Comparison Of Preferential Flow Of Solute In Porous Media With Darcy's Flow

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Abstract: Vertical flow of solute in porous media (preferential flow) is studied and compared with Darcy's flow. The methodology used for the study is experimental. The laboratory model used is similar to Darcy apparatus with slight modification. The study has compare measured velocity of first reach of solute with average velocity of flow in porous media. The laboratory model consists of 150 mm diameter High density Polyethylene pipe of 750 mm height filled uniform sand. Nine sets of experiment is conducted with 3 types of sand (D_{10} = 0.6 mm and C_u 1.42, D_{10} = 0.11 mm and C_u 1.55, D_{10} = 0.3 mm and C_u 1.4) and 3 types of brine concentration (5 %, 10 %, 20 % by weight brine solution). Brine solution is found to be 1.13 to 1.84 times faster than average velocity of flow as a result of preferential flow.

Index Terms: Brine solution, C_u, D_{10}, Darcy's flow, Laboratory model, Porous media, Preferential flow.

1 INTRODUCTION

1.1 Background

Contamination of groundwater with agricultural chemicals is becoming a serious threat. Modern agriculture relies on a broad range of fertilizers and pesticides to assure reliable crop yields. Although the amount of chemicals required can be reduced, a total ban is not currently feasible. A long-term hazard is involved: once the chemicals get into groundwater, they may remain there for decades. Preferential flow allows much faster contaminant transport and creates significant consequences for groundwater quality and has direct impacts on drinking water and human health.

1.2 Rationale

Pesticides and other agrochemicals are commonly used in developing country like Nepal to increase productivity. Agriculture land near river courses is the most fertile land where the ground water table is high from ground surface. The soil type is generally sandy soil. Among various types of agrochemicals the most critical one susceptible to pollute shallow groundwater is the one which do not react with the sandy soil. The research on the movement of chemical in soil is very limited. Hence, the detailed study is required to determine the preferential flow of solute in the porous media and compared with the Darcy's average flow of water.

1.3 Objective of the Study

The objective of the study is to determine the degree of rapidness of downward movement of water and solute and compare with theoretical Darcy model.

1.4 Limitations of the Study

The study carried out has following limitations: The laboratory model is small, Field verification has not been performed, The study is limited to the movement of brine solution in the sand used in model within laboratory condition.

2 LITERATURE REVIEW

Literatures has been collected and reviewed to get the basic idea on preferential flow and research progress made on the proposed field of study. Some of them are:

2.1 Theory and Concepts on Preferential Flow

Preferential flow refers to the uneven and often rapid movement of water and solutes through porous media, typically soil, characterized by regions of enhanced flux such that a small fraction of media (such as wormholes, root holes, cracks) participates in most of the flow, allowing much faster transport of contaminants, including pesticides, nutrients, trace metals, and manurial-pathogens. This creates significant consequences for groundwater quality. Preferred pathways in soils may result from biological and/or geological activity (e.g., macro-pores, earthworm burrows, channels consisting of highly conductive media) or from farm management practice (e.g., conservation tillage). Preferential flow-paths are also found in homogeneous and layered sandy soils due to the instability of the wetting front. Such preferred paths may transmit water and its solutes at higher velocities than those predicted by Darcy's theory [1]. Glass R. J. et al. [2] formulated diameter of three dimensional fingers using linear stability theory then compared with the theoretical result. Tensiometry is demonstrated to be a practical method of obtaining data with high temporal and spatial resolution for the study of dynamic flow fields and facilities testing of theoretical results for unstable flow fields [3]. Selker J. S. et al. [4] demonstrated experimentally that fingering can be prominent feature of flow through homogeneous soil systems under continuous non-ponding infiltration. Fingers in homogeneous coarse grained soils form instability in the wetting front and result in bypass flow which shortens the residence time in vadose zone. Once formed persists over a long period, the tip of the fringes of the fingers is on the wetting curve, while the remaining core of the finger is on a drying branch. This explains why large differences in moisture content can co-exist [5]. Soil water hysteresis model can be used to explain a fingered flow pattern is uniform sand with different initial moisture contents [6]. The pressure and water content measurement [7] show that the non-uniform moisture content exists even when the potentials are equalized horizontally as a result of soil's pressure-saturation relationship. Once the soil is wet enough, the remainder of water movement takes place in liquid films. The wetter portions of the soil can be at a lower potential than the drier portions, resulting in a horizontal driving force for a flow of water from the drier to the wetter soil. Preferential flow on hill-slopes takes place via macropores. These are formed either by biological or mechanical processes, and they come in a wide range of sizes, directional orientation, and continuity. Field studies have shown that the continuity is a dynamic state variable, with it increasing as the degree of wetness of the soil increases. Field experiments have demonstrated that under conditions commonly found in the field that macropores are able to deliver significant quantities of water to stream-flow during rainfall of snowmelt [8].

2.1.1 Preferential Flow Classification
Types of preferential flow [9] may be as follows:

a. Macro-pore Flow:
In macro-pore flow, water and chemicals flow through naturally-formed channels such as cracks, plant roots, worm holes, and voids between peds. The flow of water through a system of large pores allows fast velocities and by passes the soil matrix.

b. Fingering (unstable) Flow:
In a sandy soil where a less conductive fine sand layer is located above a coarse sand layer, the wetting front can become unstable and brake into fingers.

c. Funnel Flow:
In the funnel flow, water is directed into fewer channels on inclined surfaces where fine sand layer is located above fine or coarse sand layer.

2.1.2 Preferential Flow Modeling:
A simplified two layered model considering near surface (mixing layer) and lower profile, for the layer near the surface, the solute concentration in the layer is equal to that of percolating (including preferentially moving water). In the lower profile, the flow is partitioned between matrix and preferential flow. The solute concentration of the matrix flow is characterized by the condition near the outlet point where as the preferential flow is represented by the solute concentration in the mixing layer. The theory that is tested with three widely varying independent data sets gives good insight into some of the important factors in the loss of fertilizers and pesticides to groundwater shortly after application via preferential flow [10]. A preferential solute transport model developed simulates the effects of natural heterogeneities in the soil layer by identifying paths responsible for the transport of water and solutes. The soil-water hydraulic conductivity function is used to identify these paths and the interaction between these paths are described by mixing functions [11]. Rimmer A. et al. [12] found optimal wick length for two soil types i.e. 30 to 40 cm wick length for sandy soils and >100 cm wick length for silt loams. Model and experimental results indicate that only a fraction of the field area participates in transport to the macropores. Differences between breakthrough curves from the conventionally tilled and no-till plots are explained well by the mixing of solutes and water in the upper layer [13]. Methods that can measure field averaged preferential flow characteristics need to be developed to simulate pesticide concentration in tile lines [14]. Rimmer A. et al. [15] experimentally show that fingered flow of water into an oil-saturated porous medium has similar properties to fingered water flow into dry porous media, but with different length scales, pressure heads, and fluid contents. Theoretical analysis and model simulations indicated that finger formation depends on the shape of the main wetting and main drainage branches of that function. Once fingers are established, hysteresis causes fingers to recur along the same pathways during following rain events. Leaching of hydrophobic substances from these fingered pathways makes the soil with in the pathways more wettable than the surrounding soil. Thus, in the long term, instability driven fingers might become heterogeneity driven fingers [16]. A mathematical model for solute movement in a structured soil with well-defined and continuous preferential paths was developed. The model divides the soil profile into one mobile and one stagnant pore group. For well-structured soils, the mobile pore group consists of a few well-connected pores that conduct the non-reactive solute downward very rapidly. Only a narrow matrix layer of stagnant solute along the interface between the two pore groups takes part in solute exchange with the preferential paths. Due to differences in time scales between convection and chemical transfer, the rate of chemical exchange between the preferential path and the active matrix layer for short and moderate times after chemical application is controlled mainly by the preferential flow concentration and, to lesser extent, by the concentration in the active layer [1]. A simple, efficient and effective method of quantifying the level of heterogeneity in soil–water percolation and solute elution patterns generated from multiple sample percolation experiments has been developed. The method relies on calculating a heterogeneity index based on estimating two free parameters of the beta-distribution. Using this index, the elution patterns for a number of experiments was compared and contrasted. The index may be a valuable tool in estimating the potential risk of groundwater contamination by the preferential transport of chemicals through the vadose zone [17]. The process of preferential flow and transport has been incorporated in the well-known SWAP model also, and applied to field data of tracer transport through a water repellent sandy soil in the Netherlands. Results indicate early arrival times of bromide in the subsoil in case preferential flow is taken into account [18]. Using data collected from the multiple sample percolation experiments, Stagnitti, F. et al. [19] compared the performance of two mathematical models for predicting solute transport, the advection-dispersion model with a reaction term (ADR), and a two-region preferential flow model (TRM) suitable for modeling non-equilibrium transport. Logsdon S. D. [20] evaluated methods to independently measure macro-pore parameters with the test model MACRO, a transient-state, and two flow domain model.

2.1.3 Preferential Flow and Pesticides/Toxics
The effect of sludge processing (digested dewatered, pelletized, alkaline-stabilized, composted, and incinerated), soil type and initial soil pH on trace-metal mobility was examined using undisturbed soil columns. Soils tested were Hudson silt-loam (Glossaquic Hapludalf) and Arkport fine sandy-loam (Lamellic Hapludalf), at initial pH levels of 5 and 7 [21]. Comparisons of the flow-paths and the bulk soil (comparing dyed and non-dyed sludge plot soils) showed that enhancement of soil metal in and along flow paths in the subsoil below the zone of incorporation is slight where detectable at all [22].

2.1.4 Preferential Flow and Manure, Pathogens and Nutrients
Liquid manure applied to the soil surface at normal rates, and followed by a precipitation event, can result in bacterial contamination of a subsurface drain in soils which exhibit preferential flow characteristics. The timing of the precipitation event following the liquid manure application will influence the magnitude of the peak concentration of bacteria such as fecal coliforms. Liquid manure which had dried on the surface did not eliminate the further risk of fecal coliforms transport upon rewetting within a 6 day period. An irrigation event on the same day of liquid manure application resulted in a peak concentration of 110,000 colonies/100 ml, and an irrigation 6 days after the manure application still resulted in a peak concentration of 38,000 colonies/100 ml [23].

2.1.5 Development of Soil Water Samplers to Measure Preferential Flow of Water and Solutes

Laboratory tests showed that fibre-glass wicks have a relatively small effect on the measurement of contaminant loading. The dispersivity value of the wick was very low, indicating that, when used for sampling from unsaturated soil, fibre-glass wick contribute negligibly to the dispersion of solutes. Miscible-displacement tests using Bromide and an adsorbed blue dye applied to fibre-glass wicks revealed that the latter has a retardation coefficient of approximately 1.3, a value that is small compared with retardation of blue dye in field soils [24]. When pan samplers collected water mainly from macropores, water flux was lognormally distributed. On the other hand, when matrix pores were sampled, the water flux best fit the normal distribution [25]. Rimmer, A., et al. [26] examined how the wick sampler alters the matrix potential, streamlines, and solute concentrations in the native soil (theoretically and experimentally). Model and theory agreed well and showed that the capillary length is similar in the soil and wick. It was found that in many cases solute pulse travel time was affected more by the pressure head changes that occurred at the soil-wick interface than by the flow through the wick. De Rooij, G.H. and F. Stagnitti [27] suggest a stochastic convective transport process in the high-flow stream tubes, while convection–dispersion is predominant in the low-flow areas.

2.2 Darcy Flow Concepts

Darcy's law states that the Darcy velocity q in a porous medium is calculated from the head ∇h gradient and hydraulic conductivity K as:

$$q=-K\nabla h \quad (1)$$

Where, q with units of volume / time / area, is also known as the specific discharge, or the filtration velocity. The volume of water flowing per unit time through a unit cross-sectional area normal to the direction of flow (q = Q/A).

$$\nabla h=H/L \quad (2)$$

The average fluid velocity within the pores, called the seepage velocity V, is the Darcy velocity divided by the effective porosity (n) of the medium.

$$V=q/n=-K\nabla h/n \quad (3)$$

Darcy's law is a simple mathematical statement which neatly summarizes several familiar properties such as: If there is no pressure gradient over a distance, no flow occurs (this is hydrostatic conditions), If there is a pressure gradient, flow will occur from high pressure towards low pressure (opposite the direction of increasing gradient hence the negative sign in Darcy's law), The greater the pressure gradient (through the same formation material), the greater the discharge rate, and the discharge rate of fluid will often be different through different formation materials (or even through the same material, in a different direction) even if the same pressure gradient exists in both cases.

2.3 Wall Correction in Laboratory Model

For a cylindrical tube of diameter (D) packed with spheres of diameter (d) increased in average velocity is caused by less packing in wall of the cylinder by the fraction (fw) as per Coulson [28].

fw=(1+d/3D)^2 (4)

In our context,
d = 0.6 mm
D = 150 mm
fw = 1.0027
Since fw is nearly equal to 1, it can be neglected.

2.4 Summary of literature review

Preferential flow-paths are also found in homogeneous and layered sandy soils due to the instability of the wetting front [1]. Nieber J. L. [8] have demonstrated that under field conditions macropores are able to deliver significant quantities of water to stream-flow during rainfall of snowmelt. Soil water hysteresis model can be used to explain a fingered flow pattern is uniform sand with different initial moisture contents [6] & [16] mentioned soil hysteresis causes fingers to reoccur along the same pathways during following rain events. Considering above, Detail study is required to determine the preferential flow of solute in the porous media and compared with the Darcy's average flow of water.

3 METHODOLOGY

The methodology used in this research is described in this chapter. The research is based on the experimental study of laboratory model. The data collected during the experiments were analyzed using statistical tools. The conclusions are drawn based on the results of the study. Recommendations have been made for further study also.

3.1 Laboratory model

The laboratory model consists of HDPE pipe of 150 mm diameter and 750 mm height. The HDPE pipe is packed with sand. A PVC bucket of 10 liters volume is used for storing the influent water. Outlet bucket 10 liters capacity is used to collect the effluent water. The schematic diagram of experimental setup is shown in Figure 1.

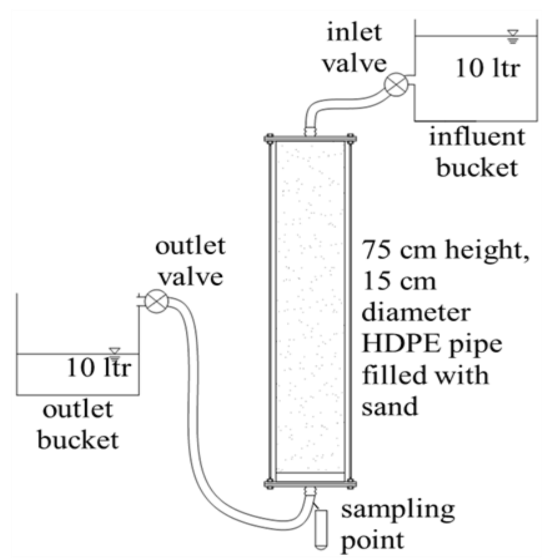

Figure 1. *Schematic diagram of Lab-Model*

Two set of laboratory models are used at a time. The study has been carried out in three types of sands. The sands used were effective size of 0.6 mm with uniformity coefficient of 1.42 (sand

1), effective size of 0.11 mm with uniformity coefficient of 1.55 (sand 2) and effective size of 0.3 mm with uniformity coefficient of 1.4 (sand 3). The details of seive analysis of sand are presented in Appendix B. The study has been conducted in brine solutions of 5%, 10% and 20% separately. The samples are collected from the bottom of the HDPE pipe to test the chloride content.

3.2 Assumptions

The following assumptions are taken in to account during experiment:

- Outlet head is neglected.
- Darcy law is considered valid.

3.3 Data Collection

The time of first reach of chloride in the sampling point is taken based on the visualization of white color in the test tube when silver nitrate is added using dropper. Time and total amount of water flow are measured. After each set of experiment the sand is cleaned with water to prepare for the next set of experiment.

3.4 Data Analysis

The hydraulic conductivity and average time of reach is calculated based on Darcy equation and are plotted in linear graph. The calculated hydraulic conductivity for various types of sand at concentrations of brine is presented in detail in table 1. The comparison of hydraulic conductivity of water with various types of sands at various concentrations of brine solution is presented in table 1. After points are plotted linear of regression is established in excel sheet [29].

4 RESULTS AND DISCUSSION

4.1 Sieve Analysis

Sieve analysis was carried out for all three types of sand used i.e. sand 1, sand 2 and sand 3. 2000 gm of dry sample of sand 1 was taken and sieve analysis was carried out. The sand 1 was found to have effective size (D_{10}) of 0.6 mm with uniform coefficient of 1.42. Loss of sand during sieving was found to be 0.36 %. Sieve analysis of sand 2 and sand 3 were performed taking 1000 gm of dry sample of each. Sand 2 was found to have effective size (D_{10}) of 0.11 mm with uniformity coefficient of 1.55 while sand 3 was found to have effective size (D_{10}) of 0.3 mm with uniformity coefficient of 1.4. The loss of sand during sieving was found to be 1.87 % and 1.18 % for sand 2 and sand 3 respectively.

4.2 Hydraulic Conductivity Calculation (Water)

Hydraulic conductivity of water is calculated from data derived from the experimental study. The detail calculation of hydraulic conductivity for various types of sand with various concentration of brine solution is presented in table 1. The plots of q versus H/L for various types of sand with various concentration of brine solution are presented in Appendix D. The hydraulic conductivity of water was found to be 0.00238 m/s for sand 1 with 5% brine solution. The plot of q versus H/L showed the regression correlation (R^2) of 0.98 indicating its good curve fitting. Similarly hydraulic conductivity of water was found to be 0.002338, 0.002384, 0.0001648, 0.0001943, 0.0001729, 0.003079, 0.002805, 0.002986 m/s for sand 1 with 10% brine solution, sand 1 with 20% brine solution, sand 2 with 5% brine solution, sand 2 with 10% brine solution, sand 2 with 20% brine solution, sand 3 with 5% brine solution, sand 3 with 10% brine solution and sand 3 with 20% brine solution respectively and their regression correlations (R^2) were calculated as 0.96, 0.94, 0.96, 0.93, 0.97, 0.98, 0.96 and 0.99 respectively indicating good curve fitting.

4.3 Hydraulic Conductivity Calculation (Water and Salt Water)

Similarly, hydraulic conductivity of brine solution is calculated from data derived from the experimental study. The detail calculation of hydraulic conductivity for various types of sand with various concentration of brine solution is presented in table 1. The hydraulic conductivity of brine solution was found to be 0.00246 m/s for sand 1 with 5% brine solution. The plot of q versus H/L showed the regression correlation (R2) of 0.93 indicating its good curve fitting. Similarly hydraulic conductivity of brine solution was found to be 0.00281, 0.00295, 0.000176, 0.0002008, 0.0002535, 0.003056, 0.00308, 0.003377 m/s for sand 1 with 10% brine solution, sand 1 with 20% brine solution, sand 2 with 5% brine solution, sand 2 with 10% brine solution, sand 2 with 20% brine solution, sand 3 with 5% brine solution, sand 3 with 10% brine solution and sand 3 with 20% brine solution respectively and their regression correlations (R2) were calculated as 0.96, 0.97, 0.96, 0.99, 0.90, 0.99, 0.94 and 0.96 respectively indicating good curve fitting. Hydraulic conductivity increased in the presence of salt.

4.4 Comparison of Observed First Reach Time with average velocity

Measured time of reach of solute is compared with time based on Darcy's average velocity in porous media. Solute transfer in the sand is found 1.38 times faster than time based on Darcy's average velocity for sand 1 with 5 % brine solution and its regression correlation (R^2) of 0.94. Similarly, Similarly solute transfer in sand is found to be 1.39, 1.84, 1.59, 1.26, 1.16, 1.2, 1.63 and 1.13 faster than time based on Darcy's average velocity for sand 1 with 5 % brine solution, sand 1 with 10% brine solution, sand 1 with 20% brine solution, sand 2 with 5% brine solution, sand 2 with 10% brine solution, sand 2 with 20% brine solution, sand 3 with 5% brine solution, sand 3 with 10% brine solution and sand 3 with 20% brine solution respectively and their regression correlations (R^2) were calculated as 0.99, 0.96, 0.91, 0.99, 0.96, 0.91, 0.95 and 0.93. Measured solute travel time is compared with that of Darcy's average velocity as shown in Figure 2 for sand of 0.66 mm effective size and uniformity coefficient of 1.42 (i.e. sand 1) at brine concentrations of 5%, 10% and 20%.

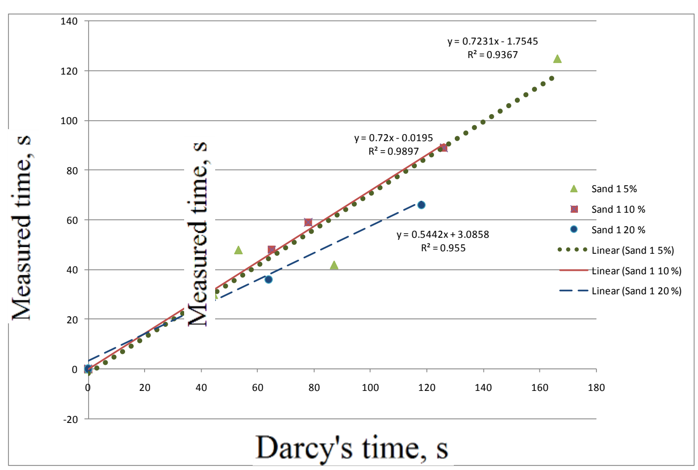

Figure 2. *Comparison of measured time with Darcy's time for sand 1*

Measured solute travel time for sand 1 is observed to be 1.38 to 1.84 times faster than time based on Darcy's average velocity.

Measured solute travel time is compared with that of Darcy's average velocity as shown in Figure 3 for sand of 0.11 mm effective size, uniformity coefficient 1.55 (i.e. sand 2) with all three set of brine concentrations of 5%, 10% and 20%.

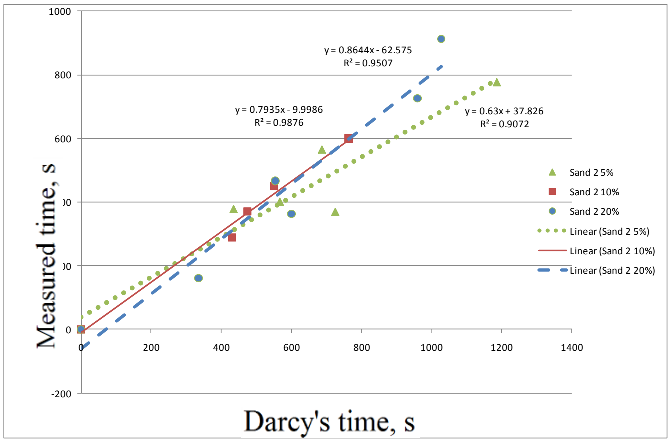

Figure 3. *Comparison of measured time with Darcy's time for sand 2*

Measured solute travel time is for sand 2 is observed to be 1.16 to 1.59 times faster than time based on Darcy's average velocity. Measured solute travel time is compared with that of Darcy's average velocity as shown in Figure 4 for sand of 0.3 mm effective size and uniformity coefficient of 1.4 (i.e. sand 3) of brine concentration of 5%, 10% and 20%.

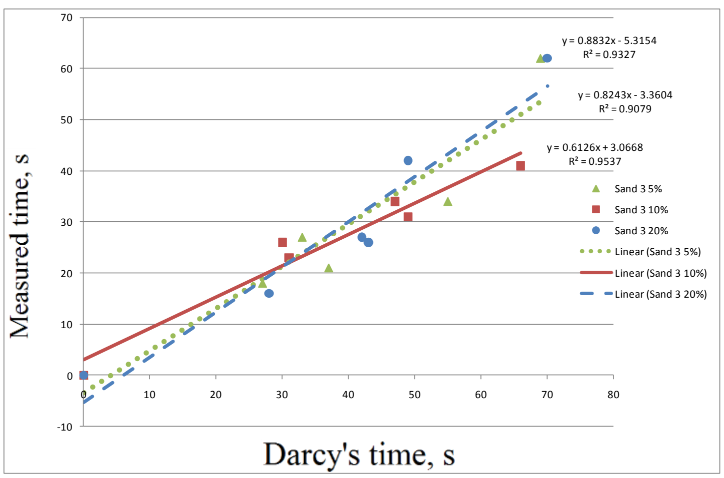

Figure 4. *Comparison of measured time with Darcy's time for sand 3*

Measured solute travel time for sand3 is observed to be 1.13 to 1.63 times faster than time based on Darcy's average velocity. Measured solute travel time is compared with that of Darcy's average velocity as shown in Figure 5 for 5% brine concentration for all three types of sand (i.e. sand 1, sand 2 and sand 3).

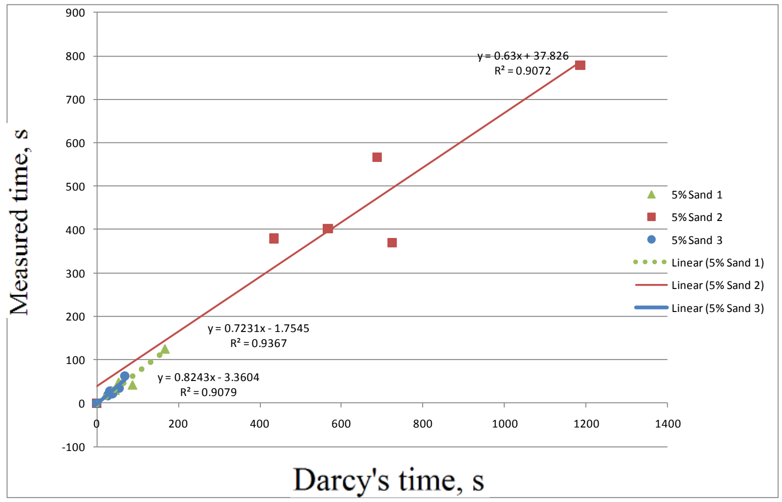

Figure 5. *Comparison of measured time with Darcy's time for 5 % brine solution*

Measured solute travel time for 5% brine solution is observed to be 1.2 to 1.59 times faster than time based on Darcy's average velocity. Measured solute travel time is compared with that of Darcy's average velocity as shown in Figure 6 for 10% brine concentration for all three types of sand (i.e. sand 1, sand 2 and sand 3).

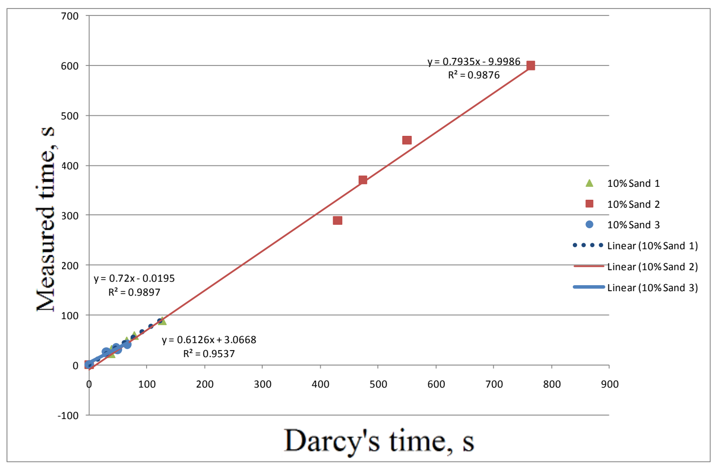

Figure 6. *Comparison of measured time with Darcy's time for 10 % brine solution*

Measured solute travel time for 10% brine solution is observed to be 1.26 to 1.63 times faster than time based on Darcy's average velocity. Measured solute travel time is compared with that of Darcy's average velocity as shown in Figure 7 for 20% brine concentration for all three types of sand (i.e. sand 1, sand 2 and sand 3).

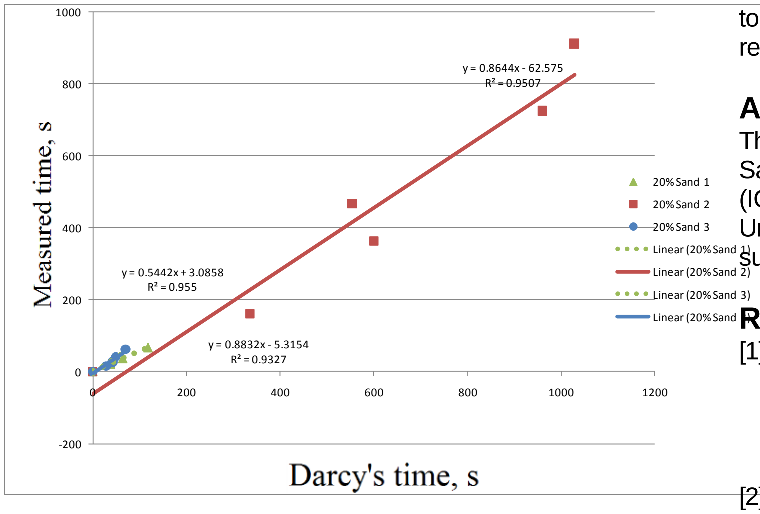

Figure 7. *Comparison of measured time with Darcy's time for 5 % brine solution*

Measured solute travel time for 20% brine solution is 1.13 to 1.84 times faster than time based on Darcy's average velocity. The comparison of hydraulic conductivity of water with and without saltwater for various types of sands under study at the various brine concentration is shown in table 1. The result shows that the solute travel time is faster than Darcy's average velocity in all cases.

Table 1 *Comparison of hydraulic conductivity*

Media type	Brine % by weight	Uniformity coefficient (C_u)	Effective size (D_{10}, mm)	Hydraulic Conductivity of water ($K_{w, m/s}$)	R^2	Hydraulic Conductivity of water with brine solution ($Ks_{, m/s}$)	R^2	Faster than Darcy's time (t_d/t_p)	R^2
Sand 1	5	1.42	0.60	2.380E-03	0.98	2.460E-03	0.93	1.38	0.94
	10			2.338E-03	0.96	2.810E-03	0.96	1.39	0.99
	20			2.840E-03	0.94	2.950E-03	0.97	1.84	0.96
Sand 2	5	1.55	0.11	1.648E-04	0.96	1.760E-04	0.96	1.59	0.91
	10			1.943E-04	0.93	2.008E-04	0.99	1.26	0.99
	20			1.729E-04	0.97	2.535E-04	0.9	1.16	0.96
Sand 3	5	1.4	0.30	3.079E-03	0.98	3.056E-03	0.99	1.20	0.91
	10			2.805E-03	0.96	3.080E-03	0.94	1.63	0.95
	20			2.986E-03	0.99	3.377E-03	0.96	1.13	0.93

5. Conclusion

Since solute transfer in the sand used is found to be faster than time based on Darcy average velocity [29] in all cases, preferential flow exists in uniform sand. The following conclusions are deduced: Measured solute travel time is 1.38 to 1.84 times faster than time based on Darcy's average velocity for sand 1(Cu=1.42, D_{10}=0.6 mm), Measured solute travel time is 1.16 to 1.59 times faster than time based on Darcy's average velocity for sand 2(Cu=1.55, D_{10}=0.11 mm), Measured solute travel time is 1.13 to 1.63 times faster than time based on Darcy's average velocity for sand 3(Cu=1.4, D_{10}=0.3 mm), Measured solute travel time is 1.2 to 1.59 times faster than time based on Darcy's average velocity for 5% brine concentration, Measured solute travel time is 1.26 to 1.63 times faster than time based on Darcy's average velocity for 10% brine concentration, Measured solute travel time is 1.13 to 1.84 times faster than time based on Darcy's average velocity for 20% brine concentration. It is recommended to use wide range of size of media as well as wide range of uniformity coefficient to know precise relationship with media size and solute concentration. Further investigation considering worm holes and roots on undisturbed sandy soil is recommended. Most of the hazardous chemicals last for long period (from few months to few decades), hence continuous investigation in the field is recommended for accurate result.

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