Creep Behavior of the Slip Zone of a Giant Slow-Moving Landslide in Northwest China: The Suoertou Landslide as an Example

Xiu-zi Jiang and Bao-ping Wen

Abstract

The Suoertou landslide, a giant landslide with a volume of 72.85 × 10^6 m^3 in Zhouqu County, Gansu province of China, has been reactivated with a rate ranging from 300 to 600 mm/year since 1990s. The slow-moving dynamic nature indicates that the creep nature of its slip zone may play one of the predominant roles in the reactivation of the landslide. To clarify this, creep behavior of the saturated soil collected from the landslide's slip zone was investigated via a series of direct shear creep tests. It was found that the creep behavior of the landslide's slip soil was strongly dependent on the stress-level for both normal and shear stresses. It was also found that the accelerated creep stage could not be reached until the shear stress exceeded 125, 187.5 and 300 kPa and the initial strain rate at 3.141, 3.688 and 4.5 min^{-1}, under the normal stresses of 100, 200 and 400 kPa, respectively. Moreover, both the critical shear stresses and the initial stain rates at which the accelerated creep stage begins seem to have a linear correlation with the normal stress.

Keywords

Slip zone • Direct shear creeping test • Creep behavior • Critical shear stress • Initial strain rate

Introduction

Slow-moving landslides are generally known to undergo time-dependent deformation, namely creep (Di Maio et al. 2013; Huvaj-Sarihan 2010; Macfarlane 2009; Mansour et al. 2011; Van Asch et al. 2009). The Suoertou landslide, a giant slow-moving landslide with a volume of 72.85 × 10^6 m^3 in Zhouqu County, Gansu province of China, has been observed reactivating slowly since 1990s. The slide has caused severe damage to a road and local communities, and is moving at a rate ranging from 300 to 600 mm/year (Gansu Geological Disaster Survey and Design Institute 2012). Since a landslide's behavior is largely controlled by mechanical characters of its slip zone, it is of great significance to study the creep behavior of the slip zone to understand the mechanism of the sliding and to forecast the landslide's moving dynamic. The creep behavior of landslides is normally studied via two approaches: displacement monitoring in field (Corominas et al. 2005; Macfarlane 2009; Mansour et al. 2011; Van Asch et al. 2009) and laboratory testing of creep behavior of landslides' slip zones (Bhat et al. 2011; Di Maio et al. 2013; Huvaj-Sarihan 2010). Due to absence of systematic monitoring data, the creep behavior of the Suoertou landslide's slip zone was investigated experimentally.

The Suoertou Landslide and Its Slip Zone

The Suoertou landslide was located on the north bank of the Bailongjiang river, about 1 km upstream of Zhouqu County, Gansu province of China (Fig. 1). The landslide fully developed within a regional active fault zone, namely the

X.-z. Jiang (✉) • B.-p. Wen
School of Water Resources and Environment, China University of Geosciences (Beijing), No.29 Xueyuan Road, Haidian District, Beijing 100083, China
e-mail: jyz5671@163.com; wenbp@cugb.edu.cn

K. Sassa et al. (eds.), *Landslide Science for a Safer Geoenvironment*, Vol. 2,
DOI 10.1007/978-3-319-05050-8_23,

Fig. 1 View of the Suoertou landslide

Fig. 2 Slip zone of Suoertou landslide from borehole ZK3

Pingding-Huama fault zone. The landslide is 3,300 m long with a width of 80–700 m. The elevations at front and back of the landslide are 1,300 and 1,970 m, respectively, with a height difference of 670 m. Boreholes revealed that the maximum and minimum of thickness of the landslide body is 100 and 20 m, with an average thickness of 60 m. Its sliding body consists of grey clayey soil with abundant carbonate rock fragments in the upper part and dark grey clayey soil with carbonaceous slate rock fragments in the lower part. The latter was wet, soft and sludged. The bed of the landslide is carbonaceous slate cataclasite. The slip zone of the landslide is a dark clayey seam, with a thickness of 1.3–4.3 m (Fig. 2), developed along the interface between carbonaceous slate cataclasites and clayey soil. The slip soil was very wet and highly soft. Groundwater level in the slide was observed to be 5–26.5 m under the ground surface.

The test soil sample in the study was collected from borehole ZK3, in the middle portion of the landslide (Figs. 1 and 2). The sampling depth was 60–64 m. Basic physical properties of the sample were presented in Table 1. Grain size distribution and Atterberg limits of the sample were obtained in compliance with CNS GB/T50123-1999 (SAC 1999). Results showed that there was 10 % clay fraction with 52 % silt, 8 % sand and 30 % gravel. The liquid limit and plasticity indices were 35 and 19, respectively. X-ray diffraction analysis showed that the sample had primarily quartz, pyrophyllite and clay minerals, which primarily consisted of illite, kaolinite and pyrophyllite with some interlayered illite/smectite and cholorite (Table 2).

Testing Program

Consolidated and drained direct shear creep test was adopted to investigate the creep behavior of the sample. A triple set direct shear creep test apparatus was employed in this study.

Table 1 Physical properties of the sample

	Particle size fraction (mm, %)					
Particle density (g/cm^3)	Clay (<0.005)	Silt (0.005–0.075)	Sand (0.075–2)	Gravel (>2)	Liquid limit (%)	Plasticity index
2.73	10	52	8	30	35	19

Table 2 Mineralogical compositions of the sample

	Whole soil (%)							Clay portion (%)			
Quartz	Potassium feldspar	Siderite	Dolomite	Plaster	Pyrophyllite	Clay in total	I/S	Py	I	K	C
7.5	0.7	2.5	1	0.3	41.3	46.7	7	33	25	29	6

Note: *I/S* Interlayered illite/smectite, *I* illite, *K* kaolinite, *C* Chlorite, *Py* pyrophyllite

Normal and shear stresses were loaded through weights. The creep test was carried out following MT/T 895–1998 (State Bureau of Coal Industry 1998). Shear stresses were applied in increment. Each level of increment was estimated to be a fraction of the peak shear stress, which was obtained through a series of direct shear test under normal stresses of 100, 200, 300 and 400 kPa. The number of fractions was 6–8 in this study. The next level of increment was applied when the deformation of the specimen was observed less than 0.01 mm in 24 h. In this study, each shear stress increment was maintained for at least 1 week.

Since the slip zone was basically below the groundwater table and had primary particles finer than 2 mm, remoulded specimens with particles <2 mm were used with a water content about its liquid limit.

Results

Strain-Time Behavior

Figure 3 shows the strain versus time (γ–logt) behavior under different levels of normal stresses. It could be seen that the instantaneous deformation ($t = 0$) occurred once a shear load was applied, and these deformations became greater with the increment of shear stress. When the shear stress was less than 50, 75 and 125 kPa under the normal stresses of 100, 200 and 400 kPa, respectively, only attenuating creep was observed, during which shear strain became constant and the strain rate became nearly zero. When the shear stress was greater than the value mentioned above, steady-state flow was observed, during which the creep rate reached a constant value. When the shear stresses reached 125, 187.5, and 300 kPa respectively, the specimens underwent transient attenuating creep, steady creep and then went into accelerating creep until the specimens failed. These shear stresses 125, 187.5 and 300 kPa could be defined as critical stresses corresponding to the normal stresses of 100, 200, and 400 kPa.

The creep behavior of the landslide's slip zone illustrated above indicates that it is strongly dependent on the stress level. Interestingly, the values of shear stress leading to failure of specimens in creeping shear seem to have an approximately linear correlation with the normal stress (Fig. 4). Such correlation could be used to estimate the creep state of the Suoertou landslide given the sliding mass thickness, density of its materials and the occurrence of its slip zone is known. For example, at the sampling site (ZK3), dip of the slip zone was about 10°, given the slide materials' bulk gravity is 18 kN/m^3, the normal stress and shear stress are about 1,134 and 200 kPa, respectively. According to the relationship shown in Fig. 4, shear stress calculated was less than the critical stress (726 kPa) leading to failure of the slip

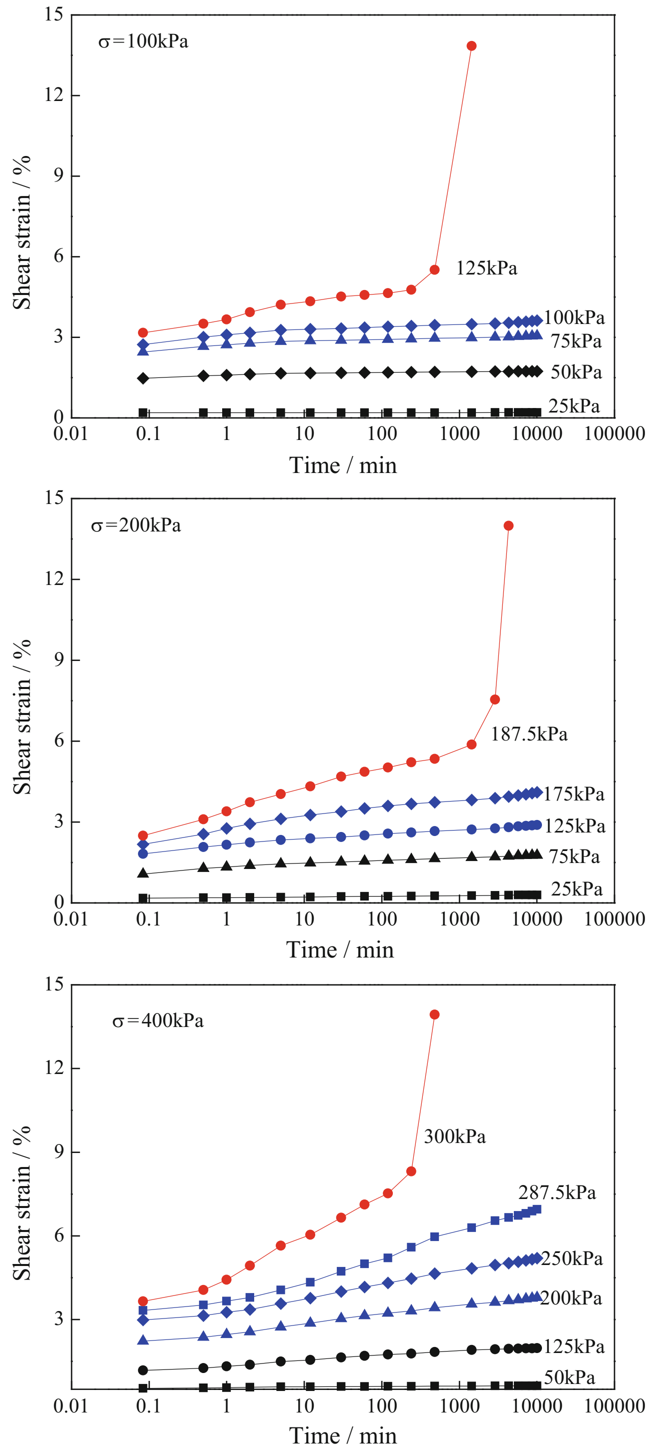

Fig. 3 Creep curves under normal stress of 100, 200 and 400 kPa

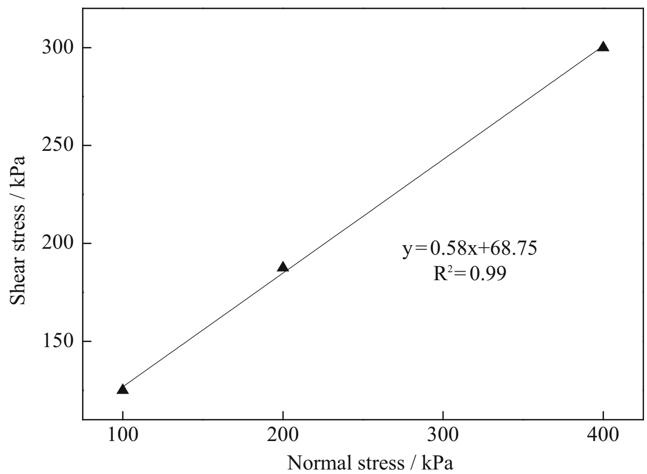

Fig. 4 Relationship between shear stress at failure and normal stress

zone. Therefore, the landslide at ZK3 has not reach the accelerated creep state yet, but it is already under a steady creep state.

Strain Rate-Time Behavior

Figure 5 shows the creep rate (shear strain rate) versus time (log-log scale) under different levels of normal stress. The results show that the initial shear stain rate increased with the shear stress. When the initial strain rate was less than 0.653, 1.023 and 1.529 min^{-1} at normal stresses of 100, 200 and 400 kPa, respectively, the specimens were under attenuating creep and the relationship between strain rate and time could be described using Eq. (1) ($A < 0$). When the initial strain rate was higher than the rate mentioned above, creep of the specimens occurred in steady-state flow, the relationship between strain rate and time is found from Eq. (2). When the initial strain rate reached 3.141, 3.688 and 4.5 min^{-1}, the specimens illustrated accelerated creep, and the curves had a point of inflection (minimum strain rate) when the strain rate changed from a decreasing to an increasing trend, and the relation between the strain rate and time could be described by Eq. (1) ($A > 0$). Clearly greater initial strain rates were needed for the sample to experience creep from attenuating state to steady state and to accelerated state. Notably the initial shear strain rates leading to accelerated creep also had an approximately linear corelation with the normal stress similar to those of shear stresses (Fig. 6). On the other hand, the minimum strain rate (e.g. 2.67e–3 min^{-1} at 240 min in Fig. 5a, 0.52e–3 min^{-1} at 480 min in Fig. 5b, 6.58e–3 min^{-1} at 240 min in Fig. 5c) and the time to failure were almost linearly related as well (Fig. 7). If the displacement of the landslide is monitored, the slide's creep state could also be estimated based on the correlation shown in Fig. 6. Unfortunately, for the landslide no systematic monitoring data has been recorded at present. However, in any case, such correlation revealed another criteria that could be used to estimate the creep state of the landslide.

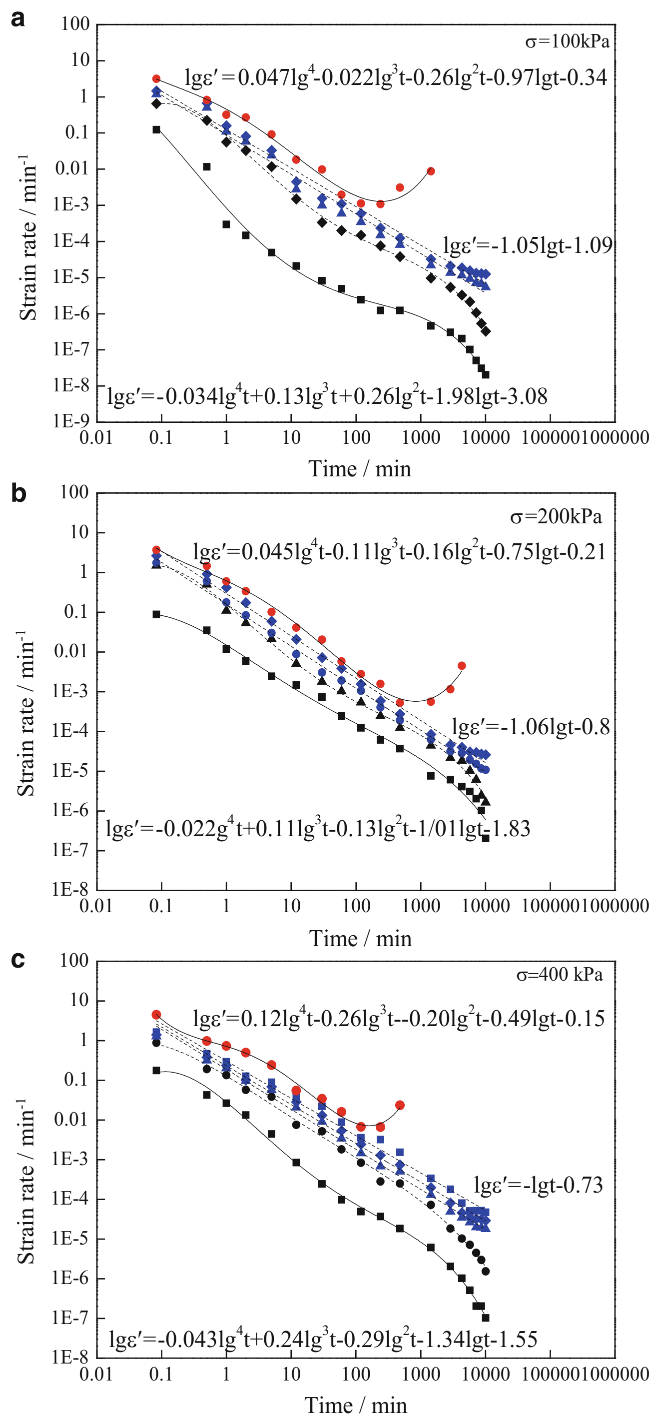

Fig. 5 Creep rate behavior of slip soil

$$\lg \dot{\varepsilon} = A \times \lg^4 t + B \times \lg^3 t + C \times \lg^2 t + D \times \lg t + E \quad (1)$$

$$\lg \dot{\varepsilon} = A \times \lg t + B \quad (2)$$

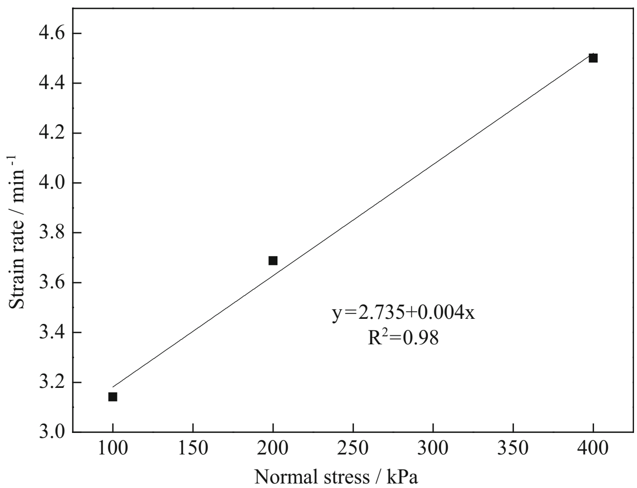

Fig. 6 Relationship between initial strain rates and normal stress at accelerated creep stage

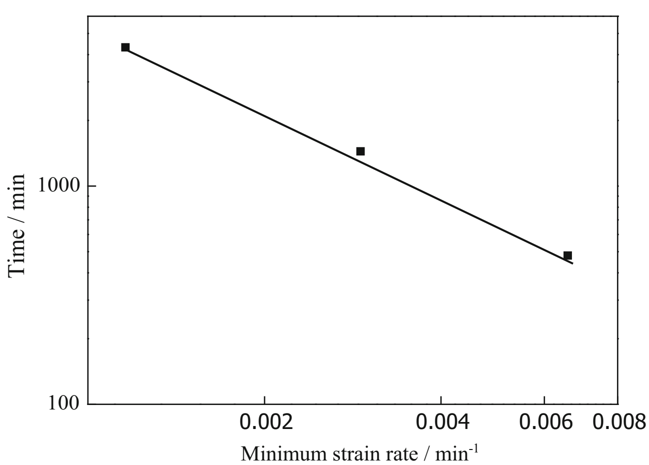

Fig. 7 Relationship between minimum strain rate and failure time during accelerating creep

in which, A,B,C,D,E are undetermined coefficients; $\dot{\varepsilon}$ the strain rate and t the time.

Conclusion

This experimental study revealed that the creep behavior of the Suoertou landslide's slip zone varies with both the stress level and the initial shear stain rate. Specifically, the following could be concluded:

1. Creep behavior of the Suoertou landslide's slip zone was strongly dependent on the stress level, including both the normal and shear stresses. When the shear stress less than 50, 75 and 125 kPa under normal stress of 100, 200 and 400 kPa, respectively, the slip zone underwent an attenuating creep. Otherwise, it reached steady-state creep. The slip zone did not reach accelerating creep until the shear stress were 125, 187.5, and 300 kPa under normal stresses of 100, 200, and 400 kPa, respectively. Such critical shear stresses had an approximately linear relationship with the normal stress. Based on this relationship, the Suoertou landslide has not reached accelerated creep yet.
2. Initial strain rate also had a significant control on the slip zone's creep behavior. When the initial strain rate was less than 0.653, 1.023 and 1.529 min^{-1} under normal stresses of 100, 200, and 400 kPa respectively, the slip zone was in attenuating creep; otherwise the slip zone reached steady-state creep. When the initial strain rate reached 3.141, 3.688, and 4.5 min^{-1}, respectively, the slip zone went into accelerating creep. The initial shear strain rates leading to accelerated creep also had an approximately linear correlation with the normal stress. This could be another criteria to estimate creep state of the landslide.
3. Creep characteristcs of the slip zone revealed in this study should be just part of its behavior as only one group of tests has been completed currently. To get more information about the creep behavior of the landslide's slip zone more tests are needed, which are in progress.

Acknowledgments This research was funded by the National Natural Science Foundation of China (No. 41372305). The authors are thankful to Mr. Shu Jiang for sampling in the field.

References

Bhat DR, Bhandari NP, Yatabe R, Tiwari RC (2011) Residual-state creep test in modified torsional ring shear machine: methods and implications. Int J Geomate 1(1):39–43

Corominas J, Moya J, Ledesma A, Lloret A, Gili JA (2005) Prediction of ground displacements and velocities from groundwater level changes at the Vallcebre landslide (Eastern Pyrenees, Spain). Landslides 2(2):83–96

Di Maio C, Vassallo R, Vallario M (2013) Plastic and viscous shear displacements of a deep and very slow landslide in stiff clay formation. Eng Geol 162:53–66

Gansu Geological Disaster Survey and Design Institute (2012) Investigation report for Suoertou landslide prevention and control engineering, Lanzhou (In Chinese)

Huvaj-Sarihan N (2010) Experimental investigation of failure time prediction in landslides. In: Paper presented at the EGU general assembly conference abstracts, Vienna.

Macfarlane DF (2009) Observations and predictions of the behaviour of large, slow-moving landslides in schist, Clyde Dam reservoir, New Zealand. Eng Geol 109(1–2):5–15

Mansour MF, Martin CD, Morgenstern NR (2011) Movement behaviour of the little chief slide. Can Geotech J 48(4):655–670

Standardization Administration of China (SAC), Ministry of Construction, Ministry of Water Resources (1999) China national standards (CNS) GB/T50123-1999: standard for soil test method. China Planning Press, Beijing, p 323, In Chinese. ISBN 9158005841607

State Bureau of Coal Industry (1998) MT/T 795–1998: testing method of rheologic charcteristic for direct shear of rock and soil. China Coal Industry Publishing House, Beijing, p 12, In Chinese

Van Asch TWJ, Malet JP, Bogaard TA (2009) The effect of groundwater fluctuations on the velocity pattern of slow-moving landslides. Nat Hazards Earth Syst Sci 9:739–749