Slope stability analysis in the Three Gorges Reservoir Area considering effect of antecedent rainfall

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ABSTRACT

Effects of different initial conditions of pore water pressure distribution on slope stability are investigated based on rainfall data in the Three Gorges Reservoir Area. A method to incorporate the initial condition of pore water pressure distribution into the slope stability analysis is suggested. Then, sandy and clayey slopes are taken as examples to investigate the effect of antecedent rainfall on slope stability. Results indicate that the influence of antecedent rainfall on the slope stability increases as the saturated permeability coefficient of the soil decreases.

1. Introduction

Landslides are one of the most common natural hazards (Ho and Ko 2009). Statistical data show that most of the landslides occurred during or after the rainfall. Numerous studies have been conducted on rainfall-induced landslides, but few of them focus on antecedent rainfall. Effects of the antecedent rainfall remain unclear to the geotechnical community. Research on landslides in Hong Kong (Brand 1984, 1992), Italy (Aleotti 2004), Singapore (Pitts 1985), and Spain (Corominas and Moya 1999) showed that there is no direct relationship between antecedent rainfall and slope failure. However, Tan et al. (1987) concluded that the antecedent rainfall is one of the key triggering factors of landslides. The Bukit Batok landslide in Singapore (Wei et al. 1991), which remained stable during the rainfall but failed after the rainfall, provides a persuasive evidence for the key role of antecedent rainfall and slope failure. Therefore, how many days of antecedent rainfall should be considered for the slope stability analysis is still an open question. Moreover, the antecedent rainfall used in most of previous studies is hypothetical (Ng, Wang, and Tung 2001). It is worth investigating the effect of antecedent rainfall on slope stability using real precipitation data.

Based on the daily rainfall data in the Three Gorges Reservoir Area, this paper investigates effects of different initial conditions of pore water pressure distribution on slope stability. The method to obtain the initial condition, which reflects different responses of initial pore water pressure distribution of different soils to the climate environment, is suggested. Then, sandy and clayey slopes are used as examples to investigate effects of antecedent rainfall on the slope stability.

2. Methodology

2.1. Model and boundary conditions

As the antecedent rainfall has potential influence on slope stability, it is necessary to consider a sufficient long period of antecedent rainfall in the slope stability analysis, and thus, to minimise the errors in the numerical analysis. However, the duration of antecedent rainfall considered varies in previous studies. Lumb (1975) used a 15-day antecedent rainfall for the slope stability analysis in Hong Kong. Rahardjo, Leong, and Rezaur (2008), Rahardjo et al. (2001) and Rahimi, Rahardjo, and Leong (2011) used a five-day antecedent rainfall for the slope stability analysis in Singapore. Guzzetti et al. (2007) summarised the threshold of rainfall triggering landslides and found that the duration of antecedent rainfall used by researchers varies from 1 to 120 days. Therefore, how many days of antecedent rainfall should be considered for the slope stability analysis is still an open question. Moreover, the antecedent rainfall used in most of previous studies is hypothetical (Ng, Wang, and Tung 2001). It is worth investigating the effect of antecedent rainfall on slope stability using real precipitation data.

Based on the daily rainfall data in the Three Gorges Reservoir Area, this paper investigates effects of different initial conditions of pore water pressure distribution on slope stability. The method to obtain the initial condition, which reflects different responses of initial pore water pressure distribution of different soils to the climate environment, is suggested. Then, sandy and clayey slopes are used as examples to investigate effects of antecedent rainfall on the slope stability.
Rahardjo et al. (2007) is used in the study, as shown in Figure 1. Rahardjo et al. (2007) studied effects of soil properties, rainfall intensity, ground water table and shape of the slope on slope stability. It was found that soil properties and rainfall intensity are the most influential factors for slope stability. Ground water table and slope shape, however, have less significant effects on the slope stability. As shown in Figure 1, AB, BC, and CD are flux boundaries. The unit flux is set to be equal to the rainfall intensity if the rainfall intensity is less than or equal to the permeability coefficient of the soil. Otherwise, it is taken as equal to the permeability coefficient of the soil when the rainfall intensity is greater than the permeability coefficient of the soil. Water pond is not allowed in the analysis. AH, DE, and FG are impermeable boundaries. EF and GH are water head boundaries, and the total heads are equal to heights of point H and E, respectively.

Figure 2 shows the finite element mesh of the model used for the seepage analysis. There are a total of 7133 nodes and 7143 elements. To guarantee the accuracy and reduce the computational efforts in the meantime, the soil mass close to the slope is refined using 0.2 m-element, while the part far away from the slope are discretised into 0.4 m-element. The bottom part of the model is meshed using even larger elements, as shown in Figure 2 since most of the bottom part is saturated in the analysis. Using the homogenous slope model also saves computational efforts compared with using a real slope. Nevertheless, it is worthwhile to further explore the effect of antecedent rainfall on real slopes in the future study.

The real daily rainfall of the Three Gorges Reservoir Area shown in Figure 3 (China Meteorological Administration 2012), is used in this study. The Three Gorges Reservoir is located at the subtropical monsoon climate zone, where 70% of the annual rainfall concentrates in the period from May to September. The daily rainfall data of 153 days from May to September (see dashed box shown in Figure 3) in 1998 are used in this study. The rainfall of each day is averaged over 24 hours.

2.2. Soil properties

The SEEP/W (GEO-SLOPE International Ltd 2010a) module of GeoStudio is used to perform the unsaturated
in this study: respectively; $Q$ model proposed by Fredlund and Xing (1994) is adopted Water Characteristic Curve (SWCC). The SWCC $t$ of water; vertical directions of the model, respectively; $\varphi$ is the matric suction; and $\varphi_r$ is the matric suction at residual state. In this study, $C(\varphi)$ is taken as equal to 1, as suggested by Leong and Rahardjo (1997).

The permeability function is estimated using the method proposed by Fredlund, Xing, and Huang (1994), by which means, the permeability function is obtained by integrating along the SWCC:

$$k_w(\varphi) = k_s \frac{\int_{\ln(\varphi_s)}^{\ln(10^6)} \frac{\theta(e^\prime) - \theta(\varphi)}{e^\prime} e^\prime dy}{\int_{\ln(\varphi_s)}^{\ln(10^6)} \frac{\theta(e^\prime) - \theta(\varphi)}{e^\prime} \theta(e^\prime) dy},$$  

where $b$ is equal to ln($10^6$) kPa; $y$ is a dummy variable of integration representing ln($\varphi$); $\varphi_{sea}$ is the air-entry value; $\theta$ is the derivative of Equation (2) with respect to $\varphi$; and $k_s$ is saturated permeability coefficient.

Two soils with relatively high and low saturated permeability coefficients, namely sandy soil and clayey soil, are chosen from three types of soils in Rahardjo et al. (2007). Table 1 summarises the hydraulic properties of the two soils. The sandy soil has a saturated permeability coefficient $k_s$ of 8.64 m/d and SWCC fitting parameter $a$ of 10 kPa. The clayey soil has a saturated permeability $k_s$ of 0.0864 m/d and SWCC fitting parameter $a$ of 100 kPa. The other parameters, that is, $m$, $n$, and $\theta_0$, are taken as the same values for both soils because they are relatively less influential. The respective SWCCs and permeability coefficient curves for the two soils are plotted in Figures 4 and 5. According to the soil statistics in the Three Gorges Reservoir Area (Liu et al. 2009; Tang et al. 2002), the saturated permeability coefficient ranges from 0.028 to 10 m/d. It is shown that the saturated permeability coefficients of the two soils in this study fall within this range.

The shear strength equation adopted in the SLOPE/W (GEO-SLOPE International Ltd 2010b) module of GeoStudio for the slope stability analysis is (Fredlund,}

![Figure 3. Daily rainfall of year 1998 in the Three Gorges Reservoir Area and the data (dashed box) adopted for this study.](image)

![Figure 4. SWCCs of the two soils.](image)

### Table 1. Properties of unsaturated soils used in this study.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>SWCC fitting parameters</th>
<th>Saturated permeability coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$ (kPa)</td>
<td>$m$</td>
</tr>
<tr>
<td>Sandy soil</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Clayey soil</td>
<td>100</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 5. Permeability coefficient curves of the two soils.

Figure 6. Annual rainfall in the Three Gorges Reservoir Area during 1995–2000.

Morgenstern, and Widger 1978):

\[
\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \varphi^b,
\]

where \( \tau \) is the shear strength of unsaturated soils; \( c' \) is the effective cohesion; \( (\sigma_n - u_a) \) is the net normal stress; \( (u_a - u_w) \) is the matric suction; \( \phi' \) is the effective internal friction angle; and \( \varphi^b \) is the friction angle corresponding to the part of shear strength due to matric suction. In this paper, the shear strength parameters \( c' \), \( \phi' \), and \( \varphi^b \) are 10 kPa, 26\(^\circ\), and 26\(^\circ\), respectively. In addition, the unit weight of the soil \( \gamma \) is taken as 20 kN/m\(^3\).

2.3. Initial conditions

The initial condition of pore water pressure distribution is the key input information for transient seepage analysis. Luo (2008) investigated the effect of different initial pore water pressure distributions on slope stability with different permeability coefficients. It was assumed that the maximum negative pore water pressure at the surface of the slope is −75, −50, and −25 kPa, respectively, and the pore water pressure distribution follows hydrostatic pressure at around the water table. However, pore water pressure distributions for soils with different permeability coefficients may be different under the same climate environment. The actual humidity situation of different soils cannot be reflected by simply assuming the same initial pore water pressure distribution. To make the initial pore water pressure distribution consistent with the real situation in the soil profile, Rahardjo et al. (2007) obtained the initial condition from field observation. Rahimi, Rahardjo, and Leong (2011) applied a small rainfall on the slope in the steady seepage analysis, and used the result of the steady seepage analysis as the initial condition for the transient seepage analysis. Zhan et al. (2012) used the average annual rainfall as the boundary condition in the steady seepage analysis to obtain the initial condition of the transient seepage analysis. The GeoStudio manual (GEO-SLOPE International Ltd 2010a) also suggests that the initial condition obtained from the steady seepage analysis with a small, but nonzero, rainfall as the boundary condition is more reasonable compared with the initial condition by applying a zero rainfall as the boundary condition.

To explore the influence of different methods for determining the initial condition of pore water pressure distribution on slope stability, two methods, namely setting the maximum negative pore water pressure directly and using the result of the steady seepage analysis as the boundary condition, are compared in this paper.

2.4. Procedure

The SEEP/W and SLOPE/W modules of GeoStudio are used to perform seepage analysis and slope stability analysis, respectively. The main procedures are summarised as below.

Firstly, the initial condition for the transient seepage analysis is determined. By applying the average annual rainfall as the boundary condition on the slope, the pore water pressure distribution is obtained from the steady seepage analysis and is then used as the initial condition for the transient seepage analysis. In contrast, for the case that a maximum negative pore water pressure is assumed as the initial condition, the initial condition is set directly.

Secondly, the transient seepage analysis is performed using SEEP/W module after applying different durations of antecedent rainfall on the slope as boundary conditions. The pore water pressure distribution at the end
of the analysis is used as input in the slope stability. For example, to obtain the pore water pressure distribution of the slope at the end of the 20th day considering 10-day antecedent rainfall, the rainfall between 11th and 20th days is applied as boundary condition for the transient seepage analysis.

Thirdly, the SLOPE/W module is used to perform slope stability analysis. The result of pore water pressure distribution from the transient seepage analysis is used as input in slope stability analysis. Then, Bishop’s simplified method is used to calculate the safety factor of slope stability.

This study makes use of deterministic methods to explore effects of antecedent rainfall on safety margin of slope stability, in which various uncertainties (e.g. uncertainties in soil properties) in rainfall-induced landslides are not taken into account. Nevertheless, it is worthwhile to point out that these uncertainties can be incorporated into rainfall-induced landslide analysis by probabilistic methods (e.g. Ali et al. 2014; Huang et al. 2015). Effects of antecedent rainfall on reliability of slope stability shall be systematically explored in future study under a probabilistic framework.

3. Results and discussion

3.1. Comparison of initial conditions

A sensitivity study is performed to explore the feasibility of four different initial conditions in reflecting the climate environment. The four initial conditions include those with the maximum negative pore water pressure of $-25$, $-45$, and $-75$ kPa, and the pore water pressure distribution obtained from steady seepage analysis by applying the average annual rainfall as the boundary condition. Figure 6 shows the annual rainfall in the Three Gorges Reservoir Area from 1995 to 2000 (China Meteorological Administration 2012). The average daily rainfall is calculated as ratio of the average annual rainfall over 365 days, and it is 2.6 mm in this area.

Figure 7 presents the pore water pressure distribution for the two soils under the four different initial conditions. For sandy soil, the pore water pressure distribution for the case with average annual rainfall as boundary condition is close to that of directly setting maximum negative pore water pressure to be $-45$ kPa. For clayey soil, however, the pore water pressure distribution for the case with average annual rainfall as boundary condition is, on average, close to that of directly setting maximum negative pore water pressure as $-25$ kPa.

As a conclusion, when conducting transient seepage analysis, setting the maximum negative pore water pressure is the most direct and efficient method provided that the field observation data are available. However, if there are no field observation data, assuming the same maximum negative pore water pressure for different soils cannot reflect the real response of soils to the climate environment. It is suggested applying the average annual rainfall on the slope for steady seepage analysis to obtain the initial pore water pressure distribution.

3.2. Effect of the initial condition on slope stability

The procedure described in Section 2.4 is adopted in the analysis for sandy and clayey slopes, respectively, to demonstrate effects of the initial condition on slope stability.

![Figure 7](image-url)
3.2.1. Sandy slope

Figure 8(a)–(d) show the variation of safety factor of sandy slope as a function of time for 20-day, 30-day, 40-day, and 50-day antecedent rainfall, respectively. In each subfigure, four curves plot safety factors under different initial conditions, including those with the maximum negative pore water pressure of −25, −45, and −75 kPa, and that with the pore water pressure distribution obtained from steady seepage analysis. For example, point A in Figure 8(a) represents the safety factor evaluated at the end of the 40th day, during which 20-day antecedent rainfall is considered and the maximum negative pore water pressure is taken as −75 kPa. The curves of safety factor in different subfigures start at different time because different durations of antecedent rainfall are considered. For example, the curves of safety factor start at the 20th day when considering 20-day antecedent rainfall (see Figure 8(a)), while curves of safety factor start at the 30th day when considering 30-day antecedent rainfall (see Figure 8(b)).

Some conclusions can be drawn from the results shown in Figure 8, including (1) as the duration of antecedent rainfall considered increases, the safety factors corresponding to different initial conditions become closer. This indicates that the influence of initial condition on the slope stability decreases as the duration of antecedent rainfall increases; (2) when the duration of antecedent rainfall is longer than 50 days, the safety factors calculated from different initial conditions tend to converge. This means that the initial condition has minimal influence on the slope stability as the duration of antecedent rainfall is longer than 50 days; (3) the safety factors for the initial condition with the maximum negative pore water pressure of −45 kPa plot close to those obtained by applying the average annual rainfall as boundary condition. It is not surprising to see this since the pore

Figure 8. Influence of initial conditions on safety factor of sandy slope with time considering different antecedent rainfalls: (a) 20 days; (b) 30 days; (c) 40 days; (d) 50 days.
water pressure distributions are close to each other in the two cases, as shown in Figure 7(a).

### 3.2.2. Clayey slope

Similarly, the safety factors for clayey slope are calculated. As shown in Figure 9, as the duration of antecedent rainfall considered increases, the safety factors for different initial conditions tend to converge. The influence of initial condition on the stability of clayey slope is more significant than that for sandy slope. For example, when the 50-day antecedent rainfall is considered for sandy slope, there is obvious difference among safety factors corresponding to different initial conditions, as shown in Figure 9(d). This is different from the observation in Figure 8(d) for sandy slope. The initial conditions still have considerable effects on the slope stability for clayey slope even if the duration of antecedent rainfall is relatively long. In addition, curves of safety factor for the case with initial condition obtained by applying the average annual rainfall as boundary condition on the slope is almost identical with those corresponding to the case that the initial condition obtained by setting the maximum negative pore water pressure as $-25$ kPa. This might be attributed to similar average pore water pressure in the two cases, as shown in Figure 7(b).

Comparing safety factors for sandy slope shown in Figure 8 with those of clayey slope shown in Figure 9, it is found that effects of initial conditions on slope stability depend on the soil type. Appropriate initial conditions should be chosen to obtain reasonable results of slope stability analysis. Under the same climate condition, assuming the same maximum negative pore water pressure as the initial condition for different slopes might be inappropriate. The initial condition, which has the pore water pressure distribution obtained from the steady seepage analysis by applying average annual rainfall as boundary condition, is similar to the cases with the maximum negative pore water pressure of $-45$ and $-25$ kPa for sandy slope and clayey slope in this study, respectively. This is attributed to the fact that the water storage capability of clayey slope is greater than that of
sandy slope. Thus, the clayey slope is more humid than sandy slope. It is recommended to apply the average annual rainfall as boundary condition in the steady seepage analysis and then use the result of pore water pressure distribution as the initial condition for transient seepage analysis if there are no field observation data.

3.3. Effect of the antecedent rainfall on slope stability

3.3.1. Sandy slope

Based on the above analysis, the average annual rainfall is applied on the slope in the steady seepage analysis. Then, the pore water pressure distribution obtained from the steady seepage analysis is used as the initial condition in the transient seepage analysis. The safety factor is finally calculated using the result of transient seepage analysis. Figure 10 shows the safety factor of the sandy slope versus time with the consideration of different durations of antecedent rainfall. For comparison, the histogram of the daily rainfall is also included in the figure. Some conclusions can be drawn as follows.

(1) When the duration of antecedent rainfall exceeds 30 days, the curve of safety factor versus time tends to be stable. This means that 30-day antecedent rainfall should be considered in the analysis to generate safety factor with reasonable accuracy.

(2) The safety factors at the end of the 63rd day and 108th day are the minimum values during the rainfall process at around 61st day and 101st day, respectively. When the duration of antecedent rainfall considered exceeds 15 days, the minimum safety factors for different periods of antecedent rainfall almost overlap. This indicates that the minimum safety factors after heavy rainfalls are stable if 15-day antecedent rainfall are considered. The safety factors calculated with consideration of antecedent rainfall less than 15 days cannot reflect the actual safety margin of slope stability. Thus, it is suggested using the duration of antecedent rainfall longer than 15 days in the engineering design.

(3) The influence of antecedent rainfall on sandy slope is minimal. Safety factors considering different durations of antecedent rainfall are not significantly different. The influence is particularly small between the 1st and 60th days when the rainfall intensity is relatively small.

(4) Different types of antecedent rainfall have different influence on slope stability. Although the total rainfall for the two series of rainfall at around the 61st day and the 101st day are similar (say 300 and 390 mm, respectively), they have different characteristics. The rainfall at around the 61st day has a high intensity but a short duration, while the rainfall at around the 101st day has a low intensity but a long duration. Consider, for example, the safety factor at the 68th day. If 5-day antecedent rainfall is considered, the antecedent rainfall at around 61st day is not included, but it is included for the case with 10-day antecedent rainfall. Effects of the antecedent rainfall at around 61st day can be explored by comparing the safety factors at the 68th day considering different durations of the antecedent rainfall. The maximum difference between the safety factor obtained by considering the antecedent rainfall at around 61st day and that obtained without considering it is about 0.25.
but the difference for the antecedent rainfall at around the 101st day is only 0.22. To conclude, under the similar total amount of antecedent rainfall, the antecedent rainfall which has high intensity but short duration has more significant impacts on sandy slope.

As shown in Figure 10, the minimum safety factor does not occur at the time with the highest rainfall intensity, but at the end of the rainfall process. Hence, the minimum safety factor has no direct relationship with the maximum daily rainfall. Figure 11 shows the relationship between the safety factor of sandy slope and the accumulating rainfall with different durations. The safety factor generally decreases as accumulating antecedent rainfall increases. Hence, the scale value of the right vertical axis is intentionally reversed so that the trend of accumulating antecedent rainfall and the safety factor can be compared conveniently. It is shown that the variation of safety factor is generally consistent with that of 10-day accumulating rainfall. According to the curve of 10-day accumulating rainfall, the accumulating antecedent rainfall at around 63rd day is greater than that at around the 108th day. This is consistent with the observation that the minimum safety factor at around the 63rd day is smaller than that at around the 108th day. Thus, for sandy slope, the 10-day accumulating antecedent rainfall is closely related to the minimum safety factor in this study.

3.3.2. Clayey slope

Similar to the sandy slope, the safety factors of clayey slope considering different durations of antecedent rainfall are calculated and are plotted versus time in

![Figure 11. Relationship between the safety factor of sandy slope and the accumulating rainfall with different durations.](image-url)

Figure 11. Relationship between the safety factor of sandy slope and the accumulating rainfall with different durations.

(1) When the duration of antecedent rainfall exceeds 40 days, curves of safety factor tend to be stable, indicating that more than 40-day antecedent rainfall shall be considered to obtain reasonable estimates of safety factor for clayey slope.

(2) The safety factors at the end of the 63rd day and the 108th day are the minimum values during the rainfall process at around 61st day and 101st day, which is the same as the observation obtained from the sandy slope. When the duration of antecedent rainfall exceeds 20 days, the minimum safety factors are almost the same. In other words, the minimum safety factor obtained by considering 20-day antecedent rainfall is stable, while the safety factor considering less than 20-day antecedent rainfall cannot reflect the real safety margin of slope stability. It is suggested using 20-day antecedent rainfall in the engineering application.

(3) Comparing the overall trend of the safety factor varying with time, the difference in safety factors of clayey slope considering different durations of antecedent rainfall is greater than that of sandy slope. In other words, the influence of antecedent rainfall on clayey slope is more significant than that on sandy slope.

(4) Comparing the difference between the safety factors obtained by considering the antecedent rainfall at around the 61st day and the 101st day, respectively, and that obtained without considering them, it is found that the influence of antecedent rainfall at
around the 101st day on the slope stability is greater than that at around the 61st day. Hence, the antecedent rainfall in a long term and with a low intensity has more significant influence on stability of the clayey slope. This is different from the case of the sandy slope.

Figure 13 shows the relationship between the safety factor and the accumulating antecedent rainfall of different durations. It is found that the variation of safety factor is generally consistent with the variation of 15-day accumulating antecedent rainfall. When the 15-day accumulating antecedent rainfall reaches the peak, the minimum safety factor is obtained. When the 15-day accumulating antecedent rainfall decreases, the safety factor of the clayey slope increases. As shown in Figure 13, the accumulating antecedent rainfall at around the 108th day is greater than that at around the 63rd day, and the safety factor at the 108th day is smaller than that at the 63rd day. Thus, for clayey slope, the 15-day accumulating antecedent rainfall is closely related to the minimum safety factor.

4. Conclusions
This paper investigated effects of initial condition and antecedent rainfall on slope stability based on the daily rainfall data in the Three Gorges Reservoir Area. Several conclusions are drawn from this study:

(1) The initial condition of the transient seepage analysis is important for the slope stability analysis. It is suggested using the pore water pressure distribution...
obtained from the steady seepage analysis under the average annual rainfall as the initial condition for the transient seepage analysis if there are no observation data.

(2) The influence of antecedent rainfall on the slope stability becomes more and more significant as the permeability coefficient of the soil decreases. For sandy and clayey slopes, the influence of antecedent rainfall on slope stability becomes minimal as the 30-day and 40-day antecedent rainfalls are considered, respectively. To obtain reasonable safety factor of sandy and clayey slopes, 30-day and 40-day antecedent rainfall shall be considered in the analysis.

(3) As for the minimum safety factor after a heavy rainfall, the safety factor calculated by considering antecedent rainfall less than 15 days for sandy slope and 20 days for clayey slope cannot reflect the real safety margin of slope stability.

(4) Under the similar amount of total antecedent rainfall, antecedent rainfall in a short duration and with a high intensity has more significant impacts on the sandy slope, while antecedent rainfall in a long duration and with a low intensity affects the clayey slope more significantly.

(5) The accumulating antecedent rainfall can be related to the minimum safety factor of slope stability. The time when the minimum safety factor occurs is close to those corresponding to the maximum 10-day and 15-day accumulating antecedent rainfall for sandy and clayey slopes, respectively.

Disclosure statement
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References


