Geotech Geol Eng (2018) 36:469–482
https://doi.org/10.1007/s10706-017-0340-7

ORIGINAL PAPER

Identifying the Main Control Factors for Different Deformation Stages of Landslide

Fulin Tan · Xinli Hu · Chuncan He · Yuming Zhang · Han Zhang · Chang Zhou · Qiang Wang

Received: 14 October 2016 / Accepted: 14 August 2017 / Published online: 5 September 2017

Abstract Water level fluctuations and rainfall, as external factors, are typically the two dominant causal factors of landslide deformation in the Three Gorges Reservoir Area. A quantitative model capable of evaluating landslide deformation processes is critical for early warning of landslide. The primary purpose of this paper is to take the Zhujiadian landslide as an example to determine the main control factors for different deformation stages of landslide. Original field date collected from the Zhujiadian landslide was examined using the grey relational grade analysis (GRGA). The approach consists of three steps: determination of landslide type, data processing, and identifying the main control factors of landslide deformation. The results obtained suggest that the Zhujiadian landslide is typical retrogressive landslide, and its deformation occurred first at the front part of the landslide and progressed upslope due to drawdown of reservoir water level and heavy rainfall. In the whole deformation process, the main control factors of different parts of landslide changed with the landslide development. Thus, the findings of the study are useful for rapidly predicting landslide deformation relating to water level fluctuations and rainfall, and the GRGA is useful for interpreting the main control factors of landslide deformation from a quantitative point of view.

F. Tan · X. Hu (✉) · C. He · Y. Zhang ·
H. Zhang · C. Zhou · Q. Wang
Faculty of Engineering, China University of Geosciences, Wuhan 430074, Hubei, People's Republic of China
e-mail: huxinli@cug.edu.cn;
1044671318@qq.com

Keywords Landslide deformation · Water level fluctuations · Rainfall · GRGA

1 Introduction

A large number of landslide geological disasters are induced by reservoir water storage in the reservoir area. The water-related events provide favorable external conditions for landslide development. Generally, rainfall and water level fluctuations are the two dominant impact factors on the landslide deformation (Genevois and Ghirotti 2005; He et al. 2008; Wang et al. 2008; Hu et al. 2013; Xia et al. 2013; Huang et al. 2014; Ma et al. 2016; Singh et al. 2016; Sharma et al. 2017a, b). Figure 1 is the schematic diagram of landslide system under the coupled action of rainfall and reservoir water level fluctuations in the Three Gorges Reservoir Area. The data of reservoir water level and rainfall were from the official database. The reservoir water level fluctuates between 145 and 175 m each year periodically. As a result, there are more than 5300 landslides that have been found in this reservoir area (Yi et al. 2011). After the reservoir operating, some well-known landslides occurred, for instance, Qianjiangping landslide in Zigui County,

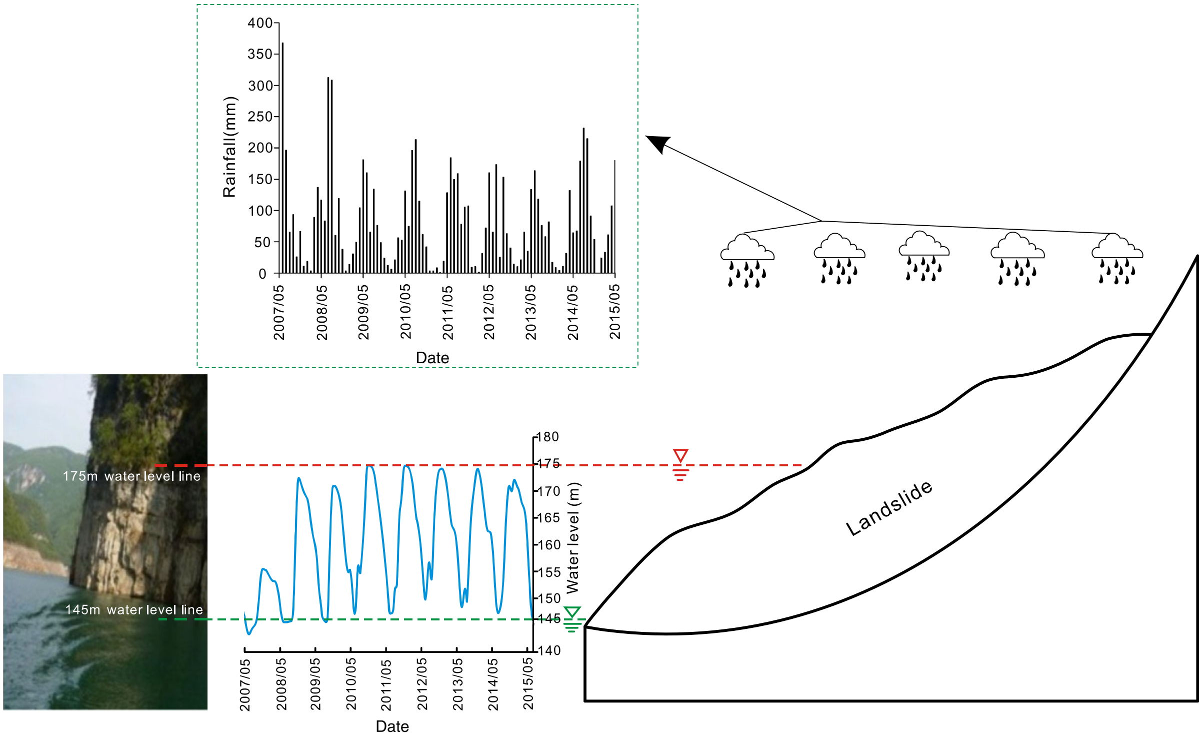


Fig. 1 The schematic diagram of landslide under the coupled action of water level fluctuations and rainfall in the Three Gorges Reservoir Area

which was caused by the water level fluctuations and the heavy rainfall (Cojean and Cai 2011). Therefore, in order to be able to achieve effective control of the landslides, some researchers studied the deformation characteristics and failure modes of the landslides and evaluated the stability of the landslides under the action of rainfall and water level fluctuations (Rahardjo et al. 2001; Jian et al. 2014; Kulatilake and Ge 2014; Tang et al. 2015; Hsieh et al. 2016; Sharma et al. 2017a, b; Umrao et al. 2017). Meanwhile, the method based on the field monitoring is another effective and practical way to reveal the deformation of landslide (Massey et al. 2013; Palis et al. 2016; Wang et al. 2016). The field monitoring is a powerful means which can provide detailed data to understand and express the kinematic aspects of landslide deformation. The result analyzed with the monitoring field data is much more reliable and accurate.

However, most previous studies focused on the effects of water level fluctuations and rainfall on the whole stability of landslide. With the time going, many researchers found that the concept of progressive failure might explain the real deformation process of the landslide (Tang 2008; Khan and Lateh 2011; Troncone et al. 2014; Lu 2015; Samaneh and Hossein 2016; Song and Cui 2016). The current study on the effects of reservoir water levels and rainfall on the deformation of different parts of landslide is rarely reported in the literature. In addition, the complex relationships between hydrologic factors and landslide deformation are difficult to express using conventional analysis methods (Yao et al. 2015).

In this paper, the Zhujiadian landslide in the Three Gorges Reservoir Area was taken as example. An integrated monitoring system has been installed to measure the deformation of landslide. Historical records of landslide deformation, precipitation and reservoir levels are analyzed using the grey relational grade analysis (GRGA). The relationships between hydrologic factors and the deformation of different parts of landslide are expressed using definite mathematical method. This research can provide reference for landslide monitoring analysis and early warning.

2 Geological Setting of Zhujiadian Landslide

The Zhujiadian landslide is located on the left bank of the Yangtze River, approximately 74 km northwest of Three Gorges Dam and 12 km northeast of Badong County, in Hubei Province (Fig. 2). The length of the landslide is approximately 423 m and the width is 60–125 m. The average thickness of the landslide mass is approximately 25 m and its volume is estimated at 1 million m^3. The landslide mass extends from an elevation of 145–330 m, and the sliding direction is approximately perpendicular to the Yangtze River. The landslide surface has an average slope gradient of 35° (Figs. 2, 3, 4).

The geological units and structure of the Zhujiadian landslide were determined from a field investigation and exploration (Hu et al. 2013). This site-specific investigation indicates that the geological units mainly contain superficial deposits, sliding-zone soil, and bedrock (Fig. 4). The superficial deposits involves material of Quaternary age and consists of three layers from the surface to the bottom of the sliding mass: arable soil, colluvium deposit and residual deposit. The surface of the sliding mass is arable soil with a thickness of 1–2 m. The colluvium deposit is 5–10 m thick and is composed of silty clay and gravel clasts. The gravel soil are 0.2–2 m in diameter and represent up to 70% of this layer by weight. The bottom of the sliding mass is residual deposit with a thickness of 10–15 m and consists of silty clay and gravel clasts with diameters of 0.1–0.5 m. The boreholes indicate that the sliding zone is approximately 0.1–0.3 m thick and is between the superficial deposit and the bed rock. This sliding zone is composed of 90% silty clay and 10% gravel clasts. The bedrock of landslide mainly consists of purple-red argillaceous siltstone and gray marlite of the Badong Formation with an average dip direction of 20° and a dip angle of 16°. Consecutive failures occur preferentially in the sliding-zone soil because the strength of the sliding zone soil is even lower than superficial deposits and bedrock.

By the means of field investigation, 4 cracks numbered C1, C2, C3 and C4 were found, approximately parallel to the Yangtze River and perpendicular to the sliding direction. Crack C1 with an elevation of 208 m, was first found in June 2010 after a period of heavy rainfall. Now the crack C1 is about 160 m long, 5–12 cm wide, and accompanied with obviously ground surface subsidence before crack (Figs. 3, 4, 5a). Crack C2 was first found at the same time as crack C1 with an elevation of 202 m. Its length is about 42 m and its width is 7–11 cm (Figs. 3, 4, 5b). Crack C3 with an elevation of about 195 m, is at the edge of the landslide. It have expanded to a length of 40 m and a width of 5–8 cm (Figs. 3, 4, 5c). The largest and earliest crack, C4, was first found in May 2009. It was

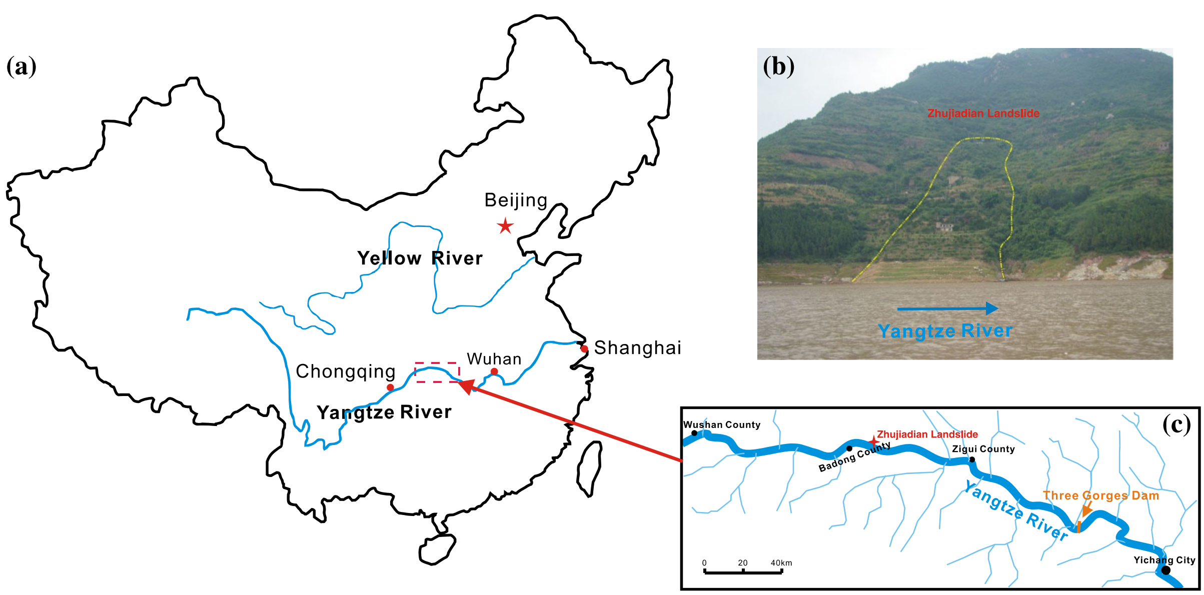
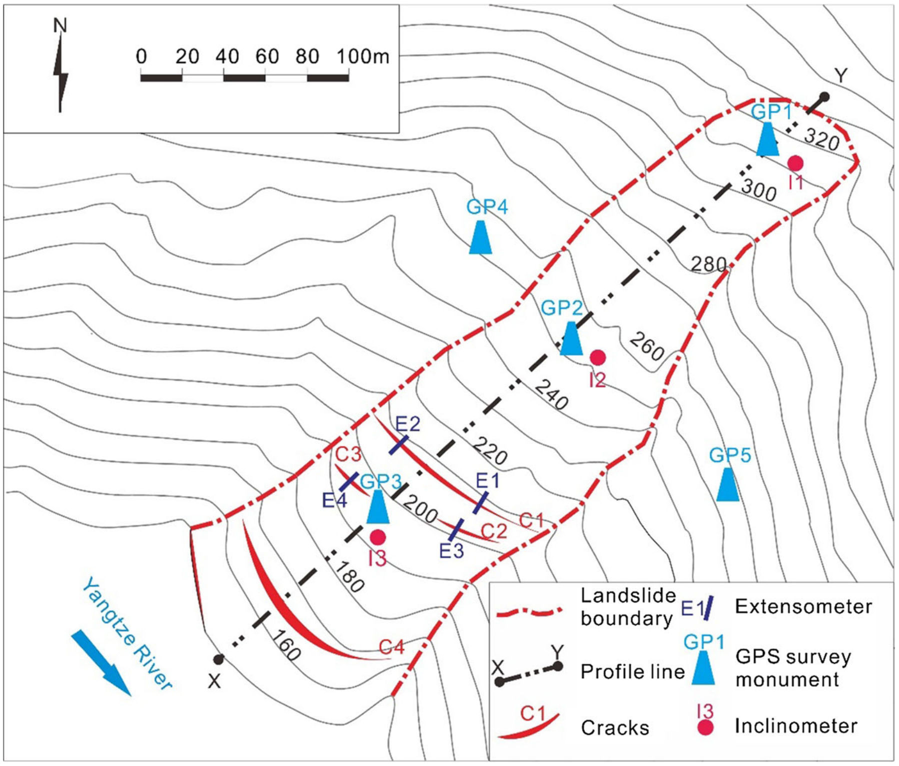


Fig. 2 Location of the Zhujiadian landslide, Three Gorges Reservoir area, China (**a**, **c**) and a photograph of the Zhujiadian landslide taken from opposite bank facing north (**b**)

Fig. 3 Topographic map of the Zhujiadian landslide showing locations of monitoring works



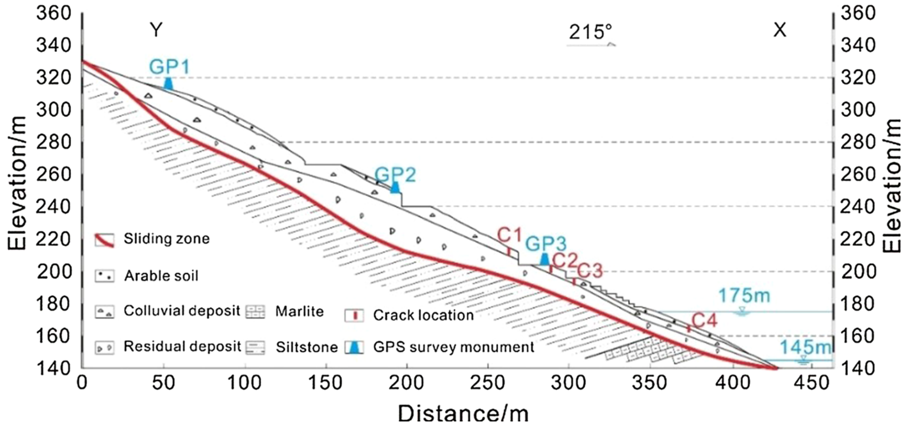


Fig. 4 Geological profile along section X–Y showing locations of monitoring works (see Fig. 3 for location)

Fig. 5 Cracks in the landslide. **a** Crack C1, **b** crack C2, **c** crack C3, **d** crack C4

almost closed and had a length of 155 m and a vertical displacement of 650 mm (Figs. 3, 4, 5d). The length and vertical displacement of cracks increase gradually under the action of rainfall and reservoir water level fluctuations. In particular, the serious tilt deformation of GPS monitoring station was caused by crack C3 with a vertical displacement of 7 cm in Jun 2015 after a period of heavy rain.

3 Monitoring of the Zhujiadian Landslide

In order to track the deformation behavior of the landslide, a monitoring system was installed on the Zhujiadian landslide in 2007. This monitoring system consisted of three parts: three inclinometers, four extensometers, five GPS monitoring stations, their locations are shown in Fig. 3. Three GPS survey monuments were located on the landslide (Figs. 3, 4), and two were placed on intact ground nearby. The displacements were surveyed monthly. The cumulative displacements measured at GP1 and GP2 were 9.1 and 13.4 mm respectively from March 2007 to December 2013, while the cumulative displacements measured at GP1 and GP2 were 37.1 and 32.9 mm respectively from March 2007 to Jun 2015. It indicates that the deformation of middle part and back part of the landslide was very small in the early stage and the rate of deformation increases gradually in the late stage. The cumulative displacement measured at GP3 was 2203 mm. It showed clearly that the deformation of the Zhujiadian landslide occurred first at the front of the landslide and progressed gradually to the middle and back parts. Approximately 8 years of monitoring data have been collected. In view of periodic fluctuations in the reservoir water level and the precipitation, the displacement time history can be described as a series of steps consisting of significant displacements at certain periods (periods of heavy rainfall and drawdown of reservoir water level) and moderate deformation during other time periods (Fig. 6).

4 Identifying the Main Control Factors of Landslide Deformation

The mechanisms of landslide deformation can be complex. The landslide deformation is affected by a variety of factors such as basic geological, hydrologic conditions and geomorphic. As a matter of fact, it is far from completely understood how these causal factors combine to affect landslide movements. Even if a clear understanding of landslide mechanisms could be obtained, it would remain difficult to express the complex mechanisms of landslide deformation as a function of the multiple causal factors using simple algebraic models.

However, the relational analysis method as a complementary method is widely used to describe the relational grade between two things in the various fields. Thus, the relational analysis method can be used as a decision tool to interpret the main control factors in different deformation stages of landslide.

4.1 The Grey Relational Grade Analysis (GRGA)

The GRGA is an essential contents of the grey system theory proposed by Deng (1982). This method can be used to solve problems with complicated correlations between multiple factors and variables. Through grey relational analysis, one can obtain the grey relational grade (GRG) to evaluate the correlation of different measurement data. The range of the GRG is 0–1, the closer the value to 1, the higher the correlation of two sequences. Jiang et al. (2016) applied the GRGA to determine the correlation between periodic deformation of landslide, water level and rainfall. Wei et al. (2017) used the GRGA to confirm the main characteristics of rainfall that influenced runoff. Besides, this method has attracted wide attention and was used in various fields (Wang 2011; Kondapalli et al. 2015; Yilmaz 2015; Sylviana et al. 2015; Yin et al. 2015; Sun et al. 2015).

In the present study, the mathematical implementation process of GRGA is mainly divided into five steps in the analysis of response relationship between landslide deformation and causal factors. Four causal factors, i.e., the rainfall intensity, the drawdown rate of reservoir water level, the rise rate of reservoir water level, the coupled change rate of rainfall intensity and reservoir water fluctuation, are considered in this paper. The process is described as follows:

① Determination of calculation sequences. Four causal factors are selected as sub-sequences. Landslide displacement velocity is selected as primary-sequence. X = [X0, X1, X2, X3, X4] = [landslide displacement velocity,

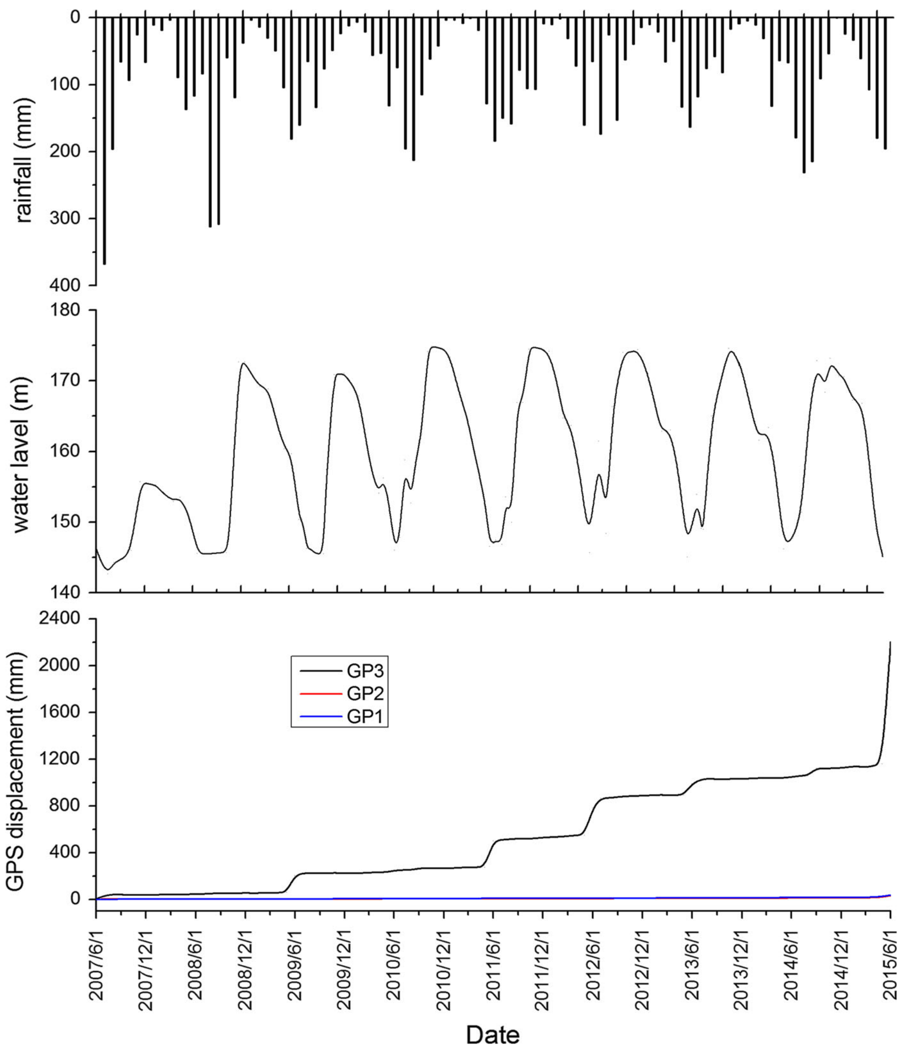


Fig. 6 Time series of landslide displacement at GP1, GP2, GP3 spanning the period of Jun 2007–Jun 2015

monthly rainfall intensity, monthly reservoir water level drawdown, monthly reservoir water level rise, the coupled change rate of rainfall intensity and reservoir water fluctuation].

② Equalization of sequences. According to Eq. (1), the sequences data is equalized.

$$X_i(k)' = X_i(k) / \frac{1}{n}\sum_{k=0}^{n} X_i(k) \quad (1)$$

where $i = 0, 1, \ldots, m$; $k = 0, 1, \ldots, n$; m. the number of influencing factors; n, the number of data points.

③ Calculation of correlation coefficients. Correlation coefficients between primary-sequences (X0) and sub-sequences (X1, X2, X3, X4) can be calculated by Eq. (2).

$$\xi\left(x_0(k)', x_i(k)'\right) = \frac{\min\limits_i \min\limits_k \left|x_i(k)' - x_0(k)'\right| + \rho \max\limits_i \max\limits_k \left|x_i(k)' - x_0(k)'\right|}{\left|X_i(k)' - X_0(k)'\right| + \rho \max\limits_i \max\limits_k \left|x_i(k)' - x_0(k)'\right|} \quad (2)$$

where $\xi(x_0(k)', x_i(k)')$, the correlation coefficients between sequences Xi and sequences Xj; ρ, the resolution coefficient, which normally is selected 0.5.

④ Determination of the GRG. The expressions of the GRG are described as follows:

$$r(x_0, x_i) = \frac{1}{n}\sum_{k=1}^{n} \xi\left(x_0(k)', x_i(k)'\right) \quad (3)$$

⑤ GRG ranking. The GRG represents a numerical measurement of correlation between the primary-sequence and the sub-sequences. The more coincidence those two sequences are, the closer that the value of GRG is to 1. If r (x_0, x_i) > r (x_0, x_j),denoted as {x_i} > {x_j}.

4.2 The Main Control Factors Analysis of Landslide Deformation

Based on the method mentioned above, the analysis process of the main control factors of the Zhujiadian landslide is shown in Fig. 7. This detailed process consists of three steps: determination of landslide type, data processing, and identifying the main control factors of landslide deformation.

① Determination of landslide type

Some previous studies indicated that the rise of reservoir water level and the decrease of reservoir water level act differently on the behavior of the reservoir wading landslides (Luo et al. 2008; Zhao et al. 2013). The reservoir water level increase triggered and accelerated the deformation of some landslides, while the reservoir water level drawdown triggered and accelerated the deformation of other landslides. In order to distinguish the effects of the rise of reservoir water level and the decrease of reservoir water level, we cross-compared the monitoring data during the reservoir fluctuations (Fig. 6). The results show that nearly no deformation occurred in the front part of the landslide during water level increase. In

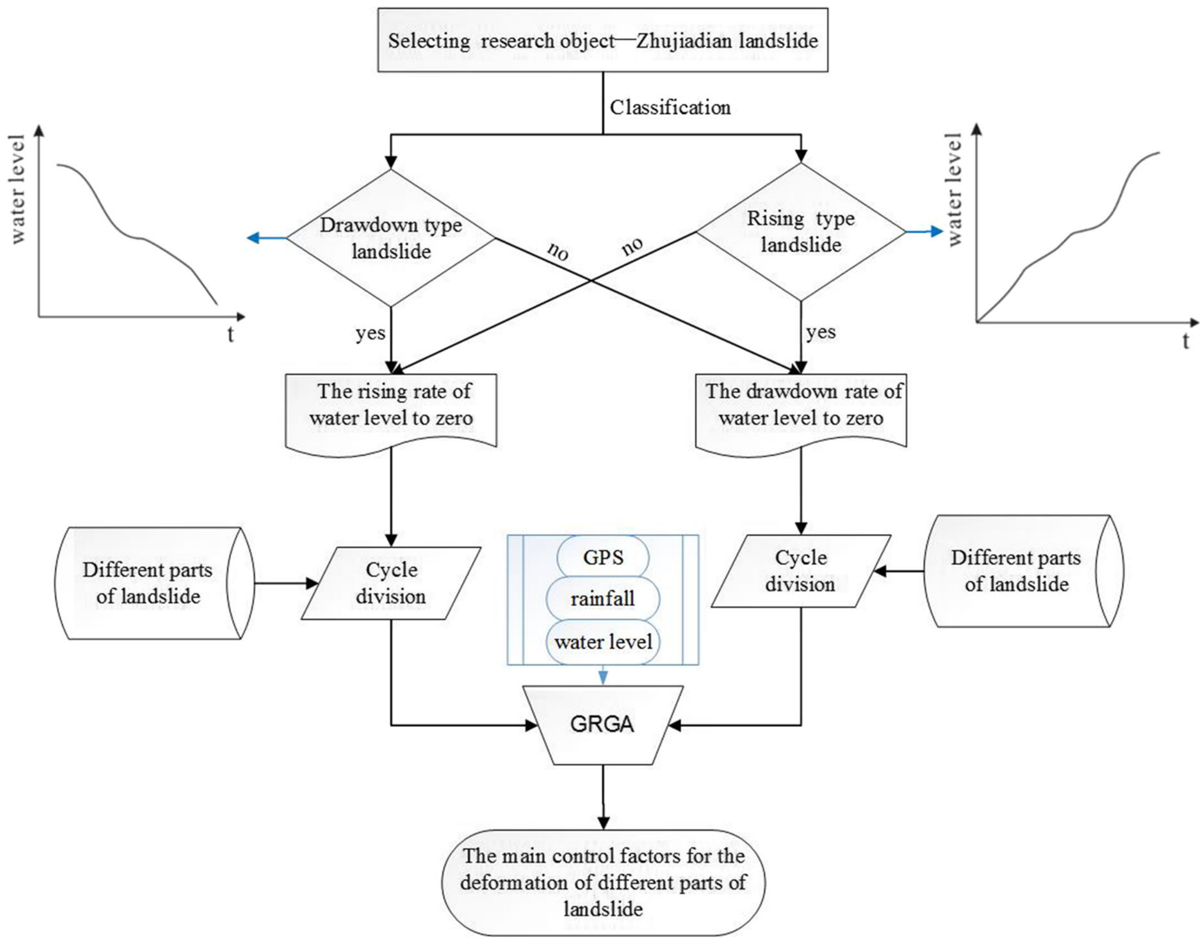


Fig. 7 Flow chart of the main control factors analysis of landside

contrast, the water level drawdown can cause an acceleration of the deformation in the front part of the landslide. It can provide the evidence that the Zhujiadian landslide is water level drawdown type landslide.

② Data processing

The displacements measured at GP1 (GP2, GP3) spanning the period of March 2007 to Jun 2015. In order to better reflect the influence of the dynamic cyclic load caused by reservoir water level fluctuation and rainfall on the landslide deformation, the whole monitoring period is divided into eight cycles (i.e., from June last year to June next year). The cycle division is shown in Fig. 8.

In addition, the displacement of Zhujiadian landslide was surveyed about every month, while the rainfall and the reservoir water level were monitored daily. Because of the different monitoring frequencies, the raw data were preprocessed on a monthly basis. In the present study, the monthly displacement increment at GP1, GP2, GP3, the monthly rainfall intensity, the monthly fluctuation rate of reservoir water level, and the coupled change rate of monthly rainfall intensity and monthly drawdown of reservoir water level were used for the GRGA. Meanwhile, because the Zhujiadian landslide is water level drawdown type landslide, the monthly rise rate in water level was simplified to zero. The result of data processing is shown in Fig. 9.

③ Identifying the main control factors of landslide deformation

The quantitative rules characterizing the relationships between hydrological variables and the deformation of different parts of landslide were shown in Figs. 10, 11, 12. The deformation of Zhujiadian landslide was strongly correlated with reservoir water level drawdown and rainfall. The larger the value of the GRG, the better is the multi-response characteristics. The results show that the order of importance of the causal factors for the deformation of the front part of landslide in the first two cycles is the water level drawdown, the coupled action of rainfall and water level drawdown, rainfall [i.e., $r(x_0, x_2) > r(x_0, x_4) > r(x_0, x_1)$]. After the second cycle, the order of importance of the causal factors for the deformation of the front part of landslide is the coupled action of rainfall and water level drawdown, rainfall, water level drawdown [i.e., $r(x_0, x_4) > r(x_0, x_1) > r(x_0, x_2)$]. However, in the first five cycles, the order of importance of the causal factors for the deformation of the middle part of landslide is rainfall, the coupled action of rainfall and water level drawdown, water level drawdown [i.e., $r(x_0, x_1) > r(x_0, x_4) > r(x_0, x_2)$], while the most important factor of the deformation of the middle part of landslide is the coupled action of rainfall and water level drawdown after the fifth cycle. [i.e., the value of $r(x_0, x_4)$ is maximum]. Likewise, the order of importance of the causal factors for the deformation of the back part of landslide in the six cycles is rainfall, the coupled action of rainfall and water level drawdown, water level drawdown [i.e., $r(x_0, x_1) > r(x_0, x_4) > r(x_0, x_2)$]. After the sixth cycle, the most important factor of the deformation of the back part of landslide is the coupled action of rainfall and water level drawdown [i.e., the value of $r(x_0, x_4)$ is maximum].

From above all, we can conclude that the main control factors of the deformation of different parts of landslide change with the development of landslide (Fig. 13). In the early deformation stage (i.e., from June 2007 to June 2009) of the front part, it indicated that the landslide displacement has significant correlations with reservoir water level drawdown and the water level drawdown was the main control factor of the deformation. In the late deformation stage (i.e.,

Fig. 9 Time series of monthly fluctuation rate of water level, monthly rainfall intensity, coupled factors change rate of monthly rainfall intensity and monthly drawdown in water level, and displacement increment at GP1, GP2, GP3 spanning the period of Jun 2007–Jun 2015 ▶

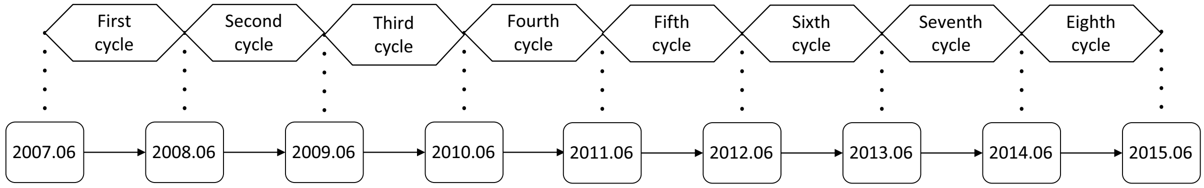
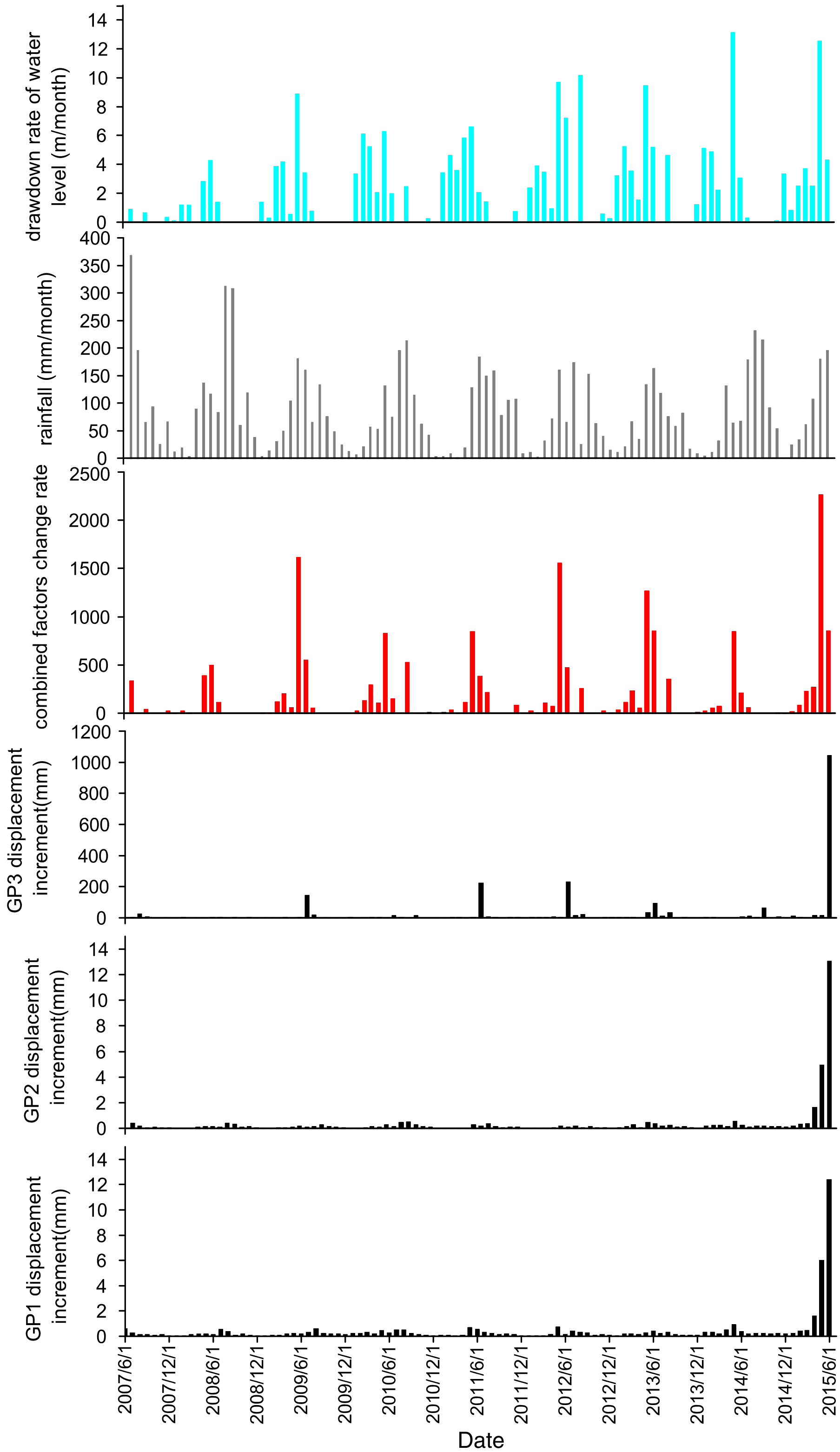


Fig. 8 Eight data monitoring cycle diagram


drawdown rate of water level (m/month)
rainfall (mm/month)
combined factors change rate
GP3 displacement increment(mm)
GP2 displacement increment(mm)
GP1 displacement increment(mm)
2007/6/1
2007/12/1
2008/6/1
2008/12/1
2009/6/1
2009/12/1
2010/6/1
2010/12/1
2011/6/1
2011/12/1
2012/6/1
2012/12/1
2013/6/1
2013/12/1
2014/6/1
2014/12/1
2015/6/1
Date

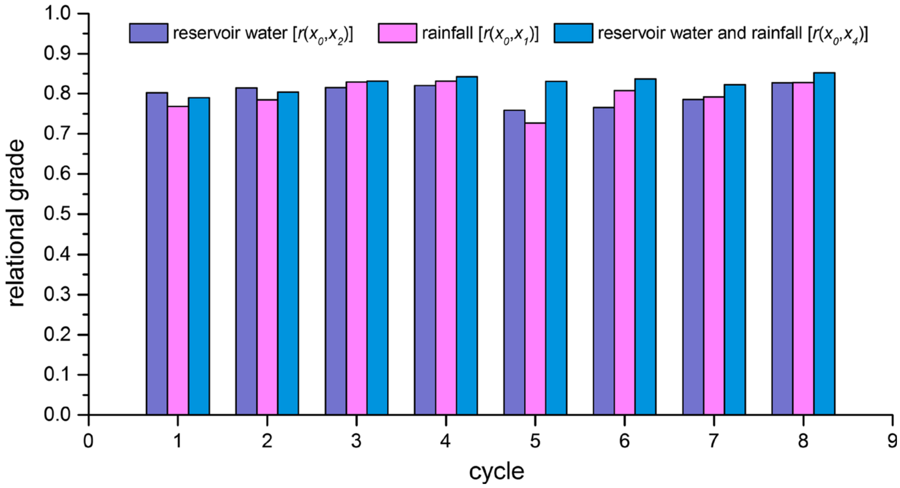


Fig. 10 The relationships between hydrological variables and the deformation of the *front part*

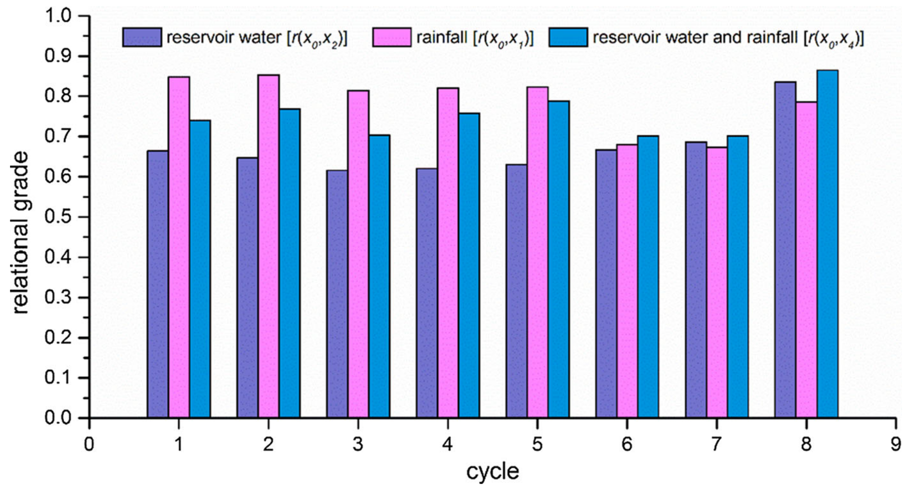


Fig. 11 The relationships between hydrological variables and the deformation of the *middle part*

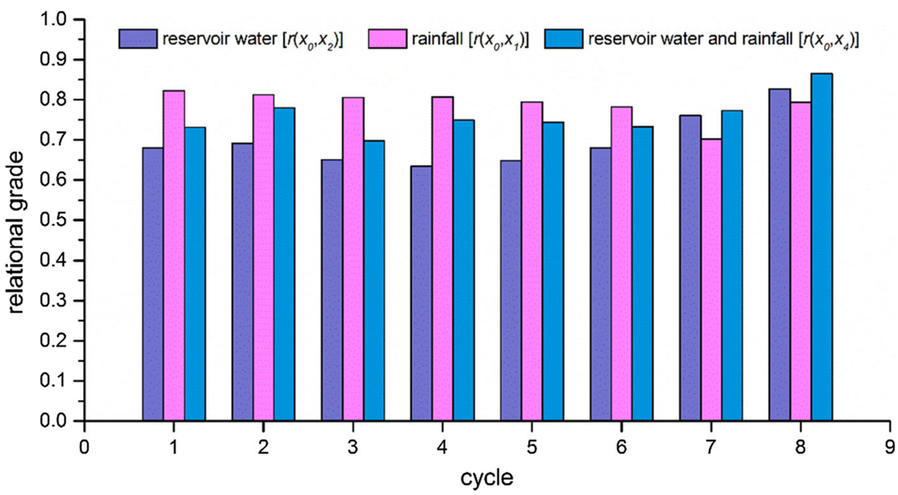


Fig. 12 The relationships between hydrological variables and the deformation of the *back part*

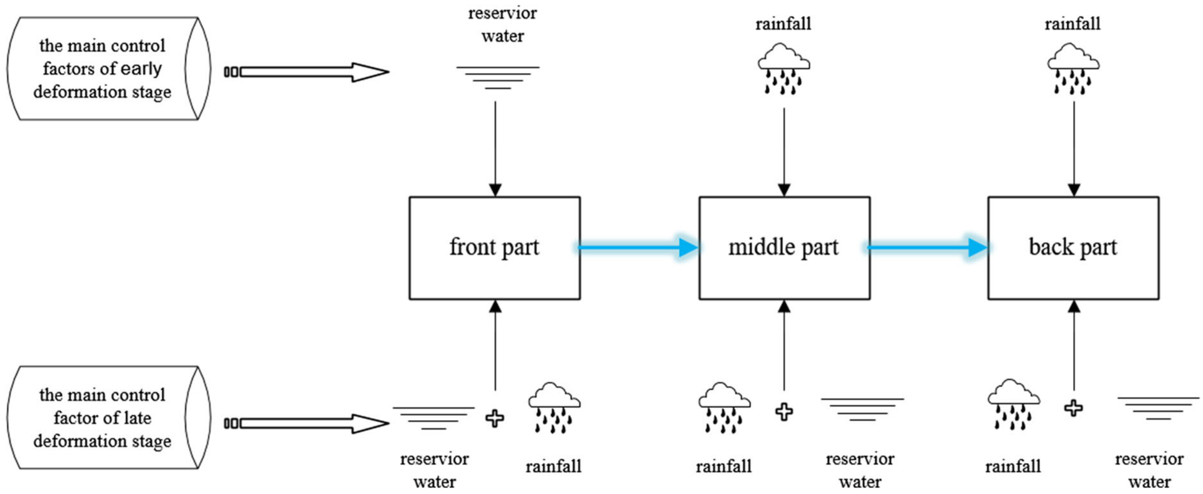


Fig. 13 The main control factors of different parts in different deformation stages

from June 2009 to June 2015) of the front part, the coupled action of rainfall and water level drawdown was the main control factor of the deformation. However, in the early deformation stage (i.e., from June 2007 to June 2012) of the middle part, the rainfall was the main control factor of the deformation. In the late deformation stage (i.e., from June 2012 to June 2015) of the middle part, the coupled action of rainfall and water level drawdown was the main control factor of the deformation. Similarly, in the early deformation stage (i.e., from June 2007 to June 2013) of the back part, the rainfall was the main control factor of the deformation. In the late deformation stage (i.e., from June 2013 to June 2015) of the back part, the coupled action of rainfall and water level drawdown was the main control factor of the deformation.

5 Analysis and Discussions

Based on above monitoring data cross-compilation and analysis, the influence pattern and degree of the effects of the reservoir water level fluctuations and rainfall on the deformation of different parts of Zhujiadian landslide are different in different deformation stages. These differences in the deformation phenomena of different parts can be explained as follows:

1. In the early deformation stage of the front part, the downslope-directed seepage pressure increases the sliding force of the sliding mass because of the water level drawdown. This factor triggered the initial deformation of the front part, resulting in four cracks numbered C1, C2, C3, C4 (Figs. 3, 5). These cracks enlarged gradually under the reservoir water level drawdown, which could provide some channels for rainfall infiltration. As a result, the seepage pressure of the infiltrating rainwater directed downslope, which increased the sliding force, and the disappearance of suction stress (Lu and Likos 2006; Wang et al. 2016) and increase in pore water pressure in the sliding surface, which decreased the resistance force. In the late deformation stage of the front part, the coupled action of rainfall and water level drawdown accelerated the deformation of the front part.
2. For the middle part and back part of the landslide, as rainfall infiltration results in the increase of the sliding force and the decrease of the resistance force, the rainfall became the main control factor of the initial deformation in the early deformation stage. More significant deformation occurred during the rainy season. Moreover, with the deformation development of the front part, the front part could not provide sufficient resistance force for the middle part and back part. In other words, the deformation of the front part would cause the middle part and back part to deform gradually during the reservoir water level drawdown. This indicated that the deformation of the middle part and back part was indirectly affected by the reservoir water level. The main control

factor of the deformation changed from the rainfall to the coupled action of rainfall and water level drawdown in the late deformation stage.
Overall, the main control factors of the different parts were different in the early deformation stage. Finally, the main control factor of all the parts was the coupled action of rainfall and water level drawdown, which indicated that the deformation of entire sliding mass exhibited an acceleration trend, making the landslide relatively dangerous. According to the forecast results, in order to ensure the safety of the people, shipping lane and Bazi highroad, the local government was advised to take measures to prevent further deformation of the landslide. Therefore, the stabilizing piles have been put into to prevent the landslide sliding since December 2016.

3. As a forementioned, landslide is a complex dynamic system affected by internal and external factors. The assessment of its stability is a central task in early warnings of landslide deformation. Lots of conventional stability analyses such as the engineering analogy method and limit equilibrium method can be performed to evaluate the factor of safety. The prevalent engineering analogy method usually depends on personal experience and expert knowledge due to its subjectivity. Limit equilibrium stability analysis provides a snapshot of the factor of safety at a particular time but requires specific data that sometimes is not readily available. For example, a heavy rainfall immediately affects the piezometric level within the landslide, and changes in the reservoir level may have effects on the stability. Besides, the numerical simulation methods have been widely used to study the deformation and failure of the landslide and evaluate the landslide stability under rainfall and water level fluctuations. Similarly, many geotechnical parameters (e.g. density, modulus of elasticity, cohesion and friction angle et al.) that sometimes are not also readily available are needed in the analysis.

However, the deformation of most reservoir wading landslides occurred first at the front part of the landslide and progressed upslope due to reservoir water level fluctuations and heavy rainfall. The stability of landslide changes continuously with the development of deformation. The conventional stability analyses are difficult to realize the accurate evaluation of the stability of landslide. What we offer is a complementary approach (GRGA), which is useful for rapidly predicting reservoir landslide deformation relating to water level fluctuations and rainfall based on readily available monitoring data.

6 Conclusions

In our study, quantitative model of the landslide deformation processes in the Three Gorges Reservoir Area was expressed in definite algebraic equations using the GRGA. The main control factors of landslide deformation is not immutable, but will change with the development of the landslide. Given the successful use of the GRGA in developing quantitative models for predicting deformation of the different parts of Zhujiadian landslide, it appears that this method could be useful for landslide monitoring analysis and early warning. With the increased availability of monitoring systems, automated data collection, and other techniques, the amount of valuable data increases exponentially, and the resulting large data sets might not be properly analyzed using conventional methods. These complementary approaches have the potential to provide useful information for interpreting and estimating landslide deformation in response to external perturbations. More specifically, the findings of the study described in this paper relating rainfall and reservoir water levels could be applicable to other cases around the world, particularly some reservoir wading landslides in the Three Gorges Reservoir area, China.

Acknowledgements This study was financially supported by the Key National Natural Science Foundation of China (41630643), the National Natural Science Foundation of China (41272305), the National Basic Research Program of China (973 Program, No. 2011CB710604). The authors are grateful for providing the valuable monitoring date by staff of Badong County in Enshi Prefecture Environmental Monitoring Station, Badong 444300, China. The authors are grateful for all these sources of support.

References

Cojean R, Cai YJ (2011) Analysis and modeling of slope stability in the Three-Gorges Dam reservoir (China): the case of Huangtupo landslide. J Mt Sci 8(2):166–175

Deng JL (1982) Control problems of grey systems. Syst Control Lett 1:288–294

Genevois R, Ghirotti M (2005) The 1963 Vaiont landslide. G Geol Appl 1:41–52. doi:10.1474/GGA.2005-01.0-05.0005

He KQ, Li XR, Yan XQ, Guo D (2008) The landslides in the Three Gorges Reservoir Region, China and the effects of water storage and rain on their stability. Environ Geol 55:55–63. doi:10.1007/s00-254-007-0964-7

Hsieh YC, Chan YC, Hu JC (2016) Digital elevation model differencing and error estimation from multiple sources: a case study from the Meiyuan Shan landslide in Taiwan. Remote Sens. doi:10.3390/rs8030199

Hu XL, Zhang M, Sun MJ, Huang KX, Song YJ (2013) Deformation characteristics and failure mode of the Zhujiadian landslide in the Three Gorges Reservoir, China. Bull Eng Geol Environ 74:1–12. doi:10.1007/s100-64-013-0552-x

Huang HF, Yi W, Lu SQ, Yi QL, Zhang GD (2014) Use of monitoring data to interpret active landslide movements and hydrological triggers in three gorges reservoir. J Perform Constr Facil. doi:10.1061/(ASCE)CF.1943-550-9.00006-82

Jian WX, Xu Q, Yang HF, Wang FW (2014) Mechanism and failure process of Qianjiangping landslide in the Three Gorges Reservoir, China. Environ Earth Sci 72:2999–3013. doi:10.1007/s126-65-014-3205-x

Jiang YN, Liao MS, Zhou ZW, Shi XG, Zhang L, Balz T (2016) Landslide deformation analysis by coupling deformation time series from SAR data with hydrological factors through data assimilation. Remote Sens 8(3):179. doi:10.3390/rs8030179

Khan YA, Lateh H (2011) Failure mechanism of a shallow landslide at tun-sardon road cut section of penang island, malaysia. Geotech Geol Eng 29:1063–1072. doi:10.1007/s10706-011-9437-6

Kondapalli SP, Srinivasa RC, Nageswara RD (2015) Application of grey relational analysis for optimizing weld bead geometry parameters of pulsed current micro plasma arc welded inconel 625 sheets. Int J Adv Manuf Technol 78:625–632. doi:10.1007/s00170-014-6665-y

Kulatilake PHSW, Ge YF (2014) Investigation of stability of the critical rock blocks that initiated the Jiweishan landslide in China. Geotech Geol Eng 32:1291–1315. doi:10.1007/s10706-014-9806-z

Lu YF (2015) Deformation and failure mechanism of slope in three dimensions. J Rock Mech Geotech Eng 7:109–119

Lu N, Likos WJ (2006) Suction stress characteristic curve for unsaturated soil. J Geotech Geoenviron Eng 132(2):131–142

Luo HM, Tang HM, Zhang GC, Xu WY (2008) The influence of water level fluctuation on the bank landslide stability. Earth Sci J China Univ Geosci 33(05):687–692

Ma JW, Tang HM, Hu XL, Bobet A, Zhang M, Zhu TW, Song YJ, Ez Eldin Mutasim AM (2016) Identification of causal factors for the Majiagou landslide using modern data mining methods. Landslides. doi:10.1007/s10346-016-0693-7

Massey CI, Petley DN, McSaveney MJ (2013) Patterns of movement in reactivated landslides. Eng Geol 159:1–19

Palis E, Lebourg T, Tric E, Malet JP, Vidal M (2016) Long-term monitoring of a large deep-seated landslide (La Clapiere, South-East French Alps): initial study. Landslides 14(1):1–16

Rahardjo H, Li XW, Toll DG, Leong EC (2001) The effect of antecedent rainfall on slope stability. Geotech Geol Eng 19:371–399

Samaneh M, Hossein T (2016) Finite element simulation of an excavation-triggered landslide using large deformation theory. Eng Geol 205:62–72

Sharma LK, Umrao RK, Singh R, Ahmad M, Singh TN (2017a) Stability investigation of hill cut soil slopes along national highway 222 at Malshej Ghat, Maharashtra. J Geol Soc India 89(2):165–174

Sharma LK, Umrao RK, Singh R, Ahmad M, Singh TN (2017b) Geotechnical characterization of road cut hill slope forming unconsolidated geo-materials: a case study. Geotech Geol Eng 35:503–515. doi:10.1007/s10706-016-0093-8

Singh TN, Singh R, Singh B, Sharma LK, Singh R, Ansari MK (2016) Investigations and stability analyses of Malin village landslide of Pune district, Maharashtra, India. Nat Hazards 81(3):2019–2030

Song HF, Cui W (2016) A large-scale colluvial landslide caused by multiple factors: mechanism analysis and phased stabilization. Landslides 13:321–335. doi:10.1007/s10346-015-0560-y

Sun BX, Jiang JC, Zheng FD et al (2015) Practical state of health estimation of power batteries based on Delphi method and grey relational grade analysis. J Power Sources 282:146–157

Sylviana S, Alchris WG, Suryadi I, Ju YH (2015) Taguchi method and grey relational analysis to improve in situ production of FAME from sunflower and *Jatropha curcas* Kernels with subcritical solvent mixture. J Am Oil Chem Soc 92:1513–1523. doi:10.1007/s11746-015-2714-4

Tang HX (2008) Analysis for progressive failure of the Senise landslide based on Cosserat continuum model. In: Proceedings of the landslides and engineered slopes. From the Past to the Future, Two Volumes + CD-ROM. CRC Press, pp 945–950

Tang HM, Li CD, Hu XL et al (2015) Deformation response of the Huangtupo landslide to rainfall and the changing levels of the Three Gorges Reservoir. Bull Eng Geol Environ 74(3):933–942

Troncone A, Conte E, Donato A (2014) Two and three-dimensional numerical analysis of the progressive failure that occurred in an excavation-induced landslide. Eng Geol 183:265–275. doi:10.1016/j.enggeo.2014.08.027

Umrao RK, Singh R, Sharma LK, Singh TN (2017) Soil slope instability along a strategic road corridor in Meghalaya, north-eastern India. Arab J Geosci. doi:10.1007/s12517-017-3043-8

Wang K (2011) A hybrid Kansei engineering design expert system based on grey system theory and support vector regression. Expert Syst Appl 38:8738–8750

Wang FW, Zhang YM, Huo ZT, Peng XM, Araiba K, Wang GH (2008) Movement of the Shuping landslide in the first four years after the initial impoundment of the Three Gorges Dam Reservoir, China. Landslides 5:321–329. doi:10.1007/s-10346-008-0128-1

Wang J, Su A, Xiang W, Yeh HF, Xiong C, Zou Z et al (2016) New data and interpretations of the shallow and deep deformation of Huangtupo no. 1 riverside sliding mass during seasonal rainfall and water level fluctuation. Landslides 13(4):1–10

Wei ZL, Shang YQ, Zhao Y, Pan P, Jiang YJ (2017) Rainfall threshold for initiation of channelized debris flows in a small catchment based on in-site measurement. Eng Geol 217:23–34. doi:10.1016/j.enggeo.2016.12.003

Xia M, Ren GM, Ma XL (2013) Deformation and mechanism of landslide influenced by the effects of reservoir water and rainfall, Three Gorges, China. Nat Hazards 68:467–482. doi:10.1007/s11069-013-0634-x

Yao W, Zeng ZG, Lian C, Tang HM (2015) Training enhanced reservoir computing predictor for landslide displacement. Eng Geol 188:101–109. doi:10.1016/j.enggeo.2014.11.008

Yi W, Meng ZP, Yi QL (2011) Theory and method of landslide stability prediction in the Three Gorges Reservoir area. Science Press, Beijing

Yilmaz K (2015) Hidden pattern discovery on epileptic EEG with 1-D local binary patterns and epileptic seizures detection by grey relational analysis. Australas Phys Eng Sci Med 38:435–446. doi:10.1007/s13246-015-0362-5

Yin YM, Cui HY, Hong M, Zhao DY (2015) Prediction of the vertical vibration of ship hull based on grey relational analysis and SVM method. J Mar Sci Technol 20:467–474. doi:10.1007/s00773-014-0299-5

Zhao DP, Wang SW, Tan YZ, Zhan QH (2013) Stability studies of buoyancy weight loss landslides under reservoir water level fluctuation. Rock Soil Mech 34(04):1017–1024. doi:10.16285/j.rsm.2013.04.020