Controlling Contaminated Fluid from Polluting Groundwater using Porous Media.

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Abstract: The study of movement of underground water helps to predict the flow of contaminated fluid from a solid waste landfill into a portable water supply. Sand samples from river bed were used as stratified porous media and a laboratory experiment was set up to look at the deflection pattern in term of volume of liquid flowing across a unit cross-sectional area per unit time at different angles. Water was made to flow through the inlet and outlet pipes filled with sands of different porosities and the volume of water discharge was determined by volumetric method. A graph of cosine of angle of deflection against porosity ratio gives a relation cos θ = 1.98ln ϕ_r + 1.13. With this established equation, a stratified porous media of known porosity ratio can be used to control the direction of contaminated fluid in sub-surface layer. [Journal of American Science 2010;6(9):247-255]. (ISSN: 1545-1003).

Key words: porosity, inclination angle, volume flux, deflection, outlet angle

1. Introduction

There are three major wastewater disposed techniques. They are treatment and discharge into surface waters, treatment and reuse and land disposal via septic tanks and spray irrigation (Henry, 2003). Major consideration will be given to land disposal of sewage in this study. The major factor influencing the suitability of the soil for filter field use is the water-saturated hydraulic conductivity.

Sewage effluent may move so rapidly in high hydraulic conductivity sand and disease organisms are not destroyed before shallow- water supplies become contaminated. Soils with low hydraulic conductivity are not suited for septic drain fields, because the sewage effluent may saturate soil and contaminate the surface soil (Henry, 2003). Thus, there is a need to seek for better or suitable soil filter for the field.

Heterogeneous medium is used as protective filter and drainage control medium, for example when a small amount of clay is mixed with sand in man- made constructions (Sower and Sower, 1970 and Cedergreen, 1976). However, it has been observed that under the same hydraulic gradient, layered (stratified) heterogeneous medium serves better than mixed heterogeneous medium (Popoola et al, 2008). In another experiment, it was observed that layered heterogeneous medium arranged in descending order of porosity from bottom serves better and gives the relationship between maximum volume flux (or specific discharge) q_{max} and porosity ratio ϕ_r as $q_{max} = 37.89\phi_r - 18.39$ (Popoola et al, 2008)

The purpose of this work is to device a means to deflect the sewage effluent from the direction of water supplies by using layered (or stratified) heterogeneous medium by establishing the relationship between angle of deflection (θ) and porosity ratio which can be used to control the direction of flow of contaminated fluid or sewage effluent in sub-surface groundwater.

2. Theoretical Background

When streamlines from a medium of a given hydraulic conductivity K_1 cross the boundary of a medium with different hydraulic conductivity K_2, they are refracted in a manner similar to optical refraction of light rays. The refraction follows the law

$$\frac{k_1}{\tan\theta_1} = \frac{k_2}{\tan\theta_2} \qquad (1)$$

(Casagrande, 1937 and Cedergreen, 1976)

where

θ_1 = angle between the normal line and the incident line in medium of hydraulic conductivity K, and
θ_2 = angle between the normal line and the refraction line in medium of hydraulic conductivity K_2

The flow lines deflect to conform to equation

$$\frac{\tan\beta}{\tan\alpha} = \frac{k_1}{k_2} \qquad \text{(Cedergreen, 1976)} \qquad (2)$$

Where

α = angle between the flow line in medium 1 and the boundary (or interface)
β = angle between the deflected flow line in medium 2 and the boundary
k_1 = permeability of medium 1
k_2 = permeability of medium 2

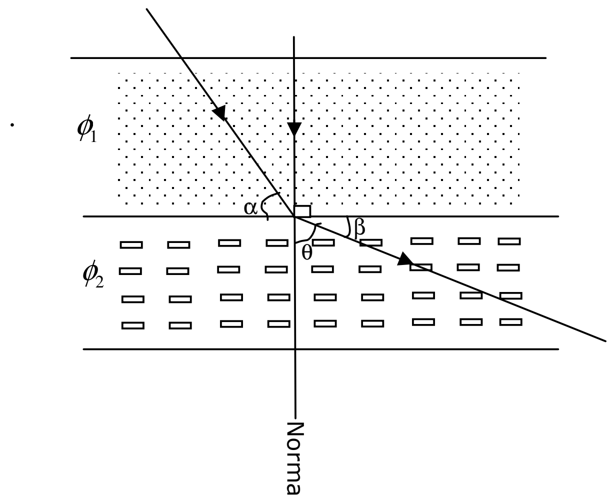


Figure 1: Schematic diagram to show the relationship between refracted angle and deflection angle.

The equation 1 above is used to construct flow net, which can be used to solve drainage and seepage problem by civil engineers (Cedergreen 1976). However this can only be used to reduce the seepage but not to deflect the fluid. Also, it is has been found that permeability varies with porosity and gradient (Popoola et al, 2007). Thus a simple parameter like porosity that can be easily determined in the laboratory will be used in the new equation to be established. The same concept is viewed in another way from the fundamental optical principle (Snell's law) to explain fluid flow in a medium of two strata of different porosity vis-à-vis hydraulic conductivity.

By using Snell's law in optics, another equation which relates angles α and β with porosity is obtained as

$$\frac{\sin\alpha}{\sin\beta} = \frac{q_2}{q_1}\cdot\frac{\phi_2}{\phi_1}$$

$$\frac{\cos\theta}{\sin\alpha} = \frac{q_1}{q_2}\cdot\frac{\phi_1}{\phi_2} \qquad (3)$$

Where $\phi_2 \rangle \phi_1$ and

α = angle between the flow line and the boundary in medium 1
β = angle between the deflected flow line and the boundary in medium 2
θ = angle between the normal line and the flow line in the medium
ϕ_1= porosity of medium 1 (fined-grained medium)
ϕ_2= porosity of medium 2 (coarse-grained medium)
q_1= volume flux in medium 1 and
q_2= volume flux in the medium 2

In other to make the equation relevant to the experimental set up for the purpose of application, angle α is assumed to be 90^0 (laminar flow) and related with angle θ (Figure. 1).

Then equation (3) becomes

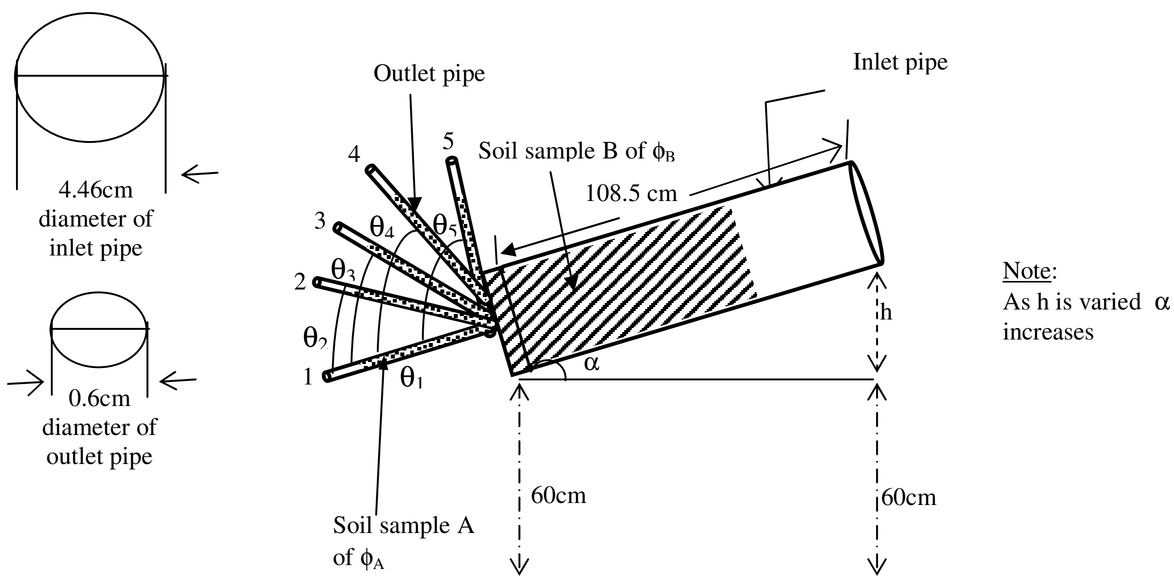
$$\cos\theta = \frac{q_1}{q_2}.\phi_r \qquad (4)$$

Where $\phi_r = \frac{\phi_1}{\phi_2} =$ porosity ratio

This shows that deflection angle θ is related with porosity ratio ϕ_r as written above.
This equation (4) can now be used as the basis for this work.

3. Material and Method

Sand samples were collected from two rivers, processed and sieved into five different sizes so as to have different porosities. Porosity of these samples were obtained by volumetric approach and the results are presented in Table 1.



θ_1 = 0^0 to the normal
θ_2 = 20^0 "
θ_3 = 50^0 "
θ_4 = 70^0 "
θ_5 = 90^0 "

α = angle of inclination. $\alpha = 0^0, 5^0, 10^0, 15^0$ and 20^0

Figure.2: Schematic Diagram of set-up to determine volume flux at different outlet angles.

A modelled experiment was performed in the laboratory using riverbed sand of varying porosities. A set-up (Figure 2) consisting of a big transparent cylindrical pipe 108.5cm long with radius 2.23cm was used as inlet pipe while five small equal cylindrical pipe of radii 0.3cm were used as outlet pipes, which were joined to the circular plastic plate on the top of the inlet pipe at angle θ of 0^0, 20^0, 50^0, 70^0 and 90^0. Water was allowed to flow through this set-up without any porous media. This serves as control experiment and thereafter the inlet and outlet pipes were filled with the sand of the same porosity. Then, outlet pipes were filled with soil of the same porosity while the inlet pipe was filled with another soil of different porosity. The volume of water discharged through each outlet pipe for 60seconds was collected with beaker and measured with measuring cylinder. This experiment was repeated for different tilt angles $\alpha = 0^0$, 5.0^0, 10.0^0, 15.0^0 and 20^0 for five different samples. .This was done in order to examine the effect of angle of inclination on angle of deflection of flow in the porous media. The volumetric flow rate and volume flux were later computed from the values of volume discharged. The outlet with maximum volume flux with respect to each porosity ratio was noted, which is an indication of angle of deflection. The results obtained were presented in table 2 – 12.

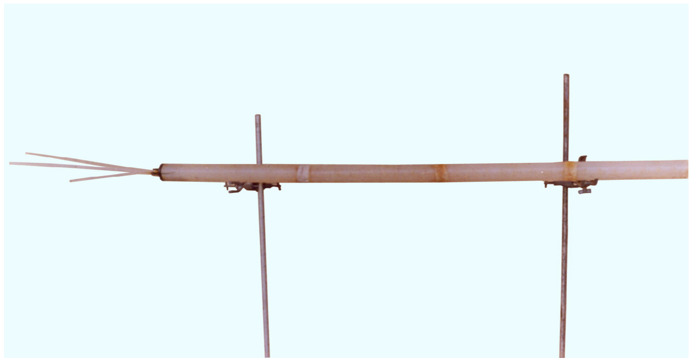


Figure. 3: Experimental set-up to determine volume flux at different outlet angles.

4. Results and Analysis

Tables 1: Porosities of the samples

S/No	Sample	Porosity
1	A	0.250
2	B	0.333
3	C	0.364
4	D	0.400
5	E	0.420

Table 2: Volume Flux at different Outlet angles for Porosity Ratio 0.5952 i.e.

$\phi_1/\phi_5 = 0.5952$

Angle of inclination α/ Degree	Outlet Angle θ/degree				
	0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	0.43	0.92	1.08	1.06	1.30
10	1.02	1.93	2.59	2.78	3.42
15	1.10	2.11	3.85	4.52	5.11
20	1.46	2.48	4.01	5.47	6.27*

Table 3: Volume Flux at different Outlet angles for Porosity Ratio 0.6250 i.e.

$\phi_1/\phi_4 = 0.6250$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	0.24	0.87	1.26	1.06	0.35
10	0.35	1.61	1.30	3.14	0.49
15	0.71	2.16	3.14	4.64	0.71
20	0.75	2.52	4.83	5.95*	1.43

Table 4: Volume Flux at different Outlet angles for Porosity Ratio 0.6868 i.e.

$\phi_1/\phi_3 = 0.6868$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	0	0.59	0.73	0.98	0.25
10	0.13	1.02	0.96	2.71	0.35
15	0.15	1.26	1.18	4.48	0.75
20	1.70	1.65	6.22*	4.60	1.30

Table 5: Volume Flux at different Outlet angles for Porosity Ratio 0.7508 i.e.

$\phi_1/\phi_2 = 0.7508$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	0.13	0.71	0.74	0.63	0.12
10	0.24	0.75	0.82	0.75	0.20
15	0.61	0.75	2.24	1.46	0.43
20	0.62	0.82	4.91*	3.14	0.75

Table 6: Volume Flux at different Outlet angles for Porosity Ratio 0.7929 i.e.

$\phi_1/\phi_5 = 0.7929$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	0	0.16	4.36	1.85	0.90
10	0.12	1.85	5.11	3.93	2.43
15	1.26	2.71	6.11	5.13	3.40
20	2.64	3.40	11.98*	10.96	5.70

Table 7: Volume Flux at different Outlet angles for Porosity Ratio 0.8325 i.e.

$\phi_2/\phi_4 = 0.8325$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	0	0	4.01	1.61	0.43
10	0	0	4.95	3.73	1.85
15	0.90	1.02	5.07	4.91	3.65
20	1.26	2.59	11.43*	10.96	4.56

Table 8: Volume Flux at different Outlet angles for Porosity Ratio 0.8667

$\phi_3/\phi_5 = 0.8667$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	0	6.13	1.89	0.90	0.61
10	0.16	9.10	4.56	2.71	2.04
15	1.34	12.45	7.35	6.09	5.35
20	3.07	15.52*	12.65	7.33	6.09

Table 9: Volume Flux at different Outlet angles for Porosity Ratio 0.9100

$\phi_3/\phi_4 = 0.9100$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	0.20	2.71	1.85	1.43	0
10	2.43	5.07	3.14	1.46	0.12
15	6.11	8.40	4.29	2.64	1.61
20	7.19	8.67*	4.36	3.92	1.02

Table 10: Volume Flux at different Outlet angles for Porosity Ratio 0.9148

$\phi_2/\phi_3 = 0.9148$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	2.48	0.90	0.90	0.75	0
10	5.13	1.89	2.43	1.89	0
15	8.31	2.71	2.64	2.43	0.12
20	8.41*	7.35	5.11	4.29	0.12

Table 11: Volume Flux at different Outlet angles for Porosity Ratio 0.9523

$\phi_4/\phi_5 = 0.9523$

Angle of inclination α/ Degree	Outlet Angle θ/degree 0 q x 10^{-3} (ms^{-1})	20 q x10^{-3} (ms^{-1})	50 q x 10^{-3} (ms^{-1})	70 q x 10^{-3} (ms^{-1})	90 q x 10^{-3} (ms^{-1})
0	0	0	0	0	0
5	7.88	2.43	1.26	0	0
10	11.02	5.35	4.29	0.20	0
15	16.82	8.41	7.19	2.48	0.12
20	17.80*	8.57	8.31	6.01	0.16

* Maximum volume flux with respect to each porosity ratio.

Table 12: The outlet angle with the maximum volume flux, which indicates the direction of fluid flow with respective porosity ratio.

Porosity ratio	Angle of Deflection, Cosθ	
(ϕ_a / ϕ_b) or ϕ_r	θ/Degree	
0.9523	0	1
0.9148	0	1
0.9100	20	0.9397
0.8667	20	0.9397
0.8325	50	0.6428
0.7929	50	0.6428
0.7508	50	0.6428
0.6868	70	0.3420
0.6250	70	0.3420
0.5952	90	0

$$\cos\theta = 1.98\ln(\phi_r) + 1.13$$

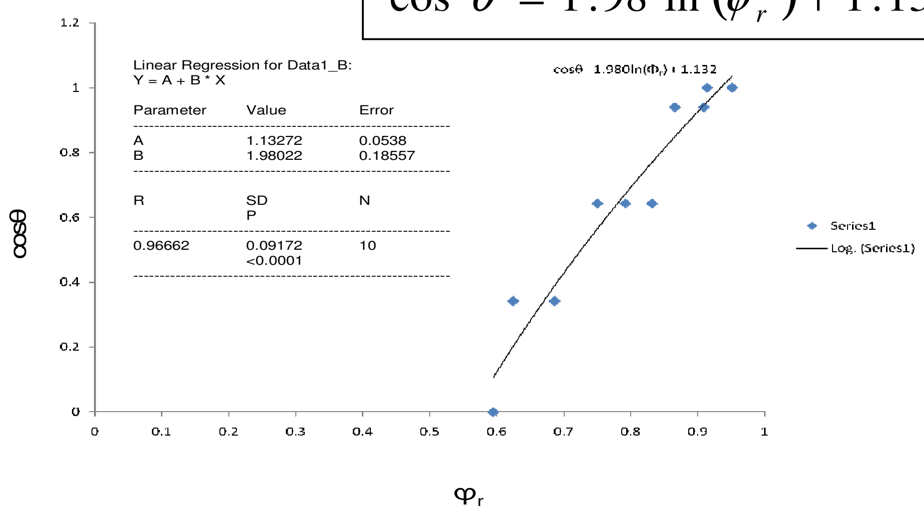


Figure 4: Cos θ against porosity ratio

The cosine of angle of deflection for respective porosity ratios were obtained and presented in table 12. The cos θ was plotted against the porosity ratio and the equation obtained is $\cos\theta = 1.98\ln(\phi_r) + 1.13$ .This equation established the relationship between θ and ϕ_r. From this equation, the maximum angle of deflection in stratified porous medium made up of fine and medium sand is 89.4°. This is true because the minimum value of porosity ratio is 0.5682 (0.25 / 0.44) for medium and fine sands (Freeze and Cherry, 1979).

It is now obvious that if porosity ratio of a stratified (or layered) porous medium is known, the angle of deflection of fluid flow through that media can be determined from the above equation.

5. Conclusions and Recommendations

From these results stratified porous media of a known porosity ratio can be used to control the direction of contaminated or unwanted fluid. This can be done by excavating the region between the source of water supply and contaminant and backfill with stratified porous media (or layered soils) of known porosities. However, the contributions or suggestions of building or civil engineering department would be necessary for full application or implementation of these fundamental results.

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