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The Role of Geological Structures to Tunnel Inflow, Modelling Strategies and Predictions

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Keywords: Groundwater, Inflow, geological structures, Characterization

1 INTRODUCTION

The main objective of the study presented herein is to investigate the geohydraulic modelling and characterization of geological structures respect to water inflow into tunnels. A conceptual model to analyze the groundwater inflow, a classification of inflow, and a framework of geological structures were proposed respect to prediction of water inflow into tunnels. These issues were used for comprehensive understanding the governing conditions in host ground around the tunnel and groundwater inflow.

2 WATER INFLOW: EFFECTS OF GEOLOGICAL STRUCTURES

Groundwater inflow into tunnels is a complicated issue associated in most of the projects. This difficulty comes from the complexity of the inflow mechanisms that are mostly control by geological structures. A conceptual model to analyze the groundwater inflow through the geological structure shows in figure 1. The flow rate, construction risks and difficulty, inflow locality increase by rotating in the anti-clockwise direction from the porosity to karst structures. Due to the increasing the heterogeneity of geological structures from porosity to karst, the inflow locality increases that leads to more construction risks and problems and also less prediction and modelling capabilities. By rotating in the anti-clockwise direction from the porosity to karst the both water storage and flow paths increase that resulted more inflow rate. More inflow rate and locality imply more hazards potential, risks, and water control problems. A classification of water inflow rate into tunnel respect to dominate geological structures, flow mechanism, and construction consequence is shown in table 1.

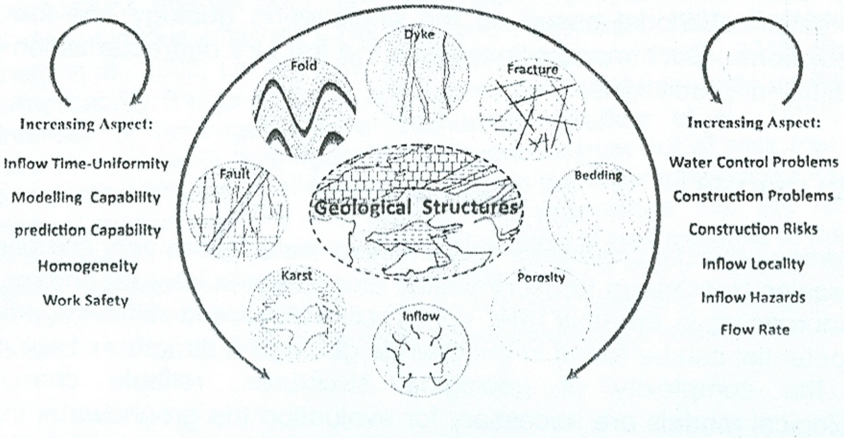

Figure 1 A conceptual model to analyze the groundwater inflow through the geological structures into tunnels

Table 1 Classification of water inflow rate (for 6 m diameter) with consequence, Dominate geological Structure, and Flow Mechanism

Class	Inflow Rate (Lit/min) per meter Length)	Description	Flow Mechanism	Dominate geological Structure	Construction consequence
I	<12.5	Very Low	Dripping	Porosity	Insignificant
II	12.5-35	Low	leakage	Porosity, Bedding	Decreasing construction rate
III	35-150	medium	Inflow	Fracture, Dyke	1-7 days work delay
IV	150-350	High	High Inflow	Fold, Fault	1-30 days work delay simultaneously construction and ground improvement
V	350-1000	Very High	Inrush	Fault, Karst	More than one month work delay necessary ground improvement before construction start
VI	>1000	Extremely High	Water Burst	Fault, Karst	Stop the construction necessary complex ground improvements before construction start

3 WATER INFLOW: PREDICTION AND MODELLING STRATEGIES

There are different hydraulic behaviors due to the different origin and tectonic regime of geological structures. Reliable characterization and hydrogeological models are necessary for evaluating the groundwater inflow into tunnel. Each geological structures has individual hydraulic behavior depends on the geological characterization related to the groundwater reservoir and flow paths. In some cases such as uniform bedding, the homogeneity assumption can be held and continuum numerical modelling approaches can be applied as a practical tool. The validity of continuum approaches for fractured rocks depends on several parameters, the most important being the existence of a representative elementary volume (REV. If these criteria do not hold for tunnel surrounding rock mass, discontinue numerical modelling such as distinct fracture network (DFN) is performed for more accurate predictions. Macro and pseudo-scale geological structures such as fold, fault zone, dyke, and karst have different hydraulic behaviors and are almost the main source of high local groundwater inflow into rock tunnels. In such situation, proper evaluation of groundwater inflow into tunnels requires a reliable hydrogeological model that briefly describes the tunnel environment. Setting up this model encounters with the lack of accurate geological input data due to the complexity and unknown tunnel environment (in most of the cases). Moreover, numerical modelling of these geological structures is practically tedious, time-consuming and expensive due to the complexity of input data and governing conditions. In such situation, empirical model based on the engineering geology has the key role in the inflow predictions. Such models linked with the fracture characterization can be adapted for more efficient predictions.

4 CONCLUSIONS

The governing physical processes and effective features are very complicated due to the different scales from mega to micro-scales and complex interdependency. A meaningful trend of increasing in the flow rate, construction risks and difficulty, inflow locality, and hazards potential can be found in the change geological structures from porosity to karst. Due to the complexity of geological structures, reliable characterization and hydrogeological models are necessary for evaluation the groundwater inflow into tunnel. For macro and pseudo-scale geological structures numerical modelling is practically tedious, therefore, empirical model based on the engineering geology linked with the fracture characterization can be adapted for more efficient predictions.

The Role of Geological Structures to Tunnel Inflow, Modelling Strategies and Predictions

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ABSTRACT

Comprehensive understanding of the field scale hydraulic behaviour of rock mass is critical to control of water inflow to underground excavations. In this paper, the geohydraulic modelling and characterization of geological structures respect to water inflow into tunnels are discussed. A conceptual model, a classification of inflow rate, and a framework of modelling method selection were proposed for evaluating the effects of different geological structures in heterogeneity, consequence, and modelling of groundwater inflow into tunnels, respectively. These geological structures are porosity, bedding, fracture, dyke, fold, fault, and karst. A meaningful trend of increasing in the flow rate, construction risks and difficulty, inflow locality, and hazards potential can be found in the change geological structures from porosity to karst. Due to the complexity of macro and pseudo-scale geological structures, empirical models based on the engineering geology linked with the fracture characterization can be adapted for more efficient predictions of groundwater inflow into tunnels.

KEYWORDS: Groundwater, Inflow, geological structures, Geohydraulic modelling, Characterization

1 INTRODUCTION

Groundwater inflow causes several difficulties such as unsafely, impairing the project schedule, mechanical instability, equipment damage, and altering the groundwater regime as well in the construction phase of any underground excavations as in the operation phase. To evaluate the related problems, the possibility and the probable water inflow into excavation must be somehow predicted in advance.

Groundwater inflow into underground excavations has been studied via empirical methods (Gattinoni and Scesi, 2010; Aalianvari et al., 2010), analytical solutions (Goodman et al. 1965; Zhang and Franklin, 1993; El Tani, 2003; Park et al. 2008; Ming et al., 2010), and numerical simulations through both continuum (Meiri, 1985; Li et al., 2009; Arjnoi et al., 2009), and discontinuous analysis (Dverstrop and Andersson, 1989; Rouleau and Gale, 1987; Molinero et al., 2002; Lin and Lee, 2009; Fernandez and Moon, 2010; Sharifzadeh et al., 2011). Applicability Range of these approaches particularly depends on the scale and also the intensity of heterogeneities of interest domain(Bear et al., 1993). Geological structures are the source of heterogeneities in hydraulic behavior of rock mass. Analytical solutions and continuum numerical simulations rely on the assumption of homogeneous and isotropic porous medium around the underground excavations that are rarely met by fractured rock masses. In such situation, the DFN concept is an alternative to the discontinue representations of fractured rock and may appear much more adapted for fluid flow simulation. Although numerical models provide a powerful means of investigating rock mass hydraulic behaviour, field application of water inflow prediction is restricted by the complexity of macro and pseudo-scale geological structures such as fold, fault zone, dyke, and karst. Each geological structures has individual hydraulic behavior depends on the geological characterization related to the groundwater reservoir and flow paths. Therefore, reliable characterization and hydrogeological models are necessary for evaluation the groundwater inflow into tunnel.

The main objective of the study presented herein is to investigate the geohydraulic modelling and characterization of geological structures respect to water inflow into tunnels. First, the governing physical processes and the most important effective features that control the mechanism of inflow into tunnels with their interdependency are discussed. For simplification of the problem, a conceptual model developed to analyze the groundwater inflow through the geological structures. The most important geological structures controlling groundwater inflow into tunnels were categorized into seven features contain porosity, bedding, fracture, dyke, fold, fault, and karst considered in the conceptual model. A classification of water inflow rate into tunnel was suggested. Moreover, a framework of geological structures was proposed respect to prediction of water inflow into tunnels throughout practical models. Finally, geohydraulic characterization of geological structures related to the groundwater inflow was discussed.

2 BACKGROUND

Groundwater inflow into underground excavations such as tunnel is a complicated issue associated in most of the projects. The most part of this difficulty comes from the complexity of the inflow mechanisms that are control by different features. In such situations, the development of realistic and robust predictive models of inflow mechanism requires a thorough understanding of the physical processes that govern flow in host ground around the tunnel. However, the governing physical processes and effective features are very complicated due to the different scales from mega to micro-scales and complex interdependency. Some of the most important effective features that control the mechanism of inflow into tunnels with their interdependency are shown in Figure 1.

The mega-scale features of geological and regional hydrology mostly control the semi macro-scales features of in-situ ground water and rock mass conditions. There is a very close interrelationship between the groundwater, rock mass condition, and geological features where some geological structures such as faults may change the groundwater condition and fractures spatial distribution and development of karst as a geological feature is a function of changes in groundwater table and water solution phenomenon. These four features can be considered as local hydrogeology condition around the tunnel. The tunnel attributes such as shape, size, depth, and construction method with local hydrogeology control the mechanism of water inflow into tunnels.

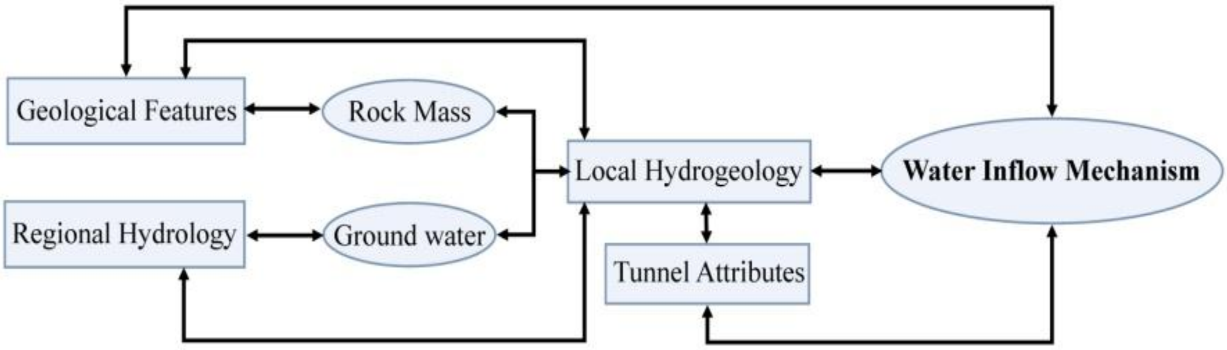

Figure 1 Effective features associated with mechanism of inflow into tunnels

Despite the complex interaction between effective features, two main factors of the aquifer (reservoir) of groundwater, and water flow paths can be considered as the controlling features of water inflow into tunnels from the modelling point of view. The interconnected vacuity spaces in rock mass such as pores, holes, dolines, karst cavities, and fractures, provide the essential storage capacity of groundwater. The main flow paths are the interconnected void pores (primary porosity), and fractures (secondary porosity) that provide the essential permeability of rock mass. Numerous field evidences indicate that the bulk of water flow in rock mass often occurs in preferred flow paths, or channels within the fractures that can significantly control the hydraulic behaviour of host rock, especially in crystalline rocks with very low permeable matrix.

3 WATER INFLOW: EFFECTS OF GEOLOGICAL STRUCTURES

The main flow paths in rock mass are mainly depended to the tectonic regime and geological structures. Most of the geological structures are complicated with multiple-scale effects due to the origin tectonic regime. Although it is practically difficult to acquire accurate geological data individually for each geological feature, it is necessary to take into account the effect of geological structures for more realistic and robust modelling to analyze the groundwater inflow into tunnels.

A conceptual model to analyse the groundwater inflow through the geological structure shows in figure 2. The most important geological structures respect to groundwater inflow into tunnels contain porosity, bedding, fracture, dyke, fold, fault, and karst were considered in the conceptual model. As shown in figure 2, the flow rate, construction risks and difficulty, inflow locality increase by rotating in the anti-clockwise direction from the porosity to karst structures. Due to the increasing the heterogeneity of geological structures from porosity to karst, the inflow locality increases that leads to more construction risks and problems and also less prediction and modelling abilities. On the other hand, by rotating in the anti-clockwise direction from the porosity to karst the both water storage and flow paths increase that resulted more inflow rate. In fact, by rotating in the anti-clockwise direction from the porosity to karst the mechanism of water inflow into tunnels changed from dripping to water burst. More inflow rate and locality imply more hazards potential, risks, and water control problems. Moreover, the computational modeling capability decreases due to the increasing the heterogeneity and complexity of geological structures by rotating in the anti-clockwise direction from the porosity to karst. Table 1 gives a classification of water inflow rate into tunnel respect to dominate geological structures and flow mechanism.

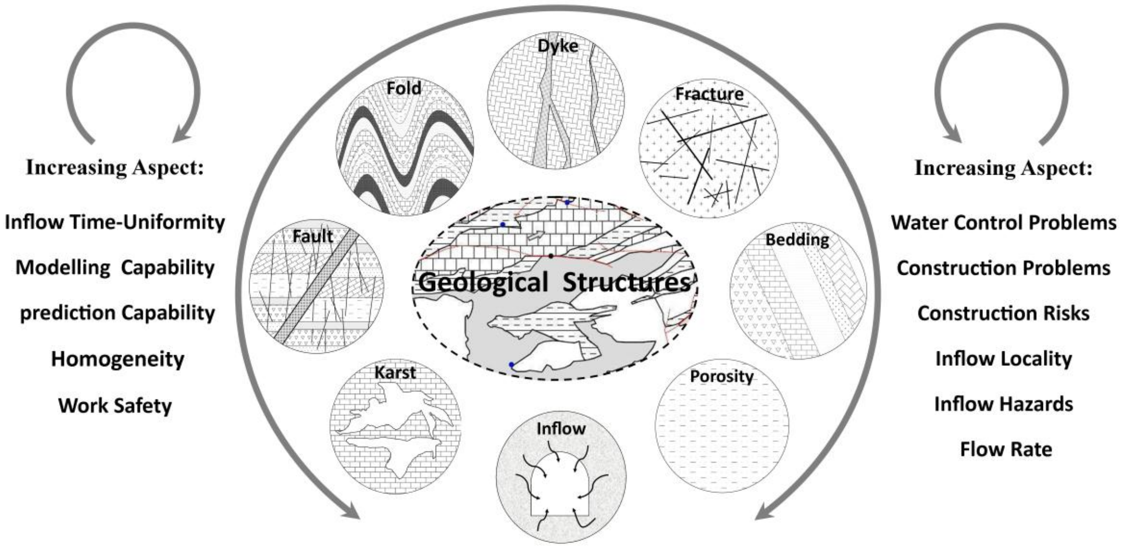

Figure 2 A conceptual model to analyze the groundwater inflow through the geological structures into tunnels

Table 1 Classification of water inflow rate (for 6 m diameter) with consequence, Dominate geological Structure, and Flow Mechanism

Class	Inflow Rate (Lit/min) per meter Length)	Description	Flow Mechanism	Dominate geological Structure	Construction consequence
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VI	>1000	Extremely High	Water Burst	Fault, Karst	Stop the construction necessary complex ground improvements before construction start

4 WATER INFLOW: PREDICTION AND MODELLING STRATEGIES

There are different hydraulic behaviors due to the different origin and tectonic regime of geological structures. In such situations, reliable characterization and hydrogeological models are necessary for evaluating the groundwater inflow into tunnel. A framework of geological structures respect to prediction of water inflow into tunnels throughout practical models is shown in figure 3. The practical models are categorized into four groups of methods, including closed-form solution, continuum numerical modelling, discontinue numerical modelling, and empirical models based on engineering geology.

Analytical solutions are based on the assumption of homogeneous and isotropic porous medium around the underground excavations. Most of the closed-solutions rely on the steady state groundwater ingress into a drained tunnel of circular cross section are derived on the basis of conformal mapping. The assumptions of homogeneous and isotropic hydraulic conductivity of media are unrealistic and rarely met by tunnel surrounding area. However, in some cases such as uniform bedding, the homogeneity assumption can be held and continuum numerical modelling approaches based on either equivalent porous medium assumption or multi-continuum approximations can be applied as a practical tool.

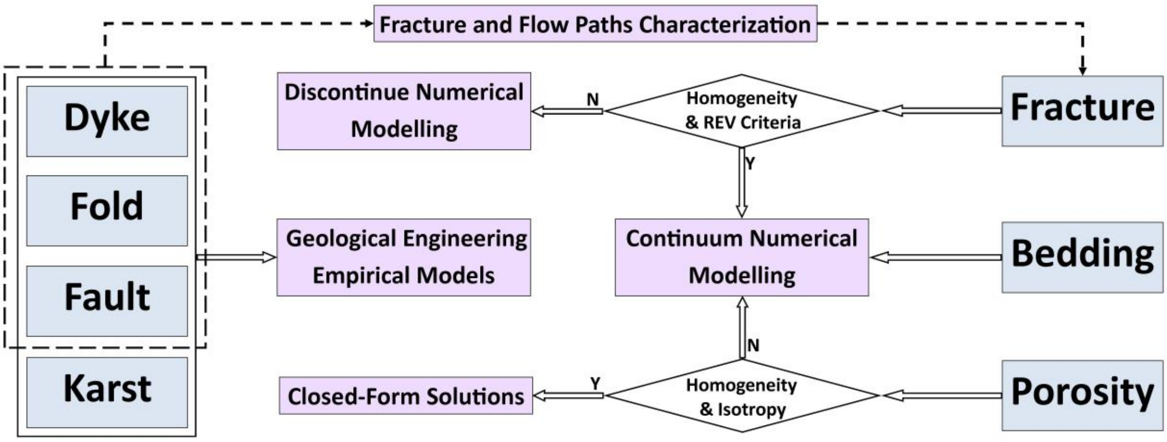

Figure 3 A framework of modelling method selection for water inflow prediction into tunnels

In fractured media, continuum behaviour is more likely to occur in extremely long and densely fractured (Lin and Lee, 2009), well-connected fracture networks with mixed fracture orientations than in sparsely fractured, poorly connected, and/or strongly anisotropic systems (Niemi et al., 2000); or where dimensions of the interested domain or scale of application are almost large compared to the heterogeneities of the medium (Schwartz and Smith, 1988; Pouya and Fouché, 2009); or where the fracture systems are statistically homogeneous (Zimmerman and Bodvarsson, 1996). The validity of continuum approaches for fractured rocks depends on several parameters, the most important being the existence of a representative elementary volume (REV), i.e. a volume above which the flow and transport properties of the fractured rock can be considered as statistically homogeneous and also should be small enough to accurately describe what happens in the volume (Bear et al., 1993). If these criteria do not hold for tunnel surrounding rock mass, discontinue numerical modelling is performed for more accurate predictions. In such situations, the distinct fracture network (DFN) concept is an alternative to the discontinue representations of fractured rock and may appear much more adapted for fluid flow simulation.

Macro and pseudo-scale geological structures such as fold, fault zone, dyke, and karst have different hydraulic behaviors and are almost the main source of high local groundwater inflow into rock tunnels. In such situation, proper evaluation of groundwater inflow into tunnels requires a reliable hydrogeological model that briefly describes the tunnel environment. Setting up this model encounters with the lack of accurate geological input data due to the complexity and unknown tunnel environment (in most of the cases). Moreover, numerical modelling of these geological structures is practically tedious, time-consuming and expensive due to the complexity of input data and governing conditions. In such situation, empirical model based on the engineering geology has the key role in the inflow predictions. Such models linked with the fracture characterization can be adapted for more efficient predictions.

5 CHARACHTERIZATION OF GEOLOGICAL STRUCTURES

There are different hydraulic behaviors due to the different origin and tectonic regime of geological structures. Therefore, reliable characterization and hydrogeological models are necessary for evaluation the groundwater inflow into tunnel. In most of the geological structures, the matrix permeability is negligible in comparison to permeability of fractures and rock mass hydraulic behavior is controlled by fractures. Therefore, fracture is the most important feature in characterization of geological structure respect to groundwater inflow into tunnels. Each geological structures has individual hydraulic behavior depends on the geological characterization related to the groundwater reservoir and flow paths that are discussed below.

5.1 Porosity

Soils and unfractured rocks can be considered as local homogeneous media. The porosity of unfractured rocks changes from less than 2% for igneous rocks, 1 to 5% for most of the sandstones, and more than 20% for soft limestones. For granular soils depending to the grain size, the porosity varies from 13% to 50%. In such media, the most important related groundwater parameter is the effective porosity where the water in interconnected pores contributes to inflow into tunnel. Porosity is primarily controlled by the shape, size and arrangement of the media grains and decrease with depth due to the compaction and confining stress. Effective porosity controls the permeability of soils and unfractured rocks that is the key parameter in water inflow into tunnels. For isotropic and homogeneous media, the water inflow into tunnels can be calculated through closed-form solutions (Goodman et al. 1965; Zhang and Franklin, 1993).

5.2 Fracture

Natural fractures in rock mass have a complicated geometry with different orientation, size, and spatial distribution at all scales. These heterogeneous situations are encountered with a high level of uncertainty with respect to the rock mass permeability due to the highly inhomogeneous spatial distribution of hydraulic conductivity. The fundamental characteristic of fractured rock aquifers is extreme spatial variability in hydraulic conductivity, and hence groundwater flow rate. However, most of the geometrical characteristics of fractures are mainly depended to the tectonic regime and main geological structures of fault and fold.

5.3 Bedding

Bedding planes can have a major influence on the hydraulic properties of the rock mass. Bedding planes serve as source-sink boundaries of adjacent porous sediments and act as a one of the discontinuity in the hydraulic behavior. Based on the thickness of bedding layers, general structure of rock mass can be categorized to massive structure (layers thickness more than 30cm) and bedded structure (layers thickness less than 30cm). Opening-mode fractures in layered sedimentary rocks are often observed to propagate across, terminate at, or step-over at a bed contact at bedding contacts. In interbedded brittle and ductile rocks fractures initiate within stiffer beds and terminate at the contact with more ductile beds. Strength of bedding contacts controls the type of fracture intersection where fracture termination is favored at very weak bedding contacts, whereas fractures propagate straight through strong contacts, and moderate-strength contacts may develop step-over fractures. Moreover, thicker beds may produce greater amounts of step-over than thinner beds (Cooke and Underwood, 2001). On the other hand, where layering plays an important role in restricting joint growth, a lognormal distribution reflects the true length population of joints whereas in more massive rocks, a power law distribution was more appropriate (Odling et al., 1999). Moreover, fracture spacing in layered sedimentary rocks is proportional to the thickness of the fractured layers (Bai and Pollard, 2000).

5.4 Dyke

Dykes are long and thin imposition of mostly fine-grained igneous rock with steep or vertical and approximately parallel sides. Hydraulic behaviour of dykes is strongly depended to the weathering and fracturing characteristics of intrusive. The basic igneous dyke rocks such as dolerite can weather to montmorillonite clays that are noted for their swelling characteristics and acting as water barrier. On the other hand, groundwater inflow through dykes depends on tectonic history after dyke emplacement and fracture intensity. Fractured dykes could act as conduit for water to flow to the opening. By contrast, non-fractured dykes act as a barrier against groundwater flow.

5.5 Fold

Fold-related fractures can be classified in three classes including an axial extensional set successively parallel to the fold axis, a cross-axial extensional set oriented perpendicular to the fold axis and two sets of conjugate shear fractures oblique to the fold axis with their obtuse angle intersecting the trend of the fold axis. However, it is necessary to draw attention to the occurrence within folded strata of fracture sets having originated before folding and being unrelated to either fold geometry or kinematics. Occurrence of such pre-folding fracture sets within folded layers clearly changes the common view of fracture–fold relationships.

5.6 Fault

Faults with different hydraulic behaviors have different impacts on groundwater inflow. Strike-slip faults have sub-vertically conjugate fractures oriented oblique to the strike of the fault;

hence, significant percolation of water to depth is expected. Normal faults form in extensional tectonic regime with vertical extension fractures parallel to the strike of the fault; therefore remarkable transmissibility is expected. On the contrary, thrust faults are created in compressive tectonic regime and extension fractures oriented sub-horizontally, often not interconnected; therefore, minor transmissibility is expected. In general, vertical fractures shows high transmissibility and inflow compared to horizontal fractures (Zarei et al., 2010). On the other hand, occurrence of pre-faulting fracture sets within the rock layers obviously changes the general hydraulic behaviour of faults.

6 Conclusion

This paper discusses the most important effective features that govern the mechanism of inflow into tunnels with their interdependency. A conceptual model to analyze the groundwater inflow, a classification of inflow, and a framework of geological structures were proposed respect to prediction of water inflow into tunnels. These issues were used for comprehensive understanding the governing conditions in host ground around the tunnel and groundwater inflow.

There are many factors that control the groundwater inflow into tunnels. The governing physical processes and effective features are very complicated due to the different scales from mega to micro-scales and complex interdependency. The mega-scale features of geological and regional hydrology mostly control the semi macro-scales features of in-situ ground water and rock mass conditions. These four features can be considered as local hydrogeology condition around the tunnel and with the tunnel attributes such as shape, size, depth, and construction method control the mechanism of water inflow. Despite the complex interaction between effective features, two main factors of the aquifer of groundwater, and water flow paths can be considered as the controlling features of water inflow into tunnels from the modelling point of view. Both of these factors are mainly depended to the tectonic regime and geological structures. The most important geological structures respect to groundwater inflow into tunnels contain porosity, bedding, fracture, dyke, fold, fault, and karst were considered in the proposed conceptual model. A meaningful trend of increasing in the flow rate, construction risks and difficulty, inflow locality, and hazards potential can be found in the change geological structures from porosity to karst.

Due to the complexity of geological structures, reliable characterization and hydrogeological models are necessary for evaluation the groundwater inflow into tunnel. For macro and pseudo-scale geological structures numerical modelling is practically tedious, therefore, empirical model based on the engineering geology linked with the fracture characterization can be adapted for more efficient predictions.

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