + 266 V_b^{2.0} (7.8 mm)

i = 0.0082 V_b^{0.5} + 1.2 V_b^{1.0} + 5.6 V_b^{1.5} + 248 V_b^{2.0} (9.0 mm)

i = 0.0074 V_b^{0.5} + 0.65 V_b^{1.0} + 4 V_b^{1.5} + 175 V_b^{2.0} (12.3 mm)

i = 0.0065 V_b^{0.5} + 0.42 V_b^{1.0} + 2.7 V_b^{1.5} + 135 V_b^{2.0} (14.8 mm)

i = 0.0056 V_b^{0.5} + 0.25 V_b^{1.0} + 1.8 V_b^{1.5} + 105 V_b^{2.0} (17.5 mm)

i = 0.0052 V_b^{0.5} + 0.15 V_b^{1.0} + 1.1 V_b^{1.5} + 84 V_b^{2.0} (20.0 mm)

For river sand:

i = 0.0558 V_b^{0.5} + 10 V_b^{1.0} + 78 V_b^{1.5} + 1400 V_b^{2.0} (1.7 mm)

i = 0.0455 V_b^{0.5} + 7 V_b^{1.0} + 60 V_b^{1.5} + 1000 V_b^{2.0} (2.4 mm)

i = 0.036 V_b^{0.5} + 5 V_b^{1.0} + 42 V_b^{1.5} + 620 V_b^{2.0} (3.3 mm)

i = 0.028 V_b^{0.5} + 3.9 V_b^{1.0} + 32 V_b^{1.5} + 435 V_b^{2.0} (4.2 mm)

i = 0.015 V_b^{0.5} + 1.9 V_b^{1.0} + 15 V_b^{1.5} + 250 V_b^{2.0} (6.7 mm)

For glass spheres:

i = 0.0015 V_b^{0.5} + 0.07 V_b^{1.0} + 4 V_b^{1.5} + 53 V_b^{2.0} (16.7 mm)

i = 0.001 V_b^{0.5} + 0.085 V_b^{1.0} + 3.5 V_b^{1.5} + 40 V_b^{2.0} (20.0 mm)

i = 0.0004 V_b^{0.5} + 0.028 V_b^{1.0} + 1.5 V_b^{1.5} + 20 V_b^{2.0} (35.0 mm)

It was then observed that the four coefficients, i.e., pre-Darcian, Darcian, post-Darcian and Forchheimer coefficients are found to have well defined relation with corresponding sizes of media. Using regression analysis, equations were fit relating these parameters with corresponding sizes of media.
They are:

For gravel

\[ a = 0.0122 \exp(-43.14 d_p) \]
\[ b = 8.22 \exp(-202.88 d_p) \]
\[ c = 37.35 \exp(-179.63 d_p) \]
\[ d = 583.61 \exp(-97.78 d_p) \]

For river sand

\[ a = 0.086 \exp(-262 d_p) \]
\[ b = 15.64 \exp(-321.9 d_p) \]
\[ c = 130.34 \exp(-327.3 d_p) \]
\[ d = 2175 \exp(-341 d_p) \]

For glass sphere

\[ a = 0.004367 \exp(-68.8 d_p) \]
\[ b = 0.0174 \exp(-52 d_p) \]
\[ c = 10.15 \exp(-54.48 d_p) \]
\[ d = 118 \exp(-51 d_p) \]

In order to make the findings more realistic and field oriented, corrections for porosity, wall effect and tortuosity were applied using the following equations.
(i) Porosity correction is applied to both size of the particle and velocity of flow. Porosity function \( f/(1-f) \) is used to obtain the size of the pore from the size of the particle. Therefore, the size of the pore is

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

(ii) The pore velocity is obtained from superficial velocity by using the equation

\[
V_p = \frac{V_b}{f}
\]

(iii) An expression for wall correction factor, following the procedure suggested by Dudgeon, flow has been developed as

\[
C_w = \left[ \frac{(D + 4.83t)}{D^3} \right]^{-1}
\]

where

\[
\begin{align*}
D &= \text{Diameter of the permeameter.} \\
t &= \text{Thickness of wall zone} = \frac{d_p}{2} \\
d_p &= \text{Size of the particle}
\end{align*}
\]

(iv) Tortuosity correction is applied to velocity of flow and hydraulic gradient as

\[
V_{\text{ct}} = V \cdot \tau \\
i_{\text{ct}} = 1 / \tau
\]

Therefore, total corrected velocity

\[
V_c = \frac{V_b}{f}
\]
A similar analysis was carried out after applying corrections for pore size, velocity of flow and hydraulic gradient. Refined four term equations relating $i_c$ and $V_c$ are proposed as follows:

(i) For gravel:

\[ i_c = 0.012 V_c^{0.5} + 0.9 V_c + 6 V_c^{1.5} + 50 V_c^2 \]  $(1.4 \text{ mm})$
\[ i_c = 0.01 V_c^{0.5} + 0.8 V_c + 5 V_c^{1.5} + 43 V_c^2 \]  $(2.15 \text{ mm})$
\[ i_c = 0.008 V_c^{0.5} + 0.6 V_c + 4 V_c^{1.5} + 38 V_c^2 \]  $(3.8 \text{ mm})$
\[ i_c = 0.006 V_c^{0.5} + 0.4 V_c + 3 V_c^{1.5} + 30 V_c^2 \]  $(5.8 \text{ mm})$
\[ i_c = 0.005 V_c^{0.5} + 0.28 V_c + 2 V_c^{1.5} + 22 V_c^2 \]  $(7.8 \text{ mm})$
\[ i_c = 0.004 V_c^{0.5} + 0.26 V_c + 1.5 V_c^{1.5} + 20 V_c^2 \]  $(9.0 \text{ mm})$
\[ i_c = 0.003 V_c^{0.5} + 0.14 V_c + 0.065 V_c^{1.5} + V_c^2 \]  $(12.3 \text{ mm})$
\[ i_c = 0.002 V_c^{0.5} + 0.07 V_c + 0.5 V_c^{1.5} + 7.5 V_c^2 \]  $(14.6 \text{ mm})$
\[ i_c = 0.0015 V_c^{0.5} + 0.05 V_c + 0.4 V_c^{1.5} + 0.4 V_c^2 \]  $(17.5 \text{ mm})$
\[ i_c = 0.0008 V_c^{0.5} + 0.04 V_c + 0.3 V_c^{1.5} + 5 V_c^2 \]  $(20.0 \text{ mm})$

(ii) For river sand:

\[ i_c = 0.0055 V_c^{0.5} + V_c + 4 V_c^{1.5} + 13 V_c^2 \]  $(1.7 \text{ mm})$
\[ i_c = 0.004 V_c^{0.5} + 0.8 V_c + 3 V_c^{1.5} + 10 V_c^2 \]  $(2.4 \text{ mm})$
\[ i_c = 0.002 V_c^{0.5} + 0.6 V_c + 2 V_c^{1.5} + 8 V_c^2 \]  $(3.3 \text{ mm})$
\[ i_c = 0.0012 V_c^{0.5} + 0.5 V_c + 1.5 V_c^{1.5} + 6.5 V_c^2 \]  $(4.2 \text{ mm})$
\[ i_c = 0.0005 V_c^{0.5} + 0.3 V_c + 0.7 V_c^{1.5} + 4V_c^2 \]  $(6.7 \text{ mm})$

(iii) For glass spheres:

\[ i_c = 0.00012 V_c^{0.5} + 0.04 V_c + 1.2 V_c^{1.5} + 10 V_c^2 \]  $(16.7 \text{ mm})$
\[ i_c = 0.0001 V_c^{0.5} + 0.02 V_c + 1V_c^{1.5} + 7 V_c^2 \]  $(20.0 \text{ mm})$
\[ i_c = 0.00005 V_c^{0.5} + 0.0019 V_c + 0.32 V_c^{1.5} + 2.5 V_c^2 \]  $(35.0 \text{ mm})$
Further, following similar steps of analysis, equations were proposed relating the four coefficients i.e. pre-Darcian, post-Darcian and Forchheimer coefficients with the size of the media.

(i) For gravel

\[ a_e = 0.013 \exp(-132 \, d_p) \]
\[ b_e = 1.144 \exp(-175 \, d_p) \]
\[ c_e = 7.24 \exp(-170 \, d_p) \]
\[ d_e = 59.7 \exp(-128 \, d_p) \]

(ii) For river sand

\[ a_e = 0.01143 \exp(-486 \, d_p) \]
\[ b_e = 1.4 \exp(-236.5 \, d_p) \]
\[ c_e = 6.7 \exp(-345 \, d_p) \]
\[ d_e = 17.7 \exp(-228.7 \, d_p) \]

(iii) For glass sphere

\[ a_e = 0.00025 \exp(-46.18 \, d_p) \]
\[ b_e = 0.57 \exp(-163 \, d_p) \]
\[ c_e = 4.12 \exp(-73 \, d_p) \]
\[ d_e = 32.45 \exp(-73.56 \, d_p) \]

From the known field conditions such as rate of flow through a known size of aquifer, size and porosity of the medium, the value of hydraulic gradient can be determined from the computed values of \( a_e, b_e, c_e \) and \( d_e \).
6.3 SUGGESTIONS FOR FURTHER WORK

Based on the conclusions arrived at from this work, the following suggestions are put forward for further work.

i) The present investigation is limited to homogeneous media only. All the above experimentation and analysis can be repeated for non-homogeneous media to improve the scope of its application.

ii) The effect of variation in porosity can also be investigated further.

iii) Fluids other than water may be used to analyze the effect of viscosity on the flow behavior through porous media.

iv) Only gravel, river sand and glass spheres are used as media in the present study. Using media of different shapes (flat, oblong, etc.,) the effect of shape (shape factor) on the flow behavior through porous media can be investigated.

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 porous media; provide 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.