ANALYSIS OF WATER TABLE MOUNDING AND RECOMMENDATIONS FOR MASS DRAINFIELD DESIGN

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November 22, 1982

1. Limitations of approaches

Any analysis of water movement in soils and underlying geologic materials is of necessity approximate at best due to the complex geometry and large variability of earth materials. One imposes many simplifications on reality to simplify its mathematical representations and hopes they are not so unreasonable as to render the results useless. Field verification is ultimately necessary to justify any such hopes. This report outlines approximate methods of estimating water table mounding and checks the predictions against field-measured data where feasible. The approach taken is purely analytical and accordingly is restricted to simple boundary conditions, geometries and soil conditions. Suggestions for dealing with more complex situations are given to extend applicability of the method.

A more precise analysis of such problems could be made using various numerical approaches. There are a number of computer codes available for the analysis of this sort of problem and it would be advisable to consider their use for final design or at least to evaluate the analytical methods by selective comparisons with numerical solutions. Numerical analysis would also make the evaluation of solute transport accompanying wastewater disposal feasible. The analytical approach given here considers only groundwater mounding.

2. Analytical methods

2.1 Perched groundwater mounds on level strata

Brock (1982) reports a solution for the problem of perched groundwater mounds beneath strip recharge basins shown in Fig.l based on the Dupuit-Forchheimer assumptions. For a strip basin of width L_e with a flux density q (volume per unit time per unit area) and for conductivities in the upper and lower layers of K_1 and K_2 respectively ($K_1 > K_2$), the steady-state mound height is given by:

$$H_0 = \frac{Le}{2}\left[\frac{q^2}{K_1K_2} - \frac{q}{K_1}\right]^{1/2}$$

Equation 1

Comparisons with numerical solutions indicate Eq. I is reasonably accurate if $K_1/K_2 > 10$ and $q/K_1 < 0.2$.

In reality flow will not be strictly two-dimensional.. For a drainfield of width L_c and length L_f, Eq. 1 is valid with $L_e = L_c$ only if $L_f >> L_c$. If $L_c = L_f$ using $L_e = L_c$ in Eq. 1 will cause H_0 to be in error due to the fact that flow in the third dimension is not accounted for. For a given Lc and H_0 the square may be expected to accommodate about twice the flux density of a long strip. However, altering the ratio L_f/L_c changes the flux density at constant effluent volume since by definition

$$q = J/L_c\,(L_f)$$

Equation 2

where J is the total volume of effluent added per unit time. As a result, at constant q (hence at constant field area for a given J) employing Le = Lc in Eq.1 will underestimate H0 for the square field. These effects may be accommodated by taking Le in Eq. 1 as an "effective" width equivalent to that for the 2-D case and calculating it .

$$L_e = L_c \left| \frac{L_f^2 + L_c^2}{L_f^2} \right|^{1/2}$$

Equation 3

Defining the geometric factor a as

$$a = L_f/L_c$$

Equation 4

Yields for Eqs. 2 and 3:

$$L_e = L_c \left| \frac{1 \ + \quad ^2}{\alpha^2} \right|^{1/2}$$

Equation 5

$$a = J/a L_c^2$$

Equation 6

Combining equations 1, 5 and,6 gives

$$H_0 = \frac{(1+\alpha^2)}{2\alpha^2}^{1/2}\left[\frac{J^2}{K_1 K_2 L_c^2} - \frac{\alpha J}{K_1}\right]^{1/2}$$

Equation 7

which may be employed to evaluate mounding caused by groundwater perching over a fine layer if no permanent water table exists under natural recharge conditions.

The lateral extent of the perched mound from the drainfield perimeter (L_d) maybe calculated as:

$$L_d = \frac{qL_c}{K_2} - \frac{L_c}{2}$$

Equation 8

$$L_d = J/a L_c K_2 - Lc/2$$

Equation 9

2.2 Groundwater mounds on permanent level water tables

The preceding analysis is directly applicable only for perched groundwater mounds. We may extend the analysis for mounding on permanent water tables if we make some further assumptions. We assume a uniform conductivity K1 in the natural vadose zone (above the water table). We regard the ratio K1/K2 to reflect the ability of the aquifer to dissipate the additional hydraulic load laterally. Specifically, we take the ratio of lateral to vertical impedance to be reflected by the ratio of the lateral to vertical mound dimensions giving:

$$\frac{K_1}{K_2} = \frac{L_d + L_c/2}{H_0}$$

Equation 10

Substituting Eq. 10 into Eq. 7 gives

$$\frac{(1+\alpha^2)^{1/2}}{2\alpha^2 K_1}\left[\frac{J^2 L_d}{H_0 L_c^2} + \frac{J^2}{2H_0 L_c} - \alpha J K_1\right]^{1/2} - H_0 = 0$$

Equation 11

In certain instances, L_d. may be clearly defined by site conditions as for example when artificial drainage is to be installed or when a natural seepage face seems likely. Often L_d will not be clearly defined. An approximation of L_d may be obtained in such cases using the empirical relation:

$$L_d = L_c^2/4W - L_c/2$$

Equation 12

where W is the aquifer thickness.

2.3 Groundwater mounds on sloping strata

Groundwater mounding in tilted aquifers (Fig. 3) may be evaluated analytically using the Dupuit-Forchheimer assumptions to give:

$$L_c = \frac{2JL_d(1+\alpha^2)^{1/2}}{\alpha K_1 N}\left[H_0^2 + H_0(2W + L_d S) + 2L_d WS\right]^{-1}$$

Equation 13

where W is the mean aquifer thickness; S is the fractional slope; K1 is the conductivity of the homogeneous aquifer above an impermeable lower surface; N is a correction factor depending on the drainfield location on the slope; and the other terms are as previously defined.

The derivation of Eq. 13 assumes all water flows down slope and gives N = 1. This will always be the case when the difference between the elevation of the drainfield and the local topographic high is greater than the soil depth. When this is not the case, some water may flow “upslope” across the drainage divide. We may accommodate this possibility approximately by employing the factor N evaluated by:

$$N = 1 \qquad (B/Z = 1)$$

$$N = 2 - B/Z \qquad (B/Z < 1)$$

Equation 14

where B is the difference in elevation between the local topographic high and the average elevation of the drainfield and Z is average soil depth (to the impermeable lower boundary).

An expression analogous to Eq. 12 is postulated to estimate Ld:

$$L_d = \frac{L_c^2}{2WN} - \frac{L_c}{2}$$

Equation 15

Combining Eqs. 13 and 15 eliminates the unknown Ld. If the calculated value of Ld exceeds physica1 limits imposed by topography then the lower value should be employed in Eq.13.

3. Application of theory

A summary of the analytical mode1s for estimating groundwater mounding is given in Fig. 4. Cases 1 and 2 are for approximately level sites, i.e., less than 5-10%. “Site” should be taken, to mean the drainfield plus a surrounding area within about 2Lc to 3 Lc from the drainfield perimeter. Case 1 applies when no permanent water table exists above a high impedance layer and Case 2 applies when one does exist. A “high impedance layer” may be functionally defined as the first layer beneath the drainfield lines which has a saturated conductivity less than about 10-4 m/day or is less than an order of magnitude of that of the overlying layer. Cases 3 and 4 are for sloping sites where B/Z is less than a or greater than 1, respectively.

In all cases, hydraulic conductivities and soil and aquifer thicknesses employed in the equations should represent spatial average values. If layer thicknesses and conductivities ‘are evaluated at k locations on the site, the mean site conductivity of layers m to n (e.g. the aquifer) may be calculated as

$$\bar{K} = \frac{\sum_{j=1}^{k} \sum_{i=m}^{n} L_{ij} K_{ij}}{\sum_{j=1}^{k} \sum_{i=m}^{n} L_{ij}}$$

Equation 16

where j is the location number (horizontal index) and i is the layer number (vertical index) and Land K are the layer thickness and conductivity. Simple means of aquifer thicknesses and water table depths over the site may be calculated for use in the equations.

Examples of the various calculations follow.

3.1 Case 1: Level perched table

A drainfield is desired to dispose of 25 m^3 /day (~6500 gal/day) of effluent on a level site. Site investigation indicates

Bore Hole 1			Bore Hole 2			Bore Hole 3	
Depth (m)	K(m/day)		Depth (m)	K(m/day)		Depth (m)	K(m/day)
0.5-2.0	0.05		0.5-3.5	0.10		0.5-1.5	0.08
2.0-6.0	0.15		3.5-5.0	0.05		1.5-4.5	0.10
6.0+	0.001		5.0+	0.002		4.5+	0.0005

The perching strata is the third layer with average depth and conductivity:

D =(6 + 5 + 4.5)/3 = 5.2 m

K2 = (0.001 + 0.002 + 0.0005)/3 = 0.0012m/day

The value of K1 is calculated by Eq. 16 as:

$$K = \frac{(2 - 0.5)(0.05) + (6-2)(0.15) + (3.5-0.5)(0.1) + (5 - 3.5)(0.05) + (1.5 - 0.5)(0.08) + (4.5 - 1.5)(0.01)}{(6.0 - 0.5) + (5.0 - 0.5) + (4.5 - 0.5)}$$

= 0.102 m/day

With the drainfield installed 0.5 in deep, the maximum value of H_0 to keep the mound 0.5 m below the lines is 5.2 - 1.0 = 4.2 m. Assuming a square drainfield (a = 1) Eq. 7 gives Lc 135 m and from Eq. 9 the lateral extent of the perched mound from the drainfield perimeter.(Ld) is 87 m . For a = 5 we obtain Lc = 45 m and Ld = 78 m. This indicates an approximately 50% reduction in field area (aL^2 equals 18225 m^2 to 8820 m^2 respectively) when the field is elongated rather than square. This will generally be found to occur.

3.2 Case 2. Level unconfined aquifer

Data reported by Ali and Chan (1982 on a mass drainfield in Ontario may be used to evaluate the analytical solution for this case. The site was nearly level and the soil WAS 9-15 m to bedrock (average value 12 in). A permanent water table occurred which fluctuated seasonally between 1.5 and 3.0 in depth (average 2.0 m). Thus we have D = 2.0 m and W = 10.0 m. The hydraulic conductivity of the soil was measured in situ using three methods and also in the lab on core samples. The large diameter rising and falling head auger hole tests below the water table gave average K values of 0.20 and 0.44 rn/day, respectively. Constant head tests with driven well points gave values about 10 times lower as did laboratory tests on core samples. Percolation tests at a depth of 1 m incidentally gave rates of 0.56 min/inch or 65 m/day -- over 100 times the conductivity! Loading rates (J) were maintained at 41 m3/day (~10,600 gal/day) through the summer and fall over a field area 84 by 64 (Lc = 64 m, a =1.3).

From Eq. 12 we find Ld = 70 m which is in reasonable agreement with field measurements of water table fluctuations in the vicinity of the drainfield. Solving Eq. 11 by trial using K1 = 0.20 m/day gives H0 = 3.3 m. Using K1 = 0.44 m/day gives H0 = 1.6 m. The measured water table mounding was 1.5 m which agrees well with the value predicted using the larger K value.

3.3 Case 3: Sloping site near hilltop

A drainfield is desired to dispose of 25 m (~6,500 gal/day) of effluent on a site located on a side slope. The average elevation of the site is 500 m above sea level. The top of the hill is at 507 m elevation (B = 7 m) and the bottom of the is 100 m down slope on the horizontal. The soil is 10. m deep to nearly impermeable bedrock (Z = 10 in). Accordingly B/Z = 0.7 and N = 2 - B/Z = 1.3. The soil has an average conductivity (via Eq. 16) between the drainfield lines and bedrock of 0.1 m/day. The average slope of the site is 15% (S = 0.15).

A natural water table occurs at 6 m (W = 10 – 6 = 4 m). To keep the mounding at least l m below the soil surface we have a maximum value for H0 of 5 m. Assuming a rectangular drainfield with a = 4 and solving Eqs. 13 and 15 by trial gives Lc = 41 m and Ld = 141 m. However since it is only 100 m to the bottom of the hill Ld should not be taken greater than this. Fixing Ld at 100 m in Eq. 13 gives Lc = 38 for a field area of aL_c^2 = 5800 in (1.4 acres).

3.4 Case 4: Sloping site below hilltop

Considering the same situation as in Case 3 but with B/Z > 1 and N = 1, we find no difference from the results calculated in section 3.3.

4. Site investigation

4.l Preliminary Investigation

Preliminary estimations of site suitability may be made using conductivities estimated from soil texture and structure evaluated on site. Any evidence of drainage restriction within the upper 1 m should be cause to reject the site at the outset.

Hydraulic conductivities for purposes of preliminary analysis may be estimated as follows.

USDA Texture	K, m/day
Sand	5.0 — 0.5
Loamy sand to sandy loam	1.5 – 0.05
Sandy clay loam, si1ty clay loam, or clay loam	0.05 – 0.001
Sandy clay, silty clay or clay	0.02 – 0.0001

The higher of the values in the range are appropriate for loose or well-structured materials and the lower values for dense or poorly structured soil.

4.2 Detailed investigation

The analytical methods described above may be used for final design analysis. Numerical analysis should be considered as an alternative. If this is done, it would be useful to compare the numerical results with those of the analytical methods both as a rough check on the numerical calculation and to further evaluate the utility of the analytical methods.

In any event, it is critical that soil hydraulic properties be measured as accurately as possible. In situ hydraulic conductivity tests should be run in at least 5 locations distributed over the site area. Several test depths may be necessary as indicated by the preliminary investigation. For appropriate test methods see Boersma (1965). Laboratory conductivity tests on undisturbed cores may be allowed but it is probable that the values will be lower than those in situ resulting in lower calculated permissible loading rates.

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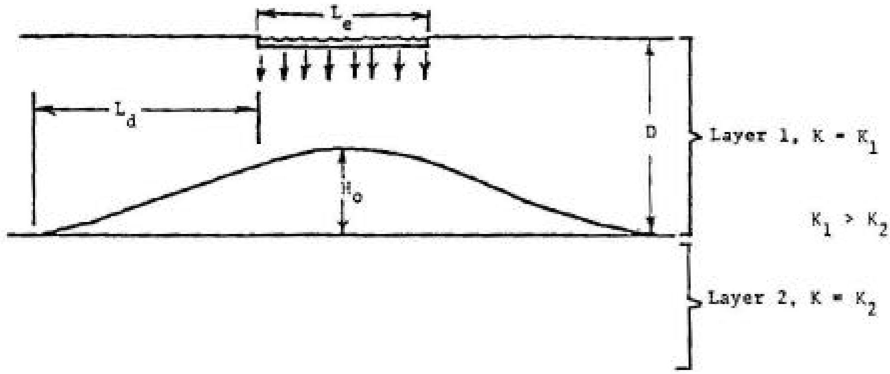

Fig. 1. Geometry of perched groundwater mound.

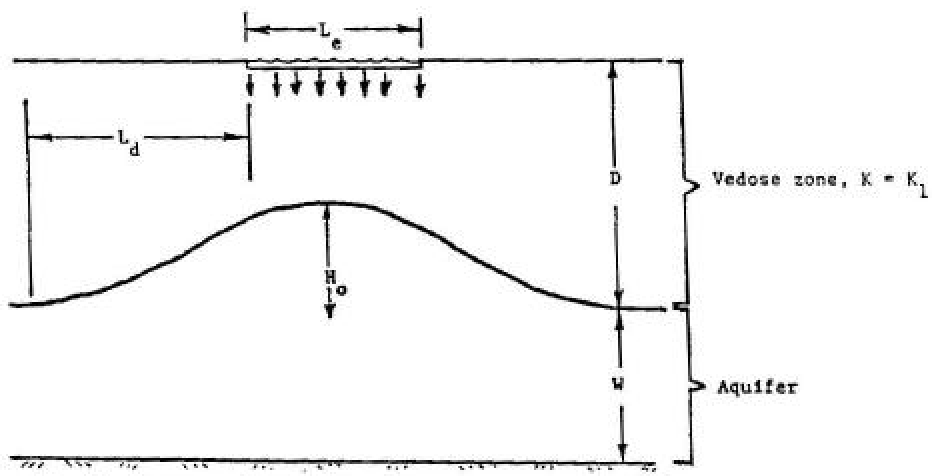

Fig. 2. Geometry of mounding above permanent water table.

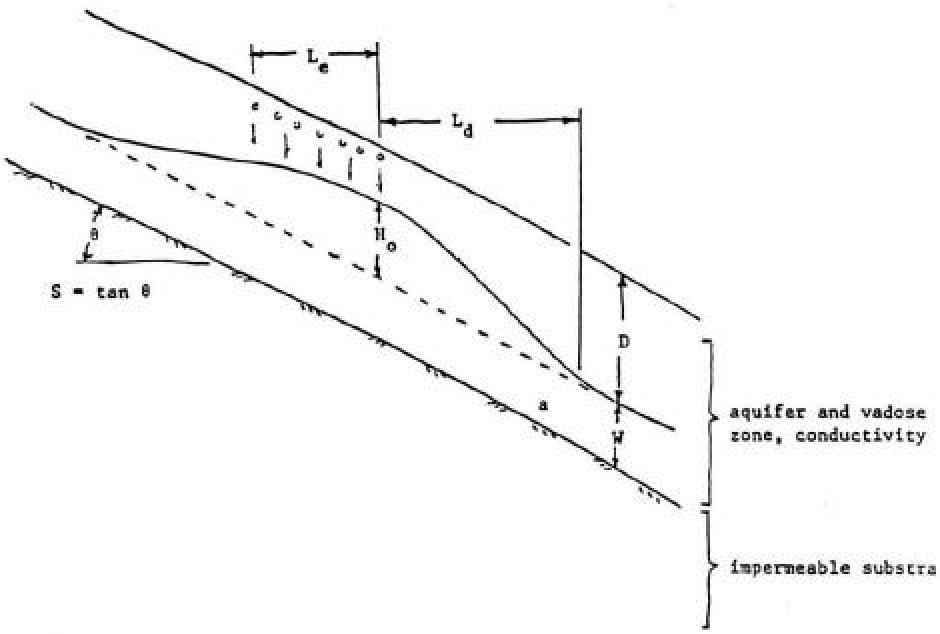

Fig. 3. Geometry of tilted aquifer.