Effect of sample size on the fluid flow through a single fractured granitoid

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A R T I C L E   I N F O

Article history:
Received 19 August 2015
Received in revised form 19 November 2015
Accepted 8 December 2015
Available online 11 March 2016

Keywords:
Rock mass
Single fracture
Fluid flow
Sample size
Size effect
Fracture roughness

A B S T R A C T

Most of deep geological engineered structures, such as rock caverns, nuclear waste disposal repositories, metro rail tunnels, multi-layer underground parking, are constructed within hard crystalline rocks because of their high quality and low matrix permeability. In such rocks, fluid flows mainly through fractures. Quantification of fractures along with the behavior of the fluid flow through them, at different scales, becomes quite important. Earlier studies have revealed the influence of sample size on the confining stress–permeability relationship and it has been demonstrated that permeability of the fractured rock mass decreases with an increase in sample size. However, most of the researchers have employed numerical simulations to model fluid flow through the fracture/fracture network, or laboratory investigations on intact rock samples with diameter ranging between 38 mm and 45 cm and the diameter-to-length ratio of 1:2 using different experimental methods. Also, the confining stress, σ3, has been considered to be less than 30 MPa and the effect of fracture roughness has been ignored. In the present study, an extension of the previous studies on “laboratory simulation of flow through single fractured granite” was conducted, in which consistent fluid flow experiments were performed on cylindrical samples of granitoids of two different sizes (38 mm and 54 mm in diameters), containing a “rough walled single fracture”. These experiments were performed under varied confining pressure (σ3 = 5–40 MPa), fluid pressure (p ≤ 25 MPa), and fracture roughness. The results indicate that a nonlinear relationship exists between the discharge, Q, and the effective confining pressure, σeff, and Q decreases with an increase in σeff. Also, the effects of sample size and fracture roughness do not persist when σeff ≥ 20 MPa. It is expected that such a study will be quite useful in correlating and extrapolating the laboratory scale investigations to in-situ scale and further improving theoretical/numerical models associated with fluid flow through rock masses.

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1. Introduction

Investigations on the movement of fluid through rock mass and the factors that affect such movements are great concerns in geoenengineering field. Constructions of deep geological engineered structures, such as rock caverns, radioactive/nuclear waste disposal repositories, metro rail tunnels, multi-layer underground parking, or exploitation of oil, natural gas, geothermal energy, mineral resources and CO₂ sequestration, are few important areas where such studies have significant roles. In general, most of these engineering activities are associated with hard or crystalline rocks, or highly consolidated sedimentary rocks, where fluid flows mainly through fractures (Walsh, 1965; Brace, 1980; Bandis et al., 1983; Zimmerman et al., 1991; Cook, 1992; Bear et al., 1993; Zimmerman and Bodvarsson, 1996; Klimczak et al., 2010), and the discharge, Q, through such fractures is much higher than that through the intact rock (Singh et al., 2015). As such, the flow capacity of the fractures is mainly governed by the flow properties of the “most prominent fracture” or the “single fracture” (Hakami and Larsson, 1996; Brown et al., 1998; Ranjith, 2010; Singh et al., 2014). In general, investigation on the behavior of fluid flow through rock mass at regional scale, i.e. in the field/in-situ condition, which consists of agglomeration of fracture(s) of variable geometry (size, shape, aperture, orientation, density and roughness), is difficult and requires in-depth knowledge of fracture systems (Illman, 2006). Also, in the deep Earth’s crust, quantification of the interconnected fractures and their in-filling
materi\als, boundary condition, along with their behaviors due to change in surrounding stress conditions requires detailed geological,
geophysical and geotechnical inputs. This involves huge cost, complicated instrumentations, and laborious and cumbersome test
procedures, along with technical and logistical difficulties.

Therefore, investigation on the fluid flow properties of “single fracture” at different scales, under a controlled laboratory condi-
tion, becomes an excellent stepping-stone, which would assist researcher to generalize the laboratory experiments to larger scale in
an enhanced approach. The scale effect on the permeability was studied by Witherspoon et al. (1980), Brace (1980, 1984), Raven and
Gale (1985), Gueguen et al. (1996), Butler and Healey (1998a, 1998b), Hunt (2003), and Feng et al. (2009). Scale effects on hy-
draulic conductivity, \( K \), under in-situ condition were studied at a granitic site at Central Spain by Guimera et al. (1995) and values of \( K \) were measured on the same fracture at different distances from
the pumping well. Several researchers have mentioned that the
collapse on permeability is still under considerable debate,
which is mainly due to the present insufficient experimental
knowledge, lack of consistency in measurement and interpretation of data (Clauser, 1992; Gueguen et al., 1996; Butler and Healey,
1998a, 1998b; Zlotnik et al., 2000; Hunt, 2003; Neuman and Di
Federico, 2003). Gueguen et al. (1996) revealed field evidence of
a directional permeability scale effect from multiple cross-hole pneumatic injection tests conducted in a geologically distinct unit
of unsaturated fractured tuff. It was observed that the scale effect on
permeability is controlled by the connectivity of fluid-conducting fractures, which increases with the scale. Illman (2006) concluded that there is a difficulty in characterizing the
permeability at multiple scales with a single or consistent method.
Several researchers (Raven and Gale, 1985; Gueguen et al., 1996;
Wang et al., 2002) have concluded their work by mentioning that
“further work is required to investigate the behavior of fluid flow
through fracture(s) at different scales in combination with quan-
tification of fracture properties (i.e., connectivity, size, density
and roughness) to provide a solid basis for normal stress-fracture flow theory”. Matsuki et al. (2006) studied the size effect on aperture
and permeability of synthetic fractal fractures (ranging from 0.2 m
to 12.8 m) generated by a new spectral method. They mentioned that
different granites are subjected to different flow and boundary
conditions, and hence it is very difficult to draw firm conclusions on
the relation between the size of the sample and the fracture
permeability.

Few researchers (e.g. Witherspoon et al., 1979; Raven and Gale,
1985) have investigated the influence of sample size on the
confining stress—permeability relationship. The effects of stress on
fluid flow through single fracture or fractured rock mass have been
studied mainly by numerical modeling (e.g. Tsang, 1984; Oda, 1986;
Bai and Elsworth, 1994; Zhang and Sanderson, 1996; Chen and Bai,
1998; Bai et al., 1999; Pyrak-Nolte and Morris, 2000; Koyama et al.,
2006; Nazridoust et al., 2006; Zhao et al., 2013; Briggs et al., 2014;
Hao et al., 2015; Zou et al., 2015) or in-situ scale pumping tests (e.g.
Theis, 1935; Stober, 1986; Boonstra, 1989; Krusemann and de
Ridder, 1990; Genter et al., 2010; Stober and Bucher, 2015). Lab-
oratory scale investigations are very limited (Lomize, 1951; Louis,
1969; Gangi, 1978; Witherspoon et al., 1979, 1980; Brown, 1987;
Brown et al., 1998; Qian et al., 2005; Ranjith, 2010; Singh et al.,
2014, 2015), or mainly focus on intact rock samples with the diameter of 38–450 mm and the diameter-to-length ratio of 1:2
(Raven and Gale, 1985; Tain et al., 2014; Selvadurai, 2015). Also, the
confining stress, \( \sigma_3 \), has been considered to be less than 30 MPa and
the effect of fracture roughness has been ignored. It can be
observed from the above literature review that most of the re-
searchers have used numerical simulation/in-situ scale testing or
complicated test setups to study the behavior of fluid flow through
the fractured rock mass, and have not identified the influence of
fracture roughness in association with the effect of sample size on
the fluid flow. In addition, investigations on fluid flow in fractured
rock samples with different sizes, employing a consistent method
under controlled laboratory conditions, are lacking, which is quite
significant for understanding the effect of sample size on the
fractured rock permeability and would assist researchers to un-
derstand the basic mechanism of fluid flow.

In this paper, an extension of the previous studies on “laboratory
simulation of flow through single fractured granite” was performed,
in which consistent fluid flow experiments were con-
ducted on cylindrical granitoid sample of two different sizes (38 mm and 54 mm in diameters, with a constant diameter-to-
length ratio of 1:2), containing a “rough walled single fracture”.
These experiments were performed under varied conditions of
confining pressure (\( \sigma_3 = 5–40 \text{ MPa} \)), fluid pressure (\( p_f \leq 25 \text{ MPa} \)),
and fracture roughness (by selecting 3 types of granitoid rocks
based on their grain size) to quantify the effect of sample size in
association with fracture roughness on the fluid flow through
fractured rock mass. Further, fracture roughness was characterized by employing three-dimensional (3D) laser scanning technique
conducted on the fracture surfaces and an attempt was made to
examine the relationship between fracture aperture closure and
discharge quantitatively.

2. Methodology

The experimental procedures and methodologies employed in
this study to investigate the behavior of fluid flow through the
granitoid samples of different sizes, comprising a single fracture,
were introduced in detail in the following sections.

2.1. Sample selection and preparation

In the present study, three types of granitoid rocks were
collected under in-situ conditions from an open quarry in and
around Euroa-Strathbogie road, Victoria, Australia (Fig. 1). These
granitoid rocks were selected based on their grain size (coarse,
medium and fine grained), quality (strength and modulus) and low
matrix permeability. This was done mainly to create different
roughness and to ensure that the flow takes place only through the
fracture but not through the matrix. The granitoid blocks were
brought to the laboratory (Fig. 2) and then cylindrical rock core
samples of two different sizes (38 mm and 54 mm in diameter)
with the constant diameter-to-length ratio of about 1:2 were ob-
tained, according to the recommendation of Indian Society of Rock
Mechanics (ISRM). These core samples were designated as S1-CG-
38, S2-MG-38, S3-FG-38 and S1-CG-54, S2-MG-54, and S3-FG-54
representing sample number, grain size (coarse, medium, and fine
grained) and sample diameter, respectively. The samples’ number,
their geometrical details, and location coordinates in degree deci-
nal (DD) format along with their engineering properties are pre-
sent in Table 1.

Optical properties of these granitoid samples are studied under
transmitted light microscope and the photomicrographs of the
samples S1-CG-38, S2-MG-38 and S3-FG-38 are depicted in
Fig. 3a–c, respectively. In addition, to characterize these granitoid
samples chemically, mineralogically as well as by modal count (in
hand specimen and under microscope), analysis was performed
based on the classification approach of the Sub-commission on the
International Union of Geological Sciences (IUGS) (Streckeisen,
1974). The results are plotted on quartz-alkali feldspar-plagioclase
(QAP) diagram as depicted in Fig. 4. Optical and mineralogical
properties of these granitoids rocks were investigated mainly to
characterize the granites, observe the variation in the grain sizes,
and identify the presence of hard (quartz and amphiboles) and soft minerals (feldspars and biotite).

The core samples obtained were grinded and polished accurately according to the American Society of Testing Manual (ASTM) standards for rocks (ASTM D4543, 2008), and oven-dried for 24 h. Then, a single vertical fracture of certain roughness was created by employing a direct tensile-split test, conducted on the cylindrical granitoid sample, running along the length of the sample (Fig. 5). The detailed methodology can be referred to in Singh et al. (2015). Three different types of fracture surfaces were created based on the grain sizes (coarse, medium and fine) of the rock mass and the variable rough surface was quantified employing laser scanning technique as mentioned in the following section.

Roughness measurement was performed on both of the cylindrical halves/fracture surfaces (produced from direct tensile split tests) of the sample at 0.04 mm point spacing, by employing 7-axis ROMER 3D laser profile absolute arm scanner, certified to ASME B89.4.22 (2004) specifications. The 3D laser profile scanner was used to capture the texture of fracture surface profiles or the topography of the surfaces using the laser beam. The path of the scanned surface was performed manually by rotating the scanner in different directions with respect to the vertical axis (Fig. 6a and b). This was mainly to avoid the problems of shadows and reflection from the mineral grains (especially quartz and alkali feldspar) and to measure the coordinates $X$, $Y$ and $Z$, representing the point coordinates along the width, length and asperity height of the fracture surface, respectively. Further, the coordinates of the scanned surface were brought into ASCII or binary files. Then, statistical analysis was performed on these obtained data sets and the classical statistical parameters, e.g. mean, median, mode, skewness, kurtosis, standard deviation, etc., were generated, as listed in Table 2. Several researchers have used the root mean square (RMS)
of roughness, $R_q$, and the average roughness, $R_a$, to detect the variation in the fracture surface of different topographies quantitatively (Mellott et al., 2001; Guerrero et al., 2002; Vasconcelos et al., 2008; Singh et al., 2015).

$R_q$ is a mathematical representation of the asperities height and depth of the fracture surface, and is defined as the average between the asperity height deviations and the mean of the line/surface, taken over the entire surface. $R_a$ is the mean height over the entire surface. $R_q$ and $R_a$ were computed by employing the following equations, respectively (Mellott et al., 2001; Guerrero et al., 2002; Vasconcelos et al., 2008; Singh et al., 2015):

$$ R_q = \frac{1}{n} \sum_{i=1}^{n} (Z_i - \bar{Z})^2 $$

(1)

$$ R_a = \frac{1}{n} \sum_{i=1}^{n} |Z_i - \bar{Z}| $$

(2)

where $n$ is the number of data points, and $Z$ is the asperity height.

Further, 3D surface roughness profiles of the cylindrical halves/fracture surfaces corresponding to different grain sized samples, i.e. coarse, medium and fine grained, were generated by employing ArcGIS software v.10.2.2, as depicted in Figs. 7–9, respectively.

The obtained coordinates $X$, $Y$ and $Z$ were converted into a point coverage shape file. Then using this shape file for all the samples, a 3D surface was generated in ArcGIS by employing the raster interpolation technique (Kriging function) of the 3D-analyst tool. A section $AB$ was taken along the center of the generated 3D surface roughness image, as represented by the dotted line in sample S1-CG-38 in Fig. 7. Then, by using the 3D-graph profile tool of the 3D-analyst, the sample length, $L_1$, and the length of flow path, $L_2$ (defines tortuosity) were computed along the section $AB$ (refer to S1-CG-38 in Fig. 7). The results of all the samples are listed in Table 3.

Subsequent to the roughness measurement, both of the cylindrical halves were joined together by means of a silicon adhesive, applied on the side walls of the sample all along the length as depicted in Fig. 10. In this manner, several cylindrical rock samples of two different sizes, comprising a “single vertical fracture”, were produced. The application of silicon adhesive ensures that side walls of the sample were completely sealed and the water flows through a fracture from the top to the bottom only or vice versa, and no leakage was found to be out of the side walls.

### 2.2. The fluid flow test setup and working principle

High pressure triaxial cell (HPTC), employed by Singh et al. (2015), was modified as per the present objective and test requirements. The photograph of the experimental setup is shown in Fig. 11. The modified test setup consists of a loading system, a loading frame, a triaxial cell, top and base pedestals of two sizes (38 mm and 54 mm in diameter), a compressor unit, a hydraulic oil reservoir, a high pressure hydraulic pump, and a water pressure pump. For further details of the setup and the working principle, one can refer to Singh et al. (2015).

### Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock type</th>
<th>Location ($X$, $Y$ in DD)</th>
<th>$D$ (mm)</th>
<th>$L$ (mm)</th>
<th>$\sigma_I$ (MPa)</th>
<th>$E$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-CG-38</td>
<td>Coarse grained granitoid (monzogranite)</td>
<td>145.7088, 36.832</td>
<td>39.7</td>
<td>76.2</td>
<td>150</td>
<td>42</td>
</tr>
<tr>
<td>S1-CG-54</td>
<td>Coarse grained granitoid (monzogranite)</td>
<td>53.8</td>
<td>106.94</td>
<td>126</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>S2-MG-38</td>
<td>Medium grained granitoid (granodiorite)</td>
<td>145.746, 36.8347</td>
<td>39.5</td>
<td>73.3</td>
<td>172</td>
<td>24</td>
</tr>
<tr>
<td>S2-MG-54</td>
<td>Medium grained granitoid (granodiorite)</td>
<td>53.94</td>
<td>96.08</td>
<td>127</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>S3-FG-38</td>
<td>Fine grained granitoid (monzogranite)</td>
<td>145.6452, 36.8102</td>
<td>39.6</td>
<td>74.6</td>
<td>249</td>
<td>77</td>
</tr>
<tr>
<td>S3-FG-54</td>
<td>Fine grained granitoid (monzogranite)</td>
<td>53.83</td>
<td>99.92</td>
<td>181</td>
<td>62</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 11. The modified test setup consists of a loading system, a loading frame, a triaxial cell, top and base pedestals of two sizes (38 mm and 54 mm in diameter), a compressor unit, a hydraulic oil reservoir, a high pressure hydraulic pump, and a water pressure pump. For further details of the setup and the working principle, one can refer to Singh et al. (2015).

Fig. 3. Photomicrographs of the granitoid samples: (a) S1-CG-38, (b) S2-MG-38, and (c) S3-FG-38.
was recorded at every 3 sample in an airtight container kept on weighing balance, and it became stabilized. For each the required coarse grained rock, showing inequigranular texture with 3. Results and discussion

Table 4. The obtained results are analyzed as follows.

Fluid flow tests were performed on the fractured granitoid specimen at different combinations of $\sigma_3$ (5 MPa, 10 MPa, 15 MPa, 20 MPa, 30 MPa and 40 MPa) and $f_p$ (1 MPa, 2 MPa, 3 MPa, 4 MPa, 6 MPa, 8 MPa, 10 MPa, 14 MPa, 18 MPa, and 25 MPa). The required $\sigma_3$ was applied on the sample, and the fluid was injected to the bottom of the sample. The discharge, Q, was collected from the top of the sample in an airtight container kept on weighing balance, and it was recorded at every 3–10 s. The test was continued until the flow became stabilized. For each $f_p$, the test lasted for approximately 30–45 min. There were 33 experiments in total. For each sample, about 600–3000 test points were obtained, depending upon the stabilization time of the discharge. After each experiment, the sample was again exposed to different target $\sigma_3$. To ensure side wall leakage and stabilize the fluctuation in the target $\sigma_3$, the sample was exposed to the required $\sigma_3$ for a period of 6–8 h. In the same manner, several samples were tested and for the sake of brevity, a typical data sheet used for recording experimental observations and calculated parameters for the sample S1-CG-38 (up to 105 s only) is listed in Table 4. The obtained results are analyzed as follows.

3. Results and discussion

Microscopically, the sample S1-CG-38 can be characterized as a coarse grained rock, showing inequigranular texture with subhedral to anhedral grains of quartz (white to grey in color), K-feldspar (grey color with cross-hatched twinning), plagioclase (dark grey, lamellar texture) and biotite (light to dark brown, Fig. 3a). The sample S2-MG-38 is a medium grained rock, showing hypidiomorphic texture with anhedral grains of quartz, plagioclase, and K-feldspar with high mafic content, mainly amphiboles (greenish) and biotite (Fig. 3b). The sample S3-FG-38 is a fine grained rock, showing equigranular texture with anhedral grains of quartz (grey to variegated cyan to purple color), subhedral grains of plagioclase, and K-feldspar (microcline in black and white color with cross-hatched twinning; and orthoclase in grey with cloudy appearance) with very less amount of mafics (Fig. 3c). The sample S2-MG-38 shows alteration of plagioclase into epidote and biotite into chlorite high magnification.

Data obtained from modal count and mineralogical classification are plotted as triangular plots, as depicted in Fig. 4. It can be observed from the figure that the samples S1-CG-38 and S3-FG-38 fall in the field of monzogranite, whereas S2-MG-38 falls at the boundary of granodiorite. The monzogranite is a typical granitoid rock consisting of almost the same proportion of K-feldspar and plagioclase with some quartz, whereas the granodiorite is rich in plagioclase. The sample S2-MG-38 is rich in mafics as well (Fig. 3b).

Data obtained from the 3D laser scanning of the fracture surface for the samples S1-CG-38, S2-MG-38, S3-FG-38 and S1-CG-54, S2-MG-54, and S3-FG-54 were analyzed statistically, and the following classical statistical parameters such as mean, median, standard deviation, skewness, kurtosis along with RMS roughness, $R_q$ and roughness average, $R_s$ were computed and presented in Table 2. It can be observed from Table 2 that the standard deviation and range (Max.–Min.) values for small samples S1-CG-38, S2-MG-38, and S3-FG-38 are 1.89, 2.23, 0.95 and 9.81, 10, 5.07, respectively, and are 1.4, 1.53, 0.86 and 7.96, 8.31, 5 for large samples S1-CG-54, S2-MG-54, and S3-FG-54, respectively. In general, the higher values of standard deviation and range indicate a rough surface, whereas lower values indicate a smooth fracture surface. Further, it can be observed from the 3D surface profile of samples S1-CG-38 and S1-CG-54 (Fig. 7), that more asperities are visible in the sample S1-CG-54 as compared to that in S1-CG-38, and the asperity height varies from 0 to 7.96 mm and 0 to 9.81 mm, respectively. It can be observed from Fig. 9 that more small asperities are present in the sample S3-FG-38/54, and the asperity range varies from 0 to 5 mm. It can be attributed to the fact that the sample with coarse grain size (Fig. 7) has fewer number of small asperities as compared to the fine grained sample, where more small asperities are present (Fig. 9). It can also be observed from Table 2 that $R_q$ and $R_s$ values of coarse grained samples of both small and large sizes (1.89, 1.4, 1.61, 1.16, respectively) are significantly higher than those of the fine grained samples (0.95, 0.86 and 0.8, 0.65, respectively), which further strengthens the fact that the fracture surface of the coarse grained rocks developed after the split test was rougher as compared to that of the fine grained samples. It is interesting to note that the fracture surfaces of these samples can be systematically correlated with the grain size, that is, the finer the grain size, the more smooth the developed fracture surface, and vice versa. However, a slightly higher value of standard deviation (2.23 mm) and range (10 mm) for the sample S2-MG-38 than those of the sample S1-CG-38 (1.89 mm and 9.81 mm, respectively) can be attributed to the development of irregular and inhomogeneous fracture surface in the sample S2-MG-38, mainly due to the mineralogical and structural flaws, such as presence of softer mineral (plagioclase and biotite, Fig. 3b), and linear structural fabric. Further, it can also be noted that the samples S2-MG-38 and S2-MG-54 have low values of $E$ (24 GPa and 21 GPa, respectively), as depicted in Table 1. Such samples are more susceptible to deformation and irregular breakage.
Experimental results of fluid flow tests on the samples of different sizes (38 mm and 54 mm in diameter) and constant diameter-to-length ratio of about 1:2 were analyzed, and the relationship between the discharge, \( Q \), and the fluid pressure, \( f_p \), corresponding to various values of \( \sigma_3 \), for coarse grained samples was plotted in Fig. 12. It can be observed from the figure that a linear relationship exists between \( Q \) and \( f_p \), and \( Q \) increases with the increase in \( f_p \). It can also be observed from Fig. 12 that \( Q \) decreases significantly with the increase in applied \( \sigma_3 \). The observations are consistent with the findings reported by earlier researchers (Gangi, 1978; Cook, 1992; Pyrak-Nolte and Morris, 2000; Singh et al., 2014, 2015). The flow behavior is almost laminar for most of the data points except for the case where the difference between \( \sigma_3 \) and \( f_p \) is less than 1 MPa (i.e. \( \sigma_3 = 15 \) MPa and \( f_p = 14 \) MPa). In such cases, most probably, the flow starts entering in between the sample and the membrane, and hence the data deviate from the linear relationship between \( Q \) and \( f_p \) and are enclosed in a circle (Fig. 12). As most of the experimental data of \( Q \) vs. \( f_p \) plot follow the linear trend, it can be assumed that the flow through the fracture obeys the Darcy’s law. So the hydraulic fracture aperture, \( e \), can be computed by assuming that the density of water is 997.05 kg/m\(^3\) at 25 °C and the dynamic viscosity of water is 8.90 × 10\(^{-4}\) kg/(m s) at 25 °C, employing the well-known cubic law, which assumes a linear flow between two parallel smooth plates (Gangi, 1978; Kranz et al., 1979; Tsang and Witherspoon, 1981; Schrauf and Evans, 1986). Further, it must be noted that highly sophisticated instrumentation is required to measure hydraulic aperture of the fracture, especially when it decreases with the change in incremental \( \sigma_3 \).

The slope of \( Q-f_p \) curves corresponding to coarse, medium and fine grained samples of both sizes (38 mm and 54 mm) was computed, and the variation in the slope, \( s \), of \( Q-f_p \) curves with \( \sigma_3 \) is plotted in a bar graph, as shown in Fig. 13a–c. It can be observed from the figure that \( s \) is significantly high for coarse, medium and fine grained rocks of small samples (38 mm) when \( \sigma_3 \leq 15 \) MPa. It can also be observed from Fig. 13a–c that \( s \) becomes low with increasing \( \sigma_3 \) and almost becomes constant when \( \sigma_3 \geq 20 \) MPa. However, for the fine grained sample, the critical \( \sigma_3 \geq 30 \) MPa. This indicates less resistance in flow through the smooth fracture (Fig. 9 and Table 2) when \( \sigma_3 \) increases, and the effect of fracture roughness on fluid flow is not much significant when \( \sigma_3 \) is beyond a certain critical value (30 MPa).

The relationship between \( Q \) and the effective confining pressure, \( \sigma_{\text{eff.}} (= \sigma_3 - f_p) \), for coarse, medium and fine grained rocks of both sizes was plotted and shown in Fig. 14a–c. It can be observed from the figure that the relationship is nonlinear and \( Q \) decreases with the increase in \( \sigma_{\text{eff.}} \). However, \( Q \) is significantly less for the large sample S1-CG–54 than that for S1-CG–38 up to \( \sigma_{\text{eff.}} \) less than 10 MPa (Fig. 14a). Such observations were also reported by Cook (1992). The variation in \( Q \) for small (S1-CG–38, S2-MG–38, and S3-FG–38) and large (S1-CG–54, S2-MG–54, and S3-FG–54) samples is negligible when \( \sigma_{\text{eff.}} \geq 10 \) MPa, 15 MPa and 25 MPa, respectively (Fig. 14a–c). It can be noticed that the fracture roughness has a strong influence on \( Q \) for coarse grained samples when \( \sigma_{\text{eff.}} \leq 10 \) MPa, and this influence

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**Table 2**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean (mm)</th>
<th>Median (mm)</th>
<th>Standard deviation (mm)</th>
<th>Sample variance (mm(^2))</th>
<th>Kurtosis</th>
<th>Skewness</th>
<th>Standard error (mm)</th>
<th>Range (mm)</th>
<th>Minimum (mm)</th>
<th>Maximum (mm)</th>
<th>RMS of roughness, ( \sigma_3 ) (mm)</th>
<th>Average roughness, ( \sigma_3 ) (mm)</th>
<th>Confidence level (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-CG-38</td>
<td>4.56</td>
<td>4.22</td>
<td>1.89</td>
<td>3.59</td>
<td>-0.79</td>
<td>0.36</td>
<td>0.003</td>
<td>9.81</td>
<td>0</td>
<td>9.81</td>
<td>1.89</td>
<td>1.61</td>
<td>0.007</td>
</tr>
<tr>
<td>S2-MG-38</td>
<td>5.57</td>
<td>5.64</td>
<td>2.23</td>
<td>4.97</td>
<td>-1.02</td>
<td>-0.17</td>
<td>0.004</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>2.23</td>
<td>1.9</td>
<td>0.008</td>
</tr>
<tr>
<td>S3-FG-38</td>
<td>2.36</td>
<td>2.27</td>
<td>0.95</td>
<td>0.9</td>
<td>-0.73</td>
<td>0.32</td>
<td>0.002</td>
<td>5.07</td>
<td>0</td>
<td>5.07</td>
<td>0.95</td>
<td>0.8</td>
<td>0.003</td>
</tr>
<tr>
<td>S1-CG-54</td>
<td>4.29</td>
<td>4.3</td>
<td>1.4</td>
<td>1.95</td>
<td>-0.7</td>
<td>-0.1</td>
<td>0.002</td>
<td>7.96</td>
<td>0</td>
<td>7.96</td>
<td>1.4</td>
<td>1.16</td>
<td>0.004</td>
</tr>
<tr>
<td>S2-MG-54</td>
<td>5.03</td>
<td>5.17</td>
<td>1.53</td>
<td>2.33</td>
<td>-0.73</td>
<td>-0.31</td>
<td>0.002</td>
<td>8.31</td>
<td>0</td>
<td>8.31</td>
<td>1.53</td>
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<tr>
<td>S3-FG-54</td>
<td>1.96</td>
<td>1.92</td>
<td>0.86</td>
<td>0.73</td>
<td>0.38</td>
<td>0.48</td>
<td>0.001</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>0.86</td>
<td>0.65</td>
<td>0.003</td>
</tr>
</tbody>
</table>

---

**Fig. 2.** Laser scanning on the cylindrical half of the granitoid sample in different directions: (a) parallel to the sample length; (b) at an angle with the sample length.

**Fig. 6.** Laser scanning on the cylindrical halve of the granitoid sample in different directions: (a) parallel to the sample length; (b) at an angle with the sample length.

**Fig. 7.** 3D surface profile of coarse grained samples (38 mm and 54 mm in diameter),
is not obvious when $\sigma_{\text{eff}} \geq 10$ MPa (Fig. 14a). On the contrary, for fine grained samples S3-FG-38 and S3-FG-54, the variation in $Q$ is quite perceptible for $\sigma_{\text{eff}}$ even up to 25 MPa (Fig. 14c). It can be inferred that faster closure of fracture aperture is due to more asperities contact at $\sigma_{\text{eff}} \geq 10$ MPa for coarse grained samples in contrast with the fine grained samples (Fig. 14c), and hence, for coarse grained samples, fluid flow through samples S1-CG-38 and S1-CG-54 ceases and approaches to a point when $\sigma_{\text{eff}} \geq 10$ MPa (Fig. 14a).

Further, the variation in $Q$ with $\sigma_{\text{eff}}$ for both small and large samples with various grain sizes was plotted, as shown in Fig. 15a and b. It can be observed from the figure that the variation is nonlinear and initially there is a rapid decrease in $Q$ until $\sigma_{\text{eff}} \leq 15$ MPa and $\sigma_{\text{eff}} \leq 10$ MPa for small and large samples, respectively. When $\sigma_{\text{eff}} \geq 15$ MPa (Fig. 15a) and $\sigma_{\text{eff}} \geq 10$ MPa (Fig. 15b) for small and large samples, respectively, the variation in $Q$ with $\sigma_{\text{eff}}$ is negligible and fluid flow becomes almost constant. These results are quite consistent with the observations of Engelder and Scholz (1981) and Pyrak-Nolte and Morris (2000). These results indicate that fracture roughness does not contribute to fluid flow when $\sigma_{\text{eff}}$ is beyond a certain critical value (20 MPa and 15 MPa for small and large samples, respectively (Fig. 15a and b)). The fracture aperture changes to the residual aperture when $\sigma_{\text{eff}} \geq 20$ MPa and $\sigma_{\text{eff}} \geq 15$ MPa for small and large samples, respectively. It can be inferred that most of the asperities come in contact with each other at higher effective stress and fluid flow through such fractures completely ceases and approaches a point, and hence the variation in $Q$ with $\sigma_{\text{eff}}$ becomes constant, as shown in Fig. 15a and b.

Further, the Reynolds number, $Re$, is computed for all samples based on the measured $Q$ and sample dimensions, employing the following relationship (Zimmerman et al., 2004; Ranjith, 2010; Ranjith and Viete, 2011; Singh et al., 2015):

$$Re = \frac{\rho Q}{\mu W}$$  \hspace{1cm} (3)

where $\rho$ and $\mu$ are the density and dynamic viscosity of the fluid, respectively; and $W$ is the fracture width, which is a function of $e$.

The variation in $Re$ with $\sigma_{\text{eff}}$ for small samples with various grain sizes was plotted in Fig. 16. Two lines representing $Re = 10$ (Hassanizadeh and Gray, 1987) and $Re = 4$ (Ranjith and Viete, 2011) were added to mark the transition of flow from laminar to turbulent. It can be observed from the figure that $Re$ decreases nonlinearly with $\sigma_{\text{eff}}$, and most of the data points fall below the line $Re = 10$, indicating laminar flow conditions (Hassanizadeh and Gray, 1987), except for some data at $\sigma_{\text{eff}} \leq 2$ MPa for fine grained sample and $\sigma_{\text{eff}} \leq 1$ MPa for coarse grained sample. It should be noted that the sample S1-CG-38 is a coarse grained sample with moderately high $R_q$ and $R_v$ values (Table 2), indicating rough fracture surface with large asperities. In such a case, the effect of surface roughness on fluid flow is negligible (Ranjith, 2010) and hence higher $Q$ and $Re (>10)$ values can be observed. However, the sample S3-FG-38 is a fine grained sample and has small $R_q$ and $R_v$ values (Table 2), indicating the smooth fracture roughness with small asperities. It can be inferred that the discharge through the fracture of fine grained sample S3-FG-38 follows less tortuous path of flow (Table 3), and hence yields a high $Q$, and thereby $Re > 10$ can be observed. It can also be observed that $Re$ decreases rapidly with $\sigma_{\text{eff}}$ initially up to $\sigma_{\text{eff}} \leq 20$ MPa, and when $\sigma_{\text{eff}} > 20$ MPa, data of all the samples become asymptotic and no significant variation can be perceived. It can be inferred that the effect of surface roughness on $Re$ is insignificant when $\sigma_{\text{eff}} > 20$ MPa. This is mainly because of complete closure of fractures when $\sigma_{\text{eff}} > 20$ MPa, and as fluid flow through fractures becomes very less, $Re$ becomes almost constant.

4. Conclusions

A simple and well defined methodology has been developed and presented in this paper to simulate the effect of sample size on the fluid flow through a fractured granitoid rock containing a “rough walled fracture” under the laboratory environment. It has been demonstrated that split test technique was quite successful in creating a single fracture, and the variation in the grain sizes of the rock can be utilized to create a fracture surface of certain roughness, which can be quantified precisely by employing high precision 3D laser scanner. It has been observed that the variation in surface roughness of coarse and fine grained samples is quite distinct, as can be observed from the 3D surface roughness profiles. Based on a series of fluid flow experiments performed on samples of both sizes with variable roughness, it has been found that a linear relationship exists between $Q$ and $f_r$, and $Q$ is significantly less for large samples (54 mm in diameter) as compared to that for small samples (38 mm in diameter). It has been clearly demonstrated that the size effect on fluid flow exists, however, it does not contribute at higher stress,
i.e. when \( \sigma_{\text{eff}} \) is beyond a critical value (25 MPa). The discharge is quite sensitive to the effective confining pressure, flow pressure and fracture roughness when \( \sigma_{\text{eff}} \leq 10 \) MPa. However, when \( \sigma_{\text{eff}} \geq 20 \) MPa and \( \sigma_{\text{eff}} \geq 15 \) MPa for small and large samples, respectively, the fracture roughness does not contribute to fluid flow and the variation in \( Q \) with \( \sigma_{\text{eff}} \) is negligible or approaches a constant value. In such cases, the fracture aperture approaches the residual aperture, which is mainly attributed to the increase in the contact area of asperities at high confining stress and complete closure of fracture aperture. When \( \sigma_{\text{eff}} \) is beyond the critical value, further closure of aperture is impossible. Furthermore, there is a critical flow pressure beyond which deviation in linearity occurs. Also the study clearly demonstrates that the cubic law relationship is still useful for computing the hydraulic aperture, \( f_p \), of the fracture from the experimental fluid flow data, which is otherwise quite difficult and intricate to be measured and requires highly sophisticated instrumentations. The Reynold number is quite sensitive to \( f_p \), fracture roughness and \( \sigma_{\text{eff}} \), and a nonlinear relationship exists between \( Re \) and \( \sigma_{\text{eff}} \). "Re" values tend to be high (>10) for (i) fracture surface with larger aperture/coarse grained rock and (ii) fracture surface with smaller aperture/fine grained rock. In the case of (i), the effect of surface roughness on fluid flow is negligible because of larger aperture (Ranjith, 2010), and hence higher \( Q \) and \( Re \) (>10) values can be observed. However, in the case of (ii), the discharge through the fracture of fine grained sample S3-FG-38 follows less

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**Table 3**

Computed \( l_2 \) and \( l_1 \) values (in mm) of samples obtained from two-dimensional roughness profile.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( l_2 )</th>
<th>( l_1 )</th>
<th>( l_2 - l_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-CG-38</td>
<td>87.7</td>
<td>76.2</td>
<td>11.5</td>
</tr>
<tr>
<td>S2-MG-38</td>
<td>85.8</td>
<td>73.3</td>
<td>12.5</td>
</tr>
<tr>
<td>S3-FG-38</td>
<td>82</td>
<td>74.6</td>
<td>7.4</td>
</tr>
<tr>
<td>S1-CG-54</td>
<td>122.91</td>
<td>106.94</td>
<td>15.97</td>
</tr>
<tr>
<td>S2-MG-54</td>
<td>112.41</td>
<td>96.08</td>
<td>16.33</td>
</tr>
<tr>
<td>S3-FG-54</td>
<td>109.91</td>
<td>99.92</td>
<td>9.99</td>
</tr>
</tbody>
</table>

---

**Fig. 10.** Cylindrical samples with sealed axial walls comprising a single fracture (after Singh et al., 2015).

**Fig. 11.** The modified test setup used for determining the flow characteristics of water through the fractured rock mass (modified after Shukla et al., 2012; Singh et al., 2015).

**Fig. 12.** The variation of \( Q \) with \( f_p \) corresponding to various \( \sigma_{3} \) for samples S1-CG-38 and S1-CG-54.
Fig. 13. The variation in the slope, s, of Q–f_p curves with σ_3 corresponding to both sizes (38 mm and 54 mm) for (a) coarse, (b) medium and (c) fine grained samples.

Fig. 14. Q as a function of σ_{eff} for both sizes (38 mm and 54 mm) of (a) coarse, (b) medium and (c) fine grained samples.
tortuous path of flow (Table 3) and hence yields a higher Q value, thereby, higher Re (>10) values can be observed, especially at initially applied stress.

The methodology developed in the present work can be used quite satisfactorily to simulate the responses of extreme elevated flow pressures, confining pressures and fracture roughness collectively. Such studies are quite useful in correlating and extrapolating the laboratory scale experimental results to field/regional scale, it is essential to understand in detail (i) regional scale fracture system, (ii) its roughness characteristics, (iii) the relationship among fracture roughness, aperture and Q−σeff. properties, and (iv) regional scale deformation pattern.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

The authors are thankful to the IITB-Monash Research Academy, Indian Institute of Technology Bombay, Mumbai, India for providing the opportunity to work on this project. This work was supported and funded by BHP Billiton Ltd., Melbourne, Victoria, Australia. The authors are also grateful to the Head, Civil Engineering laboratory, Monash University for providing necessary laboratory support. The first author is also grateful to the Geological Survey of India, Southern Region for scrutiny and granting permission to publish this paper.

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