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Study on Failure Mechanism of Instability about Unsaturated Soil Slope under Extreme Rainfall

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Abstract: Landslide is a major natural disaster, and large number of landslide disasters show that rainfall infiltration is a main factor to induce instability for unsaturated soil slope. To explore the failure mechanism of soil slope under extreme rainfall, the influence of rainfall infiltration for soil slope's saturation, pore water pressure and displacement are analyzed based on fluid-structure coupling and theory of unsaturated soil mechanics under different extreme rainfall conditions. The results show that: (1) It has same rainfall discharge and rainfall duration for the four kinds of rainfall patterns, but they have different space-time effect on soil slope's saturation, pore water pressure and displacement. (2) The rainfall pattern has large impact on slope's displacement, and gradually increasing rainfall has most effective for slope's displacement than other rainfall patterns after rainfall last 48h, followed by first increasing and then decreasing rainfall after the first type, the third is gradually decreasing rainfall, and the least is stability rainfall. (3) Different rainfall patterns have different danger points during rainfall, but it occurs at the time that when rainfall intensity up to the maximum. According to the paper, gradually decreasing rainfall has most impact on slope's stability at early-term of rainfall, first increasing and then decreasing rainfall has most impact on slope's stability at medium-term of rainfall, and gradually increasing rainfall has most impact at last-term of rainfall.

Keywords: *soil slope; failure mechanism; extreme rainfall; fluid-structure coupling; stability*

Introduction

A lot of high and steep soil slopes appear into many construction projects with the development of engineering constructions and other infrastructures. One characteristic of these soil slopes is that their initial state is unsaturated and relatively stable, but the structure of soil changes and affects the stability of slope when encountering extreme rainfall or other inclement weathers. It had been researched through experiments and theoretical analysis by many researchers (Brand, 1984; Rahardjo, 2007; Chen, 2009). LIN Hong-zhou et al.(2009) pointed out the influence of rainfall on unsaturated soil slope's stability included three aspects.

Researches about soil slope's stability under rainfall were achieved by scholars in all over the world. The consolidation theory of coupling was researched by Wong (1998). The model of coupling movement about water, gas and thermal was put forward by Thomas (1997) and Yang (1998). The effects of rainfall intensity and rainfall duration on slope's stability were analyzed by Li Zhao-ping (2000).The influence of rainfall characteristic and hydro-geologic condition on slope's seepage field and safety factor were analyzed by Wu Hong-wei (1999) and Debasis(2009). The regularity between slope's suction with the variation of rainfall duration and slope's safety factor with rainfall intensity were researched by Guo Zhi-yuan (2012). The influence of rainfall on unsaturated loess slope's water content was researched through calculating unsaturated seepage by Zhu Li-juan (2009). The stability of soil slope was studied by some scholars through combining finite element strength reduction and seepage theory (Rui Hong-hua, 2009; XIA Yuan-you, 2009). At the same time, some scholars established the model of rainfall infiltration through indoor tests and simulated the process of rainfall infiltration (WANG Fu-heng, 2009; Liu Bao-jian, 2004; ZHANG Lei, 2012; Kimoto.S, 2013).

The researches of before have important practical significance in studying the stability of soil slope under rainfall infiltration. However, the current researches do not fully consider the impact of extreme rainfall on soil slope's stability (Antoni, 2013), and there were a few reports about the influence of rainfall patterns for soil slope's saturation, pore water pressure and displacement. This paper considers four different extreme rainfall patterns and analyzes the influence of rainfall characteristics for unsaturated soil slope's saturation, pore water pressure and displacement based on fluid-solid coupling of unsaturated soil and numerical analysis software ABAQUS.

Fluid-structure coupling and shear strength of unsaturated soil

Differential equation of infiltration about unsaturated soil

Take an unsaturated soil unit as object and it's size of three-dimensional space is dx , dy and dz , and there is one-dimensional seepage in the soil unit. The seepage velocity of influent is v_y and the seepage velocity of effluent is, $v_y + dv_y$, so the water that flow into soil unit is expressed as:

$$\Delta q = \left(v_y + \frac{\partial v_y}{\partial y} dy \right) dxdz - v_y dxdz = \frac{\partial v_y}{\partial y} dxdydz \tag{1}$$

It is reasonable that assumed the seepage of soil unit as laminar flow, because the pore of soil is extremely slight and the seepage velocity is very small. Accordingly, Darcy's law can be used to describe the seepage that in the soil unit, seepage velocity of v_y is expressed as:

$$v_y = -k_y \frac{\partial h}{\partial y} \tag{2}$$

$$h = y + \frac{u_w}{\rho g} \tag{3}$$

Where k_y permeability coefficient of soil is, h is total head of soil unit, y is gravity head, $u_w/\rho g$ is pressure head.

The water that flow into soil unit can be expressed base on Darcy's law:

$$\Delta q = -\left(\frac{\partial k_y}{\partial y}\frac{\partial h}{\partial y} + k_y \frac{\partial^2 h}{\partial y^2} \right) dxdydz \tag{4}$$

The Eq. (4) is seepage rate of net flow in the soil unit and it is equal to the change of water's volume in the unit time, namely:

$$\frac{\partial V_w}{\partial t} = -\left(\frac{\partial k_y}{\partial y}\frac{\partial h}{\partial y} + k_y \frac{\partial^2 h}{\partial y^2} \right) dxdydz \tag{5}$$

Where $\partial V_w/\partial t$ is net flow that through soil in the unit time.

The volume of soil unit is $V_0 = dxdydz$. Thus, Eq.(5) becomes:

$$\frac{\partial V_w}{\partial t} = -\left(\frac{\partial k_y}{\partial y}\frac{\partial h}{\partial y} + k_y \frac{\partial^2 h}{\partial y^2} \right) \cdot V_0 \tag{6}$$

$$\frac{\partial (V_w/V_0)}{\partial t} = -\left(\frac{\partial k_y}{\partial y}\frac{\partial h}{\partial y} + k_y \frac{\partial^2 h}{\partial y^2} \right) \tag{7}$$

Eq. (3) substitute into Eq. (7) becomes:

$$\frac{\partial (V_w/V_0)}{\partial t} = -\left(\frac{\partial k_y}{\partial y} + \frac{1}{\rho g}\frac{\partial u_w}{\partial y}\frac{\partial k_y}{\partial y} + \frac{k_y}{\rho g}\frac{\partial^2 u_w}{\partial y^2} \right) \tag{8}$$

The liquid constitutive relation of soil can be expressed with the change of net normal stress $d(\sigma_y - u_a)$ and net suction $d(u_a - u_w)$:

$$\frac{dV_w}{V_0} = m_1 d(\sigma_y - u_a) + m_2 d(u_a - u_w) \tag{9}$$

Where m_1 variation coefficient with the change of net normal stress is $d(\sigma_y - u_a)$, m_2 is variation coefficient with the change of net suction $d(u_a - u_w)$.

Thus, Eq. (9) becomes:

$$\frac{\partial (V_w/V_0)}{\partial t} = m_1 \frac{\partial(\sigma_y - u_a)}{\partial t} + m_2 \frac{\partial(u_a - u_w)}{\partial t} \tag{10}$$

So Eq. (8) equal to Eq. (10), namely:

$$-\left(\frac{\partial k_y}{\partial y} + \frac{1}{\rho g}\frac{\partial u_w}{\partial y}\frac{\partial k_y}{\partial y} + \frac{k_y}{\rho g}\frac{\partial^2 u_w}{\partial y^2} \right) = m_1 \frac{\partial(\sigma_y - u_a)}{\partial t} + m_2 \frac{\partial(u_a - u_w)}{\partial t} \tag{11}$$

Eq. (11) is collated as:

$$m_2 \frac{\partial u_w}{\partial t} = -(m_1 - m_2)\frac{\partial u_a}{\partial t} + \frac{\partial k_y}{\partial y} + \frac{1}{\rho g}\frac{\partial u_w}{\partial y}\frac{\partial k_y}{\partial y} + \frac{k_y}{\rho g}\frac{\partial^2 u_w}{\partial y^2} \tag{12}$$

Eq. (12) is differential equation of seepage about unsaturated soil. To facilitate the analysis in the paper, it's assume that soil is homogeneous and pore air pressure is atmospheric pressure, so $\partial k_y/\partial y = 0$ and $u_a = 0$. Thus, Eq. (12) becomes:

$$m_2 \frac{\partial u_w}{\partial t} = \frac{k_y}{\rho g}\frac{\partial^2 u_w}{\partial y^2} \tag{13}$$

Model of fluid-structure coupling

Take an unsaturated soil unit as object and analyze its mechanical characteristic we can find that the volume of force about soil unit only has gravity, so the balance equation of mechanical can be expressed as:

$$[\partial]^T \{\sigma\} = [\partial]^T \left[\{\sigma'\} + \{M\} u_w \right] = \{g\} \tag{14}$$

The relationship between stress and displacement can be obtained base on geometric equation and constitutive equation, namely:

$$\{\sigma'\} = [D]\{\varepsilon\} = -[D][\partial]\{\omega\} \tag{15}$$

Eq. (15) substitute into Eq. (14) becomes:

$$-[\partial]^T [D][\partial]\{\omega\} + [\partial]^T \{M\} u_w = \{g\} \tag{16}$$

The continuity equation of seepage about homogeneous soil can be obtained base on mass conservation law and Darcy's law:

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{\partial \upsilon_x}{\partial x} + \frac{\partial \upsilon_y}{\partial y} + \frac{\partial \upsilon_z}{\partial z} = -k\left(\frac{\partial^2 u_w}{\partial x^2} + \frac{\partial^2 u_w}{\partial y^2} + \frac{\partial^2 u_w}{\partial z^2} \right) = -k\nabla^2 u_w \tag{17}$$

The volume strain can be calculated as $\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z$, namely:

$$\varepsilon_v = \{M\}^T \{\varepsilon\} = -\{M\}^T [\partial]\{\omega\} \tag{18}$$

Eq. (18) substitute into Eq. (17) becomes:

$$\frac{\partial \{M\}^T [\partial]\{\omega\}}{\partial t} = k\nabla^2 u_w \tag{19}$$

Therefore, the model of fluid-structure coupling about homogeneous soil is expressed as:

$$\begin{cases} -[\partial]^T [D][\partial]\{\omega\} + [\partial]^T \{M\} u_w = \{g\} \\ \dfrac{\partial \{M\}^T [\partial]\{\omega\}}{\partial t} = k\nabla^2 u_w \end{cases} \tag{20}$$

Shear strength of unsaturated soil

The theory of unsaturated soil's shear strength had been in-depth studied with the development of theory about unsaturated soil. The shear strength of unsaturated soil was expounded by Bishop (1963).

$$\tau_f = c' + (\sigma_n - u_a)\tan\varphi' + \chi(u_a - u_w)\tan\varphi' \tag{21}$$

Where τ_f is shear strength, c' is effective cohesion, φ' is effective internal friction angle, σ_n is normal stress, χ is empirical coefficient. The theory of Bishop was rarely applied because χ is very difficult to acquire. Another theory of shear strength about unsaturated soil was expounded by Fredlund (1993) base on normal stress and suction:

$$\tau_f = c' + (u_a - u_w)\tan\varphi^b + (\sigma_n - u_a)\tan\varphi' \tag{22}$$

If we premise, $c = c' + (u_a - u_w)\tan\varphi^b$, so Eq. (22) becomes: $\tau_f = c + (\sigma_n - u_a)\tan\varphi'$ (23)

From Eq. (23) we know that its structure is similar to Mohr-Coulomb criterion, so it can be referred to amendment Mohr-Coulomb criterion, and used to analyze the stability of unsaturated soil slope for this paper.

The model of slope

Unit properties and constitutive model

The plane strain model of two-dimensional is established based on ABAQUS and element type of soil is CPE4P. The biggest difference between pore pressure unit and entity unit is that node of unit has pore water pressure.

The relationship between stress and strain is very complex for soil, such as non-linear, elastic-plastic, dilatation and anisotropy. The models of constitutive are suited for saturated soil in ABAQUS, so the model of amendment Mohr-Coulomb criterion is used to analyze the stability of unsaturated soil slope under rainfall through writing subroutine.

Geometric model and material parameter of slope

The model of homogeneous soil slope is shown on Fig.1 and the angle of slope is 60°, the height of slope is 20m.The underground water line is located at the foot of slope and four monitoring points are also shown in Fig.1. The boundary of upper surface is free face. And the boundary of bottom surface is displacement constraint, both horizontal displacement and vertical displacement are constrained. The boundary of left and right sides are horizontal displacement constraint and pore water pressure constraint. The boundary of pore water pressure is defined through distribution function, so the pore water pressure of boundary sides is equal to $10*(10-y)$ .The parameters of soil are shown in table 1 through the density test and direct shear test.

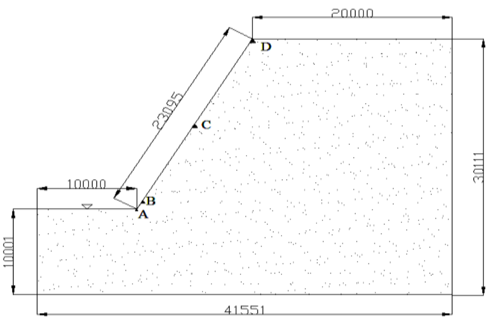


Fig 1. *The model of slope*

Table 1: *Initial parameters of model*

E	v	c'	ϕ'	φ^b	ρ_d	e	k_{ws}
10MPa	0.35	18kPa	35°	4°	1.65g/cm^3	1.0	0.015m/h

Hydraulic permeability curves and soil-water characteristic curve

The permeability coefficient of saturated soil is constant. However, it is change with soil's saturation for unsaturated soil. When analyze the seepage of unsaturated soil, the relationship between permeability coefficient and suction is defined as:

$$k_w = \frac{a_w k_{ws}}{\left[a_w + b_w^{c_w}(u_a - u_w)^{c_w}\right]} \tag{24}$$

Where k_{ws} is permeability coefficient of saturated soil; a_w, b_w and c_w are material parameters and their magnitude are 1000, 0.01 and 1.7. Therefore, the curve of permeability coefficient and saturation is shown in Fig.2. The data between saturation and suction is achieved and shown in table 2 through the SWCC test. The SWCC of soil is fitted based on the model of Van Genuchten and the formula is expressed as:

$$S_r = 20.48 + \frac{79.52}{\left[1+(0.041s)^{3.148}\right]^{0.682}} \tag{25}$$

Table 2: *The suction and saturation of soil*

Suction（kPa）		25	50	75	100	150	200	300	400	600	800	1000
Saturation S_r (%)	Test 1	88.16	41.78	29.89	27.97	25.66	25.35	24.49	23.91	23.21	23.04	22.98
	Test 2	88.85	40.29	28.14	27.97	25.01	23.21	21.71	20.77	19.03	18.86	18.81
	Mean value	88.51	41.04	39.02	27.97	25.34	24.28	23.10	22.34	21.12	20.95	20.89

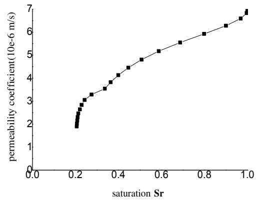


Fig.2 Permeability coefficient

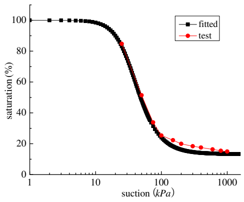


Fig.3 The curve of SWCC

The effect of rainfall on soil slope's stability

In order to consider the impact of extreme rainfall characteristics for soil slope's stability, the initial state of slope is analyzed before rainfall and then researched the effect of rainfall on slope's stability from different extreme rainfall in this paper.

The state of soil slope before rainfall

Fig.4 is slope's saturation contours before rainfall. The figure shows that slope's saturation is evenly distributed in the role of groundwater; the saturation of soil below the water line is 1; the saturation of soil above the water line up gradually decreases from 1 to 0.161, the saturation of soil near the water line rapidly distribute and vary from 0.930 to 0.441; the saturation of soil about slope's hill change smaller than other parts, and the saturation of much soil between 0.161 to 0.231.It shows that the transport diffusion effect of groundwater is gradually decrease from the bottom of slope's water line, and which is consistent with migration law of reality water. The saturation of half slope is residual saturation before rainfall from the figure.

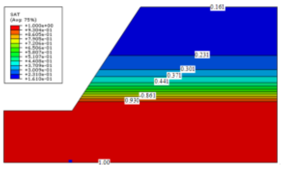


Fig.4 Saturation before rainfall

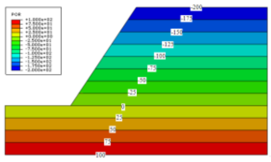


Fig.5 Pore water pressure before rainfall

Fig.5 is slope's pore water pressure contours before rainfall. The figure shows the distribution of pore water pressure is linear, the pore water pressure of slope's bottom is 100kPa, and the pore water pressure of slope's crest is negative and its size is 200kPa. The saturation and pore water pressure of slope's crest are 0.1602 and -200kPa from contours of saturation and pore water pressure, and it is consistent with initial condition.

***Table 3:** The conditions of rainfall*

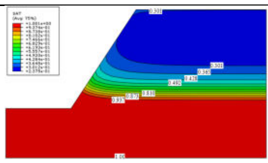
Rainfall pattern	Rainfall intensity/ mm/h	Rainfall duration/ h	Rainfall discharge/ mm
Stability rainfall (1A)	$q=15$	48	720
Gradually increasing rainfall(1B)	$q=5/8t$	48	720
Gradually decreasing rainfall (1C)	$q=30-5/8t$	48	720
First increasing and then decreasing rainfall (1D)	$q=5/4t$, $0\le t\le 24$ $q=60-5/4t$, $24<t\le 48$	48	720

The rainfall pattern

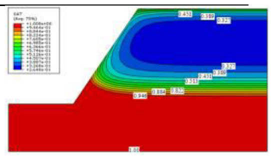
The criteria of extraordinarily rainfall are that the rainfall discharge is no less than 140mm within 12h or 250mm within 24h according to China's meteorological department. In order to analyze the impact of extreme rainfall on soil slope, four different rainfall patterns are considered in this paper. They are stability rainfall, gradually increasing rainfall, gradually decreasing rainfall, first increasing and then decreasing rainfall; as shown in Table 3. They have same rainfall discharge and rainfall duration for the different rainfall patterns.

Effect of rainfall on soil slope's saturation

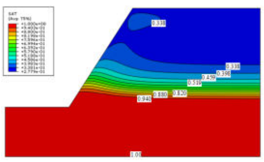
Fig.6 is slope's saturation contours after rainfall under different rainfall conditions. The figure shows that the slope's saturation distributions have different regularity between different rainfall patterns, though they have same rainfall discharge and rainfall duration.



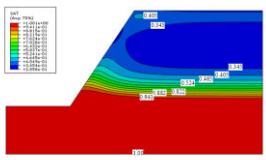
(a) Rainfall pattern 1A



(b) Rainfall pattern 1B



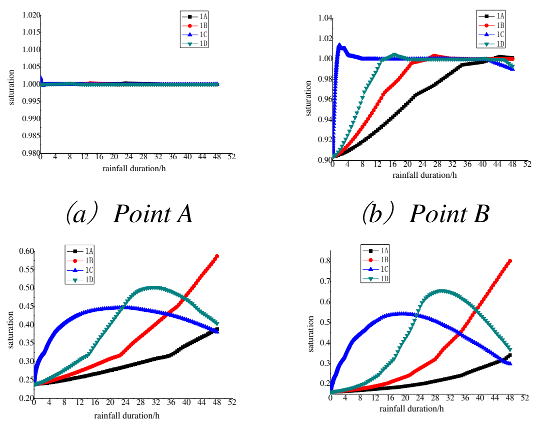
(c) Rainfall pattern 1C



(d) Rainfall pattern 1D

***Fig.6** Contours of saturation after rainfall*

Fig.6(a) is slope's saturation contours under stability rainfall. The intensity of rainfall is equal to the permeability coefficient of saturated soil, so all the rainfall discharge infiltrates into slope and the contours of saturation is very homogeneous. At the same height, the saturation of surface of slope is bigger than that inner of slope. It is because that the soil of slope's crest is unsaturated and permeability coefficient is less than the intensity of rainfall, so some rainfall discharge runoff along the surface of slope. The saturation of slope's top increased from 0.161 to 0.301 after rainfall. Fig.6(b) is slope's saturation contours under gradually increasing rainfall. The figure shows that the distribution of slope's saturation is rendering from high to low, then back to high from the top of slope to the inner of slope and the height of free surface also rises after rainfall. This closed phenomenon is consistent with S.E.Cho's(2001) researching. The top of the slope appeared transient saturated zone and the saturation of part soil reached to 0.7. The cause of closed phenomenon is that the intensity of rainfall is bigger than the permeability coefficient of saturated soil and appears pools zone in the top of slope at last-term of rainfall. Fig.6(c) is slope's saturation contours under gradually decreasing rainfall. The figure shows the distribution of slope's saturation is similar with that under stability rainfall and the contour line of saturation is a convex line. At early-term of rainfall, the intensity of rainfall is greater than the permeability coefficient of soil, so the top of slope appears pools; but the intensity of rainfall is less than the permeability coefficient of soil at last-term of rainfall, so the pools and rainfall discharge has enough time to infiltrate into slope. Fig.6(d) is slope's saturation contours under first increasing and then decreasing rainfall. The characteristic of this rainfall is similar to gradually increasing rainfall and gradually decreasing rainfall, so the distribution of slope's saturation under this rainfall is compatible with that under gradually increasing rainfall and gradually decreasing rainfall. All of rainfall discharge infiltrates into slope along the surface and top of slope because the intensity of rainfall is less than the permeability coefficient at early-term of rainfall. But the top of slope appears pools because the increment of rainfall intensity at medium-term of rainfall. At last-term rainfall, pools and rainfall discharge infiltrates into slope with the decreasing of rainfall intensity and appears closed phenomenon.



(a) Point A *(b) Point B*

(c) Point C *(d) Point D*

***Fig.7** Time-history curves of saturation about monitoring points*

Fig.7 is time-history curves of saturation about monitoring points under different rainfall conditions. The influence of rainfall for saturation about monitoring points is analyzed in the paper.

Fig.7(a) shows that the saturation about monitoring point A had reached saturated due to diffusion effect of groundwater, so the saturation of point A is 1 no matter what the type of rainfall.

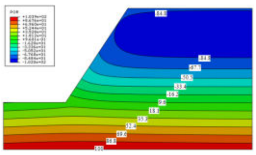
Fig.7(b) shows that the saturation of monitoring point B is 0.9 before rainfall, but it reaches to 1.0 with the increasing of rainfall duration. The rainfall duration is different for point B to reach saturated under different rainfall patterns from time-history curves of saturation. It is need 33h under stability rainfall, 23h under gradually increasing rainfall, only 2h under gradually decreasing rainfall, and first increasing and then decreasing rainfall takes about 12h. Therefore, the impact of rainfall pattern on saturation of point B is that gradually decreasing rainfall > first increasing and then decreasing rainfall > gradually increasing rainfall > stability rainfall.

The regularity of distribution about saturation for points C and D is similar from Fig.7(c) and 7(d). The saturation of this two points increase with the increasing of rainfall duration and time-history curves of saturation have inflection point, it occurs in 36h under stability rainfall and occurs in 24h under gradually increasing rainfall. The regularity of time-history curves of saturation is first increases and then decreases with the increasing of rainfall duration under gradually decreasing rainfall and first increasing and then decreasing rainfall. The saturation up to maximum value at 20h under gradually decreasing rainfall, and it is at 30h under first increasing and then decreasing rainfall. At early-term of gradually decreasing rainfall the intensity of rainfall is bigger than other rainfalls and the saturation of monitoring points quickly reach maximum value, but the saturation of points decrease due to decreasing of rainfall intensity at last-term of rainfall. The growth rate of saturation under first increasing and then decreasing rainfall is bigger than stability rainfall and gradually increasing rainfall.

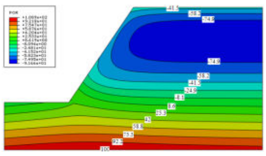
Therefore, the effect of rainfall pattern on the slope's saturation can be summarized as follows: (1) At early-term of rainfall ($0<t\leq 24h$), the effect of rainfall pattern on the slope's saturation is that gradually decreasing rainfall>first increasing and then decreasing rainfall>gradually increasing rainfall >stability rainfall. (2)At medium-term of rainfall ($24<t\leq 38h$), the effect of rainfall pattern on the slope's saturation is that first increasing and then decreasing rainfall>gradually decreasing rainfall>gradually increasing rainfall> stability rainfall. (3) At last-term of rainfall ($38<t\leq 48h$), the effect of rainfall pattern on the slope's saturation is that gradually increasing rainfall> first increasing and then decreasing rainfall>gradually decreasing rainfall>stability rainfall. (4)From the time-history curves of saturation about monitoring points we can suspect that the risk time is at the end of rainfall under stability rainfall and gradually increasing rainfall, the risk time is at about 24h for gradually decreasing rainfall, and first increasing and then decreasing rainfall is at about 36h.

Effect of rainfall on soil slope's pore water pressure

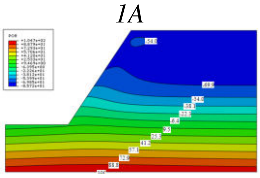
Fig.8 is slope's pore water pressure contours after rainfall under different rainfall conditions. The figure shows that the negative pore water pressure of unsaturated soil increases on the impact of rainfall, but it has little impact on soil that below the groundwater. The negative pore water pressure increased to -102kPa, -91.7kPa, -85.7kPa, -84.5kPa under four different rainfall patterns. The distribution contours of pore water pressure occurs closed phenomenon under stability rainfall and gradually increasing rainfall.



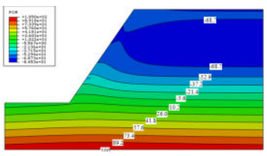
(a) *Rainfall pattern 1A*



(b) *Rainfall pattern1B*

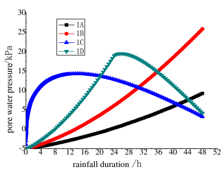


(c) *Rainfall pattern 1C*

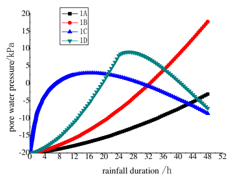


(d) *Rainfall pattern1D*

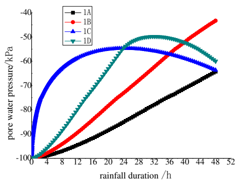
Fig.8 *Contours of pore water pressure after rainfall*



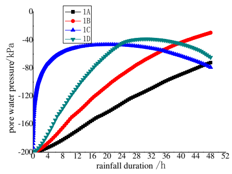
(a) *Point A*



(b) *Point B*



(c) *Point C*



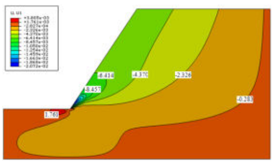
(d) *Point D*

Fig.9 *Time-history curves of pore water pressure about points*

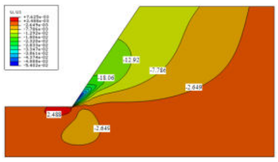
Fig.9 is time-history curves of pore water pressure about monitoring points under different rainfall conditions. It reflects the regularity of pore water pressure about monitoring points during the process of rainfall. The figure shows that the pore water pressure about monitoring points increase with increasing of rainfall duration and arrive to maximum at the end of rainfall under stability rainfall and gradually increasing rainfall. At the same time, it first increases and then decreases with increasing of rainfall duration under gradually decreasing rainfall and first increasing and then decreasing rainfall. So the affect of rainfall pattern on pore water pressure is gradually increasing rainfall>stability rainfall>first increasing and then decreasing rainfall>gradually decreasing rainfall.

At early-term of rainfall(0<t≤20h), the rainfall intensity of gradually decreasing rainfall is bigger than other patterns and the pore water pressure increases more quickly, so the affect of rainfall pattern on pore water pressure is that gradually decreasing rainfall>first increasing and then decreasing rainfall>gradually increasing rainfall>stability rainfall. At medium-term of rainfall(20<t≤36h), the rainfall intensity of first increasing and then decreasing rainfall up to maximum and the affect of rainfall pattern on pore water pressure is that first increasing and then decreasing rainfall>gradually decreasing rainfall>gradually increasing rainfall>stability rainfall. At last-term of rainfall(36<t≤48h), the rainfall intensity of gradually increasing rainfall is bigger than other patterns and the pore water pressure increases quickly under this rainfall, so the affect of rainfall pattern on pore water pressure is that gradually increasing rainfall>stability rainfall>first increasing and then decreasing rainfall>gradually decreasing rainfall. The effect of rainfall patterns on other monitoring points is similar to point A.

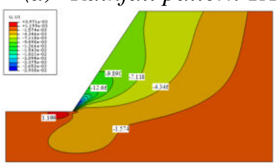
Effect of rainfall on soil slope's displacement



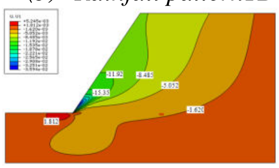
(a) *Rainfall pattern 1A*



(b) *Rainfall pattern1B*



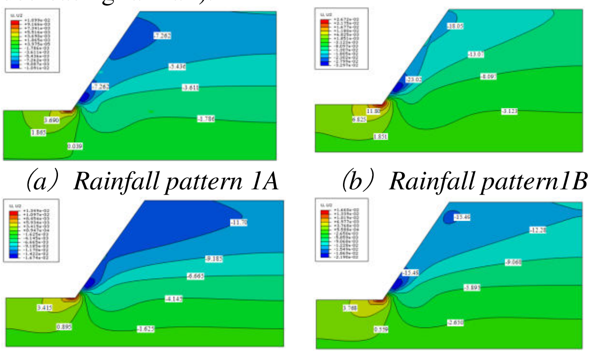
(c) *Rainfall pattern 1C*



(d) *Rainfall pattern1D*

Fig.10 *Contours of horizontal displacement after rainfall*

Fig.10 is slope's horizontal displacement contours under different rainfall conditions. The figure shows that the maximum horizontal displacement of slope occurs in the near of toe. The maximum horizontal displacement under different rainfall patterns are 20.72mm (stability rainfall), 54.02mm (gradually increasing rainfall), 29.30mm (gradually decreasing rainfall) and 35.94mm (first increasing and then decreasing rainfall).



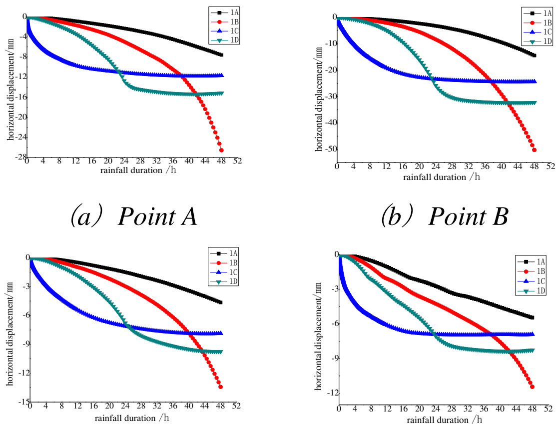
(a) Rainfall pattern 1A (b) Rainfall pattern1B

(c) Rainfall pattern 1C (d) Rainfall pattern1D

Fig.11 *Contours of vertical displacement after rainfall*

Fig.11 is slope's vertical displacement contours under different rainfall conditions. It shows that the position of maximum vertical displacement is at the toe or crest of slope. The maximum vertical displacement under different rainfall patterns are 10.91mm (stability rainfall), 32.97mm (gradually increasing rainfall), 16.74mm (gradually decreasing rainfall) and 21.9mm (first increasing and then decreasing rainfall).

The rainfall patterns have large impact on slope's horizontal displacement and vertical displacement, and gradually increasing rainfall has most effective for slope's displacement than other rainfall patterns after rainfall, followed by first increasing and then decreasing rainfall after the first type, the third is gradually decreasing rainfall, and the least is stability rainfall.



(a) Point A (b) Point B

(c) Point C (d) Point D

Fig.12 *Time-history curves of horizontal displacement about points*

Fig.12 is time-history curves of horizontal displacement about monitoring points under different rainfall conditions. The influence of rainfall for horizontal displacement about monitoring points is analyzed in the paper.

1) From the horizontal displacement of monitoring points, rainfall has most effective for point B's displacement than other points, followed by point A, the third is point C, and the least is point D.

2) The horizontal displacement of monitoring points increase with the increasing of rainfall duration under stability rainfall. The growth rate of point A, point B and point C are very slowly at early-term of rainfall, but they rapidly rise at last-term of rainfall. Point D's horizontal displacement increases linearly with the increasing of rainfall duration under this rainfall pattern.

3) The horizontal displacement of monitoring points increase with the increasing of rainfall duration under gradually increasing rainfall. The time-history curves of horizontal displacement about monitoring points can be divided into three phases. At early-term of rainfall (0<t≤12h), the horizontal displacement of monitoring points are very small and slope can be considered as quiescent state. At medium-term of rainfall (12<t≤36h), the horizontal displacement of monitoring points increase linearly with the increasing of rainfall duration. At last-term of rainfall (36<t≤48h), the horizontal displacement of monitoring points increase rapidly with the increasing of rainfall duration and horizontal displacement up to mutation.

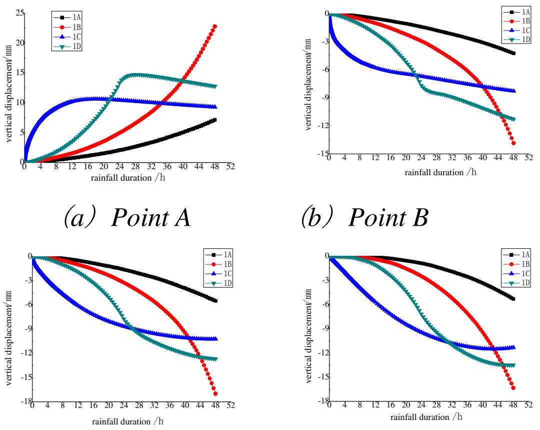
4) The horizontal displacement of monitoring points first increase and then up to invariance with the increasing of rainfall duration under gradually decreasing rainfall. At early-term of rainfall(0<t≤8h), the horizontal displacement of points increase rapidly with the increasing of rainfall duration due to rainfall intensity is large. At medium-term of rainfall(8<t≤24h), the horizontal displacement of points increase slowly with the increasing of rainfall duration due to rainfall intensity reducing to saturated permeability coefficient. At last-term of rainfall(24<t≤48hh), the rainfall intensity decreases to zero from the saturated permeability coefficient and the horizontal displacement of monitoring points up to stability.

5) The horizontal displacement of monitoring points first increase and then up to invariance with the increasing of rainfall duration under first increasing and then decreasing rainfall. The time-history curves of horizontal displacement about monitoring points can be divided into three phases. At early-term of rainfall (0<t≤12h), the rainfall intensity is less than saturated permeability coefficient, so all of the rainfall infiltrate into slope and the horizontal displacement of monitoring points increase slowly. At medium-term of rainfall (12<t≤32h), the rainfall intensity is bigger than saturated permeability coefficient, so the horizontal displacement of monitoring points increase rapidly and the curves appear inflection point at 24h. At last-term of rainfall (32<t≤48h), the rainfall intensity decreases to zero and the horizontal displacement of monitoring points up to stability.

6) Different rainfall patterns have different danger points during rainfall, but their potential danger points basically appear at the time that rainfall intensity up to maximum. Gradually decreasing rainfall have most impact on slope’s stability at early-term of rainfall, first increasing and then decreasing rainfall had most impact on slope’s stability at medium-term of rainfall, and gradually increasing rainfall have most impact at last-term of rainfall.

Fig.13 is time-history curves of vertical displacement about monitoring points under different rainfall conditions. The influence of rainfall for vertical displacement about monitoring points is analyzed in the paper.

Fig.13(a) shows that the vertical displacement of point A is positive due to squeezing of slope under rainfall. The vertical displacements of points first increase and then up to invariance with the increasing of rainfall duration under gradually decreasing rainfall and first increasing and then decreasing rainfall. So the state of slope is stable state at the end of rainfall. The vertical displacements of points increase with the increasing of rainfall duration under stability rainfall, but they are lesser than that under other rainfalls. The vertical displacements of points first increase slowly and then increase rapidly with the increasing of rainfall duration under gradually increasing rainfall, and it is still increases rapidly at the end of rainfall from the curve.



(a) Point A (b) Point B

(c) Point C (d) Point D

***Fig.13** Time-history curves of vertical displacement about points*

Therefore, the effect of rainfall patterns on vertical displacement about monitoring points can be summarized as follows: (1)at early-term of rainfall (0<t≤24h), the effect of rainfall pattern on the slope’s vertical displacement is that gradually decreasing rainfall>first increasing and then decreasing rainfall>gradually increasing rainfall>stability rainfall; (2)at medium-term of rainfall (24<t≤40h), the effect of rainfall pattern on the slope’s vertical displacement is that first increasing and then decreasing rainfall>gradually decreasing rainfall>gradually increasing rainfall>stability rainfall; (3)at last-term of rainfall (40<t≤48h), the effect of rainfall pattern on the slope’s vertical displacement is that gradually increasing rainfall>first increasing and then decreasing rainfall>gradually decreasing rainfall>stability rainfall.

Conclusions

Rainfall is a major factor in inducing landslide. The differential equation of seepage and mathematical model of fluid-solid coupling are derived based on soil mechanics theory about unsaturated soil in the paper. The impact of extreme rainfall on the stability of soil slope is analyzed through ABAQUS and main conclusions as follows:

(1)It has same rainfall discharge and rainfall duration for the four kinds of rainfall conditions, but they have different space-time effects on soil slope’s saturation, pore water pressure and displacement.

(2)Different rainfall patterns had different impact on slope’s saturation. Gradually decreasing rainfall has most impact on slope’s saturation at early-term of rainfall, first increasing and then decreasing rainfall has most impact on slope’s saturation at medium-term of rainfall, and gradually increasing rainfall has most impact at last-term of rainfall.

(3)The affect of rainfall pattern on saturation and pore water pressure after rainfall is that gradually increasing rainfall>stability rainfall>first increasing and then decreasing rainfall>gradually decreasing rainfall.

(4)The pore water pressure about monitoring points increase with increasing of rainfall duration and arrive to maximum at the end of rainfall under stability rainfall and gradually increasing rainfall. At the same time, it first increases and then decreases with increasing of rainfall duration under gradually decreasing rainfall and first increasing and then decreasing rainfall.

(5)The rainfall pattern has large impact on slope’s displacement, and gradually increasing rainfall has most effective for slope’s displacement than other rainfall patterns after rainfall last 48h, followed by first increasing and then decreasing rainfall after the first type, the third is gradually decreasing rainfall, and the least is stability rainfall.

(6)Different rainfall patterns have different danger points during rainfall, but their potential danger points basically appear at the time that rainfall intensity up to maximum. Gradually decreasing rainfall has most impact on slope’s stability at early-term of rainfall, first increasing and then decreasing rainfall has most impact on slope’s stability at medium-term of rainfall, and gradually increasing rainfall has most impact at last-term of rainfall.

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References

[1] Brand,E.W.(1984),"State-of-the-art report of landslides in southeast asian", *Proc.,4th Int. Symp. on Landslides,Toronto,*17-37.

[2] Rahardjo, H. et al. (2007),"Factors controlling instability of homogeneous soil slopes under rainfall",*Journal of Geotechnical and Geoenvironmental Engineering*,133(12),1532-1543.

[3] Chen,R.H. et al.(2009),"Simulation of a slope failure induced by rainfall infiltration", *Environmental Geology*.58(3),943-952.

[4] LIN Hong-zhou, YU Yu-zhen, LI Guang-xin, et al (2009), "Influence of rainfall characteristics on soil slope failure",*Chinese Journal of Rock Mechanics and Engineering*,28(1),198-204.

[5] Wong T T, Fredlund D G, Krahn J(1998),"Numerical study of coupled consolidation in unsaturated soils",*Canadian Geotechnical Journal*,35(6),926-937.

[6] Thomas H R, He Y(1997),"Coupled heat-moisture transfer theory for deformable unsaturated soil and its algorithmic implementation",*International Journal for Numerical Methods in Engineering*,40(18),3421-3441.

[7] Yang D Q, Rahardjo H, Leong E C, Choa V(1998), "Coupled model for heat, moisture, air flow, and deformation problems in unsaturated soils", *Journal of Engineering Mechanics* ,124(12), 1331-1338.

[8] Li Zhao-ping, Zhang Mi(2000),"Study on Effects of rainfall infiltration on safety of excavation slope", *China Safety Science Journal*, 10(3),6-22.

[9] Wu Hong-wei, Chen Shou-yi, Pang Yu-wei(1999), "Parametric study of effects of rain infiltration on unsaturated slopes", *Rock and Soil Mechanics*, 20(1), 1-14.

[10] Debasis Roy, Chiranjeevi K, Raghvendra Singh. et al.(2009), "Rainfall induced instability of mechanically stabilized earth embankments", *Geomechanics and Engineering*, 1(3), 193-204.

[11] GUO Zhi-yuan, HE Chang-rong, YU Xiao-hui, et al. (2012),"Analysis of Unsaturated Soil Slope Stability under the Condition of Rainfall", *High speed railway technology*, 3(1), 20-23.

[12] ZHU Li-juan, WANG Tie-hang, HU Yi (2009),"Influence of rainfall on moisture content in unsaturated loess slope", *Chinese Journal of Underground Space and Engineering*,5(1),95-99.

[13] Rui Hong-hua, Li Kai, Lou Yi-qing(2009),"Slope seepage and stability analysis based on strength reduction finite element method",*Journal of China Three Gorges University(Natural Science Edition)*, 31(3),15-17.

[14] XIA Yuan-you, ZHANG Liang-liang(2009), "Numerical analysis on highway slope stability considering rainfall infiltration", *Journal of Highway and Transportation Research*, 26(10),27-32.

[15] WANG Fu-heng, LI Jia-chun, TIAN Wei-ping (2009), "Test on rainfall filtration in loess slope", *Journal of Chang an University (Natural Science Edition),* 29(4), 20-24.

[16] Liu Bao-jian, Xie Yong-li, Yu You-cheng(2004), "Test on rainfall filtration in loess slope", *Chinese Journal of Rock Mechanics and Engineering*, 23(24), 4156-4160.

[17] ZHANG Lei, GUO Hai-qing, XIE Xing-hua, et al. (2012),"Experimental study on artificial rainfall infiltration into slope", *Hydro science and engineering*, (6),21-27.

[18] Kimoto.S,Garcia.E.F, Oka.F(2013),"Multiphase coupled numerical simulation of the rainfall infiltration into unsaturated embankments", *Poromechanics V*,33(5), 2103-2112.

[19] Antoni Florkiewicz and Albert Kubzdela(2013), "Factor of safety in limit analysis of slopes", *Geomechanics and Engineering*, 5(5), 485-497.

[20] Bishop A W, Blight G E(1963),"Some aspects of effective stress in saturated and unsaturated soils", *Geotechnique*,13(3),177-197.

[21] Fredlund,D.G, Rahadjo, H.(1993),"Soil Mechanics for Unsaturated Soils", New York: *John Wiley and Sons Inc Publications*.

[22] S.E.CHO, S.R.LEE (2001),"Instability of unsaturated soil slopes due to infiltration", *Computers and Geotechnics*, 28(3), 185-208.