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Design and Experimental Study of A Detachable Slope Rainfall Infiltration Device

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Abstract

Based on the Richards differential equation of saturated and unsaturated seepage, taking Houguan Lake lakeshore zone in Wuhan as the study area, and taking two-dimensional phreatic seepage trough in groundwater dynamics as the indoor physical model, the existing device was designed and improved, and an experimental method was proposed for the study of rainfall infiltration of the existing riparian slope. The device improves the slope simulation of uneven rainfall problem, overcomes the slope can not change the shape of the problem, can help complete a variety of physical quantity monitoring. The experimental personnel used the modified device to analyze the slope rainfall infiltration and seepage law under different rainfall intensity (long and weak, short and strong), the slope rainfall infiltration and seepage law under different rainfall intensity (long and weak, short and strong).

Keywords

Two-dimensional seepage trough; Richards equation; Slope; Groundwater.

1. INTRODUCTION

1.1. Resources Background

1.1.1 Water Resources background

(1) Resource constraints become tighter

The precipitation value in Hubei province is 750~2100mm, and the difference between north and south is nearly 3 times. The self-produced water resources of Hubei province are not abundant, and the per capita water resources are 1719m^3, lower than the national average of 2200m3.There is water shortage in engineering and water quality as well as resources, and the water shortage in moderate drought year is 5.57 billion m^3, the annual water shortage of 12.08 billion m^3 [1].

(2) Serious environmental pollution

The coastal pollution zones of cities along the Yangtze and Han Rivers are getting longer and longer, and the main stream and some tributaries of the Han River have repeatedly seen "blooms". Non-point source pollution of rural land and lake pollution are serious, a few reservoirs are seriously eutrophicated, and the quality of some drinking water sources fails to meet functional requirements. The length of super III reach of medium and small rivers accounted for 22% of the total length of the assessed river [2].

(3) Ecosystem degradation

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The number of lakes over 100 mu decreased from 1,332 in the 1950s to 755, and the area of lakes decreased from 8,528 km^2 to 2,707 km^2. Some rivers have stopped flowing and their ecological functions have declined[3].

1.1.2 Technical background

Accompanied by secondary disasters have a lot of landslide and rainfall close relationship, many experts and scholars for a long time for the relationship between landslide and rainfall have done a lot of research, in which there are two main ways: one is based on the physical process of rainfall induced landslide instability to establish the corresponding physical model, using the quantitative evaluation on the physical model; The other is to seek the correlation law between rainfall and landslide based on statistical analysis or experimental methods. Physical model device is easy to operate, simple structure, easy to obtain materials, and can well simulate the process of rainfall infiltration. This design is to simulate the process of rainfall infiltration under natural conditions by designing a detachable rainfall infiltration device.

1.2. The Research Status

The study of rainfall infiltration process has important value in agriculture, environment, engineering and other fields. Laboratory models are usually established to simulate rainfall conditions in the natural environment. Many scholars at home and abroad have conducted a large number of studies on rainfall infiltration models and put forward a variety of models, among which Green-Ampt model, Mein-Larson model, Philips model and Richards model are common [4].

1.2.1 Foreign research status

Mallari et al. [5] comparatively analyzed the applicability of Horton and Green-Ampt infiltration models in overland flow, and believed that the Green-Ampt equation could describe the conditions of antecedent water content and flow process in soil more accurately than the Horton equation.Wang et al. [6] combined the Green-Ampt model with the law of mass conservation to establish a rainfall infiltration model considering vertical and parallel slope seepage [7]. Based on saint Venant continuity and momentum equation of surface runoff, green-Ampt model and explicit finite difference method are used to calculate rainfall and runoff of embankment slope. Yao et al. [8] proposed the SGA model to evaluate slope rainfall infiltration process based on the concept of layered soil moisture content above the wetting front. Gavin et al. [9] improved the Green-Ampt model by assuming that the matric suction of soil increases linearly with depth after rainfall. Tsai et al. [10] used sandy soil with different particle sizes to conduct infiltration tests and established a dynamic effect MGAM infiltration model considering capillary pressure on the basis of the traditional Green-Ampt model.

1.2.2 Domestic research status

Li Ning et al. [11] improved mein-Larson rainfall infiltration model by using UNSATURATED soil VG model and Green-AMPT model, and proposed a calculation model of shallow landslide induced by rainfall. Based on the Green-Ampt model, Jian Wen Xing et al. [12] derived a rainfall infiltration model considering the influence of slope dip Angle and small rainfall intensity. Tong Longyun [13] deduced a landslide rainfall infiltration model suitable for the Three Gorges Reservoir area under different rainfall conditions on the basis of green-Ampt model. Ma Shiguo [14] introduced closed pressure into slope stability analysis and modified the classic Green-Ampt model under heavy rainfall conditions. Shi Zhenming et al. [15] proposed a method for calculation of rainfall infiltration depth and stability analysis of multi-layer unsaturated soil slope with unequal thickness, and discussed the influence of different rainfall intensity and rainfall time on slope stability. Tang Yang et al. [16] improved the Green-Ampt model and believed that the initial water content of slope body had a certain influence on the rainfall infiltration process of landslide.

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Based on the previous research content and the deficiencies found in the experiment process, considering the non-uniformity of initial slope moisture content and various rainfall conditions, a detachable rainfall infiltration device was designed, we carry out research and design of a detachable rainfall infiltration device, so that the model can reflect the rainfall infiltration situation under natural conditions as much as possible, so as to further expand the engineering practicability and scope of the model.

2. DESIGN PRINCIPLE

The design principle of the device is based on the Richards differential equation, which describes the flow of water in unsaturated soil, and can describe isotropic soil, incompressible liquid and unsaturated water movement in three dimensions. The device is used to simulate slope rainfall. During the whole infiltration process, the soil in the slope is a process from unsaturated to half-full, and its final saturation depends on the intensity of rainfall. Its equation is shown in Equation (1):

$$\frac{\partial\theta}{\partial t}=\frac{\partial\left[K(\theta)\frac{\partial\psi}{\partial x}\right]}{\partial x}+\frac{\partial\left[K(\theta)\frac{\partial\psi}{\partial y}\right]}{\partial y}+\frac{\partial\left[K(\theta)\frac{\partial\psi}{\partial z}\right]}{\partial z} \tag{1}$$

Where, θ is water content,

T is time,

K is the permeability coefficient,

ψ is the total water potential of unsaturated soil,

X, y, and z represent the axis direction.

Richards differential equation is derived from three other equivalent standard forms according to different application conditions.

H-based: with pressure head H as an independent variable:

$$C(h)\frac{\partial h}{\partial t}-\nabla\cdot\mathbf{K}(h)\nabla h-\frac{\partial K_z(h)}{\partial z}=0 \tag{2}$$

θ-based: in the form of water content θ as an independent variable:

$$\frac{\partial\theta}{\partial t}-\nabla\cdot\mathbf{D}(\theta)\nabla\theta-\frac{\partial K_z(h)}{\partial z}=0 \tag{3}$$

Mixed: the Mixed form with pressure head H and water content θ as variables:

$$\frac{\partial\theta}{\partial t}-\nabla\cdot\mathbf{K}(h)\nabla h-\frac{\partial K_z(h)}{\partial z}=0 \tag{4}$$

The θ-based Richards equation takes soil water content θ as a variable. Generally, there are layers in soil structure, and different soil properties have different water retention, so θ will show discontinuity at the boundary of soil layer. Under the condition of saturated soil, the

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constitutive relation between h and θ degrades, and the form of θ-based Richards equation fails to describe the problems such as groundwater seepage. In the h-based Richards equation, the pressure head h is continuous in the whole soil region, and this equation was once the preferred one to describe unsaturated inflow and infiltration problems[17].

Under some simplified conditions, the adequacy of the solution of Richards differential equation has been fully discussed in many literatures[18].Due to the heterogeneity of soil media, highly nonlinear soil constitutive relationship, complexity of initial value conditions, boundary conditions and regional characteristics, it is difficult to solve Richards differential equation by analytical method[20], and through the physical device combined with finite element analysis will not be the same as the analytical method of massive data or direct calculation difficulties.

Slope rainfall infiltration device can directly provide a visual change of two-dimensional seepage flow section, through the adjustment of different types of soil in the soil bin slope Angle, slope simulation of the actual environment in various complex geological and shape, adjust the maximum slope Angle is 90 °, the minimum Angle of arctanλ (λ is soil bin height and bottom edge length ratio).The adjustable permeable plate is a flexible device that can not only fix the slope shape, but also change the size of the slope. The improved flexible and detachable fine-mouth nozzles at the top can easily control the flow of water to a range of 5-15L, supporting lower rainfall intensity during simulated rainfall, while avoiding excessive water flow to the slope surface damage and soil loss.

The seepage process of slope rainfall under outdoor natural conditions is not only complicated, but also difficult to obtain effective data by means of measurement, and has unpredictable interference factors and safety problems. According to previous experiments and experience summary, it often requires a lot of manpower and material resources to obtain data under outdoor natural conditions, and the acquisition of experimental data cannot be repeated each time. Therefore, it is difficult to distinguish the authenticity of data when some failures occur in measuring means and measuring instruments[21].This design of indoor slope rainfall infiltration device, not only can easily obtain experimental data, but also through a large number of repeated experiments, self-coupling test experimental data.

3. DEVICE MODEL

ABAQUS and SolidWorks software are respectively used to establish the three-dimensional model of soil trough device. In the model diagram established by the two software, the structure and principle of the indoor soil trough device can be more intuitively understood. The device mainly solves the problem that the experiment may be disturbed greatly due to complicated field conditions, such as uncertain rainfall factors. With the help of the improved seepage tank, the experimenter can simulate rainfall infiltration under various natural conditions without interference from irresistible factors such as climate. ABAQUS model diagram is shown in Figure 1:

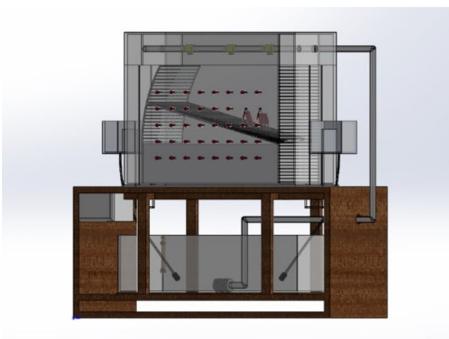

Figure 1. ABAQUS model diagram of the device

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The biggest innovation of the device lies in its ease of disassembly. The disassembly and assembly process are as follows:

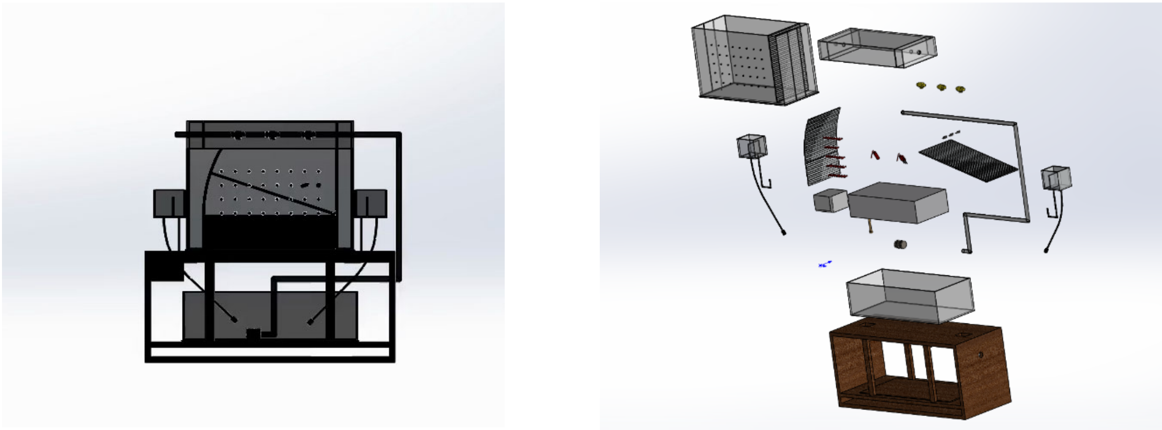

Figure 2. Device combination diagram and device separation diagram

3.1. Design of Rainfall Device

The rainfall device is mainly composed of water pump, flow meter, nozzle with fine mouth and a shelf with nozzle.

The adoption of fine-mouth nozzle is the innovation point of this device. According to previous experimental experience, after being pumped by electric pump, it is vertically led to the evenly perforated acrylic rain plate through 2mm caliber PVC pipe. Because the precipitation is mainly affected by gravity and directly falls at the pipe mouth, it will cause a series of erosion problems. Although it can provide a large water flow, the damage to the experimental model is also relatively large, especially in the slope surface soil loss and slope shape structural damage. Using multiple thin nozzles can also achieve the effect of large nozzle nozzle, and has little influence on the experiment.

The scale position of the float meter can be designed according to the hydrometeorological rainfall data. The hydrometeorological data are shown in Table 1 below. The rainfall in this experiment is calculated as $30mm/m^2$.

Table 1. Hydrometeorological rainfall data

Rainfall level	The phenomenon of description	Rainfall in 24 hours (mm)
Light rain	Rain keeps the ground moist, not muddy	1-10
Moderate rain	The rain trickled down on the roof and puddled in the hollow	10-25
The heavy rain	Rain poured down, splashing on the ground	25-50
Heavy rains	It rains harder than heavy rain and can cause flash floods	50-100.
Torrential rain	Rain that is heavier than a rainstorm or lasts longer, causing flooding	100-200.
The rainstorm	It rains more than a storm and can cause flooding	> 200

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The diameter of the collection funnel is 0.2m, the area of the collection funnel is 0.0314m2, the diameter of the collection bottle is 0.3m, the height is 0.4m, and the volume is 0.02826m3. The collection container is shown in Figure 3:

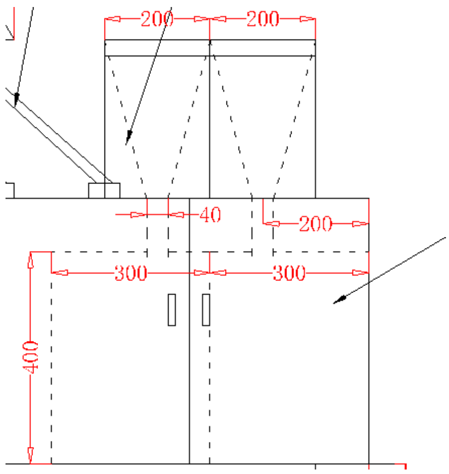

Figure 3. Collection container schematic diagram

The collection volume is calculated as half of the collection bottle, i.e: 0.01413m^3, and the collection time is 0.01413/0.0314/0.0324=360 h.

That is, if the continuous heavy rain lasts 360h, half of the bottle can be collected to depict the flow-rainfall scale line of the float of the same shape. This is the rain gauge design method.

Another set of wipers is added to the rainfall device in the same position, and the operator controls the corresponding inflow flow by adjusting the valve connected with the faucet. In case of sudden indoor power failure, the equipment can still operate manually.

3.2. Design of Observation Holes

The inspiration of observation holes comes from the idea of finite element analysis. The more observation holes are, the more dense they are, the more detailed the hydraulic characteristics of soil can be described, and the smaller the experimental measurement error is. The number of observation holes is 58, and each observation hole is equivalent to a point on the two-dimensional plane. Every 4 points can be used as an equivalent finite element. Sufficient physical data can be obtained by measuring physical quantities of different observation holes.

The observation hole can be connected to the external gummy soft water pipe and the external head pipe. When the rainfall is stable, the water head value of each observation hole can be obtained. By connecting the water heads of different observation holes with isolines in the two-dimensional plane, the equal water head distribution of the whole soil trough can be obtained. When using, the air between the observation hole and the measuring head device should be emptied to prevent the air in the rubber hose from affecting the test of the head.

In order to observe water flow movement near each observation hole unit in detail, color tracer can be injected into the observation hole to judge water flow movement in the soil trough according to the diffusion and flow of color tracer. By measuring the diffusion position of color tracer at different time points, the velocity of water flow can be calculated.

A clay head and electrode are installed on the observation hole for soil water quality observation: Fine clay head Kong Mao porcelain cup, diameter is about 1.0 to 1.5 (including m, are key components in tension meter when measured soil clay head inserted into the pipe free water through a porous clay wall in contact with the soil water, after switching to the water

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balance, at this point, from the number is soil water tension meter reading (clay) head of the suction value, also is the matric potential after ignoring gravitational potential value[22], and then according to the relationship between soil moisture content and matrix potential (soil water characteristic curve[24]) can determine the moisture content of the soil; By burying two electrodes in the soil and measuring the resistance between the two electrodes, the resistance of soil with different rainfall intensity and saturation degree can be obtained.

3.3. Adjust the Design of the Penetration Plate

The adjustable permeable plate is located inside the soil tank. One end is fixed to one side of the soil tank, and the other end can be positioned in different positions according to different slope requirements. It is fixed by a curved fixed slot[25].In the experiment, it is convenient for researchers to switch the Angle at any time, which can not only ensure that the slope soil shape is fixed, but also achieve the experimental effect consistent with the natural environment.

4. THE EXPERIMENTAL SIMULATION

4.1. The Experiment Purpose

The purpose of this device is to theoretically analyze the lakeshore water process under different experimental conditions by using soil trough physical simulation device (laboratory scale) and variable saturation numerical model (actual scale) to set up various experimental scenarios. Experimental purpose:

1. Observe the seepage phenomenon and characteristics of two-dimensional stable flow with infiltration replenishment.

2. Calculate the rainfall infiltration intensity W value and compare it with the measured value.

3. Calculate the permeability coefficient K value of aquifer.

4.2. The Experimental Steps

The equipment is a soil trough model with a length of 120cm, a width of 40cm and a height of 60cm (Figure 4). Water tanks are set on both sides of the soil trough to control the change of water level and simulate the buried depth and slope of different diving surface[26].Rainfall simulation device is set on the surface of soil trough, and rainfall intensity is controlled by flow meter. Twelve groups of negative pressure gauges (or 5TE water content monitoring probes) and soil water collectors are installed in the soil trough to monitor water potential and water content distribution in the soil trough profile and collect water samples. The probes are arranged at horizontal intervals of 20cm. Medium sand, fine sand and loam were filled in the three sets of trough models respectively to simulate different lakeshore lithology. The soil was evenly filled into the trough after drying and screening, and compacted every 5cm during the soil filling process to ensure the uniform distribution of soil.

Solid pollutants were put into the experiment as simulated agricultural pollution sources, which were fully mixed with a certain amount of filled soil and evenly put into the soil surface of the whole lakeshore zone, or only put into the soil surface within a certain range, so as to simulate the pollutant migration law at different locations.

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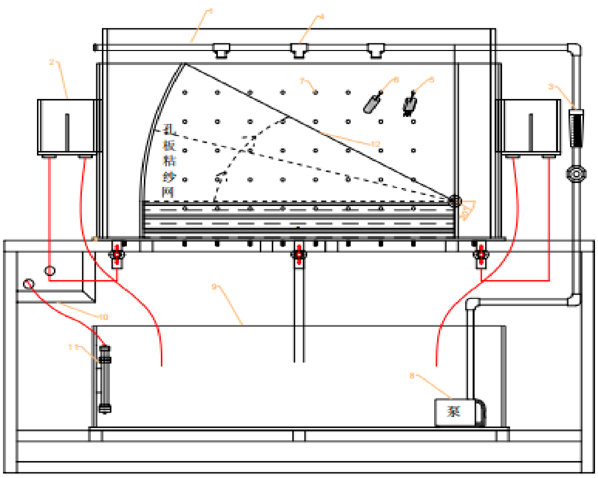

Figure 4. Schematic diagram of experimental device

The experimental steps are as follows:

(1) Check and remove any bubbles that may exist in the pressure tube. When removing bubbles, the bubbles can be washed out by suction ball. Get a gauge and a stopwatch (a stopwatch can be replaced with a cell phone).The schematic diagram of the experimental device is shown in Figure 1.

(2) CAD software was used to design the device plan: to make the internal structure of the indoor soil trough device clearer, as shown in Figure 1:

(3) insert the power supply, make the system electricity, open the switch socket, diving operation, open the inlet valve and the water tank through submersible pump into the voltage regulator of the water in the water tank, by adjusting the water flow meter change water flow, water through the hose into the analog channel and at the same time and mud, part of the water through the return hose into the tank.

(4) Open the socket switch at the same time, the submersible pump runs, and open the rainfall valve. At this time, the water enters the rainfall pipe through the flow meter, and the rainfall is changed by adjusting the flow meter. The socket switch can be turned off when rainfall infiltration is not simulated.

(5) Observe the position of the watershed and the shape of the water table of the interfluvial block under the condition of infiltration recharge and equal water level (HA=HB).

(6) Determination of river excretion (volume method). To figure out what W is. When measuring, the volume can be measured by placing the reflux hose into the measuring cylinder.

(7) Read rainfall QM by rotor flowmeter (M).

(8) Raise and lower the overflow device A or B to make HA>HB (the height difference should not be too large), observe the change of the water level of the pressure tube and the movement of the watershed, and record the reading of each pressure tube after it is stable.

(9) Repeat steps (5) and (6)

4.3. Experimental Experimental Design Reference

(1) Two-dimensional seepage experiment of section under subsection rainfall condition. The rainfall inlet valve was adjusted to form the segmented rainfall stable infiltration condition, and the watershed position, water table shape, head distribution and flow network characteristics of interriver block were observed under the condition of equal water level between two rivers.

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(2) Observation of seepage surface and surface runoff of river bank. Adjust the rainfall water purification valve to gradually increase or decrease the rainfall intensity, and observe the surface runoff and the seepage surface of the river bank under different rainfall conditions.

5. CONCLUSION AND PROSPECT

5.1. Conclusion

This device can solve a kind of problems of slope rainfall infiltration, analyze the slope rainfall infiltration and seepage law under different rainfall intensity (long and weak, short and strong), provide a feasible method for slope rainfall finite element numerical analysis of boundary conditions.

(1) Two-dimensional seepage experiment of section under subsection rainfall condition. The rainfall inlet valve was adjusted to form the segmented rainfall stable infiltration condition, and the watershed position, water table shape, head distribution and flow network characteristics of interriver block were observed under the condition of equal water level between two rivers.

(2) Observation of seepage surface and surface runoff of river bank. Adjust the rainfall water purification valve to gradually increase or decrease the rainfall intensity, and observe the surface runoff and the seepage surface of the river bank under different rainfall conditions.

5.2. Insufficient

This device not only solves the problem of rainfall infiltration, but also provides some research ideas for exploring slope stability in rock and soil mechanics and experimental methods for some problems in rock and soil mechanics and groundwater dynamics.

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