Control of non-Darcian flow by consolidation grouting in the surrounding rocks of a concrete-lined pressure tunnel

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Abstract. A concrete-lined hydraulic tunnel is currently under construction for water diversion and power generation in the Yangjiang Pumped Storage Power Station, Guangdong Province. This tunnel will be subjected to a maximum hydrostatic pressure of ~ 8 MPa during operation. This will present an extremely high pressure gradient in the surrounding rocks, which in turn may induce non-Darcian flow and even hydraulic fracturing in the fault and fracture system. How to control this unfavourable effect becomes one of the key technological issues for design and reinforcement of this tunnel. In this study, the groundwater flow behaviours in the surrounding rocks are investigated with Forchheimer’s law-based numerical simulations. The hydraulic properties are determined by in-situ packer tests and a universal correlation between hydraulic conductivity $K$ and non-Darcian coefficient $\beta$ (i.e., $\beta = k K^{−1.5}$). The performance of high-pressure grouting in suppressing the non-Darcian flow effect is quantified. The numerical results show that when the depth of grouting reaches 6 m, the grouting zone is effective in controlling the groundwater flow in the regime of Darcian flow in the fault zones and fracture network, and in reducing the amount of leakage out of the tunnel and lowering the risk of hydraulic fracturing in the surrounding rocks. This work provides valuable insights for understanding the role of consolidation grouting in controlling the groundwater flow behaviours in fractured rocks surrounding high-water pressure tunnels.

1. Introduction

Located in Guangdong Province, southern China, the Yangjiang Pumped Storage Power Station is currently under construction for load balancing. The station consists of an upper reservoir, a lower reservoir, and an underground tunnel and cavern system for water diversion and power generation (Figure 1(a)). The diversion tunnel, 7.5 m in diameter, is composed of an upper horizontal section, a middle horizontal section, a lower horizontal section, and two shaft sections connecting the horizontal ones. The tunnel is concrete-lined (1.0 m in thickness), and will be pressurized at ~ 8 MPa (with an extra surge pressure up to 3 MPa) during operation at the lower horizontal section. The depth of the lower horizontal section is around 505~530 m, and the surrounding rocks are mainly composed of unaltered medium coarse-grained granite ($f^s_{20}$). The main geological structures at the site consist of faults (e.g., $f_{21}$, $f_{47}$, $f_{751}$) and a fracture system critically striking towards N10°W~N5°E, N65°~75°E, N70°~80°W, N20°~30°W and EW, which form the potential leakage paths (Figure 1(b)).
Under such a high water pressure on the inner surface, cracking of the concrete lining will inevitably occur, leading to the onset of non-Darcian flow or even dilation and fracturing in the fault and fracture system [1]. It is therefore of paramount importance to evaluate if this unfavourable effect could be effectively suppressed by consolidation grouting and how the parameters of grouting could be optimized for this purpose.

Recently, many studies reported that high-quality grouting could both improve the strength and cut down the permeability of fractured surrounding rock [2-5]. However, in those studies, the methods and models are commonly derived from the linear Darcy’s law, and the influence of non-Darcian flow cannot be described. In this study, the groundwater flow behaviours in the surrounding rocks of the tunnel are investigated through Forchheimer’s law-based numerical simulations. The hydraulic properties of the aquifer system are determined by in-situ packer tests and a universal correlation between the viscous hydraulic conductivity $K$ and the non-Darcian coefficient $\beta$ (i.e., $\beta = \sigma K^{-1.5}$) [6]. The performance of high-pressure grouting in suppressing the non-Darcian flow regime is then quantified, and the optimized design parameters of consolidation grouting are proposed.

![Figure 1. Overview of the study area: (a) layout of the Yangjiang pumped storage power station; and (b) geological cross-section along the tunnel system.](image)

### 2. Methodology

#### 2.1 Description of non-Darcian flow

In the case of high flow velocity or high hydraulic gradient, the inertial effect of flow becomes important, and the relationship between flow velocity and hydraulic gradient deviates remarkably from the linear Darcy’s law [1, 6-14]. The flow behaviour is then governed by the Forchheimer’s law [14], which uses an additional quadratic term to represent the non-negligible inertial loss:
\[-\nabla h = \frac{v}{K} + \beta v |v| = (1 + Fo) \frac{v}{K}\]  

(1)

where \(h\) (m) is the pressure head, \(v\) (m·s\(^{-1}\)) is the flow velocity, \(K\) (m·s\(^{-1}\)) is the viscous hydraulic conductivity, \(\beta\) (s\(^2\)·m\(^{-2}\)) is the non-Darcian coefficient, \(|v|\) denotes the Euclidean norm of a vector, and \(Fo\) is the Forchheimer number defined as the ratio of the nonlinear to linear head loss:

\[Fo = \beta K |v| = \frac{E}{1 - E}\]  

(2)

where \(E\) is the non-Darcian effect factor proposed by Zeng and Grigg [15], defined as the ratio of the nonlinear to the total head loss. It is generally accepted that when \(E > 10\%\) (corresponding to \(Fo > 0.11\)), the non-Darcian effect is considered to be significant and should not be neglected [14-18].

2.2 Determination of non-Darcian flow coefficient \(\beta\)

One of the difficulties in performing Forchheimer’s law-based numerical simulation is to determine the values of \(K\) and \(\beta\) representative of the site conditions. These parameters can be directly interpreted from high-pressure packer test (HPPT) data [9, 19] or pumping test data [20-21]. When the test data is not available, a third strategy can be adopted for estimating the value of \(\beta\) from the more easily and economically obtained representative value of \(K\) [22]. This strategy uses traditional packer test data to determine the value of hydraulic conductivity \(K\), and then estimates the value of \(\beta\) using the universal power-law correlation between \(K\) and \(\beta\) recently developed by Zhou et al. [6] through a broad synthesis of published data and computational simulations:

\[\beta = \sigma K^{-1.5}\]  

(3)

where \(\sigma (s^{0.2} m^{-0.5})\) is an empirical coefficient related to the geometries of the media.

Due to lack of test data, the value of \(\sigma\) at the site has to be properly estimated. Figure 2 plots a subset of \((K, \beta)\) data obtained from HPPTs at other sites, with the lithology including granite [23-24], glutenite [1, 6], dolomite [25], limestone [22] and basalt [19]. The plot shows a significant power-law correlation between \(K\) and \(\beta\), with \(\sigma = 76.56\) s\(^{0.5}\)m\(^{-0.5}\) for the rocks at the field scale by best curve fitting to equation (3). The 95% confidence intervals of \(\sigma\) are 2.31 s\(^{0.5}\)m\(^{-0.5}\) and 2533.73 s\(^{0.5}\)m\(^{-0.5}\), respectively. Table 1 lists the representative values and ranges of \(K\) for rocks at the site determined by pack tests. With the assumption that the estimates of \(\sigma\) in Figure 2 are also valid at the site, the values and the 95% confidence intervals of \(\beta\) can be estimated by equation (3), as listed in Table 1.

![Figure 2](image_url)

**Figure 2.** The universal power-law correlation \(\beta = \sigma K^{-1.5}\) between non-Darcian coefficient \(\beta\) and hydraulic conductivity \(K\). The lithological type includes granite, glutenite, dolomite, limestone and basalt. The solid and dash lines show the best-fitted curve and the 95% confidence interval of \(\sigma\), respectively, from the collected data.
2.3 Numerical setup
The non-Darcian flow in the surrounding rocks, assumed to be steady-state, which is reasonable after long-term operation, is simulated with the finite element (FE) method based on the Forchheimer’s law (i.e., using equations (1) and (2) in the equation of continuity $\nabla \cdot \mathbf{v} = 0$, together with the water head, flux and seepage boundary conditions). Figure 3 presents the 3D numerical mesh, which contains 643,949 nodes and 2,074,930 brick or tetrahedral elements. The topographical and geological conditions (e.g., faults 1721, 1747 and 1751), and the engineering structures (e.g., the seepage-proof and drainage systems), are well represented in the numerical model. The pool water levels (i.e., 773.7 and 103.7 m) of the upper and lower reservoirs are prescribed as water head boundary condition. The inner surface of the high-pressure tunnel is also prescribed as water head boundary. The drainage system is prescribed as the potential seepage boundaries satisfying the Signorini’s complementary condition [26]. The base of the model is assumed to be impervious. Sensitivity analysis shows that the lateral recharge has little effect on the groundwater flow behaviors in the surrounding rocks, and hence the lateral boundaries are also assumed impervious. The FE computer code used for numerical simulation is modified from THYME3D [22, 26-27], which has been developed and validated for over 10 years.

![Figure 3. 3D finite element mesh for numerical simulation.](image)

3 Results and Discussion

3.1 Effect of consolidation grouting
Similar to [15], we accept that the non-Darcian effect becomes significant as $E > 10\%$ (i.e., $Fo > 0.11$), and we call the region having significant non-Darcian effect as non-Darcian flow region. We use the

| Material                  | Hydraulic conductivity $K$ (m·s$^{-1}$) | Non-Darcian coefficient $\beta$ (s$^2$·m$^{-2}$) |
|---------------------------|------------------------------------------|-----------------------------------------------|
| Completely-weathered granite | $8.6 \times 10^{-6}$                   | $3.04 \times 10^9$                             |
| Strongly-weathered granite  | $6.4 \times 10^{-7}$                   | $1.50 \times 10^{11}$                          |
| Weakly-weathered granite   | $3.0 \times 10^{-7}$                   | $4.66 \times 10^{11}$                          |
| Fresh granite              | $6.0 \times 10^{-8}$                   | $5.21 \times 10^{12}$                          |
| Faults and their influence zones | $2.0 \times 10^{-6}$ | $7.1 \times 10^{10}$                           |
| Reinforced concrete lining  | $1.0 \times 10^{-7}$                   | $2.42 \times 10^{12}$                          |
| Consolidation grouting     | $5.0 \times 10^{-8}$                   | $6.85 \times 10^{12}$                          |
| Grout curtain              | $5.0 \times 10^{-8}$                   | $6.85 \times 10^{12}$                          |
size of non-Darcian flow region, the amount of discharge out of the high-pressure tunnel and the maximum hydraulic gradient to evaluate the effect of consolidation grouting on controlling the non-Darcian flow. In numerical simulation, the initial depth of consolidation grouting is taken as 6 m.

Figure 4 plots the non-Darcian flow regions along the central profile of fault f747, with the value of $\sigma$ is 76.56 $s^{0.5} m^{0.5}$. The plot shows that when consolidation grouting is conducted around the tunnel, the non-Darcian flow region is well controlled within the grouting zone as a result of limited amount of discharge through the fault. If no consolidation grouting is performed, the size of the non-Darcian flow region increases up to ~ 30 m along fault f747, and the maximum value of $F_o$ increases from 0.34 to 1.83, indicating a significant role of the grouting zone in suppressing the non-Darcian flow along the fault system.

**Figure 4.** Plot of non-Darcian region along the central profile of fault f747: (a) with consolidation grouting; and (b) without consolidation grouting. The value of $\beta$ for each rock zone is estimated by equation (3) with $\sigma = 76.56 s^{0.5} m^{0.5}$. The symbols CWZ, SWZ, WWZ and FBZ refer to completely weathered, slightly-weathered, weakly-weathered and unaltered rock zones, respectively.

Figure 5 plots the variation of discharge out of the whole high-pressure tunnel with increasing non-Darcian coefficient $\beta$ of the fresh granitic rock (see Table 1 for its range). The plot indicates that consolidation grouting can effectively reduce the amount of discharge out of the tunnel, but with a decreasing rate as the degree of nonlinearity ($\beta$) increases. Quantitatively, the consolidation grouting results in a decrease of leakage by 17.0% and 2.2% when $\beta$ takes the lower-bound and upper-bound values, respectively.

**Figure 5.** Variation of discharge $Q$ with non-Darcian coefficient $\beta$ of the fresh granitic rock.
Figure 6 plots the distribution and variation of hydraulic gradient around the tunnel as the $\beta$ value of fault f747 increases from its lower bound to upper bound (see Table 1 for its range). When no grouting is taken, the maximum gradient ($i_{\text{max}}$) of f747 is no less than 25.2, and increases with the degree of flow nonlinearity (Figure 6(a)), leading to a high risk of dilation, seepage erosion or hydraulic fracturing in the fault zone. With consolidation grouting, much higher pressure loss and $i_{\text{max}}$ value occur in the grouting zone (Figure 6(a)), which lowers the $i_{\text{max}}$ value in the untreated fault zone to a magnitude no more than 5 even flow nonlinearity significantly develops (Figure 6(c)). This indicates that consolidation grouting is also effective in improving the stability of the fault system against seepage erosion or hydraulic fracturing.

![Figure 6](image)

**Figure 6.** Distribution and variation of hydraulic gradient in fault f747 as non-Darcian coefficient $\beta$ increases from lower to upper bound: (a) comparison of the maximum hydraulic gradient ($i_{\text{max}}$) with and without grouting; (b) distribution of hydraulic gradient around the tunnel when consolidation grouting is conducted; and (c) $i_{\text{max}}$ in f747 outside the grouting zone. The value of $i_D$ means the maximum gradient with non-Darcian coefficient $\beta$, $i_D$ is the maximum gradient in Darcian flow regime, and $i_D^*$ represents the maximum gradient when $\beta$ takes the optimal estimate $\beta^*$.

### 3.2 Optimization design of consolidation grouting

The purpose of consolidation grouting is to limit the amount of discharge out of the tunnel, and to improve the stability of faults and fractures against seepage erosion and hydraulic fracturing. Since the onset of flow nonlinearity increases the hydraulic gradient and hence the risk of erosion in the fault zone, the degree of flow nonlinearity and the size of the non-Darcian flow region should be properly controlled as well. The major design parameters for consolidation grouting that influence the flow behaviours include the depth of grouting zone ($D$) and the hydraulic conductivity of faults/fractures in the grouting zone ($K_c$). The latter is ensured by properly selecting the grout, the spacing of boreholes and the injection pressure, and can be measured by packer tests after grouting.

Figure 7 evaluates the performance of consolidation grouting as $D$ changes from 4 to 8 m and $K_c$ varies from $1.0 \times 10^{-6}$ to $1.0 \times 10^{-5}$ cm/s. The size of non-Darcian flow region (Figure 7(a)) and the amount of discharge along fault f747 (Figure 7(d)) increase with increasing $K_c$ and decreasing $D$. To suppress the non-Darcian flow region within the grouting zone, $K_c$ should be controlled lower than $5.0 \times 10^{-6}$ cm/s for $D < 6$ m. Such a small magnitude of permeability is hard, if not possible, to guarantee during construction, and hence a minimum depth of $D = 6$ m should be taken for grouting zone. Of
course, higher pressure loss in the grouting zone (Figure 7(b)) and lower hydraulic gradient and risk of hydraulic fracturing in untreated fault zone (Figure 7(c)) will be resulted for larger $D$ and smaller $K_G$. As long as the fault and fracture system is grouted with its permeability decreased to the magnitude of surrounding rocks (i.e., $K_G = 5.0 \times 10^{-6} \text{cm/s}$), the grouting depth of $D = 6 \text{m}$ is capable of reducing the hydraulic gradient in the untreated fault zone below 5 and the discharge along fault f747 below 0.16 L/s. Therefore, the values of $K_G = 5.0 \times 10^{-6} \text{cm/s}$ and $D = 6 \text{m}$ can be taken as the optimal design parameters for consolidation grouting, from the point of view of both seepage control performance and technical feasibility.

4 Conclusions
In this study, Forchheimer’s law-based numerical simulations were performed to investigate how consolidation grouting can be properly designed to suppress the occurrence of non-Darcian flow and improve the stability against seepage erosion and hydraulic fracturing in the surrounding rocks of a high-pressure tunnel. The hydraulic tunnel in the Yangjiang Pumped Storage Power Station was taken for illustration, which will be subjected to a maximum hydrostatic pressure up to ~ 8 MPa during operation. The hydraulic properties of surrounding rocks were interpreted from packer test data and estimated by a power-law scaling between non-Darcian coefficient $\beta$ and hydraulic conductivity $K$. 

Figure 7. Performance evaluation for the design parameters of consolidation grouting: (a) size of non-Darcian region in fault f747; (b) maximum hydraulic gradient in the grouting zone; (c) maximum hydraulic gradient in untreated fault zone; and (d) discharge along fault f747.
The numerical results show that the optimal design parameters for consolidation grouting are $D = 6$ m (the depth of grouting zone) and $K_C = 5.0 \times 10^{-6}$ cm/s (the hydraulic conductivity of grouted fault and fracture zones). With this design scheme, non-Darcian flow is well suppressed in the fault zone with limited amount of leakage and improved stability against seepage erosion and hydraulic fracturing.

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