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Study on the selection of unsaturated flow model for the different types of soil and soft rock

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Abstract Precise estimation of unsaturated hydraulic properties of porous media is indispensable in various study areas, such as analyzing the moisture flow, the drying process occurring from the surface, and the pollutant migration beneath the ground surface. Although many empirical/theoretical models describing the unsaturated hydraulic properties have been proposed by several previous researchers, the best model for the different types of soil/rock may not be identical. Thus, the model selection process and the estimation technique of the parameters included in the models should be developed. In the present study, the inverse technique based on the transient evaporation change was investigated to select the model and estimate the model parameters. The experimental work was based on a relatively low permeable soft rock and a relatively high permeable sandy soil (Toyoura standard sand). Experimental equipment was developed to precisely measure the evaporation rate for the high permeable sandy soil. The Genetic Algorithm (GA) was adopted in the inverse technique as an optimization tool. In order to simplify the problem, only the drying process from the saturated condition was considered. It was established that the information concerning the transient evaporation change could be used for the model selection and parameter estimation. Further, the saturation distribution could be used for the selection of the models. The present study provides important information for the development of the model selection process.

Keywords Unsaturated hydraulic properties · Porous media · Genetic algorithm · Inverse estimation · Saturation distribution

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Introduction

Worldwide, the problem of conserving water in unsaturated soil has been a very important issue. Thus, the estimation of the unsaturated flow and the migration of the pollutants should be precisely analyzed. Consequently, the estimation of the hydraulic properties in porous media is an essential issue. The relationships between the water retention curve $\varphi(\theta)$ and the hydraulic conductivity curve $k(\theta)$ are essential for this estimation; where θ is the volumetric water content, φ is the capillary head, and k is the hydraulic conductivity. The most popular way to define these relationships is the closed form of equations proposed by several researchers, e.g., Brook and Corey (1964), Campbell (1974), and van Genuchten (1980). Numerous articles devoted for finding the parameters of these functional equations can be found in literature. These attempts essentially can be divided into two parts: direct measurements and indirect estimation methods. However, the direct methods (Bruce and Klute 1956;

Dirksen 2000; Gardner and Miklich 1962; Klute and Dirksen 1986) are time consuming and tedious as emphasized by some researchers (Ritter et al. 2003; Šimůnek et al. 1998).

On the other hand, the indirect estimation methods (Eching et al. 1994; Kool et al. 1985) of parameter identification, particularly involving inverse numerical modeling of the flow, have become popular among the soil scientists. The indirect estimation methods are easier than the direct measurement methods (van Dam et al. 1990). These can be based on the numerical solution of the equations governing the flow process, which is subjected to the imposed boundary conditions (Eching and Hopmans 1993). There are two common experimental approaches among the indirect methods: the infiltration (Kool et al. 1985; Young et al. 2002) and the upward flow induced by evaporation (Ali et al. 2000; Campbell 1985; Šimůnek et al. 1998; Minasny and Field 2005).

The indirect methods (also called parameter optimization) based on evaporation are relatively simple and faster in comparison to the other methods. In the above mentioned methods, the transient evaporation rate is measured and then the parameters are inversely estimated from the measured data. Although the evaporation method is used by several researchers, many of them do not consider the saturation distribution profile in soil. Several previous studies have used fans to accelerate the evaporation (Fujimaki and Inoue 2003; Šimůnek et al. 1998). Therefore, the vapor transport in the sample may become significant when the saturation becomes low. Nevertheless, the numerical models applied by most researchers based on the Richard's equation, only account for the water flow (Minasny and Field 2005; Zarei et al. 2010). Under any accelerated (e.g. using fans) or natural drying soil conditions (e.g. arid/semi-arid region due to high evaporation rate), the vapor flow may be significant. Thus, the water and the vapor flows through the soil should be considered (Campbell 1985).

Similarly, the selection of a reliable equation is important for determining the unsaturated hydraulic properties of the porous media. The soil science literature and practices are flourished with examples using the van Genuchten (VG) as well as the Campbell (CB) equations for hydraulic parameter estimation. The above mentioned equations are mostly based on the researchers' subjective judgment and preferences, even though, the application of the VG equation has been more common (Eching and Hopmans 1993; Porebska et al. 2006; Schaap and van Genuchten 2006; Schaap and Leij 2000; Young et al. 2002). Romano and Santini (1999) suggested that the VG equation is more theoretical and mostly suitable for sandy soils. Thus, it should be used with great care for clay soils and loamy soils. A recent study by Maung et al. (2008) established that the CB equation could be applied for soft rocks using the inverse technique of transient evaporation change. The assessment of the suitability of the VG equation for igneous rocks, such as granite, can be found in the literature (Watanabe et al. 1995). However, the suitability of the VG equation has not been theoretically evaluated for all porous media, such as the sedimentary soft rock and crystalline rock. There is a remarkable difference between the CB and VG models. Although the CB model has a threshold value called "air entry value," the VG model has no threshold value. Therefore, the equation (VG, CB, or other) which can be better applied for sandy soil and soft rock in inverse parameter optimization is an important issue to explore.

Even though the inverse technique is widely used, this approach faces certain problems, such as local minima problem, ill-posedness due to non-uniqueness, and instability in the optimization process (Ali et al. 2000; Minasny and Field 2005). Most of the studies for parameter optimization have used non-linear least-squares (e.g. Levenberg–Marquardt method), which tend to give local minima. Under the non-uniqueness situation, the optimization results could vary based on the initial guess values of the parameters. In addition, instability causes serious errors in the parameter estimation. Thus, the stability should be examined.

Halbertsma (1996) suggested that the evaporation experiments were not suitable for parameter estimation by inverse estimation because of the non-uniqueness and the local minima problems. For addressing such problems, the Genetic Algorithm (Goldberg 1989) as a global optimization technique based on the evolutionary computation method was applied in the present study. Genetic Algorithm (GA) has been established as a promising tool for inverse optimization in the process of hydraulic property estimation by Ines and Droogers (2002) and has also been recently applied by other researchers as well (Gwo 2001; Harroini et al. 1996; Karpouzos et al. 2001).

The present study considered transient evaporation at the soil–atmosphere interface (Campbell 1985), while many previous studies mainly used the soil matric potential evaluating the parameters. This eliminated the measurement need of the transient soil matric potential. Thus, the experiments could be performed rapidly. However, to evaluate the parameters from evaporation change, the water as well as the vapor flow through the soil/rock sample in the numerical modeling should be considered. After considering the above mentioned issues, the aims of the present study can be summarized as:

- Applicability of the VG and CB models for soft rock and sandy soil.
- Basic study to develop a technique for model selection and parameter estimation using information on evaporation as well as saturation.

Materials and methods

Experimental setups

The experiment was arranged considering the Campbell technique (Campbell 1985), which is based on the transient evaporation change. Both the water and the vapor flows were considered with some assumptions. Information, such as the saturation distribution of the profile was not considered in the Campbell technique. However, both the evaporation and the saturation distribution data were used in the present study.

Two types of experiments (setup I and setup II) were used in the present study for the estimation of the parameters in the two models (CB and VG) for soft rock and sandy soil. Setup I and II were applied for the soft rock and sandy soil, respectively. As the soft rock was a thin sample as explained below, it was difficult to measure the saturation distribution accurately. Usually, only the evaporation from the rock surface can be well measured from the weight change of the sample. Alternatively, setup II was used for the relatively high permeable sandy soil. When considering the sandy soil, it is difficult to measure the evaporation rate by the weight change. Thus, equipment based on the wind chamber technique was developed to measure the evaporation by the soil surface. Moreover, the saturation profiles in sandy soil were precisely measured.

Experimental setup I

The soft rock samples (Tertiary sandstone) were collected from the tunnels of the Rokkasho Low-Level Radio-active Waste disposal site in the Aomori prefecture of Japan. In this area, a Neogene sedimentary rock called Takahoko formation is distributed. It mainly consists of sandstone and pumice tuff (Maung et al. 2008). It is important to estimate the drying process around the surface of tunnel used in the radio-active waste disposal. This is because many micro-fractures would be created in the drying process, thereby forming a damaged zone around the tunnel. The hydraulic conductivity in the damaged zone may be increased, which may decrease the ability of isolating the hazardous waste. Therefore, the estimation of the unsaturated properties of the soft rock becomes an important issue.

The thin disk-shaped samples of soft rock were fully saturated by submerging in a container filled with distilled water and sucking air by a vacuum pump. Next, all the surfaces except the upper surface of the sample were completely sealed with a silicon sealant. Thus, evaporation was allowed only from the top surface. Under the controlled humidity (40% ± 5%) and temperature (25°C ± 1°C) conditions, the hourly transient evaporation change was calculated from the weight change of the sample. The experiment was terminated when the weight change of the sample was less than 0.01 g/h (minimum limit of the weight balance).

Experimental setup II

A transparent vertical column, 50 cm tall and 18 cm in diameter, was used for setup II. The column has a porous plate at the bottom to allow water to infiltrate into the soil media. A constant water level was given by a box at the bottom of the column. At the top, an evaporation chamber was tightly fixed and sealed with silicon sealant to prevent air leakage. There were two valves through which the inflow air entered the chamber and exited from the other (inlet valve and outlet valve, respectively). The schematic diagram of the experimental setup II is shown in Fig. 1.

The column was filled uniformly with homogeneous sandy soil (Toyoura standard sand) with the mean particle diameter of 0.19 mm and porosity of 0.445. Next, the column was fully saturated with water using a vacuum pump installed to the evaporation chamber. Soon after a full saturation, the vacuum pump was stopped and the evaporation measurement was started by giving a dry air flow into the evaporation chamber. This inflow air was given by an air pump through the silica gel chamber for decreasing the moisture in the air. This low humid air was injected into the evaporation chamber through the inlet valve and exhausted through the outlet valve. The relative humidity and temperature of inflow and outflow were continuously measured by the humidity and temperature sensors. The air flow rate was measured by a flow meter. All the measured data were saved in a computer. The absolute humidity was calculated using the relative humidity and temperature (Brutsaert 1982). Next, the evaporation (E_v) in mm/day was calculated by Eq. 1 (Ali et al. 1997):

$$E_{\mathrm{v}} = \frac{Q(D_{\mathrm{out}} - D_{\mathrm{in}})}{A} \tag{1}$$

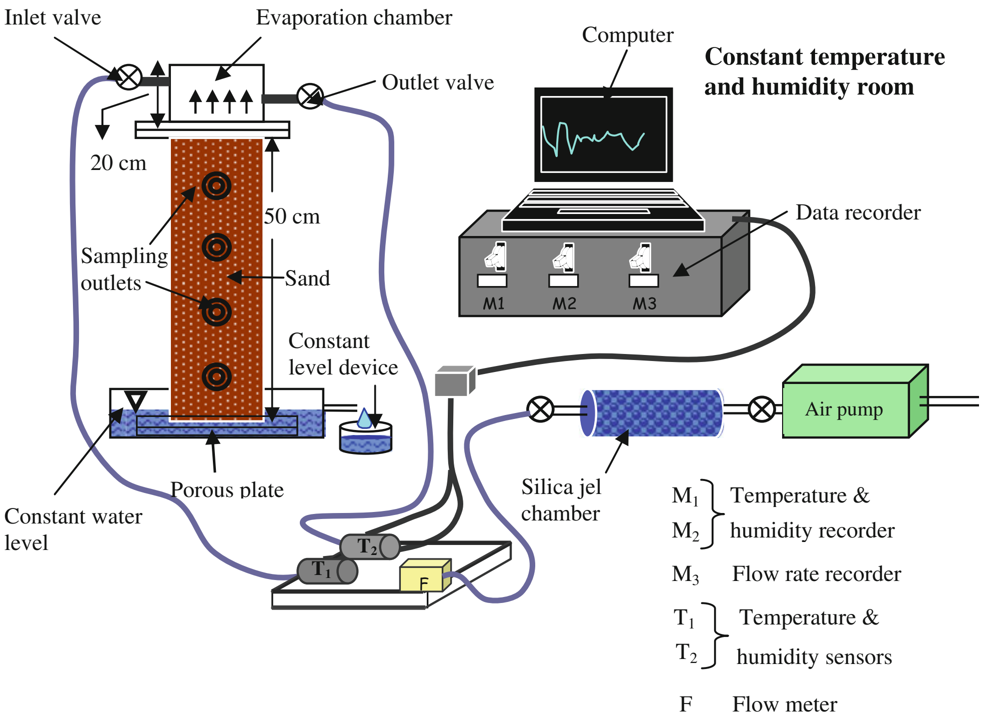
where Q is the volumetric flow rate of air (L min^{-1}), and D_{in} and D_{out} are the absolute humidity (g m^{-3}) values of inflow and outflow air, respectively. A is the area covered with the chamber (m^2).

The experiment was performed in conditions of constant humidity (40% ± 5%) and air temperature (25°C ± 1°C). The average air flow rate was kept as 40 L min^{-1}.

After the evaporation achieved a near steady state, the samples were taken from the soil column to determine the saturation distribution. The saturation was determined by drying the samples at 105°C in the oven for 24 h.

The saturated hydraulic conductivity (k_s), porosity (ϕ) and dry bulk density were measured before conducting experiments I and II. The porosity of the samples was measured using the standardized saturation technique

Fig. 1 Schematic diagram of the experimental setup II for sandy soil



(Fetter 1994). θ_r and θ_s are the residual and saturated water content in an actual unsaturated condition, respectively. θ_s could be measured in the laboratory. There are many definitions of θ_r. According to Nimmo (1991), van Genuchten et al. (1991), and Kosugi (1994), the residual water content is a fitting parameter which has no real physical significance. Vanapalli et al. (1998) mentioned that it was not the minimum water content in porous media. Alternatively, the value $\theta_r = 0$ could be set for many soils without invalidating the parametric models (Russo 1988). The water content after 10 days under the same condition of the experiment was defined as θ_r in the present study.

The measured parameters of the Toyoura sand and soft rock are summarized in Table 1. Although about 20 soft rock samples were used in the present study, only one representative result was reported.

Governing equations

Evaporation in vertical unsaturated porous media

The technique used in the present study followed the method proposed by Campbell (1985). Accordingly, if the potential evaporation rate is known, the actual evaporation (E_v) from the surface can be written as Eq. 2:

$$E_v = E_p \frac{(h_s - h_a)}{(1 - h_a)} \tag{2}$$

where h_s is the surface humidity of porous media and h_a is the atmospheric humidity. h_s is estimated from the saturation at the top surface (Campbell 1985). E_p is the initial potential evaporation (mm/day).

Table 1 Measured parameters for Toyoura sand and soft rock

Sample	ϕ (%)	k_s (m s^{-1})	θ_r	θ_s	Bulk density (g cm^{-3})
Toyoura sand	44.5	2.0E−4	0.01	0.44	1.58
Soft rock	58.0	4.8E−6	0.10	0.58	1.46

ϕ porosity

Vapor transport equations

Vapor transport in the isothermal vertical porous medium is expressed by Fick's law as:

$$q_v = -D_v \frac{dc_v}{dz} \tag{3}$$

where q_v is the vapor flux (m s^{-1}) and D_v is the water vapor diffusivity in soil (m^2 s^{-1}), z is the vertical coordinate (m) and $c_v = c_v^* \cdot h_r$ is the vapor concentration in porous media (g m^{-3}). c_v^* is the saturation water concentration and h_r is the relative humidity.

According to Campbell (1985), Eq. 3 can be finally rearranged and the vapor flux (q_v) can be written as:

$$q_v = -K_v \frac{d\varphi}{dz} \tag{4}$$

where K_v is the vapor conductivity (m s^{-1}) and φ is the matric potential (J kg^{-1}).

Water transport equations

The water flow through the unsaturated porous media is described by Darcy's Law (Jury and Horton 2004), which is based on two assumptions. According to the above mentioned law, the unsaturated water flux q_l (kg m^{-2} s^{-1}) can be written as

$$q_l = -k(\theta)\left\{\frac{\partial\varphi}{\partial z} + 1\right\} \tag{5}$$

where $k(\theta)$ is the unsaturated hydraulic conductivity (m s^{-1}).

Equations 4 and 5 are combined for estimating the total water flux. In this approximation, it is assumed that the vapor content is in the equilibrium condition with the suction pressure in porous media (Campbell 1985).

The water and vapor transport equations were solved numerically by the Newton–Raphson procedure proposed by Campbell (1985). In the above mentioned analysis, the sample was divided into many layers and the mass balance for every layer was calculated by considering the both flows.

Application of models

The unsaturated hydraulic properties in porous media can be characterized using different empirical and theoretical models. Two models, namely the Campbell model (CB) and the van Genuchten model (VG), have been used in the present study. One of the biggest differences between these models is whether the threshold value (air entry potential) has included or not, as explained below.

The Campbell model (Campbell 1974) is described as follows:

$$k(\theta) = k_s\left(\frac{\theta}{\theta_s}\right)^m \tag{6}$$

$$\theta = \theta_s\left(\frac{\varphi_e}{\varphi(\theta)}\right)^{\frac{1}{b}} \tag{7}$$

$$m = 2b + 3 \tag{8}$$

where θ and θ_s are the volumetric and saturated water contents (m^3 m^{-3}) of the porous media, respectively, φ_e is the air entry potential (J Kg^{-1} ~0.102 m of water), $\varphi(\theta)$ is the matric potential of water (J Kg^{-1} ~0.102 m of water), and b and m are the parameters related to the pore size distribution. $k(\theta)$ is the soil hydraulic conductivity (m s^{-1}) and k_s is the saturated hydraulic conductivity (m s^{-1}).

The van Genuchten model (van Genuchten 1980) is expressed as follows:

$$k(\theta) = k_s\theta_e^{1/2}\left[1 - \left(1 - \theta_e^{1/l}\right)^l\right]^2 \tag{9}$$

$$\theta_e = (1 + |\alpha\psi|^n)^{-l} \quad (\alpha > 0) \tag{10}$$

$$\theta_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \quad (0 \le \theta_e \le 1) \tag{11}$$

$$n = 1/(1 - l) \quad (0 < l < 1, n > 1) \tag{12}$$

where α (m^{-1}), n (>1), and l are the empirical constants. θ_r and θ_s are the residual and the saturated water contents (m^3 m^{-3}), respectively. θ_e is the effective water content (m^3 m^{-3}).

Inverse estimation

Genetic Algorithm

Genetic Algorithm (GA) is an evolutionary optimization algorithm currently used for the optimization process (Unsal et al. 2005). It offers several advantages over the conventional search algorithms.

The procedure to estimate model parameters by transient evaporation in the GA application can be summarized as follows:

(a) Each unknown parameter combination is assumed as a chromosome.

(b) These chromosomes are composed of only two parameters. Thus, each combination is encoded as binary digits (0 and 1). Initial chromosomes were generated by random numbers.

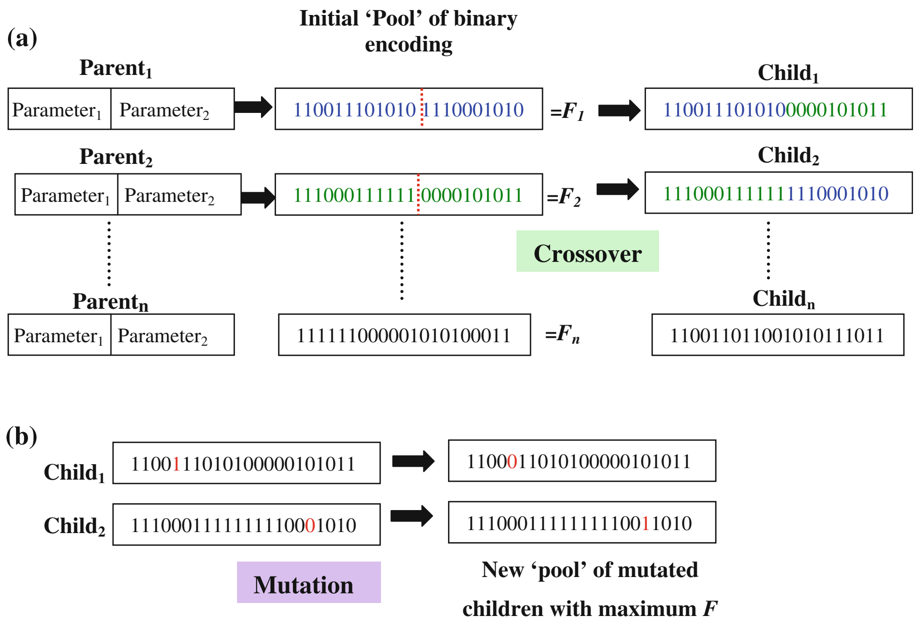
(c) The transient evaporation calculated ($E_{\mathrm{cal}}(t)$) for all the chromosome combinations is compared with the measured evaporation ($E_{\mathrm{mea}}(t)$) to obtain the objective function of summation of the square difference (SSD).

$$\mathrm{SSD} = \sum_{t=1}^{n}\left[E_{\mathrm{mea}}(t) - E_{\mathrm{cal}}(t)\right]^2 \tag{13}$$

(d) Two criterions were adopted for the termination of the iteration process. When the difference between the minimum and maximum SSD values (i.e. $D_{\mathrm{SSD}} = \mathrm{SSD}_{\mathrm{max}} - \mathrm{SSD}_{\mathrm{min}}$) is almost constant and the minimum value of SSD is less than the critical value of SSD ($\mathrm{Cr}_{\mathrm{SSD}}$), the GA process will terminate. $\mathrm{Cr}_{\mathrm{SSD}}$ is a value which does not change with iteration and this value is specimen specific.

Genetic Algorithm (GA) works with three genetic operations namely selection, crossover, and mutation for producing a new and unique generation (Goldberg 1989).

Fig. 2 **a** Schematic diagram of single point crossover; **b** schematic diagram of mutation in the Genetic Algorithm



The crossover and mutation processes are schematically described in Fig. 2a and b.

The detailed steps adopted in the present study are shown in Fig. 3 and described as follows:

1. The number of genes in a chromosome was defined for both the models; in the case of Campbell model, *b* and ψ_e and VG model, α and *l*.
2. The population size was defined as 50 in the present study. The maximum and minimum value of each parameter was given on the empirical calculation.
3. Encoding of a chromosome (combination of 2 unknown parameters): as shown in Fig. 3, the chromosomes generated of genes were defined by random numbers. Binary encoding was done (0 and 1) with the 22 length of binary digits by converting real values of each parameter and sent to an initial "pool."
4. The transient evaporation in the "pool" was calculated as ($E_{\mathrm{cal}}(t)$) for every chromosome. According to Eq. 13, the sum of the square difference (SSD) and the fitness value (*F*) were calculated. The fitness value relates to the performance of the chromosome and is defined as the value to minimize the SSD (i.e. $F = 1/\mathrm{SSD}$).
5. The roulette wheel selection criterion (Holland 1975) was done randomly to select the best chromosomes (parents).
6. The new generation (children) was selected (see Fig. 2) by the crossover and mutation operations. In the present study, the crossover rate was taken as 0.6 and the mutation probability was 0.005.

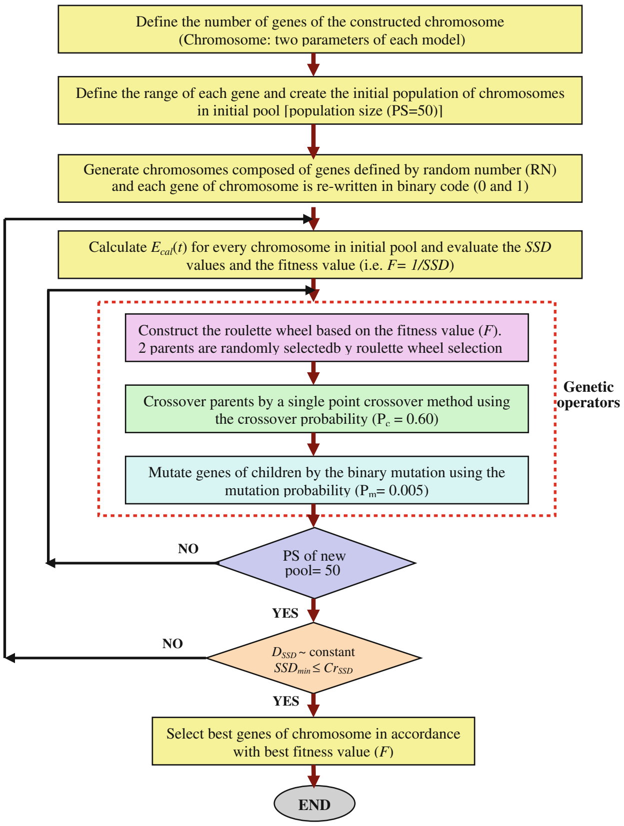


Fig. 3 Flow chart of the GA application in inverse estimation (Maung et al. 2008)

7. Each parent and children combinations were compared according to their *F* value and the two combinations having the maximum *F* values were selected and sent

to the new pool. This generation creation was repeated until the new pool of the next generation reached to the population size of 50. A generation cycle was then completed.

8. The total procedure was repeated as shown in Fig. 3 until the SSD value became lower than the critical value of the given SSD and the difference between the maximum and minimum SSD values became a constant.

Results

Performance and accuracy of the evaporation equipment in experimental setup II

The average temperatures of the inflow and outflow air were almost identical (see Fig. 4a). When the evaporation occurred, the humidity of the outflow increased in comparison to the inflow air humidity. The value of the evaporation rate was inversely proportional to the value of outflow air humidity, as shown in Fig. 4b.

Performance of GA

The three basic operations of GA: the selection, crossover, and mutation were repeated for 100 generations to produce the best fit parameters, which optimized the problem under study. As the inclusion of too many parameters in inverse estimation tends to result in non-uniqueness (Ines and Droogers 2002), only two parameters for each model were focused in the present study. The objective function of SSD was calculated till it was lower than the $\mathrm{Cr}_{\mathrm{SSD}}$ value as well as till the D_{SSD} value became constant. According to the results, the difference of the SSD values started with a large variation. However, the variation became almost minimal after the 24th generation. Furthermore, it could be concluded that GA is a robust technique for parameter estimation.

Estimation of potential evaporation (E_{p})

Although the potential evaporation (E_{p}) for the saturated soil/rock is indispensable for the inverse estimation, the direct measurement of E_{p} is particularly difficult for sandy soil. This is because of the water condition in the soil. Figure 5a schematically illustrates the change of the evaporation condition from the sandy soil. As shown in stage (1) of Fig. 5a, a thin water film exists over the soil at the beginning of the experiment and the evaporation occurs from the water surface. Due to the evaporation and the downward flow through the soil column, the amount of water covering the soil surface decreases. Next, in stage (2) of Fig. 5a, a film partly covering the soil with water is formed. Further, as the evaporation progresses, the water over the soil evaporates, as shown in stage (3). This makes the soil partially unsaturated. Finally, the soil just beneath the surface becomes fully unsaturated as shown in stage (4) of Fig. 5a. The pattern of the transient change of evaporation develops, as shown schematically in Fig. 5b. This indicates that the definition of E_{p} is difficult by the experimental results, as E_{p} is defined by the evaporation from the saturated soil. Therefore, some trial calculations were performed with changing E_{p} values. Subsequently, the root mean square error (RMSE) values between the measured and the calculated evaporation changes were obtained. The value that gave the minimum RMSE was selected as the suitable E_{p}. The mathematical expression of RMSE value can be written as follows:

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n} \right]^{1/2} \tag{14}$$

where S_i is the simulated values, O_i is the observed values, and n is the number of data. The RMSE is an indicator to show by how much the simulated values overestimate or underestimate the observed values.

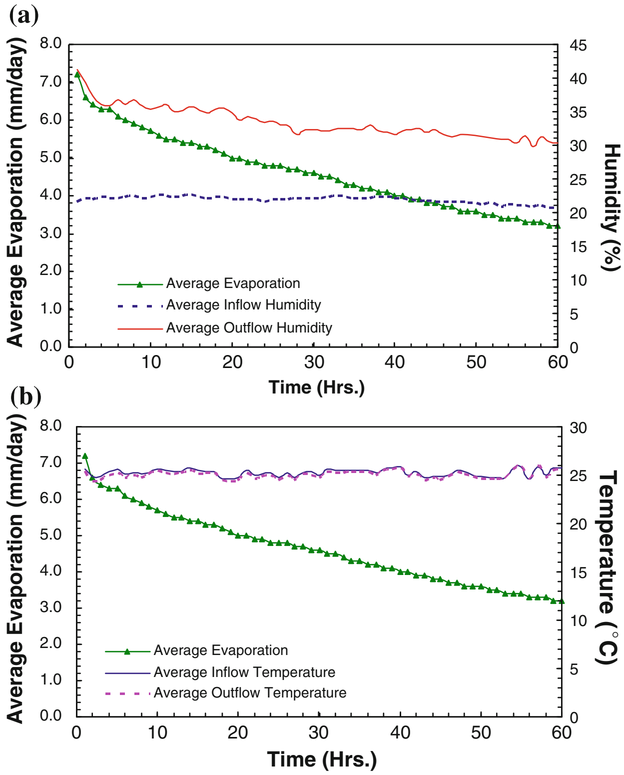


Fig. 4 **a** Average inflow and outflow temperature with the transient evaporation change; **b** average inflow and outflow humidity with the transient evaporation change

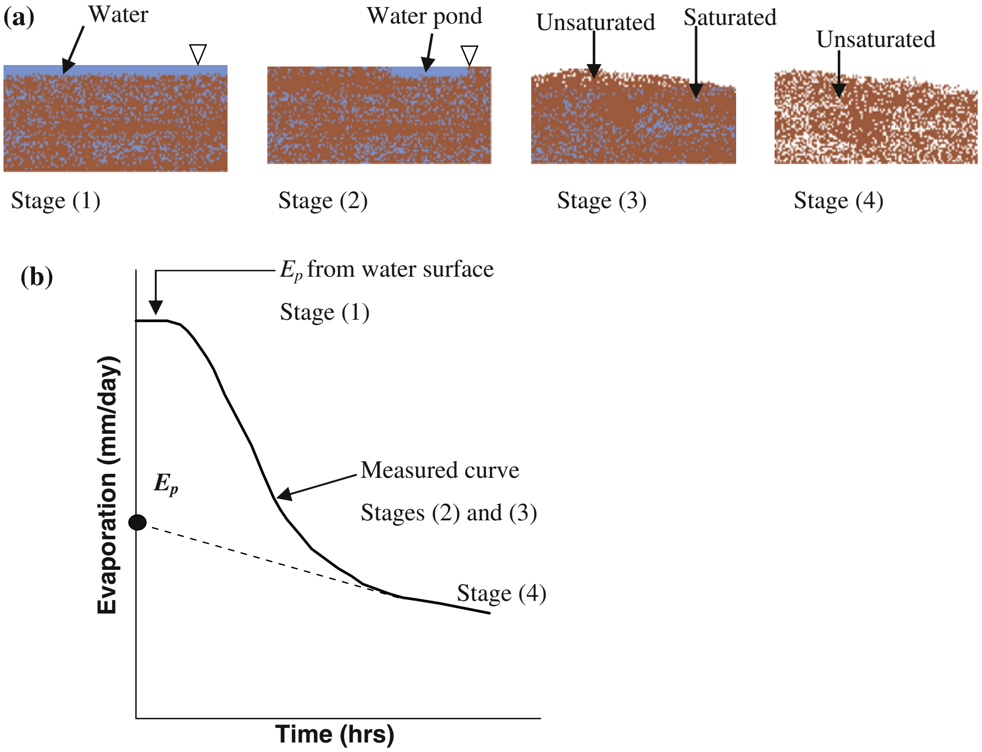


Fig. 5 **a** Schematic diagram of water condition near the soil surface; **b** the transient evaporation change and E_p

Table 2 Estimated parameters for soft rock

Sample	CB model		VG model	
	b	Ψ_e (m)	α (m^{-1})	l
Soft rock	4.6	−1.90	0.01	0.30

Estimation of unsaturated hydraulic properties for soft rock

The objective function of SSD between the measured and calculated evaporation was minimized by the inverse technique using the GA. Subsequently, the optimized model parameters were obtained. The estimated parameters of the soft rock samples are summarized in Table 2.

Figure 6a shows the transient evaporation change of the soft rock specimen. Using the optimized model parameters (see Table 2), the retention curve and the relative hydraulic conductivity curve were obtained (see Fig. 6b). Although the CB and VG models gave considerably good accordance in Fig. 6a, the CB model looked better in comparison to the VG model. Similar results were also obtained for the other soft rock samples. Thus, it necessitates the discussion of the saturation distribution data in detail.

Estimation of unsaturated hydraulic properties for sandy soil

The optimized model parameters were obtained similarly for the sandy soil using the transient evaporation change, as explained above for the soft rock. The potential evaporation (E_p) was determined as 6.4 mm/day by the technique described in "Estimation of potential evaporation (E_p)" section. The estimated parameters of sandy soil are summarized in Table 3.

The measured and calculated evaporation rates for sandy soil are shown in Fig. 7a. It was found that both the CB and the VG models were in good accordance with the measured one. Using the optimized parameters, the retention curve and the relative hydraulic conductivity curve were obtained for both the models. According to Fig. 7b, both the models gave similar results for water retention. However, these two trends were different when the relative hydraulic conductivity curves of the two models were considered. The relative hydraulic conductivity in both the models was more compatible in the higher saturation region and showed discrepancy at the drier conditions of the soil, as seen from the graph. Alternatively, a relatively good estimation of the retention characteristics need not always imply a good estimation of the unsaturated hydraulic conductivities (Romano and Santini 1999). Thus, it is

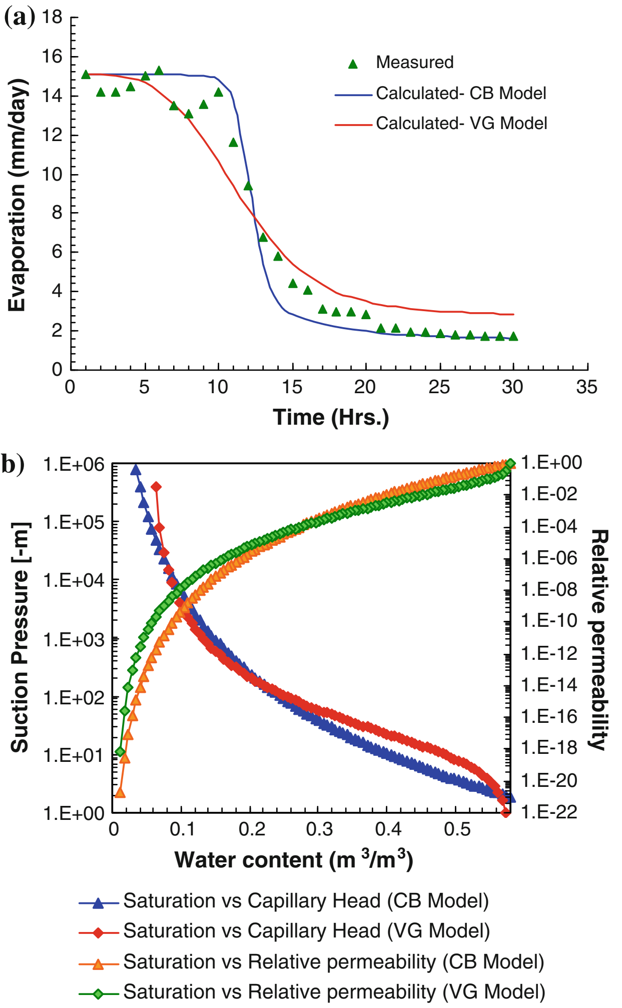


Fig. 6 **a** Measured and calculated evaporation rate of soft rock; **b** estimated hydraulic functions of soft rock

Table 3 Estimated parameters for Toyoura sand

Sample	CB Model		VG Model	
	b	Ψ_e (m)	α (m^{-1})	*l*
Toyoura sand	2.5	−0.28	2.71	0.82

necessary to evaluate the saturation distribution data to check the suitability of the model.

The obtained saturation distribution of sandy soil is illustrated in Fig. 8. From the obtained results, it is apparent that the VG model is more applicable for sandy soil.

Discussion and conclusions

Several models have been proposed and extensively used to approximate the hydraulic properties of unsaturated soil. Trials to fit these models to other porous media, such as clay, and soft rock have been performed by several previous researchers. The selection of the best model and the estimation of those model parameters for the selected porous media are very important to analyze the unsaturated groundwater flow. As a basic study for developing the

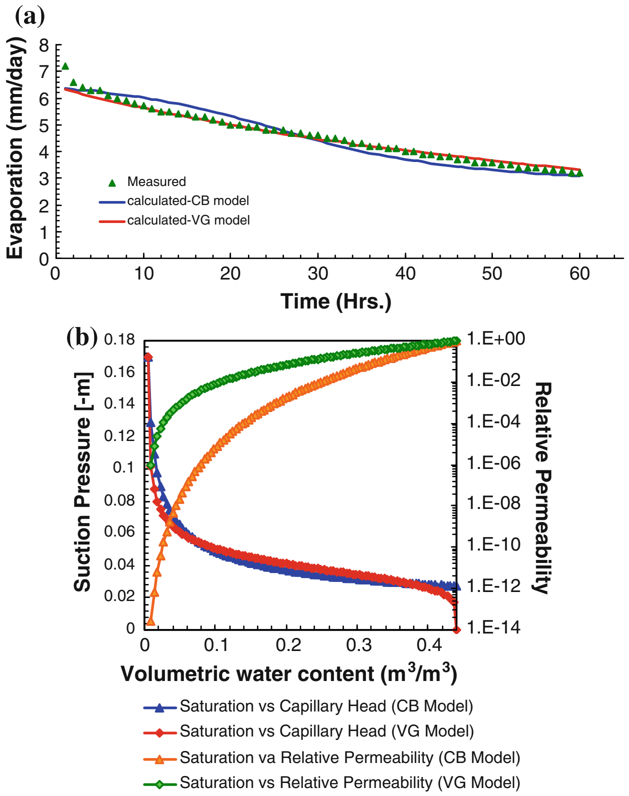


Fig. 7 **a** Measured and calculated evaporation of Toyoura sand; **b** Estimated hydraulic functions of Toyoura sand

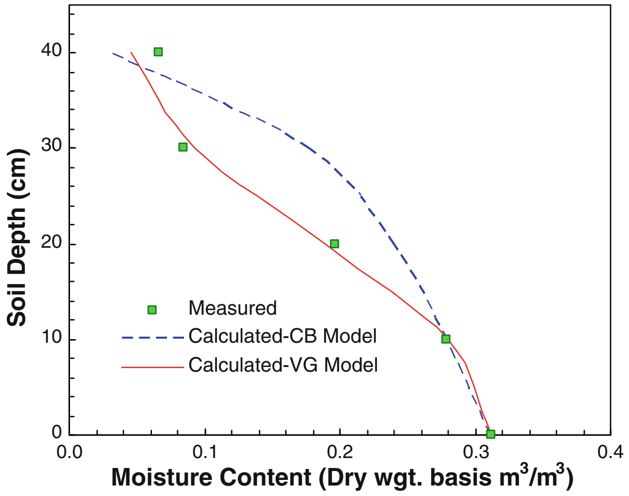


Fig. 8 Comparison between measured and calculated moisture content of Toyoura sand

processes of the model selection and parameter estimation, the applicability of the Campbell model (CB) and the van Genuchten model (VG) to soft rock and sandy soil were investigated. These two models were selected because they have been commonly used in the research field, especially the VG model. Further, there is a remarkable difference among these models, whereby the CB model has a thresh hold value named "air entry potential," while the VG model has no such value defined.

Laboratory experiments for measuring the transient evaporation changes from soft rock (Tertiary sandstone) and sandy soil (Toyoura standard sand) were performed. Subsequently, the optimum parameters in the two above mentioned selected models were inversely estimated with fitting the calculated evaporation change to the measured one with consideration to both the water flow and vapor flow. To estimate the optimum model parameters, GA was used instead of the conventional methods, such as Levenberg–Marquardt's technique (Romano and Santini 1999). It was established that the best parameters in these models could be well estimated by GA with a relatively shorter computational time. The water retention and relative hydraulic conductivity properties of the soft rock and sandy soil samples were also calculated by the above mentioned estimated model parameters.

The potential evaporation (E_p) should be well evaluated in the inverse technique of the parameter estimation. However, the direct measurement of the E_p value, especially for sandy soil was very difficult. A new method was proposed to evaluate the potential evaporation on the basis of the RMSE between the calculated and measured evaporation changes in the present study. It was found that the obtained value through this method gave a reliable simulation for the transient evaporation.

The measured and the calculated evaporation changes were compared after estimating the optimum model parameters. It was found that the CB model was better than the VG model for soft rock. However, both the models gave a considerably good accordance with the measured data. Unfortunately, the saturation distribution in soft rock could not be measured as the thickness of the sample was low. Thus, only the information on the transient evaporation change could be the most practical data in the model selection and parameter estimation process for soft rock. The above mentioned issue is one of the limitations in the present study. However, both the evaporation change and the saturation distribution were used in the model selection process and parameter estimation for sandy soil. The calculated evaporation changes using both the models showed better agreement with the measured one in sandy soil. The saturation distribution in sandy soil was also measured and compared with the calculated distributions by both the models. The calculated values by the VG model fitted well with the measured saturation data. Thus, the VG model was better than the CB model for the estimated unsaturated hydraulic properties in sandy soil. Accordingly, both evaporation change and saturation distribution data should be used in the model selection and parameter estimation process for any porous media.

The inverse estimation technique from the transient change of evaporation using GA for the parameter estimation can be applied to other models, such as Brook and Corey (1964), Gregson et al. (1987), Russo (1988), and Rossi and Nimmo (1994). The performance of these models can be compared by using the above mentioned technique. The best model can be selected from the comparison between the measured and the calculated evaporation data. However, it is more prudent to check the performance of the models with saturation distribution.

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