Effect of clay-concrete lining on canal seepage towards the drainage region - an analysis using Finite-Element method

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Abstract. For proper design of a drainage system that utilizes lined canals, knowledge of the seepage into a soil substrate/drainage region is necessary so that the drainage blanket and /or filter type and thickness, and the size of collector pipes can all be designed. The work presented in this paper is based on the problem of steady-state seepage from a hypothetical irrigation canal into the substrate/drainage region towards asymmetrical trapezoidal concrete-lined canal. The problem is solved using a finite element based software program to determine the flow volume into the drainage region.

Typical values of soil permeability coefficients of single and two-layer subsoil from literature are used along with experimental results of a laboratory study done for the design seepage coefficient of clay-cement concrete as lining material. The water flow effect of canal seepage discharge analyzed shows that the effectiveness of canal lining in reducing seepage is less when drainage distance is large. This study may contribute towards a better understanding on design of hydraulic conductivity under hydraulic structures. It will systematically enumerate the many, often straightforward factors that determine coefficient of permeability for compliance purposes. This could also involve a re-estimation of the values of the permeability coefficient and the factors on which the coefficient depends.

Keywords. Drainage system, canals, seepage, water table, Finite Element method, canal linings

Introduction

In most irrigation projects, it is critical to maintain not only a constant flow of water, but also a constant velocity. The design of a canal or ditch is a combination of its bed width and depth, together with the resulting mean velocity. Water is conveyed to the land to be irrigated by canals, with the attendant problem of water loss through seepage. Canal concrete liners normally decrease the conveyance losses or seepage through the bottoms and sides; prevent weed growth and retard moss accumulation. They also decrease erosion from high velocities; reduce maintenance costs; and increase the capacity of the canal to convey water. However, they do not eliminate seepage losses [1]. For the correct exploitation and management of groundwater, surface reservoirs and canals, it is necessary to estimate the seepage losses from canals.

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A number of studies have assessed canal seepage losses using flow nets [2], analytical solutions [3-5] and numerical methods using the finite-element method, finite-difference method, and boundary-element method [6-8].The problems considered mainly involved idealized conditions and only one or two layers of a largely homogeneous and isotropic medium as substrate/drainage region.

As mentioned previously, the concrete lining of a canal does not reduce seepage loss to zero, because of the development of fractures in the lining, and the lining material used is not completely impervious [1]. Among the aforementioned investigators, only [9] considered the problem of seepage from a lined canal founded on a stratified medium, toward fully penetrating drainages (case study).

1. Problem statement

Generally, fluid flow is investigated within the limits of Darcy`s law, and capillary forces and surface tension are omitted for simplicity. In addition, the fluid is assumed to be incompressible and of constant density and viscosity. The problem of seepage from a lined canal toward asymmetrically placed drainages has been considered for solution. In this problem, the effect of canal lining on the canal seepage discharge has been investigated. The finite-element method (FEM) has been chosen to solve the governing partial differential equation on the steady-state seepage flow under lined canals, written as equation (1) for the saturated unconfined steady-state flow seepage in anisotropic medium.

$$K_x \delta^2 h / \delta x^2 + K_Y \delta^2 h / \delta y^2 = 0 \qquad (1)$$

Where, x and y = horizontal and vertical coordinates respectively, K_x and K_y = hydraulic conductivities in the x and y directions; and h= h(x,y) is the piezometric head above the datum. Because along the groundwater free surface, the atmospheric pressure is considered to be zero, the head of the points laid on this boundary is equal to their coordinate.

1.1. Finite Element Method

To solve the partial differential equation governing the seepage problem using FEM, first the domain is discretized to elements and nodes and then the approximation function is systematically derived over the given domain. Then, the Gaussian elimination solver type which approximates the governing equation, is derived over each element. Finally, the equations over all elements of the collection are converted by the continuity of primary variables. The boundary conditions of the problem are imposed and the connection set of equations is solved. The connection set of equations are of the general form as follows:

$$[A][H]= [Q] \qquad (2)$$

Where [A] = [nxn] elemental property matrix (generally referred to as the stiffness matrix in structural problems) and the permeability matrix in seepage problems (n is the number of nodes); [Q] = load vector in structural problems and is composed of known boundaries, source, and sink terms in seepage problems; and [H] = vector of known and unknown heads.

1.1.1. Computation of canal seepage discharge

Canal seepage discharge is the normal flux passing through the canal bed and canal sides. The normal flux across a node and the hydraulic heads at the nodes directly connecting to the node under consideration are interrelated by Eq. (3). The equation for a specified node (say, node i) can be written as:

$$A_{ij}h = q_i \tag{3}$$

Where j= nodes directly connecting to node i, including node i itself [10].

In this paper, five common field cases for fluid flow characteristics of anti-seepage materials are analyzed based on design permeability coefficient obtained from the literature. In all cases, the seepage analysis was done using the finite element seepage module of the computer program Phase2 version 7.0 of Rocscience [11]. The analysis only considered the fluid flow behavior of anti-seepage materials, i.e. deformation of the canal is ignored and all displacement degrees of freedom are prescribed to zero. The roughly trapezoidal shaped canal was taken from literature [12]; it consists of a channel 154 km long built in 1908 using horses and mules. For this analysis, the channel shape was modified to be representative of a typical hypothetical trapezoidal canal of dimensions: top width (B) of 17.8 m, and water depth (H_w) (i.e the trapezoidal height of the canal) of 2.5 m, having a side slope angle, α of 45°, and bottom width (W_b) of 13.3 m. The total head in the canal was taken to be 52.5 m in order to simulate full ponding at steady state seepage, as shown in Figure 1.

2. Case studies of hypothetical irrigation canals

2.1. Unlined canal

Case 1. Single-Layer Subsoil Unlined Irrigation canal: The model condition beneath the unlined canal is a permeable layer. The hydraulic conductivity of the underlying single-layer subsoil silty sand was take to be 1.0×10^{-5} m/s. The critical water head, h_1 and differential heads of 10.75 m, 19.65 m and 28.55 m were used in the analysis. It was assumed that all the materials are isotropic.

2.2. Concrete irrigation canals

Case 2. Hypothetical canal: 50 mm thick clay-cement concrete founded on single-layer silty sand subsoil.

Case 3. Hypothetical canal: 75 mm thick clay-cement concrete founded on single-layer silty sand subsoil and two-layer subsoil fine sand underlying silty sand.

Case 4. Hypothetical canal: 100 mm thick clay-cement concrete founded on single-layer silty sand Subsoil and two-layer subsoil fine sand underlying silty sand.

For the concrete canals, the mix of clay, cement and aggregates used, was designed to correspond to the requirement of anti-seepage material. The mix should be workable and typically of composition: water/ (cement + clay) = 0.85 and clay/cement =2/3 or 40% clay content. Its compressive strength is usually greater than 6 MPa while its water permeability ranges from 5×10^{-10} to 1×10^{-10} m/s [13]. Figure 1 indicates how the canal is installed in the canal for the control of seepage. In literature, large dams with slightly sloping core, were also built in Macedonia, Turiya dam [14].

In this paper, Case 1 represents unlined canals while the others, Case 2 to 4 are concrete lined canals. Table 1 gives the permeability coefficients applied in analysis of the cases.

3. Seepage analysis by Finite Element method

In the FEM of analysis, the foundation and different lining thicknesses of hypothetical irrigation canals are modeled using the computer software [11]. Typical values of soil permeability coefficients of single-layer subsoil from literature were used along with the experimental results from a laboratory study done for clay-cement concrete use as a lining material. The model set up extends below the thickness of lined canal and is fixed into an impervious layer. Material permeability is required in the finite element analysis in order to solve the seepage problem. Permeability, K_2/K_1 is a factor which specifies the relative permeability in the direction orthogonal to the K_1 direction. Note that the K_1 permeability is the “primary” permeability defined by the saturated permeability K_s; while K_1 is the angle which specifies the direction of the K_1 permeability and is given relative to the positive x (horizontal) direction. In the analysis, it is considered that, K_2/K_1 =1(unity) and K_1 angle = 0, i.e. the permeability in the horizontal direction = K_s (in saturated zone), and the permeability in the vertical direction = 1x K_s (in saturated zone). The set boundary conditions are the total head (H), and zero pressure (p=0) and hydraulic parameters are also given in the Table 1. An example of details of the Finite Element analysis set up is shown in the Figure 1.

3.1. Presentation of results

The canal seepage was computed for different values of physical and hydraulic parameters. Canal seepage discharge was converted to dimensionless form by dividing, h_1 and the hydraulic conductivity of the medium. All the physical parameters have been converted to dimensionless form by dividing by h_1. A summary of the results is presented along with Figures 1 to 3 giving the output results for each of the case studies. All cases can be further sub-categorized into two conditions (of lined and unlined canal) depending on the physical and hydraulic parameters employed.

Table 1. Hydraulic permeability properties of Case 1 to 4

Materials	Case 1	Case 2, 3, 4 Permeability(m/s)		
	Silty sand [15].	**Silty Sand [15].**	**50 ,75, 100 mm thick clay-cement concrete [13].**	**Fine Sand [15].**
Coefficient of permeability (m/s)	$1x10^{-5}$	$1x10^{-5}$	$6.90x10^{-10}$ (50 mm thick) $5.00x10^{-10}$ (75 mm thick) $3.47x10^{-10}$ (100 mm thick)	$1x10^{-2}$

Drainage distances L/h_1 are taken from top of trapezoidal height water head, H_w= 2.5 m (i.e. the total head in the canal is 52.5 m) towards horizontal direction as shown Figure 1; k_L/k for non-lined canal (being earth liner) is such that k_L=k. The analysis is done for varied thicknesses of lining i.e 50 mm (k_L/k= 0.000069), 75 mm (k_L/k = 0.00005) and 100 mm (k_L/k = 0.0000347). In order to examine the effect of the canal lining (with a thickness of d_L and a permeability of k_L) on canal seepage discharge, the values of q/kh_1 have been plotted (as shown in Fig.2) against the values of k_L/k for different drainage distances as shown in Figure 1.

The values of q_L/q_U have been plotted against the values of d_L/h_1 for 50 mm lining (d_L/h_1= 0.0047), 75 mm lining (d_L/h_1= 0.00698) and for 100 mm lining (d_L/h_1= 0.0093) for different drainage distances shown in Figure 1, where q_L= value of canal discharge for lined canal, while q_U=canal discharge when everything is the same but there is no lining (NL) the result shown in Figure 3. The other two conditions follow the same procedure as condition 1 but h_1 changes to 19.65 m and 28.55 m.

In the case of single layer subsoil condition, the total discharge velocity (m/s) is in the range of $5.55x10^{-07}$ to $1.11x10^{-05}$ m/s (see Fig.1a). Furthermore the discharge section can be selected for the different drainage distances to display the steady-state, volumetric flow rate of water, normal to the plane of the discharge section. At h_1=10.75 m and drainage distances shown in Figure 1 L_0= 0 m, L_1= 7.1 m, L_2= 29.1 m, L_3= 51.1 m and L_4= 88.6 m from the top of the water, the flow rates were calculated as $1.38x10^{-05}$, $5.9661x10^{-06}$, $3.7228x10^{-06}$ and $6.9429x10^{-06}$ m^3/s respectively as shown in the Figure 1b.

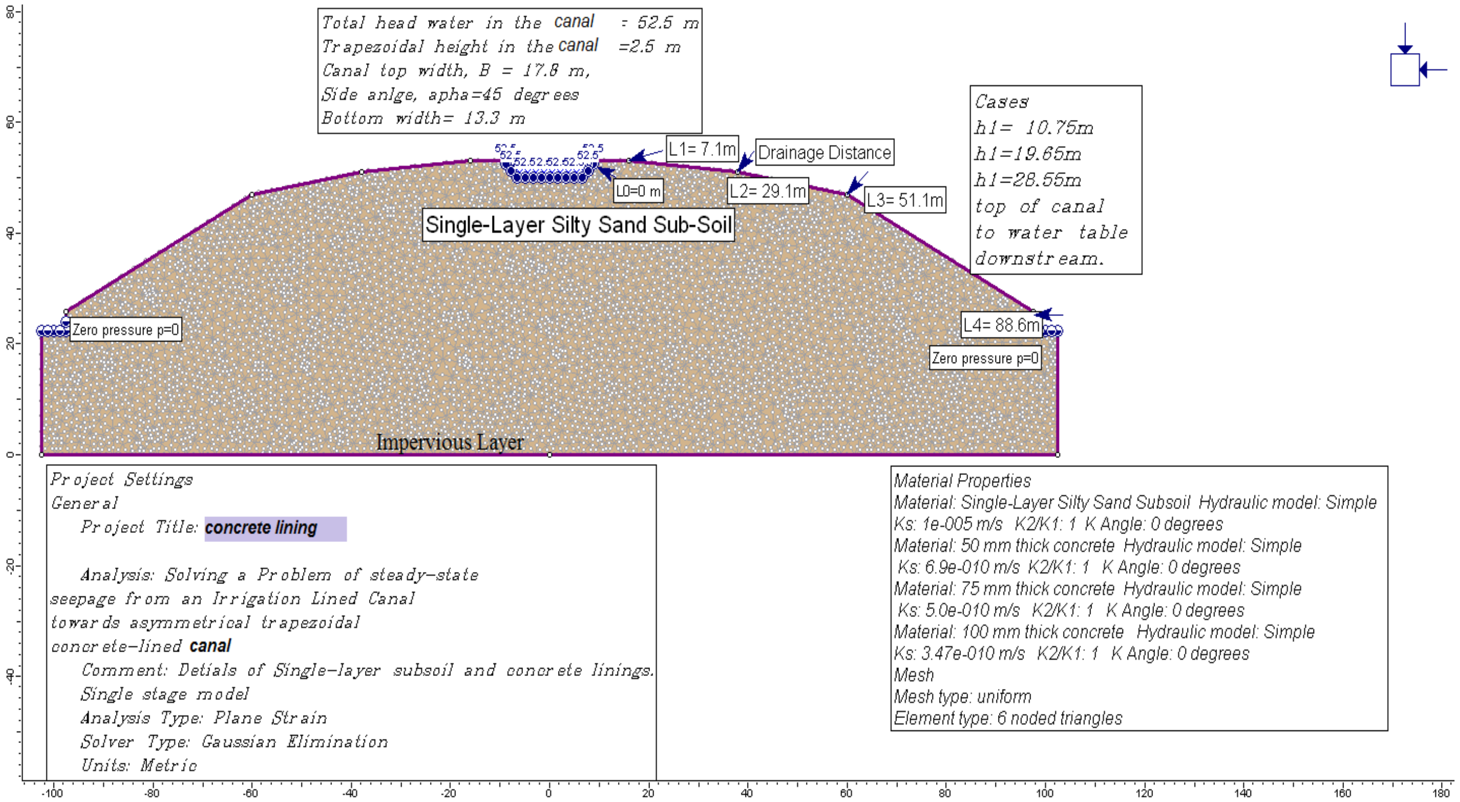
Similar calculations were done for case studies at h_1=10.75, 19.65 m and h_1= 28.55 m, with and without a lining of 50 mm, 75 mm and 100 mm thick concrete. For instance, the 100 mm thick concrete lining at 10.75 m differential head elevation gave values of discharge flow rates of 1.39910^{-05},$6.0695x10^{-06}$, $3.4714x10^{-06}$, $1.1307x10^{-05}$ m^3/s at distances L_1= 7.1 m, L_2= 29.1 m, L_3= 51.1 m and L_4= 88.6 m respectively. The water flow effect of canal seepage discharge analyzed shows that the effectiveness of canal lining in reducing seepage is less when drainage distance is large.

3.1.1. Effect of lining permeability on canal seepage

The effect of lining permeability on canal seepage (see Table 2) and effect of lining thickness (see Table 3) on canal seepage were analyzed and compared against the unlined canal. In order to examine the effect of the canal lining on canal seepage discharge, the values of q/kh_1 have been plotted against the values of k_L/k for different drainage distances as shown on Figure 2.

3.1.2. Effect of lining thickness on canal seepage

Table 2 and corresponding Figure 2 indicate that when the thickness of lining is increased, the ratio of k_L/k decreases due to the nature of the anti-seepage barrier so that the greater the length, the longer the water paths, as follows: at drainage distance L_1= 7.1 m (Fig. 1) 75 mm thick concrete lining produces the lowest ratio of q/kh_1 which is 0.1169, followed by the use of 50 mm lining (q/kh_1 = 0.1263), NL (q/kh_1 = 0.1288), and lastly 100 mm lining (q/kh_1 = 0.1301). At L_2 i.e. 29.1 m (Fig.1), the same trend was experienced that 75 mm gave lowest value (q/kh_1 = 0.0474), followed by NL (q/kh_1 = 0.0555), 100 mm (q/kh_1 = 0.0565), and 50 mm lining (q/kh_1 = 0.0569). For the further drainage distance L_3 i.e 51.1 m (Fig.1) the trend continues in favour of 75 mm (q/kh_1 = 0.0282), followed by 100 mm (q/kh_1 = 0.0323), 50 mm lining (q/kh_1 = 0.0334), with the highest value being given NL (q/kh_1 = 0.0346). Down further to the tail head water L_4 i.e. at 88.6 m, the water flow effect changed. At L_4 the lowest value of the dimensionless ratio, i.e q/kh_1 was 0.0646 for NL, followed by 75 mm lining (0.0949), 100 mm (0.1052) and finally 50 mm lining (0.1504). In general, the 75 mm thick concrete was effective in reducing seepage up to drainage distance of approximately 50 m, but beyond this distance, it was not as effective as the NL. This is because as more water was discharged along the drainage distances, the water flow effect diminished.



Total head water in the canal : 52.5 m
Trapezoidal height in the canal =2.5 m
Canal top width, B = 17.8 m,
Side anlge, apha=45 degrees
Bottom width= 13.3 m

Cases
h1= 10.75m
h1=19.65m
h1=28.55m
top of canal
to water table
downstream.

Project Settings
General
Project Title: concrete lining

Analysis: Solving a Problem of steady-state seepage from an Irrigation Lined Canal towards asymmetrical trapezoidal concrete-lined canal
Comment: Detials of Single-layer subsoil and concrete linings.
Single stage model
Analysis Type: Plane Strain
Solver Type: Gaussian Elimination
Units: Metric

Material Properties
Material: Single-Layer Silty Sand Subsoil Hydraulic model: Simple
Ks: 1e-005 m/s K2/K1: 1 K Angle: 0 degrees
Material: 50 mm thick concrete Hydraulic model: Simple
Ks: 6.9e-010 m/s K2/K1: 1 K Angle: 0 degrees
Material: 75 mm thick concrete Hydraulic model: Simple
Ks: 5.0e-010 m/s K2/K1: 1 K Angle: 0 degrees
Material: 100 mm thick concrete Hydraulic model: Simple
Ks: 3.47e-010 m/s K2/K1: 1 K Angle: 0 degrees
Mesh
Mesh type: uniform
Element type: 6 noded triangles

Figure 1. Details of case single-layer silty sand subsoil (case 1)

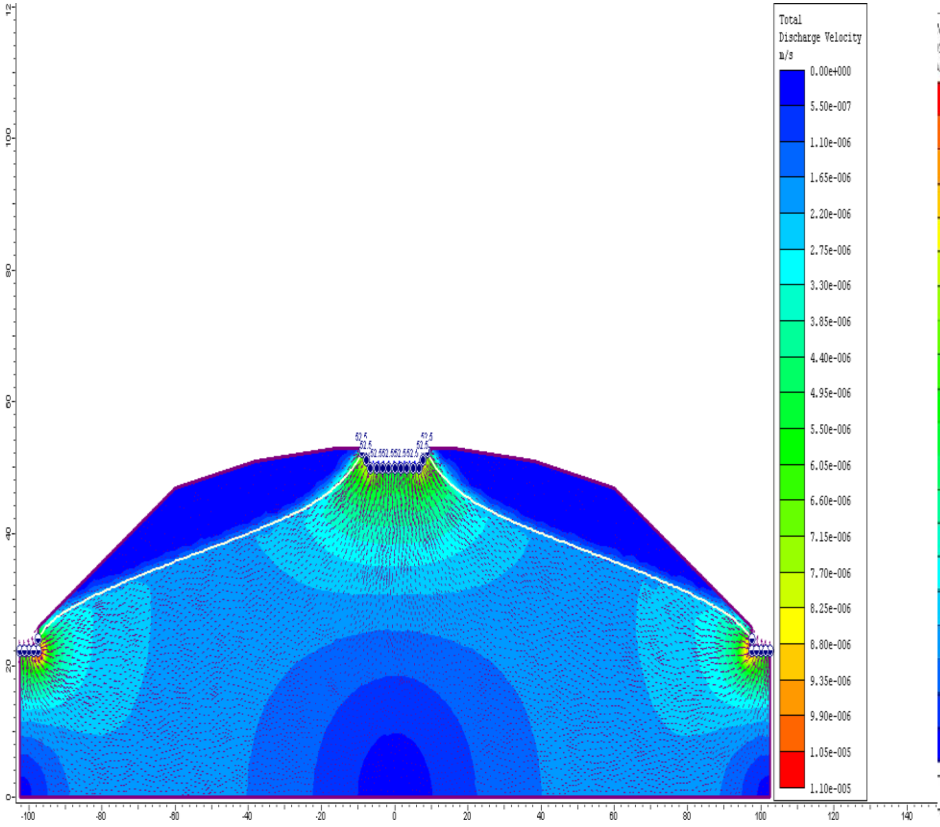


Figure 1a. Display of total discharge velocity (v_t) and flow lines (case 1)

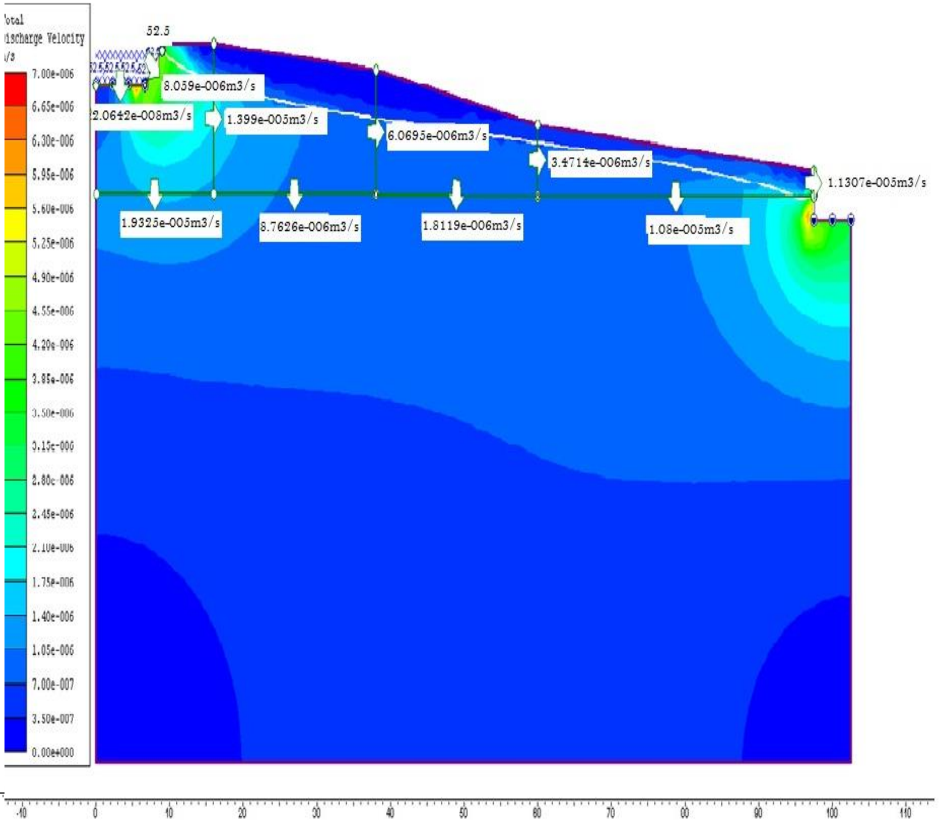


Figure 1b. Display of discharge section drainage distances across for case no lining and at h_1=10.75 m

Table 2. Effect of lining permeability on canal seepage

Head to tail water table=h_1	**on water table**	**Discharge section taken to simulate steady-state, volumetric flow of water, normal to drainage distances.**				
			Non-lined (NL)	**50 mm**	**75 mm**	**100 mm**
	Ratio	**K_L/k**	**1**	**0.000069**	**0.00005**	**0.0000347**
h_1=10.75 m	L_1/h_1=142/215	q/kh_1	0.1288	0.1263	0.1169	0.1301
	L_2/h_1=582/215	q/kh_1	0.0555	0.0569	0.0474	0.0565
	L_3/h_1=1022/215	q/kh_1	0.0346	0.0334	0.0282	0.0323
	L_4/h_1=1772/215	q/kh_1	0.0646	0.1504	0.0949	0.1052
h_1=19.65 m	L_1/h_1=142/215	q/kh_1	0.1776	0.1672	0.1719	0.1717
	L_2/h_1=582/215	q/kh_1	0.0983	0.0883	0.0912	0.0966
	L_3/h_1=1022/215	q/kh_1	0.0708	0.0658	0.0679	0.0694
	L_4/h_1=1772/215	q/kh_1	0.0708	0.0289	0.0311	0.0592
h_1=28.55 m	L_1/h_1=142/215	q/kh_1	0.1907	0.1885	0.1855	0.1821
	L_2/h_1=582/215	q/kh_1	0.1276	0.1331	0.1232	0.1196
	L_3/h_1=1022/215	q/kh_1	0.105	0.1016	0.0963	0.0907
	L_4/h_1=1772/215	q/kh_1	0.0947	0.0754	0.0187	0.0638

Table 3. Effect of lining thickness on canal seepage

Head to tail water table=h_1	**On water table**	**Discharge section taken to simulate steady-state, volumetric flow of water, normal to drainage distances**			
h_1=10.75 m	**Thickness(mm)** **Ratio**	**d_L** **d_L/h_1**	**50 mm** **0.0047**	**75 mm** **0.00698**	**100 mm** **0.0093**
h_1=10.75 m	L_1/h_1=142/215	q_L/q_U	0.9799	0.907	1.01
	L_2/h_1=582/215	q_L/q_U	1.0241	0.8548	1.0173
	L_3/h_1=1022/215	q_L/q_U	0.9633	0.8134	0.9325
	L_4/h_1=1772/215	q_L/q_U	2.3284	1.4687	1.6286
h_1=19.65 m	**Ratio**	**d_L/h_1**	**0.0025**	**0.0038**	**0.0051**
h_1=19.65 m	L_1/h_1=142/215	q_L/q_U	1.9913	1.9592	1.9233
	L_2/h_1=582/215	q_L/q_U	1.043	0.9654	0.9374
	L_3/h_1=1022/215	q_L/q_U	0.9676	0.9169	0.8652
	L_4/h_1=1772/215	q_L/q_U	0.7969	0.1978	0.6747
h_1=28.55 m	**Ratio**	**d_L/h_1**	**0.0018**	**0.0026**	**0.0035**
h_1=28.55 m	L_1/h_1=142/215	q_L/q_U	1.9913	1.9592	1.9233
	L_2/h_1=582/215	q_L/q_U	1.043	0.9654	0.9374
	L_3/h_1=1022/215	q_L/q_U	0.9676	0.9169	0.8652
	L_4/h_1=1772/215	q_L/q_U	0.7969	0.1978	0.6747

The effect of lining thickness on canal seepage can be determined by plotting the value of q_L/q_U against the values of d_L/h_1 for different drainage as in Table 3 and Figure 3 where q_L= value of canal discharge for lined canal, q_u=canal discharge when all factors are the same but with no lining.

For h_1=19.65 m (see Table 2). The lowest discharge ratio was experienced at the drainage distance L_1 by a 50 mm lining giving (q/kh_1= 0.1672), followed by 100 mm lining (q/kh_1= 0.1717), 75 mm (q/kh_1= 0.1719), while the highest value was given by NL (q/kh_1= 0.1776).

From the results, it was found that the lowest value of seepage was given by the 100 mm thick concrete lining applied all the way into the drainage region, except for the tail at the end, where 75 mm thick lining gave the lowest seepage. In the whole analysis, it is noticed that the values of the ratio q/kh_1 did not vary by a large margin for h_1=28.55 m, i.e 100 mm lining gave q/kh_1=0.1821 compared to 75 mm lining which gave q/kh_1=0.1855 at L_1. But a big margin except at the end i.e. L_4 with 75 mm lining giving q/kh_1=0.0187 and 100 mm giving q/kh_1=0.0638. This indicates that there is no signficant difference in performance between 100 and 75 mm lining, of course the lower thickness has an effect on the economy especially when providing several kilometers of concrete canal lining constructed to upgrade the earlier earth canal.

The results also indicate that with a decrease in the permeability of the canal lining, the canal seepage decreases. However, the decrease in canal seepage is relatively more when the ratio of k_L/k is in the region of between 50 mm and 75 mm for h_1=10.75 m and h_1=28.55 m, the reductions being 36.9% and 75.2% respectively (see Table 2).

3.2. Discussion of results

The foregone analysis done, indicates that, with a decrease in the permeability of the canal lining, the canal seepage decreases as shown in Figure 2 for drainage distance L_4 i.e. at 88.6 m. However, the decrease in canal seepage is relatively more when ratio of k_L/k lies in the range of $6.9\text{x}10^{-5}$ to $5.0\text{x}10^{-5}$.

The effect of lining thickness on canal seepage has been assessed for different values of drainage distances at h_1=10.75 m, 19.65 m and 28.55 m. Figure 3 shows that the initil decrease in canal seepage is very as the lining thickness increase up to 75 mm for a given drainage distance. However, with a further increase in lining thickness (beyond $d_L/h_1>0.00698$ value for 75 mm lining, as shown Table 3), the decrease in canal seepage is less significant. After wards, the seepage gently increases with increase in thickness of canal. Therefore, the ratio of lining permeability to soil permeability should range between $6.9\text{x}10^{-5}$ to $5.0\text{x}10^{-5}$ and the lining thickness should be kept less than $0.00698h_1$, which is equivalent to 10.75 times 0.00698 i.e. 75 mm thick concrete. It is possible to conclude from Table 3 and Figures 3, that there is no significant difference in results regardless of whether the canal is lined or not. It is clear from Figure 3 that at, drainage distance L_4 region the canal lining is not effective at all in reducing seepage, even with increase in thickness of the lining. A direct comparison is not of much value since the choice of canal type (concrete or earth canal) in the particular irrigation site is dependent on the subsoil type, particularly the quantity and type of clay present in the soil.

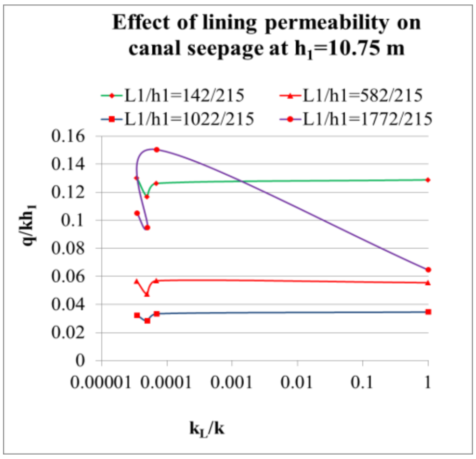


Figure 2. Effect of lining permeability on canal seepage

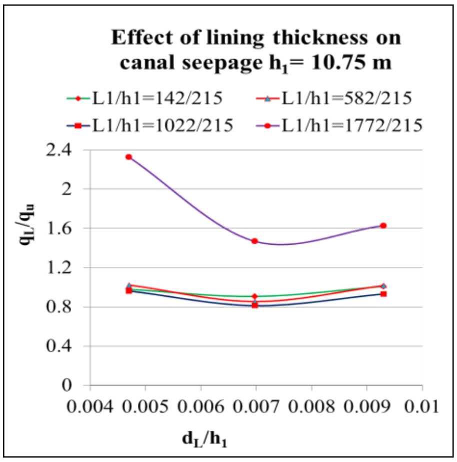


Figure 3. Effect of lining thickness on canal seepage

4. Conclusions

The foregone analysis illustrates the extent of the influence of lined canal seepage on the land drainage problem, which can be difficult to determine in most cases. Also, the effects of seepage are not always readily evident on site. The seepage water from canals that are on higher ground often disappears into pervious underground stratum and re-appears in a low-lying area at some distance from the canal. Thus, the land drainage problem exerts a marked influence on the justification for installation of canal lining to prevent seepage.

In the fluid flow problem from lined canal analysis, case studies of the effects of lining permeability and lining thickness on canal seepage were compared. With a decrease in permeability of the canal lining, the canal seepage also decreased. However, the decrease in canal seepage is more significant when the ratio of concrete lining permeability to subsoil permeability lies between $6.9\text{x}10^{-5}$ to $5.0\text{x}10^{-5}$. The decrease in canal seepage is not very significant with initial increase in the lining thickness. However, further increase in the lining thickness must be kept to less than $0.00698h_1$, which in this case was less than 75 mm thickness. In general, water flow effect of canal seepage discharge is less when drainage distance is large.

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