Summary of Rainfall Simulation Methods in Centrifuge

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Abstract. In the field of geotechnical engineering, in order to study the effects of rainfall erosion and seepage on the stability of slopes, the use of rainfall simulation tests in centrifuges has become a hot issue for scholars. In this context, many researchers have developed rainfall simulation devices in centrifuges and studied related theories. This paper summarizes the research status of the rainfall simulation device in the centrifuge in recent years, and it discusses the research status of the force exerted on the raindrop in centrifuge. The characteristics of various devices and analysis methods are reflected by comparison. This paper provides an important reference for future scholars in the study of centrifuge rainfall simulation.

1. Introduction
In the context of frequent natural disasters in recent years, the impact of rainfall erosion and seepage on slope stability will be more prominent. Under realistic conditions, the constant gravity test cannot simulate the impact of large-scale slopes under the action of long-term extreme environment. In the existing research method, the centrifuge applies a centrifugal acceleration field of Ng, and the force field is substantially equivalent to the super-gravity field under actual conditions, so that the stress and strain of the model and the prototype are equal. The method can reproduce the prototype features and achieve the test results of "scale reduction" and "time reduction". Therefore, using the special effects of the supergravity centrifuge to simulate the "rainfall" on the slope model, and studying the stability of the slope in the rainfall environment has become one of the important means for many researchers to study this direction [1]-[2]. At the same time, research on rainfall simulation devices has become popular in related research: in early 1930, researchers used simple watering cans to simulate rainfall experiments. In 1958, Meyer and McInroe produced the first complete rainfall simulation device. Subsequently, some scholars have been studying the rainfall simulation devices. Experts represented by Kimura, Take, and Liu have developed relatively mature rainfall simulation devices used in supergravity centrifuges. This paper focuses on the type and development of rainfall simulation devices used in centrifuges, and it introduces the research status of raindrop force in the process of rainfall simulation in hypergravity environment, which provides a reference for the study of centrifuge rainfall simulation experiments.

2. Research Progress on Centrifuge Rainfall Simulation Device

2.1. Drip-type Rainfall Simulation Device
Craig (1991) introduced the details of the rainfall simulation device in the centrifugal model test of the highway embankment. As shown in Fig. 1, the preliminary design of the rainfall device consists of three porous copper tubes installed on the top of the model box. The copper tubes are drilled with small holes...
of 1 mm diameter at intervals of 20 mm, and the copper tubes are connected to the closed water tank. Compressed air is introduced into the water tank to form a water supply pressure. The test results show that the device has problems such as poor uniformity of rainfall and serious erosion of the surface of the soil by droplets. The improved rainfall simulation device is shown in Figure 1. The device uses a spray nozzle instead of a porous copper tube, but the pressurization method does not change. Compared with the porous copper tube, the droplet size and mass of the spray nozzle are smaller, the raindrop is less affected by the centrifugal force, and the rainfall distribution is more uniform.

![Before improvement](image1.png) ![After improvement](image2.png)

**Figure 1.** Centrifuge rainfall simulation device developed by Craig Qian (2007) developed a rainfall simulation device. As shown in Fig. 2, the apparatus is pressurized by adding water to the closed aluminum tank to cause water to drip through the semipermeable membrane at the bottom of the aluminum tank under high pressure to form rain. By expanding the rainfall area, the device fully covers the surface of the model slope to achieve uniform rainfall. However, the droplet size formed by the device is unknown, and the semi-closed structure causes some of the droplets to float into the centrifuge simulation chamber, which may cause unnecessary safety hazards [3].

![Figure 2.](image3.png)

**Figure 2.** Centrifuge rainfall simulation device developed by Qian

2.2. *Nozzle-type Rainfall Simulation Device*

Kimura (1991) used two different rainfall simulators in his centrifugal model tests. As shown in Fig. 3, the rainfall simulation device of Type 1 uses an aluminum plate to hold the nozzle and the pipe, and a total of 10 spray nozzles are installed, and the nozzles are arranged in two rows. However, the top of the model box is not closed. Compared to Type 1, the model box in Type 2 is closed, which avoids the effects of air turbulence caused by the rotation of the centrifuge on rainfall. Type 2 has improved the position of the nozzle to ensure that the nozzle is at the same distance from the slope so that the arrangement improves rainfall uniformity and reduces Coriolis force. At the same time, in the ten test of type 2, the rainfall intensity was increased by increasing the number of nozzles, and several layers of filter paper were laid on the surface of the model slope to prevent the rainwater from scouring and eroding the surface of the model [4].
Figure 3. Centrifuge rainfall simulation device developed by Kimura

The rainfall simulation device designed by Take (2003) is shown in Figure 4. The device mainly includes components such as water pressure sensor, pressure reducing valve, solenoid valve and spray nozzle. The device monitors the water supply pressure in the pipeline through the water pressure sensor. The pressure reducing valve is used to stabilize the water supply pressure, the solenoid valve controls the spray nozzle to open and close, and the nozzle is used to simulate rainfall [5].

Figure 4. Centrifuge rainfall simulation device developed by Take

Liu (2017) introduced the rainfall simulation device developed in the shallow tunnel instability experiment of unsaturated soil slope. The device is mainly composed of a y-type filter, a pressure reducing valve, a pipe water pressure sensor, a two-position three-way solenoid valve and a Hago brand atomizing nozzle for simulating rainfall. Figure 5 is a schematic diagram of the working principle of the device. In the device, the y-type filter is used to filter impurities in the water output of the rotary joint of the centrifuge to avoid clogging the nozzle. The water pressure sensor 1 can monitor the water pressure fluctuation in the pipeline. When the acceleration value is stable after the start of the centrifuge, the water pressure sensor 2 can be used to monitor the change of the water pressure of the pipeline with the increase of the g value. The water remaining in the pipe between the solenoid valve and the nozzle is discharged through another pipe of the two-way solenoid valve to prevent it from forming a drip through the nozzle and forming an impact on the surface of the model soil. The Hago brand atomizing nozzle can achieve atomization under a small water pressure (the minimum allowable water pressure of 275kPa), which effectively reduces the erosion of the model surface by rainfall [6].

Figure 5. Centrifuge rainfall simulation device developed by Liu
3. Research Progress on The Force Exerted on Raindrops in Centrifuges

During the rainfall simulation in the centrifuge, the raindrops are in a non-inertial system due to the movement of the raindrops in the rotating centrifuge. This phenomenon causes the description of the raindrop motion in the centrifuge to be essentially different from the raindrop motion description in the conventional experiment. Because the force exerted on the raindrop has great influence on the rain trajectory, rainfall coverage and rainfall on the model's erosion degree during the rainfall simulation, this part of the research has great practical significance.

Zhang et al. (2007) put forward the following calculation method in the study of raindrop force under centrifuge: set the raindrop to drop velocity in the y direction as \( v \). The direction of rotation of the centrifuge is clockwise (negative z-axis). According to the Coriolis acceleration formula, the Coriolis acceleration \( a_c \) of the raindrop should be along the x direction [7].

\[
a_c = 2v\omega \tag{1}
\]

\[
v = v_0 + Ng \tag{2}
\]

Figure 6. Description of the coordinate system under Zhang's theory

Where: \( a_c \) is the Coriolis acceleration; \( \omega \) is the rotational angular velocity of the centrifuge; \( v_0 \) is the initial velocity of the raindrop falling in the y direction; \( N \) is the multiple of the gravitational acceleration; \( t \) is the time when the raindrop reaches the top of the slope from the rain device.

According to Newton’s second law, Liu et al. proposed different calculation theories in the study of the forces received by raindrops in centrifuges. He believes that the "supergravity" of raindrops in the centrifuge does not only exist in the falling direction, it should be described as "centrifugal force" present in multiple directions. At the same time, Liu proposed a more comprehensive control equation.

\[
m\frac{d^2x}{dt^2} = mx\omega^2 + 2m\omega \frac{dy}{dt} \tag{3}
\]

\[
m\frac{d^2y}{dt^2} = my\omega^2 - 2m\omega \frac{dx}{dt} \tag{4}
\]

\[
m\frac{d^2z}{dt^2} = mz\omega^2 \tag{5}
\]

Figure 7. Description of the coordinate system under Liu's theory

As shown in Fig. 7, a coordinate system is established in the space: the x direction is the rotation direction of the centrifuge, the y direction is the radial direction of the centrifuge (the falling direction of the raindrop), and the z direction is the opposite direction of the earth's gravity [6]. Then the motion control equation of the droplet in the x, y and z directions can be expressed as:

Where: \( mx\omega^2 \), \( my\omega^2 \), and \( mz\omega^2 \) are centrifugal forces received by raindrops in the x, y, and z directions, respectively; \( 2m\omega \frac{dy}{dt} \) and \( 2m\omega \frac{dx}{dt} \) are the Coriolis forces that the droplets receive in the x, y direction, respectively; The droplets in the z direction are not subject to Coriolis force.
4. Conclusion
In the research of the existing centrifuge rainfall simulation device, it mainly includes drip-type and nozzle-type. The drip-type rain device uses a porous tube having a small pore diameter, a porous plate, a cloth or membrane having a small permeability. The drip-type device simulates rainfall by spraying or dripping under the application of water pressure. The droplet size formed by such a rainfall simulation device is unknown, and it is difficult to accurately and quantitatively control the simulated rainfall intensity and duration. The nozzle type rainfall simulation device uses a specific type of nozzle, and the test data of the nozzle can be used to know the particle size of the droplets ejected by the nozzle under a certain water pressure. The nozzle type device can quantitatively simulate the rainfall intensity and duration in a certain range by combining components such as a water pressure gauge and a flow meter.

At present, scholars have less research on the force exerted on the raindrop in centrifuges. Under the existing research, scholars are in the stage of exploring the theory: scholars have less research on the movement of raindrops in the non-inertial system under the rotation of the centrifuge. At the same time, the effect of air resistance on the fall of "raindrops" was not systematically studied, which led to gaps in the field.

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