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OPTIMAL DESIGN OF A SUBSURFACE PIPE DRAINAGE SYSTEM

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An optimization model consisting of minimization of total cost of a pipe drainage system subject to constraints on design variables was formulated. Data from Mardan SCARP was used as input to the optimization model. The output was obtained in the form of various combinations of design variables with total cost. The optimal values for lateral depth, spacing, diameter and length were found to be 1.60 m, 66.7 m, 9.20 cm and 250 m, respectively which resulted in a total of 60 laterals and 2 collectors for an area of 100 ha. Collector diameter and length respectively were 25.0 cm and 1000 m with a minimum cost of Rs.28152/ha. As expected the laterals were of the smallest size i.e., 9.20 cm to keep the total cost minimum. The optimization procedure was also used to identify the nearly-optimal designs. The cost of nearly-optimal designs being close to the minimum cost showed these designs equally good which shows the flexibility of the procedure to find out number of equally feasible designs.
Keywords: Subsurface, pipe, drainage, system, coefficient, salinity

INTRODUCTION

Waterlogging and salinity have become major problem confronting the irrigated areas in Pakistan. The magnitude of the problem can be assessed by the fact that millions of hectares of irrigated land have been seriously affected (Alam et al., 2000). Realizing pipe drainage a viable solution to waterlogging and salinity problems (HARZA/NESPAK, 1984), a number of subsurface pipe drainage projects have been started in the last 20 years in Pakistan (FAO, 2002). Since 1977, tile drainage projects have been implemented on an area of 200,000 ha (Scheumann and Memon, 2003).

While designing pipe drainage system, drain depth, spacing and pipe size are important variables to be decided. There can be several combinations of these variables that would control water table to a specified depth but each with different cost. Wider drain spacing would be required with increased drain depth for which installation cost increases with drain depth. But the total cost of a drainage system can be less due to increased drain spacing which in turn reduces the material cost. Conversely, cost of installation can be reduced by installing shallower drains but shallower drains need to be spaced closely which in turn increase the material cost.

Installation cost is more for a large size pipe than for small one as large earthwork is involved in the installation of larger pipe. Further, large size pipes are costly but may reduce the number of manholes required due to longer drainlines. On the other hand, small pipes are cheaper but may increase total cost due to shorter drainlines which require more manholes. Thus, optimal combination of drain depth, spacing and pipe diameter that results in minimum cost is desirable from economic point of view. Therefore, a procedure is needed to find out the optimum combination of drain depth, spacing and diameter that could be used in the field.

MATERIALS AND METHODS

The methodology mainly consisted of formulation of an optimization problem and its application to a case study. The optimization problem was formulated assuming rectangular area drained by parallel drainage system in which laterals and collector are perpendicular and laterals enter into a collector on both sides where possible.

Theoretical Background

The design of subsurface drainage system involves the determination of drain spacing, drain depth and drain diameter. Drain spacing is calculated using drain spacing formulae. In Pakistan, most of the drainage projects in operation were designed on the steady state formulae. East Khairpur Tile Drainage Project, Mardan SCARP, Fourth Drainage Project Faisalabad, Khushab SCARP and Chashma Drainage Projects were designed using Linderberg, Hooghoudt, Modified Donnan, Kirkham Toksoz and Donnan equations, respectively. Accuracy with which drain spacing can be determined is limited by the accuracy of the soil parameters rather than by the formula adopted. Therefore, all the drain spacing equations yield similar results when applied with the same boundary conditions (Tariq, 1995). Because of simplicity and accuracy, Hooghoudt drain spacing formula was used in this study, which is

$$S = \sqrt{\frac{8Kd_e h + 4Kh^2}{q}} \quad 1$$

in which, S is drain spacing, m; K hydraulic conductivity, m/d; h water table height above drain level at mid point, m; d_e equivalent depth, m and q drainage coefficient, m/d.

Equivalent depth is an artificially reduced depth from drain level to the barrier that corrects for radial flow convergence losses in subsurface drain design. Several equations such as Hooghoudt (Luthin, 1978), Van Beers (ILRI, 1973), Moody (USBR, 1978) and Smedema and Rycroft (1983) formulae are available to calculate the equivalent depth. Moroojo and Willardson (1995) compared various equations of equivalent depth calculation and concluded that Moody (USBR, 1978) and Van Beers (ILRI, 1973) equations result in more conservative drain spacing. Therefore, Van Beer (ILRI, 1973) equation was used in this study, which is

$$d_e = \frac{D_s}{1+\left(\frac{8D}{\pi S}\right)\left(\frac{8D_s}{\pi^3 r}\right)} \qquad 2$$

where, r is radius of drain pipe, m, D is drain depth, m and D_s is thickness of the aquifer below drain level.

Comparing the pipe capacities calculated on uniform and nonuniform approaches shows that the allowable pipe capacity calculated on the basis of uniform flow is 1.73 times higher than that of nonuniform flow approach. International Land Reclamation Institute (ILRI) recommends that the maximum design discharge capacity be limited to $0.75Q_{non}$ (where, Q_{non} is pipe capacity under nonuniform flow). This allows for possible reduction in the net capacity of pipe due to deposition of silt.

Depending upon the view point taken, the uniform flow approach is considered to provide a safety allowance of 73% when compared to nonuniform flow approach. This safety allowance accommodates slight differences in roughness of pipe and accumulation of sediment. Moreover, it provides additional capacity for lateral drain to receive more water. Therefore, uniform flow approach was used to calculate the discharge carrying capacity of lateral and collector without providing additional allowance for reduction in capacity as uniform flow equation implicitly includes these allowances. Discharge carrying capacity of a pipe can be calculated using Manning's equation, which is

$$Q = qSL = \frac{0.312}{n} d^{2.667} i^{0.5} \qquad 3$$

in which, Q is pipe capacity, m^3/s; n Manning roughness coefficient for pipe, d inside diameter of pipe, m; i hydraulic gradient, m/m and L is length of a drainline, m.

Formulation of Optimization Problem

An optimization problem consists of an objective function, a set of independent variables and a set of constraints. The objective function considered in this study was to minimize the total cost of a drainage system, which is

$$Minimize\ C_T = C_1 + C_2 + C_3 \qquad 4$$

where C_T, C_1, C_2 and C_3 denote for the total cost, material cost and costs of installation and maintenance, respectively.

For a pipe drainage system with gravity outlet, the total cost of the system was considered as the sum of material, installation and maintenance costs. Material cost includes costs of pipe, gravel envelop and manholes, etc. As unit cost of a pipe is nonlinear function of its size/diameter, a power function of the following form was fitted to the cost data of Mardan SCARP.

$$\alpha_p = 0.2855 d^{1.7184} \qquad 5$$

where α_p is unit cost of pipe, Rs./m and d is pipe diameter, cm. The cost of pipe (C_p) was estimated by multiplying the unit cost (Eqn. 5) with the pipe length.

A filter is required around the drain pipe to prevent/minimize inflow of finer soil material. In Pakistan, a minimum of 10 cm thick gravel envelop is recommended around the drain pipe. The cost of gravel (C_g) was estimated from the unit cost (α_g) times the volume of gravel required, which is

$$C_g = 1.25\alpha_g\left[0.215d^2 + 0.4066d + 0.04133\right]L \qquad 6$$

Manholes are installed at all major junctions between lateral and collector for the purpose of flushing, changing direction, water measurement and changing the size of collector. Assuming laterals join a collector from both sides, the cost of manholes (C_{man}) was determined by the number of manholes required times the cost of one manhole (α_{man}), which is

$$C_{man} = \alpha_{man}\left[\frac{L_f W_f}{2S_l L_l}\right] \qquad 7$$

where L_f and W_f are length and width of drainage area, respectively, m; S_l spacing of lateral drains, m and L_l is length of a lateral drainline, m. The cost of material was taken as the sum of costs for pipes (lateral and collector), gravel and manholes.

Drain pipes are installed by trenchers and/or trenchless machinery. Trenchers dig a trench of width larger than pipe diameter to accommodate the pipe and gravel envelope, then lay drain pipe at the bottom of a trench. Backfilling is done by bulldozers, motor grader or one special type of machinery which moves soil with an auger mechanism. To the authors' knowledge, installation cost as a function of drain depth and diameter is not available in Pakistan. Therefore, installation cost data was obtained from Fitz et al (1980) who used it in evaluating the economic feasibility of installing a subsurface tile drainage system in Panoche Water District San Joaqin valley, California. A nonlinear function of the following form was fitted to the cost data with conversion rate in 1984 (13 Rs./US$).

$$\alpha_i = 49.06 d^{0.9645} D^{1.9811} \qquad 8$$

where α_i is the unit cost of installation, Rs./m. The installation cost of a pipe was obtained from its unit cost of installation times its length. Thus, the total cost of installation (C_2) was taken as the sum of installation costs for lateral and collector, which is

(Equation No.9)

in which d and D, respectively, are diameter and drain depth, where the subscripts *l* and c stand for lateral and collector.

The cost of maintaining the drainage system depends upon the quality of installation and performing routine inspection and preventive maintenance. Subsurface drainage system is susceptible to clogging from plants and plant roots, silt, organic growth and mineral deposition. Maintenance cost is usually taken as some fixed percentage of the total cost. In mathematical programming, constant value does not affect the final solution; maintenance cost therefore was not included in the total cost of the drainage system. Thus, total cost was calculated as the sum of material (C_1) and installation costs (C_2), which after rearranging is

(Equation No.10)

To restrict the design variables to feasible values, some constraints have to be satisfied. Drain depth, diameter and spacing were constrained in this study. For most of the crops, desirable depth to water table to provide sufficient aeration in root zone is considered to be 0.91 to 1.22 m (HARZA/NESPAK, 1984). Drains have to be installed at a depth which will maintain the desirable watertable. Watertable depth used in Mardan SCARP, Fourth Drainage Project, East Khairpur and Khushab SCARP were 1.07 m, 1.22 m, 1.04 m and 1.22 m, respectively. For Mardan SCARP, minimum depth was 1.167 m. The maximum drain depth depends upon the ability of the machine to dig a trench to impervious layer and the outlet conditions. Most of the machines can lay pipe up to 3.66 m. Since depth to impervious layer was 6.09 m and gravity outlet was available in Mardan SCARP, maximum drain depth was constrained by the machine ability. Therefore, constraints on drain depth can be written as:

$$1.167 \le D_l \le 3.5 \quad \textit{and} \quad D_c \ge D_l + 0.10 \qquad 11$$

Pipe should be of sufficient size to carry design discharge at available grade. As recommended by SCS, USBR, OMF, uniform flow equation without providing additional safety factor was used for lateral and collector design. Six pipe sizes (9.20 cm, 15.00 cm, 18.80 cm, 25.00 cm, 30.00 cm and 38.00 cm) were being manufactured at that time in Pakistan. As available in discrete sizes, thus the pipe size was subjected to the following constraints.

(Equation No. 12)

At a given drain depth, pipe drains should be spaced such that they maintain watertable below or at the specified design depth. Several steady state and non-steady state equations are available that relate drain spacing, drainage coefficient, hydraulic conductivity and drain depth. Further, drain spacing is also affected by the field geometry, existing roads, canals, railway lines etc. Even if hydraulics principles allow wider drain spacing, maximum drain spacing cannot be more than the field dimensions. In order to avoid optimization

$$C_2 = \left(49.06 d_l^{0.9645} D_l^{1.9811}\right) L_l + \left(49.06 d_c^{0.9645} D_c^{1.9811}\right) L_c \qquad 9$$

$$C_T = 1.25\alpha_g \left[0.215\left(L_l d_l^2 + L_l d_c^2\right) + 0.4066\left(L_l d_l + L_c d_c\right) + 0.04133\left(L_l + L_c\right)\right]$$
$$+0.2855\left(L_l d_l^{1.7184} + L_c d_c^{1.7184}\right) + \alpha_{man}\left(\frac{L_f W_f}{2 S_l L_l}\right) + 49.06\left(d_l^{0.9645} D_l^{1.9811} L_l + d_c^{0.9645} D_c^{1.9811} L_c\right) \qquad 10$$

$$0.092 \le \left[\frac{nqS_l L_l}{0.312 i^{0.50}}\right]^{0.37495} \le 0.38 \quad \textit{and} \quad 0.092 \le \left[\frac{2nqL_l L_c}{0.312 i^{0.50}}\right]^{0.37495} \le 0.38 \qquad 12$$

procedure to select zero spacing, minimum spacing should be greater than zero. Using Hooghoudt equation, the constraint on the drain spacing is given below:

$$0 \le \left[\frac{8Kd_e h + 4Kh^2}{q}\right]^{0.50} \le L_f, W_f \qquad 13$$

Since, the number of laterals, collectors and manholes are integer variables, integer constraints are

$$N_l, N_c, N_{man} > 0, \ integer \qquad 14$$

Application to a Case Study

Data on hydraulic parameters such as drainage coefficient, hydraulic gradient, water table depth, depth to impervious layer, Manning's roughness coefficient and cost coefficients were taken from the Mardan SCARP Project. Table-1 shows the input data used in optimization. The data were used as input to the optimization model and output was obtained in the form of total cost for various combinations of design variables within the feasible range for an assumed drainage area of 100 ha. The results are discussed in the following paragraphs.

RESULTS AND DISCUSSION

For the input data of Table-1 and average K = 1.0 m/d, Table-2 shows the optimal and near-optimal design variables obtained from the optimization procedure. The first row in Table-2 shows the optimal design (i.e., the one with the minimum cost). The other rows represent the so-called nearly-optimal designs (i.e., the designs with cost more than the minimum cost by a maximum of 2.5%).

The optimal values for lateral depth (D_l), spacing (S_l), diameter (d_l) and length (L_l) were found to be 1.60 m, 66.7 m, 9.20 cm and 250 m, respectively. Collector diameter (d_c) and length (L_c) respectively were 25.0 cm and 1000 m with a minimum cost of Rs.28152/ha. The optimal values of L_l and S_l resulted in a total of 60 laterals (N_l) and 2 collectors (N_c) for an area of 100 ha. As expected the laterals were of the smallest size i.e., 9.20 cm to keep the total cost minimum. But the collectors composed of large size pipe of 25.0 cm to carry the design discharge of 0.003 m/d from the area at available slope of 0.002 m/m.

The cost/ha predicted by the minimum cost design at 1.51m depth was Rs.28736/ha for 9.20 cm lateral diameter against an actual cost/ha for Mardan SCARP at a depth of 1.52 m of Rs.19760/ha (HARZA/NESPAK, 1984). The differences in the actual and model-predicted cost/ha can be due to the use of the approximate installation cost in relation to depth and diameter which was not available for use.

The drain spacing used by HARZA/NESPAK (1984) for Mardan SCARP was 56, 70, 83, 98 and 112 m at drain depths of 1.50, 1.75, 2.0, 2.25 and 2.75m, respectively for 9.20 cm diameter lateral. The drain spacing predicted by the optimal design procedure at these depths was found to be 59, 77, 100 and 125 m, respectively which are very close to the actual values.

As depends upon drain depth, maximum permissible lateral length varied with lateral spacing. For Manning's rougness n=0.014 and q=0.003 m/d, lateral length was 1220, 798, 533, 400 and 320m against lateral

Table 1. Input data

Parameter	Value
Drainage coefficient, m/d	0.00305
Hydraulic gradient, m/m	0.002
Watertable height, m	1.067
Depth to barrier, m	6.09
Unit cost of manhole, Rs.	2000
Unit cost of gravel, Rs./m^3	170
Manning's roughness coefficient, n	0.004
*Unit cost of pipe, α_p , Rs./m	α_p = 0.2855$d^{1.7184}$, d = pipe diameter, cm
*Unit cost of installation, α_i, Rs./m	α_i = 49.06 $d^{0.9645}$ $D^{1.9811}$, d= pipe diameter, cm & D=Drain depth, m

* Based on 1984 costs

Table 2. Optimal and near-optimal design parameters

D_l, m	S_l, m	d_l, cm	d_c, cm	L_l, m	L_c, m	N_l	N_c	Total Cost, Rs./ha	Difference from minimum cost, %
1.60	66.7	9.2	25	250	1000	60	2	28152	0.00
1.41	50	9.2	38	500	1000	40	1	28321	0.59
1.67	71.4	9.2	25	250	1000	56	2	28337	0.65
1.55	62.5	9.2	25	250	1000	64	2	28360	0.73
1.74	76.9	9.2	25	250	1000	52	2	28374	0.78
1.61	66.7	9.2	25	250	1000	60	2	28411	0.91
1.68	71.4	9.2	25	250	1000	56	2	28591	1.53
1.75	76.9	9.2	25	250	1000	52	2	28622	1.64
1.56	62.5	9.2	25	250	1000	64	2	28626	1.65
1.62	66.7	9.2	25	250	1000	60	2	28671	1.81
1.71	76.9	15.0	38	500	1000	26	1	28714	1.96
1.51	58.8	9.2	25	250	1000	68	2	28736	2.03
1.69	71.4	9.2	25	250	1000	56	2	28846	2.41
1.76	76.9	9.2	25	250	1000	52	2	28871	2.49

spacing of 30, 60, 90, 120 and 150m, respectively (HARZA/NESPAK, 1984). At a depth of 1.52 m, the lateral length in Mardan SCARP used by HARZA/NESPAK (1984) was 169m/ha. In the optimal design, the lateral length at a depth of 1.51m was found to be 250 m resulting in 170m/ha for an area of 100 ha with lateral spacing of 66.7m. Optimal lateral length per hectare was found to be very close to that of Mardan SCARP that indicates the accuracy of the optimal design procedure.

The optimization procedure was also used to identify the nearly-optimal designs. As can be observed from Table-2, the difference in the cost of various designs is not significantly different from the minimum cost, the designs are equally-good as that of the minimum cost design which shows the flexibility of the procedure to find out number of equally feasible designs.

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