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A New Model to Measure in Situ Saturated Hydraulic Conductivity Using Auger Hole with Flat Bottom

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Abstract

The value of saturated hydraulic conductivity (K_s) are essentially required for the design of subsurface drainage and design of elevated field beds for reclamation and management of waterlogged saline as well as sodic soils. Hooghoudt (1936) model for K_s was modified in the present study to improve the estimate. A model for K_s measurement was also developed and compared with existing model. Ernst (1950) model is widely used for field application. The newly proposed model calculated the value of K_s as 0.248 m day^{-1}. Hooghoudt, modified Hooghoudt and Ernst model gave the values of K_s as 0.436, 0.455 and 0.255 m/day. The K_s value obtained by newly developed model was closest to the value obtained by the Ernst model with deviation of 0.8% only. The new model is quite simple to understand with best accuracy hence recommended for field application.

Key words: Auger hole method, Elevated field bed, Saturated hydraulic conductivity, Subsurface drainage, Waterlogged saline soil

Introduction

India is suffering with salt accumulation in soil over an area of 9.5 Mha. out of which 3.0 Mha is sodic. Indo - Gangetic plains is having sizable area of 1.31 Mha under sodic condition (Singh *et al.,* 2016). Sizable area of sodic soil located in large canal command is suffering with twin problems of waterlogging and sodicity. Subsurface natural drainage of the area is insufficient to handle the seepage loss from the large canals at different reaches of the canals. Waterlogged saline soil mostly lying in arid and semi-arid area and are easily reclaimed by improving internal drainage through subsurface drainage. Design and proper functioning of subsurface drainage in waterlogged saline soil as well as elevated field bed of integrated farming system in waterlogged sodic area is dependent on saturated hydraulic conductivity (K_s) of the soil which is a basic input parameter to the drain spacing or raised bed width calculation equations. The K_s is space and time-dependant hence one must adequately assess a representative value. Estimation of a representative value of K_s conductivity is time consuming and expensive, hence one has to optimize for the available budget and desired accuracy. K_s of soil can be obtained by correlation methods or with hydraulic methods which maybe either laboratory or in-situ methods (Woesten, 1990). Correlation methods are quick and based on predetermined relationships of soil properties (Woesten and van Genuehten, 1988). Aronovici (1947) correlated silt and clay content with hydraulic properties of soil. Singh and Verma (2010a and b) derived viscous resistance model and drag resistance model for estimation of K_s from particle size distribution data. These model have their own limitations and merits for field applicability. Smedma and Rycroft (1983) generalized tables with K_s values for various soil textures. These methods are subjected to random errors. Hydraulic methods based on flow conditions in the soil making use of Darcy's law and the boundary conditions of the flow.

Researchers also proposed field dripper methods for in-situ measurement of unsaturated hydraulic functions (Warrick, 1985; Shani *et al.*, 1987; Ojha *et al.*, 2020).The K_s value is also calculated from the equation using the values of hydraulic head and discharge recorded in fields or laboratories. Gallage *et al.* (2013) developed a new permeameter for the measurement of unsaturated hydraulic conductivity of the soil using directly measured suction. Jacka *et al.* (2014) compared K_s values obtained from Guelph permeameter, laboratory permeameter and single ring infiltrometer for mountain podzols. All the test provided similar mean values. Laboratory methods are laborious than correlation methods but quick and cheap also eliminate uncertainties involved in relating soil properties to K_s values. Laboratory methods also have limitations as that of correlation methods in terms of variability and representativeness. In situ hydraulic methods may be either small scale or large scale. The small scale methods are quick covering many locations and avoiding complexities with least expense. Variability is minimized in case of the in-situ methods due to coverage of large soil volume. Infiltro meter and inverse auger hole methods employ similar hypothesis for measuring in-situ K_s of soil in absence of water table. Infiltrometer method measures vertical saturated hydraulic conductivity of surface soil while inverse auger hole method measures horizontal K_s of subsoil (Hoorn, 1979). The auger hole method for measurement of in-situ K_s of the soil in presence of water table for design of subsurface drainage systems is a quick, simple and reliable (Hooghoudt, 1936; Kirkham, 1945, 1955; Bavel and Kirkham, 1948; Ernst, 1950; Johnson *et al.*, 1952). Hooghoudt (1936) developed first auger hole model for in-situ K_s measurement which is quite simple. Ernst (1950) reported by van Beers (1970) and Bouwer and Jackson (1974) developed another model of in-situ K_s using auger hole data. Method is used for field applications too. Accurate estimation of K_s is needed for the design of sub-surface drainage systems (Barua and Alam, 2013). Barua and Alam (2013) analyzed the flow of auger hole numerically when it is penetrating to impervious layer and when it is suspended above an impervious layer and developed similar expression of K_s as that by Ernst (1950). These models are complex and still there is a need for simpler model for in-situ K_s estimation. Inverse auger hole method by Hoorn (1978) is used for K_s estimation in absence of water table. The present study is devoted to develop a new model of K_s estimation using auger hole data.

Materials and Methods

Hooghoudt (1936) auger hole Model

A definition sketch of auger hole method for in-situ K_s measurement are shown in Fig. 1. Hooghoudt (1936) developed following equation for K_s.

$$K_s = \frac{2.3\,r\,S}{(2D+r)}\tan\alpha_H \quad (1)$$

$$\tan\alpha_H = \frac{\log_{10} H_o - \log_{10} H_t}{t} \quad (2)$$

where,

H_o = water table depth in the hole below static water level after bailing out water

H_t = water table depth in the hole below static water level after time t of bailing out water

D = Water level depth before bailing

S = rD/0.19

r = radius of the hole

t = time

Modification of Hooghout (1938) auger hole model

Hooghoudt Eqn. (1) can be modified by replacing the expression for S = rD/0.19 with an expression of S=1/C. C is the geometry or shape factor of Ernst (1950). The Eqn. (1) with this modification becomes.

$$K_s = \frac{2.3\,r}{C(2D+r)}\tan\alpha_H \quad (3)$$

Ernst (1950) developed following equation for K_s.

$$K_s = C\,\frac{\Delta h}{\Delta t} \quad (4)$$

C= geometry or shape factor f(h, D, r, d) defined by following expressions

When, depth of impervious layer d > 0.5 D

$$C = \frac{4000\frac{r}{h'}}{\left(20+\frac{D}{r}\right)\left(2-\frac{h'}{D}\right)} \quad (5)$$

When, depth of impervious layer d =0

$$C = \frac{3600\frac{r}{h'}}{\left(10+\frac{D}{r}\right)\left(2-\frac{h'}{D}\right)} \quad (6)$$

If all the values are written in cm and time in sec the K_s value would be in m/d.

New Model Development

Hypothesis: Rate of rise of water level within the auger hole ($\frac{dh}{dt}$) after bailing out water below static water level is directly proportional to effective saturated area of the auger hole (A_s) causing flow within the hole (Fig. 1). Mathematically it can be expressed as below.

$$\frac{dh}{dt} \propto A_{sT} \quad (7)$$

Further, the rate of rise of water level within the hole ($\frac{dh}{dt}$) is inversely proportional to the specific empty volume of the hole (V_{es})

$$\frac{dh}{dt} \propto \frac{1}{V_{es}} \quad (8)$$

Rate of rise of water level within auger hole is also directly proportional to geometry or shape factor C. It can be written as below.

$$\frac{dh}{dt} \propto C \quad (9)$$

Combining Equation (6), (7) and (8) one will get the following hypothesis expression.

$$\frac{dh}{dt} \propto \frac{CA_{sT}}{V_{es}} \quad (10)$$

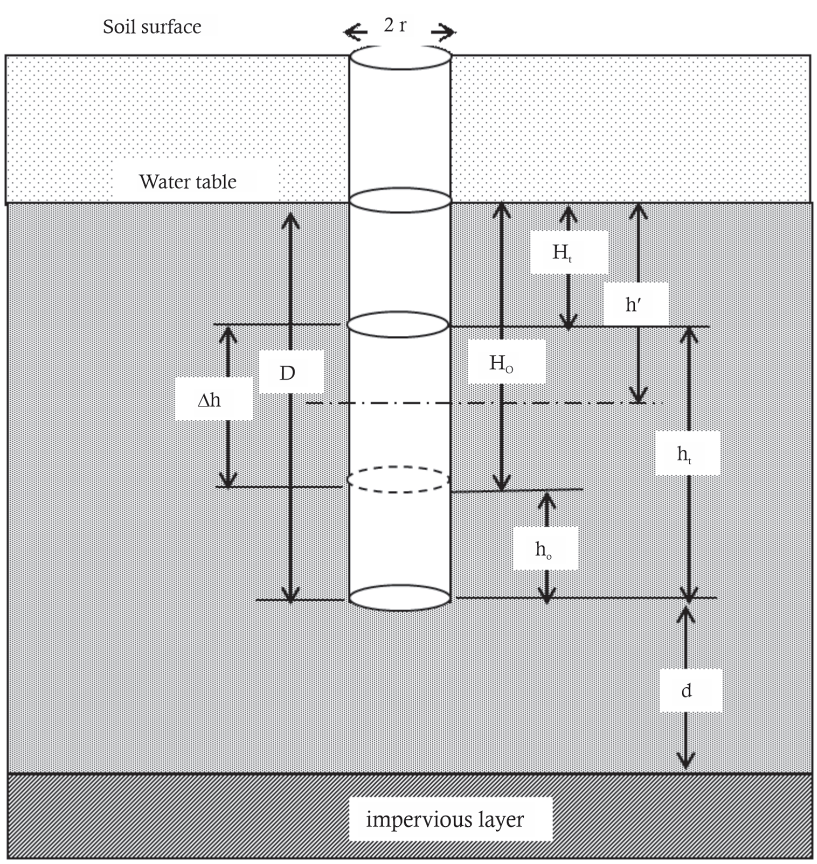

Fig. 1 Definition sketch of auger hole

Introducing a proportionality constant of water flow towards the flow, K_s known as saturated hydraulic conductivity of the soil, if the hydraulic gradient is unity (i=1) as that of Infiltration rate from Infiltrometer [$v=K_s\, i$ $v= K_s$]. Therefore, Eqn. (4) becomes

$$\frac{dh}{dt} = K_s \frac{CA_{sT}}{V_{es}} \tag{11}$$

a) When depth of impervious layer is below the bottom of the hole (s>0)

Eqn (10) can be solved for flat bottom geometry. Saturated bottom area of the hole through which water entering the hole can be written as below.

$$A_{sT} = \pi r^2 \tag{12}$$

Saturated circumferential area through which water entering the hole can be written as below.

$$A_{sT} = 2\pi r\,(D-h) \tag{13}$$

Thus Total saturated area through which flow is taking place can be written as below

$$A_{sT} = \pi r^2 + 2\pi r(D-h) \tag{14}$$

$$A_{sT} = 2\pi r\left\{(D-h)+\frac{r}{2}\right\} \tag{15}$$

Specific volume of hole is defined as the volume of hole per unit depth of saturated hole i.e. $\left(\frac{V_{sh}}{D}\right)$. Since the saturated volume of the soil removed from hole i.e. the volume of the hole up to static water level within the soil is $\pi r^2 D$ when the depth of the saturated portion of the hole is D, hence the specific empty saturated volume of the hole becomes.

$$V_{es} = \frac{\pi\ r^2 D}{D} = \pi r^2 \tag{16}$$

Substituting Eqn (14) and (15) into Eqn (9) one will arrive at,

$$\frac{dh}{dt} = CK_s\left[\frac{2\pi\ r\left\{\ (D-h)+\frac{r}{2}\right\}}{\pi\ r^2}\right] \tag{17}$$

$$\frac{dh}{dt} = CK_s\left\{\frac{2\pi\ r\ (D-h)+\pi\ r^2}{\pi\ r^2}\right\} \tag{18}$$

$$\frac{dh}{dt} = CK_s\left\{\frac{2}{r}(D-h)+1\right\} \tag{19}$$

$$\frac{dh}{dt} = CK_s\left\{\frac{2D}{r}-\frac{2h}{r}+1\right\} \tag{20}$$

$$\frac{dh}{dt} = CK_s\left\{\left(1+\frac{2D}{r}\right)-\frac{2h}{r}\right\} \tag{21}$$

$$\frac{dh}{dt} = CK_s\left\{\left(\frac{2D+r}{r}\right)-\frac{2h}{r}\right\} \tag{22}$$

Separating variable and integral the above equation under the limit of

$$t = o,\ h = h_o \text{ and } t = t,\ h = h_t \tag{23}$$

$$\int_{h_o}^{h_t} \frac{dh}{\frac{2D+r}{r}-\frac{2}{r}h} = CK_s\int_o^t dt \tag{24}$$

If $\alpha = \frac{2D+r}{r}$ and $\beta = \frac{2}{r}$ the above Equation can be also written as below.

$$\int_{h_o}^{h_t} \frac{dh}{\alpha-\beta\ h} = CK_s\int_o^t dt \tag{25}$$

General solution of the indefinite integral of the above form can be written as below.

$$\int \frac{dx}{ax\ +\ b} = \frac{1}{a}\ln(ax+b) \tag{26}$$

Where a=β and b =α

Therefore the integration of equation (23) be can

$$-\frac{1}{\beta}\ln(\alpha-\beta h)\Big]_{h_o}^{h_t} = \frac{K_s}{C}t\Big]_o^t \tag{27}$$

Substituting the volume of $\alpha = \frac{2D+r}{r}$ and $\beta = \frac{2}{r}$

$$CK_s\, t\Big]_o^t = \frac{r}{2}\ln\left\{\left(\frac{2D+r}{r}\right)-\frac{2h}{r}\right\}\Big]_{h_t}^{h_o} \tag{28}$$

$$CK_s t = \frac{r}{2}\ln\left\{\left(\frac{2D+r}{r}\right)-\frac{2h_o}{r}\right\}-\ln\left\{\left(\frac{2D+r}{r}\right)-\frac{2h_t}{r}\right\} \quad (29)$$

$$K_s = \frac{r}{2C}\frac{\ln\left\{\left(\frac{2D+r}{r}\right)-\frac{2h_o}{r}\right\}-\ln\left\{\left(\frac{2D+r}{r}\right)-\frac{2h_t}{r}\right\}}{t} \quad (30)$$

$$K_s = 1.15\frac{r}{C}\frac{\log_{10}\left\{\left(\frac{2D+r}{r}\right)-\frac{2h_o}{r}\right\}-\log_{10}\left\{\left(\frac{2D+r}{r}\right)-\frac{2h_t}{r}\right\}}{t} \quad (31)$$

Which can be further simplified as below.

$$K_s = 1.15\frac{r}{C}\frac{\log_{10}\left\{\left(D+\frac{r}{2}\right)-h_o\right\}-\log_{10}\left\{\left(D+\frac{r}{2}\right)-h_t\right\}}{t} \quad (32)$$

$$K_s = 1.15\frac{r}{C}\tan\alpha_p \quad (33)$$

Where,

$$\tan\alpha_p = \frac{\log_{10}\left\{\left(D+\frac{r}{2}\right)-h_o\right\}-\log_{10}\left\{\left(D+\frac{r}{2}\right)-h_t\right\}}{t} \quad (34)$$

Eqn. (32) can be finally written as below.

$$K_s = \frac{K_{s-index-p}}{C} \quad (35)$$

Where,

$$K_{s-index-p} = 1.15 r \tan\alpha_p \quad (36)$$

(b) When depth of impervious layer is at the bottom of the hole (d=0)

When bottom of the auger hole is penetrating the impervious layer, the flow from the bottom reduces to zero. Thus total saturated area through which flow is taking place can be written from Eqn. (13) as below

$$A_{sT} = 0 + 2\pi r(D-h) = 2\pi r(D-h) \quad (37)$$

Since the specific volume of hole is πr^2 Eqn. 16 reduces to,

$$-\frac{dh}{dt} = CK_s\left[\frac{2\pi r\{(D-h)\}}{\pi r^2}\right] \quad (38)$$

$$-\frac{dh}{dt} = CK_s\left\{\frac{2(D-h)}{r}\right\} \quad (39)$$

Separating variables and integrating the above equation under the limit of Eqn. (39)

$$CK_s\int_o^t dt = -\frac{r}{2}\int_{h_o}^{h_t}\frac{dh}{D-h} \quad (40)$$

General solution of the indefinite integral of the above form can be written as below.

$$\int\frac{dx}{a-x} = -\ln(a-bx) \quad (41)$$

Therefore the integration of equation (39) would be

$$CK_s t\Big]_o^t = -\ln(D-h)\Big]_{h_o}^{h_t} \quad (42)$$

$$K_s = \frac{r}{2C}\frac{\ln(D-h_o)-\ln D-h_t}{t} \quad (43)$$

Changing the natural log to the base of 10 as below.

$$K_s = 1.15\frac{r}{C}\frac{\log_{10}(D-h_o)-\log_{10}(D-h_t)}{t} \quad (44)$$

Which can be further simplified as below.

$$K_s = 1.15\frac{r}{C}\tan\alpha_{pp} \quad (45)$$

Where,

$$\tan\alpha_{pp} = \frac{\log_{10}(D-h_o)-\log_{10}(D-h_t)}{t} \quad (46)$$

Eqn. (44) can be finally written as below.

$$K_s = \frac{K_{s-index-pp}}{C} \quad (47)$$

Where,

$$K_{s-index-pp} = 1.15 r \tan\alpha_{pp} \quad (48)$$

Application of the Model

Three auger holes of 10 cm diameter and 150 cm deep were constructed near Mahraura village along the Sharda Sahayak Canal in district Raebareli. After the preparation of the holes they were left for 24 hours for attaining their static water level. Impervious layer in the region lies below 3 m of ground surface. Average static water level was observed as 50 cm below the ground surface. The water was bailed out upto 120.5 cm depth and rate of rise was measured. Average rise of water table is shown in Fig. 2. Water depth before the bailing out of water was 100 cm. Water depth below ground surface was changed to water level height above the bottom of the hole. $(D+r/2-h_o)$ and $(D+r/2-h_t)$ and their respective $\log_{10}$ values were calculated. $\log_{10}(D+r/2-h_o) - \log_{10}(D+r/2-h_t)$ were plotted against elapsed time t and slope of the line (tan α) was worked out. Eqn. (26) was employed to calculate K_s value of the soil. K_s value was also calculated be Hooghoudt (1936) model, Ernst (1950), infiltrometer and constant head permeameter method for the purpose of comparison.

Results and Discussion

Water level fluctuations

The water level within the hole rose from 120.5 cm to 83.2 cm below the ground surface over a time span of 900 second. Saturated depth of auger hole or the depth of water filled in the hole before bailing out of water was measured as 100 cm. The variation of water level within the hole against time is shown in Fig. 2. The variation in water level height above bottom of the hole (h_t) in cm against time (t) in minute was well explained by the following function.

$$h_t = 43.05342\left(1.71808 - e^{-0.11201357\,t}\right) \quad (49)$$

Calculation of K_s value

1. Proposed method

The water in the auger hole which was initially 50 cm deep below the soil surface came down to a level of 70.5 cm (H_o=120.5 cm bgl) below the static water level which rose to the level of 33.2 cm (H_t=83.2 cm bgl) below static water level over a time of 900 s. Thus the rise in water table in time Δt=900 s was recorded as Δh= 37.3 cm and rate of rise was calculated as $\Delta h/\Delta t$=0.04144. The height of water level above the bottom of hole immediately after the bailing was h_o=29.5 cm and after 900 s it was h_t= 66.8 cm. The value of h^1 was calculated as 51.85 cm. The value of 20+D/r was calculated as 40 and $2-h^1/D$ as 1.4815 and their product as 59.26. The value of $4000\,(r/h^1)$ was calculated as 385.7281. The value of C was calculated by taking ratio of $4000\,(r/h^1)$ and $(20+D/r)(2-h^1/D)$ as 6.5091.Calculation of $K_{s\text{-index}}$ is presented in Table 1. Plotted values of $\log_{10}(D+r/2-h_o) - \log_{10}(D+r/2-h_t)$ against time is shown in Fig. 3. The variation was linear ($\log_{10}(D+r/2-h_o) - \log_{10}(D+r/2-h_t)$= 0.030622478 + 0.019463673 t) and slope of the line was worked out 0.019463673. The $K_{s\text{-index}}$ was calculated as 1.612 m/day and K_s value was calculated as 0.248 m/day.

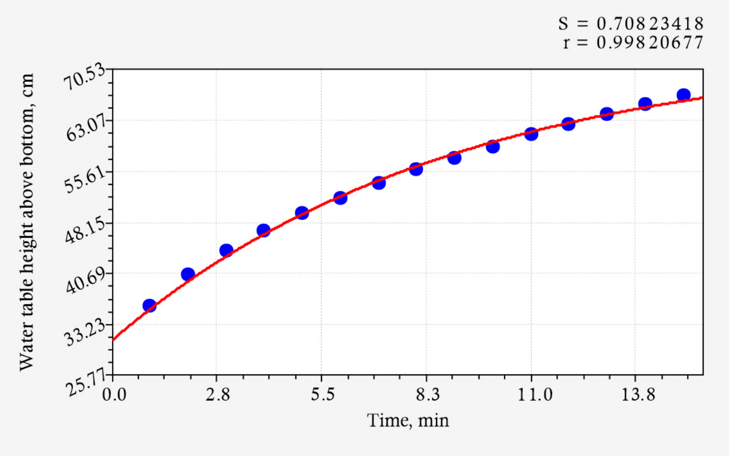

Fig. 2 Variations of water level within the hole after the bail out

Table 1. Calculation of tan α and K_s using proposed auger hole method

Time min	Depth to water level bgl D_T cm	Saturated depth, D cm	r cm	Water level height above bottom h_t= 150-D_T cm	D+r/2 cm	D+ (r/2)-h_o cm	D+(r/2)-h_t cm	$\log_{10}$ [(D+(r/2)) -h_o]	$\log_{10}$ [(D+(r/2)) -h_t)	$\log_{10}$ [(D+(r/2)) -h_o]-$\log_{10}$ [(D+(r/2)) -h_t]
0	120.5	100	5	29.5	102.5	73	73	1.863323	1.863323	0
1	114	100	5	36.0	102.5	73	66.5	1.863323	1.822822	0.040501
2	109.5	100	5	40.5	102.5	73	62	1.863323	1.792392	0.070931
3	106	100	5	44.0	102.5	73	58.5	1.863323	1.767156	0.096167
4	103	100	5	47.0	102.5	73	55.5	1.863323	1.744293	0.11903
5	100.5	100	5	49.5	102.5	73	53	1.863323	1.724276	0.139047
6	98.2	100	5	51.8	102.5	73	50.7	1.863323	1.705008	0.158315
7	96	100	5	54.0	102.5	73	48.5	1.863323	1.685742	0.177581
8	94.1	100	5	55.9	102.5	73	46.6	1.863323	1.668386	0.194937
9	92.4	100	5	57.6	102.5	73	44.9	1.863323	1.652246	0.211077
10	90.7	100	5	59.3	102.5	73	43.2	1.863323	1.635484	0.227839
11	89	100	5	61.0	102.5	73	41.5	1.863323	1.618048	0.245275
12	87.5	100	5	62.5	102.5	73	40	1.863323	1.60206	0.261263
13	86	100	5	64.0	102.5	73	38.5	1.863323	1.585461	0.277862
14	84.5	100	5	65.5	102.5	73	37	1.863323	1.568202	0.295121
15	83.2	100	5	66.8	102.5	73	35.7	1.863323	1.552668	0.310655

C= 6.5091, tan α = 0.019463673, $K_{s\text{-index}}$ = 1.15 r tan α, $K_{s\text{-index}}$=1.612 m/day, K_s=$K_{s\text{-index}}$/C=1.612/6.5091=0.248 m/d

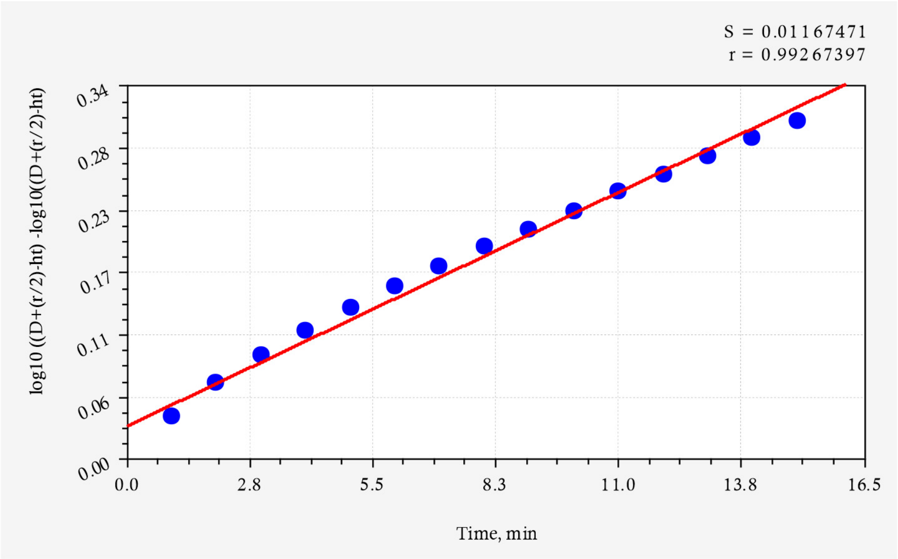

Fig. 3 Variations of $\log_{10}$ (D+r/2-h_o) – $\log_{10}$ (D+r/2-h_t) against time

2. Hooghoudt (1936) method

The plotted line between $\log_{10} H_o - \log_{10} H_t$ against time t is shown in Fig. 4. The variation is linear and slope was measured as 0.020512578 and variations was explained by the following linear equation.

$$\frac{\log_{10} H_o - \log_{10} H_t}{t} = \frac{2.3 r S}{K_s (2D + r)} \quad (50)$$

Eqn. (50) after plotting the data was obtained as below.

$$\log_{10} H_o - \log_{10} H_t = 0.03108224 + 0.020512578\, t \quad (51)$$

The K_s value was calculated as 0.436 m/day for S=rD/0.19= 0.263158 and tan α= 0.020512578 using following equation.

$$K_s = \frac{2.3\ r\ S}{(2D + r)} \tan\alpha \quad (52$$

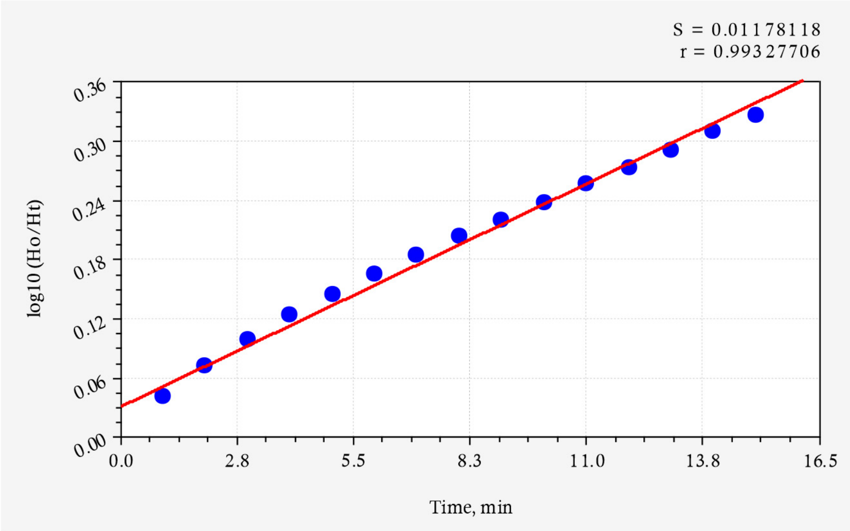

Fig. 4 Variation of $\log_{10} H_o - \log_{10} H_t$ with time

3. Modified Hooghoudt (1936) method

The Hooghoudt (1936) model was modified by replacing S=rd/0.19 with S=1/C. The value of C is the same as that of Ernst (1950) geometry factor. The value of K_s was obtained as 0.455 m/day.

4. Ernst (1950) method

The water in the auger hole which was initially 50 cm deep below the soil surface came down to a level of 70.5 cm (H_o=120.5 cm bgl) below the static water level which rose to the level of 33.2 cm (H_t=83.2 cm bgl) below static water level over a time of 900 s. Thus the rise in water table in time Δt=900 s was recorded as Δh= 37.3 cm and rate of rise was calculated as Δh/Δt=0.04144. The height of water level above the bottom of hole immediately after the bailing was h_o=29.5 cm and after 900 s it was h_t= 66.8 cm. The value of h^1 was calculated as 51.85 cm. The value of 20+D/r was calculated as 40 and 2-h^1/D as 1.4815 and their product as 59.26. The value of 4000 (r/h^1) was calculated as 385.7281. The value of C was calculated by taking ratio of 4000 (r/h^1) and (20+D/r)(2-h^1/D) as 6.5091. Finally the K_s value was calculated as 0.27 m/day.

Considering the K_s value obtained from Ernst (1950) model as a reference value the per cent deviations of the K_s values obtained as 74.40, 2.00 and -0.80% by Hooghoudt (1936), Modified Hooghoudt (1936) and Proposed Model, respectively. The proposed model gave identical value of K_s with minimum percent deviation. Modified Hooghoudt (1936) model gave the second best value of K_s. Except for the Hooghoudt (1936) model all three models gave K_s values extremely close to each other hence recommended for field application.

Conclusions

In-situ measurement of K_s value provides more accurate value for the design of subsurface drainage and the width of elevated field beds of fish pond based integrated farming system models under waterlogged sodic or saline conditions. Auger hole method of Hooghoudt (1936) was used initially for in-situ K_s estimation which uses empirical relationship of S=rD/0.19 based on sand tank model studies. Ernst (1950) model gives accurate value of K_s and recommended for the field application. Barua and Alam (2013) obtained another solution analyzing the flow of auger hole numerically giving identical values of K_s as that by Ernst (1950). The proposed correction in Hooghoudt model yielded good result. A newly developed model which is simple to understand flow process gave extremely close value of K_s as that of Ernst model. The new model is recommended for field application due to its simplicity and accuracy.

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