

## Assessment of the Gravimetric Method to Determine Isothermal Soil Water Diffusivity

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### ABSTRACT

Moisture transport in porous media is a fundamental subject in soil physics and civil engineering and therefore it is necessary to understand its mechanisms and processes involved. In this paper, the isothermal moisture diffusion, is estimated with gravimetric method for loamy sand, silty loam and clay loam soils. The basis of the method is to measure the amount of water absorbed by the small soil columns with different heights as a function of time. To evaluate the accuracy of the obtained diffusivity data they were compared with those obtained from Bruce-Klute method. Considering calculated logarithmic RMSE between two mentioned methods, it was confirmed the gravimetric technique may be more reliable to estimate the isothermal moisture diffusivity especially in finer texture soils. Moreover, this technique is quite simple and may be carried out with minimum laboratory facilities. Moreover, the results showed that the gravimetric method somewhat underestimated moisture diffusion  $D(\theta)$  as compared to Bruce-Klute method, and the difference between the two methods increased with increasing at moisture content which will be discussed in the current paper.

**Keywords:** Bruce-Klute method, diffusivity, porous media, soil texture, soil columns.

### INTRODUCTION

Moisture transport in porous media is a fundamental subject in soil physics and civil engineering. It has a key role to control the soil mass and energy budget in soil water near the surface (Novak 2010, Cahill and Parlange 1998, Smits *et al.* 2011). Originally, moisture diffusivity was calculated by using pressure plate outflow data (Gardner, 1956). The moisture diffusivity  $D(\theta)$  (usually in  $\text{cm}^2 \text{s}^{-1}$ ) represents a basic parameter to evaluate amount of moisture transported in porous media that changes with both moisture and temperature (Philip and De Vries 1957). In isothermal condition, this value may be calculated with moisture change measurement at soil profile by well-known  $\gamma$ -ray attenuation technique or nuclear magnetic resonance (NMR) by using Boltzmann transfer function (Crausse 1983, Perrin 1985, Bruce and Klute 1956). Šimunek *et al.* (2000) proposed an approach to estimate moisture diffusivity by applying horizontally infiltration data. Wang *et al.* (2004) determined moisture diffusivity by using data obtained from wetting front zone, infiltration rate and cumulative infiltration,

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but their assumptions is appropriate for near saturated soils. Ma *et al.* (2009) developed a method to determine moisture diffusivity by estimation of the Brooks and Corey model parameters using analytical solution via HYDRUS-1D software. Evangelides *et al.* (2010) could generate soil moisture profile to estimate moisture diffusivity by using data such as sorptivity, initial and final soil water content and wetting front zone distance. Apart from their accuracy, these techniques often require expensive equipment that may not exist in many laboratories especially in developing countries. To eliminate this obstacle, Goual *et al.* (2000) proposed a gravimetric method that estimates isothermal moisture diffusion coefficient in concrete material. In the current work we applied their method to estimate soil moisture diffusivity in three soils with various textures and investigated its accuracy with comparing to the Bruce-Klute method (1956).

### THEORETICAL CONSIDERATION

The one-dimensional flow of water in saturated homogeneous porous material in vertical direction under the action of hydraulic gradient (pressure and gravitational gradients) is described by well-known Darcy's equation:

$$q = - K_s \left( \frac{\partial P}{\partial Z} + \frac{\partial Z}{\partial Z} \right) \quad (1)$$

where  $q$  is the soil water flux ( $\text{cm s}^{-1}$ ),  $K_s$  is the saturated hydraulic conductivity of soil ( $\text{cm s}^{-1}$ ),  $P$  is the potential pressure of soil (cm) and  $Z$  is the vertical distance (cm).

In the cases of unsaturated flow in horizontal direction, the extended Darcy equation is substituted (Kaufmann, 1997) by:

$$q = - K(\theta) \frac{\partial \psi}{\partial x} \quad (2)$$

where  $\psi$  is the capillary potential (cm),  $x$  is the distance (cm) and  $K(\theta)$  is the unsaturated hydraulic conductivity ( $\text{cm s}^{-1}$ ).

Since  $K(\theta)$  is largely sensitive to soil water content, combining equation (2) with the continuity equation and then writing the resultant equation in terms of  $\theta$  by substitution  $D(\theta) = K(d\psi/d\theta)$  for the "isothermal moisture diffusivity", the Richards equation is obtained:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} [D(\theta) \frac{\partial \theta}{\partial x}] \quad (3)$$

where  $\theta$  is the volumetric water content ( $\text{cm}^3 \text{cm}^{-3}$ ),  $t$  (s) the time and  $D(\theta)$  is the isothermal soil moisture diffusivity ( $\text{cm}^2 \text{s}^{-1}$ ).

Using Boltzmann transformation,  $b=xt^{-0.5}$ , (Equation 3) may be reduced to an ordinary differential equation:

$$-\frac{b}{2} \frac{d\theta}{db} = \frac{d}{db} [D(\theta) \frac{d\theta}{db}] \quad (4)$$

The isothermal soil moisture diffusion would be yielded from the integration of equation (4):

$$D(\theta) = -\frac{1}{2} \left( \frac{db}{d\theta} \right) \int_{\theta_i}^{\theta} b(\theta) d\theta \quad (5)$$

where  $\frac{db}{d\theta}$  is the inverse slope of the average curve  $\theta_L(b)$  (Figure 1) and  $\int_{\theta_i}^{\theta} b(\theta) d\theta$  is the area delimited by the average curve  $\theta_L(b)$ , the vertical axis and the horizontal line  $\theta = 0$  and a particular soil moisture content ( $\theta$ ) in this work (Figure 1) at which the  $D(\theta)$  is to be determined;  $\theta_L$  is the local volumetric water content (see Equation 6).

## MATERIALS AND METHODS

The locations for soil samples used in this study were selected from different farm lands around the Khalatpooshan research station (latitude  $38^{\circ}7'N$ , longitude  $46^{\circ}20'E$ ), University of Tabriz, Iran, with three different textures of loamy sand, silty loam and clay loam (Table 1). The samples were collected from 0 to 15 cm depth which generally corresponds to the Ap horizon in the area (USDA and Soil Survey Staff, 2010). Loamy sand soil was single grained. Silty loam and clay loam soils were weakly and moderately developed in structure, respectively. Disturbed soil samples after air drying were cleaned from plants remains, and then loamy sand soil passed through a 2-mm sieve, the next two were passed through 4-mm sieve because to preserve soil structure and stored in plastic bottles until the use. Initial moisture content of the samples were measured by oven drying at  $105^{\circ}C$  for 24 hours. The soil textures was determined by the pipette method (Gee and Bauder, 1986). Total organic carbon (TOC) by Walkley and Black wet

TABLE 1  
Basic physical and chemical properties of soils studied

Soil texture	%S	%Sil	%Cl	Bulk density ( $\text{g cm}^{-3}$ )	Particle density ( $\text{g cm}^{-3}$ )	$f(\text{cm}^3 \text{cm}^{-3})$ <sup>a</sup>	TOC (Wt%) <sup>b</sup>	Active $\text{CaCO}_3$ (Wt%)	CEC ( $\text{cmol kg}^{-1}$ )
Loamy sand	83.9	7.8	8.3	1.5	2.59	0.42	0.9	4.8	14.33
Silty loam	22.4	62.3	15.3	1.5	2.24	0.33	1.3	6.3	21.18
Clay loam	32.8	31	36.2	1.5	2.2	0.31	2.1	5.1	39.82

<sup>a</sup>  $f = (1 - D_b/D_s)$ , <sup>b</sup> percentage by weight

dichromate oxidation method (Nelson and Sommers, 1986). Carbonate content was calculated from the amount of CO<sub>2</sub> released by reaction with HCl (Loppert and Suarez, 1996). Cation exchange capacity (CEC) of each soil sample was obtained by exchanging the samples with NH<sub>4</sub>OAc at pH 7 (Sumner *et al.*, 1996).

Basic physical and chemical properties of the three examined soils are shown in Table 1. The experimental procedure for gravimetric technique expressed as following. The basis of the gravimetric method for determining D(θ) is to specify amount of water absorbed by the vertical soil columns with different heights as a function of time. In this work the height of local volume considered in specifying the evolution in moisture content was set equal to 2 cm. The fundamental assumptions for this method are that the porous material is homogenous and wetting front moves horizontally and there is a sharp boundary between wet and dry zone along the soil column (Goual *et al.*, 2000). Moreover, due to small size of the soil columns and soil dryness, it is assumed that gravity potential effect on water entry in to the columns is negligible in comparison to the matric potential. It may be a correct assumption in the early stages of water absorption (Philip, 1957).

For this technique the various steps were as follows:-

1. Providing five PVC tubes with 4.7 cm diameter and 2, 4, 6, 8 and 10 cm heights. The prepared soils were carefully packed into the tubes to achieve a uniform bulk density. For this purpose known weights of each soil was poured into the PVC tubes in 2 cm interval depths with tapping on the column wall (Smits *et al.* 2011). All of soil columns packed to the bulk density of 1.5 (g cm<sup>-3</sup>). In order to eliminate moisture evaporation from soil surface, top of the column were sealed with a plastic layer.
2. The second step was determining amount of water absorbed by capillarity as a function of elapsed time for each column. For this purpose the soil columns were hanged from the hanging scale with ± 0.01 g accuracy and were kept just in contact with the free water surface in a small container as presented in *Figure 2*. Weighing carried out for all columns at the same time intervals (every 10 seconds) until ceasing of the absorption process. The surface of water was always tagged to the end of the columns during experiment by continuous adding of enough water to the container. It has been assumed that water density was fixed at 1 g cm<sup>-3</sup>.
3. In this step, the volume of water absorbed by each soil column was plotted as a function of time by considering the local volume and then applying the following equation:

$$\theta_L(x,t) = [V_w(x+2cm,t) - V_w(x,t)] / V_L \quad (6)$$

where  $\theta_L(x,t)$  is the local volumetric water content that depend on height of the column and the elapsed time,  $V_w(x,t)$  is the volume of water absorbed by the column of height  $x$ , which were 2, 4, 6 and 8 cm,  $t$  is the elapsed time

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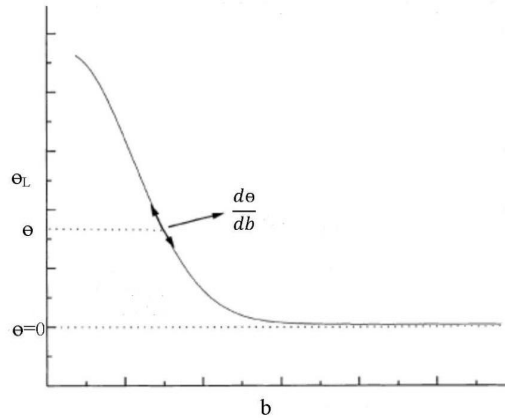


Figure 1. Schematic curve of the local volumetric water content as a function of the Boltzmann transform ( $b$ ).

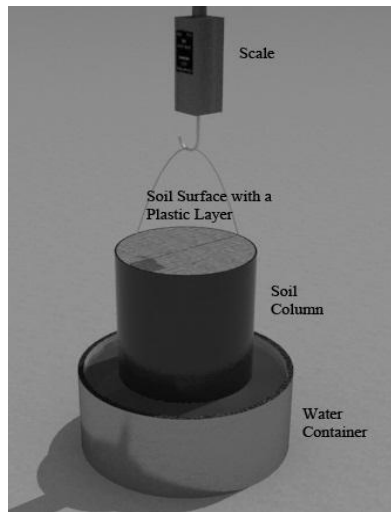


Figure 2. Schematic diagram of water absorption by the soil column.

since the water entry was commenced. VL is the local volume that was set equal to volume of smallest column (2 cm height).

4. The individual water absorbed profiles established in previous step, were combined into an average profile using the Boltzmann transform to find  $\theta$  ( $b = xt^{0.5}$ ).
5. The isothermal moisture diffusivity as a function of water content was computed considering  $\theta(b)$  by using (Equation 5).

Bruce-Klute method (Bruce and Klute, 1956) was also applied for these three soil samples with following boundary conditions:

$$\begin{aligned} \theta &= \theta_i & \text{for } b &= \infty \\ \theta &= \theta_0 & \text{for } b &= 0 \end{aligned}$$

where  $\theta_i$  and  $\theta_0$  are the initial and the inlet water content, respectively. For this purpose, soil columns with 10 cm diameter and 60 cm length were prepared from the same soils, placed horizontally and water source was allowed to contact with one end of the column with approximately zero head, and then moisture contents were measured with time along the column by using  $\gamma$ -ray attenuation technique. For more information see Bruce and Klute (Bruce and Klute, 1956). In order to compare  $D(\theta)$  obtained from the gravimetric technique with those from Bruce-Klute method, logarithmic RMSE and MAE were used:

$$\text{Logarithmic RMSE} = \sqrt{\frac{\sum_{i=1}^N [\text{Log } D(\theta)(G)_i - \text{Log } D(\theta)(BK)_i]^2}{N}} \quad (7)$$

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^N |[D(\theta)(G)_i - D(\theta)(BK)_i]| \quad (8)$$

$D(\theta)(G)_i$  = isothermal moisture diffusion obtained from gravimetric technique  
 $D(\theta)(BK)_i$  = isothermal moisture diffusion obtained from Bruce-Klute method  
 $N$  = number of coupled data that has been compared  
 Excel 2010, Sigma Plot 12.5 and Autodesk 3ds Max 2013 softwares were used to draw the plots and curves.

## RESULTS AND DISCUSSION

The amount of water absorbed by the soil columns with various heights (2, 4, 6, 8 and 10 cm) as a function of time were plotted in (Figure 3). As is shown, the volume of water absorbed by the various soil columns (height and texture) increased with decreasing rate (Figure 3).

Figure 4 presents evolution in local volumetric water content as a function of Boltzmann transform at levels  $x = 2, 4, 6$  and  $8$  cm, as evaluated from the results of Figure 3 and using the equation 6. The series of hydraulic curves for soil columns with various heights were combined into a unique curve (Figure 4). By definition of  $b(\theta_L)$  and applying Equation 5, the isothermal moisture diffusivity as a function of water content could be determined. As illustrated in Figure 4, an exponential decay model was fitted for all three soil samples, and also the fitting power of curves increased in finer textures. Goual *et al.* (2000) observed the gravimetric method for determined moisture diffusion coefficient of concrete material that has fine pores and stronger capillary absorption fit the exponential decay model well.

The comparison of moisture diffusivity curves derived using gravimetric technique to those obtained by  $\gamma$ -ray attenuation method (Bruce-Klute method) showed a distinct similarity in the evolution of  $D(\theta)$  curves between these two methods (Figure 5). This finding confirms the relative accuracy of data obtained using gravimetric technique. As could be seen, the isothermal moisture diffusivity increases with increase moisture content. This trend was reported by other researchers (Wang *et al.*, 2004; Evangelides *et al.*, 2010). Also  $D(\theta)$  by the gravimetric method for the three soils is somewhat less than that predicted from Bruce-Klute method at the wet range (about more than  $0.2 \text{ cm}^3/\text{cm}^3$  water content) in particular for the loamy sand texture. In other words the gravimetric

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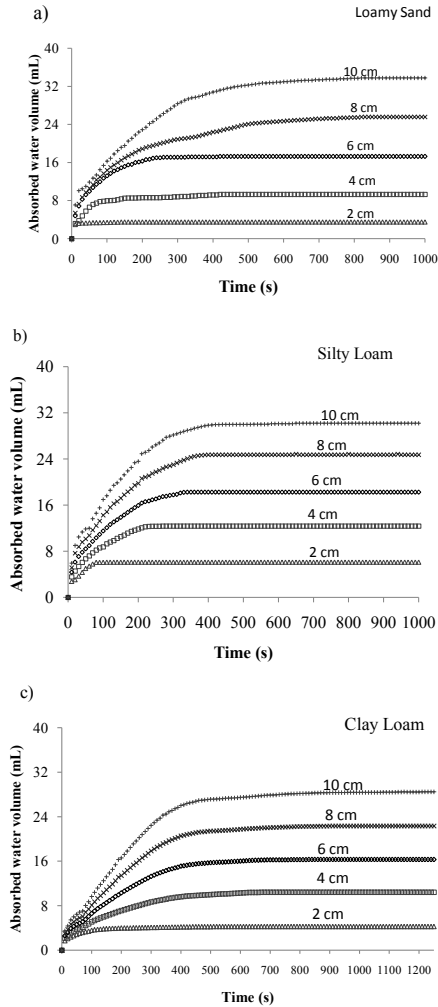


Figure 3. Volume of the absorbed water by various soil columns height and

Figure 3. Volume of the absorbed water by various soil columns height and texture of a) loamy sand, b) silty loam and c) clay loam.

method underestimated  $D(\theta)$  compared to Bruce-Klute method. Difference between the calculated values of  $D(\theta)$  from the two methods increased with increase in moisture content. This observation may be due to our assumption to disregard gravitational gradient in this technique. Since, in the earlier stages of water absorption where  $\psi$  is dominant, these two methods were similar and leads to the same results approximately. With increase in the water absorption by soil and so decrease in the matric gradient, the gravitational gradient becomes influential against matric gradient. And, therefore, our assumption somewhat failed. In this wet range, due to the prevalence of gravitational gradient that acts inversely against matric gradient in vertical direction, leading to underestimation

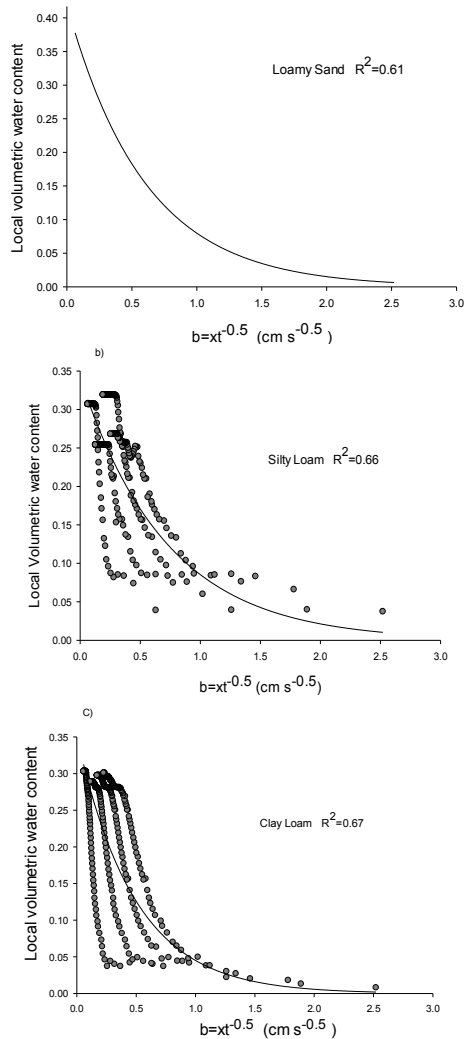


Figure 4. Volumetric water content curves as a function of the Boltzman transform for the three examined soils of a) loamy sand, b) silty loam and c) clay loam.

of  $D(\theta)$  as compared to Bruce-Klute method eventually. This phenomenon may be similar to infiltration rate which at the early stages is controlled primarily by soil matric suction (Kostiakov, 1932 ; Philip, 1957) . Hence behavior of the soil water diffusivity at low moisture ranges is more or less similar in both methods. With increasing moisture content the intrinsic differences between the two methods affect the estimated  $D(\theta)$  values. Logarithmic RMSE for loamy sand, silty loam and clay loam were 0.269, 0.233 and 0.193, respectively. Also measured MAE for loamy sand, silty loam and clay loam were  $1.54 \times 10^{-7}$ ,  $1.99 \times 10^{-2}$  and  $4.39 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$ , respectively. It has been inferred that the gravimetric method may be a reliable method to estimate isothermal moisture diffusion in many soils and



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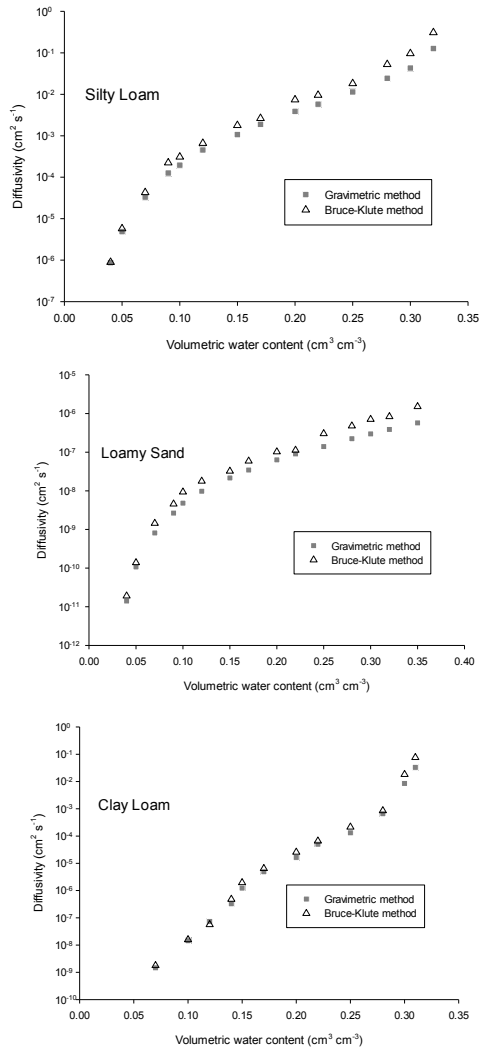


Figure 5. Comparison between the gravimetric and Bruce-Klute methods for the three soil samples a) loamy sand, b) silty loam and c) clay loam.

moreover it is easier than the Bruce-Klute method to conduct in most soil physics laboratories. Our results showed that this method for the three samples of soils was satisfactory and that the accuracy increased with finer textures. As shown by Figure 5, the values of isothermal moisture diffusivity for clay loam in nearly all moisture ranges are less than silty loam, while the clay fraction in the clay loam soil is more than twice in the silty loam. This result may be due to aggregation and the formation of inter-aggregate pores in the clay loam soil. The soil structure development certainly affects pore size distribution that may increase macropores and alter textural behavior of soils (Dorner *et al.*, 2010; Durner, 1994).

Figure 6, demonstrates the error bars between the data obtained using gravimetric technique and those obtained from the Bruce-Klute method for three soil samples. As could be seen, the differences between two mentioned methods increase with increasing diffusivity and moisture content accordingly. Thus, the gravimetric technique is more realible in low moisture levels as compared to higher moisture contents.

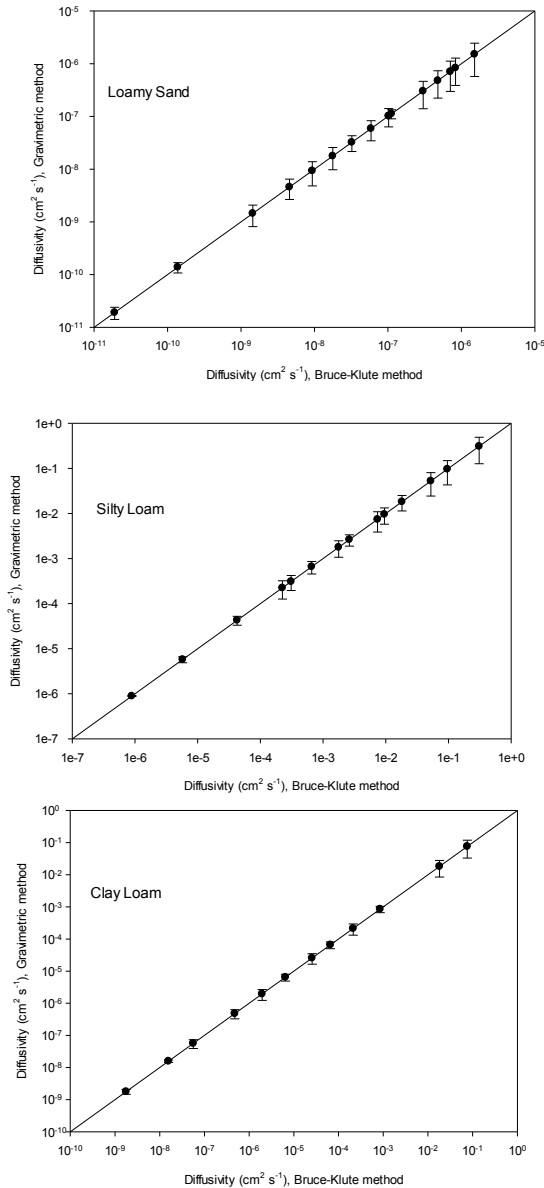


Figure 6. The error bars curves between the gravimetric and Bruce-Klute methods for the three soil samples a) loamy sand, b) silty loam and c) clay loam.

## CONCLUSION

The gravimetric method potential for the prediction of isothermal moisture diffusivity was examined for sandy loam, silty loam and clay loam soils. The results showed that the gravimetric technique is a simple and easier method to apply and has confirmed the reliability of this method especially in fine texture soils. Its accuracy may increase when the soil has more clay and shows stronger capillary absorption behavior that may reduce the prediction errors. There is a further need to continue to examine the various aspects of the presented technique for more diverse soils particularly in undisturbed samples.

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