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Evaluation of Underground Water Flow into Tabriz Metro Tunnel First Line by Hydro-Mechanical Coupling Analysis

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Abstract**—**One of the main practical difficulties attended with tunnel construction is related to underground water. Uncontrolled water behavior may cause extra loads on the lining, mechanical instability, and unfavorable environmental problems. Estimating underground water inflow rate to the tunnels is a complex skill. The common calculation methods are: empirical methods, analytical solutions, numerical solutions based on the equivalent continuous porous media. In this research the rate of underground water inflow to the Tabriz metro first line tunnel has been investigated by numerical finite difference method using $FLAC^{2D}$ software. Comparing results of Heuer analytical method and numerical simulation showed good agreement with each other. Fully coupled and one-way coupled hydro mechanical states as well as water-free conditions in the soil around the tunnel are used in numerical models and these models have been applied to evaluate the loading value on the tunnel support system. Results showed that the fully coupled hydro mechanical analysis estimated more axial forces, moments and shear forces in linings, so this type of analysis is more conservative and reliable method for design of tunnel lining system. As sensitivity analysis, inflow water rates into the tunnel were evaluated in different soil permeability, underground water levels and depths of the tunnel. Result demonstrated that water level in constant depth of the tunnel is more sensitive factor for water inflow rate to the tunnel in comparison of other parameters investigated in the sensitivity analysis.

Keywords**—**Coupled hydro mechanical analysis, $FLAC^{2D}$, Tabriz Metro, inflow rate.

I. Introduction

TUNNELING in urban areas usually requires a detailed description of the environment around the tunnel in order to reduce hazards during excavation. Underground water flow into tunnel is one of the major problems in tunneling, because it may cause structural difficulties such as unfavorable working conditions, damage to construction equipment, losing construction time in order to stem the water inflow, creating dangerous working conditions, the entry of fine grains from the surrounding ground, and collapse caused by sudden water inrush. Therefore, the feasibility and potential extent of groundwater flow in to underground excavations must somehow be predicted beforehand [1].

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Incorrect estimations of water inflow to the tunnels occur because of several reasons such as, the geological conditions for the project site may be not accurately understood; real conditions may be different from the assumptions in the water inflow calculation equations; data limitations due to the testing program and so on. There are numbers of analytical methods in the literature to compute the quantity of underground water entrance into tunnels [2]-[8], which are widely used because of their simplicity.

El-Tani [8] offered an equation for a semi-infinite isotropic and homogeneous aquifer that it is drained by a circular tunnel. Park et al. [9] used a closed-form analytical solution for the evaluation steady-state groundwater inflow into circular tunnel with focus on different boundary conditions. Ming et al. [3] presented an analytical solution for estimating the distribution of the hydraulic head and the pore pressure boundary at the tunnel in a fully saturated, homogenous, isotropic, and semi-infinite aquifer conditions. The parameters such as soil permeability, water level height above tunnel axis and tunnel radius are used in the analytical methods for estimation of ground water seepage into tunnels.

Numerical methods such as finite difference, finite element, district element and finite volume methods are used to simulate the underground water flow into tunnels and calculate of its rate. In contrast of the analytical methods, numerical methods are not simplistic in calculations, and require general information about boundary conditions and material properties. Despite of complexity and time-consuming nature, they provide more accurate results than analytical methods.

The tunnel excavation affects the natural hydrodynamic behavior of the underground water systems. Tunnel behaves as a draining structures and causes to the water table changes. The coupling of stress and pore pressure has important effect on tunneling performance but, studies concerning this subject are limited. In some of the limited studies available, the hydrodynamic nature, the influence of flow to the tunnel and their impact on the tunnel's reliability and loads carried by lining have been examined [10], [11]. There are a number of studies about the effect of tunneling on the groundwater regime in the surrounding environment [12], [13]. Gunn and Taylor [14] and Schweiger [10] have numerically investigated the steady-state seepage and stress, however they did not exactly model the fully coupled interaction behavior between the tunnel construction and the underground water. Shin [15] and Addenbrooke [16] modeled the effect of underground water on the long-term behavior of tunnel by using of a plane strain and an axisymmetric model in finite element method. Some researchers studied the interaction mechanism between tunnel excavation and groundwater by a 3D stress-pore pressure coupled finite element method [17].

The water pore pressure in the surrounding geotechnical medium has two effects: first, internal pressure prevents expansion of the water liner, and second, decreasing effective stresses change the stress field in the surrounding material of the tunnel. Some of the effects of water pore pressure on the tunnel support system have been investigated [18], [19]. Wang et al. [20] recommended a solution for a deep pressured tunnel in saturated elastic porous media that it obeys Terzaghi's effective stress principle. That solution considered the effects of the water pore pressure on the excavated structures and also its interaction with tunnel surrounding materials in the mechanical responses of the tunnel. Preisig and Cornaton [21] focused on quantitative tools in the problem of groundwater inflow and related mechanisms during and after tunnel excavation. Prassetyo [22] investigated the effect of the transient hydro mechanical interaction on applied performance of the convergence-confinement method and the longitudinal displacement profile of an advancing tunnel in deep saturated ground by numerical FDM method.

As it is mentioned, the design of tunnels below the water-table should be done carefully, taking into account the influence of pore pressure and seepage forces on the stability of excavation and loading conditions on the supporting systems. So this study has focused on existence of water in surrounding soil of the tunnel and evaluation of underground water inflow to the tunnel by application of continuum porous media method in the finite difference method (FLAC^{2D} software). Estimation of the loading on the lining of tunnel is done under three types of condition (fully coupled, one-way coupled and no water state) to investigate the effect of the underground water on tunnel lining. As sensitivity analysis, the impact of permeability of the soil around the tunnel, the depth of the tunnel, and the height of the water head at the rate of water entrance to the tunnel were investigated using a fully coupled hydro mechanical method.

The hydro mechanical (HM) coupling implies the interaction between hydraulic and mechanical processes. In geological environments involving rock and soil, there are numerous pores and fractures, so in these conditions mechanical processes are coupled with hydraulic processes. Multi-physics simulations generally have three basic algorithms including fully coupling, loose coupling and one-way coupling. To describe a fully coupled simulator, an individual set of equations (generally a large system of nonlinear coupled partial differential equations) including all of the relevant physics must be solved. For instance, the prior equations of porous flow for a rigid matrix would be improved to contain terms for mechanical deformation. Since the fully coupling theoretically generated the most realistic results, it is often the preferred method for simulating in physics. Because of modeling nonlinear and inelastic mechanical deformation in fully coupled multiphase flow simulator, applying of this method is extremely difficult, So some simplifications like as single-phase flow and the mechanisms of liner elasticity commonly are used in these simulations [23]-[25].

The other type is one-way coupling. In this approach, two sets of completely separate equations are solved simultaneously. Information is transmitted in one direction only. It means that, outputs from one simulator are passed as inputs to the other periodically. For example, pore pressure should be sent from the hydraulic computation to load the mechanics calculation of stresses, strains and displacements [26].

In loose coupling, like one-way coupling, two sets of equations are solved independently, but information is passed at defined intervals in both directions between fluid flow and geo-mechanical simulators. Although loose coupling has the simple implement advantage like the one-way coupling, it has efficiency performance for estimating of more complex nonlinear physics, in these respect it is closer to a fully coupled approach [27].

A. Methodology of Numerical Analysis

HM coupling between fluids and porous solid has been known more than one hundred years ago [28], [29], but the first specific conceptual advances in hydromechanics came from attempts to understand two apparently separate phenomena in the 1920s. Karl Terzaghi [30] tried to analyze consolidation of soil infrastructures. He created two principal ideas, the notions of effective stress and the diffusion of fluid pressure by flow. The concept of Terzaghi's effective stress is:

$$\sigma_{zz}^{'} = \sigma_{zz} - p \tag{1}$$

σ'_{ZZ} is the vertical effective stress or the part of the vertical stress acting to compress the porous matrix, and it is equal to applied load σ_{zz} minus the pore fluid pressure p (either absolute values or differences). Consolidation can be caused by excess fluid pressure loss.

Terzaghi used a diffusion-type equation to describe the dissipation:

$$\frac{k\partial^2 p^{'}}{a\partial z^2} \approx \frac{\partial p^{'}}{\partial t} \tag{2}$$

When "k" is permeability or hydraulic conductivity, "a" is a "compaction factor" or storage term, and p' is "hydrostatic overpressure in the pore water". These ideas are Terzaghi's "consolidation theory" and principle law in HM coupling and fluid flow through porous media. This permeability dependency on effective stress cannot be directly introduced in formulas for tunnel drainage, because the permeability varies differently at each point of the aquifer.

A reduction factor can be evaluated by analytical or numerical analysis and applied to correct the calculated water flow rate in the tunnel to avoid overestimation [30].

From the Terzaghi's Equation it follows that a change in effective stress can result because of (1) a variation in total stress and/or (2) a change in fluid pressure. Concerning underground excavations, an increase in total stress can occur with increasing depth, and a drop in water pressure occurs because of tunnel drainage [21].

II. Case Study

Tabriz is one of the biggest cities of Iran with population over 1,500,000 located in north western Iran. Based on Tabriz metro development plan, 4 metro lines will be constructed in the future in this city. The construction of line 1 with 17 km length has been already finished. Tabriz Metro Line 1 (TML1) generally has stretched along the east to west direction. Twin tunnels diameter of this line was designed as 6 m. Most parts of TML1 are covered by deposits of silty sand and sand soils with some fine-grained layers. As Fig. 1 shows, 18 stations are designed in this line and the tunnels are located below the underground water level after Station 12. So, in this research 13th station was selected for investigation [31].

Fig. 1 TML1 plan [31]

III. Numerical Modeling

In this research, finite difference method by using FLAC^{2D} software was used for numerical analysis. FLAC can be applied for analyzing, testing, and designing the geotechnical, civil and mining projects. FLAC models the fluid flow (e.g. underground water) through a permeable solid such as soil. This software can model the flow alone and independently of the usual mechanical calculation, or it may be performed simultaneously with mechanical modeling to obtain fluid/soil interactions [32].

In 13th station of metro line, the underground water height from the ground surface is 5.3 meters based on in situ measurements. The tunnel was excavated in full face cross section with EBP TBM. For simplicity only one half of one tunnels was modeled by using central symmetry. The center of the tunnel is at the coordinates x = 0 and y = 22.4 in the model geometry. Each mesh is 0.5 m, so total 3500 meshes were used in model (Fig. 2 (a)).

Appropriate hydraulic boundary conditions are also defined in this model, the top of the model was considered as the seepage boundary, so the water pressure at this boundary is zero. Bottom and left side of the model are fixed as impermeable bounds. During tunnel excavating, the tunnel surface is designated as a drainage boundary with zero water pressure (Fig. 2 (b)).

The physical and mechanics parameters of the soil around the thunnel are shown in Table I.

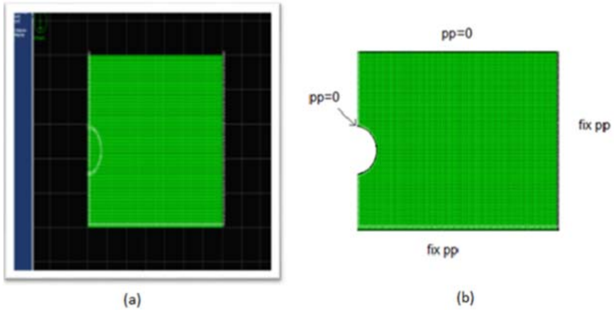

Fig. 2 (a) Mesh of model, (b) Pore pressure boundary condition of model

Some assumptions used in numerical model are as follows7:

- The surrounding soil is homogeneous, isotropic and continuously porous.
- The water head is constant.
- Conforming to Darcy theorem, water flow is stable.

A fully coupled quasi-static HM analysis in FLAC is often time-consuming, so the three main factors can help to improve this process:

- The ratio between simulation time scale and characteristic time of the diffusion process;
- The nature of the imposed perturbation (fluid or mechanical) to the coupled process; and
- The fluid to solid stiffness ratio.

TABLE I
Physical and Mechanical Parameters [31]

Parameter	Value
Modules of Bulk (Pa)	2.22×108
Shear modules (Pa)	7.407×10^{7}
Poisson's ratio	0.35
Friction angle (°)	32
Cohesive force (Pa)	1×10^{4}
Density (kg/m3)	2150
Permeability (m/s)	1×10^{-5}
Water head (m)	5.3
Tunnel depth (m)	12

By considering these factors the parameters for coupled model are estimated (Table II). Before tunnel excavation the pore pressure below the ground water table is hydrostatic (Fig. 3 (a)). After excavation, tunnel is modeled by a free water seepage boundary condition in the tunnel wall so that underground water can infiltrate into the tunnel. So the pore pressure contorts around the tunnel are changed as Fig. 3 (b). The water inflow rate to the tunnel was estimated by absolution difference in inflow and outflow values of tunnel grid points that it is about 1.4×10^{-5} m^3/s.

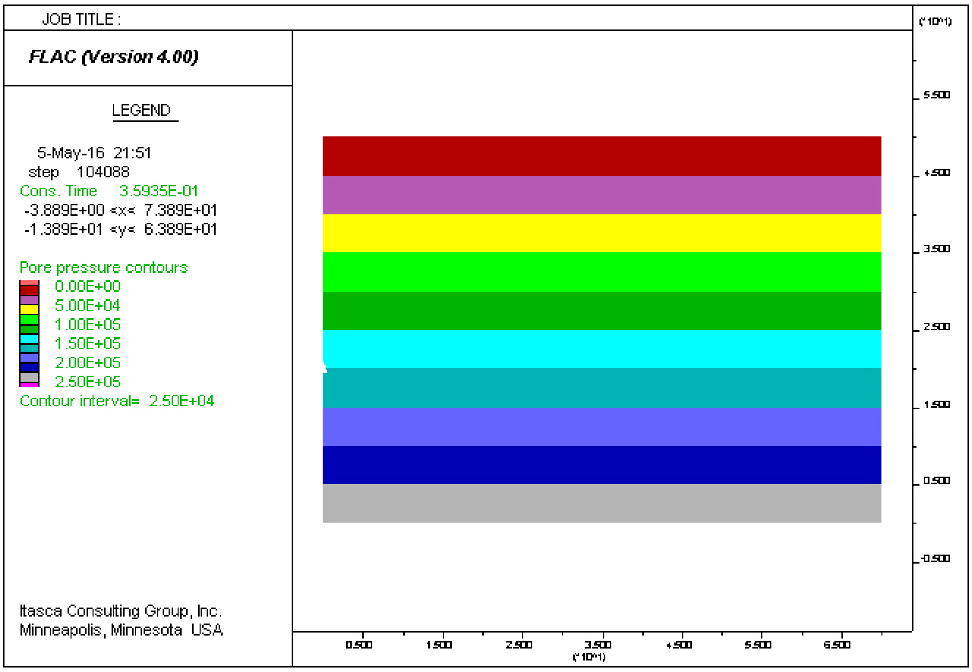

Fig. 3 (a) Distribution of pore water pressure before excavation

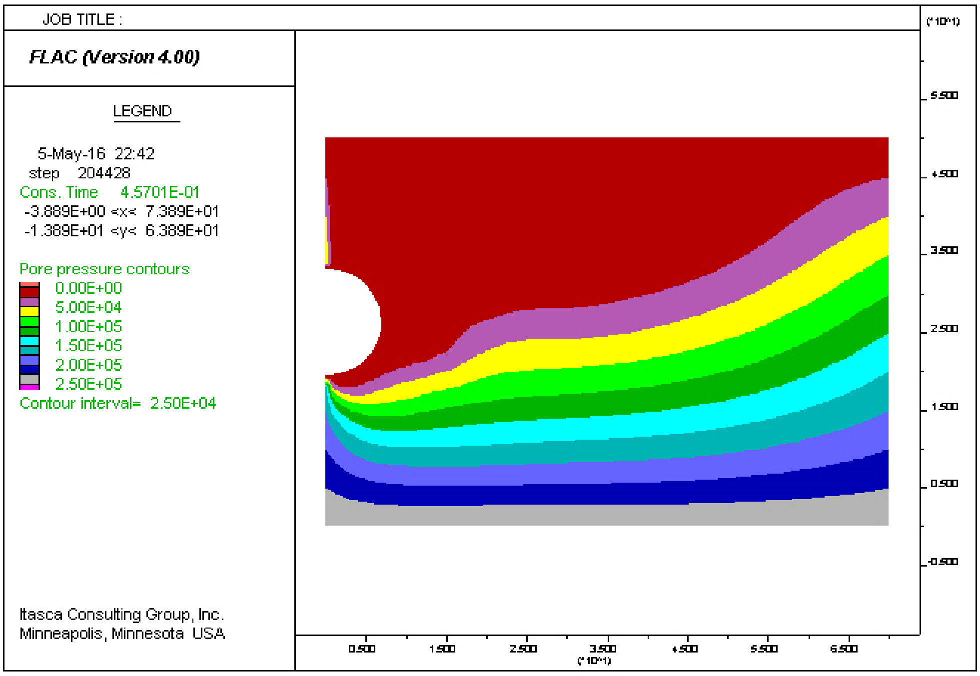

Fig. 3 (b) Pore pressure contours before support system installation

IV. Validation of Numerical Model

The numerical simulation validation is more important in practice. Therefore, the underground water inflow values obtained from finite difference simulation were compared with other standard analytical solutions. Heure [4] proposed an equation for prediction of groundwater inflow to the circular tunnel.

$$Q = \frac{2\pi KH}{\ln \frac{2z}{r}} \times \frac{1}{8} \quad (3)$$

where Q is the water inflow rate for per meter (unit of length) of the tunnel length, K is permeability of surrounding material of tunnel, H is the groundwater head height, z is the overburden height above the tunnel centerline and r is tunnel radius. The amount of inflow rate to the tunnel obtained by the Heuer method is $2.3\times10^{-5} m^3/s$, and it can be seen that there is good agreement between the two values, although the methodology used in the two methods are different.

TABLE II
HM PARAMETERS OF MODEL

Parameter	Value
Water bulk module (Pa)	1×10^9
Porosity	0.5
Soil dry density (Kg/m^3)	2510
Soil saturated density (Kg/m^3)	2640
Model characteristic length (m)	35
Smallest zone characteristic length (m)	0.5

V. COMPARISON OF LOADING ON THE TUNNEL LINING

In mechanized tunneling with Earth Pressure Balance method, supporting system includes precast concrete segmental lining, so in this research, the tunnel support system is impermeable precast reinforced concrete with a thickness of 30 cm and a width of 140 cm. Each ring of the segments contains 6 pieces. Properties of segments are shown in Table III.

TABLE III
CHARACTERISTICS OF SEGMENTS [31]

Parameter	Value
Elasticity modulus (kPa)	2.35×10^7
Uniaxial compressive strength (kPa)	45×10^3
Poisson ratio	0.2
Thickness (m)	0.3
Specific weight (KN/m^3)	24

The influence of grouting behind the segments was ignored in the numerical model. The segmental lining is modeled as a uniform ring with bedding moment reduction factor 0.7 that it is calculated with Lee [33] analytical method to consider joints influence in segments. After installation of supporting system, water pore pressure distribution has changed as shown in Fig. 4.

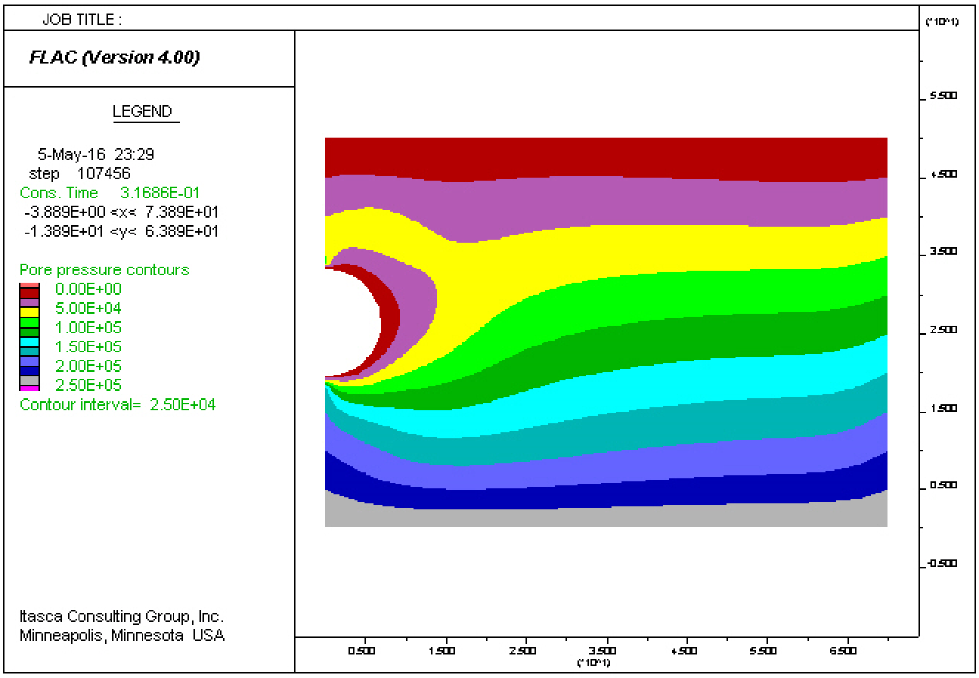

Fig. 4 Pore pressure contours after support system installation

In order to investigate the mechanism of interaction between tunneling and groundwater, three types of states including fully coupled, one-way coupled and no water conditions for soils around the tunnel have been used in numerical modeling. So, maximum axial force, bending moment and shear force are obtained for these analyses and results are in Fig. 5. Comparison of these values showed that fully coupled analysis estimates axial force, bending moment and shear force more than the other two types of analysis.

VI. EVALUATION OF GEOTECHNICAL AND GEOMETRICAL PARAMETERS' EFFECTS ON INFLOW RATE

In this section, as sensitivity analysis, the effect of the permeability of soil, underground water level and depth of the tunnel on the inflow underground water rate to the tunnel was evaluated.

Refer to Fig. 7, by increasing of permeability of soil around the tunnel in the interval of 5.005×10^{-6} m/s to 0.100005 m/s, the flow rate into tunnel grows from about 1.35×10^{-5} to 1.65×10^{-5} m^3/s. These amounts of permeability are based on the actual soil specification. Also, when the height of water table is increased from 5.3 to 26.5 m (from one to five times of the initial water level) inflow rate changed in the range of (1.4-0.4)×10^{-5} m^3/s.

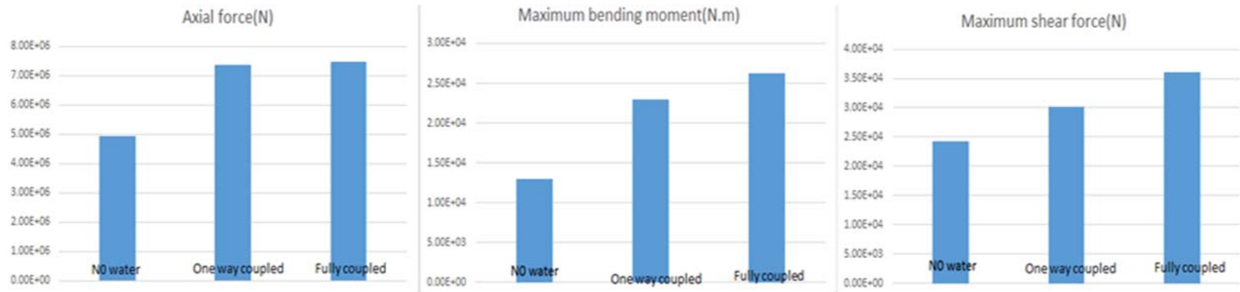

Fig. 5 Comparison of results from three modeling states

With decreasing of the water table height, the original pore pressure around the tunnel is small and the tunneling processes may be conducted in a relatively dry condition and the flow rate into tunnel can be reduced significantly (Fig. 7). And by increasing tunnel depth from 10.23 to 63.23 m (from one to five times of the initial tunnel depth), inflow rate changes from 1.4 × 10^{-5} to 2.1 × 10^{-5} m^3/s (Fig. 8).

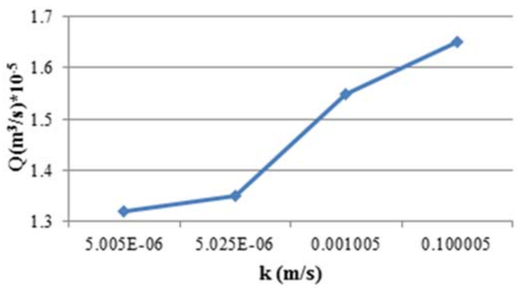

Fig. 6 Variation of inflow rate versus soil permeability

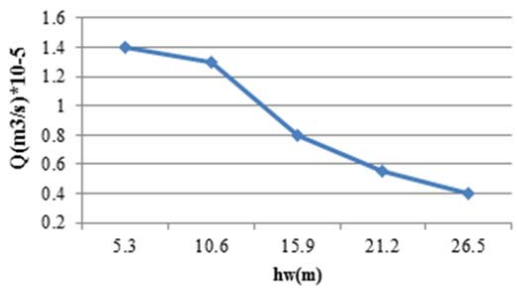

Fig. 7 Variation of inflow rate versus water table height

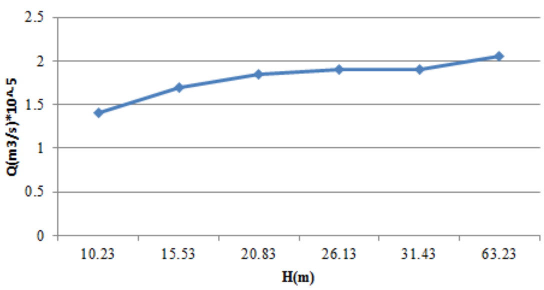

Fig. 8 Variation of inflow rate versus depth of tunnel

VII. Conclusions

This study has examined the interaction mechanism between tunnel excavation and underground water flow into the tunnel by using the 2D stress-pore pressure coupled model in TML1. Therefore, using numerical simulation of finite difference in FLAC software and focusing on the issue of groundwater flow and its effect on tunnel stability, a numerical model was constructed. Ground water flow in the surrounding soil and distribution of pore pressure is modeled before and after excavation. Comparison of the water inflow value obtained from numerical analyses and Heuer analytical solution showed good agreement between these two methods. After installation of suitable supporting system the results of stability analyses for three types of analysis (fully coupled, one way coupled, no water) have been obtained. The results showed that the axial and shear forces and bending moments were in the fully coupled simulation more than the other types of analysis. The fully coupled hydro mechanical state shows 40% axial force, 50% shear force, and 33% bending moment more than the water-free conditions in the soil around the tunnel. Therefore, the fully coupling method is more suitable for estimating the amount of load on the tunnel supporting system due to the presence of many parameters and objectivity. Finally the effects of the tunnel depth, permeability of soil and height of water level were investigated in underground water flow rate into the tunnel and it is obtained that this rate would grew by increasing tunnel depth, permeability of soil and height of water level. Meanwhile the water flow rate is more sensitive to water level in constant tunnel depth.

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