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Estimation of groundwater inflow into tunnels in layered rockmasses

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Abstract

Rockmass natural variability makes it difficult to accurately predict tunnel inflows, however; accounting for anisotropy and the effect of high permeability structures on inflow rates is important for establishing estimates of inflows and preparing dewatering schemes. While analytical methods provide a baseline for estimating inflow in anisotropic rockmasses, these methods represent simplified boundary conditions, leading to the need for numerical methods. Drawing from a synthetic dataset of numerical modelling results, this paper provides guidelines on the use of existing analytical equations for anisotropy, and illustrates the numerical equivalence between anisotropic and layered rock.

Guidance is provided for numerical modelling of inflow into tunnels in highly anisotropic rock, where anisotropy changes the boundary sensitivity in numerical models, leading to larger model size requirements for tunnels in highly horizontally anisotropic rock (e.g., interbedded high and low permeability layers).

Drawdown of the water table due to tunnel drainage is also considered, and it is demonstrated that for drawdown associated inflow, boundary sensitivity is increased for tunnels in highly horizontally anisotropic rock.

Keywords

Groundwater, tunnelling, anisotropy, layered rockmass, numerical modelling

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1 Introduction and Theory

Large civil infrastructure, such as tunnels, caverns and deep excavations are increasingly being constructed in complex geological and hydro-geological environments, which are often in dense urban areas, close to existing critical infrastructure, and beneath the water table. Estimation of groundwater inflow is essential for tunnel design and construction, however; inflow is difficult to predict, and this estimation process is even more complicated when dealing with layered and anisotropic geological formations, for which few analytical solutions exist. Further, natural variability in rockmasses and a lack of geotechnical data makes it difficult to create models which are truly representative of real-life conditions, and thus factors are adopted to account for variability. Anisotropic hydraulic conductivity is one of these factors, and is often used so that layered rockmasses can be represented as a continuum.

1.1 Anisotropy and Heterogeneity of Hydraulic Conductivity

There is a high degree of variance in hydraulic conductivity throughout most geomaterials. This variance occurs throughout space in the geological formation (heterogeneity) and can also be directional (anisotropy).

Heterogeneity can be broadly divided into three classes (Freeze and Cherry 1979). *Layered heterogeneity* is common in sedimentary rocks and unconsolidated lacustrine and marine deposits. Here, individual layers are thought to have homogeneous hydraulic conductivity, but the hydraulic conductivity varies between layers, and the entire system is considered heterogeneous. *Discontinuous heterogeneity* is caused by large scale stratigraphic features and faults, where abrupt change in the type of geological formation is associated with sharp changes in hydraulic conductivity. *Trending heterogeneity* is commonly associated with deltas, alluvial fans, and glacial outwash plains, though it can occur in any type of formation.

Anisotropic hydraulic conductivity can occur at a variety of scales. Small scale anisotropy in the hydraulic conductivity of sediments and sedimentary rock is usually due to clay mineral orientation. Core samples show that K_H/K_V is rarely larger than 10, and often less than 3 for clays and shales (Woessner and Poeter 2020). Large scale anisotropy in hydraulic conductivity occurs due to layering of relatively high and low permeability materials (Maasland 1957, Marcus and Evenson 1961). Field scale anisotropy (K_H/K_V) in layered formations is highly variable. Weeks (1959) shows examples of wells in glacial outwash in Wisconsin where K_H/K_V varied from 2 to 20, and Wenzel (1942) recorded ratios of 5 to 14 in the sediments of Grand Island, Nebraska. Domenico and Schwartz (1990) give estimates of maximum and minimum horizontal and vertical hydraulic conductivities, with an average K_H/K_V of 10 for anhydrite and shale, and a K_H/K_V of 2 for chalk, limestone, dolomite and sandstone

However, Freeze and Cherry (1979) and Woessner and Poeter (2020) both report ratios of K_H/K_V can exceed 100:1 to 1000:1 where coarse-grained and fine-grained materials are interlayered, or fracture sets dominate. While it is most common for K_H to exceed K_V in sedimentary formations, there are cases where fracturing causes rocks to behave anisotropically, due to directional variations in joint aperture and spacing, in which cases K_V can exceed K_H (Snow 1969).

1.2 Analytical Solutions for Tunnel Inflow

Analytical methods based in Darcy's Law and conservation of mass form the basis for all tunnel inflow solutions. While no analytical solution can exactly match field conditions, they provide insight into groundwater systems that, while idealized and simplified, remain relevant. One of the most common challenges in using these methods is understanding their applicability, and the boundary conditions they implicitly represent. Using the wrong method can lead to results varying by orders of magnitude.

1.2.1 Tunnel Inflow in Isotropic Materials

The two most simple solutions for tunnel inflow are radial inflow (Dupuit, 1863; Forchheimer, 1886 and the Thiem equation) and inflow with a line source (Goodman et al., 1965; Muskat, 1937; Polubarinova-Kochina, 1962).

Radial flow is practically applied to wells and shafts but can also be applied to tunnels in certain conditions. For a simple case of an unconfined radial flow into a vertical, air-filled shaft with a circular cross section, through a uniformly permeable material, the Dupuit-Forchheimer equation (Eq.1) (Dupuit, 1863; Forchheimer, 1886) can be applied.

$$Q = \pi K \frac{H^2}{\ln\left(\frac{r_0}{r}\right)} \tag{1}$$

The Thiem (1870, 1906) equation configures Darcy's Law for cylindrical coordinates around a vertical well in a confined aquifer. The modification below (Eq. 2) allows for the calculation of inflow into a deep, air-filled tunnel. The applicability of this equation is limited however, as the radius of influence (r_0) is rarely known, and is rarely uniformly radial.

$$Q = 2\pi K \frac{H}{\ln(\frac{r_0}{r})} \times tunnel\ length \tag{2}$$

Contrary to radial inflow equations, line source and sink equations recognize that inflow into a tunnel is unlikely to be radially symmetrical. These equations are representations of inflow into a tunnel beneath an infinite reservoir or water table which is not drawn down (such as a permeable aquifer with a nearby and plentiful source of recharge). Line source and sink equations are presented in various works (Freeze and Cherry 1979; Goodman et al., 1965; Muskat, 1937; Polubarinova-Kochina, 1962), but take the general form presented in Eq. 3. For the case of an infinite reservoir, the parameter z in Eq. 4 represents the height of the ground surface.

$$Q = 2\pi K \frac{H}{\ln(\frac{2H}{r})} \tag{3}$$

$$Q = 2\pi K \frac{H}{\ln(\frac{2z}{r})} \tag{4}$$

Both radial and line source and sink equations have limited applicability. They overestimate inflow in cases where drawdown occurs. They also do not account for the transient phases of flow, nor for changes in inflow due to heterogeneity and anisotropy of the geomaterials.

1.2.2 Tunnel Inflow in Anisotropic Materials

For practical engineering problems, most geological settings will have some degree of anisotropy. Depending on the degree of anisotropy, this can make the use of simple solutions difficult. El Tani (1999) proposes an equation for water inflow into a tunnel in an anisotropic medium, where inflow is calculated using an approximated integration around the tunnel perimeter based on the green's function of an anisotropic aquifer (Eq 5).

$$Q = \frac{2\,\pi\sqrt{K_H K_V} H_r}{\ln(\frac{4H}{r})\frac{\sqrt{K_H}}{\sqrt{K_H}+\sqrt{K_V}}\sqrt{1+\frac{K_V-K_H}{K_H}\frac{r^2}{4H^2}}} \tag{5}$$

In Eq. 5, H_r=H for an air-filled tunnel.

This equation has similar limitations to the line source and sink equation, in addition to further limitations due to the nature of anisotropic flow. Like the line source and sink equation, a semi-infinite recharge surface in a continuous medium are considered, and other boundary conditions are ignored. Boundary conditions are of particular importance for highly anisotropic geological media, where water can be pulled from far-away distances through highly permeable layers and fractures. Because of this, creating equivalent numerical models of the El Tani (1999) requires particular attention to boundary conditions, in order to approximate this semi-infinite condition.

2 Numerical Modelling of Tunnel Inflow in Anisotropic Rock

2.1 Equivalent Anisotropy and Layered Heterogeneity

For tunnel inflow in layered formations where there is a high contrast between the hydraulic conductivities of different layers, there are two general approaches for numerical modelling: explicit representation of layers, and anisotropic hydraulic conductivity. On a large scale, the relationship between layered heterogeneity and anisotropy (Maasland 1957, Marcus and Evenson 1961) can be used to create equivalent numerical models. Figure 1 shows two equivalent models, and the equations used to establish equivalent K_1 and K_2 with K_V and K_H, as described by Freeze and Cherry (1979).

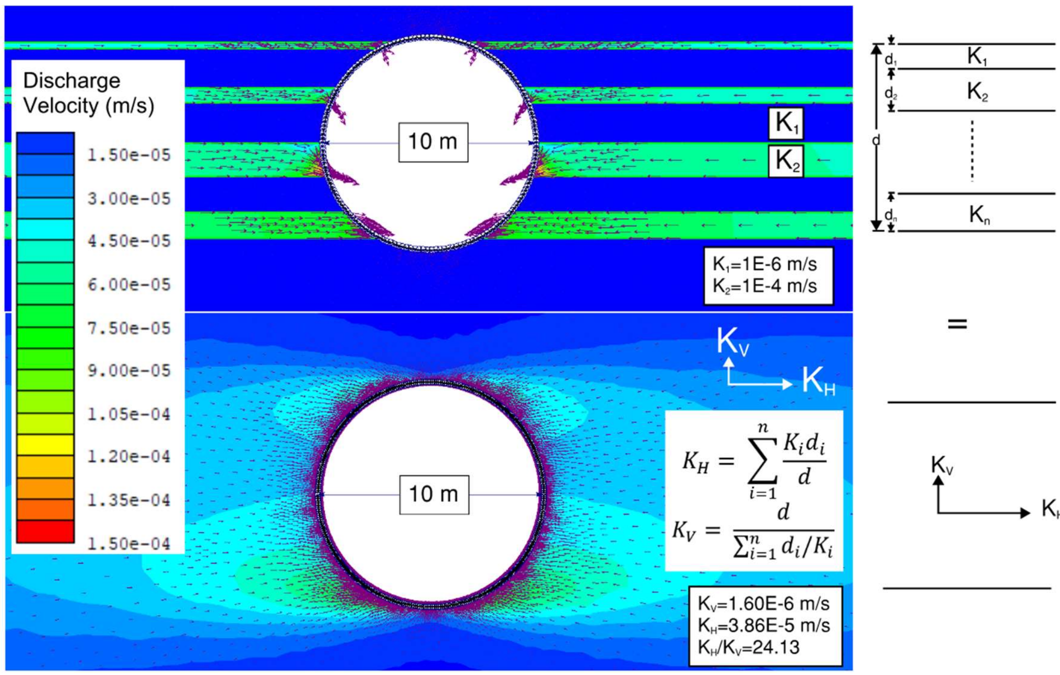

Figure 1: Relation between layered heterogeneity and anisotropy, where equivalent anisotropic hydraulic conductivity can be used to represent a layered system in a continuous numerical model. The figure shows an example of explicit representation of layers of different hydraulic conductivities (K_1 and K_2, where K_2>K_1), and a model with equivalent K_V and K_H.

2.2 Boundary Sensitivity in Anisotropic Models

The analytical solution for tunnel inflow in an anisotropic material (El Tani 1999) is based on the Green's function of an anisotropic aquifer. Similar to the line source and sink equation (Goodman et al., 1965; Muskat, 1937; Polubarinova-Kochina, 1962), it is semi-infinite, with an infinite line source above the tunnel (similar to a constantly recharging water table or infinite reservoir). The bottom and side boundaries in these cases are non-existent. For a layered system it is considered that flow will be horizontal if there is a difference in hydraulic conductivity between layers of more than 100 (equivalent to K_H/K_V > 15 to 25, depending on layer thickness) (Neuman and Witherspoon 1969). This phenomenon can be seen in the models shown in Figure 2, where for increasingly anisotropic simulated material, flow becomes increasingly horizontal. Therefore, the idealized representation of a semi-infinite aquifer, can in some cases be at odds with realistic representation of flow through a highly anisotropic material, as this flow is often unidirectional. The primary source of recharge may be at some lateral distance away from the tunnel for K_H>K_V materials (e.g., interlayered sediments), or directly above the tunnel for K_V>K_H materials (e.g., rock with vertical fracturing). Instead of only considering the idealized setting represented by the analytical solution, the boundary conditions of numerical models should be considered on an individual basis. For continuous anisotropic representation of a layered material, A side boundary condition of total head may be appropriate at some far-away distance from the tunnel. Figure 3 shows that anisotropic models are sensitive to boundary conditions, and that large models are required to see a convergence in models with and without a total head side boundary applied. The results are summarized in Table 1. In models smaller than those specified in Table 1, applying a total head side boundary condition will result in more flow being measured at the tunnel wall, compared to a model with only a top (zero pressure) boundary condition applied. This illustrates the difficulty in applying realistic boundary conditions to anisotropic flow models.

Even when minimizing boundary effects, it is noted that the El Tani (1999) solution is difficult to replicate in models with a high degree of anisotropy. Figure 4 shows convergence with the analytical solution for models of sizes meeting the conditions outlined in Table 1, for K_H/K_V between 0.01 and 100. Outside of this range, models diverge from the analytical solution.

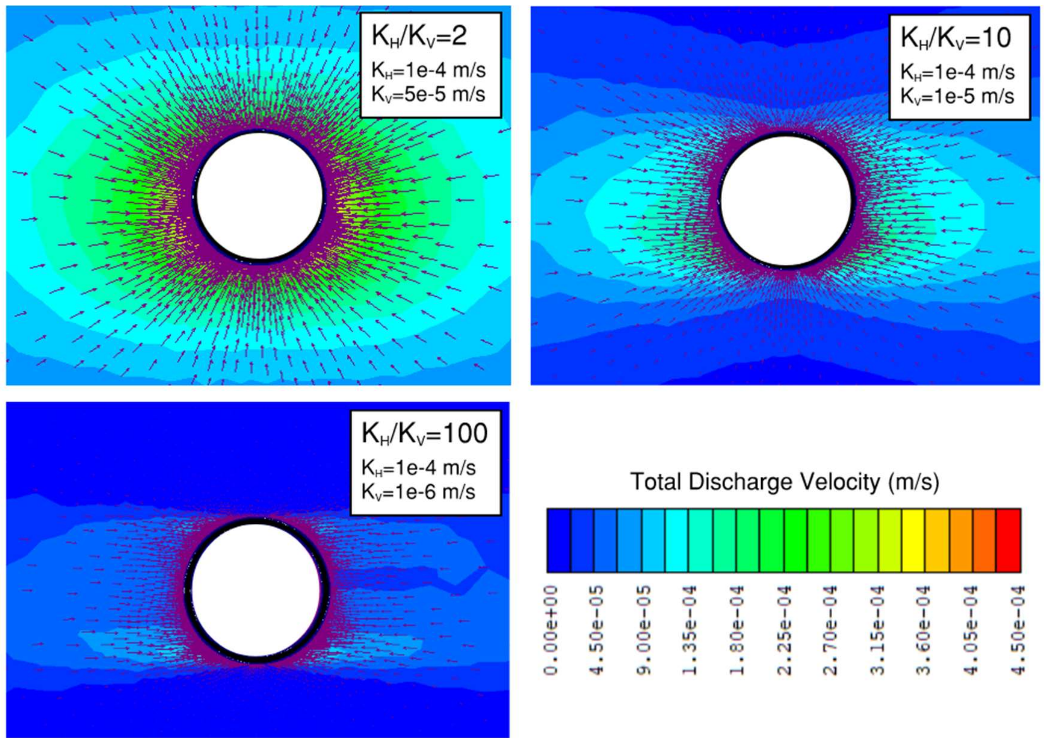

Figure 2: Effect of reducing vertical hydraulic conductivity: highly anisotropic material causes primarily unidirectional flow

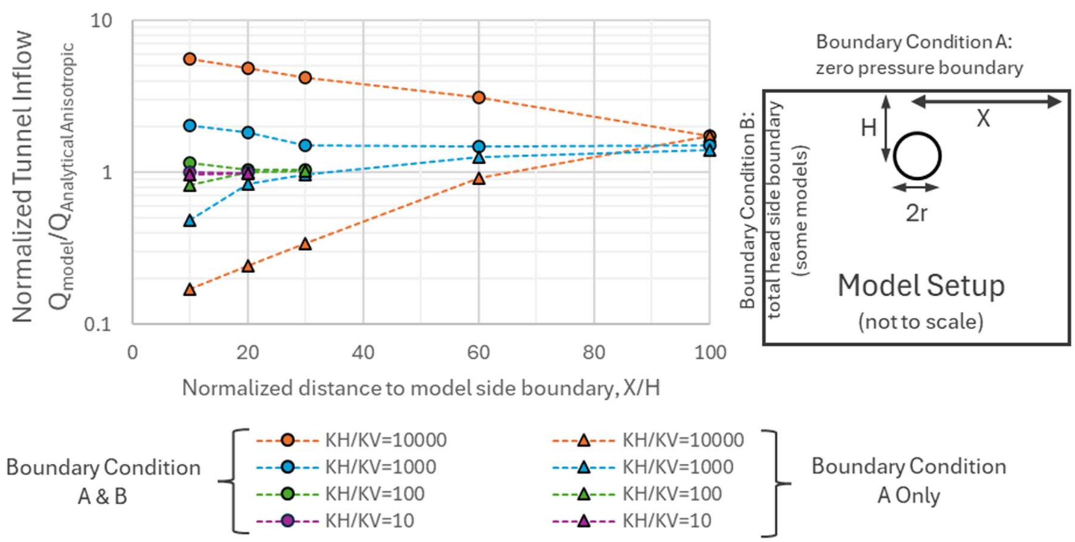

Figure 3: For FEM RS2 groundwater model of a tunnel in an anisotropic medium, showing the effect of model size on tunnel inflow with different boundary conditions.

Table 1: FEM model size requirements to reduce boundary effects in models of a tunnel excavated below an infinite reservoir or constant water table (based on results shown in Figure 3).

K_H/K_V	**X/H requirement**
10	10
100	20
1000	60
10000	1000

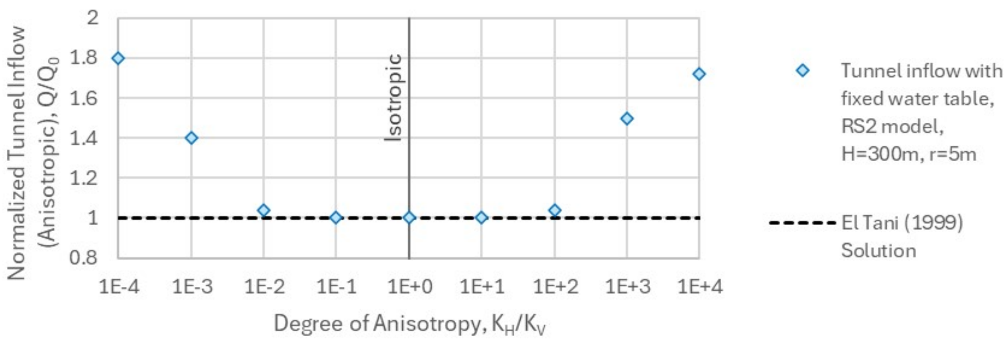

Figure 4: Variance of RS2 FEM models from the El Tani (1999) analytical solution for K_H/K_V 0.0001 to 10000.

2.3 Groundwater Drawdown in Anisotropic Ground

While it is shown in the previous section that the El Tani (1999) solution for tunnel inflow in anisotropic ground can be replicated with numerical models with boundary conditions at a sufficient distance away from the tunnel, there is no analytical solution for the influence of drawdown on inflow into tunnels in anisotropic rock. Drawdown of the water table due to tunnel inflow is of major consequence in many regions. Drawdown is a boundary problem; it depends on the distance from the tunnel at which equilibrium can be established due to recharge, which is variable and dependent on hydrogeological setting. It is shown by Markus and Diederichs (2024) that for a tunnel in an isotropic, homogenous medium, that inflow and associated drawdown are a function of H, r, and X. Where H is the depth of the tunnel below an initial water table, r is the tunnel radius, and X is the distance from the tunnel centreline to the side boundary at which equilibrium is established. The shape of a drawn down water table in steady state conditions is independent of hydraulic conductivity in an isotropic material but is affected by the ratio of K_H/K_V in an anisotropic material. For $K_H>K_V$ (e.g., layered rockmasses), tunnel drainage causes a wide radius of influence around the tunnel, as water is pulled through layers from farther-away sources. This can be of particular consequence in cases where surface reservoirs can be influenced by tunnel drainage, or where settlements induced by drawdown can damage infrastructure. For $K_V>K_H$ (e.g., rockmass with primarily vertical jointing), the magnitude of vertical drawdown can be greater, with the vertical column above the tunnel often completely draining.

Figure 5 shows an example of the influence of anisotropy on the shape of groundwater table drawdown in numerical models. In these models, a circular tunnel of radius r=5m is located 300 m below an initially flat water table, from which drawdown is permitted. Additionally, a boundary condition is enforced at a lateral distance of 6000 m from the tunnel. The model results depict steady state conditions where drawdown of the water table occurs and reaches equilibrium with the X=6000m boundary. In materials where $K_H>K_V$, a flattened drawdown shape illustrates how water flows primarily horizontally through the simulated rockmass. While the vertical magnitude of drawdown is less in $K_H>K_V$ materials, in the absence of enforced boundary conditions, drawdown would continue to extend laterally until a source of recharge was established. There is no standard boundary condition for drawdown which will provide satisfactory results simulating an analytical equation, as drawdown is a fundamentally boundary dependent problem. Because of this, the tendency for water to flow horizontally in $K_H>K_V$ anisotropic materials means that the zone of influence of the tunnel can be very wide.

The reduction in inflow due to drawdown, relative to the analytical anisotropic solution (El Tani 1999) is shown in Figure 6, for models of three different boundary conditions (X=3000m, 6000m and 9000m). While the analytical anisotropic solution can be used to predict inflow under a constant water table or infinite reservoir, it does not account for the reduction in steady state inflow associated with a drawdown water table. While the drawdown associated inflow for $K_H=K_V$ can be predicted using the method presented by Markus and Diederichs (2024), the figure shows the effect of anisotropy on drawdown associated inflow. There is no equation which accounts for both anisotropy and drawdown. Due to the flattened shape of drawdown in $K_H>K_V$ anisotropic materials, pore pressures above the tunnel remain high, inflow into the tunnel will not experience the significant reduction effect usually associated with a depressed water table (demonstrated by both Moon and Fernandez 2010, and Markus and Diederichs 2024). For $K_H>K_V$, drawdown associated inflow is more boundary dependent than an equivalent isotropic scenario, like the effect seen in no-drawdown models in Section 2.2.

In contrast, the magnitude of steady state tunnel inflow will be less in $K_V>K_H$ models, relative to the analytical solution (El Tani 1999), which does not account for drawdown. It is shown that at $K_H/K_V=0.01$, water inflow into the tunnel is pulled vertically, primarily from above the tunnel, and inflow is less boundary dependent compared to isotropic models.

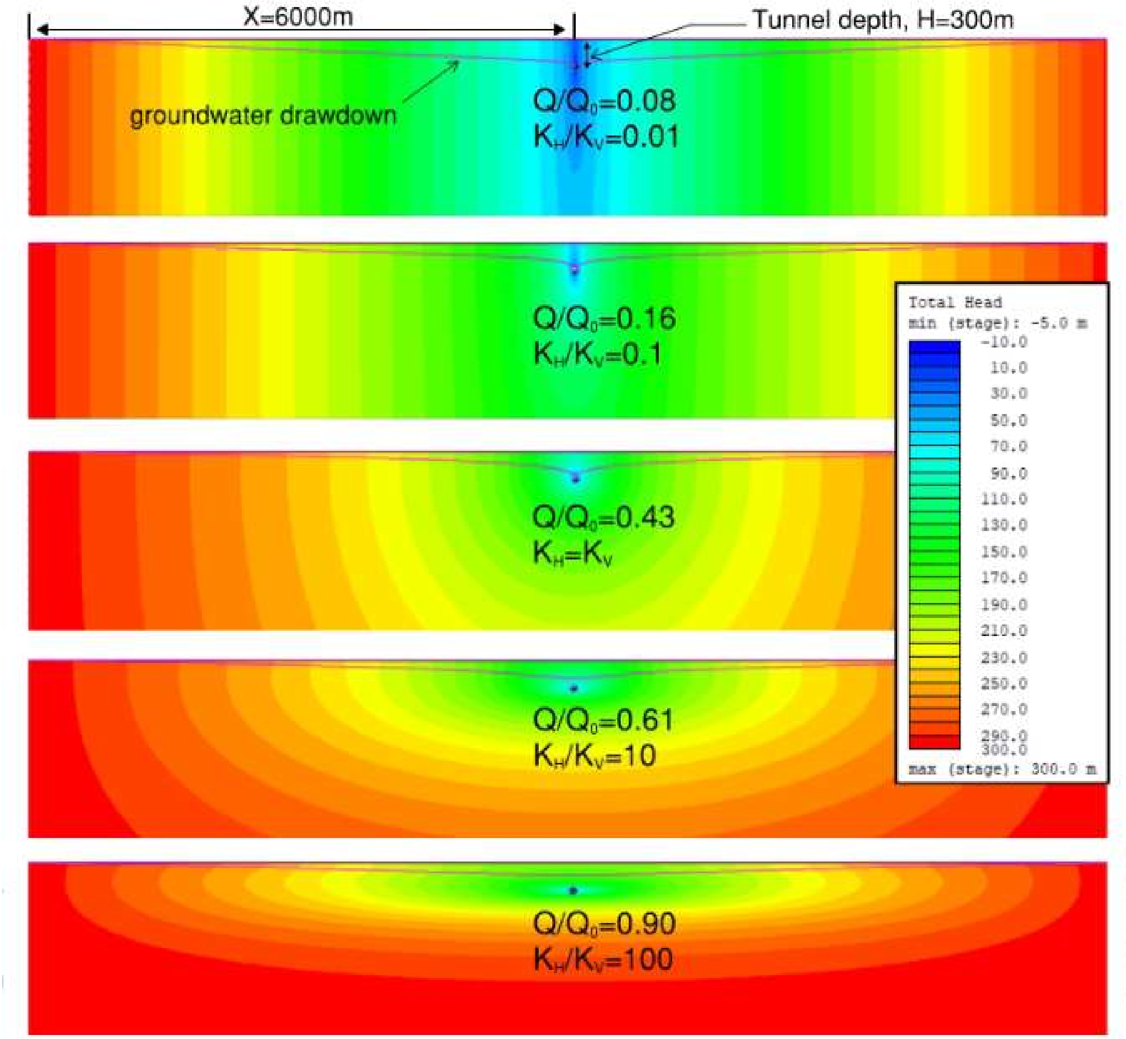

Figure 5: RS2 FEM model of inflow into a tunnel with an initial water table 300 m above the tunnel, and varying degrees of anisotropy (K_H/K_V= 0.01 to 100). Drawdown of the water table is shown for each model, with a flattened shape for $K_H>K_V$. Normalized tunnel inflow is marked for each model.

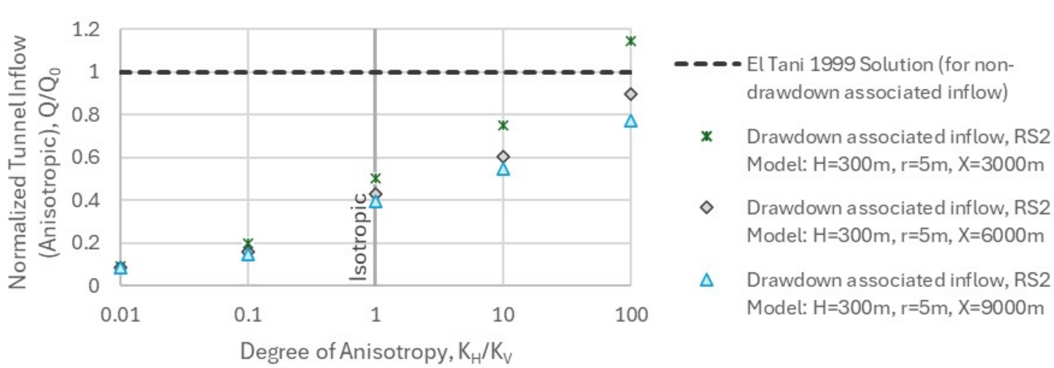

Figure 6: The effect of drawdown on variance from the analytical solution for inflow into a circular tunnel in an anisotropic material.

3 Conclusions

Estimation of inflow into tunnels in anisotropic ground poses unique challenges. While the El Tani (1999) equations provides an efficient method for estimating inflow into tunnels where sufficient recharge is available as to not draw down the water table, numerical methods are required for calculation of more complex conditions. The finite element method can be used to estimate tunnel inflow in various conditions but requires careful consideration of boundary conditions. Anisotropic models are more boundary sensitive than isotropic models. For isotropic models, and models where $K_H/K_V<10$, the distance from the tunnel centreline to the model side boundary (X) should be at least 10 times the tunnel depth below the water table (H) (X/H>10). However, as anisotropy increases, so does the required model size (X/H) needed to avoid boundary effects on inflow. Table 1 provides guidelines for model size at different degrees of anisotropy. For a smaller model configuration than prescribed in Table 1, inflow into the tunnel will be sensitive to the boundary condition placed on the side of the model. Applying a total head boundary condition of H will lead to increased inflow if the model is smaller than the required size. This applies to models where it is assumed that the water table will not be drawn down, and a zero-pressure boundary condition can be applied to the top boundary. For models with drawdown, inflow will remain sensitive to model size and is increasingly sensitive as the ratio of K_H to K_V increases. The shape of drawdown is significantly influenced by the anisotropy, where a tunnel in a horizontally anisotropic material ($K_H>K_V$) will draw water from a farther distance, leading to a flattened drawdown shape, and an increased steady state inflow, relative to a tunnel in isotropic ground. In a vertically anisotropic material ($K_V>K_H$), the shape of drawdown will be steep, and steady state inflow less than it would be in an isotropic material.

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