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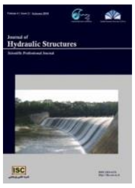

Hydraulic Response to Geometry: Finite Element Modeling of Underground Spaces in Saturated Environments

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Abstract

Tunneling operations face a significant challenge in managing water inflow into excavated underground spaces, primarily initial or excavating caused discontinuities in tunnel walls. The water flow rate is intricately linked to the geometric shape of the tunnel, making it a crucial consideration during infrastructure design and construction to mitigate the risks associated with water infiltration. This study employs the finite element numerical method to explore how different geometric shapes (circular, D-shaped, rectangular, and irregular hexagon tunnels), along with parameters like excavated space area, excavated space perimeter, water head, and permeability coefficient anisotropy, influence steady-state water inflow into tunnel as saturated environments. Results demonstrate that the geometric shape of underground spaces has a substantial impact on water ingress, with circular tunnels exhibiting notably lower inflow rates compared to other shapes under similar conditions. However, the overall dimensions of the simulation model may also influence the observed impact. The research underscores the necessity of considering both geometric shape and overall dimensions for effective drainage in tunnel design. While circular tunnels generally prove to be a safe choice, further project-specific analysis may be warranted. It is crucial to acknowledge that accurately predicting the influence radius requires intricate numerical modeling or physical experiments accounting for all relevant factors, as the impact of shape is just one facet, with other design and geological factors playing equally crucial roles.

Keywords: Water Inflow, Tunnel, Numerical Modeling, Geometric Shape.

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1. Introduction

The utilization of underground spaces is becoming increasingly widespread and diverse. One prevalent type of underground space is tunnels, constructed for various purposes. Among the primary challenges encountered in tunnel excavation is the infiltration of water into the tunnels. Issues arising from water leakage into the tunnel environment include a decrease in the stability of the surrounding rock mass, the imposition of excess pressure on both permanent and temporary support systems, and detrimental effects on the geomechanical condition of the rock, subsequently posing potential hazards to both life and finances [1-4].

One crucial factor influencing the water flow rate is the geometric shape of the tunnel. Considering the tunnel shape during the design and construction of infrastructure is essential for minimizing the risk of water infiltration and associated damages. Despite previous studies, limited attention has been given to the examination of this factor. Notable among these studies is the investigation of the impact of tunnel geometry on water leakage, exemplified by the study conducted on the Dorud-Khorramabad railway tunnel using analytical and numerical methods for estimation [5].

Due to the inherent difficulty in identifying and precisely determining all factors affecting water flow into the tunnel, especially during the excavation process, accurate prediction of water infiltration into the drilled tunnels within the rock environment is challenging. Various analytical methods and equations, based on simplifications and practical assumptions, are widely employed for calculating the water leakage into tunnels [6,7].

In addition to analytical methods providing a general estimate of leakage, considering the fundamental equations governing leakage flow and site-specific characteristics, numerical methods such as finite element, finite difference, discrete element, or finite volume approaches can be employed. Through the utilization of numerical methods, the flow of groundwater leakage into the tunnel environment can be simulated. Then, the leakage values into the tunnel can be computed in different regions of the construction site. Unlike analytical methods, numerical methods are not computationally simple, and they require comprehensive information about the construction site. They are also less reliant on simplifications and assumptions. As a result, numerical methods are more complex and time-consuming to implement, but they yield more accurate results compared to analytical methods [8,9].

The shape of the tunnel is a significant factor affecting the amount of water inflow. The geometry of the tunnel influences the flow patterns and pressure distribution within the tunnel, which in turn affects the rate of water seepage [10].

Several factors related to tunnel shape can influence water inflow, including:

Cross-sectional shape: The cross-sectional shape of the tunnel, such as circular, rectangular, or horseshoe-shaped, can affect the flow velocity and pressure distribution within the tunnel.

Tunnel size: The size of the tunnel, such as its diameter or width and height, can influence the amount of water that can be stored within the tunnel and the rate of water flow.

Tunnel alignment: The alignment of the tunnel, such as its slope and curvature, can affect the direction of water flow and the potential for water to accumulate in certain areas of the tunnel. In other words, the shape and alignment of the tunnel affect the velocity and turbulence of the flowing water. Sudden changes in direction or steep slopes can lead to turbulence, eddies, and areas of low pressure where water may settle. Also, the alignment of the tunnel entrance and exit points also influences water flow. If these points are not well-designed, water can accumulate during heavy rainfall or in situations of high water flow, leading to potential flooding.

The geometry of a tunnel significantly influences water pressure conditions, hydraulic boundary conditions, and flow of seepage. Research indicates that different tunnel shapes can lead to various water flows, where factors such as water velocity and pressure are influenced by tunnel dimensions. Furthermore, the distance from the tunnel excavation surface to geological features, such as faults, can also impact the rate of water ingress. Consequently, the shape of a tunnel plays a crucial role in determining the characteristics of seepage and the magnitude of water flow, making it a focal point in underground construction projects and water management [11-14].

Advantages of circular tunnels regarding water ingress include the following aspects:

1. Uniform Stress Distribution: Circular tunnels distribute loads more uniformly, reducing the risk of stress concentration and potential failure compared to other shapes, such as square tunnels [15].
2. Analytical Solutions: Analytical solutions exist for estimating water ingress into circular tunnels, aiding in tunnel design, construction, and environmental impact assessment [16].
3. Leakage Prevention Effect: Research has demonstrated that the leakage prevention effect of flow by injection can be assessable in circular tunnels, making it significant for water flow management [17].

However, explicitly mentioned disadvantages of circular tunnels in terms of water ingress have not been reported in the conducted studies. Nevertheless, it is essential to note that the design, construction, and maintenance of tunnels can be costly, and there may be specific constraints based on geological and hydrogeological conditions. In this article, an attempt has been made to study the impact of the geometric model of underground spaces on the steady-state groundwater inflow using finite element modeling.

2. Finite Element Method in Solving the Groundwater Inflow Equation to Tunnels:

The Seep/w software is a versatile and comprehensive computer program capable of providing analyses in dynamic and static domains. It employs the finite element method for analyzing and modeling water flow. In essence, this software is a numerical model with the ability to simulate the mathematical representation of the actual physical process of water flow in a porous medium. Seep/w, as part of the GeoStudio software suite, has the capability to analyze various flow conditions, including saturated or unsaturated flows in confined or unconfined aquifers in two-dimensional settings, assuming that hydraulic conductivity and water content are functions of the pore-water pressure [18, 19].

The fundamental equation of groundwater flow in two dimensions, considering both saturated and unsaturated flow conditions, is derived by combining Darcy's law and the continuity equation:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)=C\frac{\partial}{\partial t}(h)+Q \tag{1}$$

In this equation:

Kx and Ky are the coefficients of permeability in the x and y directions, h is the hydraulic head, t is time, x and y are Cartesian coordinates, C is the slope of the moisture characteristic curve, and Q is a flow source such as pumping or recharge.

The hydraulic head (h) is related to the volumetric water content (θ) through the relationship:

$$\frac{\partial \theta}{\partial t}=C\frac{\partial h}{\partial t} \tag{2}$$

In Seep/w, the Galerkin approximation method is used for solving the groundwater flow equation in two dimensions. This method, with appropriate consideration of boundary conditions, provides an approximate solution for the equation. The groundwater flow equation (3) can be written in the following form within the software:

$$L\left(h\right)=\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)-C\frac{\partial}{\partial t}\left(h\right)-Q=0 \tag{3}$$

The Seep/w software is a valuable tool for modeling and solving various hydrological, hydrogeological, geotechnical, and mining problems. It can be utilized for modeling tunnels with different geometric cross-sections, representing different geological layers with distinct hydraulic properties, and simulating continuous environments. However, it has limitations, such as the inability to model discontinuous environments where water flow is a function of fractures within the rock mass [20,21].

3. The Geometric Shape Effect on Groundwater Inflow into Underground Spaces:

In this study, the finite element software Seep/W was employed to investigate the impact of the geometric shape of underground spaces on groundwater inflow. A two-dimensional numerical model was used to explore variations in several geometric parameters of underground spaces, including the shape of the underground space such as circle, D-shape (combination of a rectangle and a half-circle), irregular hexagon, and rectangle, the area of the underground space (S), the perimeter of the underground space (P), the anisotropic permeability ratio (Ky/kx), and the groundwater table level (H). Two geometric dimensions of the model (domain model) were simulated, measuring 50 by 30 square meters and 100 by 60 square meters. Figure 1 illustrates the schematic geometric model of numerical simulations along with the utilized parameters.

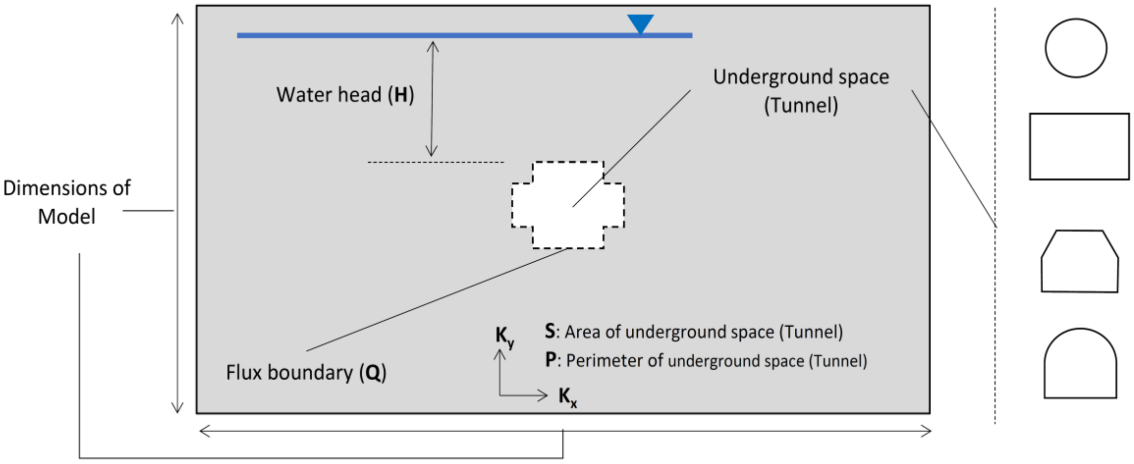

Figure 1: Schematic Geometric Model and Parameters Utilized in Numerical Simulation.

The simulations utilized boundary conditions as follows: constant head at the lateral boundaries on the right and left sides, flow boundary around the tunnel, and a no-flow boundary at the model's base. The modeling and numerical analysis procedure can be outlined as follows:

1. Geometric modeling of the domain and delineation of tunnel.
2. Application of material properties (permeability coefficient).
3. Application of appropriate boundary conditions (as mentioned above) and meshing the model for two-dimensional finite element analysis.

In the numerical analysis, the model domain, configured as a rectangular shape, underwent discretization into finite element meshes. Therefore, the type of square and triangular elements was chosen in the pattern of finite element mesh, and based on the dimensions of the model and its excavated underground spaces, for the 50 by 30 square meters model, the element number was set in the range of 326 to 469, while for the 100 by 60 square meters model, the element number was applied within the range of 342 to 499.

Figure 2 illustrates a sample of the numerical simulation of groundwater inflow into various underground spaces within a 30 square meter area. It is essential to note that the modeling was performed in a steady-state and two-dimensional configuration

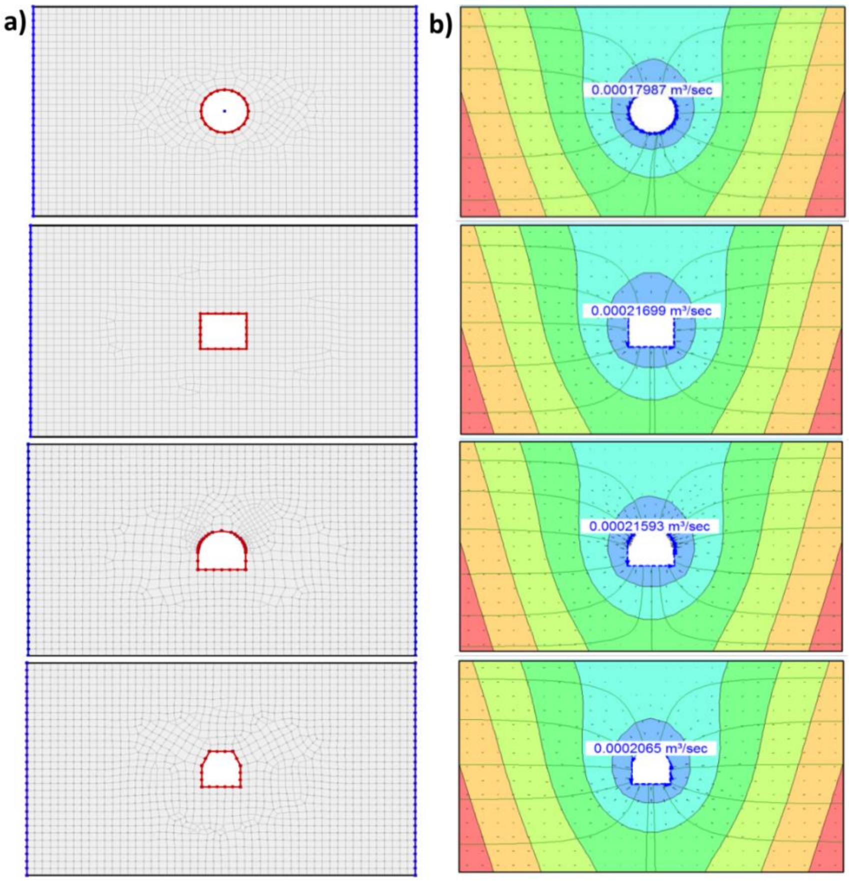

Figure 2: Simulation of various models of groundwater inflow into tunnels in spaces with an area of 30 square meters in dimensions of 50 by 30 square meters. (a) Illustration of the meshing approach and the Define state, (b) Simulated groundwater inflow into the tunnel in the Results state.

3.1 The Effect of Geometric Shape of Underground Space on the Groundwater Inflow Based on the Area of Excavated Space (S):

To investigate the influence of the geometric shape of underground spaces (circular, D-shaped, rectangular, and irregular hexagon) on groundwater inflow under various excavated space areas (5, 10, 20, 30, 40, and 50 square meters) and with different groundwater table levels relative to the center of the excavated space (20, 50, and 100 meters) in two model dimensions (50 by 30 and 100 by 60 square meters) at an anisotropic permeability ratio (ky/kx) of 1, a total of 144 different models were simulated. Figure 3 depicts the groundwater inflow into various spaces in the dimensions of 50 by 30 square meters and 100 by 60 square meters. As observed in these graphs, an increase in the area of the excavated space in different tunnel shapes results in an increased rate of groundwater inflow.

It is evident from these graphs that the circular-shaped tunnel generally exhibits the lowest rate of seepage compared to other shapes of underground spaces, such as D-shaped, rectangular, and irregular hexagon.

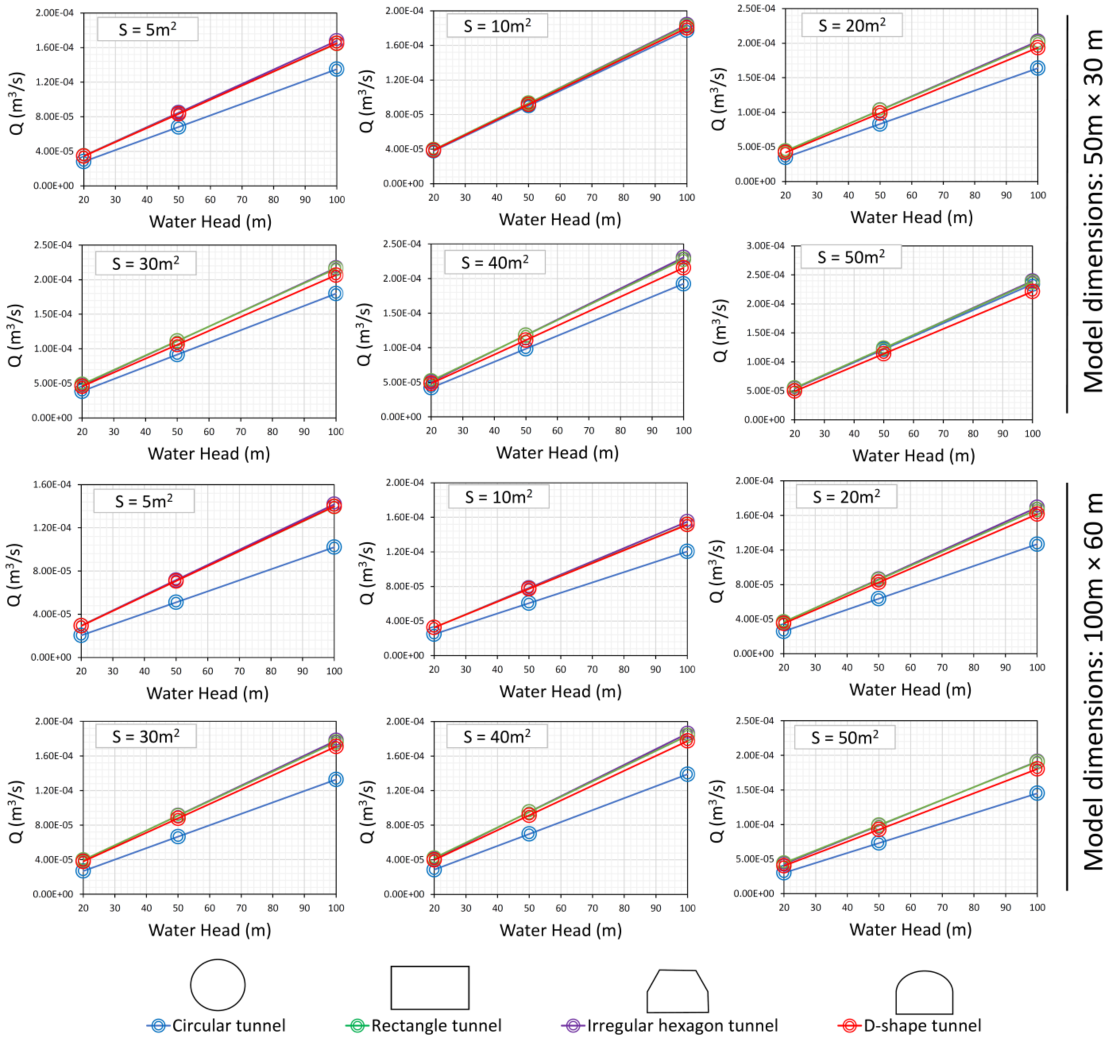

Figure 3: Groundwater inflow into the tunnel based on different geometric shapes of excavated spaces considering various areas and groundwater table levels in two different model dimensions.

3.2 The Effect of Geometric Shape of Underground Spaces on the Groundwater Inflow into the Tunnel Based on Excavated Space Perimeter (P):

To investigate the impact of the geometric shape of underground spaces (circular, D-shaped, rectangular, and irregular hexagon) on groundwater inflow under various excavated space perimeters (P: 5, 10, 20, 30, 40, and 50 square meters) and with different groundwater table levels relative to the ceiling of the excavated space (20, 50, and 100 meters) in two model dimensions (50 by 30 and 100 by 60 square meters) at an anisotropic permeability ratio (ky/kx) of 1, a total of 144 different models were simulated. Figure 4 illustrates the groundwater inflow into various spaces in the dimensions of 50 by 30 square meters and 100 by 60 square meters. As observed in these graphs, an increase in the excavated space perimeter in different tunnel shapes results in an increased rate of groundwater inflow. Although the difference is not significant in smaller areas, an increase in the area or spatial extent results in a more pronounced variation in the inflow of water into the tunnel. For instance, as illustrated in Fig. 6, concerning the model dimensions of 100 by 60 square meters at water head of 50 meter, the water inflow rate for the irregular hexagon tunnel in excavated areas of 5 and 10 square meters are 8.43e-5 m^3/sec and 9.17e-5 m^3/sec , respectively. In the excavated area of 50 square meters, the inflow rate reaches 1.14e-4 m^3/sec.

It is evident from these graphs that the circular-shaped tunnel generally exhibits the lowest rate of seepage compared to other shapes of underground spaces, such as D-shaped, rectangular, and irregular hexagon**.**

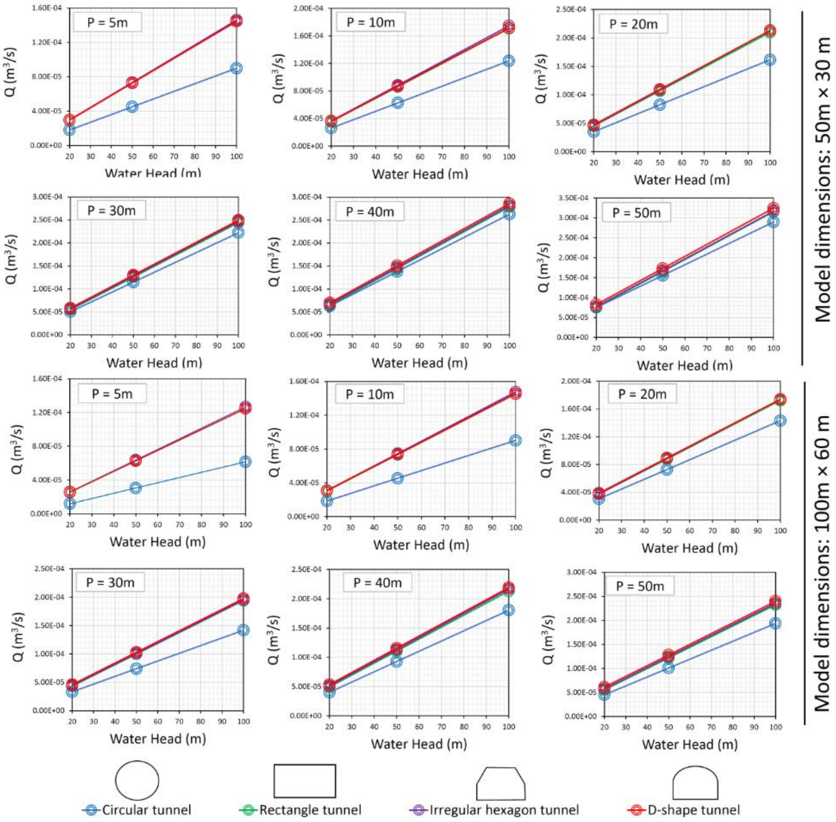

Figure 4: Groundwater inflow into the tunnel based on different geometric shapes of excavated spaces considering various perimeters and groundwater table levels in two different model dimensions.

3.3 The Effect of Geometric Shape of Underground Spaces on Water Inflow Based on Influence Radius:

The geometric shape of an underground space, specifically a tunnel, can indeed have a significant impact on the influence radius of water inflow. The circular tunnel shape offers a balanced influence radius due to its uniform perimeter. However, variations in hydraulic conductivity can still create uneven flow patterns. In the rectangular, wider bases can lead to larger influence zones, especially if water primarily enters from the bottom. However, corners can create complex flow patterns. In the D-shape tunnel, commonly used in soft ground, offers better stability. Its curved top and angled sides can influence water flow depending on the specific dimensions and orientation. Also, in the irregular tunnel, complex or non-standard shapes are harder to predict, requiring detailed analysis considering specific geometries and local hydrogeological conditions.

To investigate the impact of the geometric shape of underground spaces (circular, D-shaped, rectangular, and irregular hexagon) on influence radius as point of water inflow to tunnel view, various scenarios were examined under different excavated space areas, different excavated space perimeters and varying groundwater table levels relative to the ceiling of the excavated space (20, 50, and 100 meters). To examine the influence radius, for excavated areas (excavated perimeters) of 5, 10, 20, 30, 40, and 50 square meters (meters), the flux boundaries were set at 10, 20, 30, 40, 50, and 60 square meters (meters) from the center of the shape. The boundaries were set at 10, 20, 30, 40, 50, and 60 square meters (meters), respectively. Figure 5 illustrates the schematic geometric model of the numerical simulation along with the flux boundary.

The analysis was conducted using model dimensions of 100 by 60 square meters with an anisotropic permeability ratio (ky/kx) equal to 1, resulting in a total of 144 different simulation models. Figure 6 depicts the groundwater inflow into various spaces in the dimensions of 50 by 30 square meters and 100 by 60 square meters.

As depicted in these graphs, based on the mentioned flux boundaries (influence radiuses), with an increase in both the area and the perimeter of the excavated underground space in various tunnel shapes, the water inflow rate has significantly increased. Furthermore, the circular-shaped tunnel, when considering the impact of different geometric shapes based on the excavated area, generally exhibits the highest inflow rate within the influence radius, while the D-shaped tunnel demonstrates the lowest rate.

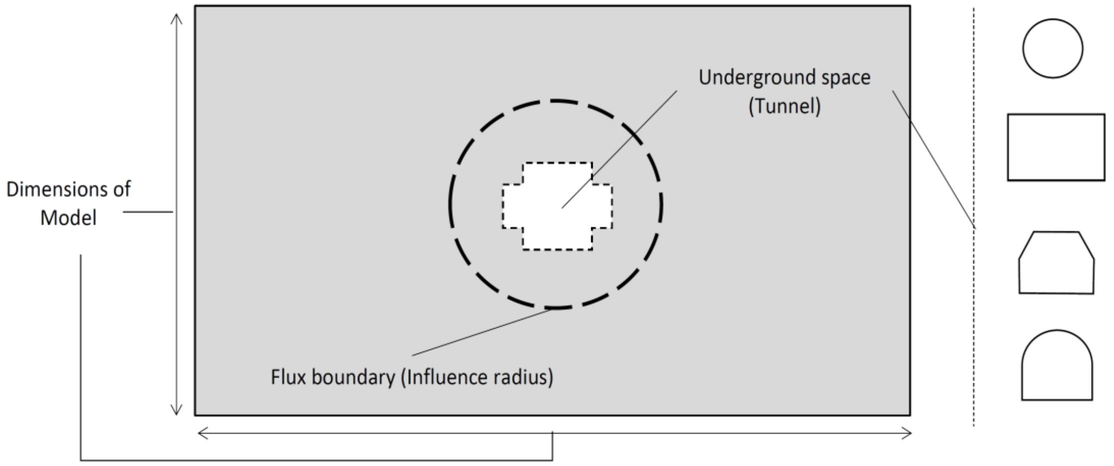

Figure 5: Schematic Geometric Model for Investigating the Influence Radius

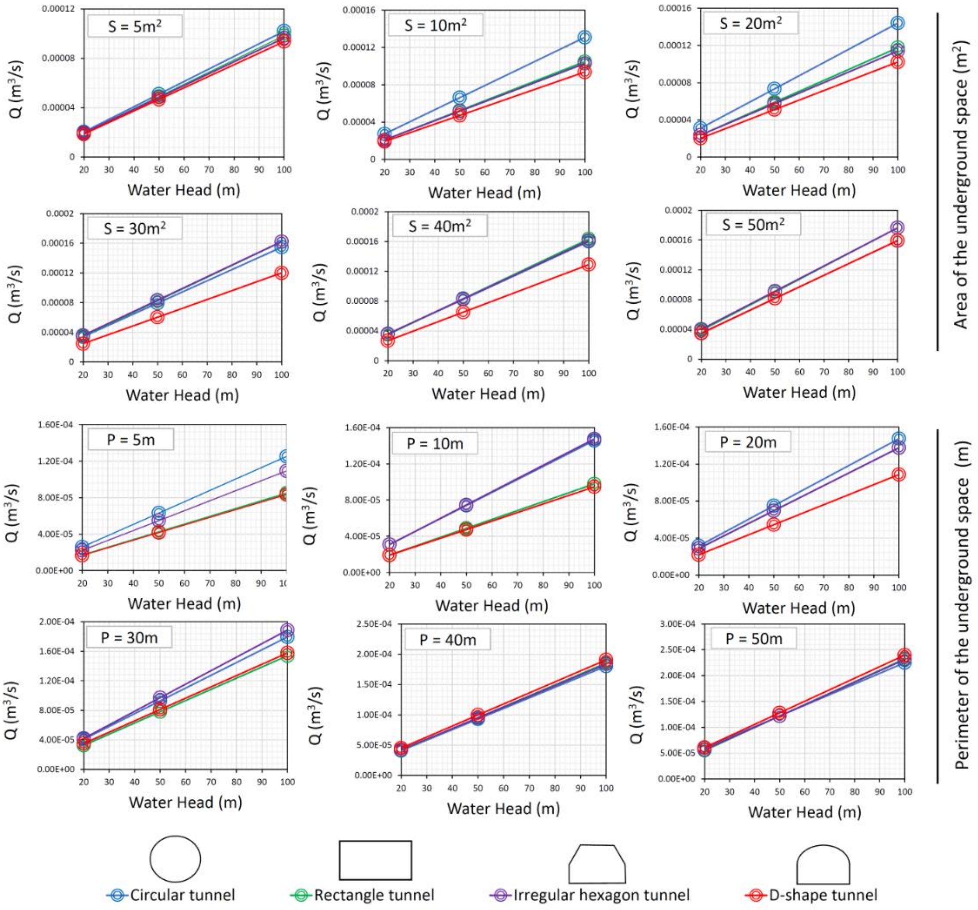

Figure 6: The Effect of Geometric Shape of Underground Spaces on water inflow based on influence radius

Regarding the effect of different geometric shapes based on the excavated perimeter, a specific trend could not be discerned. However, it can be concluded that circular-shaped tunnels, given their higher inflow rates compared to other geometric shapes, facilitate water discharge at a faster pace, especially within the influence radius.

3.4 The Influence of Geometric Shape of Underground Spaces on Water Inflow into Tunnels Considering Anisotropic Conditions of Permeability Coefficient:

To investigate the impact of the geometric shape of underground spaces (circular, D-shaped, rectangular, and irregular hexagon) on water inflow under various anisotropic conditions of permeability coefficient (the ratio of vertical permeability to horizontal permeability - Ky/Kx: 0.1, 0.5, and 1), scenarios were explored for excavated space areas of 20 square meters, and the dimensions of the excavated perimeters were 20 meters. Additionally, different groundwater table levels relative to the ceiling of the excavated space (20, 50, and 100 meters) were considered for various model dimensions, including 50 by 30 square meters and 100 by 60 square meters, resulting in a total of diverse simulation models. Figure 7 illustrates the water inflow into various spaces in the dimensions of 50 by 30 square meters and 100 by 60 square meters.

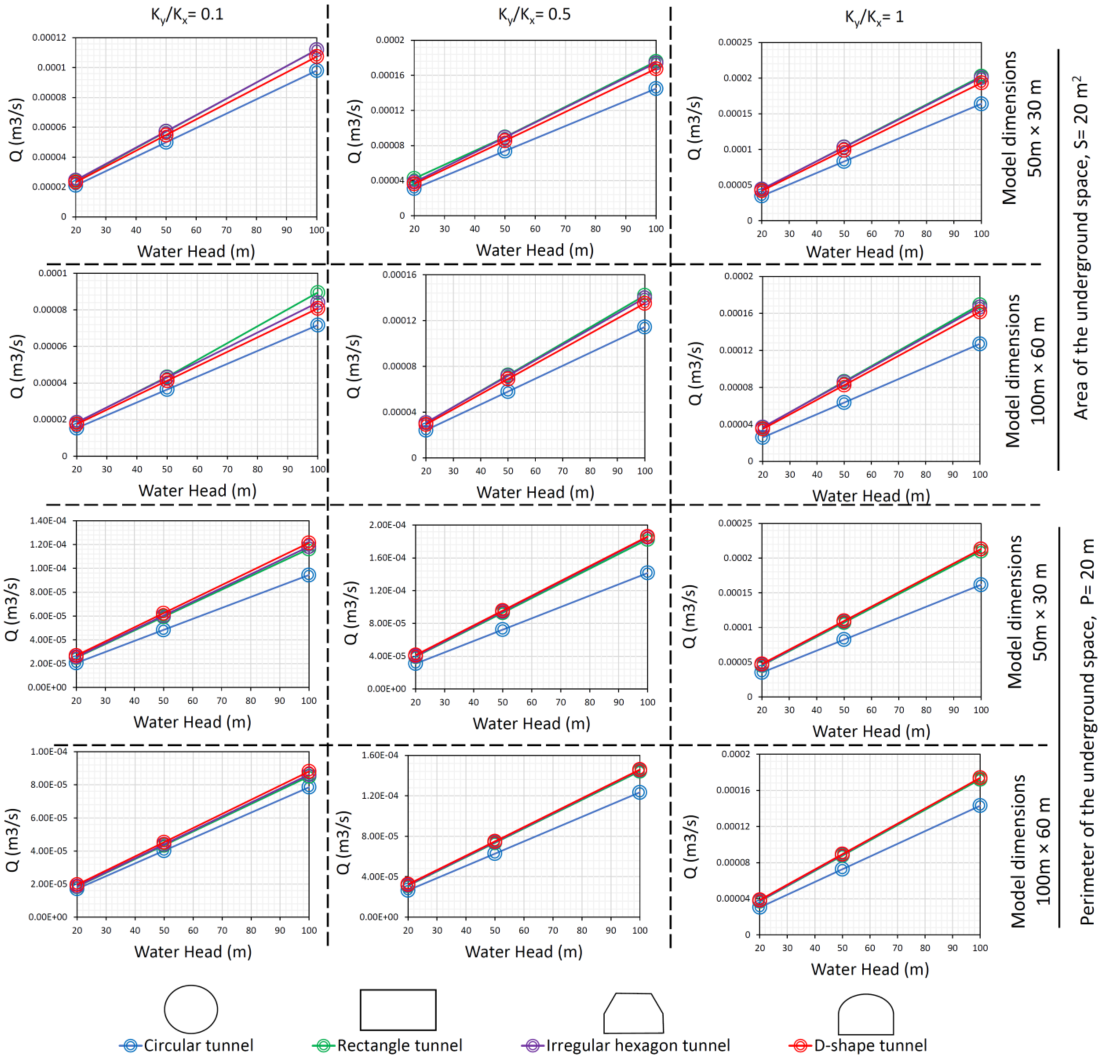

Figure 7: Influence of Geometric Shape of Underground Spaces on Water Inflow into Tunnels Considering Anisotropic Conditions of Permeability Coefficient

As observed in these diagrams, with an increase in both the area and the perimeter of the excavated underground space in various tunnel shapes, the water inflow rate has significantly increased. Notably, applying variations in the anisotropic conditions of the permeability coefficient (sensitivity analysis on Ky/Kx=0.1, 0.5, and 1) did not reveal significant changes in the trend of geometric shape influence on the water inflow into the tunnel. In the majority of simulated models, the water inflow into the circular tunnel exhibits the lowest rate both when considering the impact of the geometric shape based on the excavated area and when considering it based on the excavated perimeter.

4. Discussion:

The geometric shape of underground spaces can significantly influence the water inflow into tunnels. Sensitivity analysis on various parameters indicates that circular-shaped tunnels may be preferable for effective drainage. This preference arises from both having the lowest water inflow rates into the tunnel and the wide influence radius of such tunnels, as illustrated schematically in Figure 8. However, it is crucial to note that the overall dimensions of the geometric model also play a crucial role in the water inflow into the tunnel. The proximity of the model dimensions to the boundaries of the underground space intensifies the impact of boundary conditions on water inflow, leading to a non-linear prediction for water flow. For instance, in the model with dimensions of 50 by 30 meters and an underground space area of 50 square meters, the irregular hexagon-shaped tunnel exhibited the lowest flow rate compared to other shapes. Still, no specific trend can be generalized across various dimensions of the overall model. Conversely, in the model with dimensions of 100 by 60 meters based on the excavated area, a circular-shaped tunnel demonstrated the lowest flow rate, while a rectangular-shaped tunnel exhibited the highest flow rate. This observation extends to different sizes of excavated perimeters, indicating that, for instance, in various excavated area sizes, circular-shaped tunnels generally have the lowest flow rates, while D-shaped tunnels exhibit the highest flow rates. Analysis of the anisotropy of the permeability coefficient indicates that this parameter has no significant effect on the water inflow, and in all cases, the circular-shaped tunnel, in contrast to other geometric shapes studied in this article, has the lowest water inflow rate.

As expected, an increase in the area of the underground space leads to a higher water inflow into these environments. A larger space provides a greater surface for water to flow into the tunnel, and thus, an increase in the tunnel area can result in more groundwater infiltration.

Among the shapes studied, the circular-shaped tunnel has the lowest flow rate, followed by the irregular hexagon-shaped tunnel, then the D-shaped tunnel, and finally, the rectangular-shaped tunnel with the highest water inflow.

The overall dimensions of the model significantly affect the estimation of water inflow. Smaller model dimensions bring the boundary conditions closer to the tunnel boundary, leading to exaggerated estimates. In smaller model dimensions, it becomes challenging to provide accurate insights into the effect of the geometric shape of the underground space on water inflow.

Examination of the influence radius of the geometric shape of the excavated space shows that a circular-shaped tunnel has the highest influence radius, making it highly effective for drainage purposes.

Analysis of the anisotropy of the permeability coefficient indicates that this parameter has no significant effect on the water inflow, and in all cases, the circular-shaped tunnel, in contrast to other geometric shapes studied in this article, has the lowest water inflow rate.

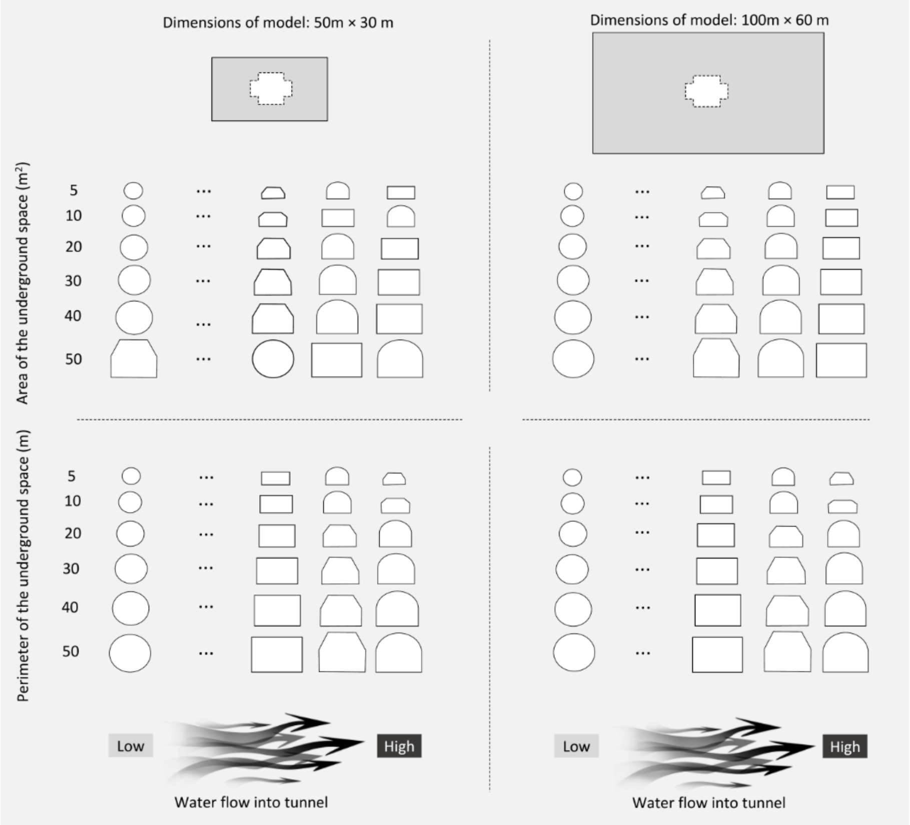

Figure 8: Schematic representation of the geometric shape effect on groundwater inflow into underground spaces

5. Conclusion:

This study aimed to investigate the impact of the geometric shape of underground spaces on water inflow into these environments. Based on calculations performed for 576 different models using Seep/w software, here are some key points:

- Circular tunnels generally have the lowest water inflow rates, regardless of model dimensions or anisotropy of the permeability coefficient. This aligns with the intuition that minimizing surface area exposed to water minimizes inflow.
- Wider influence radius of circular tunnels further helps reduce water inflow by capturing water from a larger area around the tunnel. This is illustrated in Figure 6, which you mentioned.
- Model dimensions and boundary conditions can significantly impact water inflow, making generalizations difficult. While circular tunnels performed well across various parameters, the optimal shape can change depending on the specific situation.
- Irregular hexagon tunnels can be preferable in certain limited cases, such as when model dimensions are close to the underground space boundaries. However, this finding is unlikely to be relevant for most practical tunnel designs.
- Anisotropy of the permeability coefficient, which measures how easily water flows in different directions, has minimal impact on water inflow. This suggests that the shape of the tunnel is a more important factor than the underlying soil properties.

Overall, this research highlights the importance of considering both geometric shape and overall dimensions when designing tunnels for effective drainage. It also suggests that circular tunnels are generally a safe choice, but further analysis might be needed based on specific project details. It's important to note that predicting the exact influence radius requires complex numerical modeling or physical experiments that consider all these factors. The impact of shape is just one aspect; other design and geological factors play equally important roles.

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