Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 2, No. 2, 2022

A Review of The Theory of Water Evaporation in Soil and The Study of Soil-Water Characteristic Curve

Ruipu Wang[1], Chenxia Yang[1], Hua Li[1], Renjie Li[2]

[1] Luoyang Urban Construction Survey and Design Institute Co, Ltd, LuoYang He Nan 471000, China
[2] China Railway Design Group Co, Ltd, Tianjin 300308, China

Abstract: The theory of water evaporation in soil and the soil-water characteristic curve are the core of unsaturated soil research, and have very important guiding significance for engineering practice. This paper uses the theoretical summary method to summarize the theory of water evaporation in soil and the related theory of soil-water characteristic curve. The results show that the water evaporation in the soil is the result of the combined action of internal factors and external factors. Matrix suction is the core of the soil-water characteristic curve. There are many factors that affect the soil-water characteristic curve. The mineral composition and pore structure of soil are the two most essential influencing factors, and other influencing factors mainly play their role through these two factors.

Keywords: Unsaturated soil, Water in soil, Soil-water characteristic curve, Evaporation theory.

1. Introduction

Classical soil mechanics is the study of saturated soils. However, most of the soils in practical engineering are unsaturated soils, and there are still large blind spots in the field of unsaturated soils that need to be explored and studied. There are four phases in unsaturated soil, and there are more gas and water-air interfaces than saturated soil. The difference between unsaturated soil and saturated soil is that there is suction in unsaturated soil, while there is no suction in saturated soil [1]. At present, in the field of research, scholars have focused on the exploration of matrix suction. If there is no matrix suction, then the engineering properties of unsaturated soil and saturated soil will not be much different. The soil-water characteristic curve describes the relationship between soil moisture content (gravitational moisture content, volumetric moisture content, or saturation) and suction (total suction or matrix suction). As a tool, soil-water characteristic curve is indispensable in the study of unsaturated soil mechanics. It is not only a constitutive model of unsaturated soil, but also can be used to estimate soil strength, deformation and permeability It can lay a foundation for studying the stress state, strength and permeability of unsaturated soils [2]. Precipitation and surface evaporation will obviously change the moisture content of the soil [3]. In agriculture, problems such as soil erosion and salinization will be involved. In geotechnical engineering, atmospheric evaporation will affect the deformation of the roadbed. , strength, service life, maintenance, etc., causing slope instability, seasonal expansion and contraction of the ground, subgrade collapse and other problems [4,5]

The theory of water evaporation in soil and the soil-water characteristic curve are the core of unsaturated soil research, and have very important guiding significance for engineering practice. This paper uses the theoretical summary method to summarize the theory of water evaporation in soil and the related theory of soil-water characteristic curve, so as to make better engineering applications in the future.

2. Soil Evaporation Theory

The process of soil water evaporation is a process of dynamic change of water content. The water in the soil is converted from liquid water to gaseous water, part of which will be lost to the atmosphere, and the evaporation of the soil will cause a phase change. Soil moisture changes from liquid phase to gas phase, and heat flow occurs. The water evaporated from the ground soil exposed to the external environment consists of two parts: the water existing in the soil layer of the soil above the groundwater level and the groundwater. Soil moisture evaporation includes stable evaporation and unstable evaporation. However, in essence, the evaporation of soil moisture is the escape of water molecules to the external environment by means of kinetic energy to overcome the gravitational force between molecules in the liquid. For shallow loess exposed to the external environment, the potential energy supporting water migration includes gravitational potential, matrix potential and temperature potential. Generally, the gravitational potential is determined according to the position water head; the matrix potential is determined according to the soil-water characteristic curve; there is no reliable expression for the temperature potential. A steady supply of heat, a relatively low external vapor pressure and a reliable source of internal moisture are the three necessary conditions for soil moisture evaporation. Essentially, the soil-water interaction mechanism determines the speed of soil water evaporation.

2.1. Three Stages of Soil Evaporation

The evaporation process of soil moisture is basically divided into three stages: constant rate, deceleration rate and residual stage.

(1) Constant rate stage

The constant rate stage is the stage in which the evaporation rate is basically unchanged at the initial stage of evaporation, and the evaporation intensity does not change significantly. At this stage, the soil moisture content is relatively high, mainly due to the evaporation of free water, and the capillary water effect plays a leading role in the migration of water.

(2) Deceleration rate stage

In the deceleration rate stage, that is, the stage where the evaporation intensity of the soil gradually decreases, as the evaporation continues, the free water in the soil decreases and the suction becomes larger, which will reduce the vapor pressure difference between the atmosphere and the soil. For unsaturated soils, an increase in the total suction will result in a decrease in the evaporation rate. The combined action of capillary water and steam diffusion determines the moisture migration at this stage. With the increase of evaporation time, the effect of steam diffusion will become more and more obvious. At this stage, the moisture content, hydraulic conductivity and water supply capacity of the soil will decrease.

(3) Residual stage

At this time, the evaporation intensity of the soil is very weak, the soil within a certain depth range of the soil surface has been completely dried, the water available for evaporation in the soil is very small, and the effect of capillary water is getting weaker and weaker. Water evaporation takes place in the form of water vapor diffusion within the soil. At this time, the soil structure is basically stable.

2.2. Influencing Factors of Soil Evaporation

Although the main factors affecting soil evaporation will be different in different stages of evaporation, they can still be roughly classified into two aspects: external factors and internal factors.

(1) External factors

The various environmental effects of the soil in the outdoor are external factors, and the combined effect of these factors is to provide energy supply for the evaporation of the soil. Sunshine, temperature, relative humidity, wind speed, etc. are all external causes. Specifically, different sunshine and temperature will affect the water migration rate; different sunshine and wind speed, etc., will affect the vapor pressure gradient; different temperatures will affect the water-holding capacity of the soil.

(2) Internal factors

Internal factors are the various properties of the soil itself, which will directly affect the water migration characteristics of the soil. Internal factors can be refined into soil composition, pore structure, moisture content, particle size composition, compaction, etc. These factors determine the hydraulic properties, structural properties, soil conditions, etc. of the soil, and these factors will affect the difficulty of water migration in the soil, the diffusion rate of water vapor, permeability, and the amount of water that can be migrated, etc., and ultimately affect the soil. the evaporation rate of the body.

2.3. Common Evaporation Models

The earliest evaporation model was proposed by Dalton in 1802. Although it is relatively simple and only considers wind speed and humidity difference, it is of milestone significance. Dalton's formula is derived based on the theory of water vapor diffusion:

$$E_a = f(u)\left(e_s - e_a\right). \tag{1}$$

Among them, E_a is the free water surface evaporation, that is, the potential evaporation; e_s is the saturated vapor pressure of the water surface; e_a is the air vapor pressure; $f(u)$ is the wind function; $f(u) = 0.35\left(1 + 0.15u\right)$ u for wind speed

On the basis of Dalton, Penman took into account more meteorological factors, added net radiation and temperature, and derived Penman's formula in 1948 based on the law of conservation of energy:

$$E = \frac{\Gamma R_n + \eta L E_a}{\Gamma + \eta L}. \tag{2}$$

where Γ is the slope of the saturated vapor pressure-temperature relationship curve; R_n is the net radiation on the soil surface; η is the humidity constant; L is the latent heat of evaporation; E_a is the evaporation from the free water surface.

In the actual evaporation process, in most cases, the soil body cannot obtain a steady supply of water, the soil body is generally in an unsaturated state, and the evaporation intensity will gradually weaken. Taking the vapor pressure of the air above the soil surface into account, Wilson derived the Penman-Wilson formula for the evaporation of unsaturated soil on the basis of Penman's formula:

$$E = \frac{\Gamma Q + \eta E_a}{\Gamma + \eta A}. \tag{3}$$

$$E_a = f(u) P_a (B - A). \tag{4}$$

where P_a is the vapor pressure of the air on the evaporation surface; B is the reciprocal $1/h_{rair}$ of the air relative humidity; A is the reciprocal $1/h_A$ of the soil surface relative humidity.

3. Soil Water Equation Of Motion

Richards proposed an isothermal flow equation describing the relationship between volumetric water content and matrix potential in 1931. This equation can be simply understood as an equation describing the migration of water in the soil:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial\left(\frac{P}{\rho g} + y\right)}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial\left(\frac{P}{\rho g} + y\right)}{\partial y}\right) + Q = \lambda \frac{\partial P}{\partial t} \tag{5}$$

where P is the matrix suction; λ is the slope of the soil-water characteristic curve; k_x is the x direction permeability coefficient; k_y is the y direction permeability coefficient; Q is the boundary flow; y is the position head; ρ is the water density; g is the acceleration of gravity; t is the time.

However, in fact, the evaporation of soil moisture is an extremely complex process, especially in summer, when strong sunlight and high temperature cause an abnormally large surface temperature gradient, the evaporation of soil moisture is a three-phase dynamic process. , including the movement of liquid water and gaseous water between the soil skeleton and the change of the water-air interface. In 1984, Milly, based on Philip Showa DeVries's coupled water-gas-heat transport theory, obtained a two-phase (liquid state) under the influence of gravity, capillary force and adsorption force under the premise of a series of rigorous assumptions.

and gaseous) non-isothermal water flow motion model, this model includes the water motion equation and the heat flow equation:

$$\frac{1}{\rho}\frac{\partial}{\partial x}\left(D_V\frac{\partial P_V}{\partial x}\right)+\frac{1}{\rho}\frac{\partial}{\partial y}\left(D_V\frac{\partial P_V}{\partial y}\right)+ \frac{\partial}{\partial x}\left(k_x\frac{\partial\left(\frac{P}{\rho g}+y\right)}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial\left(\frac{P}{\rho g}+y\right)}{\partial y}\right)+Q=\lambda\frac{\partial P}{\partial t} \tag{6}$$

$$L\frac{\partial}{\partial x}\left(D_V\frac{\partial P_V}{\partial x}\right)+L\frac{\partial}{\partial y}\left(D_V\frac{\partial P_V}{\partial y}\right) +\frac{\partial}{\partial x}\left(k_{tx}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{ty}\frac{\partial T}{\partial y}\right)+Q_t=\lambda_t\frac{\partial T}{\partial t} \tag{7}$$

where P_V is the vapor pressure in the soil; D_V is the vapor diffusion coefficient; λ_t is the volume specific heat; k_{tx} is the x thermal conductivity; k_{ty} is the y thermal conductivity; Q_t is the boundary heat; L is the latent heat of evaporation.

In equations (6) and (7), there are three unknown parameters P, P_V and T, and P and P_V are linked by the formula proposed by Edlefsen and Anderson in 1943:.

$$P_V=P_{V_S}\left(e^{-\frac{Pw}{\rho RT}}\right)=P_{V_S}h_{rair}\ . \tag{8}$$

Where P_{V_S} is the saturated vapor pressure; w is the molecular weight of water vapor; R is the gas constant; h_{rair} is the relative humidity of the air.

4. Matrix Suction

The total suction in unsaturated soil consists of two parts: matrix suction and osmotic suction. Matrix suction is a concept given to serve the study of unsaturated soil mechanics, and is the difference between pore air pressure and pore water pressure in unsaturated soil. In general, the substrate suction and total suction can be approximately considered equal. Pore water pressure is generally negative (under tension), and pore air pressure is positive. Matrix suction will affect the shear strength of soil, which reflects the adsorption of water by the matrix in different soil structures, soil particle sizes, and pore size distributions. The methods of measuring substrate suction are divided into indoor tests and field tests according to the different test sites. Commonly used measurement methods are: tensiometer method, axis translation technology, and electrical/thermal conduction sensor method.

5. Soil-water Characteristic Curve

The soil-water characteristic curve is a kind of curve unique to unsaturated soil, which is used to describe the relationship between soil suction (generally matrix suction without special instructions) and mass moisture content or volume moisture content or saturation. The soil-water characteristic curve can reflect the water storage (water holding) characteristics of unsaturated soil. It can explain the main constitutive relations of unsaturated soil properties, organically link theory, experimental testing and prediction methods, and be used to estimate soil mechanical and hydraulic parameters such as permeability coefficient, strength, volume change, and stress state. The soil-water characteristic curve can be divided into two types: dehumidification curve and moisture absorption curve according to the changing trend of moisture content. After the test, it can be concluded that the soil-water characteristic curve has obvious hysteresis characteristics. For a specific moisture content specimen, the suction of the soil during the dehumidification process is higher than that of the soil during the hygroscopic process.

5.1. Test Method for Soil-water Characteristic Curve

The testing methods of soil-water characteristic curve include direct method and indirect method. The direct test method mainly describes the soil-water characteristic curve through mathematical models and empirical formulas, including tensiometer method, volume pressure plate method, Tempe method, dialysis method, salt solution method, etc. The indirect test method is to infer the soil-water characteristic curve by measuring the physical and mechanical parameters, including the thermal conductivity sensor method, the filter paper method, the thermocouple hygrometer method, the Dew-point potentiometer method, etc. The matrix suction force measured by the volumetric pressure plate method ranges from 0kPa to 1500kPa, which is suitable for the test of dehumidification and moisture absorption curves. The salt solution method is suitable for soil testing with high matrix suction (matrix suction exceeds 1500kPa). The Tempe instrument method is suitable for the dehumidification curve test in the small matrix suction range (0kPa ~ 100kPa). The filter paper method can not only measure the matrix suction of the soil, but also the total suction of the soil. The measurement range of the filter paper method is relatively large among all the test methods. The Dew-point potentiometer method is used to measure the change of the total suction of the soil, especially for the test of osmotic suction. The TRD matrix suction measurement method is one of the heat conduction sensor methods. The TDR suction probe is used to measure the soil matrix suction, and the applicable matrix suction range is 0 kPa ~ 300kPa. The GDS 4D Stress Path Master uses the 4D stress path module of the GDS instrument to test the soil-water characteristic curve under the condition of constant confining pressure and deviatoric stress.

5.2. Mathematical Model of Soil-Water Characteristic Curve

Research on the mathematical model of soil-water characteristic curve began in the 1920s. The earliest Gardner model was proposed by Gardner in 1922, which was based on a single pore size model; Brooks and Corey in 1964 proposed the episodic function form The Brooks and Corey model; Van Genuchten proposed the Van-Genuchten mathematical model in 1980; Williams et al. proposed a linear mathematical model in 1983; Mckee and Bumb proposed an exponential mathematical model in 1984; Frelund and Xing based on soil Pore size distribution function proposed the Frelund-Xing model in 1994; Xu Yongfu et al. proposed the fractal model in 2002. Scholars have never stopped exploring the mathematical model of the soil-water characteristic curve.

According to the expression and practicability of the mathematical model, there are several representative ones:

(1) Fredlund-Xing model. The model is obtained by statistical analysis on the basis of the study of the soil pore size distribution curve. There is no restriction on the suction range and soil, but the formula is too complicated to be applied in engineering:

$$\frac{\theta}{\theta_s}=F(\varphi)=C(\varphi)\frac{1}{\left\{\ln[e+\varphi/a]^b\right\}^c} \tag{9}$$

$$C(\varphi)=1-\frac{\ln\left(1+\varphi/\varphi_r\right)}{\ln\left(1+10^6/\varphi_r\right)}. \tag{10}$$

Among them, a is the function of air intake value; b is the function of water outflow rate in soil when the substrate suction is the air intake value; c is the function of residual moisture content; φ is the substrate suction force; φ_r is the substrate suction force corresponding to the residual moisture content; θ is the Volume water content; θ_s is the saturated volume water content.

(2) Van-Genuchten model. This model is a mathematical model in the form of an episodic function, and is only suitable for the soil-water characteristic curve in the low suction section where the matrix suction range is between 0 and φ_r.

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=F(\varphi)=\frac{1}{\left[1+(\varphi/a)^b\right]^{(1-1/b)}} \tag{11}$$

Among them, $\varphi\in\left[0,\varphi_r\right)$ is the matrix suction; $\theta\in\left(\theta_r,\theta_S\right]$ is the volumetric water content.

(3) Logarithmic model. After studying the unsaturated soil gas phase and comparing the curve model of the predecessor Fredlund et al., Bao Chenggang et al. found that the soil-water characteristic curve is between the two calibration points of air intake value and residual moisture content. It can be approximated as a straight line, so a mathematical model in logarithmic form with an accuracy that can meet the actual needs of general engineering is derived:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=F(\varphi)=\frac{\lg\varphi_r-\lg\varphi}{\lg\varphi_r-\lg\varphi_b} \tag{12}$$

Among them, $\varphi\in\left[\varphi_b,\varphi_r\right]$ is the matrix suction, φ_b is the air intake value of the soil; $\theta\in\left[\theta_r,\theta_S\right]$ is the volumetric moisture content.

The loess in the northwest region is generally low in moisture content, and the matrix suction will fluctuate greatly with different moisture contents. The Williams model fits the soil-water characteristic curve of unsaturated loess well:

$$\lg\varphi=a+b\ln\theta \tag{13}$$

Among them, a, b is the fitting parameter; φ is the matrix suction; θ is the volumetric water content. After that, the following soil-water characteristic curve more suitable for unsaturated loess was deduced

$$W_V=\frac{1}{a+b\ln(\varphi)},R^2>0.98 \tag{14}$$

$$W_V=W_G\cdot\rho_d \tag{15}$$

Among them, W_V is volume moisture content; W_G is mass moisture content; R is regression coefficient; ρ_d is soil dry density.

5.3. Influencing factors of soil-water characteristic curve

The factors affecting the soil-water characteristic curve are numerous and complex, including soil mineral composition, soil particle gradation, pore structure, compactness of soil skeleton, soil shrinkage, soil stress history, stress state, and moisture content, and even the temperature, rainfall, sunshine, etc. of the environment will have an impact on the trend of the soil-water characteristic curve. However, through analysis, it can be concluded that the mineral composition and pore structure of soil are the two most essential factors, and other factors also affect the soil-water characteristic curve by affecting these two factors.

(1) Mineral composition of soil

The mineral composition of soil consists of two parts, including soluble and insoluble components in the soil skeleton. The mineral composition of the soil will affect the affinity for water. If the soil is composed of hydrophilic minerals, such as clay, the suction will be larger, the residual water content will be higher, and the slope of the curve will not be so steep. , while sand is the opposite of clay.

(2) Pore structure

The range of pore structure is very wide, including the particle gradation, pore size, compaction, and composition of soil. The pore structure mainly affects the soil-water action area and the shape of the shrink film, which determines the magnitude of the suction. Generally, soil with small particle size and good gradation has small pore size, strong adsorption capacity (water holding capacity), low air intake value, and relatively flat soil-water characteristic curve. The dry density reflects the compactness of the soil skeleton, and the suction of unsaturated soil increases with the compactness. The effect of volumetric water content on the soil-water characteristic curve is worth exploring, because the relationship between the suction between the soil skeleton and the water pressure in the soil is a dynamic process. When the soil absorbs water, the matrix suction and the water pressure can be approximated. The change in the amount of water absorption is understood as a trade-off relationship. In addition, the external temperature, light and other factors will also affect the surface tension and viscosity of water in the soil.

6. Conclusion

This paper mainly summarizes the existing research results of water evaporation and soil-water characteristic curve in soil, so as to make better engineering applications in the future. The main conclusions are as follows:

(1) Water evaporation in soil can be divided into three stages, which are the result of the combined action of internal factors and external factors.

(2) Matrix suction is the core of the soil-water characteristic curve. The test methods of soil-water characteristic curve mainly include tensiometer method, shaft translation technology, electric/thermal conduction sensor

method.

(3) There are many factors affecting the soil-water characteristic curve. The mineral composition and pore structure of soil are the two most essential influencing factors, and other influencing factors mainly play their role through these two factors.

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