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Limiting drainage criterion for groundwater of mountain tunnel

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Abstract: Large amount of groundwater discharging from tunnel is likely to cause destruction of the ecological environment in the vicinity of the tunnel, thus an appropriate drainage criterion should be established to balance the tunnel construction and groundwater. To assess the related problems, an limiting drainage standard ranging from 0.5 to 2.0 $m^3/(m \cdot d)$ was suggested for mountain tunnels based on survey and comparative analysis. After that, for the purpose of verifying the rationality of the standard, a calculated formula for dewatering funnel volume caused by drainage was deduced on the basis of the groundwater dynamics and experience method. Furthermore, the equation about the relationship between water discharge and drawdown of groundwater table was presented. The permeability coefficient, specific yield and groundwater table value were introduced, and then combined with the above equation, the drawdown of groundwater table under the proposed limiting drainage criterion was calculated. It is shown that the proposed drainage standard can reach the purpose of protecting ecological environment under the following two conditions. One is the permeability coefficient ranges from 10^{-4} to 10^{-5} m/s and the specific yield ranges from 0.1 to 0.001. The other is the permeability coefficient varies from 10^{-6} to 10^{-8} m/s and the specific yield varies from 0.1 to 0.01. In addition, a majority of common geotechnical layers are involved in the above ranges. Thus, the proposed limiting drainage standard which ranges from 0.5 to 2.0 $m^3/(m \cdot d)$ for mountain tunnel is reasonable.

Key words: mountain tunnel; groundwater; dewatering funnel; limiting drainage criterion; drawdown of groundwater table

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1 Introduction

Generally, tunnel is constructed below ground water table, especially the mountain tunnels in road and railway transportation construction. The deeper the tunnel is buried, the higher the groundwater table is. High groundwater table always leads to high water pressure which does harm to the safety of tunnel, therefore it is crucial to control ground water during construction stage and onward phase of maintenance [1].

Nowadays, three types of methods are usually used to deal with the groundwater: clogging entirely, drainage entirely and limiting drainage. The clogging method is employed when the groundwater table is not so high. According to the experience of foreign countries, the clogging method is always used when the groundwater table is less than 60 m; while exceeding, it is hard to block the groundwater entirely in terms of technology and economy [2].

Thus, to settle the high groundwater table problems, it is better to adopt drainage or limiting drainage method. The drainage method has its advantages, such as deducing the fund for clogging groundwater and decreasing the external water pressure that the lining bears. Hence, the drainage method seems to be a reasonable method for groundwater. However, letting the groundwater discharge without any limitation, the ecological environment may be destroyed as a result of the continuous drawdown of groundwater table. Obviously, developing economy at the price of destroying environment does not meet the demand of social advancement. Therefore, the limiting drainage method is reasonable for high groundwater table tunnels. The so-called limiting drainage method is to clog parts of groundwater by grouting or other methods, and then discharge the seepage water behind the lining out of the tunnel with drainage facility. This method not only is feasible both on economy and technology but also protects the environment in the vicinity of tunnel, meanwhile, it ensures the coordinated development between the engineering construction and ecological environment.

Most studies are associated with the tunnel design and construction, focusing on controlling inrush of groundwater during excavation and keeping the tunnel free of water [3−11], while fewer studies are available for limiting drainage standard of mountain tunnel. It is

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very necessary to know a reasonable magnitude of water discharge which can both ensure the normal order of the tunnel construction, safe operation, and protect the ecological balance and normal growth of vegetation in the vicinity of tunnel.

On the basis of the above analysis, survey method was applied in this work for the purpose of determining the limiting drainage standard and then the rationality of the standard was proved by groundwater dynamics method and case studies.

2 Limiting drainage standard of existing tunnels

The waterproofing requirement of underground construction always varies with different project types, internal facilities and using performances, meanwhile, in different regions, the standard is not the same. Taking tunnel for example, water-conveyance tunnel with internal water pressure and cross city tunnel have the higher standard than mountain tunnel for road and railway, while the projects which have the highest standard are ground station, ground marketplace, storage for significant materials and so on.

2.1 Subway tunnel

The waterproofing standards of American subway tunnels, such as San Francisco, Washington, and Atlanta, range from 0.71 to 0.82 L/(m^2·d), while the limiting leakages of Boston and Buffalo subway tunnels are 1.7 L/(m^2·d) and 0.19 L/(m^2·d), respectively. Subway tunnels in Singapore and Budapest both have a strict standard in which the water seepage value is set as 0.12 L/(m^2·d), and the confined leakage of Munich [12] is 0.07−0.2 L/(m^2·d). According to the technical code for waterproofing of underground works (GB 50108−2008), there are four waterproofing grades divided for underground construction in China. The first grade is the highest, such as subway station and office occupancy. For example, the leakage of interval for subway tunnel line 1 in Shanghai should be less than 0.1 L/(m^2·d). Subway tunnel and city road tunnel are involved in the second grade, and mountain tunnel belongs to the second grade or the third grade [13].

2.2 Subsea tunnel

For subsea tunnel, due to the approximate infinite water in the sea, it has no need to consider the drawdown of groundwater table and destruction of the ecological environment no matter how much water inflows to tunnel. The main factors that affect the allowable discharge amount for subsea tunnel are the pumping capacity of the equipment and economic problem, because the leakage water in subsea tunnel can not flow from tunnel automatically but pumping equipment is needed. For instance, the allowable leakage for Norway subsea tunnel is 300 L/(km·min), that is, 0.432 m^3/(m·d) [14−15]. Table 1 lists the waterproof and drainage design of some subsea tunnels in many countries.

It is indicated from Table 1 that the limiting drainage standard for mentioned subsea tunnels above is all below 0.432 m^3/(m·d).

2.3 Cross city tunnel

The tunnel construction is developed earlier in many countries, due to the emphasis on the protection of infrastructure and environment, and the water control requirement is always strict. For tunnels in land, the allowable water inflow is set as 0.072−0.576 m^3/(m·d) in Norway focusing on the sensitive regions above the tunnel, such as downtown, suburb and recreational areas.

The Oslofjord tunnel is a subsea tunnel, for the section under the residential and recreational area, and the allowable water inflow is defined as 0.288 m^3/(m·d) [19].

Because of closing proximity to dense urbanization,

Table 1 Waterproof and drainage design of typical subsea tunnel [16−18]

Tunnel name	Length in land/km	Length under subsea/km	Water depth/m	Cover rock depth/m	Lining type	Allowable water inflow/(m^3·m^{-1}·d^{-1})
Seikan (Japan)	30.55	23.3	140	100	Limiting drainage	0.2736
Ellingsoy-valderoy (Norway)	4.358	3.3	100	40	Limiting drainage	0.432
StoreBaelt (Denmark)	7.9	75.0	20	—	Limiting drainage	0.143
Byfjord (Norway)	5.800 (subsea+land)		Lowest point of −223 m under sea		Limiting drainage	0.0460 (Entrance), 0.2580 (Exit)
Mastrafjord (Norway)	4.400 (subsea+land)		Lowest point of −132 m under sea		Limiting drainage	0.0720 (Entrance), 0.0120 (Exit)
Qingdao Kiaochow bay (China)	2.22	3.95	26	44	Limiting drainage	0.4 (Main tunnel), 0.2 (Service tunnel)
Xiamen Xiang’an tunnel (China)	1.75	4.2	30	40	Limiting drainage	0.0324 0.123 (Weak rock section)

the T-banering is subjected to rigorous environmental controls. The surface constructions above must be protected through rigorous limitations on water seepage to the tunnel. Allowable inflow to the tunnel has been determined to be 0.1008 $m^3/(m\cdot d)$ as a minimum in the most strict areas and to be 0.2016 $m^3/(m\cdot d)$ as a maximum [14].

The rock mass of the Tåsen tunnel is mainly sedimentary rock consisting of clay shale and limestone, interfaced with igneous dykes, occurring occasionally as quite permeable. The strict defined drainage standard is 0.144 $m^3/(m\cdot d)$ [14].

The Svartdal tunnel with a minimum rock covers only 2.5 m. With particular focus on the settlement of buildings above the tunnel, the maximum allowable inflow rate is set at 0.072 $m^3/(m\cdot d)$ [14].

The Storhaug tunnel passes under an urban area with houses built between 1900 and 1950. Several of these houses are founded in peat moor by means of traditional wooden piles while some are “floating”. The maximum leakage is set at 0.0432−0.144 $m^3/(m\cdot d)$ after consideration, and the lower value for the section of the tunnels is closest to the peat moor area [14].

The rock mass of the Bragernes tunnel is mostly volcanic which is regarded as highly permeable, and the hydrostatic water pressure is presented on average of 100 m. The maximum allowable inflow is 0.144 $m^3/(m\cdot d)$ [14].

The Baneheia tunnel passes under a popular recreational area with just only 19 m rock cover. Because of the sensitivity of this recreational area, a maximum inflow rate of 0.03024 $m^3/(m\cdot d)$ is required [14].

For the purpose of controlling the settlement of buildings and preventing the environment, the limiting criterion is mainly 0.02−0.576 $m^3/(m\cdot d)$ for cross city tunnels. The above successful engineering practices have certified the availability of the limiting criterion.

2.4 Mountain tunnel

With the environmental awareness reinforcing constantly in China, on tunnel construction, the principle for groundwater treatment has been changed from “Drainage first” to “Limiting drainage” [20], which could be seen in some practical tunnels.

The Geleshan tunnel in Yu-huai railway is 4050 m long. The average burial depth is 200 m, and the deepest point reaches 280 m. The tunnel passes soluble rock regions, with developed karst cave, eroded groove and karren, so the highest hydrostatic water pressure on average is 220 m, which is equivalent to 2.2 MPa. A maximum allowable inflow of 1.0 $m^3/(m\cdot d)$ is required, with particular focus on the concern of vegetation and dwellings on the top. The total inflow of 0.95 $m^3/(m\cdot d)$ is measured after completion of the tunneling works and achieves the goal of protection of water resources and ecological environment [21].

The Qiyueshan tunnel, in Yi-wan railway, is 10528 m long, with the maximum buried depth of 670 m. The water inflow is predicted to 1.57×10^4 m^3/d as an average and 2.2×10^4 m^3/d as a maximum. The water pressure is 2.5−3.1 MPa which is equal to 310 m groundwater table. Above the tunnel, there are several houses and large amount of farmlands. By combining geological condition, permeability coefficient, and capacity of the drainage system, the maximum allowable inflow is set at 3.0 $m^3/(m\cdot d)$ to avoid surface water from drying up [22].

The Zhongliangshan tunnel in Yu-sui express way is 3853 m long and passes through 1510 m soluble rock regions which usually causes water inflow, water inrush and mud inrush accident. Based on in-site test, the hydrostatic water pressure reaches 1.0−1.5 MPa, the average water inflow is 3.4 m^3/d and the maximum is 8.5 m^3/d in wet season. Taking the high water inflow and water pressure into consideration, the limiting criterion is set at 0.7 $m^3/(m\cdot d)$ [23].

The characteristics of huge buried depth, high groundwater table and great water pressure for mountain tunnel enlarge the difficulty of controlling the groundwater. However, it is crucial to settle such problems. When dealing with it inappropriately, not only the stability of the lining will be influenced, but also it does harm to tunnel construction and operation, even the ecological environment in the vicinity of tunnel may be damaged, thus leading to severe consequences which are irreversible. The above mentioned tunnels handle the groundwater reasonably on the basis of established limiting drainage criterion, and protect local ecological surroundings and groundwater resources effectively. It is a good reference for other tunnels.

2.5 Determination of limiting drainage standard for mountain tunnels

Table 2 shows the criterion of the above mentioned tunnels.

Table 2 Limiting drainage criterion for different types of tunnel

Tunnel type	Subway tunnel	Subsea tunnel	City tunnel	Mountain tunnel
Criterion	0.07−1.7 $L\cdot m^{-2}\cdot d^{-1}$	0.0324−0.432 $m^3\cdot m^{-1}\cdot d^{-1}$	0.03024−0.576 $m^3\cdot m^{-1}\cdot d^{-1}$	0.7−3.0 $m^3\cdot m^{-1}\cdot d^{-1}$

The data suggest that the subsea tunnel has the most strict criterion while the mountain tunnel has the maximum values, and the criterion for city tunnel is between the above two types.

Subway tunnels are always beneath the urban city with thin rock cover, so focusing on the concern of settlement and displacement of buildings above the tunnel, the criterion for subway tunnel is the minimum. The rock cover for subsea tunnel and city tunnel is thicker than that for subway tunnel. The main factor for subsea tunnel in consideration is the economic problem and the pumping capacity of the equipment, and for city tunnel, the main factors are settlement control for buildings and environment protecting. Thus, the allowable drainage value for these two types of tunnel is greater than that of subway tunnel. Compared to the above three types of tunnel, the rock cover for mountain tunnel is the thickest, hence the surface settlement control is not so strict. Generally, the mountain tunnel tends to be located far from urban city and encounters with village and farmland occasionally, and the ecological surroundings, survival state of vegetation and living condition for resident are the main factors to consider. Hence, the sensitivity of mountain tunnel is not as high as that of city tunnel, and the allowable water inflow for mountain tunnel should be the maximum. Due to the above analysis, the allowable inflow for mountain tunnel can be set to be higher than that for the other three types of tunnel, which is set at 0.5−2.0 $m^3/(m\cdot d)$. The low values are suitable for the extremely sensitive region, while the big value is appropriate to high groundwater table, water pressure and karst developed tunnel.

3 Dewatering of aquifer in tunnel

Large amount of groundwater flowing from tunnel without any limit must cause dewatering of groundwater table, and the vegetation may be deteriorated even die if the drawdown exceeds a certain extent, which is not corresponding to the principle of environmental conservation and sustainable development nowadays. After the limiting drainage criterion has been determined preliminarily, the following step is to calculate the dewatering of groundwater table under the proposed criterion, and to verify whether the dewatering of groundwater table exceeds the degree that the vegetation can bear or not. If the drawdown is too large, the criterion should be justified to a reasonable scope.

The basic theory of groundwater movement reveals that when pumping water from a well for a long time, a dewatering funnel which approximates to inverted cone will be formed in the vicinity of the well. For tunnel, after drainage too much, there is also a funnel to be shaped. If the volume and scope of the funnel can be calculated, the drawdown of the groundwater table can be obtained combined with the geological parameters of surrounding rock.

3.1 Volume of dewatering funnel

For an isotropic aquifer, μ represents the specific yield, and the relationship between the volume and the total water inflow is given by the formula as

$$Q=V\mu$$

or

$$V=Q/\mu \tag{1}$$

Because the allowable inflow q is determined, taking the length of tunnel L into consideration, the total water inflow Q within time t can be obtained by $Q=qLt$, hence, the volume can be written as

$$V= qLt/\mu \tag{2}$$

3.2 Scope of dewatering funnel

After the volume of dewatering funnel V has been calculated, only when the shape and spatial distribution of the funnel are known, the relationship between V and the drawdown can be acquired.

The shape of funnel for well presents the inverted cone. However, for tunnel, the length is far more than width, the dewatering scope is similar to the inverted elliptical cone, and the surface morphology seems to the ellipse.

The groundwater flow is unsteady before the funnel is formed, so the drainage radius $R(t)$ should be calculated on the basis of the formula of unsteady flow.

There are a lot of formulas involving groundwater unsteady flow emerged since Theis formula was presented in 1935, but only a few are practical, and the most widely used one is Theis equation [24] which can be described as

$$s=\frac{Q}{4\pi T}W(u) \tag{3}$$

with

$$u=r^2/4aT=r^2\mu/4Tt \tag{4}$$

$$\begin{aligned} W(u)&=\int_u^\infty \frac{e^{-y}}{y}\mathrm{d}y \\ &=-0.577216-\ln u+u-\sum_{n-2}^{\infty}(-1)^n\frac{u^n}{n\cdot n!} \end{aligned} \tag{5}$$

where s is the drawdown of water table within the influence scope, Q is inflow, T is transmissibility coefficient, t is the time after the beginning of the water inflow, r is the distance to tunnel wall, μ is specific yield, and $W(u)$ is Theis's well function.

Within permissible error range, Jacob utilized the first two terms of series to substitute the well function to simplify the Theis formula when $u\le 0.05$, that is, Jocob expression:

$$s=\frac{0.183Q}{T}\ln\frac{2.25Tt}{r^2\mu} \tag{6}$$

It is assumed that the drawdown at the maximum influence radius is 0, so putting s=0, it is obtained

$$R=1.5(Tt/S)^{1/2} \text{ (Confined water)} \tag{7}$$

$$R=1.5(h_cKt/\mu)^{1/2} \text{ (Phreatic water)} \tag{8}$$

where S is storage coefficient of confined aquifer, h_c is the total thickness of aquifer, and K is the permeability coefficient of aquifer.

Jacob approximant is just suitable for $u≤0.05$. Because the water burst time t is short before lining, and $u= r^2\mu/(4Tt)$, the value of u is large. Similarly, u will be greater when r is far from tunnel wall. The Jacob approximant will not be more appropriate, based on curve fitting of well function. JIANG [25] suggested a straight-line analytical method of the Theis formula for the condition that u is large, which implied that the approximate expression $W(u)=10.9504u^{-0.06575}-10.85$ is most accordant to Theis formula when u varies from 0.001 to 1, with well function $W(u)$ given by $W(u)=\int_u^{\infty} \mathrm{e}^{-u}\mathrm{d}u$. Thus, the drawdown of groundwater table s and radius of influence R can be determined as

$$s=[q/(4\pi T)](10.9504u^{-0.06575}-10.85) \tag{9}$$

For s=0, there are

$$R=2.145(Tt/S)^{1/2} \text{ (Confined water)} \tag{10}$$

$$R=2.145(h_cKt/\mu)^{1/2} \text{ (Phreatic water)} \tag{11}$$

3.3 Drawdown of groundwater table

The dewatering funnel for tunnel approximately consists of two inverted half cones at both ends of tunnel and the vee trough between two ends. The two inverted half cones at both ends constitute a full cone. Equation (9) is used to calculate the volume of the dewatering funnel.

The volume of full inverted cone V' can be expressed as

$$V'=\int_0^R 2\pi rs\mathrm{d}r \tag{12}$$

Substituting Eq. (9) into Eq. (12), yields

$$V'=\int_0^R 2\pi r[q/(4\pi T)\cdot(10.9504u^{-0.06575}-10.85)]\mathrm{d}r \tag{13}$$

Solving Eq. (13) gives $u=r^2\mu/(4Tt)$, so

$$V'=3.2099(q/T)(Tt/\mu)^{0.06575}R^{1.8685}-2.7125qR^2/T \tag{14}$$

Supposing that A' is the sectional area of the inverted cone between two ends, A'' is the product of drawdown close to tunnel wall s_1 and the width of tunnel B, and the volume of the vee trough is V'', then, V'' and A can be defined as $V''=AL$ and $A=A'+A''$, respectively. A' can be given as follows:

$$A'=\int_0^R 2\pi rs\mathrm{d}r \tag{15}$$

Combining Eq. (9) and Eq. (15) yields

$$A'=2.1993(q/T)(Tt/\mu)^{0.06575}R^{0.8685}-1.7277qR/T \tag{16}$$

So

$$\begin{aligned} A &= A'+A'' \\ &= 2.1993(q/T)(Tt/\mu)^{0.06575}R^{0.8685}-1.7277qR/T+Bs_1 \end{aligned} \tag{17}$$

Further, there is

$$\begin{aligned} V'' &= AL \\ &= [2.1993(q/T)(Tt/\mu)^{0.06575}R^{0.8685}-1.7277qR/T]L+ \\ &\quad Bs_1L \end{aligned} \tag{18}$$

Combining Eq. (14) and Eq. (18) leads to

$$\begin{aligned} V &= V'+V'' \\ &= (q/T)[(Tt/\mu)^{0.06575}R^{0.8685}(3.2099R+2.1993L)- \\ &\quad R(2.7125R+1.7277L)]+Bs_1L \end{aligned} \tag{19}$$

After a translation, s_1 can be expressed as

$$\begin{aligned} s_1 &= (V-(q/T)[(Tt/\mu)^{0.06575}R^{0.8685}(3.2099R+ \\ &\quad 2.1993L)-R(2.7125R+1.7277L)])/BL \end{aligned} \tag{20}$$

The applicable scope of u in the linear analytical method ranges from 0.001 to 0.1, so the drawdown close proximity to tunnel wall can't be gained, the nearest distance that the drawdown can be obtained is r from tunnel wall, where $r=\sqrt{0.004Tt/\mu}$. Thus, the actual width of the tunnel, B', should be expressed as $B'≈2r+B$ during the calculation for A''. Hence,

$$\begin{aligned} s_1 &= (V-(q/T)[(Tt/\mu)^{0.06575}R^{0.8685}(3.2099R+ \\ &\quad 2.1993L)-R(2.7125R+1.7277L)])/B'L \end{aligned} \tag{21}$$

Based on Eq. (14), taking the parameters T, μ and L into consideration, with known V, R and q, the drawdown of groundwater table, s_1, can be calculated under the proposed limiting drainage standard.

4 Parameter study

The theoretical equation about the relationship between water inflow and drawdown is deduced above, and the equation is utilized with respect to permeability coefficient and specific yield of the common aquifer to calculate the drawdown under the proposed standard.

The common storage coefficient S for confined aquifer varies from 10^{-4} to 10^{-6} [24]. Generally, the specific yield of aquifer is far greater than storage coefficient. Thus, referring to Table 3 [26], the common values of specific yield are set in the range of 0.1−0.001.

The thickness of aquifer is defined as twice of the groundwater table and the permeability coefficients of common solid medium are shown in Table 4.

Due to the permeability coefficient of granite, gneiss and dense basalt are so small that it can be regarded as relatively water-resisting layer, the water

Table 3 Experience values of specific yield for common rock (soil)

Rock and soil layer	Specific yield	Rock and soil layer	Specific yield
Sand and gravel	0.35−0.30	Weak fractured rock formations	0.002−0.0002
Coarse sand	0.30−0.25	Strong karst formations	0.15−0.05
Medium sand	0.25−0.20	Moderate karst formations	0.05−0.01
Fine sand	0.20−0.15	Weak karst formations	0.01−0.005
Very fine sand	0.15−0.10	Shale	0.05−0.005
Sand loam	0.10−0.07	Fractured limestone	0.10−0.008
Loam	0.07−0.04	Fractured sandstone	0.03−0.02
Strong fissure rock	0.05−0.002		

Table 4 Permeability coefficient of common solid medium [27]

Rock	Permeability coefficient/(m·s^{-1})
Dolomitic limestone	10^{-3}–10^{-5}
Weathering chalk	10^{-3}–10^{-5}
Unweathered chalk	10^{-6}–10^{-9}
Dimestone	10^{-5}–10^{-9}
Dandstone	10^{-4}–10^{-10}
Granite, gneiss, dense basalt	10^{-9}–10^{-13}

inflow for which is little too. Hence, the common permeability coefficient is set in the range from 10^{-4} to 10^{-8} m/s, that is, 8.64 to 0.000864 m/d.

Generally, clogging method is utilized for the tunnel with the groundwater table less than 60. If the groundwater table is so high that the lining can't bear, the special method must be designed to deal with the water. Thus, the groundwater table ranging from 60 to 500 m is taken in this work.

The water inflow would be transformed to the flux of each day, so the drawdown is not related so much to time t and tunnel length L but mainly influenced by permeability coefficient, the depth of groundwater table, and specific yield. Thus, taking different permeability coefficients and specific yields for consideration, under the conditions that the depths of groundwater table are 60 m and 500 m, the water inflows are respectively 0.5 m^3/(m·d) and 2.0 m^3/(m·d) to calculate the drawdown of ground water. The other parameters are given as follows: t=15 d, L=2000 m, the radius of equivalent circler for tunnel r_0=6.5 m, B= 12.8 m and T=Kh_c, Taking Eq. (11) for influence radius, the calculation results are shown in Table 5.

It is indicated from Figs. 1−4 and Tables 5−6 that:

1) With the same permeability coefficient, the drawdown of groundwater table increases with decreasing specific yield. The smaller the specific yield is, the less the water is released from the unit area of

Table 5 Drawdown with groundwater table at 60 m

K/(m·d^{-1})	μ	s_1/m	
		q=0.5 m^3/(m·d)	q=2.0 m^3/(m·d)
8.64	0.1	0.76	3.04
	0.05	1.09	4.36
	0.01	2.05	8.2
	0.005	2.29	9.16
	0.001	—	—
0.864	0.1	1.82	7.28
	0.05	2.92	11.68
	0.01	7.66	30.64
	0.005	10.91	43.64
	0.001	20.46	N/A
0.0864	0.1	3.00	12
	0.05	5.36	21.44
	0.01	18.24	N/A
	0.005	29.24	N/A
	0.001	N/A	N/A
0.00864	0.1	3.75	15
	0.05	7.24	28.96
	0.01	30.04	N/A
	0.005	N/A	N/A
	0.001	N/A	N/A
0.000864	0.1	4.06	16.24
	0.05	7.99	31.96
	0.01	37.45	N/A
	0.005	N/A	N/A
	0.001	N/A	N/A

*N/A describes valve that exceeds 50 m.

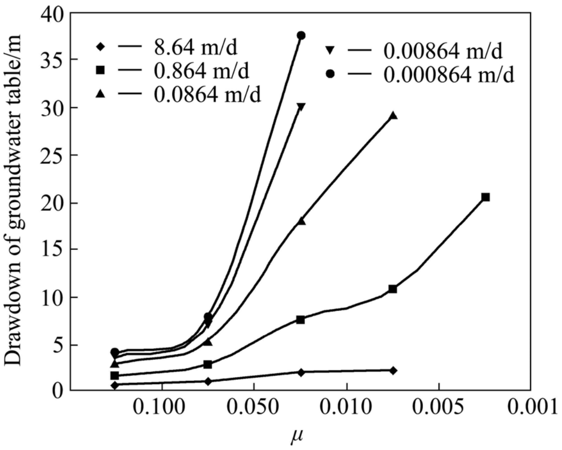

Fig. 1 Drawdown with conditions of q=0.5 m^3/(m·d) and H=60 m for different permeability coefficients and specific yields

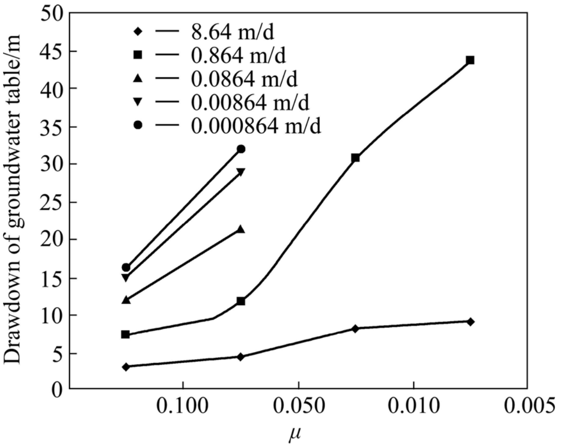

Fig. 2 Drawdown with conditions of q=2.0 m^3/(m·d) and H=60 m for different permeability coefficients and specific yields

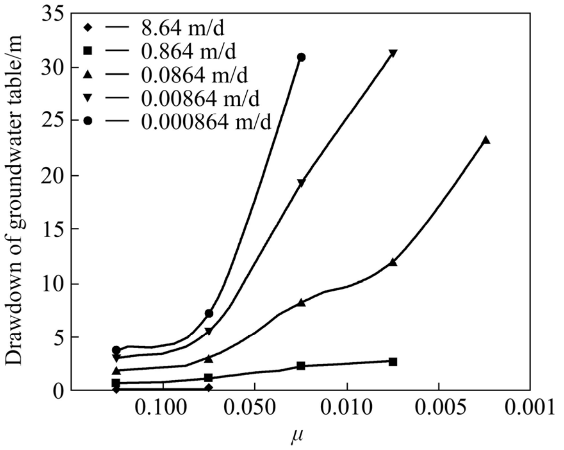

Fig. 3 Drawdown with conditions of q=0.5 m^3/(m·d) and H=500 m for different permeability coefficients and specific yields

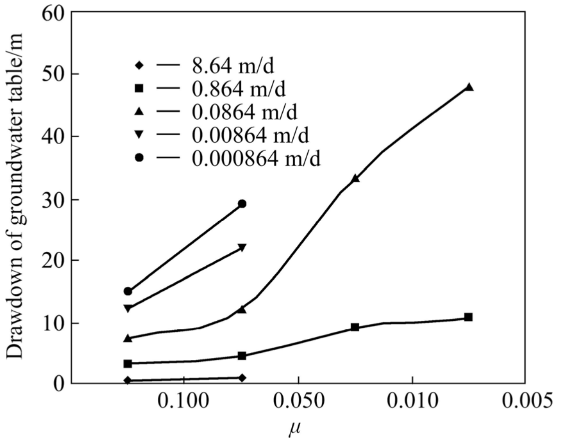

Fig. 4 Drawdown with conditions of q=2.0 m^3/(m·d) and H=500 m for different permeability coefficients and specific yields

aquifer when groundwater dewatering by one unit. Thus, the more drawdown of groundwater table is needed for the aquifer with little specific yield to discharge the same amount of groundwater.

Table 6 Drawdown with groundwater table at 500 m

K/(m·d^{-1})	μ	s_1/m	
		q=0.5 m^3/(m·d)	q=2.0 m^3/(m·d)
8.64	0.1	0.23	0.93
	0.05	0.27	1.08
	0.01	—	—
	0.005	—	—
	0.001	—	—
0.864	0.1	0.83	3.33
	0.05	1.2	4.79
	0.01	2.33	9.33
	0.005	2.71	10.84
	0.001	—	—
0.0864	0.1	1.92	7.69
	0.05	3.11	12.44
	0.01	8.32	33.26
	0.005	11.98	47.9
	0.001	23.32	N/A
0.00864	0.1	3.08	12.33
	0.05	5.54	22.14
	0.01	19.22	N/A
	0.005	31.1	N/A
	0.001	N/A	N/A
0.000864	0.1	3.78	15.13
	0.05	7.25	29
	0.01	30.82	N/A
	0.005	N/A	N/A
	0.001	N/A	N/A

*N/A describes valve that exceeds 50 m.

2) The drawdown is inversely proportional to the permeability coefficient under the same magnitude of specific yield. The small permeability means the little water inflow in unit time, and the greater scope of the dewatering funnel can reach the same magnitude of drainage. Moreover, the smaller the permeability is, the less the influence range of dewatering funnel is. So, the drawdown is enlarged with the permeability diminishing.

3) Under the same permeability and specific yield, the drawdown would be minished with the groundwater table rising. The influence scope is proportional to the depth of groundwater table. A little drawdown is needed to reach the same water inflow and volume.

It can be seen from Figs. 1−4, Tables 5 and 6 that, the drawdown of the groundwater table is lower than 40 m within the limiting drainage criterion ranges from 0.5 to 2.0 m^3/(m·d) under the following two conditions: 1) the groundwater table varies from 60 m to 500 m, the permeability ranges from 10^{-4} to 10^{-5} m/s and the specific yield is in the range from 0.1 to 0.001, 2) the groundwater table varies from 60 m to 500 m, the permeability ranges from 10^{-6} to 10^{-8} m/s and the specific yield is in the range from 0.1 to 0.01. WAN et al [28] did the research on ecological groundwater table of vegetation in arid region, which implied that the depth of roots for Tamarix chinensis can reach 40 m and the roots for Populus diversifolia can extend to 60 m in horizontal direction. The research focused on arid region to mountain tunnels in humid region of southern parts of China, and it often grew with tall trees on the top, the roots of which were more developed in general. In addition to the abundant rainfall recharge amount, the drawdown controlled below 40 m can prevent the vegetation ecology from being destroyed in the vicinity of the tunnel. Besides, the parameters selected to verify the presented standard are the common values for common rock and soil layer. Thus, the proposed limiting drainage criterion which ranges from 0.5 to 2.0 $m^3/(m\cdot d)$ can meet the requirement of groundwater control for most common mountain tunnels, and protect the local ecological environment. The established criterion is reasonable.

5 Case analysis

The proposed approach was utilized to compute the example in Ref. [29]. The Yuanliangshan tunnel of Yu-huai railway is 11068 m long, with the groundwater table H=460 m, h_c=920 m, K=0.0234 m/d, μ=0.0058, B=7 m and t=15 d. The drawdown of groundwater table was calculated under the limiting scope of 0.5−2.0 $m^3/(m\cdot d)$. When q=0.5 $m^3/(m\cdot d)$, the drawdown s_1=23.6 m, q=1.0 $m^3/(m\cdot d)$ and s_1=47.3 m. If q=2.0 $m^3/(m\cdot d)$, the drawdown will be so large that it can’t be accepted, so setting the allowable water inflow q at about 1.0 $m^3/(m\cdot d)$ is reasonable. However, in Ref. [29], the allowable perennial water inflow for recovering water balance was determined to be 1.09 $m^3/(m\cdot d)$ with precipitation and runoff taken into consideration, which is close to the result calculated by the presented method in this work. Additionally, the geological parameter and the calculated result are in the range of proposed scope, which verifies the reasonability of proposed method.

6 Conclusions

1) The drainage standards for subway tunnel, subsea tunnel, city tunnel and mountain tunnel are summarized through the survey analysis. By comparing the mountain tunnel with the other three types of tunnel on sensitivity to groundwater, the limiting drainage criterion ranging from 0.5 to 2.0 $m^3/(m\cdot d)$ was proposed.

2) On the basis of groundwater dynamics and empirical equation for seepage, the cubature formula of dewatering funnel is deduced, and the equation between the drawdown of groundwater table and water inflow for tunnel is obtained.

3) The common scopes of permeability coefficient, specific yield and groundwater table for common rock and soil layer are selected, and the equations of the drawdown of groundwater table and water inflow are combined to calculate the drawdown of groundwater table under the proposed criterion.

4) The allowable water inflows of proposed method and the example in relative reference are 1.0 $m^3/(m\cdot d)$ and 1.09 $m^3/(m\cdot d)$, respectively. In addition, the geological parameters and the calculated result are in proposed scope. Thus, the proposed method is effective.

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