



Investigation of the impacts of tunnel excavation on karst groundwater and dependent geo-environment using hydrological observation and numerical simulation: a case from karst anticline mountains of southeastern Sichuan Basin, China

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Abstract

Tunnel excavation has significant disturbance on groundwater system and related geo-environment, especially in karst regions like southwestern China. The present research was conducted to quantitatively understand the negative impacts posed by tunnel construction on the karst groundwater system and reveal the behavior of karst groundwater system under the tunnel disturbance, with the aid of field survey, hydrogeological analysis, and numerical simulation. The results suggested that negative impacts such as loss of surface and underground water, ground collapse, and house deformation would be posed directly and indirectly to the karst groundwater system and its dependent geo-environment as the result of groundwater level drawdown by tunnel excavation. The degree and range of groundwater drainage impact were determined by the lithological and hydrogeological characteristics of strata. These negative impacts were dominantly distributed in the karst depressions valleys, and the direct ones occurred at first and followed by the indirect ones. Simulation results showed groundwater level drawdown would not occur synchronously in spatial, but always occurred around the tunnel axis at first and gradually expanded towards far away over time. The maximum disturbance on groundwater system can reach to approximately 25 m vertically and 3000 m horizontally for present modeling tunnel. With the aid of numeral simulation, three response stages were identified for the karst groundwater system behavior to the tunnel disturbance. The impacts of tunnel practice on groundwater and surface water bodies can be gradually eliminated since the second stage, but would continue if existing failure of tunnel waterproof until a new balance state achieved. The present research can improve the understanding of the impacts of tunnel excavation on karst groundwater system and dependent geo-environment, and provide reference to the protection of water resources and geo-environment in karst regions like Chongqing worldwide.

Keywords Groundwater flow, · Tunnel drainage, · Numerical modeling, · Karst anticline mountain, · Chongqing

Introduction

Water inrush is one of the common geological disasters for the construction of traffic tunnels, and usually poses great

negative impacts on the tunnel construction in terms to security, cost and time (Li et al. 2015; Xiao et al. 2019; Yau et al. 2020; Zhang et al. 2019). Due to the great potential hydraulic conductivity in karst aquifers, tunneling in karst terrains has a greater possibility to encounter disastrous water inrush accidents (Li et al. 2013). To avoid the unforeseen hazards of karst water inrush to tunnels, drainage measures are extensively conducted to drain the potential substantial groundwater prior to the tunnel construction. However, karst groundwater systems would be greatly affected by the huge water drainage during the tunnel construction (Li et al. 2021), and this kind of negative effects has increased greatly in scale, especially in the karst widespread region like southwestern China (Li et al. 2016), while karst groundwater is significantly crucial to the water supply of human community and estimated providing approximately 25% of domestic water globally (Olarinoye

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et al. 2020; Pu et al. 2014). Thus, it is essential to pay attentions to the impacts of tunnel excavation on karst groundwater system (Zheng et al. 2020).

Previous researches on tunnel excavation in karst regions are dominantly focused on the geological disasters such as karst water inrush, surface water leakage, and karst collapse (Iacobellis et al. 2015; Vigna et al. 2017), while less attention has been paid to the potential disturbances of karst groundwater system caused by the tunnel excavation. Actually, the impacts of tunnel excavation on karst groundwater would be directly reflected in the flow field and hydrodynamic processes (Gisbert et al. 2009). As a result, groundwater resource would be negatively affected spatially and temporally (Li et al. 2021), and ultimately threaten the safety of water supply and ecological environment in karst regions (Gisbert et al. 2009; Gokdemir et al. 2019; Guo et al. 2013; Long et al. 2014). In addition, tunnel excavation can alter the seepage in the karst critical zone, leading to the variation of the geological karstification (Zheng et al. 2020). The magnitude of these negative disturbances is determined by the alteration of karst groundwater system caused by the tunnel excavation (Kitterød et al. 2000). In order to maintain the balance of ecosystem, geological environment and human community, the potential disturbances of karst groundwater system posed by tunnel excavation should be well recognized and assessed (Zheng et al. 2020), and then take appropriate measures in the tunnel construction process. Fully understanding of the behavior and recovery ability of karst groundwater system under the tunnel disturbances is the premise to reduce or further eliminate the negative impacts of tunnel excavation on ecology, geological environment and human society.

South China holds one of the three most concentrated karst areas in the worlds (Zhu et al. 2021), and also strong karst development, weak water retention geological condition, and fragile ecosystem (Deng et al. 2020; Pu et al. 2014). Chongqing, one of the megacities in south China, is famous as mountain city (Lu and Jiang 2018) and characterized by the karst parallel barriers fold mountains. These karst mountains usually act as the insurmountable barriers for transportation (Lv et al. 2020). In order to improve the transportation efficiency regardless the transportation forms, the excavation of tunnels is commonly performed in the past decades. According to incomplete statistics, more than 60 traffic tunnels have been built or under building in this karst mountainous megacity (Fig. 1b). It is no doubt the construction of so many tunnels would significantly disturb the karst groundwater system and result in large environmental and hydro-ecological issues.

Although some researches have been conducted to address the aforementioned problems in Chongqing, most of them are implemented with the aid of the qualitative or semi-quantitative approaches of field survey and hydrogeological analysis (Cheng et al. 2019; Du et al. 2015; Du et al. 2016; Wu

et al. 2016; Yang et al. 2014). However, it is very inadequate for the quantitative understanding of the impacts posed by tunnel excavation, and the behavior of karst groundwater system under these anthropogenic disturbances is still unclear. The present research focused on the quantitative understanding of the negative impacts posed by tunnel construction on the karst groundwater system. An integrated approach of field survey and numerical simulation was introduced to reveal the behavior and recovery ability of karst groundwater under the disturbances of tunnel excavation. This research could provide significant references for the protection of groundwater, ecology and geological environment in tunnel excavation practices in karst regions worldwide.

Description of the study area

The present study area was located in the southeastern Sichuan Basin, China (Fig. 1a). This region belongs to the Eastern Sichuan Fold Belts that characterized by a series of alternating anticline and syncline folds. The anticlines form the dominant high and steep mountains in the study area. These mountains extend more than 100 km in NE-SW, and seriously block the local traffic communication. Thus, it is significantly necessary to construct traffic tunnels to improve the local traffic conveniences.

The anticline mountains are commonly with the width of approximately 4–8 km and the elevation in the range of 220–850 m. The outcropping stratigraphy of the anticlines ranges from Permian to Jurassic in age. The Permian strata occur in the axis of the anticlines, and are dominated by the limestone of Changxing Formation (P_2c). From the axis to the wings of anticlines, strata occur symmetrically from the Triassic layers to Jurassic layers. The Triassic layers includes limestone and mudstone of Feixianguan Formation (T_1f), limestone and dolomite of Jialingjiang Formation (T_{1j}), limestone and dolomite of Leikoupo Formation (T_2l), and sandstone and dolomite of Xujiahe Formation (T_3xj). That of Jurassic layers are dominantly sandstone and dolomite. Tunnels crossing these anticlines are usually with their elevation of 220–850 m, consequently through all above-mentioned strata.

As the present region belonging to the southern karst region of China, where with highly developed karst, limestone strata of the P_2c , T_{1j} and T_2l formation are dominated with significantly high permeability, while, for the T_1f formation, there are four sub-layers of T_1f^1 , T_1f^2 , T_1f^3 and T_1f^4 . The lithology of T_1f^1 and T_1f^3 are mainly limestone with high permeability, whereas that of T_1f^2 and T_1f^4 are dominantly mudstone with relatively low permeability. The layers of T_3xj and Jurassic are also with relatively low permeability and predominantly with pore water. Groundwater is mainly karst groundwater and occurred in the above-mentioned limestone layers. This karst groundwater poses the main threats to

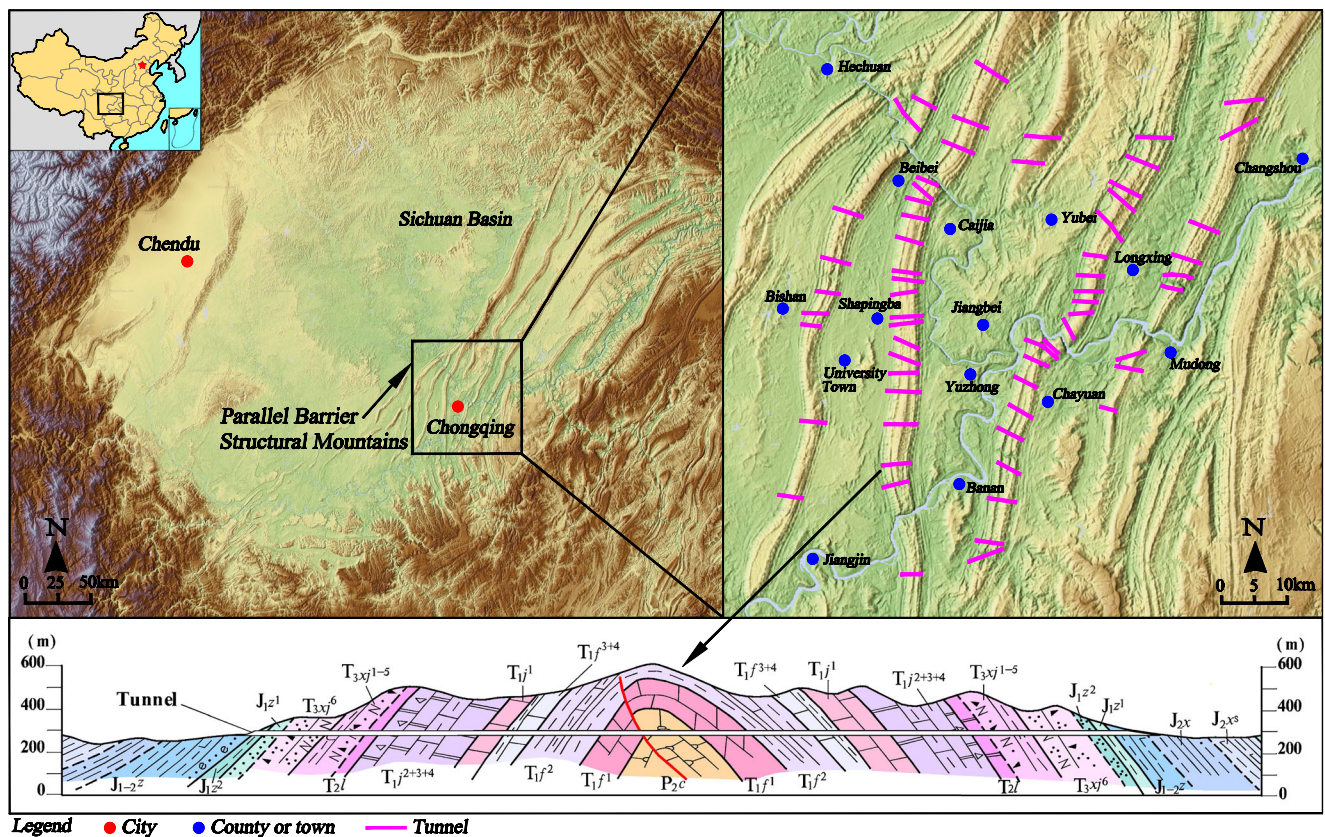


Fig. 1 (a) The parallel barrier fold mountains in southeastern Sichuan Basin, China. (b) Tunnels in the parallel barrier fold mountains. (c) The typical profile map of tunnel across the parallel barrier fold mountain

tunnel excavation in the forms like water inrush and mud burst, and also plays essential role in the eco-environment maintenance and various water supply for local community.

Field survey and analysis

Hydrological environment impact survey

Groundwater in surrounding aquifers of the tunnel was drained out to reduce/eliminate the potential geological hazards related to the high groundwater pressure. Also, this kind of anthropogenic engineering measures would inevitably break the water balance of the groundwater system occupying around the tunneling area. In order to illustrate these anthropogenic impacts during the excavation, field survey in terms to tunnel drainage was conducted in the study area. The drainage of groundwater in the study area was performed with the aid of pipelines and ditches (Fig. 2). Groundwater discharge rates of all pipes except that buried underground were investigated and presented in Table 1.

As demonstrated on Table 1, these six pipes have a wide range of water discharge rates from 0.2 to 300 L/s, suggesting different disturbances to groundwater system at different sites. Field survey showed that the negative impacts on

hydrogeological environment caused by tunnel directly lead to the water loss of various hydrological bodies including springs, wells, lakes, reservoirs, and streams (Fig. 3a,b,c). Some of the perennial streams were observed seasonally or permanently dried up. Besides, the development of cracks at the bottoms of the surface water bodies like lakes and reservoirs due to the groundwater level drawdown had resulted in significant leakage of surface water and even dried up (Fig. 3b,c). Additionally, indirect geological hazards, such as ground collapse, land cracked, ground fissures, and house deformation, occurred due to the groundwater level drawdown. Out of these indirect hazards, ground collapse was one of the most serious geological disasters, and it mainly occurred in the karst valley where developing vertical karst cave, underground river and covering thick Quaternary deposits (Fig. 3d). According to the present survey, ground collapse developed in the size of 5–100 m² horizontally and 1–10 m vertically. Some of the ground collapses occurred very close and jointed into a big one finally (Yang et al. 2014).

Spatially impacts of tunnel excavation on hydrogeological system

The spatial extent of tunnel excavation impacts on groundwater environment was revealed with the aid of field

Table 1 Groundwater drainage rates of typical tunnels in the study area

Tunnel	Location of the drainage investigation	Drainage outflow (L/s)
University Town Tunnel	Eastern entrance	14.7
	Western entrance	6.5
Zhongliangshan Tunnel on Track 6	Eastern entrance	1.5
	Western entrance	23.3
Geleshan Tunnel on Track 1	Eastern entrance	49.4
	Western entrance	11.2
Shuangbei tunnel	Eastern entrance	34.6
	Western entrance	31.7
Tiefengshan tunnel	Eastern entrance	300
	Western entrance	180
Bishan Tunnel	Eastern entrance	3.59
	Western entrance	125.6

investigation of wells, springs and surface waters. The results showed that the drawdown of groundwater level was dominantly distributed along the axis of tunnels and also extended towards both sides of the axis. The influencing ranges of tunneling on 22 tunnels in the study area were statistically demonstrated in Fig. 4 in terms to different stratum lithology. It can be clearly seen that influencing range of tunnel excavation on hydrogeological environment varied from tunnel to tunnel, and showed significant relation to the stratum lithology that representing the hydraulic connectivity of aquifers. In detail, the spatial distribution of tunnel impacts showed the following features:

- (1) The spatial distribution of groundwater level drawdown and related hazards, such as surface waters leakage, ground collapse, ground fissures, and house deformation, were demonstrated as belts along the tunnel. These impacts concentrated in the karst valleys and with the range all less than 1000 m on both sides of the tunnel axis. While ground collapses, the most serious geological hazard, were found dominantly

distributed in the karst depressions of the valleys. These areas usually benefit the water confluence of both surface and underground, and also have intense surface and underground water activities. Furthermore, this implies the response of groundwater system and related impacts on geological environment has relations with the karstification development caused by the water activities.

- (2) As shown in Fig. 1c, multiple strata, such as limestone, sandstone, shale, and mudstone, symmetrically distributed in the structure of parallel barrier fold mountains. Therefore, tunnels cross these parallel barrier fold mountains would inevitably pass through the aforementioned different strata. Different strata would pose various responses to the tunnel excavations due to their quite differences of hydrogeological characteristics like hydrological connectivity. As a result, strata with different lithological and hydrogeological characteristics were demonstrated with different response in range and degree under the tunnel

**Fig. 2** The groundwater drainage forms of (a) pipeline and (b) Ditch during the tunnel excavation



Fig. 3 Typical negative impacts of tunnel excavation on (a) groundwater well, (b) reservoir, (c) paddy, and (d) lands

excavation influences. Limestone had the strongest response to the impacts of tunnel excavation. As shown in Fig. 4, the impact range of tunnel excavation on groundwater level can reach to approximately 5 km in limestone aquifers, while that in sandstone and shale/mudstone is 3 km and within 1 km, respectively. Overall, the major and serious impacts of

tunnel excavation on groundwater system were dominantly occurred in limestone strata. The range of tunnel excavation impact on groundwater flow field varied from 1 km to greater than 5 km in limestone strata, with approximately 36% of the investigated tunnels in the range of 2–3 km, 14% in the range of 3–4 km, and 14% in the range of 4–6 km (Fig. 5).

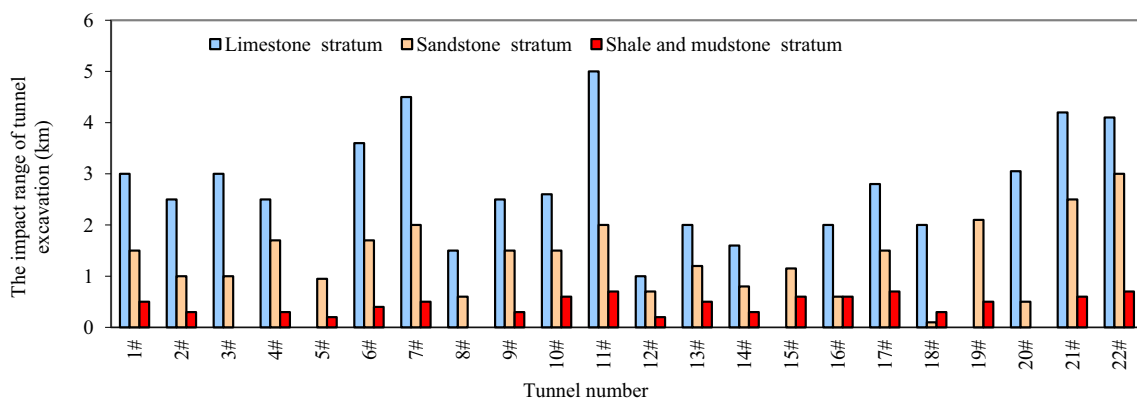


Fig. 4 Statistic summary of the impact range of tunnel excavation on groundwater flow field in various strata. (1#,University Town tunnel; 2#,Track Line 6 Zhongliangshan tunnel; 3#, Track Line 6 Tongleshan tunnel; 4#, Track Line 1 Zhongliangshan tunnel; 5#,Tiefengshan NO.1 tunnel; 6#, Tiefengshan NO.2 tunnel; 7#, Fenjieliang tunnel; 8#,

Changdangzi tunnel; 9#, Motianlin tunnel; 10#, Zoumalin tunnel; 11#, Fangdoushan tunnel; 12#, Tanjiashai tunnel; 13#, Juyunshan tunnel; 14#, Baiyun tunnel; 15#, Zhengyang tunnel; 16#, Putaoshan tunnel; 17#, Xiushan tunnel; 18#, Longfengshan tunnel; 19#,Nanshan Tunnel; 20#,Yunwushan tunnel; 21#, Bishan tunnel; 22#, Huanshanping tunnel)

Temporally impacts of tunnel excavation on groundwater system

According to the field investigation and monitoring of hydrogeological elements, most of the hydrogeological elements showed time-related responses to the tunnel excavation, but various elements were observed with asynchronous responses to the tunneling activities (Figs. 6 and 7). Taking the tunnel of University and Line NO.6 as examples, groundwater flow field had the quickest responses to the tunnel practices comparing to the other hydrogeological elements. A period after the tunnel construction starting, the tunnel drainages posed disturbances to natural groundwater flow field and resulted in groundwater level drawdown, and finally lead to the water level of wells decline and spring flow amount decrease. Stepped after the disturbances of natural groundwater flow field, leakage of surface water bodies was occurred, which can be attributed to the increasing water head between surface water and groundwater caused by groundwater drainage. This leakage would last a relatively long period and till a new balance between surface water and groundwater formed. Ground collapse, the secondary hazard of tunneling, occurred after the surface water leakage. This secondary hazard was associated to the groundwater level drawdown and can be explained by the principle of effective stress in hydrogeology.

The periods of tunneling impacts on groundwater flow field were statistically demonstrated in Fig. 7 regarding seven tunnels in the study area. It showed that the negative impacts of tunnel drainage on groundwater system can last several years, and 5–9 years in the statistical tunnels (Fig. 7). Generally, these direct and indirect responses of groundwater system and geological environment would last several years (Figs. 6 and 7) and then become stable and form a new balance status. Hydrogeological elements like well water level and spring would recover in some degree which depends on whether the hydrological structure was changed. In fact, irreversible impacts, for example ground collapse, would be posed to the geological environment, although some direct impacts, such as groundwater drawdown, on hydrogeological system may disappear finally.

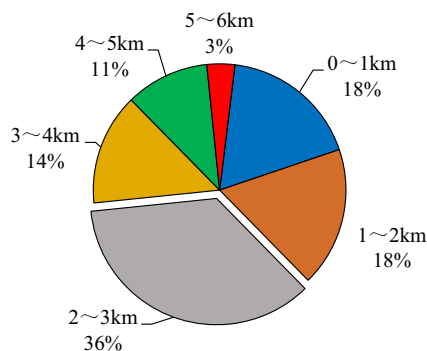


Fig. 5 Impact range proportion of tunnel on groundwater

Simulations and prediction

Groundwater numerical analysis method

Three-dimensional groundwater flow can be mathematically represented given the following equation based on water mass balance and Darcy's law equations (Akibayashi et al. 1997):

$$S_s \frac{dh}{dt} - \left[\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) \right] = q_s \quad (1)$$

where h is the piezometric head; S_s is the specific storage coefficient; q_s is a sink or source; and K_x , K_y , and K_z are the hydraulic conductivity along the x , y , and z axes, respectively.

In the study area, the governing Eq. (1), together with the appropriate boundary conditions, the initial conditions, annual-averaged infiltration and groundwater extraction quantities, the spatial distribution of the hydrogeological parameters that control the flow, constitutes the mathematical model of the groundwater flow.

Visual MODFLOW developed by the US Geological Survey for numerical simulation of groundwater, is characterized by its modular, such as River Module, Drain Module, Well Module, and so on. In present research, Drain Module was used to simulate the tunnel discharge. The comprehensive hydraulic conductivity coefficient of the tunnel reflects the head loss between the tunnel discharge and groundwater system. This parameter can be used to represent the different condition of tunnel drainage and tunneling characteristics. The tunnel discharge can be defined as following:

$$Q = C \times (H - H_s) \quad (2)$$

where Q is the tunnel discharge quantity; C is the comprehensive hydraulic conductivity coefficient of the tunnel; H is piezometric head; H_s is tunnel elevation.

Simulation of impact of typical tunnel on groundwater

Numerical model

A planned tunnel named Huayan tunnel was selected as the simulating tunnel in present study. This tunnel will track across Zhongliangshan mountain with the length of 4.5 km. The modeling domine was visually presented in Fig. 8, and involved a completed hydrogeological unit. Huafu tunnel, a finished tunnel, was located in the south with the distance about 4.85 km. Additionally, a large goaf of coal mine was found situating below the present planned tunnel. This planned tunnel was dominantly cross several significantly distinguishing strata of mudstone, sandstone and limestone.

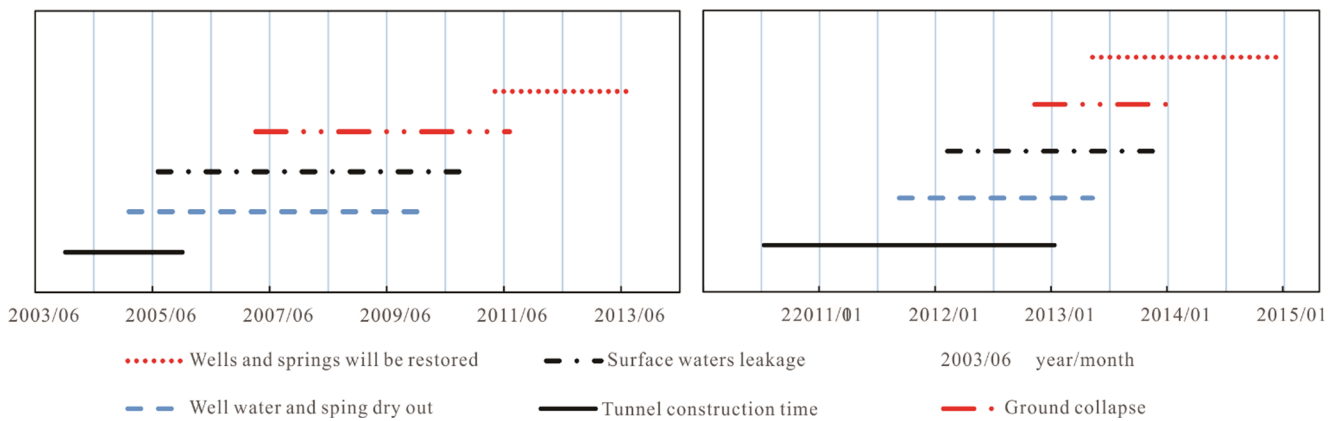


Fig. 6 The occurring time of direct/indirect impacts on various environmental factors by tunneling

Limestone strata of T_{1j} , T_{2l} , T_{1f}^1 , and T_{1f}^3 were the main aquifer in the modelling area, while the sandstone formation (T_{3xj}) and mudstone formation (J , T_{1f}^2 and T_{1f}^4) acted as the hydrogeological aquitards.

Hydrogeological boundaries were assigned according to the distribution of natural surface water and terrains (Fig. 8). The north boundary of the modelling area was assigned as non-flow boundary given its divided feature of terrain. The south boundary was the Yangtze river and thus defined as constant head boundary. The east and west boundaries situated at the foot of the mountain and were assigned as constant head boundary. The coal goaf and tunnels of Huaifu and Huayan were regarded as drains. Additionally, the upper and bottom boundaries were assigned as given flux boundary and constant head boundary, respectively. The present groundwater simulation was performed with the aid of the aforementioned MODFLOW software. All parameters and boundaries were given according to the hydrogeological survey and also previous studies in this region. PEST Module was employed to adjust the hydrogeological parameters of the present 3D groundwater flow model.

Verification of groundwater flow simulation results

The root mean square error (RMSE) (Jang et al. 2016) was introduced to gauge the performance of model calibration. The results were demonstrated in Fig. 9 and suggested the model gets a relatively good calibration performance and

can adequately reproduce the groundwater behaviors in the study area. The final parameters that after calibration were listed in Table 2.

In addition, the simulation results of the present tunnel were compared with the collected data of other finished tunnels. The drainage quantity of groundwater and responses of groundwater flow field were involved in the comparison. According to the previous field records, the drainage quantity of groundwater during the tunnel excavation varied from 1831 to 5278 m^3/d for the tunnel practices, such as University Tunnel, Line No.6 Zhongliangshan Tunnel, Line No.1 Geleshan Tunnel and Shuangbei Tunnel, across Zhongliang mountain (Fig. 10). In present study, the modeled groundwater drainage quantity during the tunneling was about 4300 m^3/d , and in the practical experience range above (Fig. 10). For the largest influencing area, i.e. groundwater level drawdown extent, the present simulated result for Huayan tunnel was approximately 3000 m, which was also in the range (2800–3000 m) of historical records for adjacent tunnels mentioned above (Fig. 11). All above suggested that the simulation results were reasonable and the established model can reflect the true behaviors of groundwater system in the study area.

Groundwater flow field under tunnel disturbance

According to the plan of Huayan Tunnel Design, the tunnel construction period would last 3 years. Generally, the disturbances on groundwater system are different in the tunnel

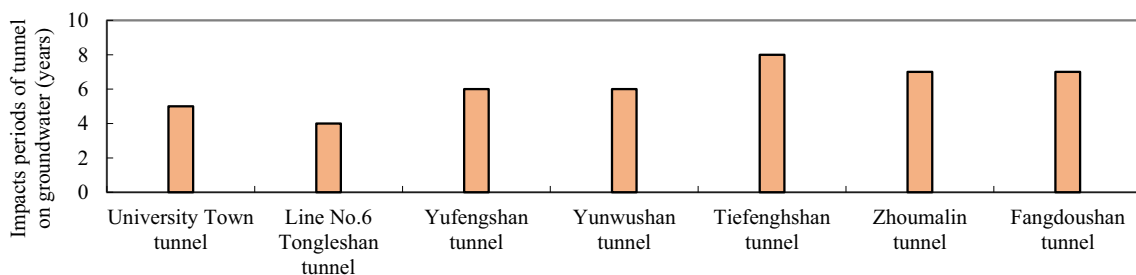


Fig. 7 Impacts periods of tunnel excavation on groundwater flow field

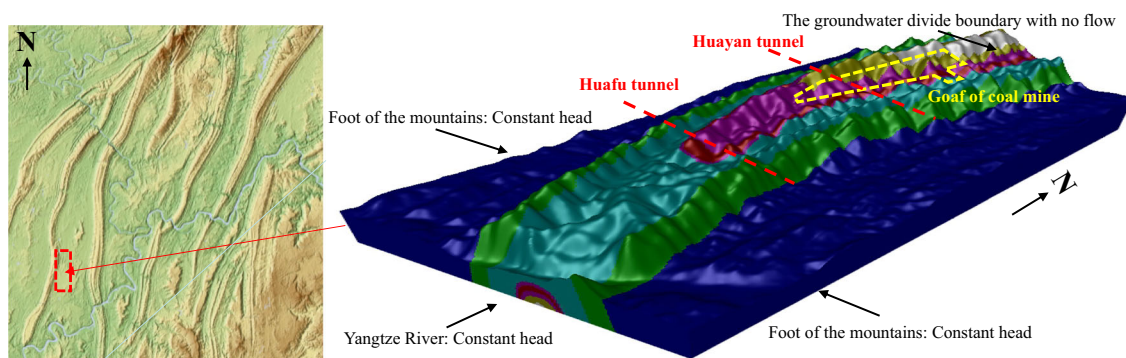


Fig. 8 Numerical model for the impact of Huayan tunnel on groundwater

excavation and operation duration. Consequently, these two disturbing durations were considered and simulated separately. The simulation results were displayed in Fig. 12. It can be clearly seen in Fig. 12a that groundwater level varies spatially as the duplication of terrains in nature under the state of non-disturbances from human society. While under the disturbances of Huafu Tunnel and Coal Mine, groundwater field demonstrated drawdowns surrounding these anthropogenic influencing sites (Fig. 12b). Groundwater flow field presented in Fig. 12b reflected the states of groundwater system before the construction of Huayan tunnel and can be regarded as the initial state of groundwater flow field in the study area. The simulation results showed that similar groundwater level drawdowns also occurred around the Huayan tunnel after its construction completed (Fig. 12c). The maximum disturbance on groundwater system occurred dominantly near the tunnel axis and reached to approximately 25 m vertically and 3000 m horizontally.

The evolution of groundwater flow field after the tunnel construction was demonstrated in Fig. 13. It is showed that the initial state of groundwater flow field that immediately after the construction of Huayan tunnel had the largest water level drawdown near the tunnel axis (Fig. 13a). Due to the effective reducing groundwater drainage of tunnel and the end of large amount water excavation, the negative effects of tunnel excavation on groundwater system gradually eliminated. With the time filed by, groundwater level near the tunnel axis raised from 340 to 348 m (Fig. 13). However, the evolution of groundwater

level was not synchronous in spatial. Groundwater level that beyond 250 m away from the tunnel axis presented a continue declining trend. The areal extent of groundwater level drawdown expanded gradually, and finally approximated 3000 m away from the tunnel axis in both directions (Fig. 13e). Figure 13f suggested groundwater level drawdown would not continue to enlarge in spatial and started to recover. Overall, the excavation of Huayan tunnel would pose negative effects on regional groundwater flow field, but these effects would gradually reduce after the construction finished, while the areal drawdown extent of groundwater flow field would go on expanding, and would evolute reversely a period later.

Groundwater level depression cone evolution

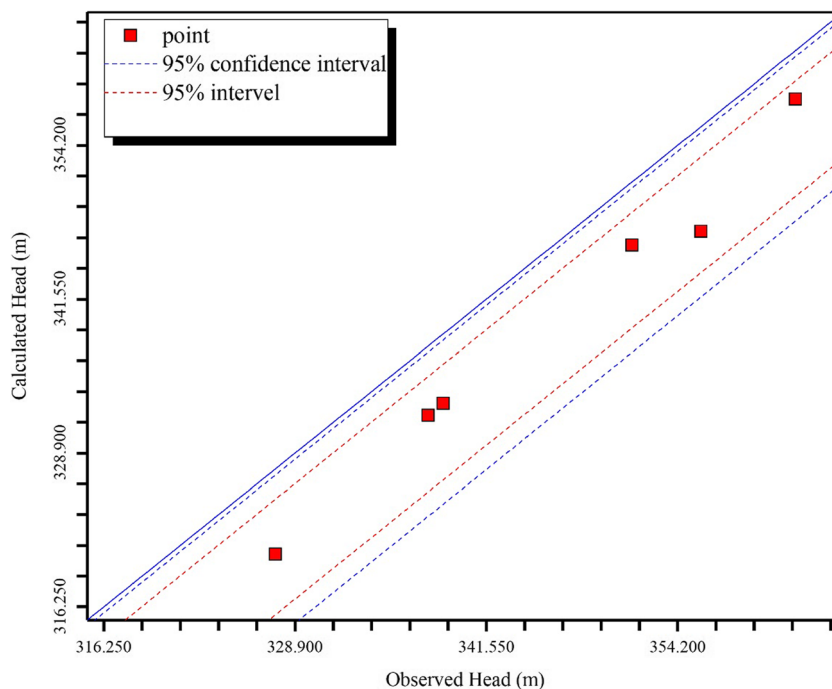
To further illustrate the impacts of tunnel practice on the vertical fluctuation of groundwater level, the evolution of groundwater level along the Huayan tunnel section was introduced as demonstrated in Fig. 14. It can be seen that a relatively large depression cone of groundwater level was formed at the tunnel axis. This groundwater level depression cone reached its deepest drawdown in depth of approximately 25 m immediately after the tunnel construction completed. After that, the groundwater level drawdown within 250 m of tunnel axis in horizontal was found gradually recovered in depth over time due to the stop of tunnel drainage and the recharge from far away. This recovery of groundwater level was beyond 10 m in depth in the followed 10 years.

Whereas groundwater level depression cone did not reach to the largest spatial extent immediately after the tunnel construction completed. The extent of groundwater level depression cone was observed continuous expanding, and reached its largest extent approximately 3000 m in horizontal distance at the 10th years after the tunnel construction completed. This continuous decline of groundwater level dominantly occurred beyond 250 m away from the tunnel axis, while the impacts of tunnel drainage varied in spatial, and presented gradual reducing disturbances on groundwater level from the nearby to far away area. The

Table 2 Calibrated hydrogeological parameters used for groundwater flow modeling

Stratum	Kx (m/d)	Ky (m/d)	Kz (m/d)	Ss	Sy
J	0.016	0.016	0.016	0.0004	0.015
T _{3xj}	0.070	0.050	0.070	0.0011	0.022
T _{1j} , T _{2j}	0.185	0.252	0.180	0.0021	0.140
T _{1f} ² , T _{1f} ⁴	0.010	0.010	0.010	0.0002	0.012
T _{1f} ¹ , T _{1f} ³	0.171	0.181	0.113	0.0020	0.106
P _{2c}	0.258	0.224	0.160	0.0022	0.132

Fig. 9 Calculated vs. observed head: steady state



deepest drawdown of groundwater level in the horizontal range of 250–2000 m away from the tunnel axis approximated 5 m at average in depth during the following 10 years after the tunnel construction completed, and that in the horizontal range of 2000–3000 m away from the tunnel axis was relatively slight.

Overall, the evolution of groundwater level depression cone after the tunnel construction completed can be divided into three stages. The first stage is reaching the deepest depth of groundwater level drawdown. This stage occurs during the tunnel excavation duration. However, groundwater level depression cone cannot reach the largest impacting range in horizontal. The second stage is reaching the largest horizontal extent of groundwater level depression cone. This stage usually occurs after the tunnel construction completed (i.e., the end of tunnel drainage), and its lasting period depends on the hydraulic connection of aquifers in horizontal and approximates 10 year for the present tunnel. The third stage is the entire recovery of groundwater level. At this stage, groundwater level would gradually recover to the initial state in both vertical and horizontal.

Simulation of tunnel drainage scenarios after tunneling

In order to further illustrate the impacts of Huayan tunnel on regional groundwater field, different scenarios of tunnel drainage due to the failure of tunnel waterproof were considered for the duration after the tunnel construction completed in present study. As demonstrated before, the drainage amount of groundwater during the tunnel excavation is about 4300 m³/d for Huayan tunnel. Fiver scenarios were considered for the different failures of tunnel waterproof after the tunnel construction, i.e., 4%, 20%, 40%, 60%, 80% ,and 100% of the drainage amount of 4300 m³/d.

The simulation results were presented in Figs. 15 and 16 regarding the disturbances on groundwater field at the 0.5th, 1st, 2nd, 3rd, 5th, 10th, and 20th years after the tunneling. As shown in Fig. 15, the largest drawdown of groundwater level in depth started to recovery after the tunnel construction completed for all scenarios. This was due to the response of groundwater system to the drainage of tunnel excavation and the recharge water arrived at the tunneling impacting area.

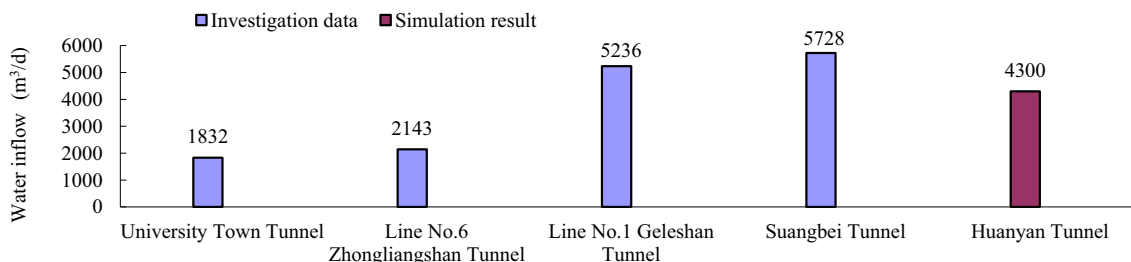


Fig. 10 Tunnel water inflow of Zhongliang mountains chian.

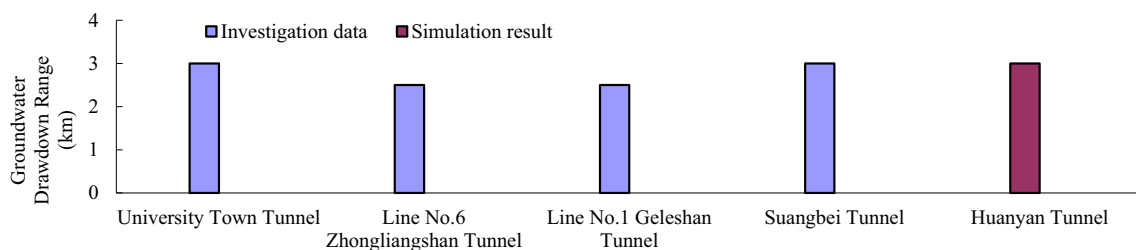


Fig. 11 Impact of the lateral extent of tunnel groundwater in Zhongliang Mountains chain

Groundwater level in different scenarios was observed being nearly stable finally after a period of recovery. These nearly stable groundwater states reflected the groundwater system achieved new balances. While times reaching balance varied

from scenario to scenario, and the bigger amount of groundwater drainage scenario showed longer time to achieve the new balance. Additionally, the new balance of groundwater presented larger drawdown depth of groundwater level for the

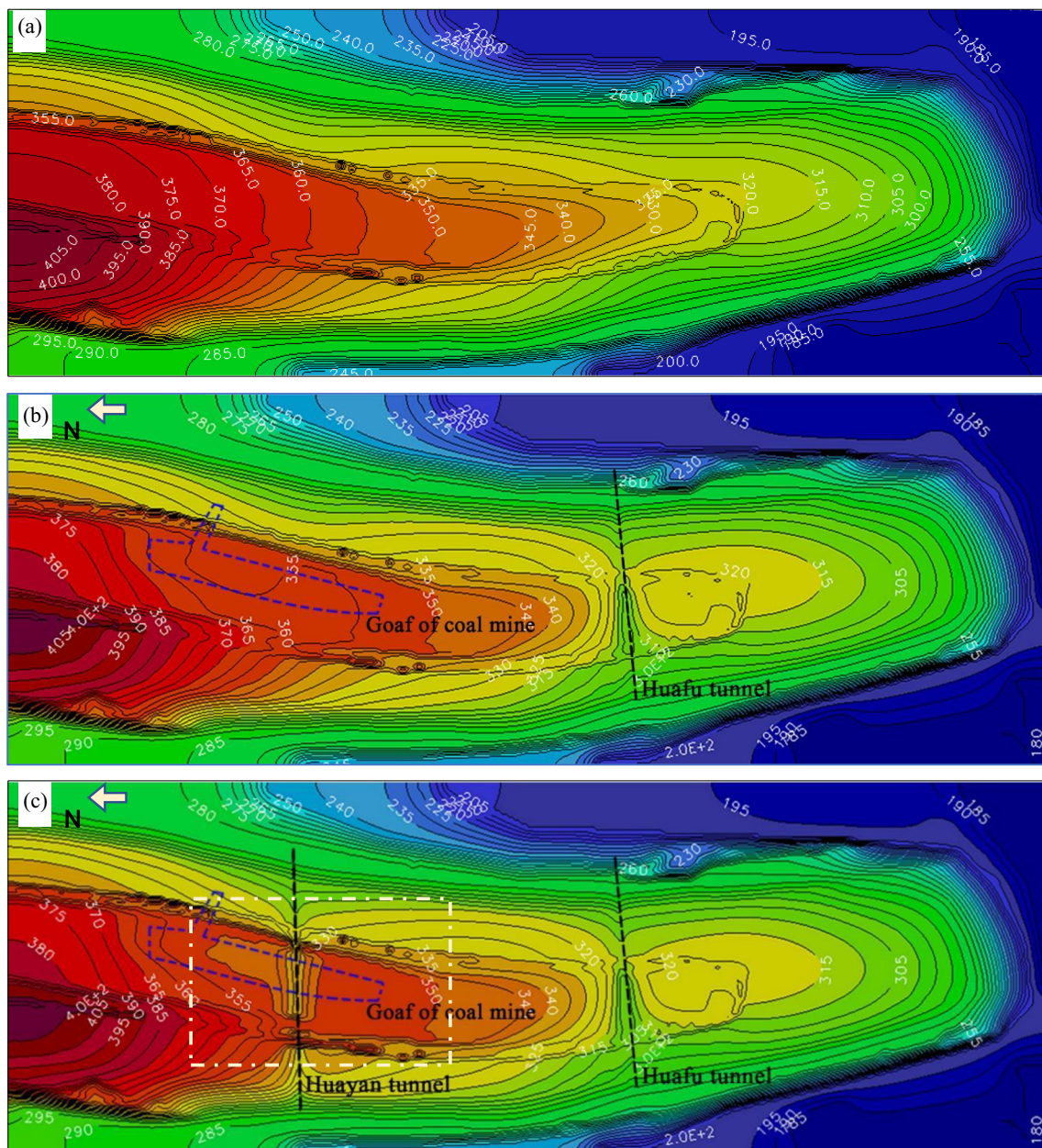


Fig. 12 Groundwater flow field under the condition of (a) natural state, (b) initial state, and (c) the completed state of Huayan tunnel

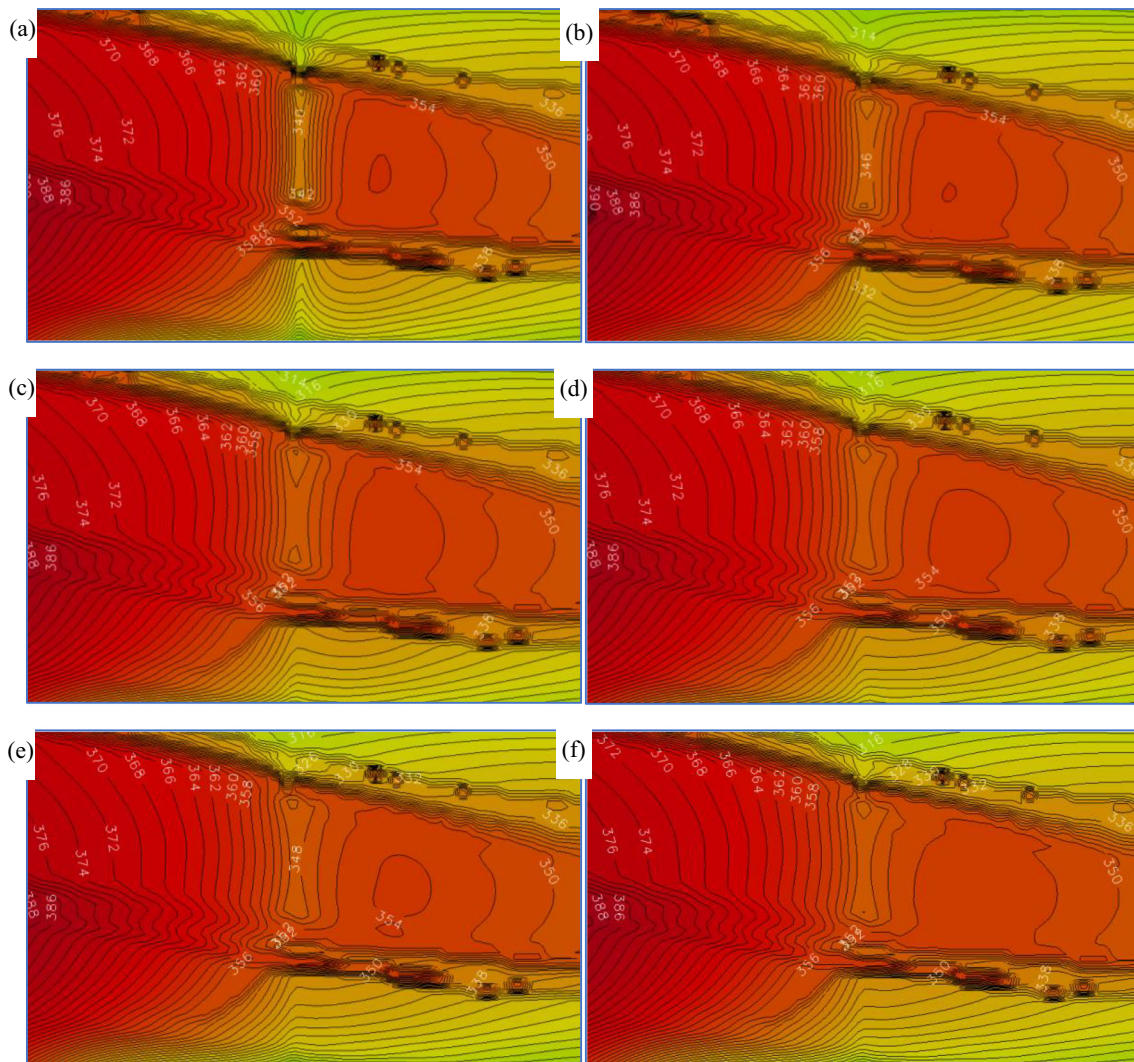


Fig. 13 Groundwater flow field at the stage of (a) immediately, (b) 1 year, (c) 2 years, (d) 5 years, (e) 10 years, and (f) 15 years after the Huayan tunnel construction completed

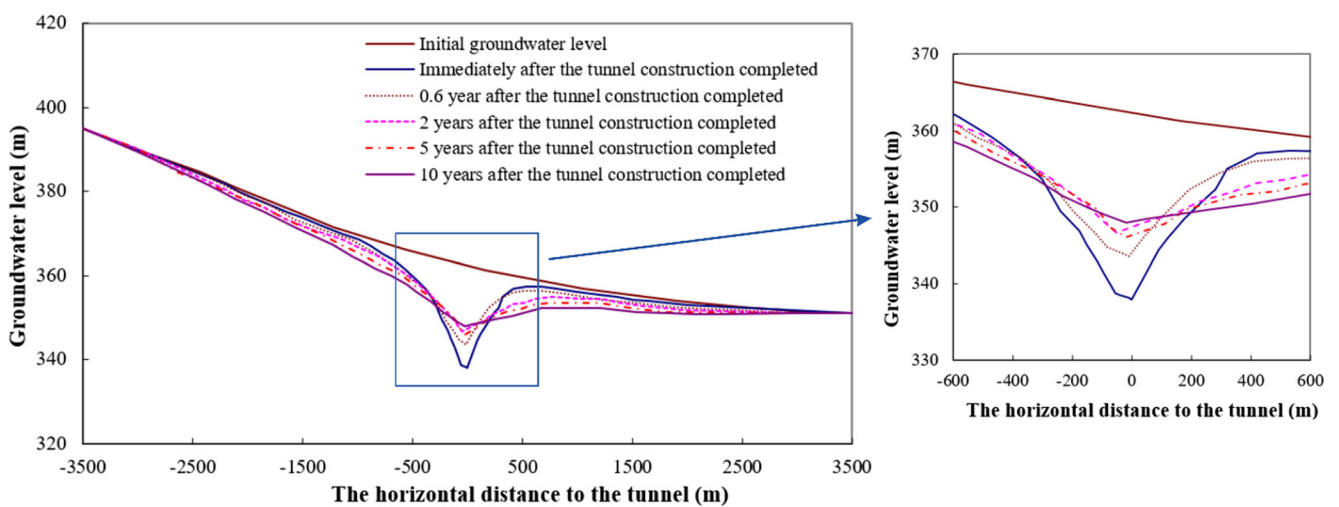


Fig. 14 Sectional view of groundwater drawdown along the tunnel section

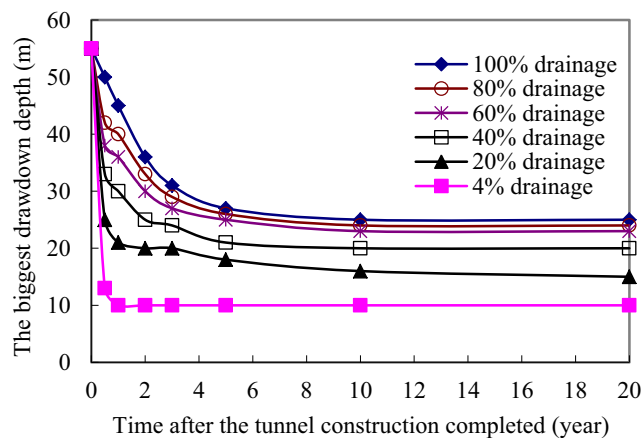


Fig. 15 Biggest drawdown depth of groundwater level over time

bigger amount of drainage scenario (Fig. 15). For the impacting extent in horizontal, the depression cones of groundwater level in all scenarios were observed expanding after the tunnel construction completed. Groundwater system under different scenario would all reach a largest groundwater depression cone after more ten years and keep nearly stable for the cone area and never reduce over time (Fig. 16). In summary, if existing failure of tunnel waterproof, the depression cone of groundwater level would continue to expand in both vertical and horizontal, and finally reach a stable state that no expanding or shrinking of the depression cone over time.

Conclusions

An integrated approach of field survey and numerical simulation was employed to better understand the impacts of tunnel excavation on karst groundwater system, and the response behavior and recovery ability of karst groundwater system to these tunnel disturbances in present study. Southeastern Sichuan Basin where with typical anticline mountains of

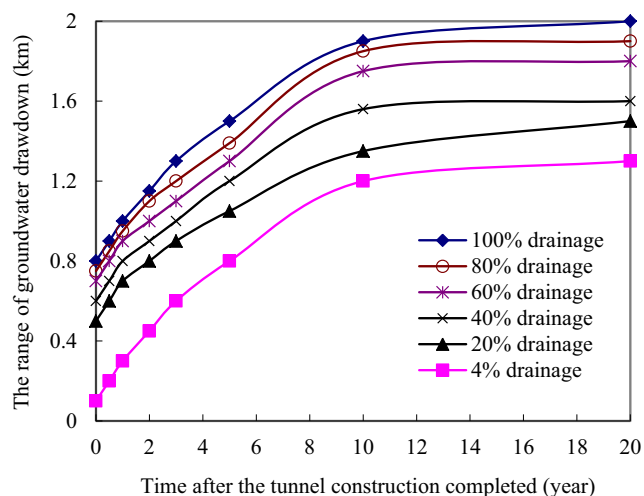


Fig. 16 Range of groundwater leakage over time

highly developed karst were selected as the study area for explore the truth of karst groundwater system and related geo-environment under the disturbance of human tunneling. The following conclusions were made:

- (1) Field survey was conducted to the reveal groundwater drainage amount and related negative impacts due to the tunnel excavation in the study area regarding other completed tunnels. The direct negative impacts included water loss of various bodies such as springs, wells, lakes, reservoirs, streams. The loss of underground water would further lead to indirect geological hazards of ground collapse, land cracked, ground fissures, and house deformation. These indirect impacts were significant for karst regions like the present study area. The indirect impacts were generally occurred after the direct impacts, and all these direct and indirect impacts would last a long period, usually several years, till new balances achieved. The drainage amount of groundwater heavily depends on the stratum lithology that representing the hydraulic connectivity of aquifers. Strata with different lithological and hydrogeological characteristics had different responses in range and degree to the tunnel excavation disturbances. Limestone had the strongest response to the impacts of tunnel excavation. Groundwater level drawdown and related geohazards like ground collapses were dominantly distributed in the karst depressions valleys.
- (2) A planned tunnel, named Huayan tunnel, was selected to numerically investigate tunnel impacts on karst groundwater system with the aid of Visual MODFLOW. The simulation results demonstrated groundwater level drawdown did not occur synchronously in spatial, but always occurred around the tunnel axis and gradually expanded towards far away over time. The largest groundwater level drawdown depth occurred immediately after the tunnel construction completed, but the largest spatial extent of groundwater level depression cone reached several or ten years later. The maximum disturbance on groundwater system can reach to approximately 25 m vertically and 3000 m horizontally for present modeling tunnel.
- (3) Three stages were occurred for the karst groundwater system under the tunnel disturbance. The first stage is reaching the deepest depth of groundwater level drawdown. This stage occurs during the tunnel excavation duration. However, groundwater level depression cone cannot reach the largest impacting range in horizontal. The second stage is reaching the largest horizontal extent of groundwater level depression cone. This stage usually occurs after the tunnel construction completed, and its lasting period depends on the hydraulic connection of aquifers in horizontal and approximates 10 year for the

present tunnel. The third stage is the entire recovery of groundwater level. At this stage, groundwater level would gradually recover to the initial state in both vertical and horizontal, while if existing failure of tunnel waterproof, the depression cone of groundwater level would continue to expand in both vertical and horizontal after the tunnel construction completed, and finally reach a stable state that no expanding or shrinking of the depression cone over time.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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