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Influence of Fractured Zone on Seepage From a Water Body

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ABSTRACT

Artificial recharge ponds/tanks offer ample scope for replenishing dwindling aquifers. In a multilayered aquifer system the recharging may be influenced by hydrogeological aspects such as geology of various layers, fractures/ discontinuities, inhomogeneity and anisotropy in the aquifer. With the existence of a confining layer having very low permeability, recharging of an underlying aquifer from a surface water body can not be successful. However, through discontinuities/ fractures in the confining layer water may percolate down. Influence of the dimension of a discontinuity in the confining layer on the seepage of water down to a semi-confined aquifer has already been studied earlier. In continuation to the previous study, the effect of positioning of a fractured zone with respect to the recharge-source in a multilayered aquifer is investigated presently. The behaviour of hydraulic potential/ discharge from the aquifer as the discontinuity (a fractured zone) is located at points away from the source is studied. Further, the influence of positioning of the fractured aquitard at different depths in the aquifer system on the flow domain is also investigated. Normalised heads/potentials in the central section, distribution of potential in the aquifer, change in discharges for various fractured zone positions etc. have been used for the purpose of analysis. Evidently, variations in the flow/discharge characteristics of the unconfined top aquifer is not significant. However, location of the opening/fractured zone in the confining layer influences the potential distribution as well as discharge from the bottom semi-confined aquifer. A gradual decrease in hydraulic potential evidenced by reduced discharge from the bottom aquifer is observed as the opening/fractured zone being placed farther from the recharging source. It is found that for a given location the extent of influence of the location of a fractured zone (opening) is high for smaller openings. As the opening becomes large, the influence of its position in the aquitard tends to minimal. Further, the fractional seepage to the bottom aquifer is found to be decreasing as the position of the fractured aquitard in the system is at larger depths. For a given position of the fractured aquitard, the maximum seepage to the bottom aquifer occurs when the fractured zone irrespective of its dimension is located centrally below the recharging source. Various cases have been studied with different openings at different locations and with different positions of the fractured aquitard. The hydraulic potential in the aquifer is found to be higher when the fractured aquitard is closer to the impermeable lower boundary, that is when the aquitard is at its lowest position with reference to the datum of the aquifer system. However, the fractional seepage occurring down to the bottom aquifer is found to be decreasing as the aquitard is placed nearer to the lower boundary. The various cases have been repeated for a range of combination of aquifer parameters so as to examine sensitivity with respect to different aquifer systems.

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1.0 INTRODUCTION

Phenomena like receding water tables and intrusion of saline water into coastal aquifers have been observed in many parts of the country due to various reasons. Collective measures need to be initiated in order to preserve the groundwater potential and to maintain equilibrium. Artificial recharge methods have been proposed and implemented in order to revamp the depleting groundwater resources, to prevent/ retard salt water intrusion and to store water underground where surface storage facilities are inadequate to meet seasonal demands. The important issues associated with artificial recharge are the nature of the rechargeable water source, the system of recharge to be used, the expected injection rates, the hydraulic response of the system to injection and the management of the injected water as part of the total water resources system.

An important means in artificial recharge practices is the usage of percolation tanks/ponds/small lakes. Various aspects demand attention in the planning, design and location of such artificial storage-recharge schemes, particularly in a complex aquifer system. Among those, geohydrological aspects deserve special attention as the hydrogeological set up of the aquifer system determines how an artificial recharge scheme can be effective/ successful. Besides, it is essential to examine the hydraulic response of an aquifer system to recharge.

Towards this end, studies need to be conducted in order to evaluate the flow behaviour in a multilayered aquifer system having a recharge source. The influence of position and dimension of a (continuous) aquitard in the system on the seepage from a water body has been reported already *(Jose and Seethapathi, 1996; 1997a)*. Studies were conducted to examine influence of a discontinuous aquitard on the recharge aspects; wherein the influence of dimension of the fractured zone (opening) on the seepage from a surface water body to a semi-confined aquifer has been examined *(Jose and Seethapathi , 1997b)*. Effect of anisotropy and system geometry on seepage as well as the distribution of seepage through lake beds had also been reported *(Mc Bride and Pfannkuch, 1975; Winter and Pfannkuch, 1984)*. It is a well known fact that numerical simulation methods have been in use for such surface water-groundwater interaction studies *(Winter 1976, Munter, 1981, Nield et al, 1994)*.

1.1 Objectives

The present study is in continuance with the earlier investigations made regarding the seepage from a surface water body in a multilayered aquifer system *(Jose and Seethapathi, 1998)*; wherein the influence of varying dimensions of a fractured-zone (opening) in the aquitard on the seepage from a source had been investigated.

The objective of the present study is to examine the influence of a fractured-zone in a confining aquitard on the seepage from a surface water body (the source). The issues covered under the purview of the present study include the influence of (i) the location (with respect to the source) of a fracture in the aquitard and (ii) the influence of position of the fractured aquitard at various depths in the aquifer system on the seepage from the source. In other words, the effect of location/ position of a fractured-zone within a multilayered aquifer system on the seepage from the surface water body is being investigated.

It may be noticed that groundwater flow in fractured systems may be modelled as equivalent continuum model, discrete fracture network model or dual porosity model (*Anderson and Woessner, 1991*). However, the attempt here is not to model flow in a fractured medium where dual porosity is dominant. Instead, the opening in the flow barrier of the present hypothetical set-up is to allow hydraulic connection between the aquifer above and below the barrier. Further, the opening is assumed to be filled with the porous aquifer material, which maintains continuity between the aquifers at the opening. Thus, the flow occuring through the opening is guided by the Darcy's law. Therefore, modelling such a system with a standard numerical groundwater flow model is deemed to be appropriate (*Seiler and Lindner, 1995*).

2.0 FORMULATION AND CONCEPTUALISATION

A hypothetical aquifer-aquitard system has been formulated with *no-flow* as well as *constant-head* boundaries on the lateral sides. A surface water source is placed in the centre of the system which may recharge the aquifers below. An aquitard with a fractured zone divides the aquifer system into a top unconfined aquifer and a bottom confined/ semi-confined aquifer. A schematic representation of the hypothetical aquifer system is shown in Figure-2.1.

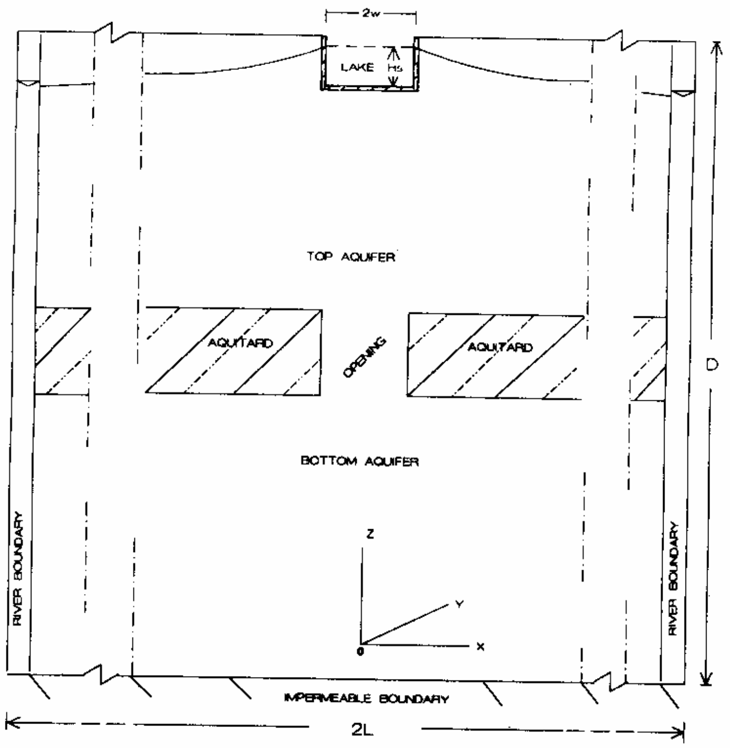


Fig. 2.1 Vertical section of the multilayered aquifer system with a fractured aquitard

The square-shaped water body (*the source*) of size *2w x 2w* is located at the centre of the plan area of an isotropic aquifer system having dimensions *2L x 2L*. The bottom of the aquifer system conforms to an impermeable bed at depth *D* from the surface.

The lateral boundaries have been located at sufficiently large distance (*L*) from the source. The sides and bottom of the lake are assumed to have a layer of sediments of low permeability. Difference between the head in the source and that in the sink (*Hb*), the head causing- flow (*dH*) is adequate to induce flow through the aquifer system. Appropriate parameter values have been assigned for the fractured aquitard so as it to act like a flow barrier between the top and bottom aquifers except at the opening. There is proviso to locate/ position the fractured zone of the aquitard any where in the system.

2.1 Discretisation

The total depth of the aquifer system to an impermeable bed (D) is 100m. The difference of heads in the water body and in the constant head boundaries (the head-causing-flow) is found to be sufficient for inducing flow to the aquifer. The dimensions of the water body vis-a-vis that of the aquifer system have been chosen appropriately. The choice of aquifer/ aquitard parameters such as hydraulic conductivity, storage coefficient etc. is well in conformity within the acceptable ranges.

To facilitate the finite difference application of the flow equations, the aquifer system is discretised into a large number of rectangular grids and many layers. Variable grid spacing is used to get detailed information from finer grids beneath and around the source. Uniform hydraulic conductivities are assumed for both the horizontal and vertical directions for any specific layer. Aquifer parameters, however, may vary from one layer to another.

Simulation of flow in the aquifer system has been contemplated for transient situation. The stress period, consisting of several time steps, of the simulation being kept sufficiently long so as to attain steady state situation. The water level in the water body (source) being maintained constant throughout the simulation. The distribution of hydraulic potentials in the medium and volumetric details have been obtained at the end of the stress period for further analysis.

3.0 METHODOLOGY

The finite difference ground water flow model MODFLOW *(McDonald and Harbough, 1984)* is employed to study the behaviour of flow/ distribution of potential in the system. The model is based on the mathematical representation of three dimensional unsteady groundwater flow through heterogeneous and anisotropic porous media:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

Where, K_{xx}, K_{yy}, K_{zz} are the hydraulic conductivities along the major axes, h is the potentiometric head, W is the volumetric flux per unit volume representing sources and/ or sinks, S_s is the specific storage of the aquifer and t is time.

The above equation together with specification of flow conditions at the boundaries of an aquifer system and specification of initial head conditions, constitutes a mathematical model of ground water flow. Since analytical solutions of the flow equation referred above are not feasible, numerical methods have been used in order to achieve approximate solutions.

4.0 ANALYSIS AND DISCUSSION

Simulation of flow has been carried out in aquifer systems having varying set of parameter values with (i) a number of locations of the discontinuity (fractured-zone) in the aquitard and (ii) with the fractured aquitard at different depths (positions) in the aquifer system. The simulation of flow/ potentials in the aquifer system and thereby the analysis are subjected to certain assumptions inherent in the formulation of the scheme. Therefore, the following premises holds good in general.

(i) the layers are continuous and parallel to the ground surface;

(ii) the aquifer parameters vary from layer to layer;

(iii) uniform horizontal and vertical hydraulic conductivities for individual layers;

(iv) impermeable lower boundary at finite depth;

(v) flow being guided by Darcy's principle;

(vi) transient simulation of the flow;

(vii) flow is predominantly toward the fully penetrating constant-head river boundaries;

(viii) head (causing flow) in the static water body remains constant throughout the simulation;

(ix) uniformly distributed seepage from the water body; and

(x) no change in the properties of water during the stress period.

To facilitate the analysis of various cases investigated for assessing the influence of position of the fractured aquitard in the medium as well as location of fractured zone in the aquitard, certain quantities/ parameters have been used as per the following definitions.

(a) *Distance ratio, X/L*: Ratio of distance from the centre of the source to any arbitrary point in the direction of the X-axis to the distance between the source and the sink.

(b) *Head Causing Flow, dH*: The difference between hydraulic head in the source and that in the sink which induces the seepage.

(c) *Aquifer potential, h:* The arbitrary variable representing hydraulic potential in the aquifer.

(d) *Head in the Boundary, H_b*: Hydraulic head in the constant head river boundary.

(e) *Percentage Opening, Op*: Discontinuity in the aquitard expressed as a percentage with respect to the dimension of the source water body.

(f) *Fractional Seepage, F_{sb}* : The seepage from the source to the bottom aquifer expressed as a fraction of the total seepage to the system.

(g) *Normalised Hydraulic Potential, $(h - H_b)/dH$* : The ratio of difference between hydraulic potential at any point in the aquifer and that in the boundary to the head causing flow.

(h) *S/T ratio*: Ratio of storage coefficient to transmissivity value; the reverse of this ratio namely, T/S is known as the *hydraulic diffusivity* of the medium.

(j) *Percentage Shift/ Shift* : The location of the opening expressed (as percentage) in terms of shifting from the centre of the aquifer system to the lateral edge of the water body; i.e., shift=0% when the opening is below the centre of the water body and shift=100% when the opening is below a lateral edge of the block-shaped water body. Shift can also be expressed in terms of X/L points in the aquifer system.

(k) *Positioning :* The position of the fractured aquitard in the aquifer system expressed as a ratio between the depth to the aquitard and the total depth of the aquifer system.

An aquitard with a fractured-zone has been positioned within the aquifer system. As the aquitard is assigned a very low permeability, it is seen that when the aquitard is full without any discontinuities/ fractures, essentially no flow takes place to the bottom aquifer. When discontinuity (opening) of varying dimensions has been introduced in the aquitard, flow enters the bottom aquifer. The fractured-zones (openings) have been quantified as percentage openings (O_p) of the width of the source body. The influence of dimensions of openings on the seepage from a surface water body may be found elsewhere *(Jose and Seethapathi, 1998)*.

As indicated earlier, the present study investigates the effect of (i) the location of a fractured-zone in the aquitard vis-a-vis the source, and (ii) the position of the fractured aquitard at various depths in the aquifer system on the seepage from the surface water body.

Simulation of various combination of cases have been carried out and the hydraulic potential (h) in the aquifer system and volumetric details were obtained. Instead of hydraulic potential, its normalised value with respect to the head causing flow (dH) and head in the boundary (Hb) is used in the analysis. The seepage from the source (water body) to the top and bottom aquifers respectively have been computed using the aquifer parameters and hydraulic gradients. The seepage per unit depth to the bottom aquifer has been normalised as a fraction of the total discharge from the aquifer system. The fractional seepage (F_{sb}) has been used as a parameter for the analysis as this quantity was found to be invariant with respect to the S/T ratio *(Jose and Seethapathi, 1998)*.

4.1 Effect of Location of Fractured Zone in the Aquitard

Four sets of cases have been designed and simulated flow/ potentials in the aquifer system to study the influence of location of fractured zone in the aquitard on the seepage from the source. Various combination of dimensions of fractured zone, their location at different points on the aquitard as well as sensitivity of results with regard to different aquifer systems have been achieved through these sets of cases which are explained below.

(i) Effect of percentage shifts of openings of varying dimensions on the seepage from the water body for a given position of the aquitard in an aquifer system.

(ii) Effect of percentage shifts of opening on the seepage from the source for a small opening and given position of the aquitard in different aquifer systems (i.e., for different S/T values).

(iii) Effect of shifts of opening in terms of X/L points on the seepage from the source for a large opening and a fixed position of the aquitard in different aquifer systems (i.e., for different S/T values).

(iv) Effect of shifts of opening from the centre to the boundary of the system on the seepage from the source for a given opening and position of the aquitard in an aquifer system

4.1.1 SET 1: Effect of percentage shifts of openings of varying dimensions on the seepage from the water body for a given position of the aquitard in an aquifer system

The effect of percentage shifts of openings of varying dimensions on the seepage from the water body in a multi-layered aquifer system is analysed with the position of the aquitard fixed at 0.53. The combination of various cases studied with different percentage openings and their percentage shifts for a given S/T value is given in the Table 4.1.1.

Percentage Opening	Percentage Shift of Opening from the centre w.r.t. source width										
	0	10	20	30	40	50	60	70	80	90	100
5	X	X	X	X	X	X	X	X	X	X	X
15	X	X	X	X	X	X	X	X	X	X	X
25	X	X	X	X	X	X	X	X	X	X	X
35	X	X	X	X	X	X	X	X	X	X	X
45	X	X	X	X	X	X	X	X	X	X	X

Table 4.1.1 Matrix table of various cases studied in simulation Set-1; position of aquitard at 0.53 and S/T = 0.1081

The percentage shifts of openings in all these cases are restricted to region below the source only. Thus a shift of the fractured zone equalling 100% implies that the opening being located below one edge of the water body. Cases pertaining to shifting of opening to larger extents being discussed under separate sections.

The distribution of hydraulic potential (as equipotential lines) in the aquifer system for three locations of the fractured zone beneath the source is shown in Figure 4.1.1.1. The vertical sections of the aquifer system through the centre exhibited is for the cases with 5% opening of the fractured zone. It can be observed that the equipotential lines also shift towards the opening. Since the aquitard is of very low permeability, flow is to take place mainly through the fractured zone only. Apparently the opening in the aquitard attracts flow towards it and transmits down.

The equipotentials in the central section of the aquifer system as seen in Figure 4.1.1.2 is obtained when openings of different dimensions are located midway between the centre and edge of the source. The dimension of the openings vary between 5% and 45%. Comparison of equipotentials in the bottom aquifer reveals that the hydraulic potential in the aquifer builds up with widening fractured-zone. This being facilitated by reduced resistance to flow when the opening becomes larger. Therefore, seepage of water down to the bottom aquifer is apparently more for a larger opening even when it is located away from the centre of the source.

The above observations are further elaborated using Figure 4.1.1.3, Figure 4.1.1.4 and Figure 4.1.1.5. The normalised values of hydraulic potential in the central section are plotted against the normalised distance (X/L) for three openings and their different locations. When the dimension of opening increases, the hydraulic potentials indicated by their normalised values also found to be raising. Another feature evident from the plots is the reduction in the hydraulic potentials, especially the peak values, as the opening shifts away from the centre of the source. Consequently, reduction of flow to the bottom aquifer can be expected with shifting of the opening. It may, therefore, be concluded that to effect optimum seepage down to the bottom aquifer, the opening, irrespective of its dimension, should be located centrally below the source.

It is already seen that hydraulic potentials in the bottom aquifer is higher for larger openings in spite their locations. Besides, comparison of hydraulic potentials in the central section obtained with 5%, 25% and 45% openings at two locations of the aquitard (Figure 4.1.1.6 & Figure 4.1.1.7) confirms this fact. Even though the pattern is similar for both the cases, one without any shifting of the opening while the other with 50% shift of the opening, the shifting of peaks towards the location of the opening may be noted.

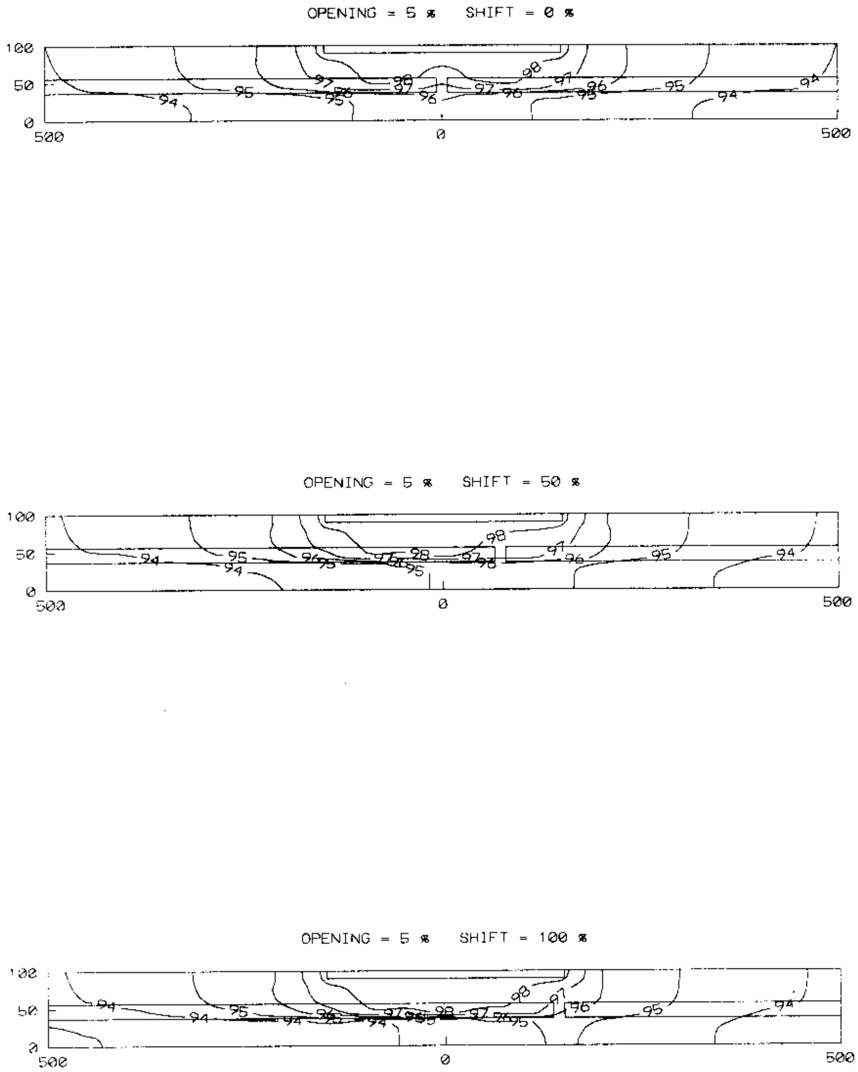
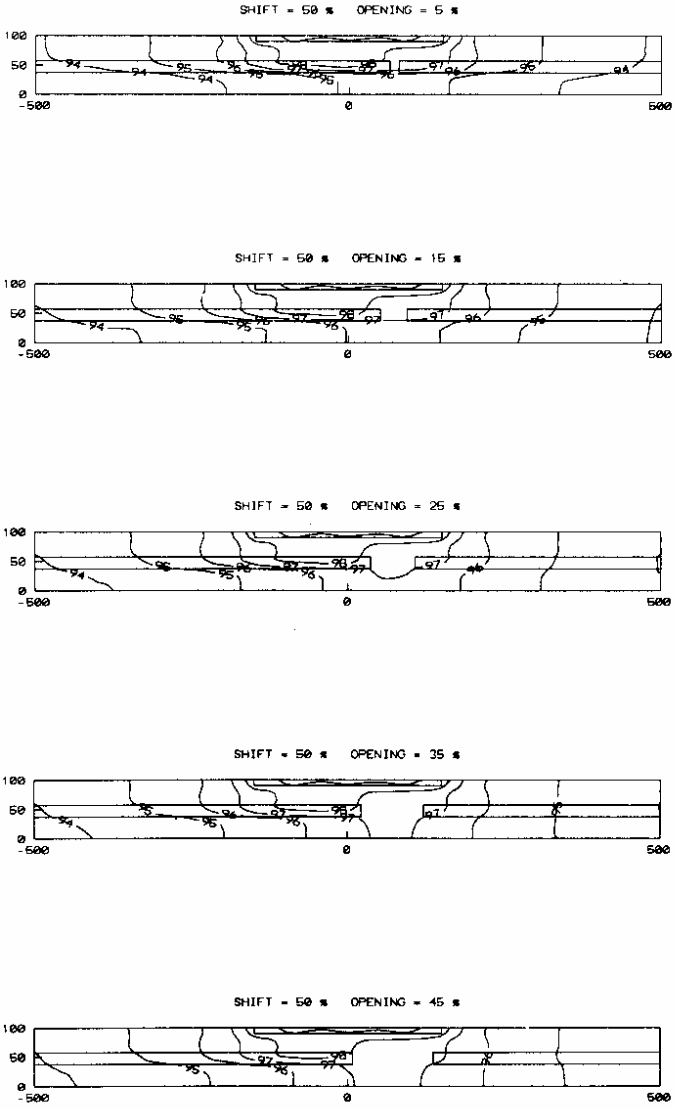


Fig. 4.1.1.1 Distribution of hydraulic potentials in the aquifer system for three locations of 5% opening in the aquitard (Shift=0%, 50% & 100%) while the fractured-aquitard is positioned at 0.53 in the system


SHIFT = 50 % OPENING = 5 %

SHIFT = 50 % OPENING = 15 %

SHIFT = 50 % OPENING = 25 %

SHIFT = 50 % OPENING = 35 %

SHIFT = 50 % OPENING = 45 %

Fig. 4.1.1.2 Distribution of hydraulic potentials in the aquifer system for different Openings with the openings located mid-way between the centre and the edge of the source (Shift=50%) while the fractured-aquitard is positioned at 0.53 in the system

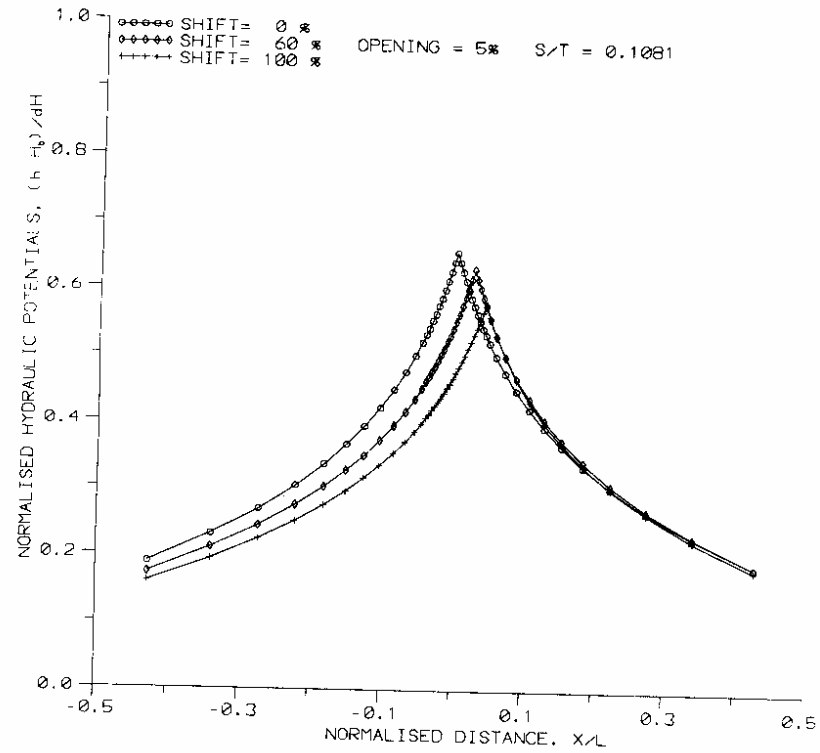


Fig. 4.1.1.3 Normalised distance versus Normalised hydraulic potentials in the bottom aquifer for three locations of opening in the aquitard below the source; Opening = 5%

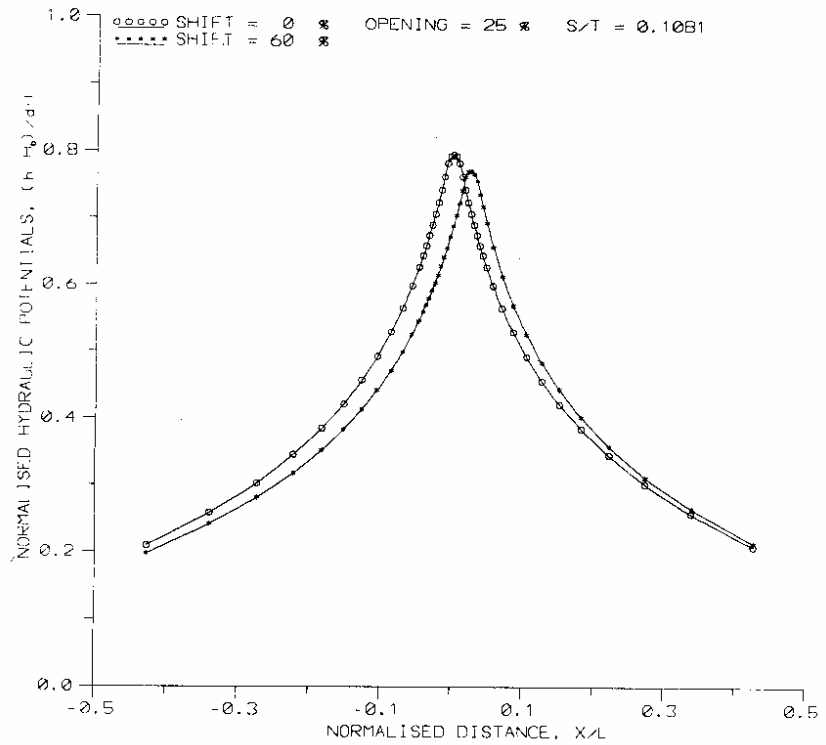


Fig. 4.1.1.4 Normalised distance versus Normalised hydraulic potentials in the bottom aquifer for two locations of opening in the aquitard below the source; Opening=25%

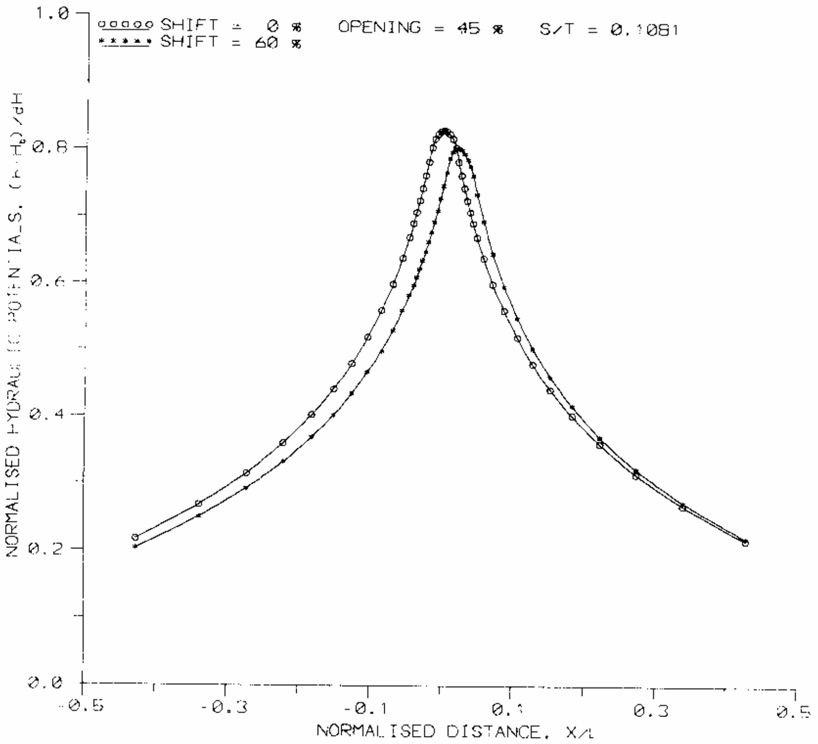


Fig. 4.1.1.5 Normalised distance versus Normalised hydraulic potentials in the bottom aquifer for two locations of opening in the aquitard below the source; Opening=45%

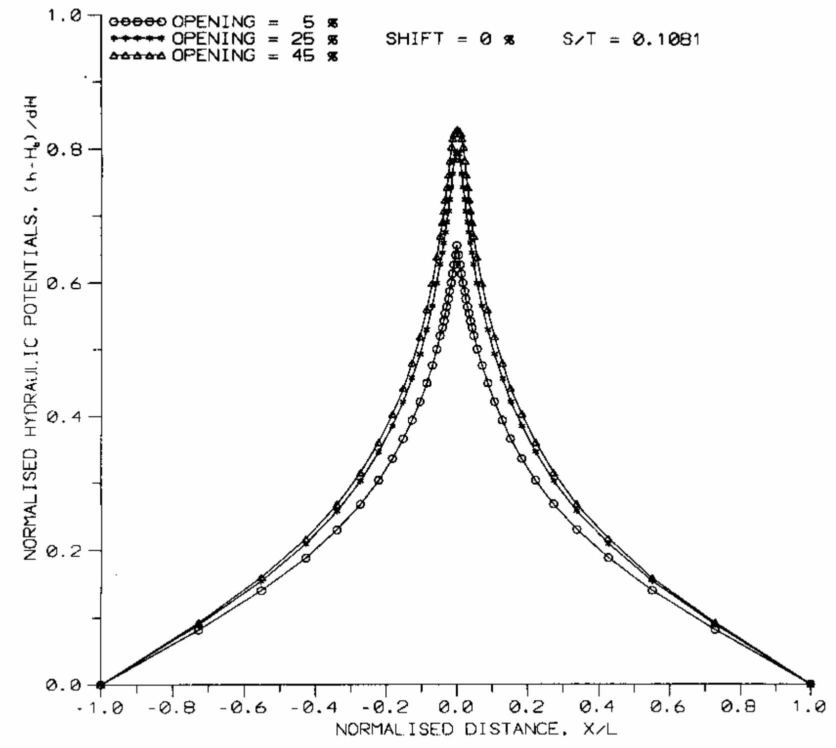


Fig. 4.1.1.6 Normalised Distance versus Normalised hydraulic potentials in the bottom aquifer for different percentage openings located at the centre (Shift=0 %) when S/T = 0.1081

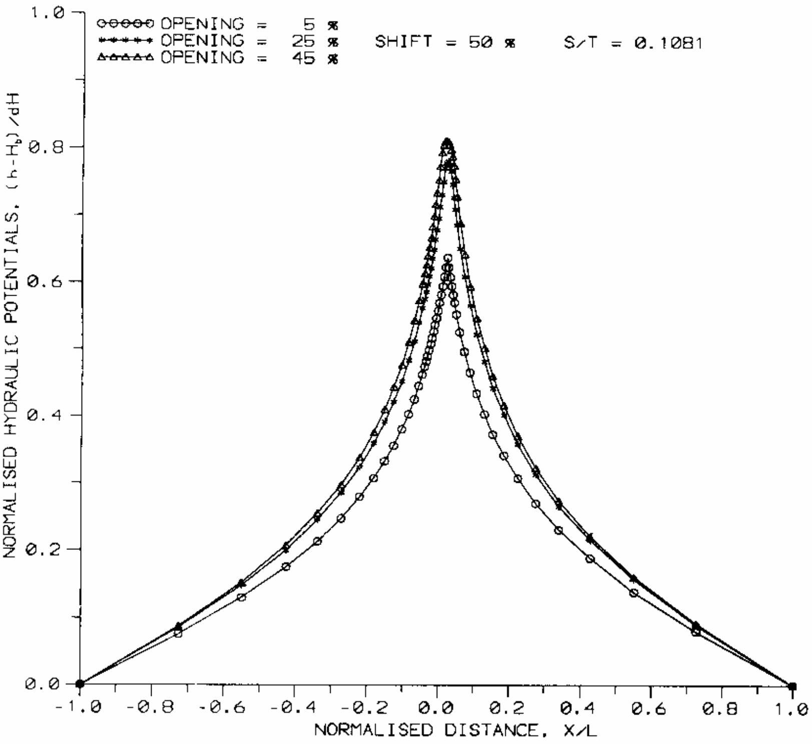


Fig. 4.1.1.7 Normalised Distance versus Normalised hydraulic potentials in the bottom aquifer for different percentage openings located half-way between the centre and the edge of the source (Shift=50 %)

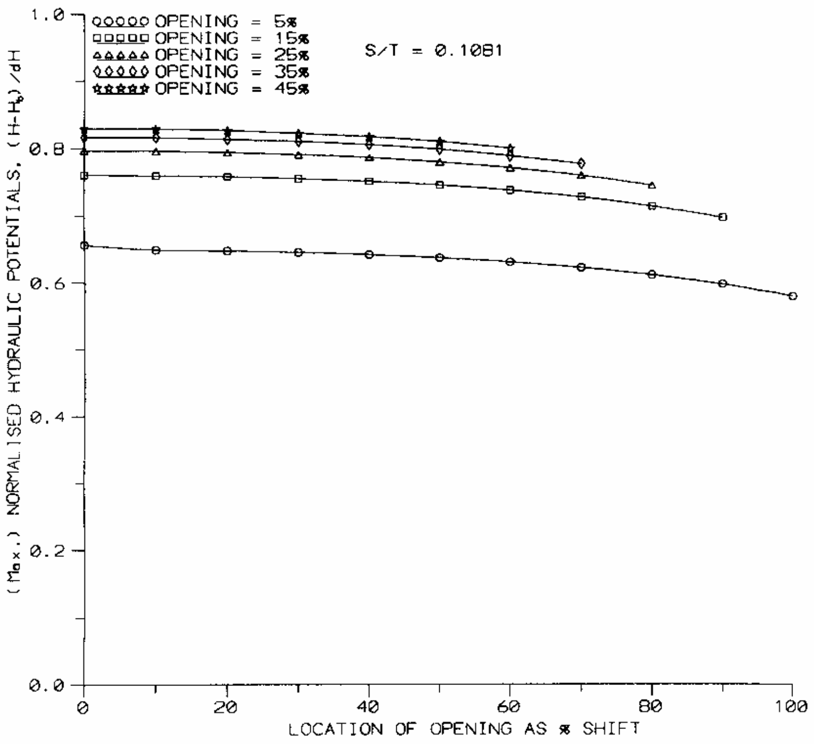


Fig. 4.1.1.8 Location of Opening below the source (from centre to the edge) versus maximum values of Normalised hydraulic potentials in the bottom aquifer for different percentage openings

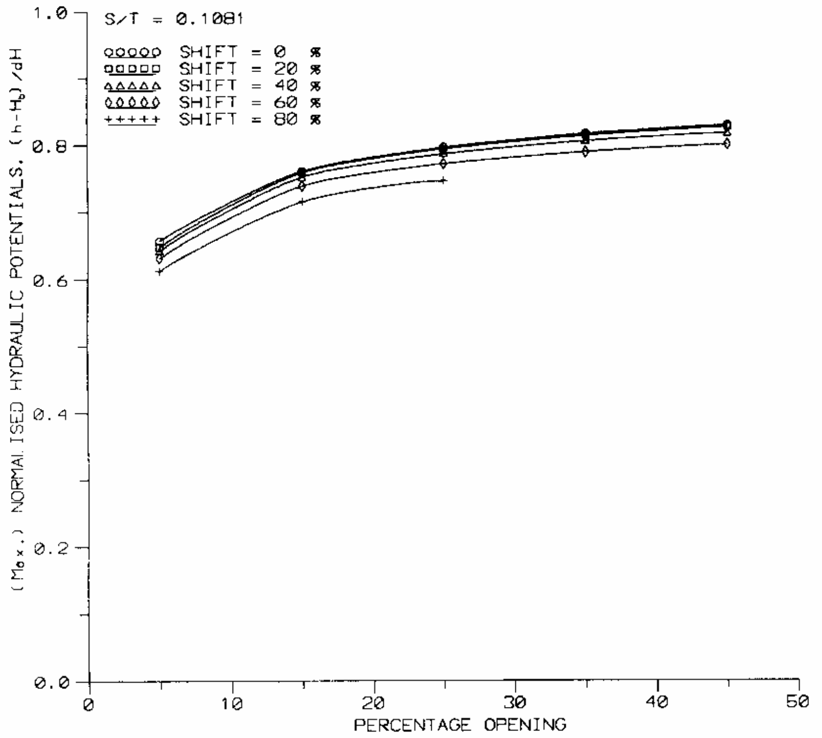


Fig. 4.1.1.9 Percentage Opening versus maximum values of Normalised hydraulic potentials in the bottom aquifer for different locations of opening below the source

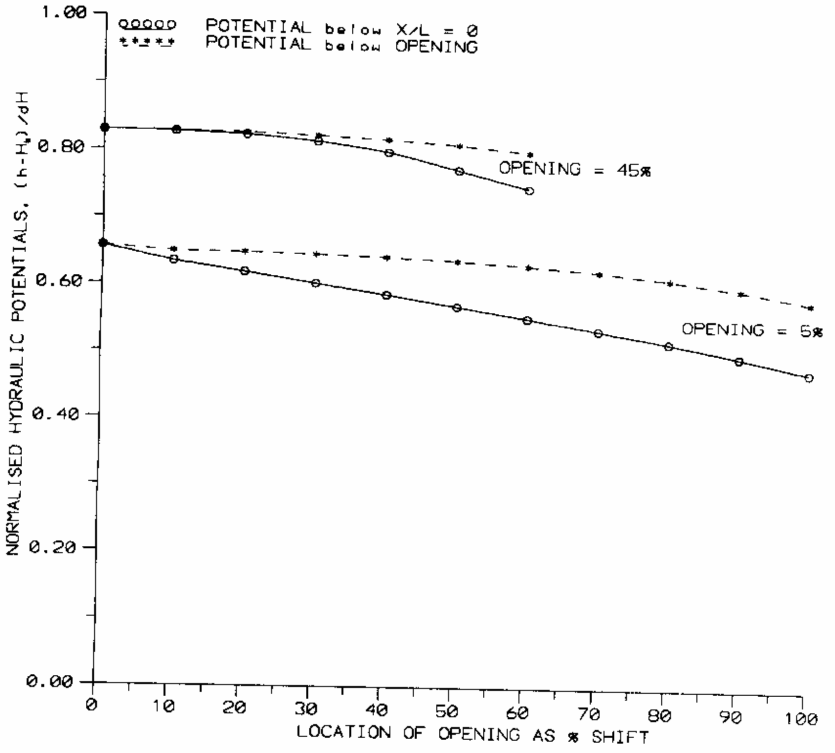


Fig. 4.1.1.10 Location of Opening below the source (from centre to the edge) versus Normalised hydraulic potentials in the bottom aquifer for two Openings; potentials below the centre of the source and that below the opening are compared.

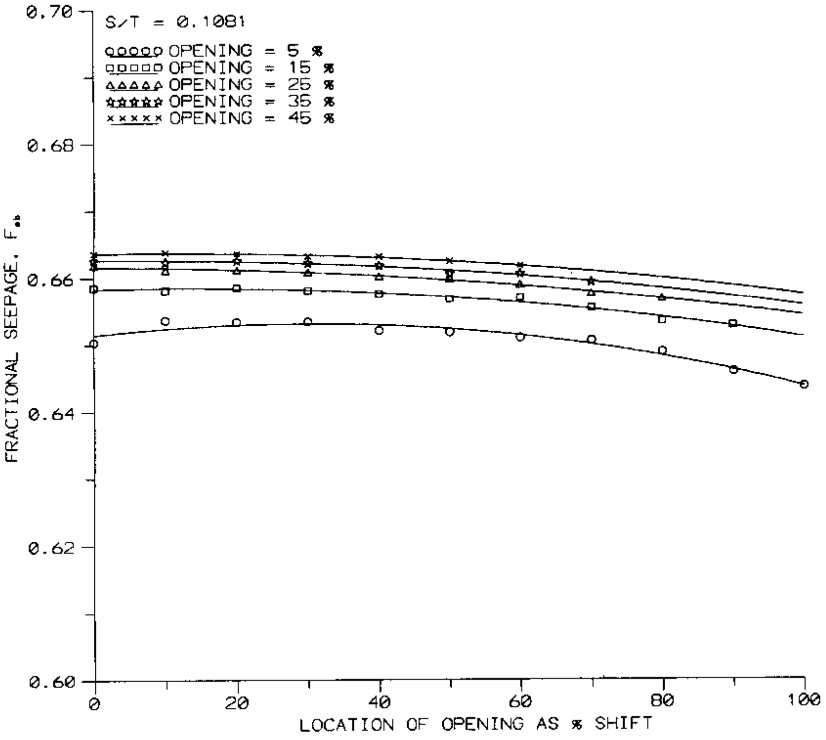


Fig. 4.1.1.11 Location of Opening below the source (from centre to the edge) versus Fractional seepage to the bottom aquifer for different Openings when S/T=0.1081

The nature of hydraulic potentials in the bottom aquifer vis-a-vis locations of opening can be understood from Figure 4.1.1.8. The peak values of hydraulic potentials corresponding to different locations of the opening are plotted therein for varying dimensions of the fractured zone. Reduction in the peak potential values is evident in all the cases regardless of the dimension of opening, as the fractured zone moves away from the centre of the aquifer system. However as discussed earlier, higher potentials are registered with larger dimension of the opening. Moreover, the peak values of normalised hydraulic potential plotted against percentage openings as shown in Figure 4.1.1.9 verify these observations.

The drop in hydraulic potentials corresponding to the centre as the opening shifts away from the centre is depicted in Figure 4.1.1.10. The normalised hydraulic potential below the opening as well as that below the centre of the source are compared for two cases with different openings. The difference between the potentials at these two points (at the centre and at the opening) is gradually increasing as the opening shifts away form the centre. This may be expected as the transmission of flow down to the bottom aquifer is predominantly through the fractured zone only by virtue of the hydraulic characteristics of the aquitard.

The effectiveness of recharging of the bottom aquifer against various locations of the fractured zone has also been evaluated. Therefore, the fractional seepage to the bottom aquifer has been computed for various cases with different openings and shifts in order to assess possible influence. Location of openings in terms of percentage shift versus fractional seepage (F_{sb}) shown in Figure 4.1.1.11 reveals the nature of seepage to the bottom aquifer. Reduction in fractional seepage with shifting of the opening away from the centre of the source is evident. Further, quantitative increment in fractional seepage for larger openings is also obvious.

It is clear from the discussions that when the opening is away from the centre of the source, irrespective of its dimension, there ought to be a reduction of flow taking place down to the bottom aquifer. Therefore, in order to achieve optimum recharging of the bottom aquifer the opening/fractured zone of certain dimension must be centrally located below the source.

4.1.2 SET 2: Effect of percentage shifts of opening on the seepage from the source for a small opening and given position of the aquitard in different aquifer systems

The effect of percentage shifts of a small opening (5%) on the seepage from the water body in aquifer systems having distinct parameter values is analysed. Various cases examined with different S/T values and percentage shifts of opening is presented in the Table 4.1.2. A few representative cases have been selected for discussion.

S/T	Percentage Shift of Opening from the centre w.r.t. source width					
	0	20	40	60	80	100
0.1081	X	X	X	X	X	X
0.2162	X	X	X	X	X	X
0.3027	X	X	X	X	X	X
0.4000	X	X	X	X	X	X
0.5045	X	X	X	X	X	X

Table 4.1.2 Matrix table of various cases studied in simulation Set-2; position of aquitard at 0.53 and Opening = 5 %

Figure 4.1.2.1 shows the location of opening versus normalized hydraulic potentials in the bottom aquifer for two S/T values of the aquifer. It may be observed that the normalized hydraulic potential in the bottom aquifer is higher for all locations of the fractured zone for an aquifer system with a smaller value of the S/T ratio. This suggests that an aquifer system with small storage coefficient values and/or large transmissivity values tends to develop higher potentials.

Figure 4.1.2.2 depicts S/T ratio versus fractional seepage in the bottom aquifer for two locations of the opening, one below the centre and the other below the edge of the water body. The fractional seepage to the bottom aquifer seems to be high for an aquifer system with a large S/T value. It implies that only the fraction of the total discharge which being transmitted to the bottom aquifer is high in the case of an aquifer system with larger S/T values; whereas the total discharge from the aquifer system is smaller for larger S/T ratios.

Hence, for a given set-up, an aquifer system with large S/T ratio may transmit higher fractions of the total discharge (which is quantitatively smaller for larger S/T ratios) to the bottom aquifer irrespective of the location of the fractured zone. Further, for any aquifer system the fractional seepage to the bottom aquifer is slightly less for an opening below the edge of the water body than that for an opening below the centre of the source. Thus, the location of a fractured zone in the aquitard appears

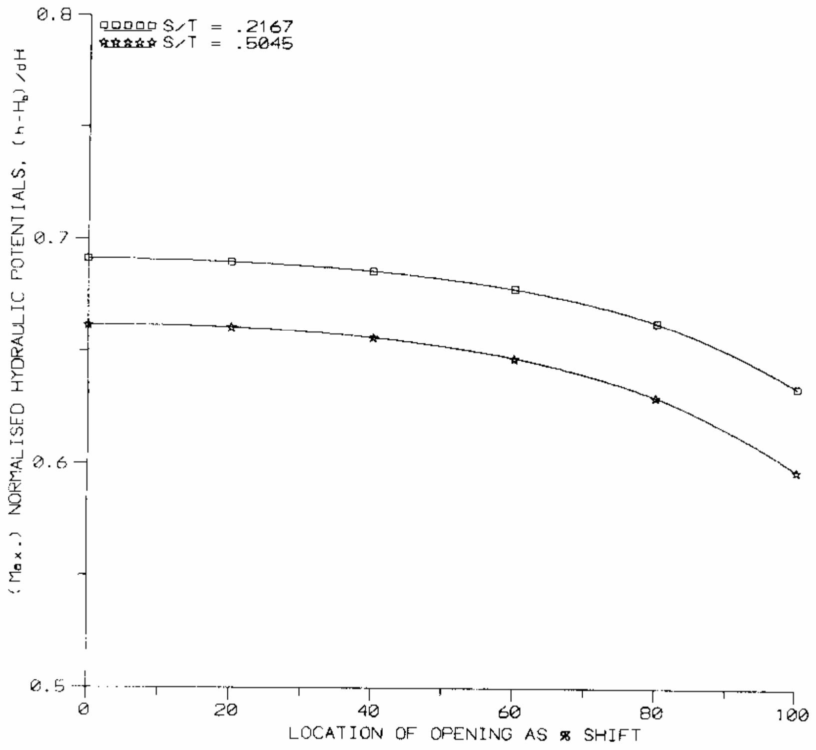


Fig. 4.1.2.1 Location of Opening below the source (from the centre to the edge) versus maximum values of Normalised hydraulic potentials in the bottom aquifer for two S/T values with 5% opening

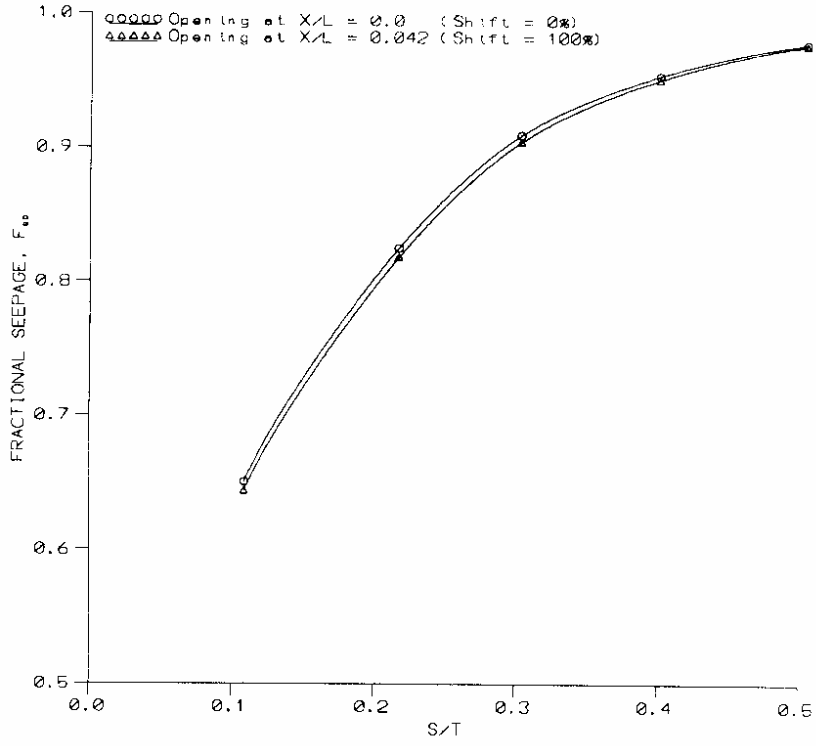


Fig. 4.1.2.2 S/T ratio versus Fractional Seepage to the bottom aquifer for two locations of the fractured-zone (Opening=5%), one at the centre (Shift=0%) and other at the edge (Shift=100%) of the water body

to influence the seepage of water to an underlying aquifer.

4.1.3 SET 3: Effect of shifts of opening in terms of X/L points on the seepage from the source for a large opening and a fixed position of the aquitard in different aquifer systems

The analyses made under the previous sections (Section 4.1.1 & 4.1.2) were pertaining to cases with locations of the fractured zone well within the region below the water body. Also, the dimension of the openings did not exceed 50% of the source width in all those cases. However, the cases dealt with under this section and the one following are extension of the previous sets in order to cover the complete aquifer system with a larger dimension of the opening and its locations anywhere between the centre of the aquifer system and the constant head river boundary. Table 4.1.3 shows the cases studied with two locations of an opening, one at the centre and the other far away from the centre, for different aquifer systems.

X/L	S/T values				
	0.1081	0.2162	0.3027	0.4000	0.5045
0	X	X	X	X	X
0.43	X	X	X	X	X

Table 4.1.3 Matrix table of various cases studied in simulation Set-3; position of aquitard at 0.53 and Opening=117%

In this section two locations of the opening, one in the middle of the aquitard and the other at a distance approximately half way between the centre and the boundary of the aquifer system, have been considered for evaluating influence of location of opening on the seepage. The equipotentials in the aquifer systems with locations of the opening at X/L = 0 and at X/L = 0.43 respectively are shown in Figure 4.1.3.1. When the opening is located at the centre of the aquitard, the equipotential lines are well distributed in the bottom aquifer. However, as the fractured zone shifted away from the source and located at a considerable distance (X/L =0.43), the potential distribution in the bottom aquifer is sparse/ absent. This indicates that the flow of water down to the bottom aquifer is meagre or no longer existent when the opening is located approximately mid-way between the source and the aquifer boundary.

When the opening is centrally located, the normalised distance (X/L) versus normalized hydraulic potential in the bottom aquifer for various S/T ratios is given in Figure 4.1.3.2. This graph may be compared with the one shown in Figure 4.1.3.3 for which the opening is located half way between the source and the boundary of the aquifer system. Higher hydraulic potential is observed for smaller S/T values when the opening is far away from the source. However, when the opening is located below the centre, eventhough higher hydraulic potentials are observed for smaller S/T values a reverse trend is noticed in a small region below the source. This can be due to stagnation of flow in the region below the source which may be attributed to the parameter values of the aquifer.

In Figure 4.1.3.4 the hydraulic potentials for the two locations of the opening at X/L =0 and X/L =0.43 are compared. It follows that the potential in the bottom aquifer is much lower when the opening is located at X/L =0.43. Regarding the sensitivity of hydraulic potentials in different aquifer systems, it is noticed that the hydraulic potential build-up in the bottom aquifer is weaker for an aquifer system with large S/T value corroborating the distributional pattern of potentials discussed above.

Further, it is noticed that the fractional seepage to the bottom aquifer is much significant when the opening is located below the centre of the source compared to the case when it is located far away from the source. S/T ratio versus fractional seepage (F_{sb}) to the bottom aquifer for the two locations of the opening plotted in Figure 4.1.3.5 is self-explanatory. Also, irrespective of the location of the opening, the fractional seepage is found to be higher for an aquifer system with high S/T value. Thus in the case of an aquifer system with smaller S/T ratios, more of the flow is discharged through the top aquifer and not contributed towards the recharging of the bottom aquifer. But, in the case of an aquifer system with large S/T value, more of the total discharge is transmitted down to the underlying aquifer.

However, from the plot of maximum values of normalized hydraulic potential in the bottom aquifer for different S/T values (Figure 4.1.3.6), it may be seen that there is a reduction in the maximum hydraulic potentials for aquifer systems with large S/T ratios particularly when the opening is located away from the source. This suggests smaller discharges when the aquifer system is of low hydraulic diffusivity (T/S) eventhough fractional seepage is more.

The results so far indicate that the location of a fractured zone in the confining aquitard has significant influence on the recharging process of the bottom aquifer as it regulates the seepage from the source. It is seen that when an opening is located at about half way in between the source and boundary, the flow to the bottom aquifer is very small regardless of the characteristics of the aquifer system.

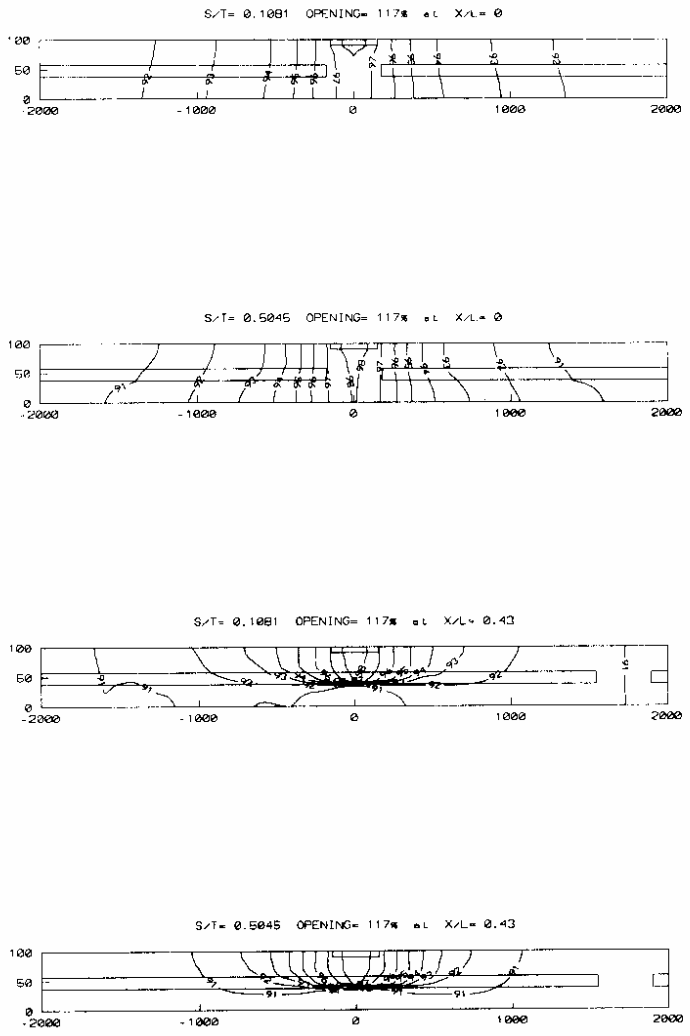


Fig. 4.1.3.1 Distribution of hydraulic potentials in the aquifer system for two S/T values with the openings located at X/L=0 and X/L=0.43 in the aquitard (the fractured-aquitard is positioned at 0.53 in the system)

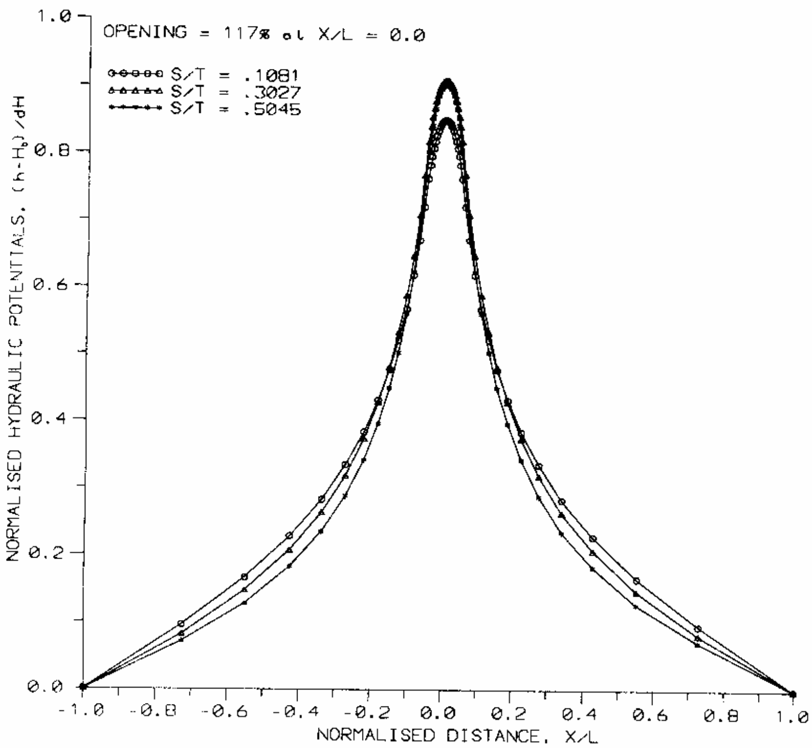


Fig. 4.1.3.2 Normalised Distance from the source to the boundaries versus Normalised hydraulic potentials in the bottom aquifer for different S/T ratios when the fractured-zone (Opening=117%) is located at X/L=0

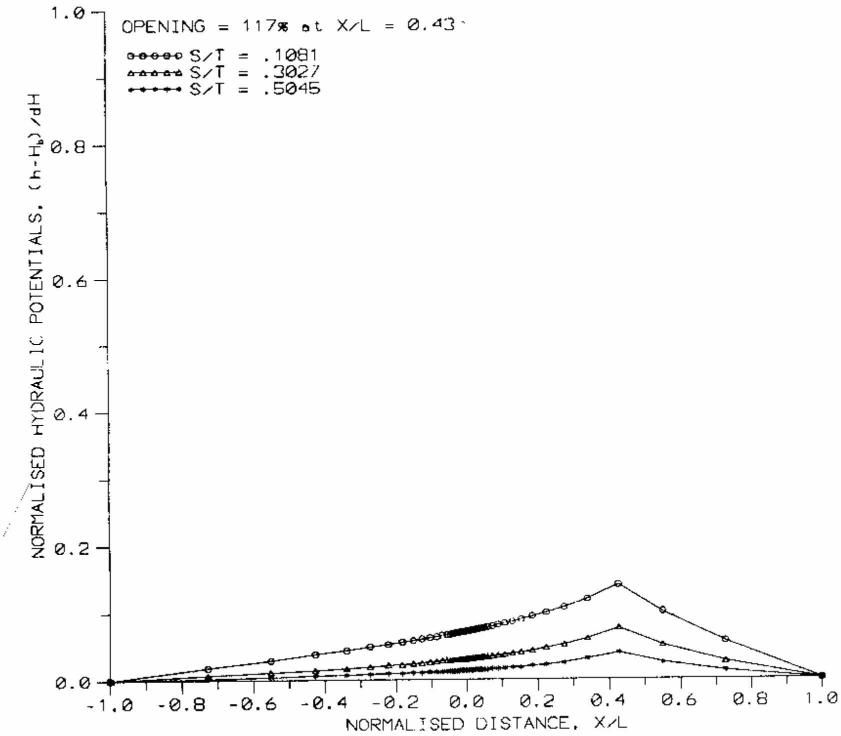


Fig. 4.1.3.3 Normalised Distance from the source to the boundaries versus Normalised hydraulic potentials in the bottom aquifer for different S/T ratios when the fractured-zone (Opening=117%) is located at X/L=0.43

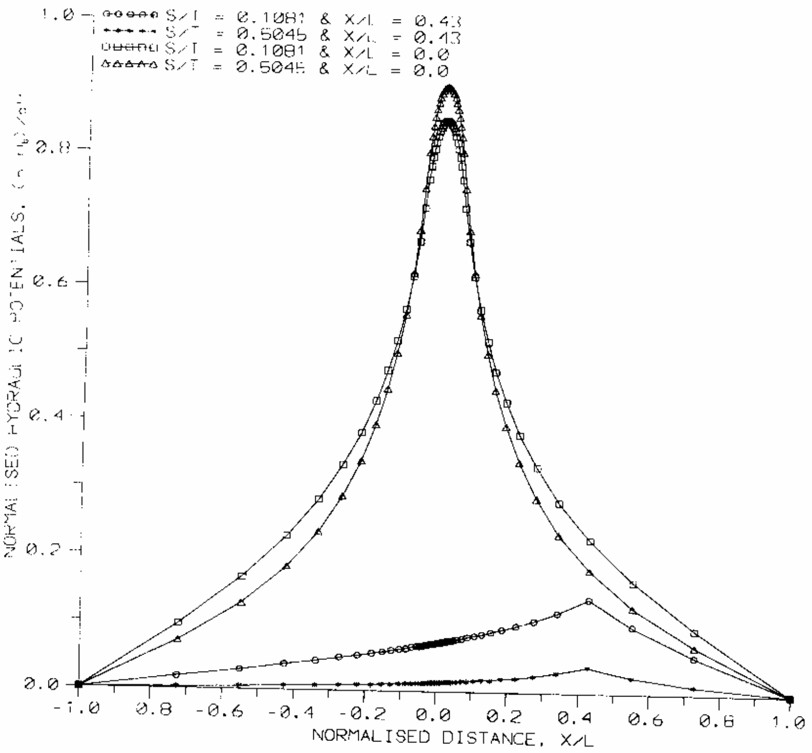


Fig. 4.1.3.4 Normalised Distance from the source to the boundaries versus Normalised hydraulic potentials in the bottom aquifer for two S/T ratios when the fractured-zone (Opening = 117%) is located at X/L = 0 and X/L = 0.43

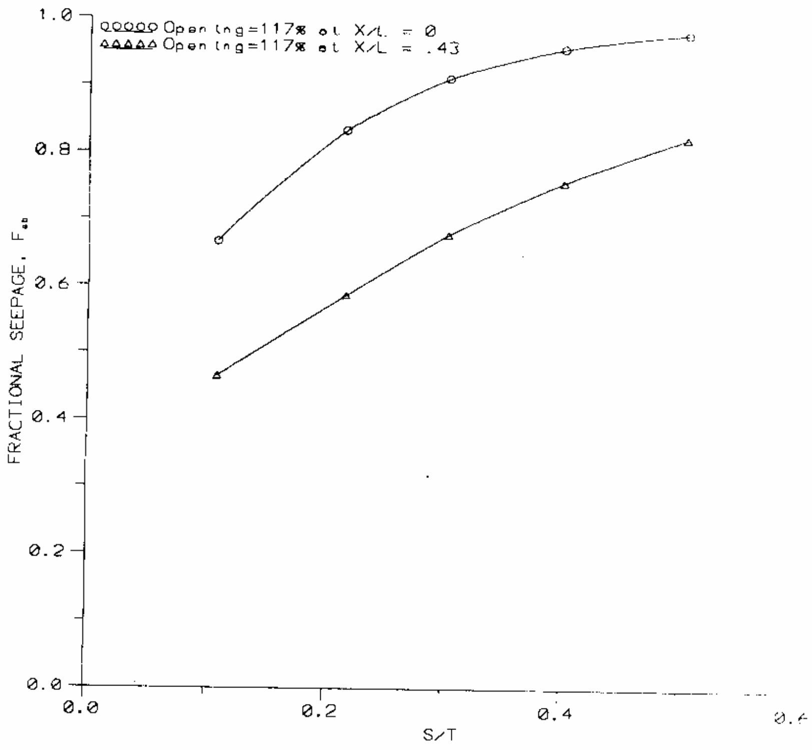


Fig. 4.1.3.5 S/T ratio versus Fractional seepage to the bottom aquifer when the fractured-zone (Opening=117%) is located at X/L=0 and X/L=0.43 respectively

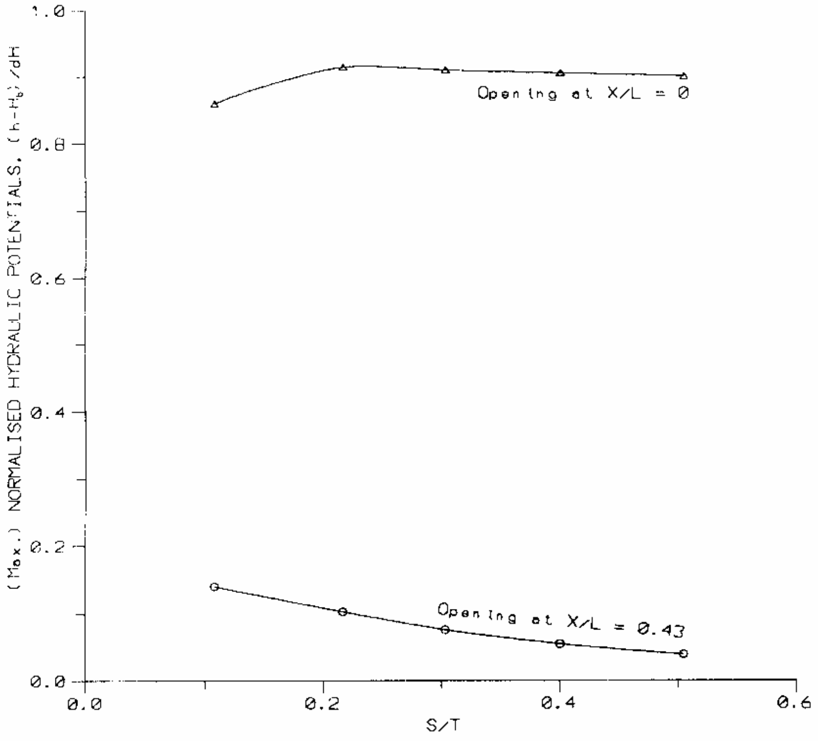


Fig. 4.1.3.6 S/T ratio versus maximum values of Normalised hydraulic potentials in the bottom aquifer when the fractured-zone (Opening = 117%) is located at X/L = 0 and X/L = 0.43

4.1.4 SET 4: Effect of shifts of opening from the centre to the boundary of the system on the seepage from the source for a given opening and position of the aquitard in an aquifer system

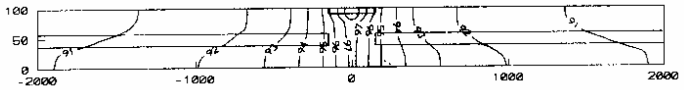
The cases simulated in this set have been formulated with uniform grid sizes in the aquifer system so as to enable the fractured zone to be located successively at regular intervals in the aquitard. The dimension of the opening for these cases has been chosen to be equal to that of the water body. Table 4.1.4 gives the cases simulated with various locations of a fractured zone between the centre and the boundary of the aquifer system for a given aquifer set-up in order to provide a continuous scenario regarding the influence of location of fractured zone on the seepage from the source. Analysis of the cases simulated with the opening located at various points in aquitard between the centre and the boundary of the aquifer system follows.

X/L	S/T = 0.1081
0	X
0.15	X
0.30	X
0.45	X
0.60	X
0.75	X
0.90	X

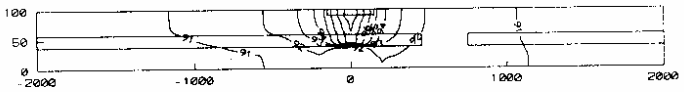
Table 4.1.4 Matrix table of various cases studied in simulation Set-4; position of aquitard at 0.53 and Opening = 100 %

Figure 4.1.4.1 presents the distribution of hydraulic potentials (as equipotential lines) for three cases; the openings being located progressively towards the boundary at three locations, X/L=0, X/L=0.15 and X/L=0.30. The change in distributional pattern of the potentials in the aquifer as the fractured zone shifts away from the source is obvious. The weakening of the potential field in the bottom aquifer as the fractured zone being located farther from the source is evident. However, the distribution in potentials in the top aquifer is apparently less susceptible to the location of the opening. The hydraulic heads in the central section of the aquifer system for three locations of the opening as indicated by Figure 4.1.4.2 support this observation. Normalized distance versus normalized hydraulic

100% OPENING at X/L= 0



100% OPENING at X/L= 0.15



100% OPENING at X/L= 0.30

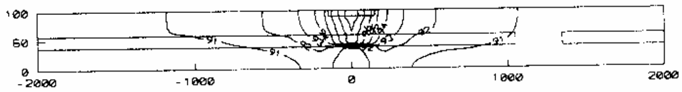


Fig. 4.1.4.1 Distribution of hydraulic potentials in the aquifer system for three locations of 100% opening in the aquitard (at X/L=0, 0.15 & 0.30) while the fractured-aquitard is positioned at 0.53 in the system

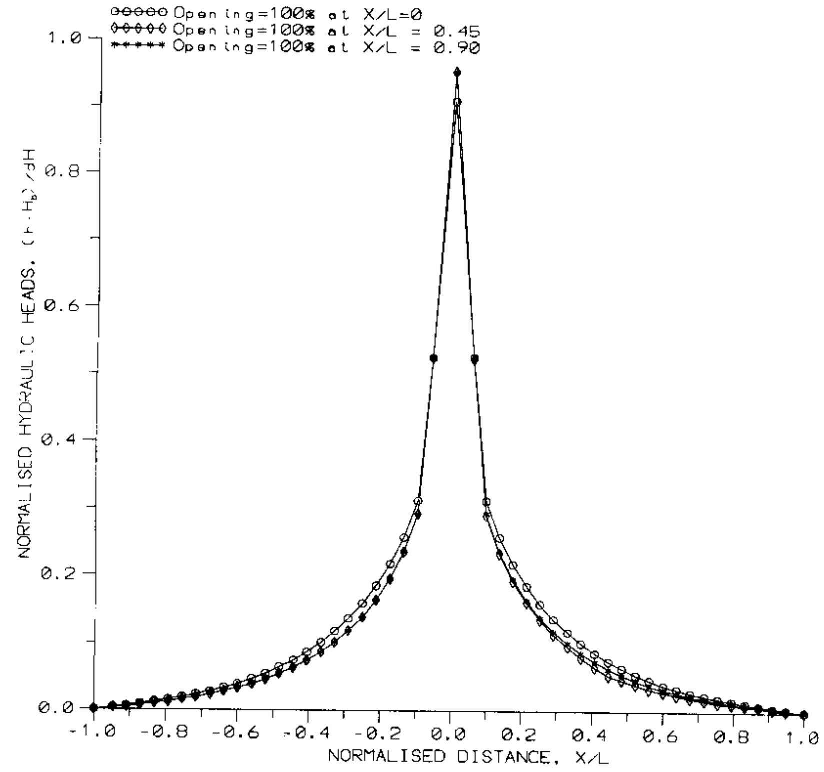


Fig. 4.1.4.2 Normalised distance (X/L) versus Normalised hydraulic heads in the top aquifer when the fractured-zone (Opening = 100%) is located at different X/L points

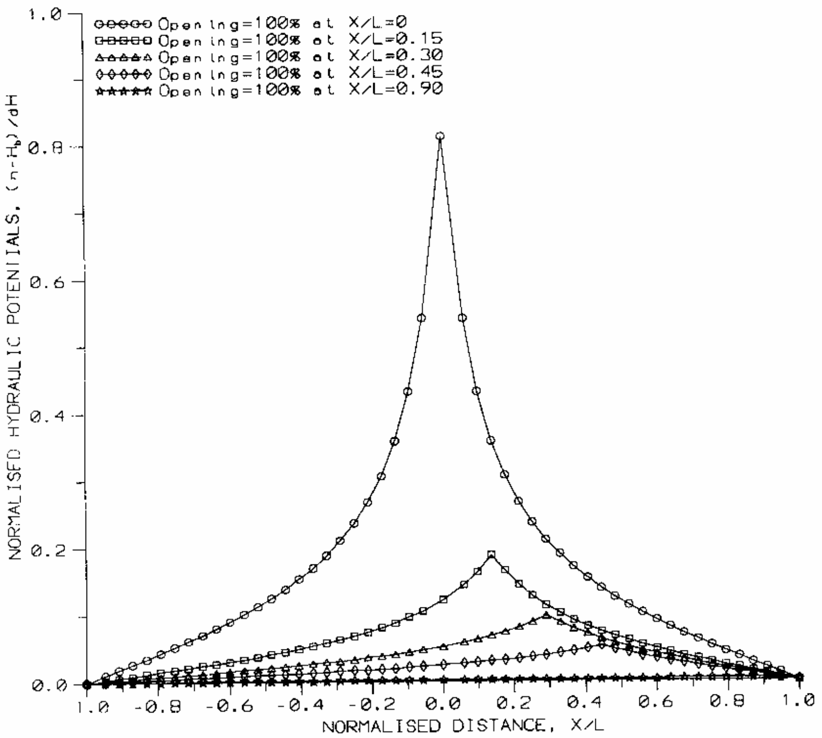


Fig. 4.1.4.3 Normalised distance (X/L) versus Normalised hydraulic potentials in the bottom aquifer when the fractured-zone (Opening = 100%) is located at different X/L points

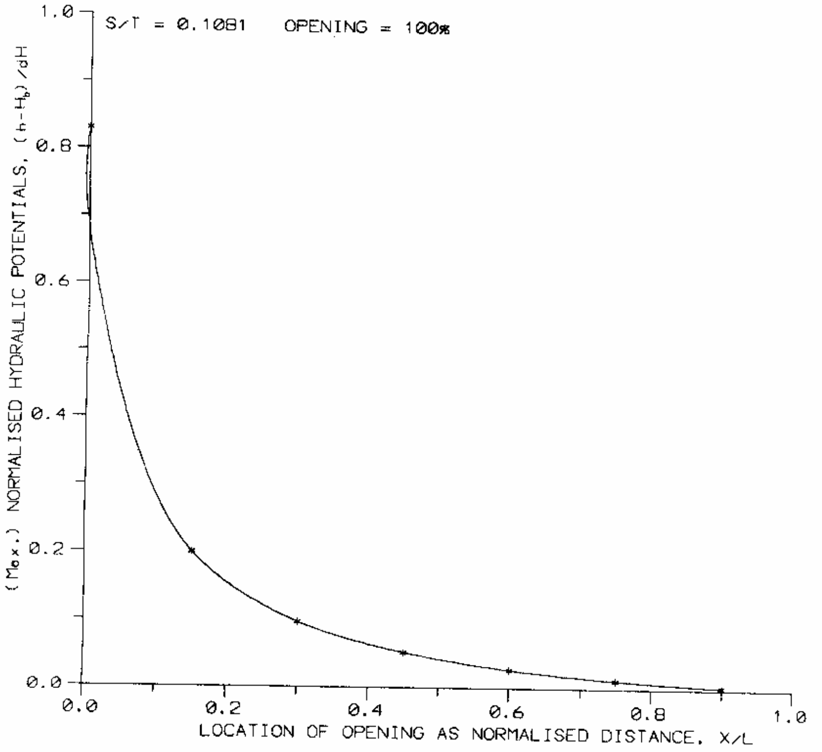


Fig. 4.1.4.4 Location of opening indicated in terms of Normalised distance (X/L) versus maximum values of normalised hydraulic potentials in the bottom aquifer when the fractured-zone (Opening = 100%) is located at different X/L points

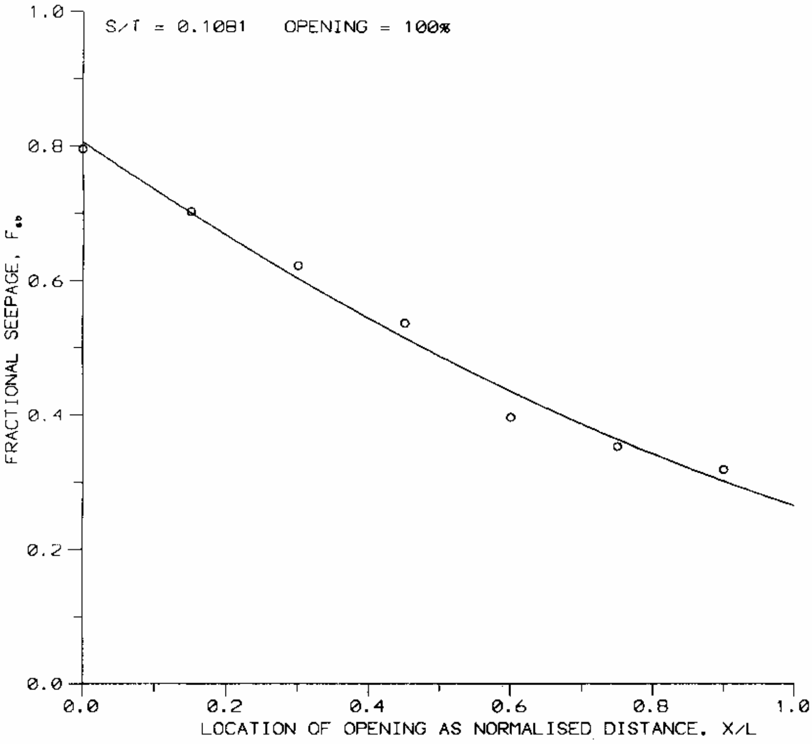


Fig. 4.1.4.5 Location of opening indicated in terms of Normalised distance (X/L) versus Fractional seepage to the bottom aquifer when the fractured-zone (Opening = 100%) is located at different X/L points

potential in the bottom aquifer for different locations of the fractured zone in the aquitard is plotted in Figure 4.1.4.3. The hydraulic potential in the bottom aquifer influenced by the shifting location of the opening is quite evident. It is interesting to note that even when the opening is placed at half way between the centre and the boundary of the system the potential in the bottom aquifer is considerably low suggesting the inadequacy of the fractured zone to transmit water down to the aquifer. Thus, beyond X/L=0.5 the location of the fractured zone has no significance.

The maximum values of normalized hydraulic potentials for various locations of the opening is plotted in Figure 4.1.4.4. Almost an exponentially decreasing pattern of the maximum hydraulic potentials as the fractured zone moves away from the source is clearly noticed. Nearly 50% reduction in the maximum value of the potential corresponding to the location of the opening at X/L=0 is observed even when the opening is shifted to a point at X/L=0.1 which is only one-tenth of the distance between the centre and the boundary. Further, the maximum value of hydraulic potential corresponding to a location of the fractured zone at X/L=0.5 is found to be very minor. This suggests that fractured zone located at farther points can not transmit water down to the bottom aquifer. Hence any recharging pond/tank should be located well within the influence domain of a fractured zone in order to effect optimum recharge. The fractional seepage values corresponding to various locations of the opening also show a diminishing pattern with the shifting of the opening away from the centre (Figure 4.1.4.5). It is observed that the fractional seepage corresponding to the location of opening at the centre reduces to half of its value when the opening is located at about midway between the centre and the boundary.

After analysing various cases in order to evaluate the influence of location of an opening (fractured zone) in the confined aquitard on the seepage from a water body, it is found that the hydraulic potential in the bottom aquifer as well as the fractional seepage tends to reduce as the fractured zone in the aquitard moves towards the aquifer boundary (i.e. away from the source). It is certain that the maximum seepage to the bottom aquifer occurs when the fractured zone irrespective of its dimension is located centrally below the recharging source.

4.2 Effect of Positioning of the Fractured Aquitard

In the preceding sections the influence of location of fractured zone in the aquitard on the seepage from the water body has been discussed. The position of the aquitard was maintained at a certain depth in the aquifer system for the cases analysed so far. The cases discussed under this section are pertaining to the effect of positioning of the fractured aquitard in the medium on the seepage from the source; the location of the fractured zone being at the centre of the aquitard. The aquitard is placed at various depths without altering the aquifer set-up. The position of the aquitard is indicated by a ratio of the depth of the aquitard to the total depth of the aquifer system to the impermeable lower boundary. By this convention, the position of the aquitard at 0.5 implies that the aquitard is exactly positioned in the middle of the aquifer system. Various cases have been formulated for a combination of S/T values and positioning of the aquitard in the system for a given opening at the centre of the aquitard.

4.2.1 SET 1: Effect of positioning of the fractured aquitard on the seepage from the source in different aquifer systems

Various cases studied with positioning of the aquitard at various depths in different aquifer systems are presented in the Table 4.1.2.

S/T	Position of the aquitard (=Depth to aquitard/ Total depth of aquifer)						
	0.68	0.63	0.58	0.53	0.48	0.43	0.38
0.1081	X	X	X	X	X	X	X
0.2162	X	X	X	X	X	X	X
0.3027	X	X	X	X	X	X	X
0.4000	X	X	X	X	X	X	X
0.5045	X	X	X	X	X	X	X

Table 4.2.1 Matrix table of various cases studied with positioning of the fractured aquitard for 5 % Opening at the centre

Several positions of the aquitard having an opening of 5% with respect to the source width have been subjected to investigation. Figure 4.2.1.1 demonstrates the distribution of hydraulic potentials in the vertical section of various aquifer systems. The variation of the potential distribution with different S/T values for one position of the fractured aquitard is given. Whereas Figure 4.2.1.2 is the equipotentials in the vertical section for several positions of the aquitard for a particular opening in an aquifer system. The changes in the distribution of the equipotential lines as the aquitard is positioned at various depths in the aquifer system is evident. Apparently, the potentials in the bottom aquifer tend to increase when the aquitard is placed nearer to the impermeable boundary.

The normalized hydraulic potentials in the top and bottom aquifer respectively have been plotted for three positions of the fractured aquitard (Figure 4.2.1.3 and Figure 4.2.1.4). In both the cases, it is observed that the hydraulic head/potential is on the increase with increasing depth of the aquitard . As result of positioning of the aquitard further downwards, the thickness of the top aquifer increases and thereby the water bearing capacity. This may gradually allow more seepage of water down to the bottom aquifer and raising the hydraulic potential.

Figure 4.2.1.5 and Figure 4.2.1.6 represents normalized hydraulic heads/potentials in the top and bottom aquifer respectively for different values of S/T ratio when the aquitard is positioned in the middle of the aquifer system. Higher potentials are observed in the case of aquifer systems with smaller S/T ratios. The sensitivity of hydraulic potentials with regard to different aquifer systems is elaborated through the above graphs.

Further, the behaviour of maximum values of normalized hydraulic potential in the bottom aquifer is plotted against the positions of the aquitard in Figure 4.2.1.7. The linearly increasing trend suggests that the potential in the bottom aquifer builds-up as the fractured aquitard moves closer to the lower boundary. However, fractional seepage (F_{sb}) exhibited a declining trend. From Figure 4.2.1.8, it is clear that unlike the case of hydraulic potentials, the fractional seepage is found to be decreasing as the aquitard position nears the impermeable lower boundary. This conforms to logic as the thickness of the bottom aquifer reduces with the downward movement of the aquitard resulting in lesser holding capacity of the bottom aquifer thereby restricting the fraction of the total seepage going down. Further, the sensitivity of fractional seepage with different aquifer systems is given in Figure 4.2.1.9. The fractional seepage is high for an aquifer system with high value of S/T ratio.

The analysis of influence of positioning of the fractured aquitard on the seepage from a water body reveals that the behaviour of hydraulic heads/potentials in the top/ bottom aquifer is similar. Precisely, the hydraulic potentials in both the aquifers are found to be higher when the fractured aquitard is closer to the impermeable lower boundary; that is when the aquitard is at lower positions with reference to the datum of the aquifer system. However, the fraction of total seepage to the bottom aquifer decreases when the aquitard is placed nearer to the lower boundary. This may be due to reduced thickness of the bottom aquifer implying lesser water holding capacity.

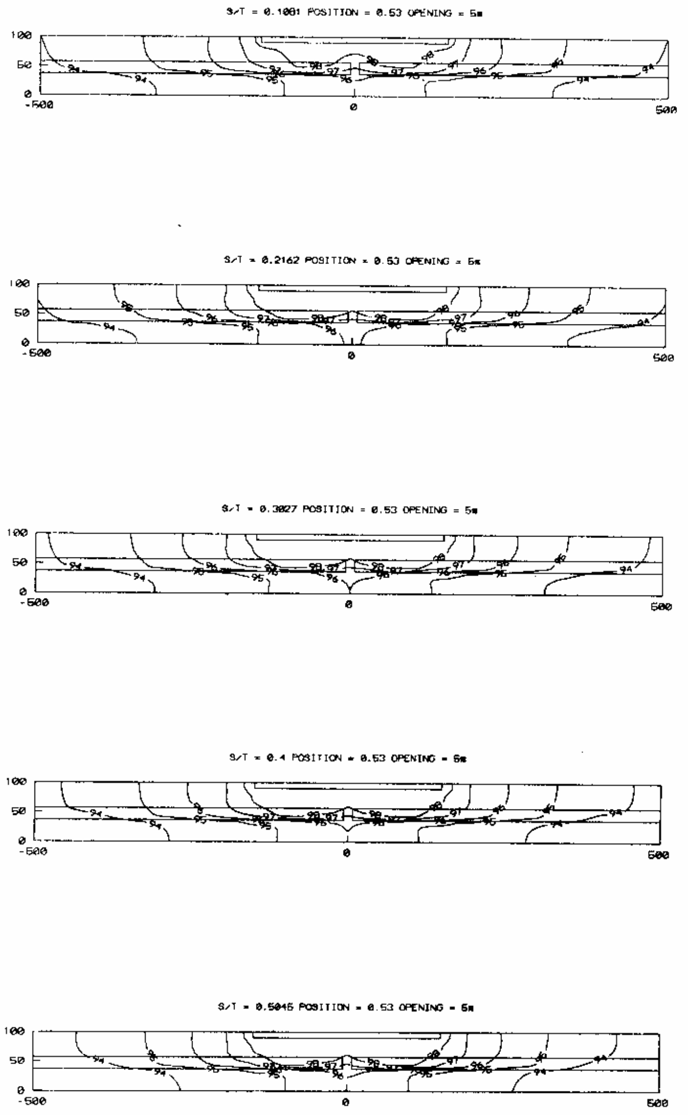
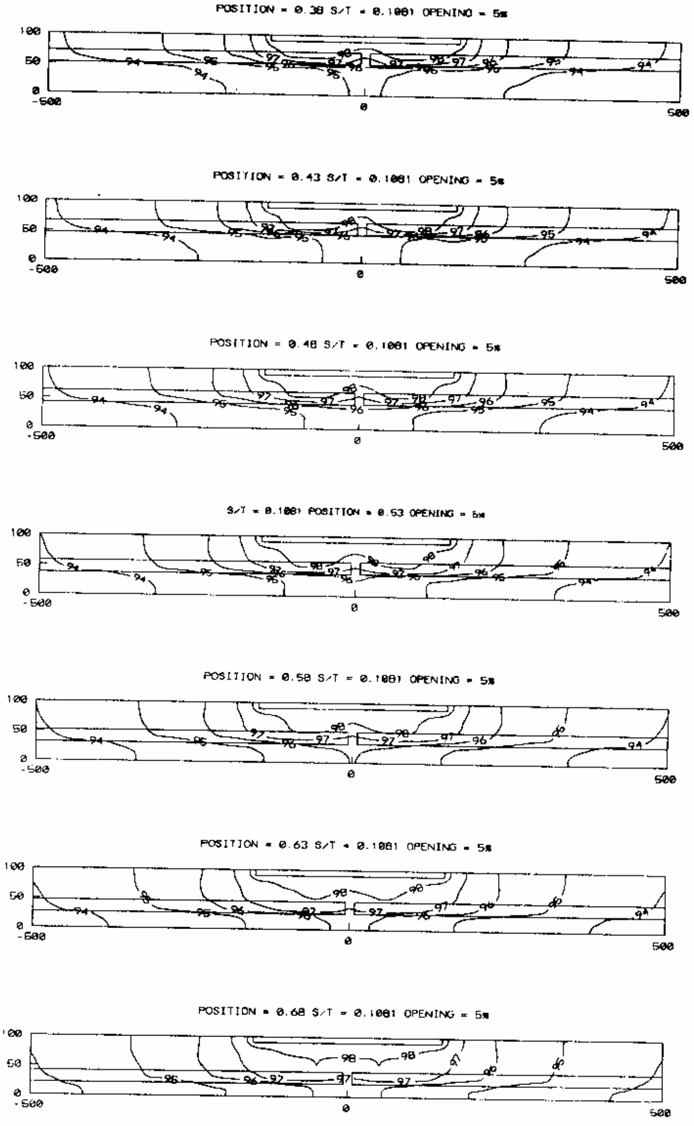


Fig. 4.2.1.1 Distribution of hydraulic potentials in the aquifer system for various S/T ratios for 5% Opening when the fractured-aquitard is positioned at 0.53



POSITION = 0.38 S/T = 0.1001 OPENING = 5%

POSITION = 0.43 S/T = 0.1001 OPENING = 5%

POSITION = 0.48 S/T = 0.1001 OPENING = 5%

S/T = 0.1001 POSITION = 0.53 OPENING = 5%

POSITION = 0.58 S/T = 0.1001 OPENING = 5%

POSITION = 0.63 S/T = 0.1001 OPENING = 5%

POSITION = 0.68 S/T = 0.1001 OPENING = 5%

Fig. 4.2.1.2 Distribution of hydraulic potentials with the fractured-aquitard positioned at various depths in the aquifer for a particular S/T ratio and constant opening

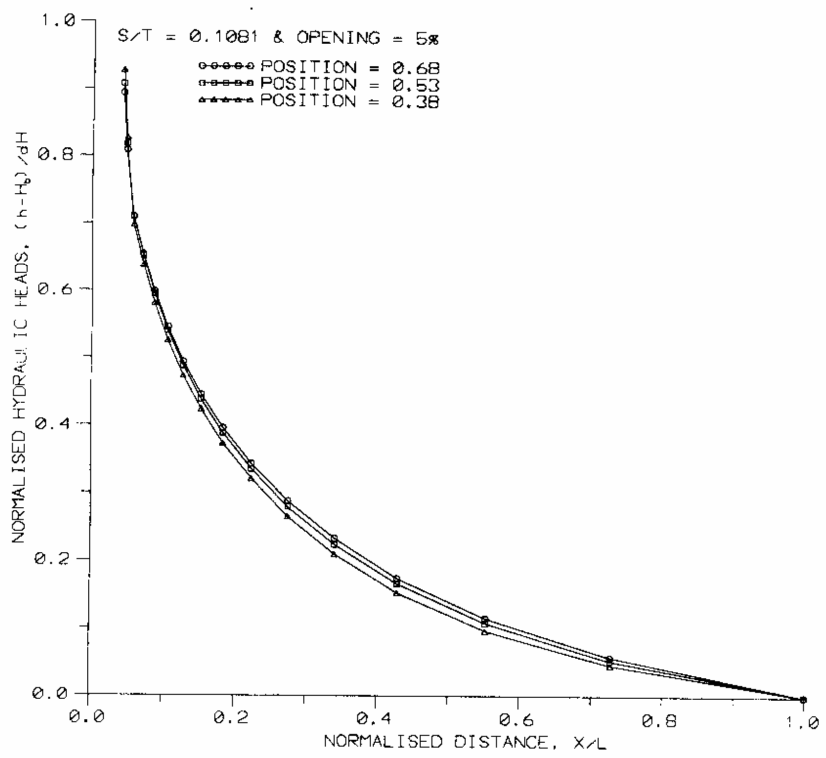


Fig. 4.2.1.3 Normalised distance from the source to the sink versus the normalised hydraulic heads in the top aquifer for different positions of the aquitard with constant S/T ratio and opening

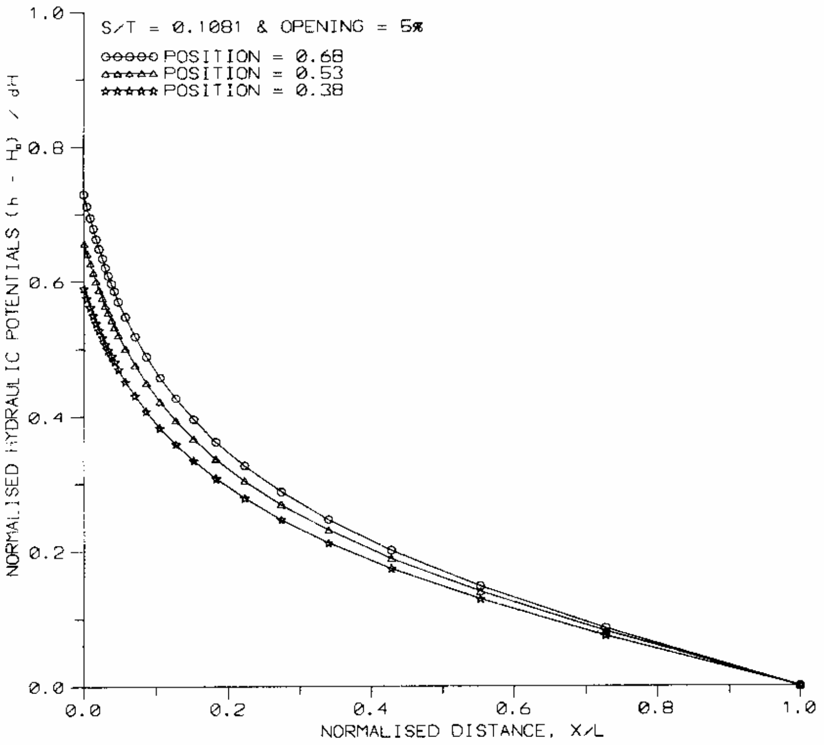


Fig. 4.2.1.4 Normalised distance from the source to the sink versus the normalised hydraulic potentials in the bottom aquifer for different positions of the aquitard with constant S/T ratio and opening

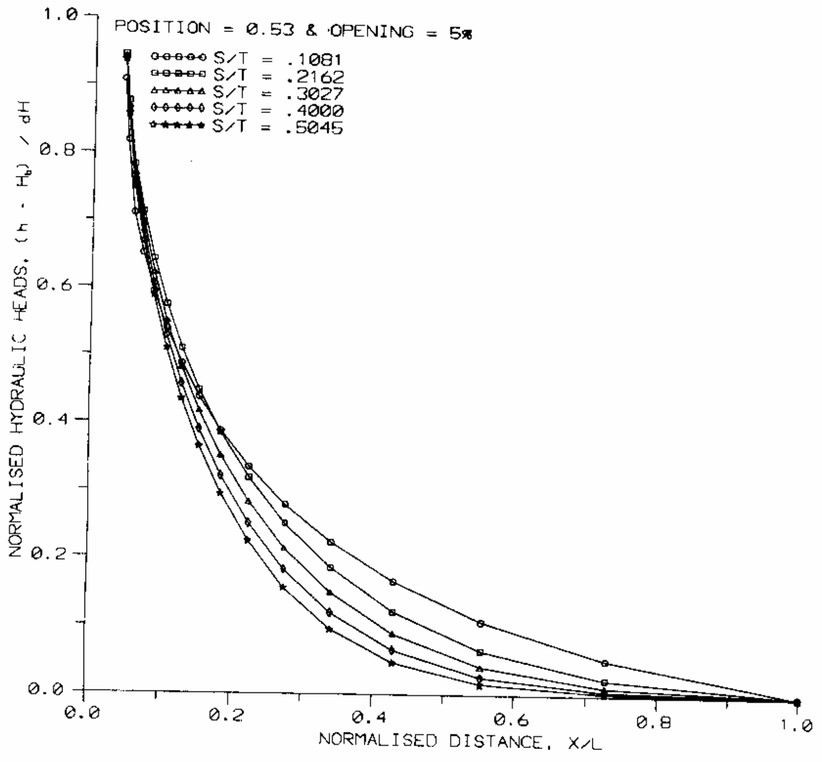


Fig. 4.2.1.5 Normalised distance from the source to the sink versus the normalised hydraulic heads in the top aquifer for various S/T ratios for a fixed position of the aquitard and constant opening

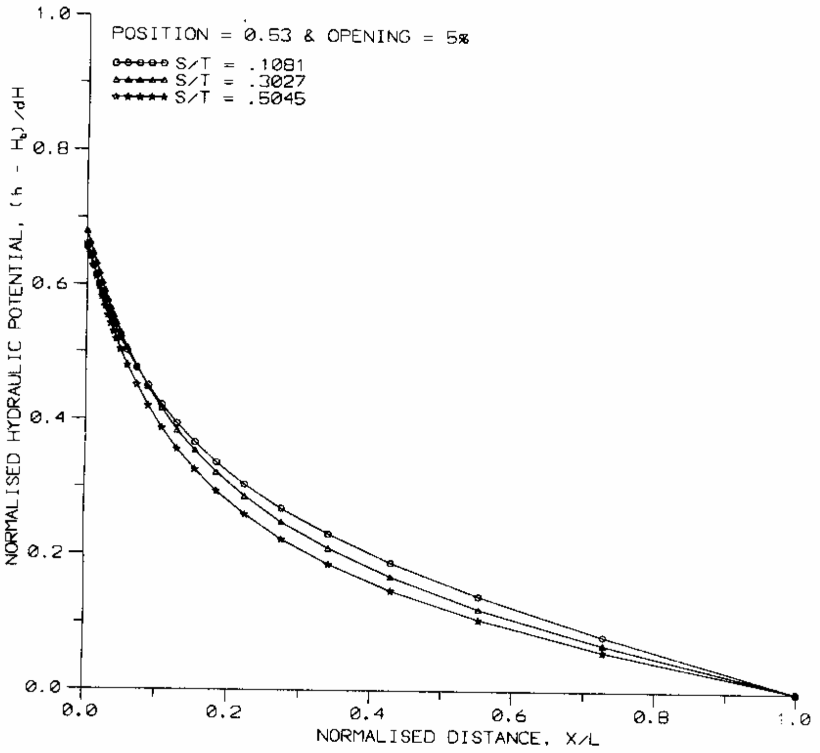


Fig. 4.2.1.6 Normalised distance from the source to the sink versus the normalised hydraulic potentials in the bottom aquifer for various S/T ratios for a fixed position of the aquitard and constant opening

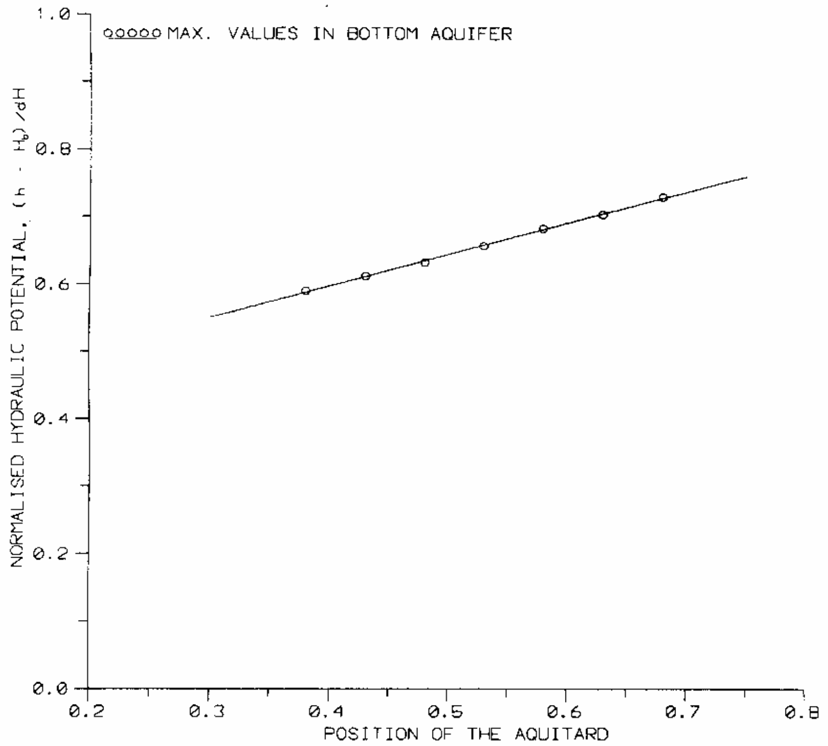


Fig. 4.2.1.7 Different positions of the fractured-aquitard versus the maximum values of normalised hydraulic potentials in the bottom aquifer

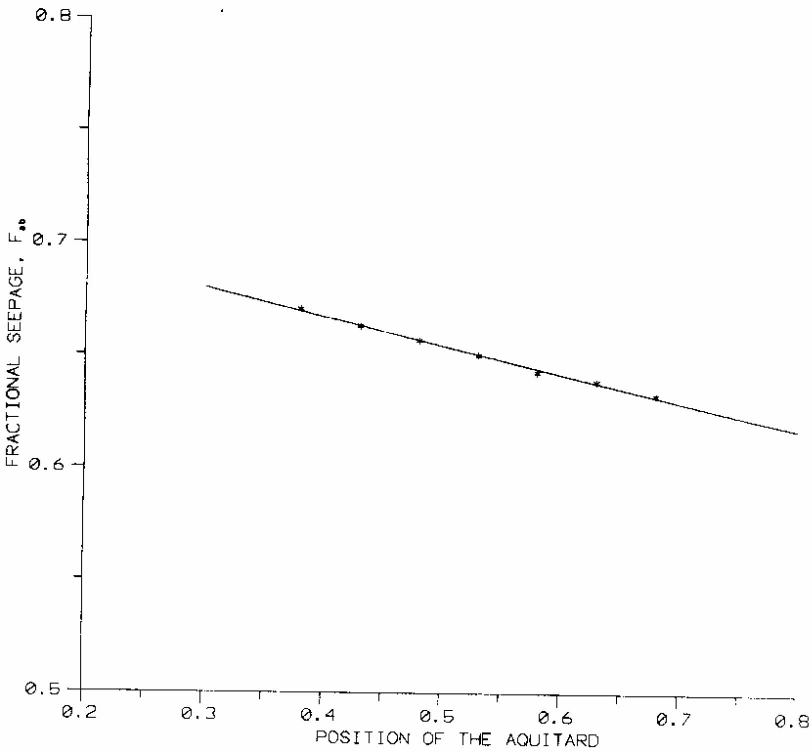


Fig. 4.2.1.8 Different positions of the fractured-aquitard versus fractional seepage to the bottom aquifer

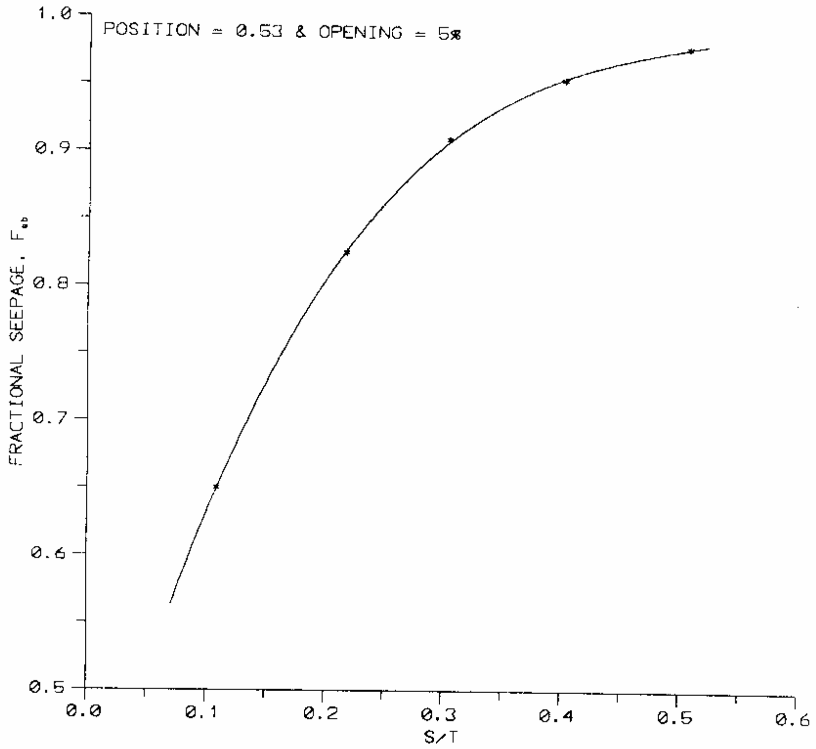


Fig. 4.2.1.9 S/T ratio versus fractional seepage to the bottom aquifer for a fixed position of the fractured-aquitard and 5% opening

5.0 CONCLUSION

The influence of a fractured-aquitard on the seepage from the water body has been investigated and analysed. The study envisaged two main aspects related to the location and position of the fractured aquitard. Precisely, the influence on the seepage from the source due to the location of the fractured zone in the aquitard as well as the position of the fractured aquitard itself in the aquifer system has been studied. The analysis revealed interaction aspects that may facilitate location of a recharge pond/ tank in order to gain optimum recharging of the underlying aquifer.

Regarding the influence of location of a fractured zone in the confining aquitard, the following aspects has been brought out:

i) The hydraulic potential in the bottom aquifer tends to reduce as the fractured zone in the aquitard moves away from the source.

ii) The hydraulic potentials in the top aquifer is not much influenced by the shifting of the fractured zone in the aquitard.

iii) The maximum hydraulic potential in the bottom aquifer is found to be directly below the opening thereby marking a shift of the maximum hydraulic potential in the direction of shifting of the opening.

iv) The fraction of total seepage to the bottom aquifer gets reduced with the shifting of fractured zone away from the centre of the system.

v) While exhibiting similarity in behaviour, there is quantitative variation in the effect of location of fractured zone on seepage for aquifer systems having different aquifer parameters.

vi) For a given location of a fractured zone, the extent of influence on seepage is found to be high for smaller openings. As the opening becomes larger the influence of its location in the aquitard tends to reduce.

It appears that the maximum seepage to the bottom aquifer occurs when the fractured zone irrespective of its dimension is located centrally below the recharging source.

The various cases analysed with different positions of the fractured aquitard to study the influence of its positioning on the seepage from a water body, disclosed that the positioning of the aquitard has a regulatory role in recharging the bottom aquifer. It is found that:

i) For all positions of the aquitard, the behaviour of hydraulic heads/potentials in the top and bottom aquifer respectively is found to be similar.

ii) The hydraulic potential in both the aquifers are found to be higher when the fractured aquitard is closer to the impermeable lower boundary; in other word when the aquitard is positioned nearer to the source the hydraulic potential field in both the aquifers is weaker compared to that for a deeper position of the aquitard with respect to the source.

iii) The fraction of total seepage to the bottom aquifer decreases as the aquitard approaches the lower boundary due to reduced thickness of the bottom aquifer implying lesser water holding capacity. Even though the aquifer system appeared to have developed higher potentials with the fractured aquitard positioned closer to the impermeable boundary, the fractional seepage to the bottom aquifer is reduced in its quantity. It may be stressed that the reduction need not be in the total discharge from the system, but only in the fraction of the total seepage which is transmitted down to the bottom aquifer with a smaller thickness.

The study carried out on the effect of location and position of a fractured-zone in the confining layer within the multilayered aquifer system on the seepage from a surface water body may be useful in assessing the geohydrological and hydraulic response of an aquifer-aquitard system vis-a-vis a recharging source.

Hydrogeological situations similar to the one postulated in the present study may be found in some parts of basaltic terrain (*Singh, 1998*). Therefore, it is desirable to carry out field studies in order to establish the validity of the results and to demonstrate practical usefulness of the findings.

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