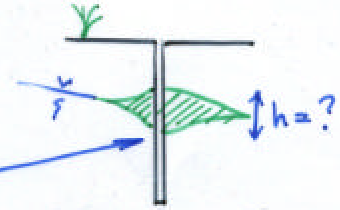
## 3.7.2 Thickness of Floating Product

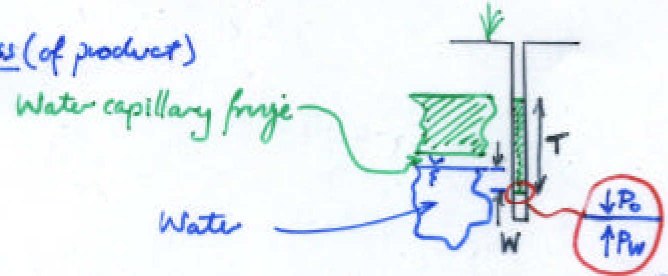
What is true depth/thickness of NAPL

Borehole will show artificial LNAPL depth

Artificial depth since.




Well thickness (of product)




$$P_o = P_w$$

$$P_o = \rho_o T g$$

$$P_w = \rho_w W g$$

Equating $\rho_o T = \rho_w W$ $\Rightarrow$ $\boxed{W = T\left(\frac{\rho_o}{\rho_w}\right)}$

Measure T, calculate W.

Volume of product $\Rightarrow$ Thickness $(T-W)$ (ignoring cap fringe height)

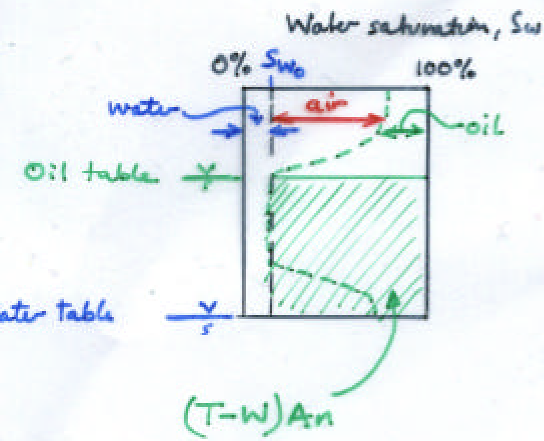
Volume of porespace $A(T-W)n$

Volume of product $\sim A(T-W)n\,(1-S_{w_o})$

$S_{nw_o}$

Not all is recoverable!!

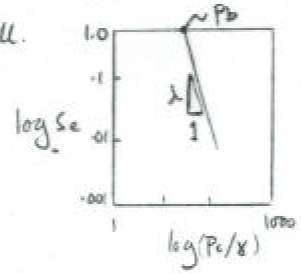
Approx recoverable volume of product $\sim A(T-W)n(1-S_{w_o}-S_{nw_o})$



# Recoverable Volume

Brooks-Corey (1966) soil.

Recall.




Se = effective saturation

$$Se = \frac{(S_W - S_{WO})}{(1 - S_{WO})}$$

Farr, Houghtalen, and McWhorter (1990) and Lenhard and Parker (1990) developed two methods to estimate the volume of recoverable LNAPL in an aquifer based on the thickness of the LNAPL floating in a monitoring well. These methods are based on the capillary soil properties. One of the two methods is based on the determination of soil properties as reported by Brooks and Corey (1966). We will look at this method in some detail using the derivation of Farr, Houghtalen, and McWhorter.

*T* as shown in Figure 5.19 is the difference between the depth to the water-oil interface in the well, $D_w^{ow}$ and the depth to the oil-air interface, $D_w^{ao}$. The values of the depth to the oil table in the aquifer, $D_a^{ow}$, and the depth to the top of the capillary fringe, $D_a^{ao}$, can be computed.

$$* \quad D_a^{ao} = D_w^{ao} - \frac{P_d^{ao}}{\rho_o g} \qquad (5.29)$$

height of oil capillary fringe

$$* \quad D_a^{ow} = D_w^{ow} - \frac{P_d^{ow}}{(\rho_w - \rho_o) g} \qquad (5.30)$$

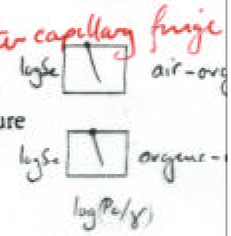
height of W + water capillary fringe

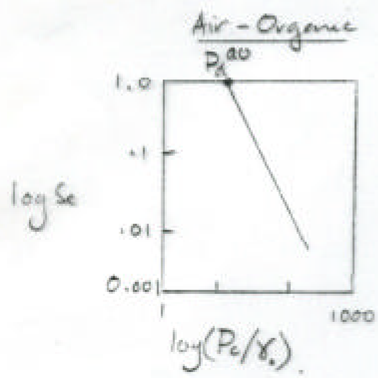
where

$P_d^{ao}$ = the Brooks-Corey air-organic displacement pressure

$P_d^{ow}$ = the Brooks-Corey organic-water displacement pressure

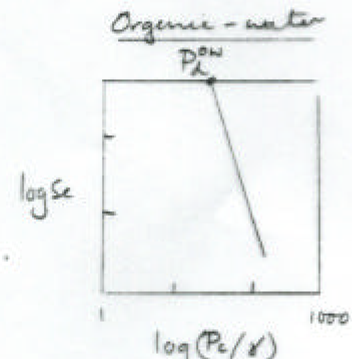
$g$ = the acceleration of gravity



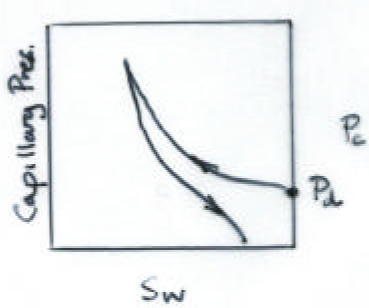

Wetting = organic

Non-wetting = air




Wetting = water

Non-wetting = organic



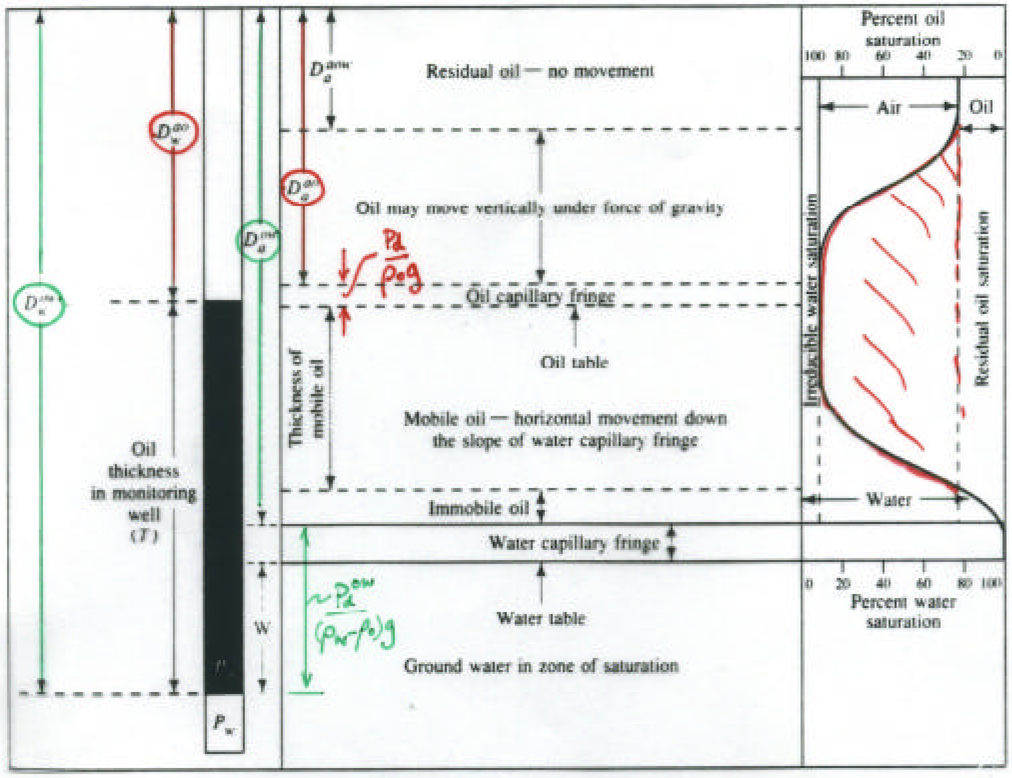



**FIGURE 5.19** Comparison of distribution of mobile oil in an aquifer with the thickness of floating oil in a monitoring well for the case where a water capillary fringe exists below the zone of mobile oil.

TERMINOLOGY: $D_W^{OW}$ — OW: organic-water interface; W: Measured in the well

Since on figure $D_w^{ow} = D_w^{ao} + T$, then

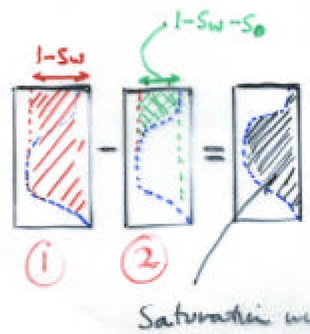
Equation 5.30 may be rewritten as

$$D_a^{ow} = (D_w^{ao} + T) - \frac{P_d^{ow}}{(\rho_w - \rho_o)g} \tag{5.31}$$

If any of the organic liquid exists at a positive pore pressure, then $D_a^{ow}$ will be greater than $D_w^{ao}$ and from Equation 5.31,

$$T \geq \frac{P_d^{ow}}{(\rho_w - \rho_o)g} \tag{5.32}$$

SUM OIL COMPONENTS




If the organic liquid is all under tension in the capillary zone, then there will be no mobile organic layer and no organic liquid will collect in the monitoring well. Under these conditions, Equations 5.29, 5.30, 5.31, and 5.32 are not applicable. However, as soon as free organic liquid appears in the aquifer, it will collect to a depth of at least $P_d^{ow}/(\rho_w - \rho_o)g$

The total volume of nonresidual organic liquid in the vadose zone is given by

$$V_o = n\left\{\int_{D_a^{owa}}^{D_a^{ow}} (1 - S_w)\,dz - \int_{D_a^{owa}}^{D_a^{ao}} [1 - (S_w + S_o)]\,dz\right\} \tag{5.33}$$

(1) (2)

where

$V_o$ = the volume of organic liquid per unit area

$n$ = the porosity

$S_w$ = the water-saturation ratio

$S_o$ = the organic liquid saturation ratio

$z$ = the vertical coordinate measured positively downward

$D_a^{ow}$ = a value determined from Equation 5.30

$D_a^{ao}$ = a value determined from Equation 5.29

$D_a^{owa}$ = the top of the zone where nonresidual oil occurs

Based on work by Lenhard and Parker (1987, 1988), the fluid-content relations are

RELATE FLUID PRESSURES TO SATURATIONS

$$S_o - S_w = (1 - S_{wi})\left(\frac{P_c^{ao}}{P_d^{ao}}\right)^{-\lambda} + S_{wi}, \qquad P_c^{ao} > P_d^{ao} \tag{5.34a}$$

$$S_o + S_w = 1, \qquad P_c^{ao} < P_d^{ao} \tag{5.34b}$$

$$S_w = (1 - S_{wi})\left(\frac{P_c^{ow}}{P_d^{ow}}\right)^{-\lambda} + S_{wi}, \qquad P_c^{ow} > P_d^{ow} \tag{5.35a}$$

$$S_w = 1, \qquad P_c^{ow} < P_d^{ow} \tag{5.35b}$$

where

$S_{wi}$ = the irreducible water saturation

$\lambda$ = the Brooks-Corey pore-size distribution index

In addition,

$$P_c^{ao} = \rho_o g(D_w^{ao} - (P_d^{ao}/\rho_o g) - z) + P_d^{ao} \tag{5.36}$$

$$P_c^{ow} = g(\rho_w - \rho_o)\left[D_a^{ow} - \frac{P_d^{ow}}{(\rho_w - \rho_o)g} - z\right] + P_d^{ow} \tag{5.37}$$

VOLUMES IF RESIDUAL ZONE PRESENT

Integration of Equation 5.33 for $D_a^{aow} > 0$, using Equations 5.34, 5.35, 5.36, and 5.37, yields the following. For $\lambda$ not equal to 1,

$$V_o = \frac{\phi(1 - S_{wi})D}{1 - \lambda}\left[\lambda + (1-\lambda)\left(\frac{T}{D}\right) - \left(\frac{T}{D}\right)^{1-\lambda}\right] \tag{5.38a}$$

($\phi$ → n)

For $\lambda$ equal to 1,

$$V_o = n(1 - S_{wi})[1 - D(1 + \ln T)] \tag{5.38b}$$

where

$$D = \frac{P_d^{ow}}{(\rho_w - \rho_o)g} - \frac{P_d^{ao}}{\rho_o g}$$

$$T = D_w^{ow} - D_w^{aw} \geq \frac{P_d^{ow}}{(\rho_w - \rho_o)g}$$

VOLUMES IF RESIDUAL ZONE ABSENT

If organic liquid above the residual saturation exists all the way to the land surface, then $D_a^{owo}$ does not exist. Under this condition integration of Equation 5.33 yields the following. For $\lambda$ not equal to 1,

$$V_o = n(1 - S_{wi})\left\{(T - D) - \frac{P_d^{ao}}{\rho_o g(1-\lambda)}\left[1 - \left(\frac{\rho_o g D_w^{ao}}{P_d^{ao}}\right)^{1-\lambda}\right] + \frac{P_d^{ow}}{(\rho_w - \rho_o)g(1-\lambda)}\left[1 - \left(\frac{(\rho_w - \rho_o)gD_w^{ow}}{P_d^{ow}}\right)^{1-\lambda}\right]\right\} \tag{5.39a}$$

For $\lambda$ equal to 1,

$$V_o = n(1 - S_{wi})\left[(T - D) - \frac{P_d^{ow}}{(\rho_w - \rho_o)g}\ln D_w^{ow} + \frac{P_d^{ao}}{\rho_o g}\ln D_w^{ao}\right] \tag{5.39b}$$

Approx. volume (simple) = $V \simeq n(1 - S_{wo} - S_{nwo})(T - W)$

Reasons not to be able to recover free product:

1. Lenses of low conductivity