ESTIMATING UNDER GROUND HYDROCARBON SPILLS IN HOMOGENEOUS AND LAYERED SOILS

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ABSTRACT

An experimental study was conducted to examine the relation between the hydrocarbon spill volume and the hydrocarbon thickness in a fully screened monitoring well in homogeneous and layered soils. This study showed that soil layering has a significant influence on the spill volume / free product thickness in monitoring wells relation and that local heterogeneity will most likely have a high effect on that relation in real life problems. The experimental results were used to assess the predictions based on theoretical and empirical models available in the literature. The results of such study will help in quantifying groundwater contamination by hydrocarbons from leaking under ground storage tanks.

KEYWORDS

Groundwater contamination; storage tanks;leak;LNAPLs;capillary pressure;saturation

INTRODUCTION

Most people around the world rely on groundwater as the main source of potable water which makes it the most important component of the total water resources. A very important problem of interest which may hinder the development of groundwater resources is its quality deterioration. A prominent source of groundwater contamination is contamination resulting from sources designed to store, transport and dispose hazardous substances. Such sources include pipelines, above ground storage tanks (AGSTs) and under ground storage tanks (UGSTs). UGSTs are often used to store light non-aqueous phase liquids (LNAPLs) like common fuels and other organic products. Such chemicals are frequently stored at farms, industrial facilities and mostly gas stations. Each gas station has at least one large UGST. An UGST may leak through holes in the tank itself or through the associated piping. Such tanks are usually made from steel which often makes them susceptible to corrosion. Once a leak starts, the LNAPL will percolate through the unsaturated zone of the soil and depending on the amount of the spilled volume it may be held by capillary forces at mini saturation values as immobile phase. If the spilled amount is high the LNAPL will con to move downward till it reaches close to the water table where it will alter the s equilibrium and will spread laterally forming what can be described as an LNAPL pool ab the water table. Small part of the LNAPL will dissolve in water and a dissolved contamir plume will be created which will spread in the general direction of the regional grad threatening the groundwater quality (Fig.1). Since such processes take place undergrou it is rare that such problem is discovered early.

Precise estimation of the volume spilled is very important to understand the magnitude of contamination problem in hand and to properly plan for groundwater and aquifer remediati A leak or spill will be indicated by the presence of a free hydrocarbon in a monitoring w The thickness of the hydrocarbon in the well is the easiest parameter to measure and it shc give an indication for the amount of spill.

This paper presents a laboratory study aimed to examine the relation between the spill volu and the hydrocarbon level in fully screened monitoring wells in homogeneous and laye porous media. The experimental results will be used to evaluate the predictions of theoret models available in the literature.

LITERATURE REVIEW

Many researchers concluded that taking the hydrocarbon thickness in monitoring wells representative of its thickness in the aquifer will result in an exaggeration in estimating spilled volume.(van Dam (1967), de Pastrovich et al. (1979), Abdul et al. (1989)). considering hydrostatic equilibrium, van Dam (1967) showed that as the hydrocarbon en a monitoring well, the water level in the well will be lowered by a distance of approximat $\gamma_o/(\gamma_w - \gamma_o)$ times its thickness above the water table. A report by de Pastrovich et al. (19 indicates that the thickness of the free gasoline in the formation is about one-fourth thickness in the monitoring well. Similar results were also suggested by Blake and H (1984). Although that this ratio is frequently used as a rule of thumb to estimate the amo of spills, specialists agree that a rule is not of reliable accuracy and that correction fact that depend on the kind of formation, size distribution, type of hydrocarbon in terms density and interfacial tension is more appropriate. The experimental results of Abdul et (1989) indicate that "the ratio between the oil-layer thickness in the well to that in the por media is not constant as is sometimes assumed in practice". Hall et al. (1984) corrected hydrocarbon thickness in the well by subtracting a quantity which they called the format factor. This factor depends on the pore size distribution of the porous media as well as surface tension of the hydrocarbon. Similar to Hall et al. (1984), Schiegg corrected hydrocarbon thickness in monitoring wells by subtracting twice the average capillary hei under drainage conditions.

A theoretical method to estimate the hydrocarbon volume from its level in a monitoring w was proposed simultaneously by Farr et al. (1990) and by Lenhard and Parker (1990). In t method a hydrostatic distribution in fluid pressures is assumed and that the two ph capillary pressure-saturation relations can be extended to the three phase situation. T method in essence uses the fluids pressure distribution, which can be obtained from the fl

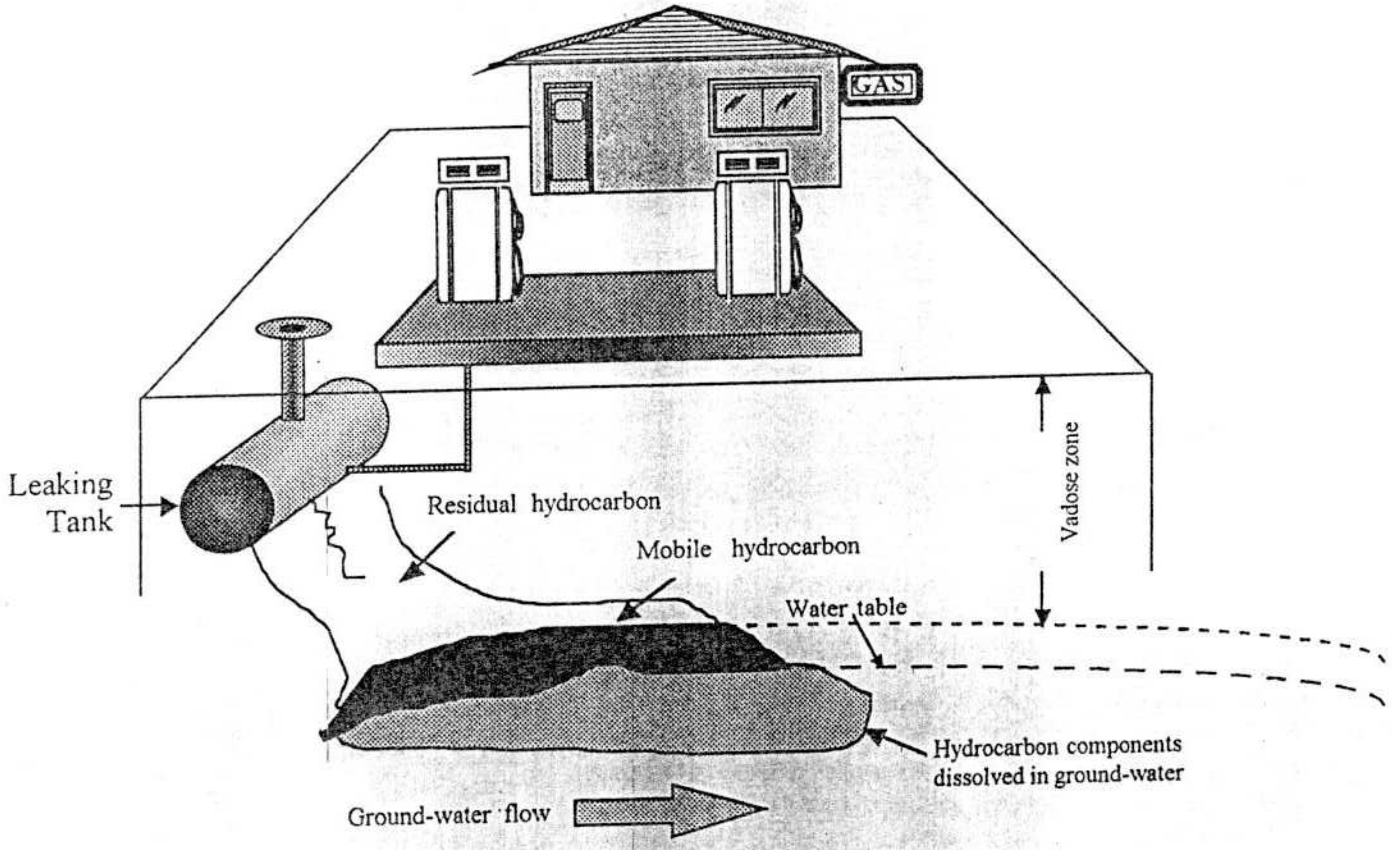


Fig. 1. Leaking UGST.

levels in the well, to obtain the saturation distribution of the hydrocarbon along the ver The hydrocarbon volume is calculated by integrating its saturation along the vertical correcting for the pore volume.

Determining the moisture characteristics of the aquifer material is the key to analytic estimating the amount of spill. The hydraulic parameters that are needed when employ the Brooks-Corey model are: the pore size distribution index (λ), displacement pressure (residual saturation (S_r). These parameters can be obtained using the experimentally obtai saturation capillary pressure curve which is difficult as well as time consuming. alternative was presented by Mishra et al. (1989). They gave a model which predicts the hydraulic parameters using the particle-size distribution of the soil which is easily obtain This method is based on an earlier model by Arya and Paris (1981) in which the particle- distribution is translated into a pore size distribution from which a relation betwee cumulative pore volume and a pore radii is obtained. Such relation can be converted into relating the saturation and the capillary pressure.

MATERIALS AND METHODS

Three circular plexiglass columns were fabricated at KFUPM central shop to be used physical model. Each column has a height of 190 cm and an inside diameter of 30 cm. T semi-circular fully screened monitoring wells 2.5 cm in diameter were fitted to each colur These wells will be used to measure the hydrocarbon thickness. To monitor changes in water table possession as a result of the spill, a piezometer with a bottom opening near base of the column was installed. An incremental amount will be spilled through a fur into a covered chamber with several uniform openings (5 cm below the top soil) in orde assure uniform areal distribution of the spill. A schematic sketch of the physical mode shown in Fig. 2.

Two type of sand are used in this study: well graded and uniform sand. The uniform s is obtained from a local sand dune near Abqaiq while the well grade sand is obtained us a blend of three different soils. The hydrocarbon used in this study is Arabian light cr obtained from Ras Tanura refinery courtesy Saudi ARAMCO.

BASIC THEORY

A typical equilibrium distribution of the three fluids air, hydrocarbon and water after a s along the vertical is shown in Fig. 3. To estimate the spilled hydrocarbon volume per u area , V_o, Farr et al. (1990) and Lenhard and Parker (1990) determined the shaded a between the total liquid saturation (S_t)and the water saturation (S_w) by integration. This a represents the part of the void space occupied by the hydrocarbon.

$$V_o = \int_0^{Tco} \phi \ S_o \ dz = \phi \int_{h_d^{ow}}^{T+h_d^{ao}} (1-S_w) \ dz + \phi \int_{T+h_d^{ao}}^{Tco} (S_t - S_w) \ dz \quad \textbf{(1)}$$

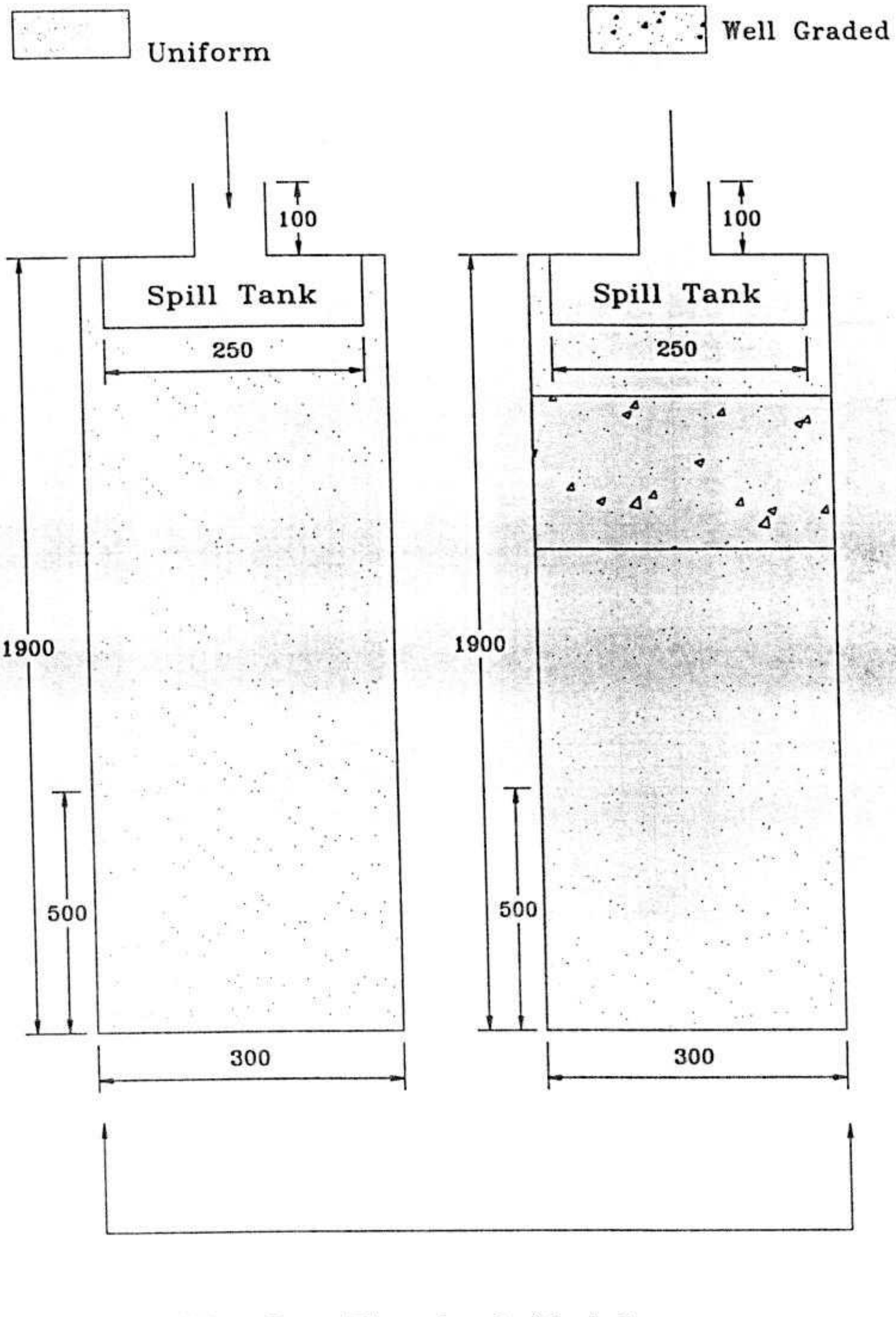
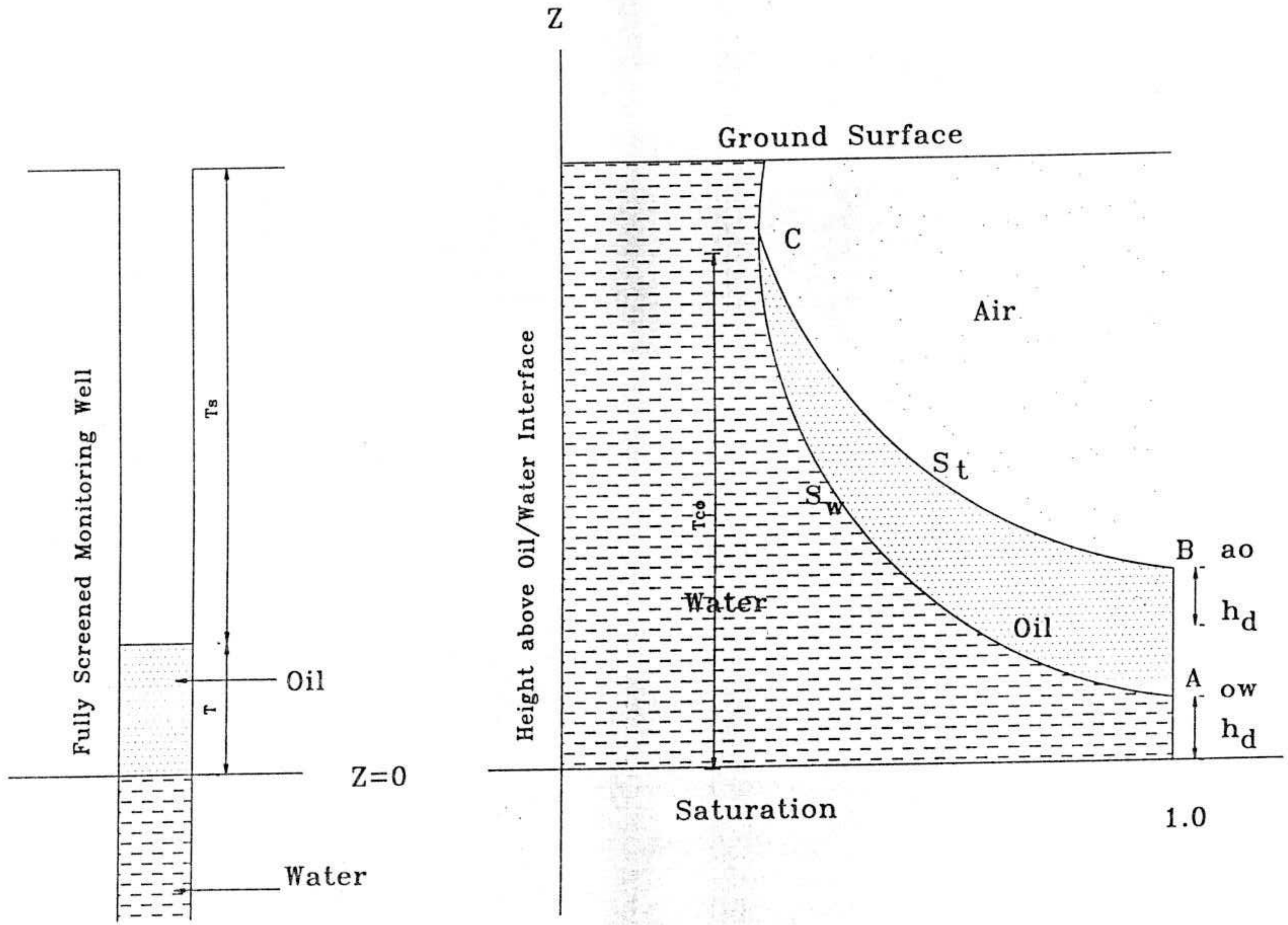


Fig 2. Physical Model

(Note: All dimensions are in millimeters)


Fully Screened Monitoring Well
Ts
T
Oil
Z=0
Water
Z
Ground Surface
C
Air
Height above Oil/Water Interface
Tco
S t
S w
B ao
h d
Water
Oil
A ow
h d
Saturation
1.0

The saturation is related to the capillary pressure through the van Genuchten or the Brooks-Corey equation. In this section the Brooks-Corey will be presented. The water saturation curve is given by:

$$S_w = (1-S_{rw}) \; [\, \frac{P_c^{ow}}{P_d^{ow}} \,]^{-\lambda_{ow}} + S_{rw} \qquad (2)$$

where:

S_w	water saturation,
S_{rw}	residual water saturation,
P_c^{ow}	the capillary pressure between water and hydrocarbon,
P_d^{ow}	the displacement pressure between water and hydrocarbon,
λ_{ow}	the pore size distribution index for hydrocarbon/water system.

The total saturation is assumed to be independent of the water hydrocarbon capillary pressure and depends only on the capillary pressure between the hydrocarbon and air. Thus the total liquid saturation can be expressed as

$$S_t = (1-S_{rt}) \; [\, \frac{P_c^{ao}}{P_d^{ao}} \,]^{-\lambda_{ao}} + S_{rt} \qquad (3)$$

where the variable are the same as defined above except that they apply for the hydrocarbon air system.

Both Farr et al. (1990) and Lenhard and Parker (1990) assume that the pore size distribution indices and the residual saturations are properties of the porous media and are independent of the fluids. The displacement pressures however,are expected to depend on the fluid pair. If the three phase parameters are not available, they can be derived from two phase parameters using the approach suggested by Parker et al. (1987) using the following relations:

$$P_d^{ow}/\sigma_{ow} = P_d^{ao}/\sigma_{ao} = P_d^{aw}/\sigma_{aw} \qquad (4)$$

The capillary pressure heads between the fluid pair as a function of the elevation above the water/hydrocarbon interface in the monitoring well, z, are:

$$P_c^{ow} = (\rho_w - \rho_o)\, g\, z \qquad (5)$$

$$P_c^{ao} = \rho_o\, g\, (z-T) \qquad (6)$$

where

ρ_w water density,
ρ_o hydrocarbon density,
g acceleration due to gravity.

Equations 2-6 are used in 1 before carrying the numerical integration to come up with estimate of the hydrocarbon volume.

Lenhard and Parker (1990) indicated that pure static conditions are usually rare in f problems and that a better representation of the problem should involve a sort of quasi-st approximation of the fluids distribution. Fluids tend to change this condition to st equilibrium. However, the low values of the relative permeability due to drainage makes process require very long time. Therefore a residual saturation is taken such that the relat permeability is very small (say 0.1% of the saturated permeability).

LAYERED POROUS MEDIA

The same principles apply for layered porous media with one exception which is that at interfaces of the soils there will be a jump in the saturation as shown in Fig. 4 (i.e. saturation function if not continuous). This means that the heterogeneous system should divided into homogeneous sub-systems which allows calculations at each sub-system using own parameters then adding the contribution of each to come up with the final spill estim

RESULTS AND DISCUSSION

Several points that define the relation between the spill volume and its thickness in f screened monitoring wells were generated experimentally for a column containing san (homogeneous column) as well as on other column with a 30 cm layer of soil 2 just be the spill tank (layered column). Initially a volume of 3000 ml of crude oil (specific gra = 0.86) was released in each column and the system was allowed to approach equilibri conditions which took about two weeks. The hydrocarbon showed in one of the monitor wells of the layered column while an additional volume of 500 ml was released before hydrocarbon was observed in any of the monitoring wells in the homogeneous column. T result confirms the prediction based on the Brooks-Corey model which suggest that ther a critical spill volume below which no product will be observed in a monitoring well.

Additional crude was released in increments and the free product thickness that correspon to different spill volumes were measured after quasi-equilibrium conditions were reached obtain the curves given in Fig. 5. The figure shows a clear difference between the measu thickness in the homogeneous soil and the layered soil for the same spill volume. T difference is higher for small spill volumes and it approaches a constant value of about 5 c This difference which may seem small, could mean an error in estimating the spill volu of close to 2 cm^3 in each square centimeter of the porous media indicating the importance considering the system layering when making spill estimates. The figure also shows that

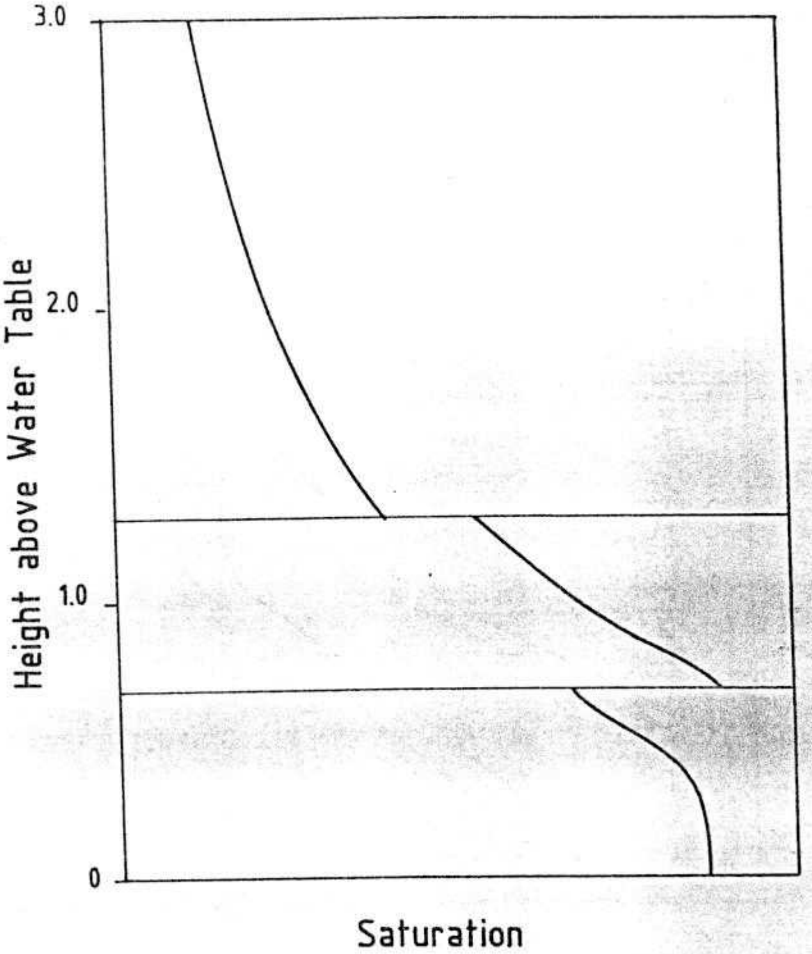


Fig. 4. Soil Saturation in a stratified Porous Media.

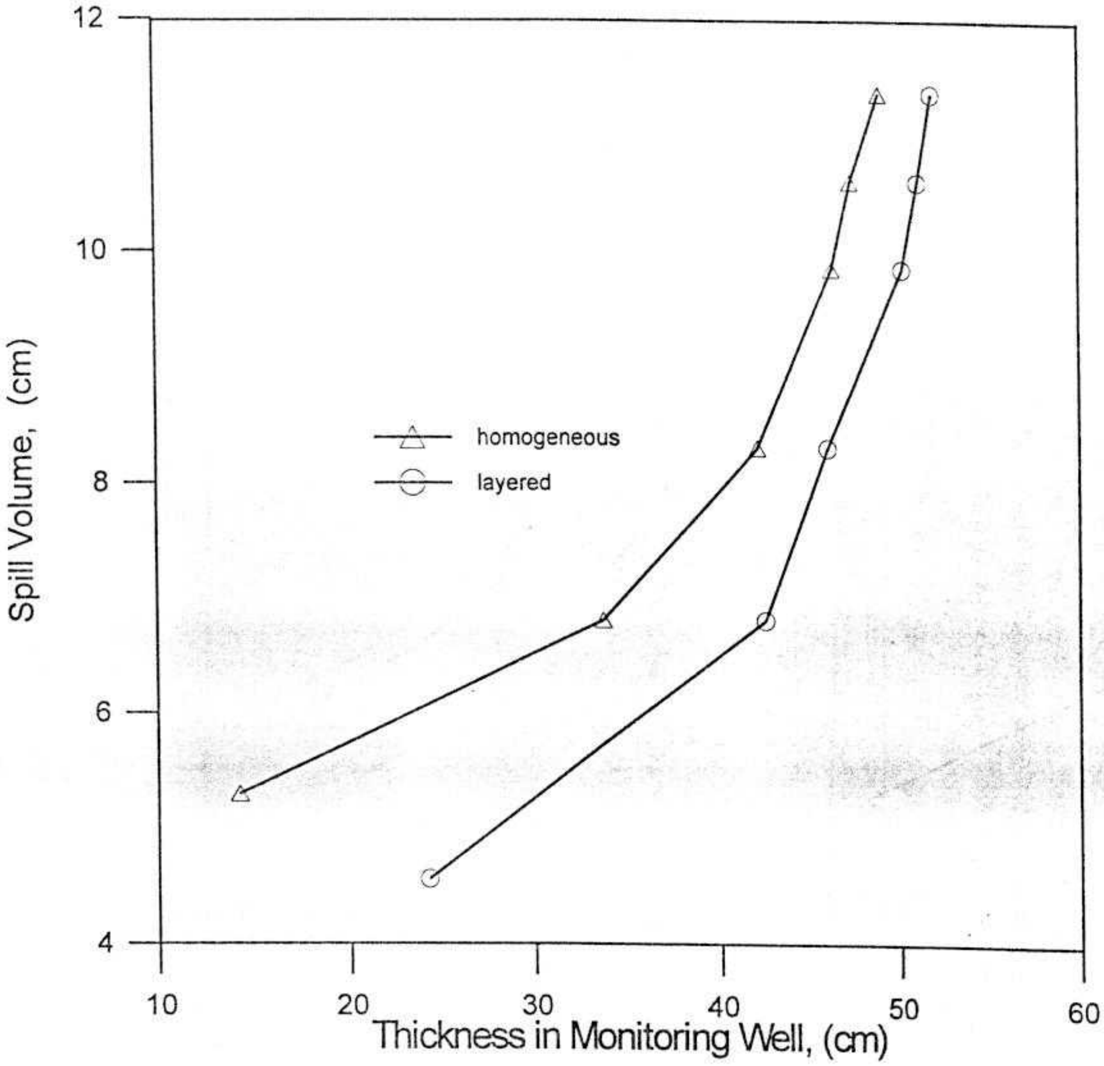


Fig. 5. Spill volume versus measured free product thickness in a monitoring well for homogeneous and layered soils.

ratio of the hydrocarbon thickness in the monitoring well and the free hydrocarbon thickness in the porous media was not constant in either column which is in agreement with the general consensus.

Each of the curves of Fig. 5 can be approximated using two straight line segments; a straight line with a gentle slope can be used at low values of the free product thickness and another with a higher slope for high values of the free product thickness. The limit that define what is low and what is high thickness obviously will depend on the characteristics of the porous media.

In both the columns there was a time lag in the appearance of the free product in the two monitoring wells. Once it appeared in both wells, its level tended to equilibrate, though a small difference between the two levels was noticed. This can be explained by the spatial heterogeneity due to uncontrollable elements like the degree of local packing and wall effects within the sand columns. This phenomenon is expected to be more noticeable in real life problems where a greater variability exists within the field scale.

The water table behavior as the spill progressed was observed using a piezometer open near the base of the column. At the initial phase of the spill, oil started to accumulate just above the water capillary fringe. After the critical spill volume was exceeded, a free product layer started to develop and it flowed into the well. Further addition of oil caused the oil level and the oil/water interface in the well to rise and fall respectively. The water table level as a function of time is shown in Fig. 6. The flat regions in this curve indicated that quasi-static conditions were reached at which additional crude was spilled.

In Fig. 7, the experimental results from the homogeneous column are compared with the two empirical models of Hall et al. (1984) and de Pastrovich et al. (1979) as well as the analytical model of Farr et al. (1990) and Lenhard and Parker (1990). All of these models clearly underestimate the spill amount which shows the need for a better method to quantify such spills.

CONCLUSIONS

Based on this study the following conclusions can be drawn:

1. The nature of the relationship between the spill volume and the free product thickness can be simplified using two straight line segments; one with gentle slope, for small values of the free product thickness, and another with high slope for high values of the free product thickness.

2. Soil layering has a significant influence on the spill volume / free product thickness in monitoring wells relation and any attempt to use the product levels to quantify the extent of contamination must take into account the system layering.

3. Local heterogeneity caused some variations in the measured free product in monitoring wells even in homogeneous laboratory columns, and it is expected to have high influence in field problems.

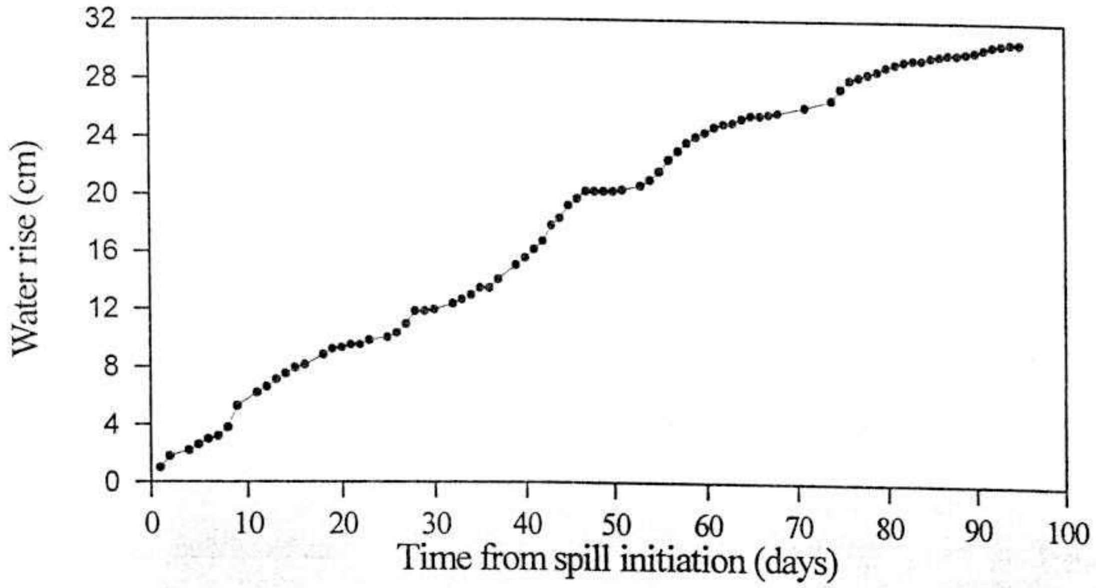


Fig. 6. Water table rise as a function of time (homogeneous column)

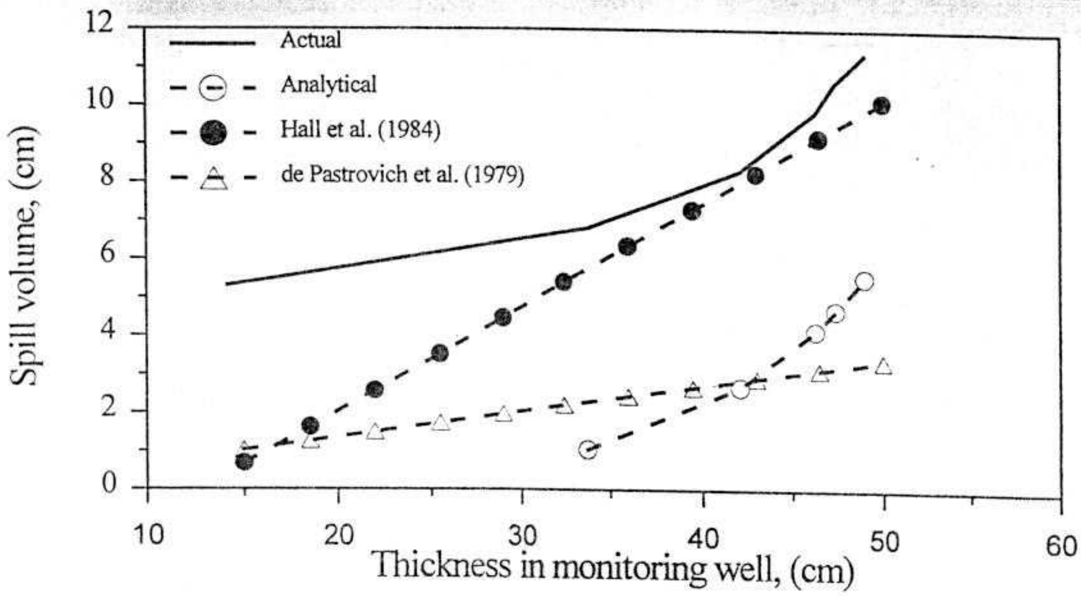


Fig. 7. Predicted and actual spill volume as a function of free product thickness in a monitoring well.

4. Neither traditional "empirical" models nor analytical models were able to accurately quantify the amount of the spills based on the free product thickness in monitoring wells.

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