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Effect of soil physical properties on infiltration rate

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Abstract. Excessive rainfall can cause runoff flows over the soil surface and as a consequence some amount of water will infiltrate into the soil. From a hydrologic modeling perspective it is necessary to estimate infiltration rate in order to calculate the actual runoff discharge. There are many parameters that can affect the infiltration rate such as soil texture, moisture and compaction. However, the most common equations used in hydrological calculations for estimating the infiltration rate do not consider the soil properties directly and estimate infiltration rate without any soil properties expressions. The purpose of this research was to investigate the relations between infiltration rate and soil texture, moisture and compaction. To achieve this purpose an experimental study was performed to show the effect of soil properties and their relations on infiltration rate by using non-linear regression.

Keywords: infiltration rate; hydrological calculation; soil texture; soil moisture; soil compaction

1. Introduction

Infiltration is defined as the amount of water entering into the soil surface over a specific period of time. It replenishes the soil moisture deficiency and the excess moves downward by the force of gravity called percolation and builds up the ground water table (Raghunath 2006). In hydrologic studies, the infiltration rate depends upon the intensity and duration of rainfall, weather, soil properties, vegetal cover, land use, initial soil moisture content, entrapped air and depth of the ground water table (Raghunath 2006, Yang and Zhang 2011, AL-Kayssi and Mustafa 2015). Quantification of infiltration rate is of great importance in engineering management considering both aspects of intensity and the amount of infiltration in design and implementation of all water structure methods and it can be used to estimate the surface runoff. Prediction of the areas and structures which are encountered with flood, soil erosion, pollutant transport and soil erodibility are dependent on infiltration rate (Tesansis 2006, Wang *et al*. 2015, Neshat and Parehkar 2007, Arsyad 2010, Khatri and Smith 2005). Amount and type of soil moisture, texture and compaction are important factors that influence the water infiltration rate and are the responsible factors for the degradation of the physical quality of soils in engineering works (Mao *et al*. 2015).

Soil compaction in nature is mainly caused by human and machine works, which reduces porosity and increases the density of soils, thus reduces water infiltration rate in comparison with

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non-compacted soil (Campbell 1985, Liebig *et al*. 1993, Radcliffe and Rasmussen 2000, Yuxia *et al*. 2001, Hamza and Anderson 2005, Raper and Kirby 2006, Mousavi *et al*. 2011, Mossadeghi-Björklund *et al*. 2015, Menon *et al*. 2015).

Infiltration is the passed flow of water into the soil profile vertically through the soil surface which is an engineering parameter that is difficult to evaluate or measure accurately (Asdak 2004, Dagadu and Nimbalkar 2012, Diamond and Shanley 2013, Mao *et al*. 2015, Latorre *et al*. 2015). In recent decades there are a lot of equations for calculating the rate of infiltration that had been presented such as Horton and Kostiakov equations. Accurate determination of infiltration rate is essential for making a reliable engineering decision. For example, quantifying the soil infiltration capacity is of great importance to understanding and describing the hydrologic analysis and modeling (Lili *et al*. 2008, Mohammadzadeh-Habili and Heidarpour 2015). Each type of soil represents different infiltration of water based on the soil conditions and properties.

Regarding to the previous researches, no comprehensive research was performed on estimating the infiltration rate respect to the soil physical properties, directly. In the present research work, effect of soil texture, compaction and moisture on infiltration rate were studied, experimentally. To do so, different types of soil textures, compaction scenarios and moisture contents were selected. Experiments were conducted in 40 different cases accurately and the infiltration rate was measured accordingly for each case. Finally, the experimental data with a numeric code were analyzed and relations between soil texture, compaction and moisture and infiltration rate were extracted by SPSS software.

2. Methodology and experimental works

Soil samples in different textures, moistures and compactions (40 samples) were prepared and settled into the experimental set up. For producing two different common textures, specific ratio of soil grain sizes with same material had been mixed together. Each sample was surrounded with a water proofed tube with 15 centimeters diameter and 20 centimeters height which had been stood on the compressed soil as the base. The base soil duty was to prevent and decreasing the leakage of water from end of the tube. After compressing the soil in three layers with specific height and hits number, the weight of each sample was measured for calculate the soil compaction. In the next step water was released into the ring until reaching to 10-15 centimeter height over the soil sample surface. For textures with bigger grains diameter and minimum compaction, the rate of infiltration was higher than other samples, therefore, for having accuracy in records, the water height was increased (see Fig. 1).

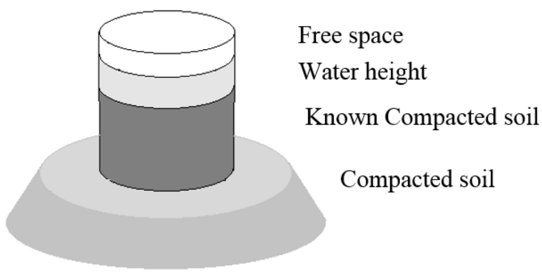

Fig. 1 A schematic view of the experimental ring

Table 1 Soil texture properties

Soil Texture	C_u	C_c	D_{20} (mm)	D_{50} (mm)	D_{80} (mm)
T_1	9.37	1.33	0.56	1.21	5.24
T_2	9.37	0.67	0.84	2.99	19.71

It should be noted that the water was released very slowly to prevent deformation in soil surface, if the soil surface be turbulent by water, soil surface voids may be filled by fine aggregates and it will be cause of negative effects on the experimental results.

With increasing in the soil grain diameters, infiltration rate increases (Hasrullah 2009). However, water surface absorbance in the soil grains decreases (Nurmi *et al*. 2012), therefore, Two different soil textures in types of smooth (fine aggregates) and rough (coarse aggregates) were selected. Properties of each texture are shown in Table 1.

where, C_u = coefficient of uniformity, C_c = coefficient of curvature, D_{20} = the diameter that 20% of soil grains have a smaller diameter than it, D_{50} = the diameter that 50% of soil grains have a smaller diameter than it and D_{80} = the diameter that 80% of soil grains have a smaller diameter than it.

Voids in a soil sample are one of the most important factors in rate of infiltration (Horton *et al*. 1994). Compaction can reduce the voids in the soil and increase the soil density. Therefore, compaction has a great effect on infiltration rate and depends on soil texture, moisture and size (Ekwue and Stone 1995, Kay *et al*. 1997, Imhoff *et al*. 2004, Gregory *et al*. 2006). In the present study, different percent of compaction which represent compacted, semi compacted and normal soils were analyzed (see Fig. 2). Properties of compaction shown in Table 2.

Table 2 Properties of compaction hits

Type name	C_1	C_2	C_3	C_4	C_5
Number of compaction hits	10	20	30	40	50

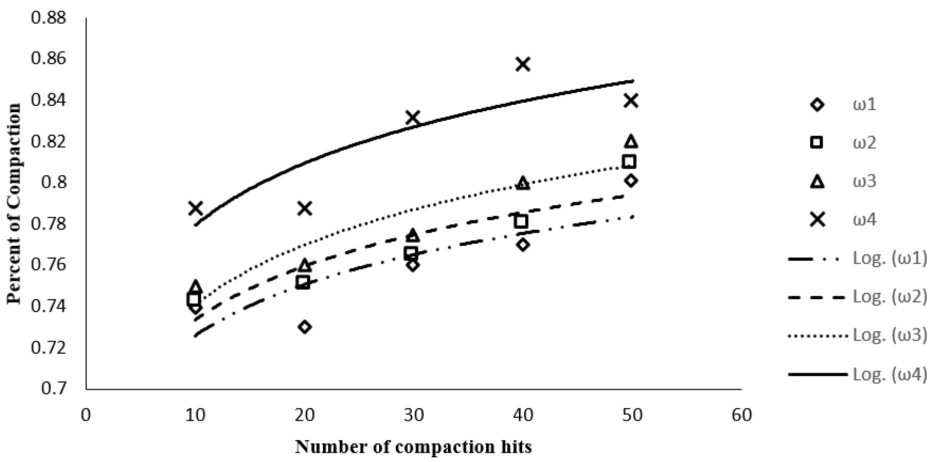

Fig. 2 Compaction percent versus compaction hits

Table 3 Soil moisture properties

Type name	ω_1	ω_2	ω_3	ω_4
Wetness	0%	2.5%	5%	7.5%

Another studied parameter in this research was soil moisture content which can be an effective factor in reducing or increasing the rate of infiltration and influence on absorbance power of grains surface. Four different percent of moistures were selected to highlight the possible and reliable soil conditions as below.

It should be noted that for reaching the specified moisture, a constant amount of soil was dried into an oven and then a known weight of water regarding the specified moisture was mixed into the dried soil.

3. Results and discussions

In each test (40 samples), the water surface changes had been measured in known times, frequently. Infiltration rate versus time for different soil conditions were plotted in known moistures with different compaction hits and times in Fig. 3.

Fig. 3 shows a meaningful difference between the initial values of infiltration rate in different types of moisture. In soil samples with lower moisture, infiltration rate was increased highly. However, in initial minutes of experiments and comparing the final infiltration rate in each experiment with different moistures shows smooth changes. Comparison of initial and final values of infiltration rate in T_1 and ω_1 and T_2 and ω_1, which differ only in texture, shows that by decreasing in diameter of soil grains, soil tendency for seepage had been decreased. Although the soil grain absorbance increased with reducing in soil grain diameter. However, by reducing the soil grain diameter which represented by D_{20} and D_{80}, parameter of number of compaction hits are more effective and reduces the soil voids and porous. By decreasing in soil voids, the downward molecule flow velocity reduced because it does not have a lot of paths to move downward to the lower layers.

A comparison between infiltration rate and compaction percent had been plotted in Fig. 4. Vertical axis shows the ratio of changes in infiltration rates and compaction percent and horizontal axis shows the value of compaction energy. Compaction energy can be calculated by converting the number of compaction hits with Eq. (1) as shown below

$$CE = \frac{n_1 \times n_2 \times w \times h}{V} \tag{1}$$

where, CE = compaction energy, n_1 = number of hits, n_2 = number of compacted layers, w = the weight of rigid body, h = falling height of hammer and V = volume of tube.

In Fig. 4, Cp and f are percent of soil compaction and infiltration rate, respectively. Fig. 4 shows the ratio of changes in compaction percent and infiltration rate versus energy of compaction. According to this figure, increment in energy of compaction does not guarantee the increment in compaction in the soil. For a soil sample with constant moisture, effective compaction occurs in a certain range of compaction hits and out of this range not effective compaction expected. To do so, increment in compaction percent decreases infiltration rate because of reducing the porous of soil

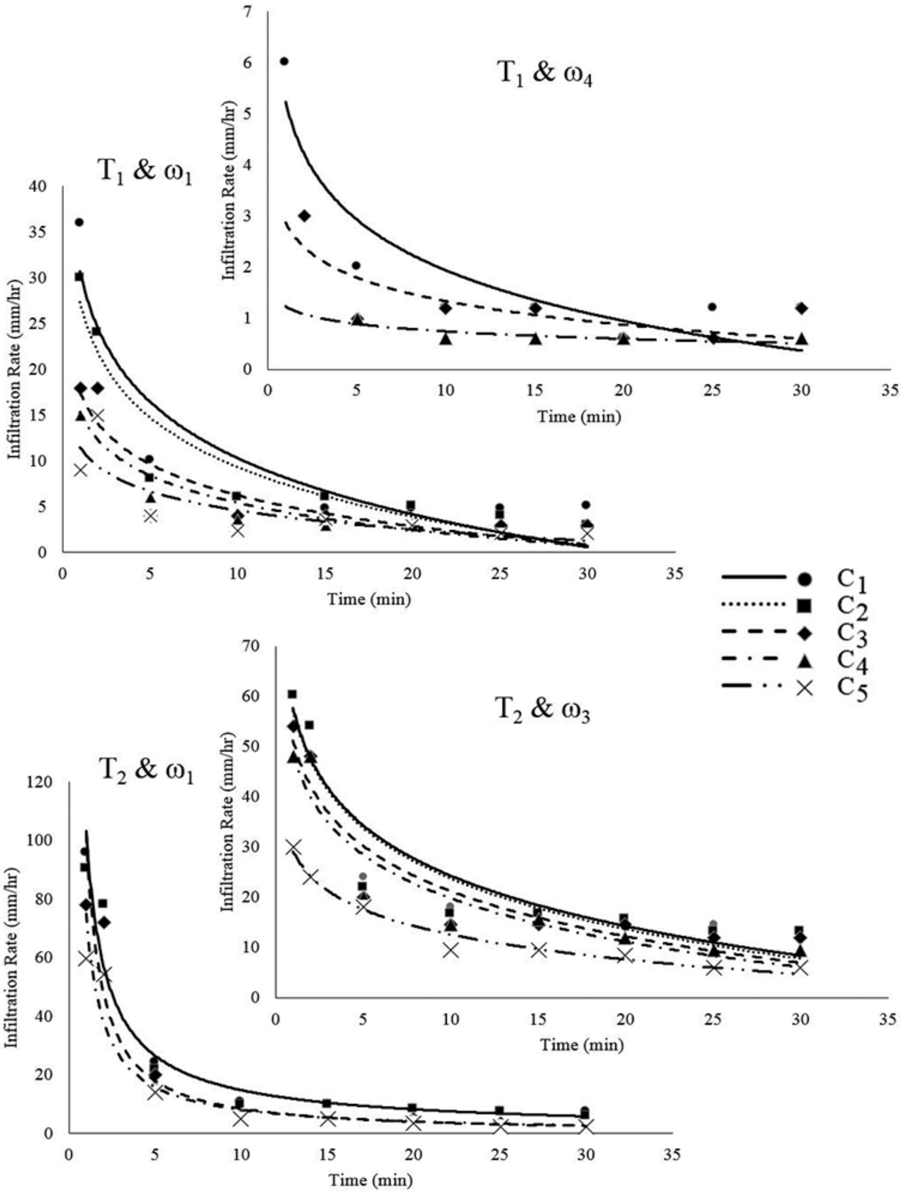

Fig. 3 Infiltration rate versus time for different soil properties

and the chance of water molecules for moving downward into the soil, and inversely decrement in compaction percent increases infiltration rate. Increment or decrement in infiltration rate for 1% decrement or increment in percent of compaction is approximately equal to about 6% and 2%, respectively.

For simulating the infiltration rate with different soil moisture, compaction, texture and the time, experimental data had been categorized in a table and had been processed with nonlinear regression analyze with the SPSS software for calculating the coefficients for model expressions. Finally, Eq. (2) was resulted.

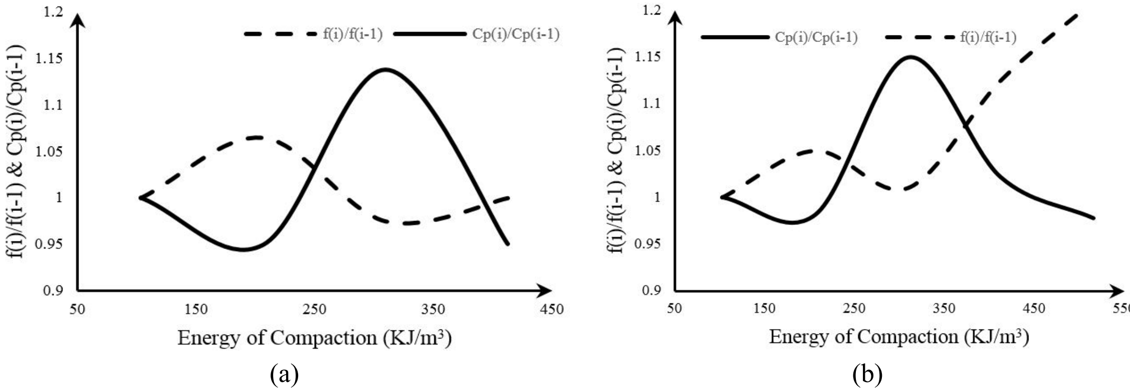

Fig. 4 Average changes in infiltration rate and percent of compaction versus energy of compaction

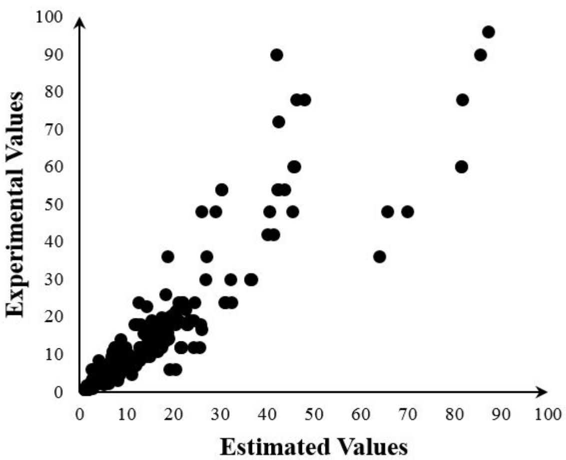

Fig. 5 Comparison between experimental and estimated values for infiltration rate

$$f = 1.17 f_c + 352.7 \times \frac{D_{20}}{t} e^{-(25.45 \times c\omega + 0.1 \times \frac{D_{80}}{D_{20}})} \tag{2}$$

where f_c = final infiltration rate (mm/hr), c = soil compaction, ω = soil moisture and t = time (hr).

Fig. 5 shows the correlation factor of Eq. (2) which is equal to 0.82.

There are equations for estimating the infiltration rate in different conditions. Two of the most famous are Horton and Kostiakov Equations which estimate the infiltration rate without considering the properties of soil, directly. The Horton model expresses the infiltration rate as a function of time, initial and final infiltration rates, empirically.

$$f = f_c + (f_0 - f_c) e^{-kt} \tag{3}$$

where f_0 = Initial infiltration rate; k = Constant for a certain soil (1/hr) and e = 2.72. Horton admitted that infiltration rate decreases during the time until it gets to final infiltration rate (Kadir

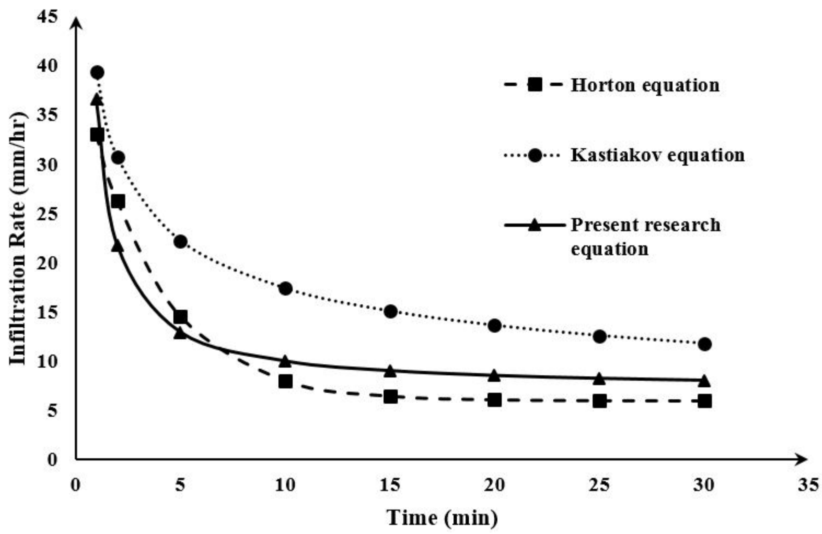

Fig. 6 Comparison between present research and other researches

et al. 2013). He also stated that decreasing in infiltration rate can be controlled by factors operating on the soil surface more than on the flow process in the soil (Lado *et al*. 2005).

Kostiakov Model is cumulative infiltration form and expresses as

$$F = at^n \tag{4}$$

$$F = at^n + b \tag{5}$$

F = Cumulative infiltration depth (mm); a, b, n = Constant for a certain soil. Process of model fitting refer to the relation $(dF/dt) = antn - 1$ (Xianliang and Yunsheng 1986, Yansheng 1992). Determination of the a and n values are performed using the relation $(F_1/F_2) = (t_1/t_2)n$ when F_1, F_2, t_1 and t_2 are known (Kostiakov 1932). In Fig. 6, a comparison between Horton and Kastiakove Equations with Equation 1 had been performed for one of the curves of soil sample T_2 & ω_3.

As can be seen from Fig. 6, the Horton Equation estimated data, more real than the Kastiakov Equation in this research. Calculated difference between Horton Equation and peresent research and also Kastiakov Equation and Peresent research were approximately equal to 21% and 52%, respectively.

4. Conclusions

In the present research, 40 soil samples were prepared in different textures, moistures and compactions and settled into the experimental setup. Each sample was surrounded with water proofed ring with 15 centimeters diameter and 20 centimeters height. Change of water surface had been measured in known times and infiltration rate for different soil conditions. Results showed that influence of moisture on infiltration rate in the first minutes of experiments obviously was very high. In the comparison of experiments, T_2 and ω_1 and T_2 and ω_3, with increasing 2.5% of water, initial infiltration decrement was about 50% but the changes in final infiltration rate was not meaningful. Influence of soil texture in the present study refers to filling the porous with fine aggregates and avoiding the water from moving downward. Moreover, results showed that with 1% decreasing in percent of compaction infiltration rate causes increasing approximately 6% of previous values and for 1% increasing in the percent of compaction, infiltration rate decreases about 2% of previous values. An equation extracted by non-linear regression for estimating the infiltration rate with correlation factor of 0.82 and involved physical properties of soil as moisture, percent of compaction and soil texture, directly. The extracted equation compared with famous equations for infiltration rate (Horton and Kostiakov equations) and a difference about 21% and 52% was observed, respectively.

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Nomenclature

The following symbols are used in this paper:

a, b, n	=	constant of Kastiakov equation
c	=	soil compaction
C_p	=	soil compaction percent
CE	=	compaction energy
C_u	=	coefficient of uniformity
C_c	=	coefficient of curvature
D_{20}	=	it is the diameter that 20% of soil grains have a smaller diameter than it
D_{50}	=	it is the diameter that 50% of soil grains have a smaller diameter than it
D_{80}	=	it is the diameter that 80% of soil grains have a smaller diameter than it
e	=	constant equal to 2.72
f_0	=	initial infiltration rate
f_c	=	final infiltration rate
f	=	infiltration rate
F	=	cumulative infiltration depth
h	=	falling height of hammer
k	=	constant of Horton equation
n_1	=	number of hits
n_2	=	number of compacted layers
t	=	time
V	=	volume of tube
ω	=	moisture of soil