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Study on Distribution Law and Influencing Factors of Subgrade Moisture Balance

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Abstract

In order to analyze the influence of different factors on the equilibrium humidity distribution and evolution law inside the subgrade, based on Darcy's law, Fick theory and Fourier diffusion formula, using VADOSE/W software, a clay slope of the Bai-se to Pan-shui secondary road in Guangxi Province, China As the research object, the dynamic change process of the internal humidity balance of the roadbed under long-term climatic conditions within 15 years was simulated, and the reliability and accuracy of the numerical simulation results were evaluated through field monitoring and standardized calculation. In view of the three major influencing factors of embankment height, side slope gradient and groundwater level, the evolution law of soil moisture content inside the subgrade under different factors is analyzed to provide theoretical basis and technical support for the design and construction of subgrade.

Keywords

Subgrade, Humidity Balance, Embankment Height, Slope Rate, Water Table.

1. Introduction

The variation of the internal humidity of the subgrade has a significant impact on the bearing capacity, the stiffness under the load of the vehicle, and the mechanical response of the pavement. The specific performance is that the roadbed has excessive humidity and the road has long-term road performance. Reduce and damage the roadbed [1-2]. However, the change of subgrade humidity is the result of multiple factors, such as: climate environment, subgrade section form, subgrade soil quality and groundwater level, etc. The method of predicting the subgrade humidity and the influencing factors are inextricably linked [3-4]. Therefore, mastering the distribution law and influencing factors of roadbed moisture balance under long-term climate can provide theoretical guidance and technical support for the design and construction of roadbed long-term stability during road operation.

There are two methods commonly used in the determination of subgrade humidity balance: experimental method and numerical simulation method. In terms of testing, Drumm [5] analyzed the humidity status and range of the subgrade through on-site moisture content exploration test, and concluded the relationship between different soil subgrades and groundwater levels. Perera [6] and so on established the relationship between the suction of different soil types and TMI through long-term on-site monitoring, and combined the soil water characteristic curve to estimate the water

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content of the subgrade soil. Yang [7] and other sub-district soil indoor model tests in different regions, under different drainage boundaries and different compaction conditions, simulate the change of subgrade soil moisture content under the factors of clear, accumulated water and rainfall. However, it takes a long time to use the test method, and it is difficult to detect the change of the humidity balance of the roadbed under the action of long-term climate. In recent years, numerical analysis software based on humidity coupling theory has been gradually applied to the study of roadbed moisture balance under climatic conditions. For example, Rajeev [8] determined the initial humidity and humidity balance of the soil inside the subgrade through indoor and on-site tests, and compared the results of the numerical simulation with the experimental data. It is found that the data obtained by the two have a good agreement. Zhang [9] simulated the variation process of the humidity change of the covered expansive soil embankment under the climate change conditions in Guangxi 10a, studied the variation law of water content with suction in the long-term action of the atmosphere and the law of humidity balance of the expansive soil embankment were studied.

In the process of highway construction and operation, the roadbed humidity field is a constantly changing process due to the long-term natural climatic conditions. The influence factors of the roadbed humidity are complex and variable, and the influence of different influencing factors on the roadbed humidity balance law and humidity state is A question worth exploring. To this end, this paper relies on the reconstruction and expansion project of the Bai-se to Pan-shui secondary road in Guangxi, and uses the numerical simulation method to predict the equilibrium humidity of the new highway subgrade, analyzes the evolution law of the long-term humidity field of the subgrade, and discusses the subgrade height and slope gradient. And the influence of the groundwater level on the equilibrium humidity of the roadbed. On the basis of numerical simulation, the numerical simulation results of the distribution of humidity balance inside the subgrade are evaluated through on-site monitoring and standard calculation.

2. Hydrothermal Coupling Calculation Theory

The atmosphere frequently exchanges water and heat with the interior and surface of the roadbed through rainfall and evaporation. The hydraulic gradient and temperature gradient generated by the atmosphere drive water vapor to move in the roadbed, thus changing the humidity state of the roadbed. This process is a hygrothermal coupling process, which can be analyzed by using unsaturated soil hygrothermal coupling calculation theory [10].

The flow of liquid water in unsaturated soil follows Darcy's law, the diffusion of water vapor follows Fick's theory, and the heat conduction follows Fourier's diffusion formula. Therefore, the governing equations respectively considering the flow of liquid water, the diffusion of water vapor generated during advection, and the hydrothermal coupling of heat conduction in unsaturated soil are:

$$\frac{1}{\rho_w \frac{\partial}{\partial x}}\left[D_v \frac{\partial P_v}{\partial x}\right]+\frac{1}{\rho_w}\frac{\partial}{\partial y}\left[D_v \frac{\partial P_v}{\partial y}\right]+\frac{\partial}{\partial x}\left[k_x \frac{\partial\left[\frac{\partial}{\partial g}+z\right]}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y \frac{\partial \frac{\partial}{\partial z}+y}{\partial y}\right]+Q_w=\frac{\partial \theta_w}{\partial t} \tag{1}$$

$$L_v \frac{\partial}{\partial_x}\left[D_v \frac{\partial P_v}{\partial x}\right]+L_v \frac{\partial}{\partial_y}\left[D_v \frac{\partial P_v}{\partial y}\right]+\frac{\partial}{\partial x}\left[\lambda_x \frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_y \frac{\partial T}{\partial y}\right]+W_t=\xi \frac{\partial T}{\partial t} \tag{2}$$

$$\psi=-\frac{RT}{w_v} ln \frac{P_v}{P_{vs}} \tag{3}$$

Where, ρ_w is the density of water; D_v is the diffusion coefficient of water vapor; P_v is the gas pressure; k_x and k_y are permeability coefficients in horizontal and vertical directions respectively; ψ is matrix suction; Q_w is the boundary flow; θ_w is subgrade humidity; z is the position head; g is gravitational acceleration; L_v is the latent heat of evaporation of water, taking 2.418×10^6 J/kg; ξ is volume heat

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capacity; λ_x and λ_y are the thermal conductivity in horizontal and vertical directions respectively. W_t is boundary heat; T is absolute temperature; R is the general gas constant, taking 8.31432J/mol; w_v is the weight of water molecules; P_{vs} is saturated vapor pressure.

The flow boundary condition and the temperature boundary condition of the calculation model must be given when using the hydro-thermal coupling control equation to calculate the subgrade moisture movement. Water flow boundary conditions are determined by rainfall and evaporation:

$$Q_w = q - E_v \tag{4}$$

Where, q is the rainfall, using the measured data provided by the meteorological department; E_v is the actual evaporation of soil on the subgrade slope surface, E_v is calculated by Penman-Wilson formula:

$$E_v = \frac{\Gamma N + 0.35\eta P_{vs}\left(1+0.146V_w\right)\left[RH_a^{-1} - RH_r(\psi)^{-1}\right]}{\Gamma + \dfrac{1}{RH_r(\psi)}} \tag{5}$$

Where, Γ is the slope of the relationship curve between saturated vapor pressure and temperature; N is the net radiation of soil surface; η is the humidity constant, taking 66Pa/k; V_w is wind speed; RH_a and $RH_{r(\psi)}$ are air relative humidity and surface relative humidity respectively.

Heat exchange between soil and atmosphere occurs on the soil surface, so the surface soil temperature can be used as the temperature boundary condition of the calculation model, and the surface soil temperature of subgrade can be calculated by Wilson's formula:

$$T_s = T_a + \frac{1}{\eta f(u)}\left(N - E_v\right) \tag{6}$$

Where, T_s is the surface temperature of the soil; T_a is the air temperature.

Based on the above-mentioned damp-heat coupling theory, a numerical calculation method for subgrade humidity can be established, and then the variation of embankment humidity under long-term climatic conditions (rainfall, air temperature, relative humidity, wind speed, etc.) can be modeled and calculated.

3. Distribution Law of Subgrade Humidity Balance

3.1 Establishment of Numerical Model

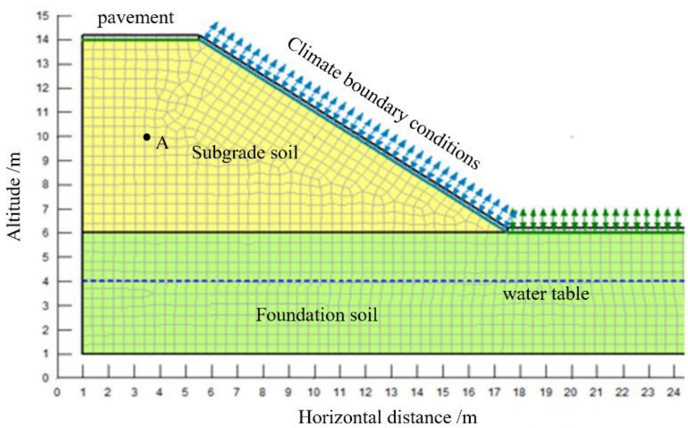


Figure 1. Finite element mesh model

Based on the construction status of Guangxi the Bai-se to Pan-shui secondary road expansion project, the geometric model of numerical calculation selected through field investigation is: embankment height is 8m, embankment top surface width is 9m, and foundation thickness is 5m. As the cross section of the subgrade is of symmetrical structure, in order to simplify the calculation, the right side

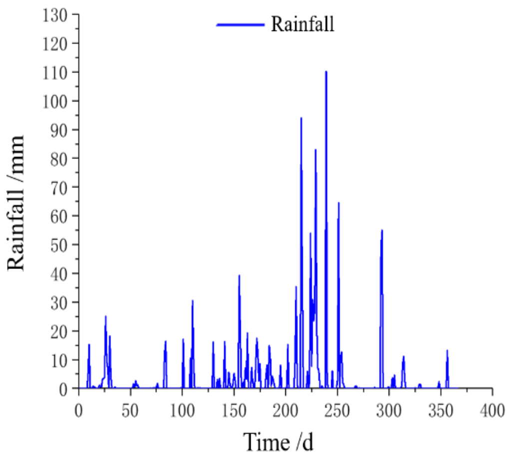
ISSN: 2414-1895 DOI: 10.6919/ICJE.202012_6(12).0063

of the subgrade centerline is selected as an example to establish the model, and point A is taken as the analysis feature point. The subgrade calculation model and grid division are shown see Figure 1.

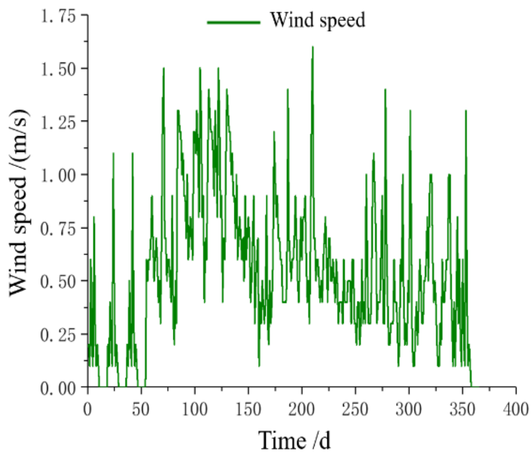
In order to fully understand the equilibrium humidity of the soil inside the subgrade after many years of construction and opening to traffic, the distribution law of the equilibrium humidity of the soil inside the subgrade under the single-factor changes of slope ratio, embankment height and groundwater level under the action of atmosphere and groundwater is discussed by referring to the local meteorological data and the basic physical and mechanical parameters, soil-water characteristics and permeability characteristics of the subgrade soil. The following three numerical simulation calculation schemes are set up to simulate the change law of the equilibrium humidity of the soil inside the subgrade slope. The main numerical simulation schemes are shown in Table 1.

Table 1. The main numerical simulation schemes

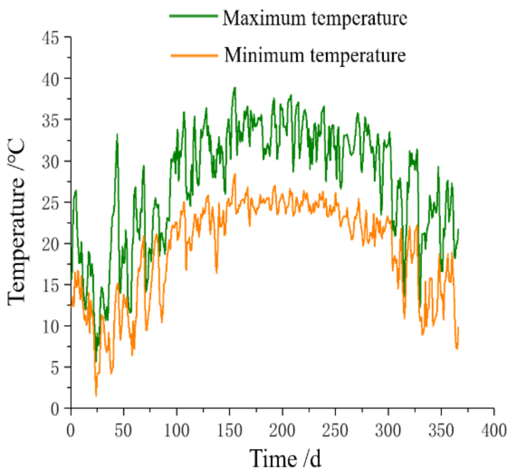
Scheme number	Embankment height /m	Slope rate	Water table /m
1	8	1:1	2
2	8	1:1.5	2
3	8	1:1.75	2
4	5	1:1.5	2
5	8	1:1.5	2
6	10	1:1.5	2
7	8	1:1.5	1
8	8	1:1.5	2
9	8	1:1.5	3



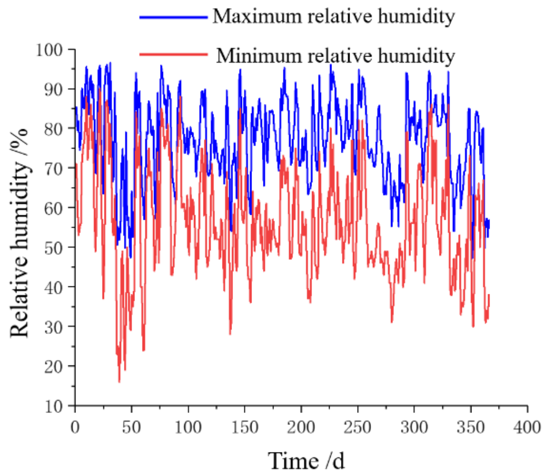
(a). Rainfall



(b). Wind speed



(c). Temperature



(d). Relative humidity

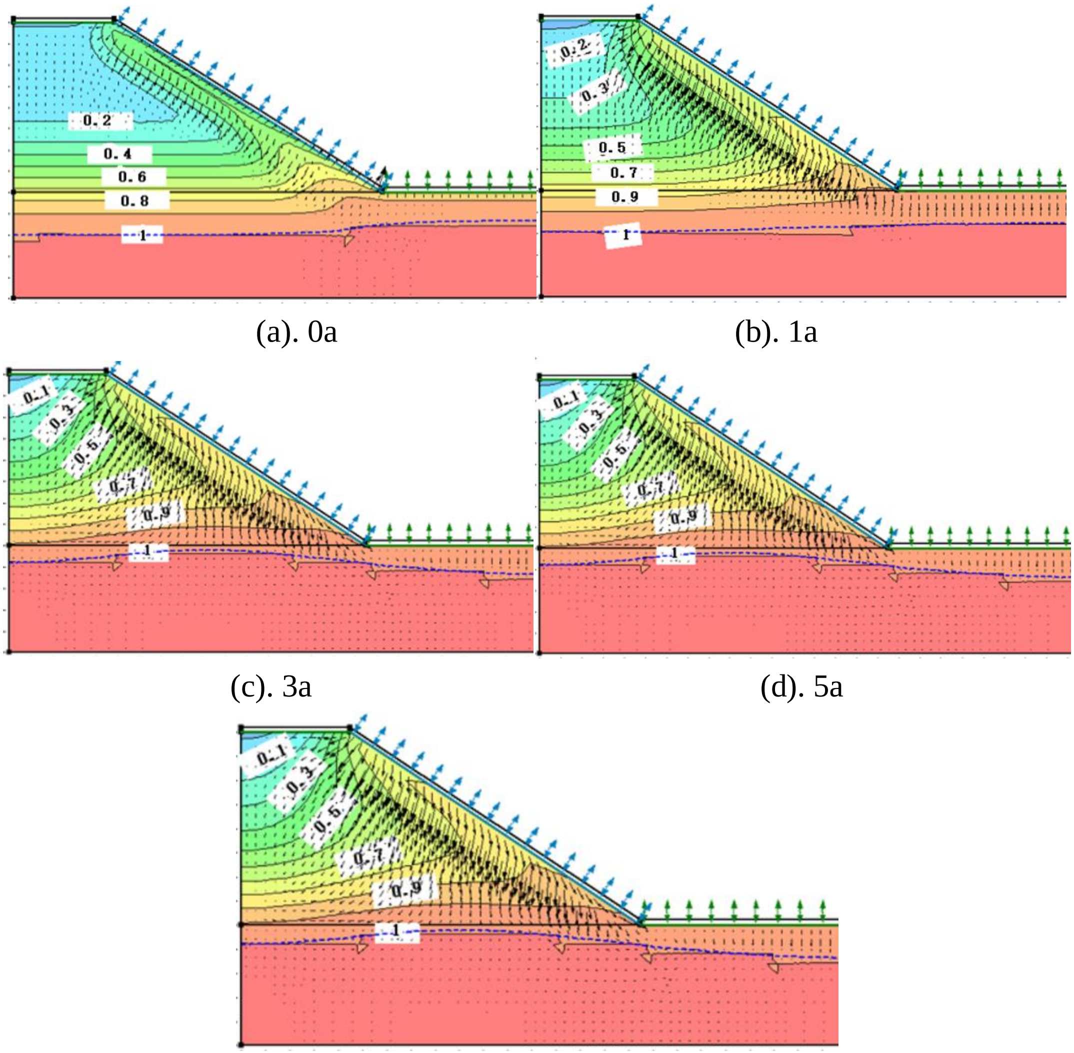
Figure 2. Calculate the climate parameters of the model

ISSN: 2414-1895 DOI: 10.6919/ICJE.202012_6(12).0063

The variation curves of meteorological data such as rainfall, wind speed, temperature and atmospheric relative humidity for 2016-2017 in the region obtained through meteorological stations are shown in Figure 2 (a-d). In order to study the evolution law of embankment humidity balance under long-term climate effect, the calculation period is assumed to be 15 years, and the annual meteorological changes are assumed to be consistent.

3.2 Variation Law of Subgrade Humidity Balance

The humidity inside the embankment changes obviously under the long-term effect of climatic conditions, as shown in Figure 3, which is a nephogram of saturation change inside the embankment within 15a.



(a). 0a (b). 1a

(c). 3a (d). 5a

(e). 15a

Figure 3. Cloud atlas of moisture changes in subgrade

In the initial state, the saturation inside the roadbed is relatively low and the humidity distribution is relatively uniform. After more than a year's climate and the influence of groundwater, the overall saturation inside the subgrade has increased to a certain extent compared with the initial state. The saturation of subgrade soil under the pavement structure layer gradually increases from top to bottom, and the saturation of subgrade soil in a certain depth of the slope surface layer is lower than the saturation inside the subgrade. Three years later, the saturation level inside the roadbed is still changing and gradually tends to be stable. After 5 years and 15 years of humidity field changes, it is not difficult to find that the saturation of soil inside the subgrade is basically not affected by climate

ISSN: 2414-1895 DOI: 10.6919/ICJE.202012_6(12).0063

conditions and groundwater effects, and the saturation has stabilized, which shows that the humidity changes go through three stages of rapid rise, slow increase and humidity balance, and the humidity inside the subgrade reaches a balanced state within 3-5 years. When the humidity inside the roadbed reaches the equilibrium state, the overall saturation of the roadbed soil will be higher than that in the initial state. Rainfall infiltration and the rise of underground water level will increase the humidity of the roadbed soil. At the same time, the closer to the groundwater level, the higher the saturation of soil, and the influence of the change of groundwater level on the internal humidity of subgrade is stronger than that of rainfall infiltration on the humidity of subgrade.

3.3 Comparison of Subgrade Humidity Prediction

Under the condition that the operation of the secondary highway is not affected, five monitoring points are arranged on site to monitor the mass moisture content of 0.3m, 1.5m, 2m, 3m and 4m from the different elevations of the water table level respectively, and the saturation is calculated by using the construction specification. Taking the data results of the two as the research object, the subgrade equilibrium humidity is estimated and compared with the simulation results of the numerical model. The results are shown in Table 2. The subgrade humidity value calculated by numerical simulation is within the range of the standard estimated value, and the difference between the value and the range value is less than 5%, which meets the standard calculation accuracy. And it is not much different from the on-site monitoring data, which shows the accuracy and reliability of using numerical simulation to predict the humidity balance change rule within 15 years.

Table 2. The main numerical simulation schemes

Elevation from water table	Normative calculation	Numerical simulation		Site monitoring
h(m)	s(%)	s(%)	w(%)	w(%)
0.3	93~100	99	18.3	15.5
1.5	76~90	92	19.2	18.9
2.0	73~88	88	20.0	23.5
3.0	68~85	76	22.5	23.8
4.0	66~83	69	24.7	24.6

4. Analysis on Influencing Factors of Subgrade Humidity Balance

4.1 Influence of Embankment Height on Subgrade Equilibrium Humidity

As can be seen from **Figure**, when the roadbed height is 5m, 8m and 10m respectively, the humidity at point a inside the roadbed reaches the humidity equilibrium state after the roadbed operates 3.16a, 4.15a and 5.38a respectively. Therefore, it can be seen that the time taken for the internal points to reach the humidity equilibrium state is different with different subgrade heights, i.e. the higher the subgrade height, the longer the time taken for the internal points of the subgrade to reach the humidity equilibrium state, the lower the subgrade height, and the shorter the time required for the internal test points to reach the humidity equilibrium state. However, it can be seen from the figure that the equilibrium humidity at point A is consistent under different subgrade heights. Comprehensive: when the height of subgrade increases, the elevation of groundwater level also increases when the soil inside the subgrade reaches the equilibrium humidity. This is because when the slope of the subgrade slope is constant, the height of the subgrade will be increased, and the slope length of the subgrade slope will have a long strain. In the same period of time, natural factors such as atmospheric rainfall and evaporation will have a greater impact on the humidity of the soil inside the subgrade. Rainfall infiltration rainwater will continuously replenish the rising capillary water, and under the condition of rainfall infiltration, rainwater accumulated at the foot of the slope will quickly penetrate into the subgrade, thus causing groundwater to rise.

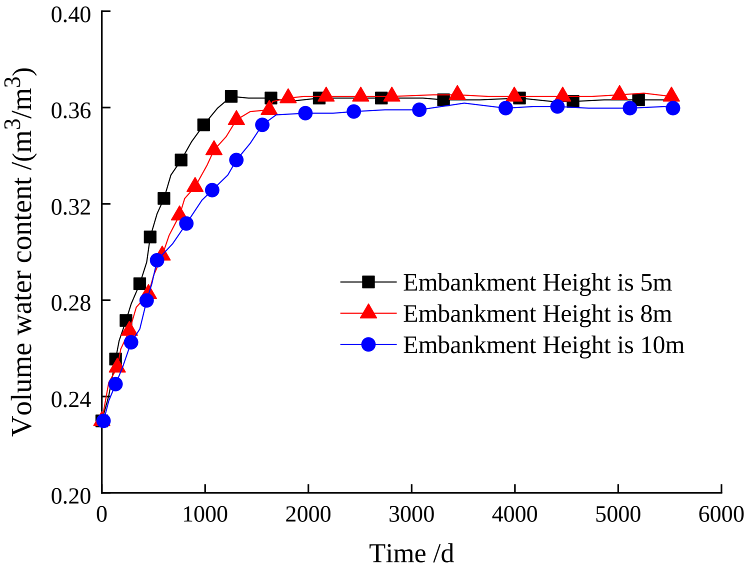


Figure 4. Variation of water content with time at different heights

4.2 Influence of Slope Rate on Subgrade Equilibrium Humidity

The time required for the soil inside the subgrade to reach the humidity equilibrium state varies with the slope of the subgrade slope. As shown in Figure 6, when the slope ratio is 1:1.75, the time required to reach the humidity equilibrium state is the shortest, the slope ratio is 1:1.5 times, and the slope ratio is 1:1 is the longest. in other words, the slower the slope of the subgrade slope, the shorter the time required to reach the humidity equilibrium state, the greater the slope, the longer the time required to reach the humidity equilibrium state, and the greater the impact on the water content of the soil sample. When the slope ratio is 1:1.75, the equilibrium humidity at point A is 37.7%, when the slope ratio is 1:1.5, the equilibrium humidity at point A is 37.6%, and when the slope ratio is 1:1.1, the equilibrium humidity at point A is 37.5%. The slope of subgrade slope has little effect on the equilibrium humidity, but only on the equilibrium time. The slower the slope of subgrade slope, the larger the infiltration surface affected by atmospheric rainfall on the slope surface, and the longer the stagnation time of atmospheric rainfall on the slope surface, so that the water accumulated in the process of atmospheric rainfall on the gentle slope is larger than that on the steep slope. Secondly, under the influence of climate factors, the area of gentle slope affected by temperature and wind speed is larger, and the temperature rise of subgrade soil is more obvious than that of steep slope.

4.3 Influence of Groundwater Level on Subgrade Equilibrium Humidity

As shown in Figure 6, as time goes by, the volumetric water content of point A gradually increases, and when it increases to a certain water content, it will tend to a stable state, and the closer the point A is to the groundwater level, the more obvious the increasing trend. The initial groundwater level is different, and the time required for the soil inside the subgrade to reach equilibrium is also different. The higher the initial groundwater level, the shorter the time required for the soil inside the roadbed to reach a moisture equilibrium state. The lower the initial groundwater level, the longer it takes for the soil inside the subgrade to reach a moisture equilibrium state. The higher the groundwater level, the greater the equilibrium humidity at point A, and the lower the groundwater level, the lower the equilibrium humidity at point A, that is, the equilibrium humidity at point B2: groundwater 1m>groundwater 2m>groundwater 3m. This is because groundwater enters the roadbed under the influence of capillary action, which increases the water content of the roadbed soil until it reaches an equilibrium state. The initial groundwater level is different, and the time required for the capillary action of the subgrade soil to rise to the same level within the subgrade is different. The closer to the initial groundwater level, the shorter the time required for the capillary action of the subgrade soil at each measurement point to rise to the same level and reach this level. The shorter the path, otherwise the opposite. Subgrade fills are all unsaturated soils. The capillary action of subgrade soil mainly comes from the matrix suction of unsaturated soil. Under the influence of capillary action, groundwater migrates into the subgrade, shortening the path of capillary action, and the soil moisture inside the subgrade gradually It can be seen that the rise and fall of the groundwater level have a significant impact on capillary action.

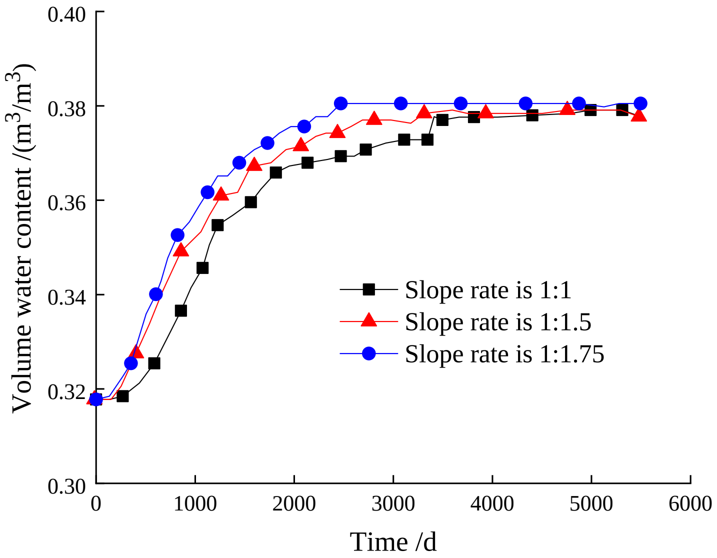


Figure 5. Variation of water content with time at different slope rates

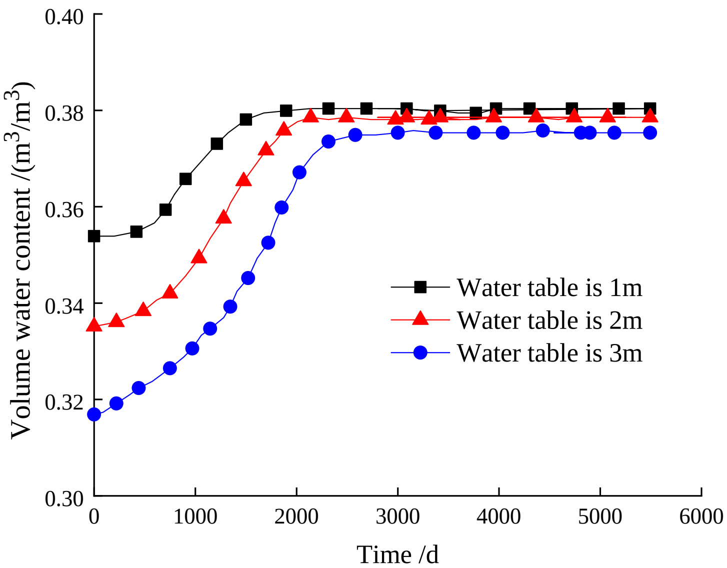


Figure 6. Variation of volume water content with time at different water tables

5. Conclusion

(1) Affected by long-term climate factors, the overall humidity of the subgrade increases with rainfall infiltration and the elevation of underground water level. The change of humidity goes through three stages of rapid increase, slow increase and humidity balance. Within 3-5 years, the humidity inside the subgrade reaches the equilibrium state. When the humidity inside the roadbed reaches the equilibrium state, the overall saturation of the roadbed soil will be higher than that in the initial state. The subgrade humidity calculated by numerical simulation is close to the equilibrium humidity calculated by the code and monitored on site.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202012_6(12).0063

(2) The higher the subgrade height, the longer it takes for the internal points of the subgrade to reach the humidity equilibrium state, and the lower the subgrade height, the shorter the time required to reach the humidity equilibrium state. Subgrade height is different, and the equilibrium humidity at the center point is the same.

(3) The smaller the slope gradient, the shorter the time required to reach the humidity equilibrium state, the greater the slope gradient, the longer the time required to reach the humidity equilibrium state, and the greater the influence on the water content of soil samples. The slope of subgrade has little effect on the internal soil equilibrium humidity.

(4) The initial groundwater level is different, and the time required for the soil inside the subgrade to reach the equilibrium state is also different. The higher the initial groundwater level, the shorter the time required to reach the equilibrium state of humidity, and the greater the equilibrium humidity.

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