Influence of rainfall on transient seepage field of deep landslides: A case study of area II of Jinpingzi landslide

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Abstract. Rainfall is one of the primary factors that induce landslides. Rainfall infiltration forms a transient seepage field in slopes, thereby leading to an increase in water content, a decrease in matric suction, and an increase in the volume weight of slopes. The increase in water content in rock and soil leads to the degradation of the mechanical properties of the slope medium and reduces the shear strength, thus causing slope instability. In this study, a large-scale accumulation landslide is taken as the research object. The front edge of the landslide is high and is not eroded by river water. Hence, rainfall is regarded as the main external factor that changes the groundwater and seepage field of the landslide. According to the landslide’s topography, geological data, local rainfall, and hydrological monitoring results, the saturated–unsaturated seepage theory of rock and soil and the finite difference method are used to analyze the impact of rainfall on the landslide’s seepage field and groundwater. The evolution law of the transient seepage field of the landslide under the condition of rainfall duration is studied. The results provide a basis for the analysis of landslide deformation and stability.

1. Introduction

Landslides caused by rainfall are common natural disasters, and a large number of landslides occur after heavy or long rain events. The mechanism generally involves rainfall causing changes in the stress state of landslides. The variation of pore water pressure of a landslide and slide belt causes a decrease in effective stress and then promotes the instability of the landslide. However, the relationship between a slope’s pore water pressure caused by rainfall or groundwater and landslide activity is considerably complex\cite{1,2}. The complex response relationship between landslide activity and groundwater is generally caused by the special geological and hydrogeological conditions of the landslide, especially the large permeability difference between its different rock and soil masses. For an unsaturated slope with deep groundwater level, rainfall infiltration causes the water pressure in the unsaturated area above the groundwater level to rise temporarily. It also causes the matric suction and the shear strength of the unsaturated soil to decrease. Furthermore, some areas above the groundwater level may show transient saturation, which results in additional transient water load. These outcomes often become the control factors for the stability of unsaturated slopes during rainy season\cite{3,4}. Therefore, the study of the influence of rainfall infiltration on slopes is particularly important.

Area II of Jinpingzi landslide is a large and deep colluvial elastic soil landslide that is considerably close to the dam of the Wudongde Hydropower Station. The front edge of the landslide is high and is
not eroded by the Jinsha River. According to the analysis of the recent monitoring data for the Jinpingzi landslide, the creep rate of the landslide in area II is closely related to rainfall, and the correlation with deep groundwater is not obvious; hence, the creep of the landslide is significantly affected by rainfall[5][6][7]. In the analysis of the deformation mechanism and stability of the landslide, the evolution law of the transient flow field of the slope should be studied. According to the landslide’s topography, geological data, local rainfall, and hydrological monitoring results, a typical numerical model is established, and the saturated–unsaturated seepage theory and finite difference method are used to study the evolution law of the transient seepage field under representative rainfall conditions. The research results can provide support for the design of landslide seepage control measures and may serve as basis for the analysis of landslide deformation and stability.

2. Geological background
Area II of Jinpingzi landslide is characterized by a wide upper and narrow lower lock groove. The upstream side is connected to the bedrock of area IV, and the downstream side is bounded by Abadagou. The front edge is wide, the back edge is narrow, and the height difference between the front edge and the back edge is more than 650 m. It covers an area of about 0.6 km², with an average slope of 26° and a general thickness of 45–100 m. The maximum thickness is 130 m, and the volume is about 2,700 × 10⁴ m³. Area II is categorized as a huge accumulation landslide. Figure 1 presents a typical geological profile of the landslide.

The sliding body is composed of two layers of materials. The upper layer is dolomite rock gravel soil (Qcol) with a loose and moderately permeable structure. The lower layer is phyllite debris soil (Qdel) with a relatively loose and weakly permeable structure. The sliding zone (Qdel) is phyllite clastic soil with a dense structure; it is categorized as a micropermeable layer. In the middle front of the landslide, the lower part of the slip zone is distributed with ancient gully deposit Qpl+col, which has a loose structure and moderate to strong water permeability. As a result of the differences in composition and structure, the accumulation body shows different water permeability characteristics. The distribution and variation of the seepage field are closely related to rainfall, topography, and rock distribution. It has obvious dynamic response to seasons and rainfall.

![Fig. 1 Landslide geological map of typical sections](image)

3. Basic theory of saturated–unsaturated seepage
The transient seepage of rock and soil caused by rainfall is an unsaturated seepage problem. FLAC’s two-phase flow module can simulate the saturated–unsaturated seepage of rock and soil. In a two-phase flow, the void space is completely filled by two fluids. One of the fluids (the wetting fluid, identified by the subscript w) wets the porous medium more than the other (the nonwetting fluid, identified by subscript g). Hence, the pressure in the nonwetting fluid is higher than that in the wetting fluid. The pressure difference $P_g - P_w$ is the capillary pressure $P_c$, which is a function of saturation, $S_w$. 
Darcy’s law is used to describe the flow of each fluid. The effective intrinsic permeability in the law is given as a fraction of the single-fluid (or saturated) intrinsic permeability. The fractions (or relative permeabilities) are functions of saturation, $S_w$. In the FLAC implementation, the curves for capillary pressure and relative permeabilities are built-in empirical laws of the van Genuchten form (van Genuchten 1980).

Wetting and nonwetting fluid transport are described by Darcy’s law:

$$q_{ij}^w = -k_{ij}^w \frac{\partial}{\partial x_j}(P_w - \rho_g g_k x_k) \quad (1)$$

$$q_{ij}^g = -k_{ij}^g \frac{\partial}{\partial x_j}(P_g - \rho_g g_k x_k) \quad (2)$$

where $k_{ij}$ is the saturated mobility coefficient (which is a tensor), $\kappa_i$ is the relative permeability for the fluid (which is a function of saturation $S_w$), $\mu$ is the dynamic viscosity, $P$ is the pore pressure, $\rho$ is the fluid density, and $g$ is the gravity. Note that the mobility coefficient (or FLAC permeability) is defined as the ratio of intrinsic permeability to dynamic viscosity.

Relative permeabilities are related to saturation $S_w$ by empirical laws of the van Genuchten form:

$$k_{ij}^w = S_w^e [1 - (1 - S_w^{1/a})^2]$$

$$k_{ij}^g = (1 - S_e)^c [1 - S_e^{1/a}]^{2a} \quad (4)$$

Under these laws, $a$, $b$, and $c$ are constant parameters, and $S_e$ is the effective saturation. The effective saturation is defined as $S_e^e = \frac{S_w - S_w^e}{1 - S_w^e}$.

$$P_e - P_w = P_c(S_e) \quad (5)$$

In FLAC, this empirical law is of the van Genuchten form: $P_c(S_w) = P_0 \left(S_e^{1/a} - 1\right)^{1-a}$.

The parameter $P_0$ is relatively large for fine materials, and its dependency on material properties may be assessed using the Leverett scaling law. This law, derived using dimensional analysis, has the following form: $P_0 = \frac{\sigma}{\sqrt{k/n}} \quad (8)$, where $\sigma$ is the surface tension (a property of the matrix), $k$ is the intrinsic permeability, and $n$ is the porosity.

4. Rainfall simulation

4.1. Model generalization

The main sliding section of landslide area II is selected as the typical section for analysis. The calculation range is 3,100 m from the riverbed center line to the mountain level, and the vertical direction starts from the 500 m elevation to the 2,130 m elevation. In the model generalization, six types of seepage media are considered: sliding body $Q^\text{col}$, sliding body $Q^\text{del}$, sliding weak zone $Q^\text{del}$, $Q^\text{bed}$, and $Q^\text{ri}$. The Mohr–Coulomb ideal elastoplasticity is adopted as the yield criterion of the medium. In this seepage calculation, the saturated permeability coefficient of the slide body is taken according to the recommended geological value. The sliding weak zone, bedrock, and $Q^\text{ri}$ are located below the groundwater level. The unsaturated media affected by rainfall infiltration are $Q^\text{col}$ and $Q^\text{del}$, both of which are mainly located above the water level.

For the unsaturated permeability characteristics of rock and soil, a few experimental results are available. In this study, the extensive literature review and model calculation reveal that relative permeabilities are related to saturation $S_w$ by the empirical laws of the van Genuchten form (van Genuchten 1980). The curve is obtained by fitting, as shown in Figure 2. The parameter values of rock and soil are shown in Table 1.

The groundwater level is obtained by fitting the groundwater level data of the geological survey. The current riverbed water level is $\nabla 820$ m. The initial stress field is considered as the gravity stress field. The
boundary conditions of the stress analysis are as follows: the left and right boundaries are constrained by normal displacement, and the bottom is fixed. The boundary conditions of seepage analysis are as follows: the bottom is assumed to be impermeable, the water head boundary conditions are below the water level of the left and right sides, the impermeable boundary is above the water level line, and the free permeable surface is on the slope surface.

![Graph showing permeabilities vs. effective saturation](image)

**Fig. 2 Relative permeabilities vs. effective saturation**

| Table 1 | Unsaturated permeability parameters of landslide rock and soil |
|---------|------------------------------------------------------------|
| rock and soil | $S_r$ | $a$ | $b$ | $P_0$ (Pa) | $k^*$ m$^2$/Pa-s |
| $Q^{[1]}$ (Sliding body) | 0.08 | 0.336 | 0.5 | 7000 | $5.05\times10^{-8}$ |
| $Q^{[2]}$ (Sliding body) | 0.08 | 0.333 | 0.5 | 9000 | $2.02\times10^{-10}$ |
| $Q^{[3]}$ (Sliding weak zone) | / | / | / | / | / |
| $Q^{[4]}$ (Bedrock) | / | / | / | / | / |
| $Q^{[5]}$ (Flac2D) | / | / | / | / | $5.05\times10^{-8}$ |
| $Q^{[6]}$ (Bedrock) | / | / | / | / | $2.02\times10^{-10}$ |

4.2. Rainfall parameters

The analysis of the rainfall and deformation monitoring data on area II of the Jinpingzi landslide shows that the deformation in the area is closely related to rainfall intensity and duration and that the displacement rate of the landslide increases remarkably after heavy rainfall. According to the statistics of the local meteorological data from 2005 to 2019, the annual rainfall is 305.5–787.2 mm, and the maximum rainfall intensity is 159.3 mm/day, which was recorded on September 4, 2013. The year 2017 had the most rainfall events at 109 rainy days, 82 of which occurred from May to October; this number accounted for more than 75% of the whole year’s rainy days, with 21 rainy days occurring every month and with 65 mm of rainfall recorded per day. According to the continuous rainy days and rainfall intensity in 2017 and the maximum daily rainfall intensity in 2013, the rainfall intensity of 70 and 200 mm/day are respectively selected for 20 consecutive days in this study. In the process of rainfall infiltration simulation, the influence of vegetation or evaporation on rainfall interception is not considered, and daily rainfall is assumed to be evenly distributed within 24 h. The saturated–unsaturated seepage theory of rock and soil and FLAC2D two-phase flow module are used to simulate and calculate the rainfall infiltration of the landslide. The effects of heavy rainfall and extreme rainfall on the transient seepage field and groundwater level of the landslide are also studied.

4.3. Calculation load

In the analysis, the steady-state seepage field before the simulated rainfall is used as the initial condition of the transient analysis during rainfall. The pore air pressure is assumed to be constant in the unsaturated seepage analysis. Considering the external water pressure on the slope facing the water at the front of the landslide, we take the rainfall intensity as the flow boundary condition on the slope.
above the riverbed surface. The potential seepage surface boundary is imposed at the same time. When the rainfall intensity is less than the infiltration capacity of the slope, the rainfall intensity is taken as the flow boundary condition; when the rainfall intensity is greater than the infiltration capacity of the slope, the boundary condition of the potential infiltration surface plays a role. The slope boundary condition is designed as a zero water head boundary condition, which means that the rainwater beyond the infiltration capacity is not stored on the surface and instantaneously flows away. In this study, we select the characteristic observation points at the front, middle, and rear edge of landslide area II and denote them as B, D, and F respectively. Meanwhile, the corresponding observation section is located in the interval from the measurement point to the buried depth of 40–60 m, with the section numbers being BC, DE, and FG (Fig. 1).

5. Influence of rainfall on seepage field and groundwater level of landslide

In the result analysis, we compare the dynamic changes of the landslide seepage field under the action of two rainfall modes in different stages, namely, continuous rainfall for 10 and 20 days and zero rainfall for 10 and 20 days. The results should help us learn the evolution law of the landslide transient seepage field caused by rainfall.

5.1. Heavy rainfall model

The phreatic line of the landslide basically coincides with the initial groundwater level. The movement mode of groundwater flows from the high water level of the mountain to the low water level of the riverbed. The groundwater in area II has good mobility in the rock and soil with strong permeability. The water flow speed of the joint parts of $Q^\text{col}$, $Q^\text{del}$, and $Q^\text{del+col}$ at the bottom of the sliding belt is faster than that of the other parts. The Jinsha River has the lowest discharge datum in this area. Groundwater is discharged near the elevation of 880 m at the front edge. It is also discharged into the Jinsha River at the elevation of 810–830 m at the bank slope.

The direction and discharge of rainwater infiltration on the slope surface are closely related to the slope type. The infiltration vector of gentle rainwater on the slope surface is obviously larger than that on the steep slope. The infiltration increases with time. The water saturation of the shallow slope increases correspondingly, and the matric suction decreases and gradually transfers to the deep. For a long and heavy rainfall event, the infiltration capacity of the slope body is less than the rainfall intensity, and part of the rainwater flows along the slope surface. Moreover, the infiltration peak at the slope foot develops upward and inward along the slope surface. At the junction of the multistage ancient landslide accumulation in area I and the back edge of area II, the groundwater level is high, the buried depth is shallow, and the distance from the slope surface is less than 30 m. The permeabilities of the geotechnical materials in this part greatly vary. A long rainfall event results in a large amount of rainwater infiltrates, and the rainwater supply in this part exceeds the lateral and vertical drainage, thus leading to the upward uplift of the seepage vector at the junction of area I and area II (Figs. 3–4). The saturation and matric suction of the different parts of the sliding body have an obvious relationship with the change of rainfall intensity and duration. The response degree of the saturation and matric suction of the different parts of the slope surface to rainfall also varies and is mainly determined by the differences in slope shape, permeability of slope body, and distance from groundwater level. In the initial state, the saturation of the slope surface is about 0.17–0.3, and the matric suction is between 100 and 700 kPa. Continuous heavy rainfall causes part of the rainwater to flow along the slope toe, thereby causing the groundwater level at the front edge of the landslide to rise. When heavy rainfall lasts for 10 days, the groundwater level at the front edge of the landslide rises by about 0.6 m relative to the initial condition. When heavy rainfall lasts for 20 days, the groundwater level rises by about 1.4 m, and the horizontal distance to the slope extension range is about 20 m.
Fig. 3 Vector diagram of transient seepage field of landslide after 20 days of heavy rainfall

Fig. 4 Distribution of matric suction of landslide after 20 days of heavy rainfall

The initial saturation values of the observation points B, D, and F are 0.28, 0.2, and 0.2, respectively; the matric suction values are 144.2, 410.9, and 381.5 kPa, respectively. When heavy rainfall lasts for 10 days, the saturation values of measurement points B, D, and F are 0.6, 0.39, and 0.45, respectively; and the matric suction values are 19.07, 61.39, and 42.72 kPa, respectively. For 20 consecutive days of heavy rainfall, the saturation values of the measurement points B, D, and F are 0.68, 0.55, and 0.56, respectively; and the matric suction values are 13.34, 24.86, and 23.21 kPa, respectively. In the whole process of heavy rainfall, the saturation of the whole slope surface increases with the duration of rainfall, and the matric suction decreases accordingly. From the distribution of slope surface saturation and matric suction, the saturation of the parts with low slope and shallow groundwater table is relatively large, the matric suction is relatively small, and the change in saturation and matric suction is nonlinear with the rainfall duration. In the early stage of rainfall, the water content of the shallow layer of the slope surface increases obviously, and the matric suction of the slope decreases rapidly. The matric suction values of observation points B, D, and F after 10 days of rainfall are 19.1, 61.4, and 42.7 kPa, respectively. With the extension of rainfall duration, the saturation of the slope surface increases, its water storage capacity gradually weakens, and the change range of the suction of the slope surface and matrix slows down in the middle and late periods of rainfall. The matric suction values of observation points B, D, and F after 20 days of rainfall are 13.3, 24.9, and 23.2, kPa, respectively. The change in the matric suction caused by 10 days of rainfall accounts for more than 90% of the change in matric suction caused by 20 days of rainfall. After 20 days of rainfall, the slope surface is still not saturated. Moreover, the saturation of the measurement points at the front of the landslide is about 0.68, and that at the middle and back of the landslide is about 0.56. After the rainfall
stops, the pore water in the shallow layer of the slope surface continues to infiltrate under the action of gravity. The saturation of the surface layer decreases accordingly, and the matric suction increases slightly. When the rainfall stops for 10 days, the saturation values of the measurement points are 0.48, 0.42, and 0.44; and the matric suction values are 34.8, 48.8, and 43.8. When the rainfall stops for 20 days, the saturation values of the measurement points are 0.45, 0.40, and 0.41; and the matric suction values are 41.1, 57.9, and 51.4 kPa (Figs. 5–6).

Heavy rainfall causes a large amount of rainwater infiltration to trigger significant changes in the water content of the slope body at a certain depth and forms an infiltration impacting zone above the water level line. The saturation and matric suction in the infiltration impacting zone are significantly different from the initial condition ratio, and the depth of the infiltration impacting zone has a significant response to rainfall intensity and duration. The curves of saturation of sections BC, DE, and FG and the matric suction along the burial depth in different periods during rainfall for 10 days indicate that the depth of infiltration of landslide BC is about 5.7 m, that of DE is about 3.6 m, and that of FG is about 5.0 m. After 20 days of rainfall, the infiltration depth of landslide BC is about 6.8 m, and that of DE and FG is about 7.2 m. Without rain, the pore water continues to move downward under the action of gravity, and the infiltration depth slightly extends. With the development of the period in which rainfall stops, the saturation of the shallow soil gradually decreases, the corresponding matric suction gradually increases, and the unsaturated characteristics of the slope surface gradually recover. The infiltration caused by rainfall is clearly a process of gradual downward development from the surface layer. During dry season, the water content in the unsaturated zone of the sliding body decreases, and the matric suction gradually increases (Figs. 7–8).
5.2. Extreme rainfall pattern

The extreme rainfall intensity of 200 mm/day is about three times that of the heavy rainfall model. Compared with the results of the heavy rainfall model for the same period, the changes in slope saturation and pore pressure with rainfall duration are more significant under the extreme rainfall conditions. The groundwater level in front of the landslide is obviously increased by extreme rainfall. The groundwater level in front of the landslide is raised by 2.6 m after 10 days of rainfall and by 3.6 m after 20 days of rainfall. The horizontal influence range in the slope is more than 40 m.

The saturation of the slope surface is greater than 0.8 after 20 days of extreme rainfall; the matric suction is about 5.0–7.0 kPa, which is an approximate saturation state (Fig. 9). In actual slope engineering, the saturation of rock and soil above the water level line is a dynamic change, which cannot reach an ideal state of complete saturation (saturation = 1.0). Compared with that for the heavy rainfall model in the same period, the saturation values of measurement points B, D, and F increase by 0.15, 0.26, and 0.26, respectively; and the matric suction values decrease by 6.9, 17.8, and 16.5 kPa (Figs. 10–11), respectively.
The depth of the infiltration impacting zone caused by extreme rainfall is significantly increased relative to that of the heavy rainfall model in the same period. For 20 days of extreme rainfall, the influence depth caused by rainwater infiltration at BC is about 11.3 m, that at DE is about 9.7 m, and that at FG is about 11.5 m. Extreme rainfall also forms transient saturation areas with different depths on the slope surface, with the saturation being greater than 0.8 and the matric suction being approximately 0 (Figs. 12–13). The observation section BC of the front edge of the landslide shows that in the range of the infiltration impacting zone, the water content of the shallow buried slope is relatively large, the matric suction is close to 0, and the saturation is nearly complete. This part of the slope is assumed to enter to the transient saturation state, and the depth of the transient saturation area is about 5.9 m. The saturation and matric suction of the slope outside the infiltration impacting zone have no obvious change relative to the initial state.
6. Conclusions
By using saturated–unsaturated seepage theory and the finite difference method, we analyze the transient seepage field, water saturation, and pore pressure of a target landslide under the action of heavy rainfall and extreme rainfall. The main conclusions are as follows:
1) Heavy rainfall for 20 days results in the formation of a 5.0–7.0 m infiltration area in the shallow layer of the slope surface. The water content of the slope in the area increases, and the matric suction decreases accordingly; however, it does not enter the fully saturated state. The depth of the infiltration impacting zone formed under the same period of extreme rainfall mode is 9.0–12.0 m. At this point, the shallow buried slope body enters the state of nearly full saturation, the matric suction is close to 0, a transient saturation zone is formed, and the depth of the transient saturation zone is close to 6.0 m. When the rainfall intensity is large and the duration is long, the increase of water saturation in the landslide is obvious, and the matric suction gradually decreases or is even eliminated. The range of the infiltration impacting zone or transient saturation zone formed by rainwater infiltration gradually expands in terms of depth.
2) After the rainfall event, the pore water in the slope moves deep under the action of gravity and hydraulic gradient, and the transient water continues to be discharged along the seepage channel. At the beginning of this period of zero rainfall, the depth of the infiltration impacting zone continues to extend slightly.
3) Under the heavy rainfall mode, the groundwater level at the front edge of the landslide increases by 1.4 m, and the horizontal distance to the slope is about 20 m. The groundwater level at the front edge of the landslide increases by about 3.6 m under the extreme rainfall mode, and the horizontal influence range in the slope is about 40 m. Under the condition in which the landslide medium is complete, the influence of rainfall infiltration is mainly shallow, the influence depth is limited, and the influence of rainfall infiltration on the change in the groundwater level is minimal.
4) Further studies are required with regard to the consideration of the presence of large pores and fractures in slopes, which may provide a rapid transportation channel for rainfall to supply groundwater.

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