

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 flow in the direction normal to the tunnel axis, using a steady-state finite-element groundwater flow model. Based on 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 in the direction normal to the tunnel axis. The predicted rise of the water table also depends on 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 on the permeability and storability characteristics of the aquifer. For typical values of the hydraulic gradient (2-5%), the predicted water table rise is in 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) on the exploitation of groundwater in urban areas can result in significant water table rises and sometimes even in the reversal of the prevailing hydraulic gradients. Under such conditions, a rising shallow groundwater table can be a significant hazard for the structures in an urban environment. Even in rural areas, a rising water table can adversely affect the root system of the vegetation thus influencing the local ecosystem. In 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 flow in 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 buildings and

other tunnels or underground structures. In general, a rising water table can have the following adverse effects on adjacent structures:

1. 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 upon wetting.
 6. Possible ground collapse in the case of soils with high collapse potential in the zone which becomes saturated by the rising water table.
 7. Potential leakage of groundwater (or simply the appearance of moisture) in basements of buildings and service ducts.
 8. Increased loads on retaining systems and basement walls of buildings.
 9. Increased need for drainage and the potential of instabilities in temporary excavations.
- In addition to the above, the rising

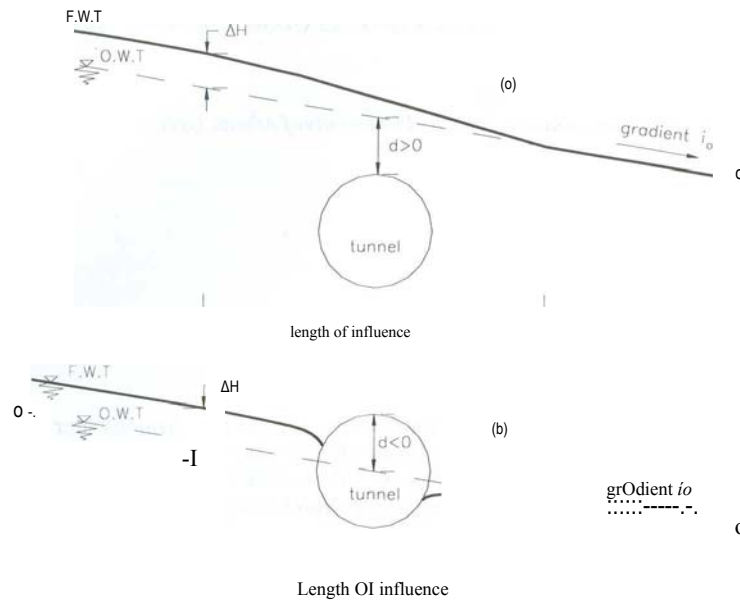


Figure 1. Sketch showing the rise (ΔH) of the Original Water Table (OWT) upstream of a tunnel located: (a) at a shallow depth below the water table and (b) at a depth intersecting the original water table. FWT=Final Water Table.

groundwater table can cause the propagation of contaminants contained in 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, in conjunction with the rapidly increasing number of underground transit systems in the urban environment, make necessary the investigation of the effects of such tunnels on 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 tunnel.

2 THE EFFECT OF TUNNELS ON GROUNDWATER LEVELS

The construction of a tunnel at a shallow depth

below the groundwater table impedes the flow in the direction normal to the tunnel axis, thus causing a rise of the groundwater table in the upstream area. Figure 1 presents a sketch of the groundwater table levels before (Original Water Table - OWT) and after (Final Water Table FWT) the construction of a tunnel in 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 in the "length of influence"; the increased hydraulic gradient in turn causes a moderate rise of the water table in the upstream area. This effect extends to some distance in the upstream direction and fades in a large distance from the tunnel, since the disturbance in the flow regime caused by the construction of the tunnel can only be local. The water table fluctuation caused by the tunnel occurs progressively in a time-scale governed by the hydraulic conductivity of the aquifer and the magnitude of the long-term rise (ΔH).

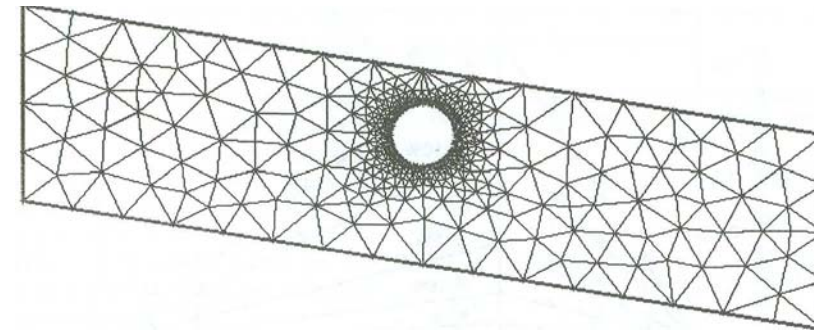


Figure 2. Typical finite element model used in the analysis of the steady-state flow around a cylindrical tunnel. The inclined top surface represents the originally uniform hydraulic gradient (i_0) in the direction perpendicular to the tunnel axis.

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 (i_0) in 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 in 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 on the magnitude of the water table rise (ΔH). The quantities involved in the analyses are further described in Figure 1.

The finite element model used in the analyses is described by Kavvas and Marinos (1994). The model is based on the Galerkin method of weighted residuals and solves the time-dependent, two-dimensional flow in a porous medium around a cylindrical object. While the model can study the time dependent evolution of the flow regime around the tunnel, only the final (steady state) response was considered in 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 life 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 on the plot correspond to the computed data points for several values of the gradient (i_0) 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 $d/D=0$ 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 on the water table is obviously zero for $d/D=-1$, 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 in the upstream area (Figure 1). The magnitude of the water table rise depends on the

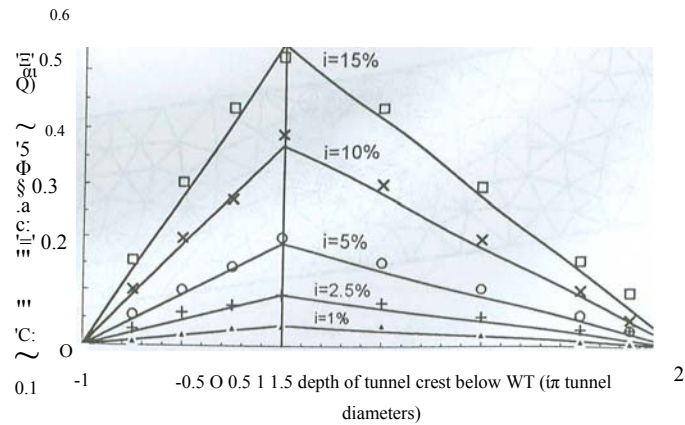


Figure 3. Finite-element predictions of the rise of the groundwater table as a function of the depth of the tunnel crest below the water table and the magnitude of the original hydraulic gradient (i) of the aquifer in the direction perpendicular to the tunnel axis.

size of the tunnel, its depth below the original water table and the hydraulic gradient in the direction perpendicular to the tunnel axis. The rise of the water table due to the construction of a tunnel is a time dependent process: the water table begins to rise when the tunnel is constructed and eventually the rise reaches a maximum value which corresponds to the steady-state condition. The time required to reach the steady-state condition depends on 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 in practically all cases; it is thus usually justifiable to 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. In the present section, a simple analytical model is proposed which results in a closed-form expression for the prediction of the steady-state rise of the water table due to the construction of a shallow tunnel. The model is based on the following assumptions:

1. The construction of the tunnel influences the groundwater table only in the direction perpendicular to its axis, i.e., the rise of the water table only depends on the component of the hydraulic gradient perpendicular to the tunnel axis. This is of course an obvious assumption.

2. The groundwater flow prior to 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 not alter the amount of the groundwater flow in the aquifer, i.e.,

$$Q_0 = Q_r \quad (1)$$

where Q_0 is the original discharge and Q_r the final discharge in the domain influenced by the construction of the tunnel. Essentially, this assumption implies that the disturbance in the flow caused by the tunnel is only local and thus the hydraulic characteristics in the flow regime around the tunnel are gradually re-adjusted to maintain the same discharge as before the construction of the tunnel.

4. The tunnel influences the elevation of the surface of the groundwater table by an appreciable amount only if it is located within a shallow zone having a thickness equal to two times its submerged thickness. This assumption is based on 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 (A_0) to that after the construction of the tunnel (A_f) is:

$$A_0 / A_f = 3D / (3D - D) = 1.5 \quad (2)$$

The same relationship also holds for partially submerged tunnels, since in such a case the near-surface zone influenced by the tunnel is also assumed to have a thickness equal to three-times the depth of the tunnel bottom below the water table.

5. The existence of the tunnel forces the groundwater to by-pass it by increasing the length

of the flow path. If L_0 is the length of the initial straight line flow path and L_f the average length of the final flow path, then:

(a) It is assumed that the length of influence of the tunnel along the flow direction is equal to four tunnel diameters for a fully submerged tunnel (or more generally equal to four times the submerged depth of the tunnel), i.e., 1.5 diameters upstream of the tunnel and 1.5 diameters in the downstream. This assumption is based on the deformed shape of the flow lines computed from the finite-element analyses.

(b) The maximum length (L_m) of the final flow path corresponds to the stream-line which is tangent to the tunnel. Assuming that the shape of this stream-line is a circular arc tangent to the tunnel, then: $L_m/L_0 = 1.16$ (for L_0 equal to four tunnel diameters).

(c) The length (L) of any stream-line is in the range (L_m, L_0) as the distance of that 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.,

$$L = L_0 + (R_m - L_0) \left(1 - \frac{x}{L_m} \right)^2$$

2

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

$$L_t = \int_0^{L_m} L dx = (1 + 0.333) \left(\frac{L_m}{2} \right) = 1.053 L_0 \quad (4)$$

i.e., the average increase in the length of the flow path is about 5.3% (for L_0 equal to four tunnel diameters).

Using the above assumptions: $Q_f = Q_0 \Rightarrow k' i_f' A_f = k' i_0' A_0 \Rightarrow$

$$\Delta h_f \Delta h_0$$

$$L_f i_f = L_0 i_0 \Rightarrow$$

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$$L_f i_f = L_0 i_0 \Rightarrow$$

$$\Delta h_f = \Delta h_0 \cdot \left(\frac{L_0}{L_f} \right) = 2.32 i_0$$

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 proportional to the hydraulic gradient (i_0) of the aquifer and to the tunnel diameter (D). This formula compares reasonably well with the

predictions of the finite element analyses as shown in the following table:

Steady-state rise of the groundwater table (Δh meters) [$\sigma \Gamma$ a tunnel with its crest located at a depth equal to one tunnel diameter

Initial hydraulic gradient i_0	Tunnel diameter $D=6m$ finite-element	Tunnel diameter $D=10m$ finite-element	Eq. (5)	Eq. (5)
0.5	0.067	0.07	0.22	0.12
1.0	0.1	0.14	0.5	0.23
2.5	3	0.35	3	0.58
5.0	0.3	0.70	1.0	1.6
10.0	2	1.39	6	2.32

The above table gives the predicted rise of the groundwater table for a tunnel with its crest located at a depth equal to one tunnel diameter. For tunnels located at different depths, the finite element 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 steady-state water table rise (ΔH) in terms of the initial hydraulic gradient (i_0) of the aquifer, the tunnel diameter (D) and the depth (d) of the tunnel crest below the water table:

1. For fully submerged tunnels ($d > D$):

$$\Delta H = 2.32 i_0 D \left(\frac{d}{D} \right) \quad (6)$$

2. For partially submerged tunnels ($d < D$):

$$\Delta H = 4.64 i_0 D \left(1 + \frac{d}{D} \right) \quad (7)$$

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

The above estimate of the water table rise represents the long-term value which can be reached in a time period governed by the hydraulic conductivity (k) of the aquifer and the magnitude (ΔH) of the long-term rise. The characteristic time (t_c) can be obtained by a dimensional analysis and is equal to $t_c = \Delta H / k$, where (k) is the engineering permeability (units: length / time). This time can vary between a few days in the case of a relatively pervious aquifer to several decades in 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 flow in the direction normal to the tunnel axis. The effects are studied using a steady-state finite element groundwater flow model. Based on the results of the finite-element analyses and reasonable arguments regarding the depth of influence of the tunnel (equal to three diameters) and the extent of the disturbance of the flow 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 in the direction normal to the tunnel axis. The predicted rise of the water table also depends on 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 table to gradually rise and eventually reach the steady-state condition is obviously 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 in 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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