Optimizing Minor Drainage Tunnel Position to Mitigate Groundwater Inflow in Main Tunnel Projects

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ABSTRACT

Optimizing the positioning of minor drainage tunnels is a crucial strategy in mitigating groundwater inflow within main tunnel projects, a significant concern in civil engineering and infrastructure development. Groundwater inflow can lead to serious challenges, including tunnel instability, flooding, and increased construction costs. This makes effective management of water in underground projects paramount. The strategic placement of minor drainage tunnels facilitates the efficient collection and diversion of seepage water, reducing the risks associated with groundwater inflows. This study employs numerical finite element modeling to examine the optimal positioning of drainage tunnels relative to main tunnels, considering various configurations and hydrogeological conditions. Results indicate that placing the drainage tunnel below the main tunnel significantly reduces groundwater inflow, especially as tunnel radii and groundwater head levels increase. These findings provide a practical framework for enhancing tunnel drainage efficiency, ensuring structural stability, and minimizing environmental impacts by introducing the final model in optimizing minor drainage tunnel positions to mitigate groundwater inflow in main tunnel projects.

KEYWORDS
Tunnel, Drainage, water inflow, Numerical modeling.

1. Introduction

Tunneling is a critical aspect of civil engineering, particularly for infrastructure projects that require the construction of underground passages such as roadways, pipelines, and transit systems. One of the prominent challenges in tunnel construction is managing groundwater inflow, which can significantly impact both the safety and economic viability of tunnel projects. Groundwater inflows are often considered unpredictable geological hazards that can lead to instabilities in the surrounding rock formations, posing serious risks such as injuries, fatalities, and substantial financial losses [1–3]. The importance of understanding groundwater conditions cannot be overstated, as they play a decisive role in the design and operation of tunnels. Accurate prediction and evaluation of these inflows are paramount for effective tunnel drainage system design and for assessing the environmental impacts of associated drainage measures [1, 4, 5]. Despite the advances in methods proposed by researchers for estimating groundwater inflow, a comprehensive review of these methodologies remains absent in the current literature [1].

In addition to groundwater inflow, tunnel construction faces various operational challenges, such as the handling and transporting of materials in confined spaces. Limited access points complicate the delivery of essential construction materials and equipment, necessitating careful planning to ensure timely and safe operations [6]. Managing the varying geological conditions is another critical aspect of tunneling, as unexpected geological features can result in construction delays and increased costs. To mitigate these risks, thorough site investigations and ongoing monitoring during and after the excavation process are essential [7–9]. Groundwater management systems, including dewatering pumps and drainage strategies, play a crucial role in controlling water-related challenges and ensuring the stability of tunnel structures [6, 9].

The positioning of minor drainage tunnels plays a critical role in managing groundwater inflows and ensuring the stability of main tunnel projects. An effective drainage system is vital for mitigating the risks associated with groundwater, which can lead to tunnel instability, flooding, and significant construction delays [4].

Correctly locating minor drainage tunnels helps in efficiently collecting and redirecting seepage water from the surrounding rock and soil strata. This is particularly important in urban tunneling projects where unexpected high-water inflows can compromise the structural integrity of both the tunnel face and surface structures above [4]. An accurate characterization of subsurface conditions and hydrological modeling is essential to predict potential inflow points and design the drainage systems accordingly [4, 10].

Mitigating groundwater inflow in main tunnel projects is critical for maintaining tunnel stability and operational efficiency. A variety of strategies can be employed to address this issue, ensuring that water management is integrated into the planning and design phases. Effective drainage systems are essential for controlling groundwater levels. Comprehensive drainage plans should be developed to efficiently divert water away from the tunnel site, incorporating features such as detention ponds and swales to manage excess water during heavy rainfall events [11]. The strategic positioning of minor drainage tunnels can enhance the overall drainage efficiency and help in the timely removal of infiltrating water. Excavated water can be reused for various purposes, such as surface dust control or aquifer recharge, which not only minimizes water wastage but also mitigates the impacts of water inflow on the main tunnel [12]. These standards advocate for comprehensive environmental impact assessments that consider water quality and the potential impacts of groundwater extraction and inflow on local ecosystems. Integrating digital monitoring systems equipped with smart sensors allows for real-time tracking of groundwater levels, water quality, and tunnel structural health [13]. By continuously monitoring these parameters, engineers can make informed decisions to mitigate groundwater inflow and address issues before they escalate. By implementing these mitigation strategies, engineers can significantly reduce the risks associated with groundwater inflow, contributing to the safety and sustainability of tunnel projects. Tunneling projects face a myriad of challenges and difficulties that can significantly impact their execution and safety. In addition to the geological and hydrological, financial considerations also pose difficulties. Securing funding and navigating bureaucratic processes for approvals and permits are crucial stages that can slow down progress. Financial planning must address the extensive costs associated with tunnel construction, and delays in securing necessary approvals can disrupt project timelines significantly [6]. The design and maintenance of tunnel systems also require rigorous attention. Insufficient or improper maintenance can lead to major dysfunctions, threatening the tunnel's operational capabilities and user safety. Thus, prioritizing the quality and durability of equipment is vital to minimizing the need for frequent maintenance interventions, which can be complicated by ongoing traffic conditions [14]. Few studies have explored the impact of the minor tunnel's position relative to the main tunnel on reducing groundwater inflow. The study of Lin et al. identified that placing a secondary (minor) tunnel beneath the primary (main) tunnel is the most effective configuration for minimizing water inflow. This arrangement achieves greater groundwater flow reduction compared to other placements, such as positioning the minor tunnel below but offset from the main tunnel. However, the effectiveness diminishes as the distance between the two tunnels increases, highlighting the importance of closer positioning [15]. Therefore, this study aims to determine the optimal location for the drainage tunnel (minor tunnel) relative to the main tunnel to effectively reduce groundwater inflow. To achieve this, a parametric study was conducted using numerical finite element modeling.

2. Numerical modeling

Numerical modeling and simulation techniques have become valuable tools for predicting groundwater behavior in the vicinity of tunnels. By creating detailed models that account for varying hydrogeological conditions, engineers can identify the most effective locations for minor drainage tunnels, thus minimizing the risk of groundwater inflows and optimizing the overall design [4]. Various methods, including analytical and empirical approaches, provide insights into inflow rates and inform decision-making in tunnel design and construction [4, 16, 17].

Over the past few decades, various numerical methods have been developed for predicting water flow into tunnels, including both continuum and discontinuous media approaches. In addition to the commonly used methods such as Continuum-Based Methods and Discontinuum-Based Methods. In continuum media typically used Finite Difference Method (FDM), Finite Element Method (FEM), Finite Volume Method (FVM), and Boundary Element Method (BEM). FDM is efficient and straightforward for solving groundwater flow equations on structured grids. However, its limitations in handling complex geometries and heterogeneous materials led us to explore more flexible approaches. FEM is well-suited for modeling irregular tunnel shapes and varying permeability distributions, making it a preferred choice for complex geological conditions. FVM is particularly advantageous because it ensures local mass conservation, which is crucial for accurately estimating water inflow in tunnel environments. BEM is effective for problems with infinite or semi-infinite domains, such as groundwater flow in unbounded media. However, its application is more suitable for simplified cases due to its reliance on boundary-only discretization. Also, in discontinuous media frequently used Discrete Element Method (DEM), Discontinuous Deformation Analysis (DDA), and Bonded Particle Method (BPM). DEM is useful for modeling fractured rock masses and discontinuous media, which can significantly influence water inflow patterns. However, it is computationally intensive for large-scale simulations. DDA is specifically designed for blocky rock masses and is effective in capturing deformation and fluid interactions within jointed rock formations. BPM is beneficial for simulating the mechanical and hydraulic behavior of fractured rock masses at a particle scale. It provides detailed insights into permeability changes due to rock fragmentation and deformation. [18–24]. Several innovative methods such as Hybrid Continuum/Discontinuum Approaches [25, 26] and Stochastic Analysis [27] have emerged that enhance the accuracy and efficiency of these predictions.

Numerical solutions play a crucial role in predicting groundwater inflow into tunnels under complex geotechnical and hydrogeological conditions. Several commercial software programs have been developed over the past decades based on FEM and DEM to analyze groundwater flow in rock masses, both in steady-state and transient regimes. Examples of such software include SEEP/W, FLAC, and UDEC for both 2D and 3D models. This study employs the finite element commercial code SEEP/W-V8.15.1.11236 to predict steady-state groundwater inflow into the main tunnel. The SEEP/W 2D model is capable of simulating various flow conditions, including saturated and unsaturated states in confined or unconfined aquifers. It takes into account the hydraulic conductivity and volumetric water content as functions of pore water pressure. This model has been widely applied to address geological and geotechnical challenges by simulating related hydrogeological issues [3, 21, 28–32]

The governing partial differential equation for two-dimensional saturated/unsaturated groundwater flow is derived by coupling the continuity equation with Darcy's law:

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

Here, K_x and K_y are the hydraulic conductivities in the x and y directions, respectively. Q represents the recharge or discharge per unit volume, h denotes the hydraulic head, t is time, and C is the slope of the water storage curve. The hydraulic head is related to volumetric water content (θ) by the following equation ([33]:

$$\frac{\partial\theta}{\partial t}=C\frac{\partial h}{\partial t} \tag{1}$$

The Galerkin approach has been utilized in SEEP/W 2D to solve this two-dimensional flow equation.

3. Analyses and discussion

In this study, to investigate the optimization of the drainage tunnel (minor tunnel) relative to the main tunnel, the water inflow to the tunnel was evaluated at five different positions of the secondary tunnel relative to the main tunnel. Since the numerical model used for the simulation is symmetrical, the five considered positions for the minor tunnel relative to the main tunnel were located at the upper, upper-right, right, lower-right, and lower sections (Figure 1). To analyze these positions, a finite element method was applied, with a numerical model of optimized dimensions of 100 by 50 meters and a square mesh grid. Detailed explanations of the methodology used to determine model dimensions and conduct sensitivity analyses can be found in previous studies [22, 23, 31]. The permeability coefficient was assumed to be 1×10^{-8} (m/s), the radius of the main tunnel was 2.5 meters, and the radius of the minor tunnel was 0.5 meters. Additionally, the water level above the tunnel center varied from 5 meters to 100 meters. It should be noted that the permeability coefficient is a crucial parameter in determining the inflow rate of water into the tunnel. Specifically, an increase or decrease in permeability directly leads to a corresponding increase or decrease in water inflow, indicating a fully proportional relationship. For instance, a tenfold increase or decrease in permeability, while keeping other parameters constant (such as water head, tunnel radius, and model dimensions), results in a tenfold increase or decrease in water inflow, respectively. Therefore, the overall trend of inflow remains consistent. Since the primary objective of this study is to identify a general trend for determining the optimal distance between the minor tunnel and the main tunnel, a permeability coefficient of 1×10^{-8} (m/s) was assumed as a default value. Figure 2 shows an example of the tunnel's position at the upper-right and lower sections, along with flow contours and potential lines. Preliminary examinations of these five positions reveal that the minor tunnel, when excavated as a drainage tunnel at the lower part of the main tunnel, experiences the lowest water inflow across different groundwater head conditions (Figure 3). This finding provides initial confirmation of Lin et al.'s study [15], which investigated various positions for drainage tunnels relative to the main tunnel.

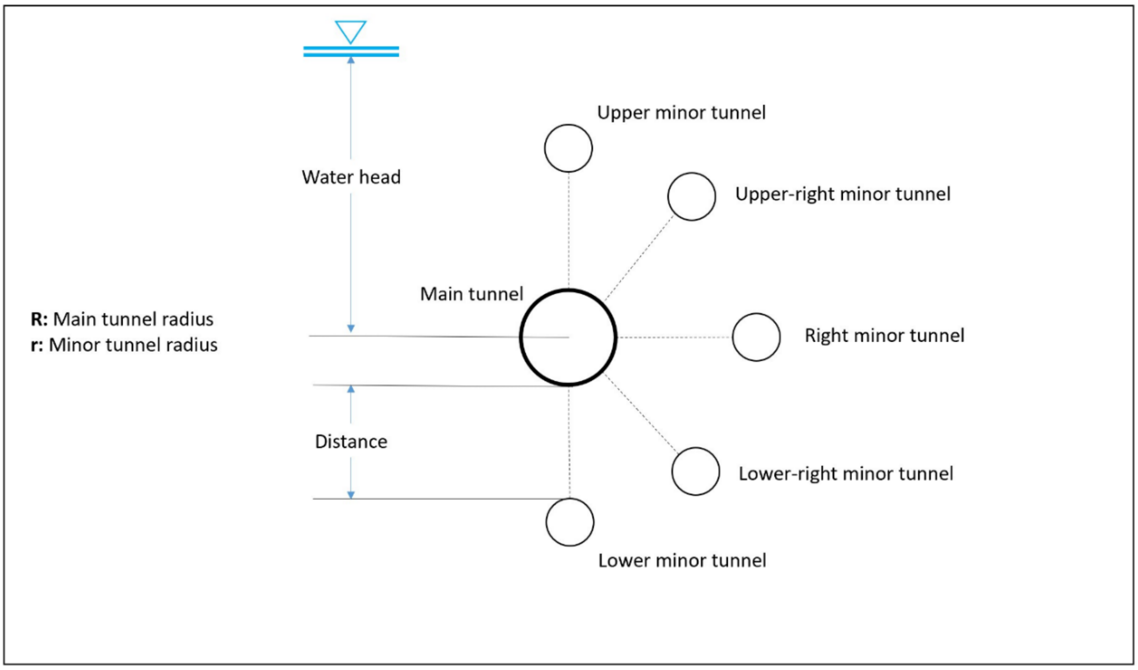

Figure 1. Schematic model of the positions of the drainage tunnels (minor) relative to the main tunnel.

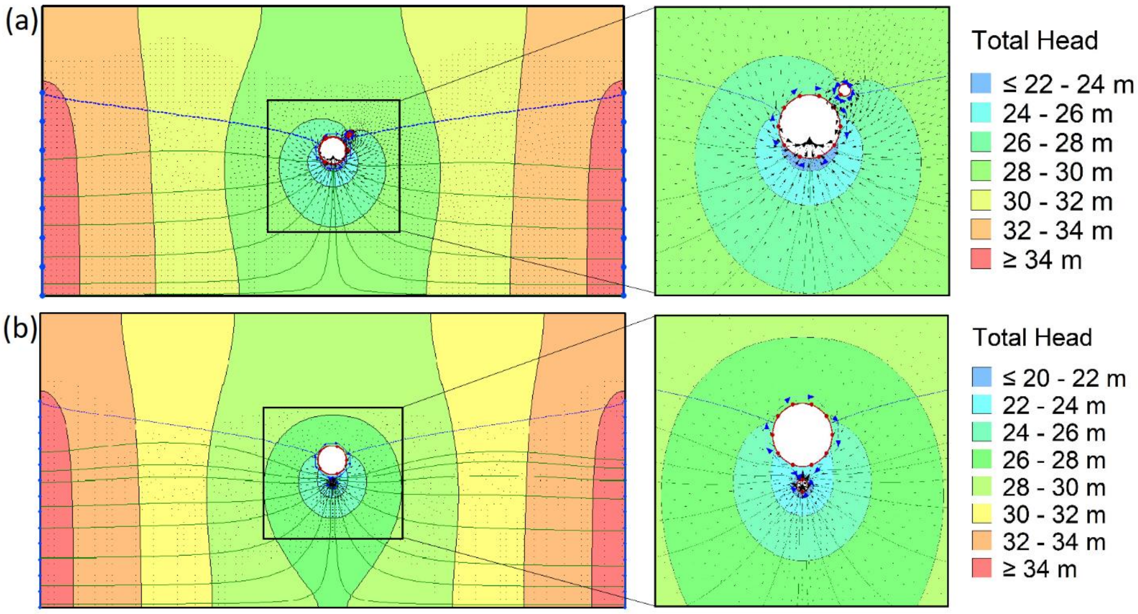

Figure 2. Simulated model of water inflow into the tunnel along with contour display of potential lines and streamlines, H: 10 m, permeability coefficient: 1×10^{-8} m/s, and tunnels distance: 1 m, R: 2.5 m, r: 0.5 m, a) Simulated model for the upper-right tunnel, b) Simulated model for the lower tunnel.

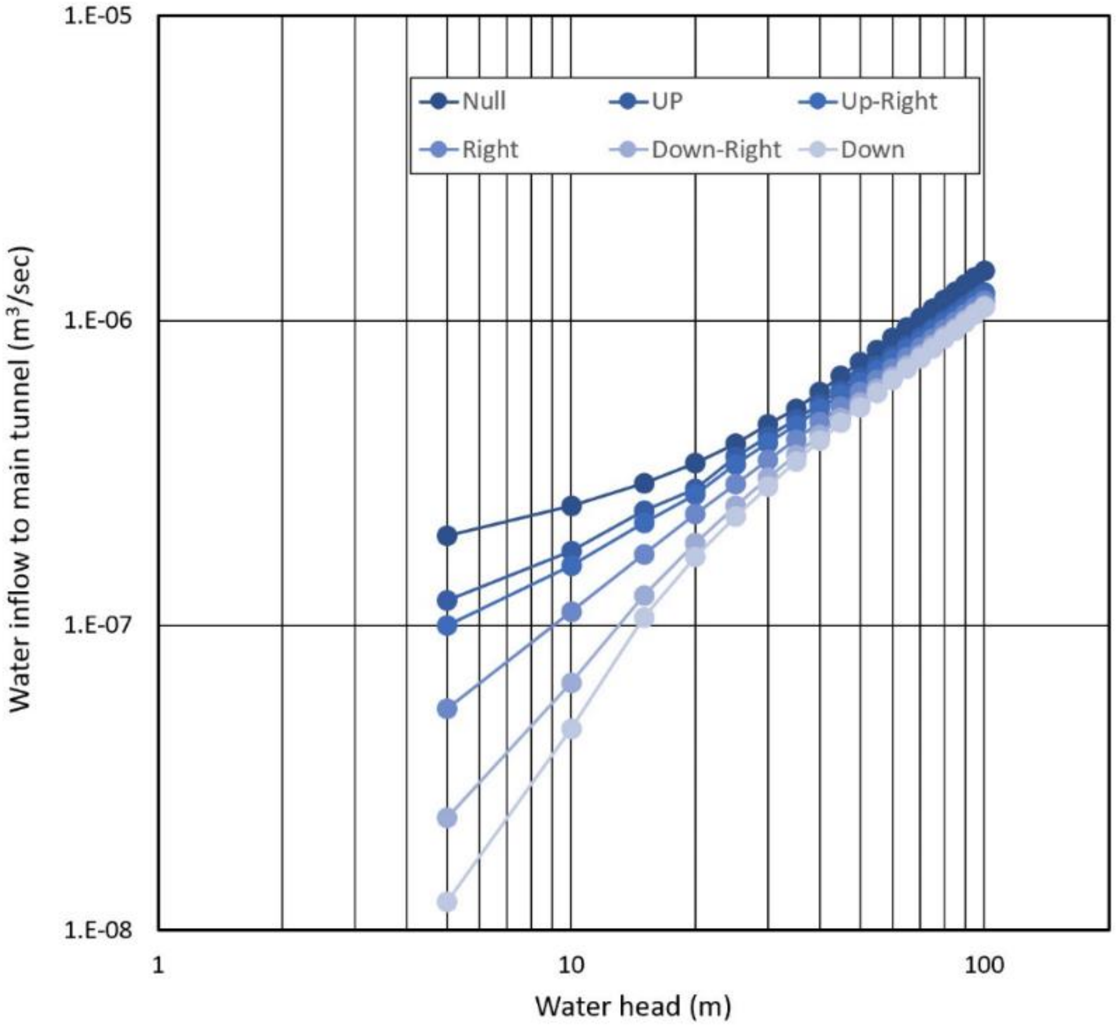

Figure 3. Inflow of water to the main tunnel concerning different groundwater head levels at various positions of the minor tunnel (Null: when the minor tunnel is not excavated).

In the next step, based on the results which indicated that the position of the lower tunnel relative to the main tunnel has the lowest water inflow to the tunnel, the water inflow rate for different water head levels was calculated considering various radii of the main tunnel and a fixed radius of the minor tunnel (0.5 meters) (Figure 4). As shown in this figure, it is expected that with the increase in tunnel radius, the water inflow to the tunnel increases as well. Additionally, as the water head above the tunnel increases, the water inflow to the tunnel also increases. However, it is important to note that as the water head increases, the water inflow to the tunnel tends to stabilize at nearly a constant value at higher waterheads (100 meters of water head and above).

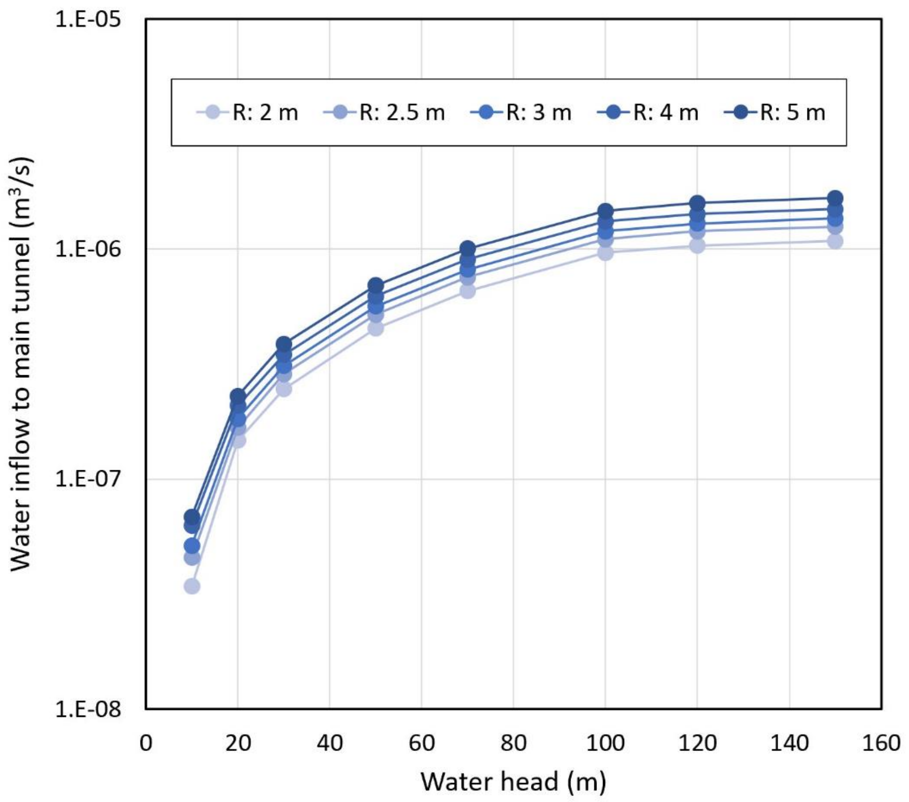

Figure 4. Inflow of water to the main tunnel concerning different groundwater head levels in various scenarios of the main tunnel radius (the minor tunnel is excavated below the main tunnel)

To achieve the desired outcome and determine the optimal distance between the drainage tunnel (minor tunnel) and the main tunnel, various scenarios were examined. In these scenarios, the position of the drainage tunnel relative to the main tunnel was considered at the lower section of the tunnel with a fixed radius of 0.5 meters. The radius of the main tunnel was set at 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 meters, with groundwater levels of 20, 50, and 100 meters, and varying distances between the main tunnel and the minor tunnel from 1 to 15 meters, with a step size of 1 meter. Additionally, a permeability coefficient of 1e-7 meters per second was used. As a result, 450 different numerical models were simulated.

Figure 5 shows the water inflow to the tunnel for different distances between the drainage tunnel and the major tunnel, considering various radii of the main tunnel and different water head levels. As seen in Figure 5a, the main tunnel is located 20 meters below the groundwater surface. As the distance between the tunnels increases, the water inflow into the main tunnel decreases. The rate of decrease in water inflow to the tunnel becomes more noticeable in tunnels with larger radii as the distance between the tunnels increases. In other words, as the distance between the tunnels increases, the water inflow to the tunnel will stabilize at a constant value after a certain distance (the threshold distance), beyond which the reduction in water inflow to the tunnel will be less than 5%. This threshold distance is marked with a dashed red line. Similarly, this behavior occurs for different water head levels of 50 meters and 100 meters (Figures 5b, 5c), with the distinction that when the main tunnel is deeper relative to the groundwater surface (at a water head of 100 meters), the water inflow to the tunnel reaches a constant value more quickly as the distance between the tunnels (minor tunnel and main tunnel) increases.

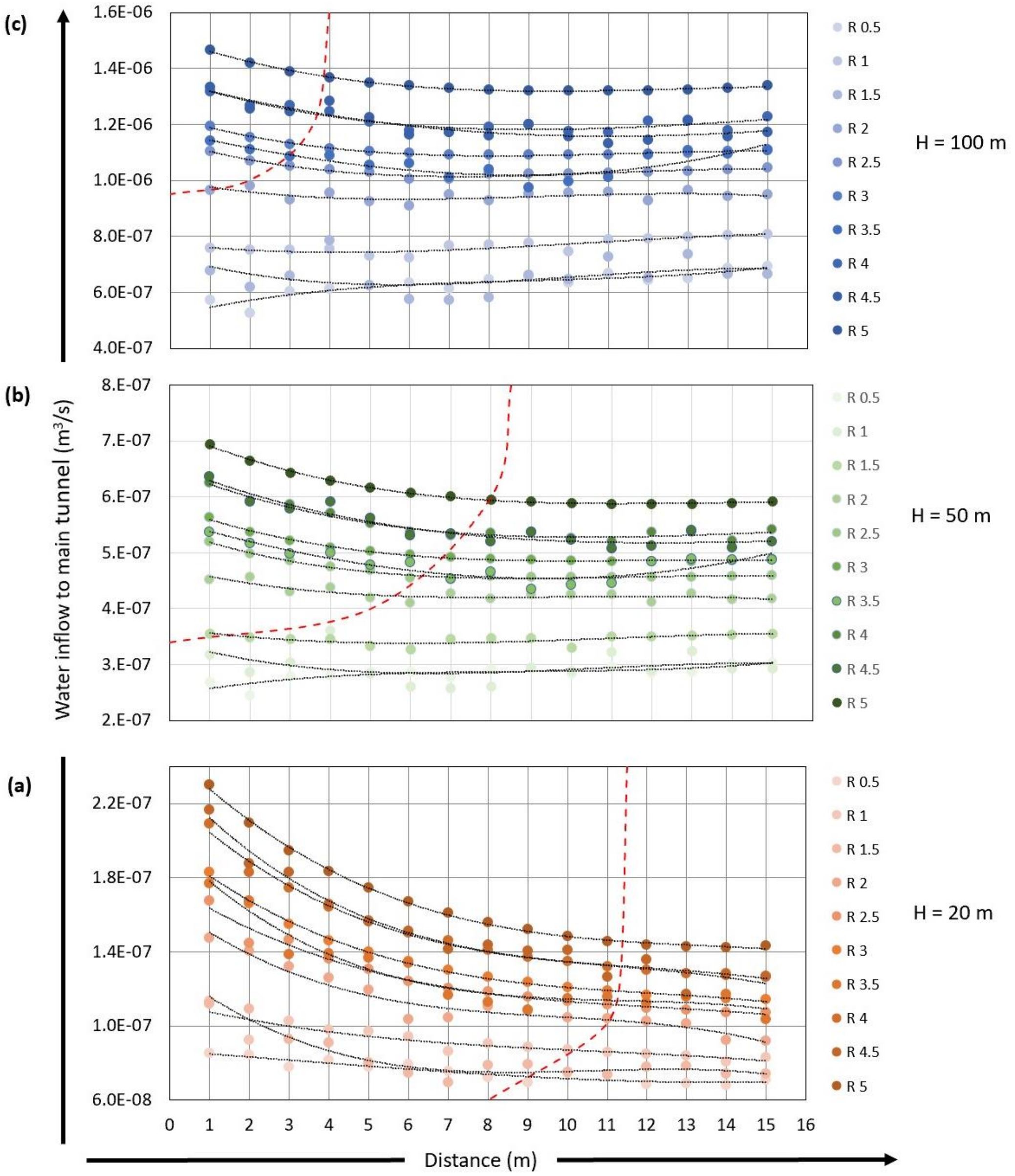

Figure 5: The inflow of water to the main tunnel relative to the different distances of the minor tunnel from the main tunnel at various main tunnel radius and different water head levels.

To present a final model, based on various groundwater head levels (the depth of the main tunnel relative to the groundwater surface), different radii of the main tunnel, and varying distances between the tunnels (main tunnel and lower sub-tunnel), Figure 6 is proposed as the final model to determine the optimal distance for reducing water inflow to the main tunnel, considering a radius of 0.5 meters at the minor tunnel. For this purpose, boundary lines for different water head levels of 20, 50, and 100 meters were initially implemented in the general diagram showing water inflow to the tunnel relative to varying distances (represented by red lines). Then, using interpolation, contour lines for the 30, 40, 60, 70, 80, and 90-meter levels were drawn. Using this figure, the optimal distance of the drainage tunnel (minor lower tunnel) relative to the main tunnel can be determined based on the radius of the main tunnel and the water head.

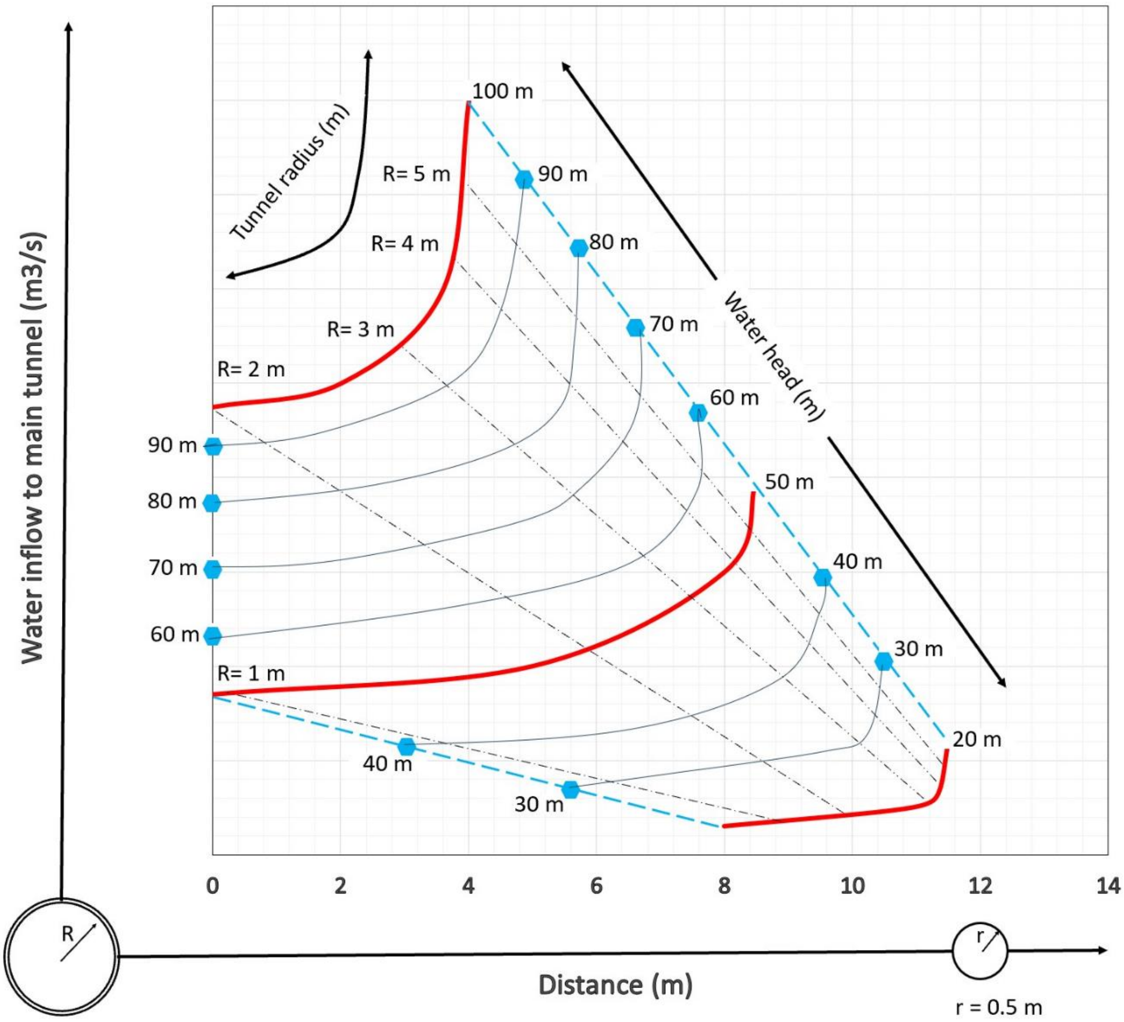

Figure 6: The final model to obtain the optimal distance of the drainage tunnel (lower minor tunnel) relative to the main tunnel based on the radius of the main tunnel and the underground water head levels.

4. Conclusion

The study confirms that the strategic positioning of drainage tunnels is vital in addressing groundwater inflow challenges in tunnel projects. Numerical simulations revealed that the optimal location for the minor drainage tunnel is below the main tunnel, where inflow rates were significantly reduced. Additionally, as the groundwater head and main tunnel radius increase, this configuration becomes even more effective. Key insights include:

1. Water Inflow Dynamics: As the distance between the drainage and main tunnels increases, water inflow stabilizes beyond a certain threshold, which varies with tunnel dimensions and groundwater levels.
2. Optimal Design Parameters: The optimal distance between the drainage and main tunnels was identified (Figure 6), providing practical guidelines for engineers. This ensures minimal inflow rates without excessive excavation.
3. Environmental and Sustainability Considerations: Integrating the findings with sustainable water management practices—such as reusing excavated water for environmental restoration—can significantly reduce the ecological footprint of tunnel construction.

This research bridges the gap between theoretical modeling and practical application, offering a robust framework for engineers to design safer and more efficient tunnel drainage systems. By adopting these strategies, projects can achieve improved cost-effectiveness, structural integrity, and environmental sustainability.

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