Rise of the groundwater table when flow is obstructed by shallow tunnels

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ABSTRACT: The paper investigates the steady-state rise of the groundwater table upstream of a shallow tunnel due to the obstruction of the groundwater low iη the direction normal to the tunnel axis, using a steady-state finite-element groundwater low model. Based oη the parametric results of the analyses, the paper proposes a simplified analytical method which gives reasonably accurate predictions of the magnitude of the water table rise via a closed-form analytical expression. It is shown that the predicted magnitude of the steady-state water table rise is proportional to the tunnel height and to the original hydraulic gradient ίη the direction normal to the tunnel axis. The predicted rise of the water table also depends oη the depth of the tunnel below the original groundwater table. For uniform ground permeability, the predicted steady-state rise is independent of the hydraulic parameters of the aquifer. It is obvious, however, that the time required for the water table to rise and eventually reach the steady state condition is dependent oη the permeability and storability characteristics of the aquifer. For typical values of the hydraulic gradient (2-5%), the predicted water table rise is ίη the order of % of the tunnel height for tunnels located just below the water table.

1 INTRODUCTION

The enforcement of strict rules (mainly for environmental reasons) oη the exploitation of groundwater ίη urban areas can result ίη significant water table rises and sometimes even ίη the reversal of the prevailing hydraulic gradients. Under such conditions, a rising shallow groundwater table can be a significant hazard for the structures ίη an urban environment. Even ίη rural areas, a rising water table can adversely affect the root system of the vegetation thus influencing the local ecosystem. Iη addition to the well-known factors. causing fluctuations of the groundwater table (e.g. the seasonal discharge and recharge of shallow unconfined aquifers), the level of a water table may rise as a result of the construction of a long tunnel at a shallow depth below the piezometric surface if that tunnel obstructs the groundwater low iη a direction perpendicular to the tunnel axis. The purpose of this paper is to investigate these effects and estimate the magnitude of the water table rise due to the construction of shallow tunnels.

The types of structures considered to be at risk by a rising groundwater table include the basements and foundations of buίldings and other tunnels or underground structures. Iη general, a rising water table can have the following adverse effects oη adjacent structures:

I. Appreciable reduction of the bearing capacity of shallow foundations.
2. Development of uplift water pressures under foundations and floor slabs.
3. Possible ground heave due to the reduction of the effective stresses caused by the increasing pore water pressures.
4. Expansion of heavily compacted fills under the foundations of structures.
5. Appreciable settlements of poorly compacted fills υροη wetting.
6. Possible ground collapse ίη the case of soils with high collapse potential ίη the zone which becomes saturated by the rising water table.
7. Potential leakage of groundwater (or simply the appearance of moisture) ίη basements of buildings and service ducts.
8. Increased loads oη retaining systems and basement walls of buildings.
9. Increased need for drainage and the potential of instabilityίties in temporary excavations.

Iη addition to the above, the rising

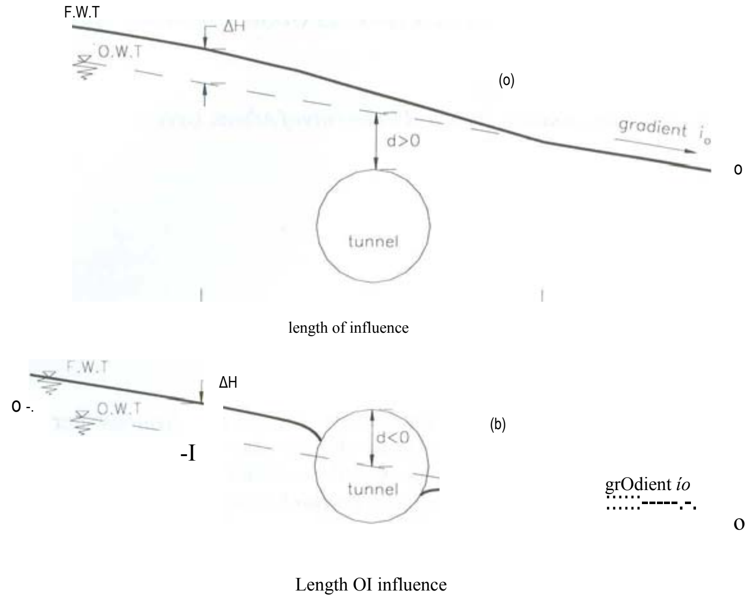

Figure 1. Sketch showing the rise (ΔH) of the Original Water Table (OWT) upstream of α tunnel located: (α) at α shallow depth below the water table and (b) at α depth intersecting the original water table. FWT=Final Water Table.

groundwater table can cause the propagation of contaminants contained ίη the previously partially saturated zone. Such previously harmless contaminants can be mobilised upon saturation, forced to migrate downstream and diffuse within the aquifer polluting the groundwater. Where the rising groundwater table can reach the surface, flooding and an increased risk of pollution of surface watercourses may become a problem. Finally, the rising of a near surface groundwater table can affect the efficiency of highway drainage systems (Johnson, 1994).

The above adverse effects of the rising groundwater tables, ίη conjunction with the rapidly increasing number of underground transit systems ίη the urban environment, make necessary the investigation of the effects of such tunnels οη the groundwater levels, since these systems are usually constructed at shallow depths close to the piezometric surface. The present paper studies these effects and proposes a method to estimate the magnitude of the groundwater table due to the presence of a tunne1.

2 THE EFFECT OP T~ELSN GROUNDWATER LEVELS

The construction of a tunnel at a shallow depth below the groundwater table impedes the flow ίη the direction normal to the tunnel axis, thus causing a rise of the groundwater table ίη the upstream area. Figure I presents a sketch of the groundwater table levels before (Original Water Table - OWT) and after (Final Water Table FWT) the construction of a tunnel ίη two cases: (a) a tunnel completely submerged below the original water table and (b) a tunnel located at a depth intersecting the original water table. The figure shows schematically the magnitude (ΔH) of the rise of the water table upstream of the tunnel. The existence of the tunnel forces the groundwater to circumvent it by locally increasing the length of the flow path and the corresponding flow velocity. The required extra energy loss is provided by the locally increased hydraulic gradient ίη the "length of influence"; the increased hydraulic gradient ίη turn causes a moderate rise of the water table ίη the upstream area. This effect extends to some distance ίη the upstream direction and fades ίη a large distance from the tunnel, since the disturbance ίη the flow regime caused by the construction of the tunnel can οηlΥ be loca1. The water table fluctuation caused by the tunnel occurs progressively ίη a time-scale governed by the hydraulic conductivity of the aquifer and the magnitude of the long-term rise (ΔH).

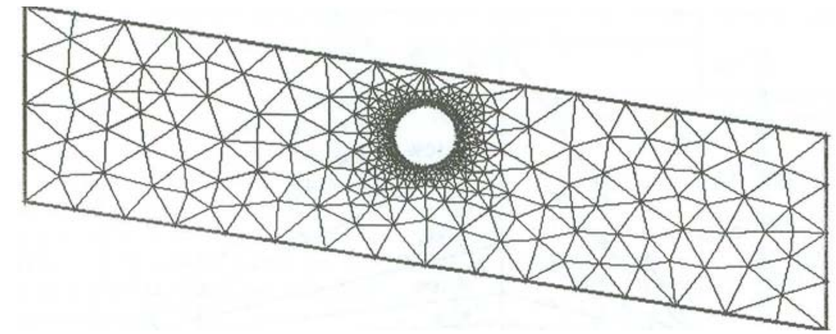

Figure 2. Typical finite element model used in the analysis of the steady-state jlow around α cylindrical tunnel. The inclined top surface represents the originally uniform hydraulic gradient (iO) in the direction perpendicular (o the tunnel axis.

The magnitude of the rise of the groundwater table due to the construction of a shallow tunnel was investigated by analysing the two dimensional steady-state flow around a cylindrical tunnel located at a depth (d) below the groundwater table. The groundwater table was assumed to have a uniform initial gradient (ίο) ίη the direction perpendicular to the tunnel axis. The analysis was performed using a two-dimensional finite element model of the steady-state groundwater flow around a cylindrical object simulating the tunnel. Figure 2 presents a typical finite element mesh layout used ίη the analyses. The inclined upper boundary presents the position of the original groundwater table. The depth (d) of the tunnel crest below the water table was varied to parametrically investigate its effect οη the magnitude of the water table Tise (ΔH). The quantities involved ίη the analyses are further described ίη Figure I.

The finite element model used ίη the analyses is described by Kavvadas andι Marinos (1994). The model is based οη the Galerkin method of weighted residuals and solves the time-dependent, two-dimensional flow ίη a porous medium around a cylindrical object. While the model can study the time dependent evolution of the flow regime around the tunnel, οηlΥ the final (steady state) response was considered ίη the present study, by eliminating the time dependent terms. The reason for this simplification is that the steady-state response corresponds to the maximum water table rise and, since tunnels are permanent structures, the steady-state response will eventually occur during the lίfe of the tunnel, regardless of the time required to reach that condition. The issue of the time required to reach the long-term steady-state condition is however briefly discussed at the end of the paper.

Figure 3 summarizes the results of the finite element analyses. The horizontal axis plots the depth (d) of the tunnel crest below the original position of the water table, normalized with the tunnel diameter. The vertical axis represents the magnitude of the steady-state water table rise (ΔH) upstream of the tunnel (also normalized with the tunnel diameter). The marks shown οη the plot correspond to the computed data points for several values of the gradient (ίο) of the water table (equal to 1%,2.5%,5%, 10% and 15%). The figure also shows the best fit lines connecting the computed data points for the same value of the hydraulic gradient. For each value of the hydraulic gradient, the peak rise of the groundwater table is observed for d/D=O i.e., when the tunnel is just fully submerged. The computed steady-state rise of the water table decreases gradually for negative values of (d), i.e., as part of the tunnel emerges above the groundwater table; the effect of the tunnel οη the water tabie is obviously zero for d/D=-I, i.e., when the bottom of the tunnel is just above the water table. For a fully submerged tunnel, i.e., for positive values of the depth (d), the rise of the water table decreases gradually as the depth (d) increases; eventually the effect becomes practically negligible when the crest of the tunnel is at a depth of about two tunnel diameters below the original groundwater table.

3 THE PROPOSED SIMPLIFIED MODEL

The construction of a tunnel at a shallow depth below the groundwater table impedes the flow and as a result causes a moderate rise of the water table ίη the upstream area (Figure I). The magnitude of the water table rise depends οη the

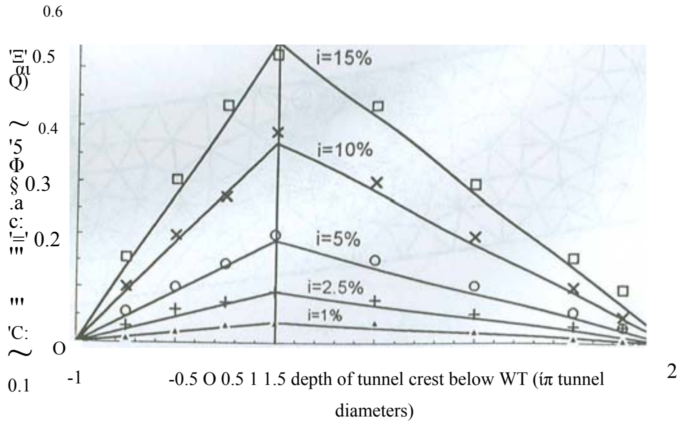

Figure 3. *Finite-element predictions o/ the rise o/ the groundwater table as α /unction o/ the depth o/ the tunnel crest below the water table and the magnitude o/ the original hydraulic gradient (i) o/ the aquifer in the direction perpendicularαr Io the tunnel axis.*

size of the tunnel, its depth below the original water table and the hydraulic gradient ίη the direction perpendicular to the tunnel axis. The rise of the water table due Io the construction of a tunnel is a time dependent process: the water table begins Io rise when the tunnel is constructed and eventually the rise reaches a maximum value which corresponds Io the steady-state condition. The time required Io reach the steady-state condition depends οη the geometrical characteristics of the project and the hydraulic parameters of the aquifer. However, since tunnels are permanent structures the steady-state condition will eventually be reached ίη practically all cases; ίι is thus usually justifiable Io design for the steady-state rise of the water table. The previous section described the finite-element analyses performed and discussed the main results of a parametric investigation of this phenomenon. Iη the present section, a simple analytical model is proposed which results ίη a closed-form expression for the prediction of the steady-state rise of the water table due Io the construction of a shallow tunnel. The model is based οη the following assumptions:

I. The construction of the tunnel infl uences the groundwater table οηlY ίη the direction perpendicular Io its axis, i.e., the rise of the water table οηlY depends οη the component of the hydraulic gradient perpendicular Io the tunnel axis. This is of course an obvious assumption.

2. The groundwater flow prior Io the construction of the tunnel is spatially and temporally uniform.

3. When the steady-state condition is eventually re-established, the presence of the tunnel does ηoΙ alter the amount of the groundwater flow ίη the aquifer, i.e.,

Qo = Qr (I)

where (Qo) is the original discharge and (Qr) the final discharge ίη the domain influenced by the construction of the tunnel. Essentially, this assumption implies that the disturbance ίη the flow caused by the tunnel is οηlY local and thus the hydraulic characteristics ίη the flow regime around the tunnel are gradually re-adjusted Io maintain the same discharge as before the construction of the tunnel.

4. The tunnel infl uences the elevation of the surface of the groundwater table by an appreciable amount οηlY if ίι is located within a shallow zone having a thickness equal Io two times its submerged thickness. This assumption is based οη the results of the finite- element analyses (Figure 3) which show that the rise of the groundwater table for fully submerged tunnels is practically negligible for depths exceeding two tunnel diameters. Thus, for a fully submerged tunnel, the ratio of the cross sectional area of the flow domain before the construction of the tunnel (Ao) Io that after the construction of the tunnel (Af) is:

Ao / Ar = 3D/(3D-D) = I.5

(2)

The same relationship also holds for partially submerged tunnels, since ίη such a case the near-surface zone infl uenced by the tunnel is also assumed Io have a thickness equal Io three-times the depth of the tunnel bottom below the water tabIe.

5. The existence of the tunnel forces the groundwater Io by-pass ίι by increasing the length of the flow path. If (Lo) is the length of the initial straight line flow path and (Lf) the average length of the final flow path, then:

(a) It is assumed that the length of infl uence of the tunnel along the f10w direction is equal Io four tunnel diameters for a [υIIY submerged tunnel (or more generally equal Io four times the submerged depth of the tunnel), i.e., 1.5 diameters upstream of the tunnel and 1.5 diameters ίη the downstream. This assumption is based οη the deformed shape of the flow lines computed from the finite-element analyses.

(b) The maximum length (Lm) of the final f10w path corresponds Io the stream-line which is tangent at the tunnel. Assuming that the shape of this stream-line is a circular arc tangent Io the tunnel, then: Lm/Lo = 1.16 (for Lo equal Io four tunnel diameters).

(c) The Iength (L) of any stream-line is ίη the range (Lm, Lo) as the distance ofthat stream-line from the tunnel increases. It is assumed that the length (L) of a stream-line decreases parabolically as the distance of that stream-line from the tunnel increases, i.e.,

I = IO + (rm - Io)(1- 3~)

2

(3)

where (R) is the tunnel radius. For a [υIIY submerged tunnel with its crest located at a depth equal Io one tunnel diameter (i.e., for a symmetric split of the stream-lines above and below the tunnel), the average length (Lt) of the final flow path is:

Iι = 3~ 31Ldx = (ι + 0.333 (~: -ι) J ιο = 1.053 IO (4)

i.e., the average increase ίη the length of the flow path is about 5.3 % (for Lo equal Io four tunnel diameters). Using the above assumptions: QJ = Qo => k 'ίι' AJ = k'ζ' Ao =>

ΔhJ Δh

-.A =~.A =>

Ιι J IO o

Mi Ξ ΔhJ -Δho = io 'Io .{(~~] (~) -ι} =>

Δ: = io . ~. { (~~ J (~) -ι} = 2.32 io

(5)

i.e., the steady-state rise (ΔH) of the groundwater table upstream of a tunnel with its crest located at a depth d=D below the water table is pro portional Io the hydraulic gradient (ίο) of the aquifer and Io the tunnel diameter (D). This formula compares" reasonably well with the predictions of the finite element analyses as shown ίn the following table:

Steady-state rise of the groundwater table (ίη meters) [σΓ a tunnel with its crest located at a depth equal to one tunnel diameter

Initial hydraulic gradient ili2.	Tunnel diameter D=6m finite-element	Eq. (5)	Tunnel diameter D=lOm finite-element --σ.π	Eq. (5)
0.5	0.067	0.07	0.22	0.12
1.0	0.1	0.\4	0.5	0.23
2.5	3	0.35	3	0.58
5.0	0.3	0.70	1.0	\.\6
10.0	2	\.39	6	2.32
	0.6		2.0\	
	4			
	1.2			
	1			

The above table gives the predicted rise of the groundwater table for a tunnel with its crest located at a depth equal Io one tunnel diameter. For tunnels located at different depths, the finiteelement results show that there exists a practically linear relationship between the predicted rise and the depth of the tunnel crest below the water table. Guided by these predictions and the simplified analytical model previously described, we can write the following approximate relationships for the magnitude of the steadystate water table rise (ΔH) ίη terms of the initial hydraulic gradient (ίο) of the aquifer, the tunnel diameter (D) and the depth (d) of the tunnel crest below the water table:

I. For [υIIY submerged tunnels (d > O):

ΔH = 232.i 'D' . o (2-:!... D) (6)

2. For partially submerged tunnels (d < O):

ΔH = 4.64. ίo 'D'(I+ ~) (7)

These relationships represent a linear variation of the water table rise with the depth (d) of the tunnel crest, as shown ίn Figure 3.

The above estimate of the water table rise represents the long-term value which can be reached ίn a time period governed by the hydraulic conductivity (k) of the aquifer and the magnitude (ΔH) of the long-term rise. The characteristic time (tc) can be obtained by a dimensional analysis and is equal Io ιο=ΔH / k, where (k) is the engineering permeability (units: length / time). This time can vary between a few days ίη the case of a relatively pervious aquifer Io several decades ίn the case of a ground with a very low permeability.

4 CONCLUSIONS

The paper investigates the steady-state rise of the groundwater table upstream of a shallow tunnel\ due to the obstruction of the groundwater low ίη the direction normal to the tunnel axis. The effects are studied using a steady-state finite element groundwater low model. Based οη the results of the finite-element analyses and reasonable arguments regarding the depth of influence of the tunnel (equal Io three diameters) and the extent of the disturbance of the tlow regime along the stream-lines (equal to four tunnel diameters), the paper proposes a simplified analytical method which gives reasonably accurate predictions of the magnitude of the water table rise via a closed-form analytical\ expression (equations 6 and 7). It is shown that the predicted magnitude of the steady-state water table rise is proportional\ to the tunnel\ height and proportional to the original\ hydraulic gradient of the aquifer ίη the direction normal Io the tunnel axis. The predicted rise of the water table also depends οη the depth of the tunnel below the original groundwater table. For uniform ground permeability, the predicted steady-state rise is independent of the hydraulic parameters of the aquifer, while the time required for the water tab\e to gradually rise and eventually reach the steady-state condition is obvious\y dependent on the permeability and storability characteristics of the aquifer. For typical\ values of the hydraulic gradient (0.5-5%), the predicted water table rise is ιη the order of 1-10% of the tunnel\ height for tunnels located just below the original level of the water table. For tunnels located at some depth below the water table or for partially submerged tunnels, the magnitude of the water table rise is lower.

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