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Opinion

Trends in forecasting groundwater ingresses into underground structures

Abstract

Often, underground structures are faced with groundwater ingresses during their erection and even during their operation. To conceive the most suitable drainage or dewatering systems, and at the same time better guarantee the sustainability of these structures, these inflows should be accurately forecasted in advance. To this end, researchers have made considerable efforts and developed various solutions. This article put forwards the recent trends and progress related to the prediction of groundwater ingresses in underground structures. Pioneering solutions (analytical, semi-analytical, empirical and semi-empirical) as well as numerical, machine learning and other solutions are widely highlighted. Besides, the paper explains that the ideal solutions are still subject of current and future investigations. The need to continually opt for better schemes or strategies for accurate groundwater ingress prediction solutions is adequately expressed. Relevant inspirations can be drawn from this article for future accurate groundwater ingress forecasting solutions.

Keywords: underground structures, complex rocky media, groundwater regime, accurate forecast of groundwater ingresses, recent solutions and future trends, dewatering systems, durability of underground structures

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Introduction

Forecasting the quantity of groundwater ingresses into underground structures remains one of the major concerns in underground engineering. These concerns are increasingly significant when it comes to accurately assessing groundwater inflows in a specific underground structure. Therefore, in order to tackle this issue, many research studies are conducted by numerous scholars and researchers. However, in spite of abundant results, it is still a difficult task to precisely evaluate groundwater ingresses in engineering structures located in underground spaces. Above all, as the burial depth of these structures is great, the behavior of the surrounding rocks is more and more complex, which makes precise prediction of groundwater ingresses more difficult. In some situations, when the rock types that predominate the structure surroundings are of very poor quality and broken, and there is a water-rich zone very close to the excavated areas, the influxes of groundwater can be uncontrollable. In such cases, the environmental impacts of these inflows can be considerable. This article highlights recent trends and advances related to groundwater inflow prediction in underground engineering. It also emphasizes the necessity to continually improve the accuracy of forecasting groundwater ingresses in underground structures.

Solutions for forecasting groundwater ingresses in underground structures

With the aim of accurately forecasting groundwater ingresses into rock tunnels that are part of common underground structures, various relevant solutions are being developed through multiple efforts made by the scientific community in the field. Most of these solutions are presented in Frenelus et al.[1] Figure 1 shows the main pertinent solutions. Analytical, semi-analytical, empirical and semi-empirical solutions are considered pioneering and rapid solutions to predict groundwater ingresses in underground structures. In fact, the ability to quickly assess groundwater inflows into underground structures is very important for taking important decisions on a given underground engineering project. However, the parameters of such solutions are difficult to estimate with high precision. This is due by the fact that the methods of such solutions are influenced by several factors which cannot be overlooked. Numerical, machine learning and other solutions require enormous relevant data to provide appreciable and interesting results. At present, to increase their precisions, newly constructed empirical, semi-empirical, analytical and semi-analytical solutions are designed on the basis of numerical techniques which model the actual surrounding rock conditions of underground structures. This was the case, for example, of a semi-analytical solution developed by Huang et al.[2] to forecast groundwater inflows into a tunnel housed in a fractured rocky environment. Further away, Maréchal et al.[3] considered a non-homogeneous unconfined aquifer and a transient flow regime to propose two novel analytical solutions for predicting groundwater ingresses in circular tunnels covering waterproof layers and in those far from waterproof layers. In their sides, considering a Darcy flow and water table drawdown, El Tani et al.[4] conceived a workable analytical solution for evaluating groundwater inflows into circular tunnels located in seismically active areas. Assuming that groundwater particularly circulates in a non-Darcian regime in rocks, Liu et al.[5] established a semi-analytical solution to predict groundwater inflows in an underground tunnel. Likewise, to estimate groundwater inflows into grouted and lined underwater tunnels situated in media obeying non-Darcian law, Xiang Liu et al.[6] proposed novel analytical solutions that are verified by field and experimental data, numerical simulation, and other analytical solutions. To decrease riskiness in underground tunnels, Mahmoodzadeh et al.[7] developed a machine learning-based solution to forecast groundwater ingresses inside excavated zones. Solutions for estimating groundwater inflows into tunnels are abundant. Despite this, thanks to the continued efforts of researchers, new solutions are emerging day by day. For instance, as showed by Dematteis et al.,[8] along the host rocks of excavated tunnels, thermal measurements can even be used to estimate potential groundwater inflows. The most commonly used solutions to date are presented in Figure 1.

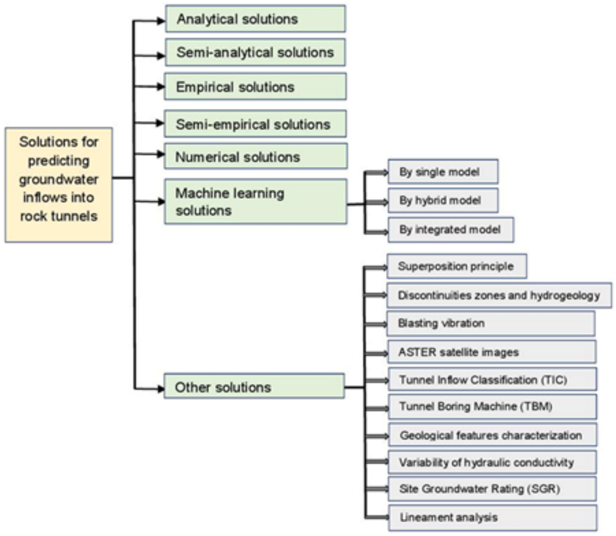

Figure 1 Solutions for predicting groundwater inflows in underground tunnels (Frenelus, 2023).[9]

The other solutions are mainly proposed in order to improve the precision when estimating groundwater inflows into underground structures. In fact, on the one hand, analytical, semi-analytical, empirical, semi-empirical, and numerical solutions often failed to accurately forecast the ingresses of groundwater in underground structures.[10, 11] The main reason is that the dominant parameters linked to hydrogeological and excavations conditions are particularly hypothesized and simplified in the aforesaid solutions. On the other hand, huge relevant data are needed by numerical and machine learning solutions to provide reasonable results. This is time consuming and costly for professionals in the field. Consequently, resorting to other solutions makes a lot of sense. Indeed, groundwater ingresses into underground excavations are also predicted on the basis of the following means: superposition principle,[12,13] discontinuity zones and hydrogeology,[10] blasting vibration,[14] ASTER satellite images,[15] Tunnel inflow classification,[16] Tunnel Boring Machine,[17] Geological features characterization,[18] variability of hydraulic conductivity,[19] site groundwater rating,[20] lineament analysis.[21,22] It should be noted that each of these solutions has its own specificities and scope of applications.

Relevance of precise forecasts of groundwater ingresses

When constructing deep underground structures, groundwater inflows can be easily triggered when the safety thickness of the surrounding rocks is significantly affected. Typically, referring to Liu et al.,[23] for underground structures situated in hard rocks, a minimum safety thickness of 3 m is necessary to protect the openings against rapid water ingresses. In karst areas, the minimum safety thickness of the surrounding rocks can be greater and varies with several factors.[24] The safety thickness, for underground excavations located in areas rich in water, is generally assessed as follows:[25]

$$S = S_c + S_f \tag{1}$$

Here, S_c stands for the thickness of fracture zone. Typically, geophysical tests are used to evaluate S_c . S_f represents the protection zone thickness. It depends on several factors as shown below:

$$\begin{cases} S_f = \dfrac{11R}{17}\left\{ln\lambda - ln\left[\lambda - \dfrac{2000Pw\sqrt{\pi a}\,tan\varphi + 2000K_{IIC}}{\gamma H\sqrt{\pi a}\left(tan\varphi - tan\varphi cos2\beta - sin2\beta\right)}\right] + \dfrac{tan\varphi + tan\varphi cos2\beta + sin2\beta}{tan\varphi - tan\varphi cos2\beta - sin2\beta}\right\}; P_w > P_{C1} \\ S_f = \dfrac{11R}{17}\left\{ln\lambda - ln\left[\lambda - \dfrac{2000Pw\sqrt{\pi a}\,tan\varphi + 2000K_{IIC}}{\gamma H\sqrt{\pi a}\left(tan\varphi - tan\varphi cos2\beta + sin2\beta\right)}\right] + \dfrac{tan\varphi + tan\varphi cos2\beta - sin2\beta}{tan\varphi - tan\varphi cos2\beta + sin2\beta}\right\}; P_w < P_{C1} \end{cases} \tag{2}$$

Where the radius of the underground structure is designated by R; The water pressure in the water-rich region is denoted by P_w ; The critical splitting rupture water pressure by P_{C1} ; The lateral pressure coefficient by λ ; while the crack half length is represented by a ; The internal friction angle, the angle between the major axis of the crack and the maximum principal stress (σ_1), and the mode II fracture toughness of the rock type are respectively noted by φ, β and K_{IIC}.

The critical splitting rupture water pressure can be estimated as follows:

$$P_{C1} = \sigma_1 - \frac{1}{tan\varphi}\frac{K_{IIC}}{\sqrt{\pi a}} \tag{3}$$

Among the multiple factors that govern groundwater ingress, hydrogeological states and structural elements play an important role.[26] Accurate prediction of groundwater ingress is of paramount importance in the overall construction and operation of underground structures. It is particularly necessary to ensure the safe accessibility and management of excavated areas, as well as to facilitate safe and sustainable operation of these structures through suitable design of appropriate drainage systems. Besides, the precise prediction of groundwater ingresses in these structures is also needed to evaluate and diminish the induced environmental effects. In fact, the consequences of unexpected groundwater ingresses into underground openings are usually significant. They generally include losses of human life, material and economic. It should be noted that the failure of underground structures can occur after long-term actions of groundwater seepage in the host rocks.[27] Inaccurate forecasts of groundwater ingresses will cause water seepage in the surrounding rocks of underground engineering projects. It should be noted that, in the event of exaggerated and uncontrollable groundwater ingresses, the construction of underground structures is generally stopped.[28] The consequences of such situations usually lead to huge losses.

Indeed, whatever the method or solutions used to predict groundwater ingresses into underground structures, accuracy must be of primary interest. It is recognized that efficiency and success of underground engineering projects rely on the accurate forecast of groundwater inflows.[7, 29–32] Regarding analytical solutions, Peng et al.[25] explained in detail the key factors that need to be carefully considered to reasonably improve the accuracy of predicting groundwater ingresses in the excavated areas of underground structures. While numerical solutions, applied artificial intelligence that involves machine learning-based solutions, as well as other solutions require enormous data to provide reasonable results. Noted that, regardless of the type of groundwater inflows in underground structures, an accurate estimate should always be sought. It should be reminded that 6 types of groundwater inflows can be distinguished for underground structure whose diameter does not overtake 6 m. These types (dripping, leakage, inflow, high inflow, inrush, water burst) widely depend on the extent of groundwater inflows. Figure 2 presents them according to their hydrological conditions and the geological states in which they are most common.

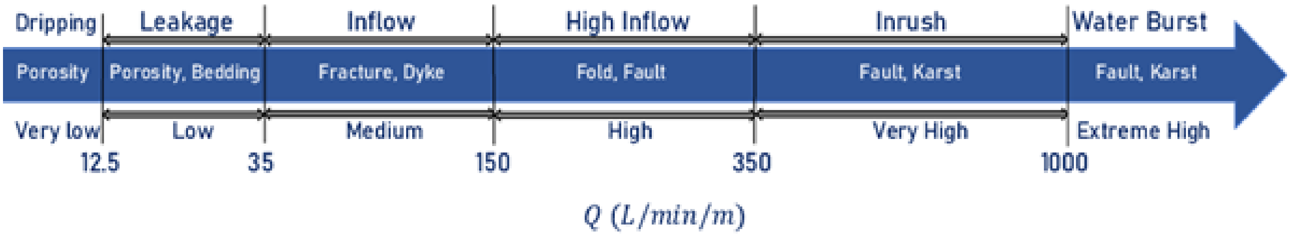

Figure 2 Types of groundwater ingresses into underground structures.[25]

Any type of groundwater inflows has deteriorating and destabilizing effects on the host rocks of any underground structure. In other words, referring to Gao et al.,[31] the surrounding rocks are generally weakened and eroded when subjected to groundwater inflows. Generally, as stated by Li et al.,[33] underground engineering suffers serious disasters due to the influx of groundwater. Damage caused by the inflows are more severe when the groundwater are corrosive. Water bursting is the type of water inflows that exhibits the most rapidly destructive effects. It is particularly characterized by its extreme high flow and great pressure.[34,35] It is particularly urgent to opt for a precise estimate of groundwater inflows into tunnels. As explained by Ma et al.[36] and Li et al.,[37] the victims caused by such inflows in underground engineering are in the order of several thousands. The precise estimate of groundwater ingresses into underground structures is normally required for the design of the most suitable drainage systems. To this end, such predictions must be properly determined in advance.[38] In fact, it is important to note that, in underground engineering, groundwater inflows can be predicted before the excavation of the host rocks or during the construction stages. Nonetheless, the prediction carried out before rock excavation is the most important because it helps analyse any risk of groundwater ingresses into underground structures.[39] For instance, proper grouting techniques rely on accurate prediction of groundwater inflows into underground structures. In fact, suitable grouting thickness is one of the key conditions required to alleviate groundwater inflows and guarantee the safety of the secondary support of underground structures.[40–44] If groundwater inflows are underestimated, progress in the construction of underground structures may be slow in the event of vast unforeseen influxes. Indeed, the immense inflows of groundwater during the construction of underground structures generally cause additional costs since the pumping of water is thus imposed.[45–48]

When the predictions before rock excavations are accurate, the design of drainage or dewatering systems can be really efficient to withstand any type of groundwater inflows into underground structures. In this way, adequate accessibility and safety of the construction stages as well as the sustainable operation of underground structures can be effectively guaranteed.

Towards future trends in groundwater ingress forecasting

In order to continually improve the precision in the prediction of groundwater ingresses into underground structures, future solutions would tend towards the simultaneous consideration of two or more methods. Precisely, different relevant combined schemes can be taken into consideration. This trend is already noted by certain researchers convinced of the urgency of continually enhancing the forecast of groundwater ingresses into underground structures. For instance, to estimate groundwater inflows into circular tunnels constructed in drained conditions, Wu et al.[49] developed a combined analytical-numerical solution. Analytical solution, numerical and field measurement have been adequately incorporated by Wang et al.[42] to forecast groundwater ingress into an underground oil storage facility. A large-scale approach consisting in considering multiscale hydrogeological properties of water-bearing structures has been employed by Xu et al.[50] to propose a solution aiming at predicting groundwater inflow in mined sandstones, based on the analysis of field data on hydraulic conductivity. To properly estimate groundwater inflows into a deep tunnel, a combined scheme including analytical-numerical-field data was adopted by Luo et al.[51] On their sides, Farhadian and Shahraki[52] focused on numerical simulation of the impacts of several relevant factors and proposed improved analytical solutions that are validated using field data in the Amirkabir tunnel. Recently, aiming at improving the prediction of groundwater inflows in rock tunnels embedded in karst regions, Li et al.[53] proposed a dynamic modelling approach which consists of considering different MODFLOW modules where the numerical results are compared to a real engineering case for accurate verifications. Various other relevant examples can be considered. Emphasis should be placed on the fact that combined schemes or solutions are gradually imposed to improve the precision of groundwater inflow prediction into underground structures.

Due to the complexity associated with surrounding rocks at depth, it is very difficult to capture their exact behavior. This is the main reason why their accurate representation remains a difficult task. Subsequently, it is not easy to determine with great precision the factors governing the groundwater inflows into underground structures. Therefore, it is of tremendous interest to reasonably use geographic information systems and appropriate remote sensors to obtain more accurate data on the complex behavior of deep rock engineering. Thereby, they can be adequately combined with relevant methods in order to improve the accuracy of groundwater inflow prediction in underground engineering. Moreover, although it remains difficult, the time-dependency of groundwater ingresses should be greatly considered in next solutions. Solutions that prioritize both the steady state and time-dependency of groundwater ingresses into underground structures can also be experimented in the search for ideal solutions of groundwater inflow prediction. Furthermore, in terms of flow regime, most progress has already made regarding the steady state. Nevertheless, the transient flow of groundwater is little explored, and the turbulent flow is ignored till now. Ideally, as pointed out by Liu et al.,[54] a dynamic process reasonably characterizes groundwater inflows into underground structures. It is recognized that colossal efforts have already been made in the field of underground engineering. However, as the burial depth of new underground structures is continually considerable, groundwater ingresses are increasingly inevitable and should be predicted as accurately as possible. Hence, when the hydrogeological states and the excavation conditions are known, the combination of different pertinent methods can increase the precision of groundwater ingress prediction.

Conclusion

In this paper, the trends related to the prediction of groundwater ingresses into underground structures have been highlighted. Existing solutions for forecasting these inflows are abundant. As pertinent geohazards, groundwater ingresses into underground openings should be accurately forecasted in advance and the influencing factors are required to be adequately considered. Hence, the most suitable drainage or dewatering systems can be effectively designed. But, at present, it is still difficult to forecast the exact solutions for predicting groundwater inflows in underground structures. As a result, future solutions will tend to appropriate combination of various methods or schemes in order to continually increase the accuracy of forecasting these ingresses.

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Conflicts of interest

The author declares no conflict of interest.

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