

Evaluation of Treatment Effects of Jinpingzi Landslide Zone II Control Using Precipitation Influence Factor

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Abstract. The concentrated precipitation has a great influence on the stability and deformation rate of the landslide in rainy season. The conventional methods often take the variation curves of total landslide deformation displacement, rate, and the anti-slide construction deformation or stress as indicators to evaluate the effect of the landslide control. But the precipitations are different in each year, which may affect the accuracy of the evaluation. Therefore, a reasonable indicator which is not dependent on the precipitation have to put forward. Based on the statistics of precipitation and deformation rate of Jinpingzi landslide in Wudongde hydropower station, the relationship between them has been concluded. And the precipitation influence factor of each year has been calculated and compared separately to evaluate the landslide control effect of Jinpingzi zone II. It is a new method which can be applied in hazard forecast based on weather forecast. The research results have important reference value for the same type landslides in this area.

1. Introduction

In recent years, landslides frequently happen in China. The National Bureau of Statistics [1] reported 196,956 landslides from 2004 to 2013, making it the dominant geological hazard in China, which accounted for around 72% of total geological hazards (Fig. 1). According to the statistics in reference [2], precipitation-induced landslides took up 70% of total landslides, and about 95% of the landslides happened in rainy season. Hence, precipitation-induced landslide is the focus in the research on landslides. A large number of scholars studied the causal mechanism [3], stability evaluation [3], and effect of precipitation on landslide [4], prediction and forecast system [5], etc. for precipitation-induced landslides. With different models and indicators, they explored the effect of precipitation on the stability and deformation rate of landslide. Additionally, some scholars studied the engineering treatment effect of precipitation-induced landslides by analyzing and monitoring the sliding surface displacement curve, pile-top deformation of anti-slide supporting and retaining structure, anchor cable stress curve, surface crack observation, and other data. Nevertheless, precipitation-induced landslide is affected significantly by precipitation, while precipitation varies dramatically in most regions, especially southwest region [10]. For this reason, the data from monitoring cannot be compared



longitudinally, so it is impossible to evaluate them in a completely objective manner. Under this circumstance, this paper presents a statistical analysis on the data from long-term monitoring of Jinpingzi landslide zone II at Wudongde hydropower station, including precipitation and deformation rate. By combining the geological conditions for the landslide and the measures for engineering treatment, this paper explores the relationship between the factors related to annual precipitation and the deformation rate of Jinpingzi landslide, and proposes an influence factor representing the state of landslide deformation, which relates to both annual precipitation and landslide deformation characteristics. After comparing the conditions before and after the application of this factor in the landslide treatment, the treatment effect of landslide is objectively evaluated.

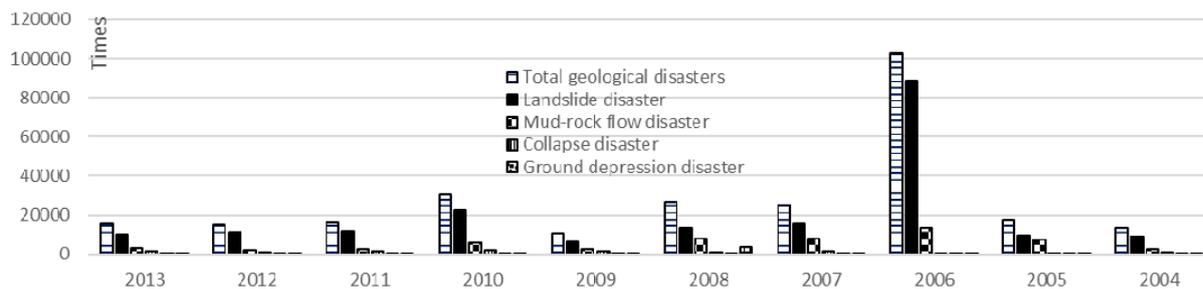


Figure 1. Frequency of various geological disasters in China from 2004 to 2013

2. Geological Characteristics of the Landslide

2.1. Overview of the Landslide

According to the survey [7], Jinpingzi landslide is a gigantic landslide at the dam site of Wudongde hydropower station in the lower Jinsha River valley. The landslide is divided into five zones (Fig. 2), i.e. bedrock meander core at the front edge near the river (Zone V); bedrock beam in the middle (Zone IV); creeping deformation body above bedrock beam (Zone I); creeping deformation body to the west of bedrock beam (Zone II); Jinpingzi ancient landslide deposit body under bedrock beam (Zone III). Among them, the volume of Zone II subject to creeping deformation is around $2700 \times 10^4 \text{m}^3$.



Figure 2. Image of Jinpingzi landslide

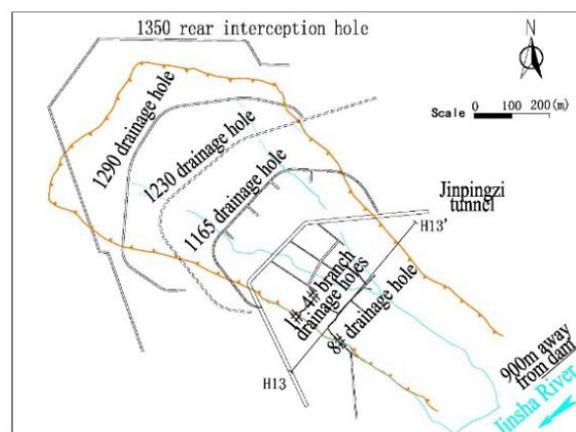


Figure 3. Layout of underground drainage system in zone II

The treatment of Jinpingzi landslide Zone II is a key project in the construction of Wudongde hydropower station by implementing the surface water and groundwater interception and drainage works. Among them, the most important works must be underground drainage works, including 1350

rear interception hole, 1290 drainage hole, 1230 drainage hole, 1165 drainage hole as well as 4 branch drainage tunnels and 8# drainage hole inside Jinpingzi tunnel (see Fig. 3). By the end of 2015, 1350 rear interception hole had been completely excavated; 1290 elevation drainage hole had excavated the supporting and retaining surface by 726.25m, around 72.5% completed; 1165 elevation drainage hole had excavated the supporting and retaining surface by 688.75m, around 86.1% completed; the JS01~JS04 branch drainage holes inside Jinpingzi tunnel had been all completed, and started drainage through drain ports; 8# drainage hole had played a role in the drainage [7].

2.2. Basic Geological and Hydrogeological Characteristics

The landslide Zone II is around 1,200m long and 275m-591m wide, and has the elevation from 880m to 1480m. On its upper and lower sides, it is connected to bedrock and Abai Large Ditch in Zone IV respectively. The deposit body in Zone II is thick in the front, normally 90m~130m, and thin in the rear, normally 45m~60m.

The deposit body in Zone II is divided into 4 layers from top to bottom (Fig. 4): ① collapse block stone layer (Q^{col}), loose; ② phyllite fragment and soil layer (Q^{del}), moderately dense; ③ phyllite fragmentary soil (sliding belt, del), dense; ④ ancient gulch fragment stone, gravel and soil, loose~moderately dense (Q^{pl+col}).

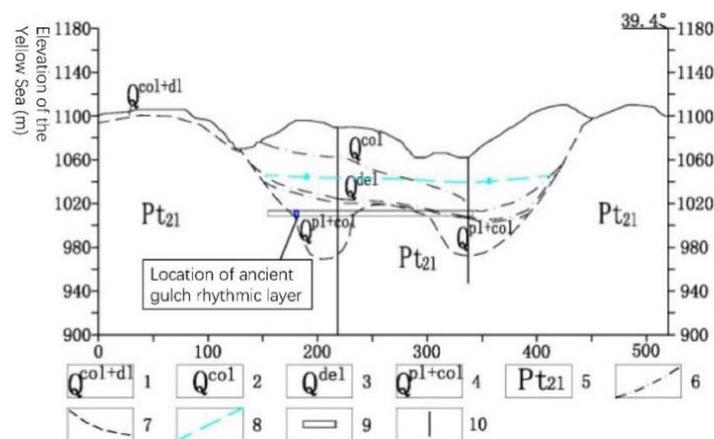


Figure 4. H13-H13' Geological section

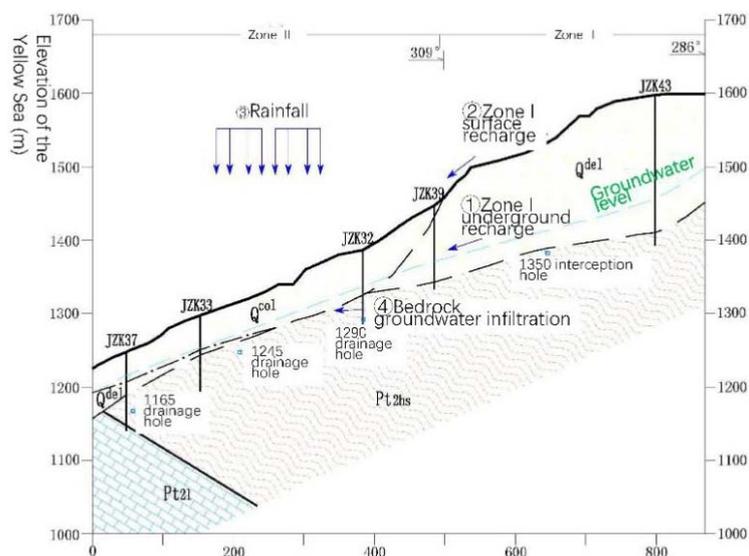


Figure 5. Recharge, run-off and drainage characteristics

The underlying bedrock is Middle Proterozoic Heishan formation phyllite in the middle rear, and Luoxue formation dolostone and marble-converted dolostone in the middle front. The longitudinal slope of bedrock surface is normally $18^{\circ}\sim 36^{\circ}$. The underlying bedrock surface is intersected by 2 ancient gulches to form the “two-gulch one-beam” groove.

3. Analysis of Precipitation Influence on Landslide Deformation

3.1. Factors Affecting Landslide Stability and Deformation Rate

The deformation rate of landslide is normally affected by such factors as rainfall, groundwater recharge, reservoir water level, earthquake and people's production and living activities. The front bedrock covering surface of Jinpingzi landslide Zone II has the elevation of around 880m, but the normal water level of Jinsha River at the position is around 810m~840m for years, so it is much higher than the water level of the river. In this case, the fluctuation of reservoir water level has no influence on its stability and deformation rate.

The groundwater recharge sources of Jinpingzi landslide Zone II include groundwater recharge from Zone I behind Zone II, surface water recharge from Zone I, rainfall, and groundwater recharge from bedrock in the rear of Zone II. Among them, the groundwater and surface water in Zone I mainly comes from rainfall in Zone I. Hence, the groundwater recharge for Zone II eventually relies on the rainfall in Zone I and Zone II.

As Jinpingzi Zone II receives the continuous groundwater recharge from Zone I, the soil in the sliding belt of landslide Zone II is saturated for years. In rainy season, rainfall affects the stability and deformation rate of landslide in two aspects: 1. The rising groundwater level inside sliding body increases the volumetric weight of sliding body; 2. The dynamic water pressure arising from infiltration and discharge of precipitation lowers the stability of landslide (Equation 1), resulting in higher deformation rate.

$$K = \frac{W \cos \theta \tan \varphi + cA}{W \sin \theta} \quad (1)$$

In which, K is stability coefficient; W is volumetric weight of sliding body; A is area of sliding belt; θ is inclination of sliding belt; φ is internal friction angle of soil in sliding belt; c is cohesion of soil in sliding belt.

3.2. Positive Correlation between Deformation Rate of Jinpingzi Landslide Zone II and Precipitation

Jinpingzi landslide Zone II is provided with 15 surface displacement monitoring points, which are evenly arranged in the front, middle and rear of landslide body (Fig. 6).

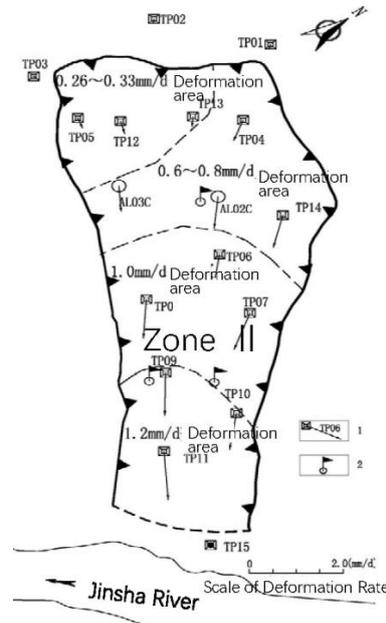


Figure 6. Surface deformation monitoring layout

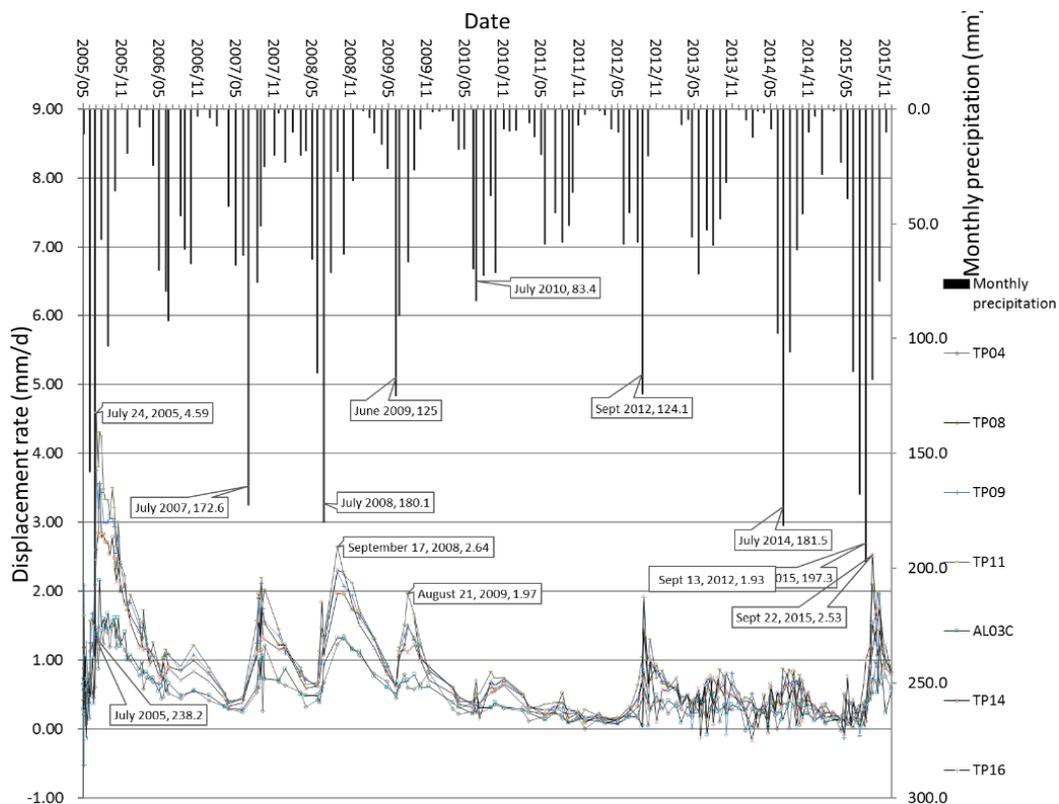


Figure 7. Correlation between deformation rate and monthly precipitation

The surface deformation monitoring and rainfall observation started in May 2005. After analyzing the data gathered for years (Fig. 7), the relationship between landslide deformation rate and precipitation is concluded as follows:

(1) In the past 11 years, the precipitation at Jinpingzi ranged from 300mm to 775mm, and the rainy season normally extended from June to October. It rained most frequently in July, August and September, and the highest monthly precipitation normally happened in July.

(2) Landslide deformation rate often started rising in June and reached its peak in September. Subsequently, it decreased in October and hit the bottom in next April-June. Moreover, higher precipitation led to larger deformation rate. For this reason, there is the significantly positive correlation between the deformation rate of Jinpingzi landslide Zone II and precipitation.

4. Precipitation Influence Factor of Landslide Deformation Rate

4.1. Rate Variation Process

At present, Jinpingzi landslide Zone II is in the phase of creeping deformation on the whole. As the concentrated precipitation exists in Jinpingzi region and there is basically no precipitation in dry season, this paper studies the varying landslide deformation rate caused by the increased volumetric weight of sliding body after precipitation due to the positive correlation between deformation rate and precipitation. Hence, the variation is divided into 3 periods:

(1) Ancient landslide is reactivated under the effect of a heavy precipitation, while the volumetric weight of sliding body increases due to precipitation. The infiltration of precipitation may result in dynamic water pressure, lowering the stability of landslide. Since sliding force is stronger than sliding resistance force, the sliding body moves at an increasing speed. When the heavy precipitation ends (normally in rainy season), the sliding body keeps a certain deformation rate.

(2) When it is dry season, the external force caused by rainfall to landslide deformation disappears or weakens. At this time, sliding force is weaker than sliding resistance force, so the stability is improved, and the deformation rate of landslide starts decreasing.

(3) When the next rainy season starts, rainfall exerts an effect on the landslide again. When sliding force exceeds sliding resistance force again, the deformation rate of landslide starts increasing till the end of the rainy season. The alternation between rainy season and dry season results in the periodical increase and decrease of landslide deformation rate constantly, as shown in Fig. 7 and Fig. 8.

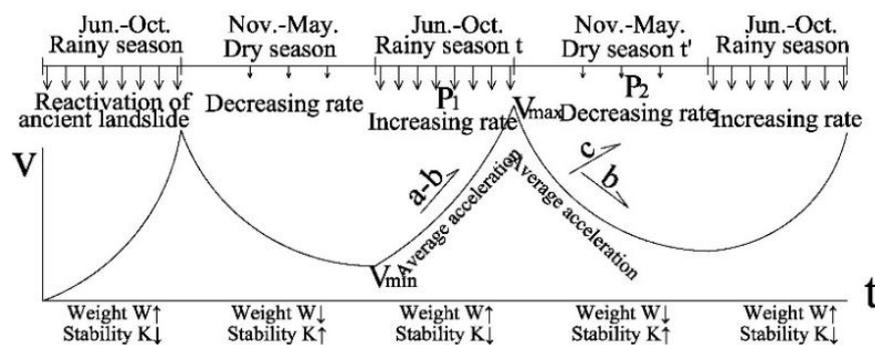


Figure 8. Generalized diagram of the landslide deformation rate variation process

In which, a is defined as the acceleration caused by the total precipitation in the rainy season of the year to the deformation rate of landslide body (unit: mm/d^2);

b is defined as the acceleration caused by the adjustment of landslide body to the decreasing rate in the full year (unit: mm/d^2);

c is defined as the acceleration caused by the total precipitation in the dry season of the year from November to next May to the deformation rate of landslide body (unit: mm/d^2).

Based on Equation (1), it is deduced that:

$$a-b = \frac{W_1 \sin \theta - W_1 \cos \theta \tan \varphi - cA}{W_1} * g \quad (2)$$

$$b = \frac{W_2 \cos \theta \tan \varphi + cA - W_2 \sin \theta}{W_2} * g \quad (3)$$

$$a = \frac{cA(W_1 - W_2)}{W_1 W_2} * g \quad (4)$$

In the above equations, W_1 is volumetric weight of sliding body in rainy season; W_2 is volumetric weight of sliding body in dry season; and g is the gravitational acceleration.

4.2. Influence Factor Representing the State of Landslide Deformation

The deformation rate of landslide body goes up when the rainy season starts (in June), and begins to decrease when the rainy season is about to end (in October) until the next rainy season starts, as shown in Fig. 8. Based on the overlapping of rate at the mass point, the following equations can be obtained:

(1) The period from the start of rainy season to the end of rainy season:

$$v_{\min} + (a - b)t = v_{\max} \quad (5)$$

(2) The period from the end of rainy season to the start of the next rainy season:

$$v_{\max} - bt' + ct' = v_{\min}' \quad (6)$$

(3) λ is defined as the influence factor of precipitation to the deformation rate of landslide body during the precipitation process (including rainy season and dry season), i.e. the acceleration of the deformation rate of landslide body under the effect of each millimeter of precipitation (unit: mm/(d²*mm)), so there is:

$$\lambda = a / P_1 \quad (7)$$

$$\lambda = c / P_2 \quad (8)$$

In which, v_{\min} is the minimum deformation rate before the rainy season in the first year (unit: mm/d), which is normally the deformation rate in June;

v_{\max} is the maximum deformation rate during the rainy season in the first year (unit: mm/d), which is normally the deformation rate in September;

v_{\min}' is the minimum deformation rate before the rainy season in the second year (unit: mm/d);

t is the time period when the rate goes up, i.e. the period of rainy season (unit: d);

t' is the time period when the rate goes down, i.e. the period from the end of the rainy season in the first year to the start of the rainy season in the second year (unit: d);

P_1 is the total precipitation in the rainy season of a year (June to October) (unit: mm);

P_2 is the total precipitation in the period from the end of the rainy season in the first year to the start of the rainy season in the second year (November to next May) (unit: mm).

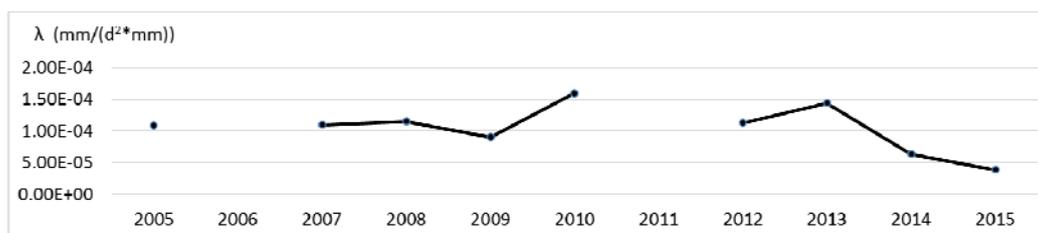
Through the analysis and statistics of the relevant data regarding Jinpingzi landslide Zone II from 2005 to 2015 (the data in 2006 and 2011 were not included as there were not enough data available), the precipitation influence factor in each year is calculated as presented in Table 1.

Table 1. Precipitation influence factors over the years of the Jinpingzi landslide zone II

| Year | When to Start | When to End | v_{max} (mm/d) | v_{min} (mm/d) | t (d) | t' (d) | P ₁ (mm) | P ₂ (mm) | a (mm/d ²) | b (mm/d ²) | c (mm/d ²) | λ (mm/(d ² *mm)) |
|-------------------------|----------------|----------------|---------------------|---------------------|----------|-----------|------------------------|------------------------|---------------------------|---------------------------|---------------------------|--|
| Rainy season in 2005 | Jun. 19, 2005 | Oct. 9, 2005 | 3.50 | 0.49 | 112 | / | 474.00 | / | 0.0513 | / | / | 1.0824E-04 |
| Dry season in 2005~2006 | Oct. 9, 2005 | May 29, 2006 | 3.50 | 0.80 | / | 232 | / | 118.20 | / | 0.0244 | 0.0128 | |
| Rainy season in 2007 | Jun. 23, 2007 | Sept. 21, 2007 | 2.19 | 0.44 | 90 | / | 362.70 | / | 0.0397 | / | / | 1.0957E-04 |
| Dry season in 2007~2008 | Sept. 21, 2007 | Apr. 19, 2008 | 2.19 | 0.64 | / | 211 | / | 118.20 | / | 0.0203 | 0.0130 | |
| Rainy season in 2008 | Jun. 14, 2008 | Sept. 17, 2008 | 2.64 | 0.67 | 95 | / | 393.30 | / | 0.0452 | / | / | 1.1497E-04 |
| Dry season in 2008~2009 | Sept. 17, 2008 | Jun. 25, 2009 | 2.64 | 0.61 | / | 281 | / | 150.10 | / | 0.0245 | 0.0173 | |
| Rainy season in 2009 | Jun. 25, 2009 | Sept. 19, 2009 | 1.66 | 0.61 | 86 | / | 254.80 | / | 0.0230 | / | / | 9.0075E-05 |
| Dry season in 2009~2010 | Sept. 19, 2009 | Apr. 21, 2010 | 1.97 | 0.30 | / | 214 | / | 48.70 | / | 0.0107 | 0.0044 | |
| Rainy season in 2010 | Jun. 28, 2010 | Sept. 15, 2010 | 0.83 | 0.30 | 79 | / | 200.10 | / | 0.0320 | / | / | 1.5973E-04 |
| Dry season in 2010~2011 | Sept. 15, 2010 | Jun. 8, 2011 | 0.83 | 0.35 | / | 266 | / | 146.80 | / | 0.0253 | 0.0234 | |
| Rainy season in 2012 | May 23, 2012 | Set. 23, 2012 | 1.44 | 0.12 | 123 | / | 296.00 | / | 0.0334 | / | / | 1.1275E-04 |
| Dry season in 2012~2013 | Sept. 23, 2012 | Jun. 20, 2013 | 1.44 | 0.17 | / | 270 | / | 159.10 | / | 0.0226 | 0.0179 | |
| Rainy season in 2013 | Jun. 20, 2013 | Sept. 22, 2013 | 0.87 | 0.17 | 94 | / | 178.30 | / | 0.0257 | / | / | 1.4401E-04 |
| Dry season in 2013~2014 | Sept. 22, 2013 | Jun. 14, 2014 | 0.87 | 0.34 | / | 265 | / | 112.70 | / | 0.0182 | 0.0162 | |
| Rainy season in 2014 | Jun. 14, 2014 | Aug. 21, 2014 | 0.87 | 0.34 | 68 | / | 309.80 | / | 0.0196 | / | / | 6.3203E-05 |
| Dry season in 2014~2015 | Oct. 10, 2014 | Jun. 9, 2015 | 0.78 | 0.13 | / | 242 | / | 138.10 | / | 0.0118 | 0.0087 | |
| Rainy season in 2015 | Jun. 9, 2015 | Oct. 16, 2015 | 1.98 | 0.13 | 129 | / | 668.60 | / | 0.0257 | / | / | 3.8493E-05 |
| Dry season in 2015~2016 | Oct. 16, 2015 | Jan. 20, 2016 | 1.98 | 0.94 | / | 96 | / | 14.60 | / | 0.0114 | 0.0006 | |

5. Evaluation of Landslide Treatment Effect Based on Precipitation Influence Factor

Jinpingzi landslide Zone II treatment project started engaging in drainage gradually in October 2013. Before the underwater drainage project began drainage, the precipitation influence factor was normally $9.0 \times 10^{-5} \sim 1.6 \times 10^{-4}$, and 1.2×10^{-4} on average. After October 2013, the precipitation influence factor decreased dramatically, and reached 6.3×10^{-5} in 2014. As drainage holes were constantly excavated and played a role in drainage, the precipitation influence factor was further lowered to 3.8×10^{-5} in 2015, as shown in Fig. 9.

**Figure 9.** Variation of precipitation influence factors over the years of the Jinpingzi landslide zone II

Through the continuous implementation of underground drainage system, the precipitation influence factor was lowered significantly. This reveals that, after the underground drainage project in Jinpingzi landslide Zone II started playing a role in drainage, the sensitivity of landslide deformation rate to precipitation was reduced. In other words, the stability of landslide was improved, and the treatment project under construction had achieved the preliminary effect.

6. Conclusion

Considering the geological characteristics of Jinpingzi landslide Zone II, this paper analyzes the main factors affecting the deformation of landslide, and puts forward the positive correlation between landslide deformation rate and precipitation. Based on the periodical variation law of landslide displacement rate and the rate overlapping, the relationship between landslide displacement rate and precipitation is concluded. Using the data from 2,152 times of monitoring at 15 displacement monitoring points on the landslide surface from May 2005 to December 2015, and the results of observation with rainfall recorder at Jinpingzi for 128 months, this paper proposes an influence factor representing the state of landslide deformation, which relates to both annual precipitation and landslide deformation characteristics, so as to evaluate the effect of Jinpingzi landslide Zone II treatment project. Before the treatment project was implemented, the precipitation influence factor was normally $9.0 \times 10^{-5} \sim 1.6 \times 10^{-4}$, and 1.2×10^{-4} on average. Since the excavation of drainage holes was commenced in October 2013, the precipitation influence factor decreased dramatically as these drainage holes started drainage gradually, and reached 6.3×10^{-5} in 2014. Along with the progress of the project, the precipitation influence factor was further lowered to 3.8×10^{-5} in 2015. Additionally, the dramatic decrease of this influence factor after landslide treatment proved that the landslide treatment project had achieved the preliminary effect.

This study offers an approach to evaluate the engineering treatment effect of precipitation-induced landslide. Moreover, after consulting many scholars' studies on the warning threshold of landslide deformation rate [14], and gathering the data of landslide deformation rate and precipitation within a certain period to calculate the average and maximum values of precipitation influence factor in the period, the rate warning threshold can be set to calculate the warning annual precipitation in turn. As rainy and dry seasons are distinct in the southwest region, and rainy season is normally in June-October, the warning annual precipitation can be used to further obtain the warning monthly precipitation. Hence, this approach can be promoted and applied in the prediction, forecast, and risk level evaluation of landslide disaster on the basis of weather forecast.

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