Study on the Shear Resistance Characteristics of Landslide Deposits in Southwest China

Zelin Zhou[1], Jiaming Zheng[1], Kai Wang[1], Maoyi Liu[2,*]

[1]China 19th Metallurgical Corporation Chengdu, Sichuan, 610000, China
[2]Chongqing Construction Investment (Group) Co., Ltd. Chongqin, 400010, China

*Corresponding author's e-mail:maoyiliu2023@163.com

Abstract. This paper compiles and organizes in-situ tests from publicly available literature pertaining to deposit strata in Southwest China. A database was constructed, encompassing shear strength parameters, water content, particle size distribution, and sample size. Based on this database, the overall distribution pattern of deposit shear strength was analyzed. The probability density functions for cohesion and internal friction angle are presented both formulaically and tabulated. This study also delves into the variations in in-situ shear strength of deposits concerning water content, soil density, and particle size distribution. The research findings provide valuable theoretical insights for the prevention and treatment of landslides in the deposit regions of Southwest China.

Keywords: Landslide; Deposit; Shear Strength.

1 Introduction

The deposits are a transitional type of soil-rock mixture with highly complex physical and mechanical properties, lying between soil and rock. Statistics reveal that among the landslide geological disasters occurring in the southwestern region of China, 42.85% are attributed to landslides in the loose deposits of the Quaternary system. Numerous studies worldwide have investigated the mechanical properties of deposits. Li (2004)[1] conducted in-situ direct shear tests on samples from the Baiyian Landslide in the Three Gorges Reservoir Area, revealing that the cohesion and internal friction angle of the deposits samples increase with the stone content. Xu Wenjie (2006)[2] conducted large-scale in-situ horizontal direct shear tests in different stone content states, both in the natural and submerged states, at six experimental points distributed in the Longpan right bank area of the Hutiaoxia Gorge. Studies by You Xin (2002)[3], Li Xiao (2007)[4], Hu (2014), among others, analyzed the failure patterns of soil-rock mixtures under different stone content, water content, size, and stress conditions through in-situ horizontal shear tests. Li Weishu (2006)[5] established a relationship between shear strength indicators and water content based on a large number of experiments, providing a weakening formula for shear strength indicators under different stone content. Zhang Yujing (2008)[6] conducted large-scale triaxial shear tests on samples from the

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valley shoulders of the left bank of the Xiluodu Hydropower Station, dominated by ice-water and alluvial slope deposits, revealing a hyperbolic stress-strain relationship for the soil samples. Zhang Jiqing (2009) analyzed the influence of water content, stone content, and compaction on the physical-mechanical properties of loose deposits through large-scale indoor shear tests. Zhang (2015)[7] conducted ring shear tests on the sliding zone soil of the Luoziwan ancient slope and discovered a significant decrease in the soil's shear strength due to deformation caused by slope toe excavation. Deng Yiping (2016)[8] obtained the mechanical parameters of collapsed deposits through limit equilibrium state inverse analysis. Yan Qiurong (2016)[9] derived the physical-mechanical characteristics of remolded soil in the disturbance zone under different porosity ratios through primary graded large-scale direct shear tests. Wu Ruian (2017)[10] conducted field direct shear tests comparing the original and remolded samples of loose deposits, studying the shear strength characteristics under different normal stresses, gradations, and water content conditions. Zhang Zhen (2017)[11] conducted large-scale triaxial compression tests under different water content conditions on ice-water deposits in the Linzhi region, proposing and validating a modified Duncan-Zhang constitutive model considering strain softening and volume expansion. Zhao Meng (2021)[12] studied the sliding zone of the Linjiang I landslide in the Loess Plateau, developing constitutive models for unsaturated sliding zone soil shear deformation characteristics under different water content conditions and landslide seepage field models. Frost and colleagues [13,14]studied the mechanical properties of granular and clay mixed soils and the failure mechanisms at their interfaces.The southwestern region of China is characterized by its complex topography, and landslides pose a significant threat to infrastructure stability. In response to the frequent occurrences of landslides in this region, this study focuses on a comprehensive investigation of the in-situ mechanical properties of deposit formations. Specifically, the research aims to establish a robust database encompassing shear strength parameters, moisture content, saturation levels, particle size distribution, and sample dimensions.

Motivated by the imperative to deepen our understanding of the factors influencing the physical properties of deposits, particularly shear strength, this research seeks to contribute essential insights to the prevention and mitigation of landslides. The significance of this study lies in its potential to provide a theoretical foundation for rock and soil engineering in the southwestern region, enhancing our ability to safeguard lives and property and maintain the stability of engineering projects. While acknowledging the limitations inherent in data availability and methodological constraints, this study innovatively employs probability density functions derived from a comprehensive database. The integration of these statistical analyses enables a nuanced exploration of shear strength distributions, offering a more holistic comprehension of the physical characteristics of deposits in the southwestern region.

The limitations, such as potential data incompleteness and methodological constraints, necessitate careful consideration in the interpretation of the results. Comparisons with existing studies may reveal divergences attributable to regional differences, methodological nuances, or variations in research focus.

Looking ahead, the outcomes of this research are poised to contribute significantly to rock and soil engineering practices in the southwestern region. By offering a nuanced understanding of deposit properties, especially shear strength, this study provides a scientific basis for improved landslide prevention and management strategies, thereby addressing a critical need in engineering applications in this geographically challenging area.

2 Database

For this project, a database was compiled by collecting in-situ test data on deposit strata from publicly available papers. The database contains 76 natural peak in-situ shear strength data entries and 18 in-situ shear strength data entries under saturated or submerged conditions for deposits. Therefore, collecting and analyzing patterns in in-situ shear strength indicators is of paramount importance for practical engineering applications(Table 1).

Table 1. In-situ shear test indicators for the deposited materia.

Location	φ(°)	C (kPa)	ω (%)	γ (kN/m³)	>0.075mm Grain Content (%)	>2mm Grain Content (%)	>5mm Grain Content (%)	Sample Horizontal Size (dm×dm)	References
Fengjie New District	17.23	65	9.76		46				Li Huizhong et al.[15]
	20.82	82.5	15.77		10				
	16.18	27	16.25		5				
	20.31	65	17.26		28				
	22.30	62	32.61		38				
	31.82	70	10.41		26				
	23.76	40	9.55		23				
	14.04	10	26.28		41				
	16.71	25	7.71		30				
	16.71	70	15.13		28				
	30.13	51.3	14.68		23				
	23.28	54.5	11.55		31				
	18.27	40	22.13		23				
	26.58	70	22.08		29				
Fengjie Baiyi'an	41.62	22.6			95	54	46	9×6	Li[1]
	39.02	18.7				42.1			
	29.32	18.4				38.3			
	43.8	47.91					40	8×8	Li Xiao[4]
	65.4	55.48					50		
	50.3	32		2.36			59	9*6	You Xinhua[3]
	34.4	37		2.24		0	0		
	66.5	51		2.16			54		
Hutiao Gorge	47.83	0.42		1.74	100	85	80	8×8	Xu Wenjie[2]
	49.81	1.58		1.75	100	83	75		
	42.61	2.09		1.79	100	71	60		
	57.96	0.27		1.96	100	85	80		
	60.31	0.25		1.97	100	83	75		
	59.83	0.28		1.98	100	71	60		
	36.46	12.56		2.31			46	6×6	Tan Rujiao[16]
	29.52	21.04		2.18			25		
	37.10	11.4			80.45	49.79	32.13		Hu Yunpeng[17]

Baihetan Reservoir Area	39.30	16.4				61		2	
	43.10	18.3				69			
	41.20	17.9			86.4	63.15	52.31		
Liyuan Hydropower Station	22.00	4.69		1.97	95	65	70	10×10	Wang Zigao[18]
	26.50	4.33		1.97	95	65	70		
	39.60	1.8		2.05	98	95	90		
	38.50	0.87		2.05	98	95	90		
Certain Slope	30.5	110	6.5	2			70	5×5	Yang Jihong[19]
	22.8	50	12.5	1.9			50		
	27.0	60	7.5	1.95			60		
	19.8	10	15	1.9			50		
Loess Slope	17	39.2	16.5	2.41					Peng Zhenghua[20]
	16.5	34.3	16.5	2.35					
	17.5	39.2	16.5	2.30					
	17.5	19.6	16.5	2.21					
	16.5	37.24	16.5	2.25					
	14	39.2	16.5	2.30					
Suwalong Hydropower Station	34.60	60					48.7	5×5	Bai Jinping[21]
	40.70	10					61.2		
	41.70	50					70		
	41.30	10					73		
Wenchuan Earthquake Zone, Xuankou	32.82	19.4	15.8	2.12	89.6	78.5	57.6	5×5	Wu Ruian[10]
Minjiabao	30.13	90	9.3						Tang Aisong[22]
	21.32	65							
Shizibao	22.79	60	16.3						
	19.81	52							
Papaya Creek	25.19	34	16.8						
	21.81	31							
Yunyang	13.18	28.35							
	12.03	6.22							
Fengjie	18.68	67.47							
	17.08	61.8							
Wushan	17.28	19.51							
	15.33	19.55							
	29.48	32.22							
	25.89	29.04							
	25.89	23.33							
	24.71	20.48							
Qianping	40.39	180						5×5	
	31.40	60							
Xulong Power Station	37.25	210					70		
	31.82	70					70		
	36.89	60							
	32.64	30							
Shuibuya Dam Area	15	80					3		Xiong Shihu[23]
	13	65					5		
	12	10					6		
	19	18					6		
	27	30					6		
	17	13					8		
	14	102					25		
	20	18					27		

16	63	30
14	130	35
15	25	39
26	80	43
25	20	46
30	70	50
17	83	57
23	39	60
31	55	60
29	80	90

Test sites are predominantly located in the Three Gorges Reservoir area and along the upper reaches of the Yangtze River in the southwestern part of China. All data were sourced from publicly published papers collected by the team. The disclosed data content in these papers is not uniform. This study selected deposit sample indicators related to rock fragment content, particle size distribution of deposit materials, water content, and test size, which are associated with shear strength indicators. Based on this database, the variation patterns of in-situ shear strength in deposits were analyzed.

A portion of the data in the database was obtained through graph readings, which might lead to discrepancies in the combinations of friction angle and cohesion with the actual in-situ shear strength of the deposits. However, since this study analyzed friction angle and cohesion separately, the aforementioned discrepancies do not affect the conclusions of the analyses on these parameters. Some papers referenced in the database did not provide a strict definition for rock fragment content; in this study, it is uniformly defined as the content of broken stones with a particle size larger than 5mm. Furthermore, samples soaked for either 12 or 24 hours are defined as saturated samples in this paper. The database includes 28 entries with water content data for deposits, 28 entries for in-situ samples containing particle size proportions of 0.075mm, 19 entries for 2mm, and 50 entries for 5mm, 26 entries with natural unit weight data for in-situ samples, and 29 entries with in-situ sample size data. Due to the different focuses of each paper, in-situ shear data containing all the above information is rare.

3 Overall distribution patterns of cohesion and friction angle

3.1 Probability Distribution of Cohesion

In the samples, the natural peak cohesion of the deposits is primarily concentrated in the ranges of 10~40kPa and 60~70kPa. The mean value is 45.38kPa, the median stands at 38.12kPa, and the standard deviation is 37.44. The overall distribution is shown in Figure 1.

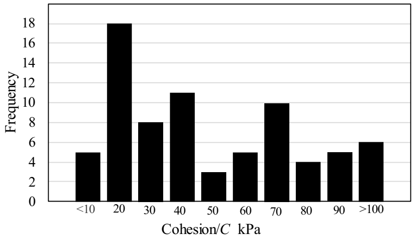
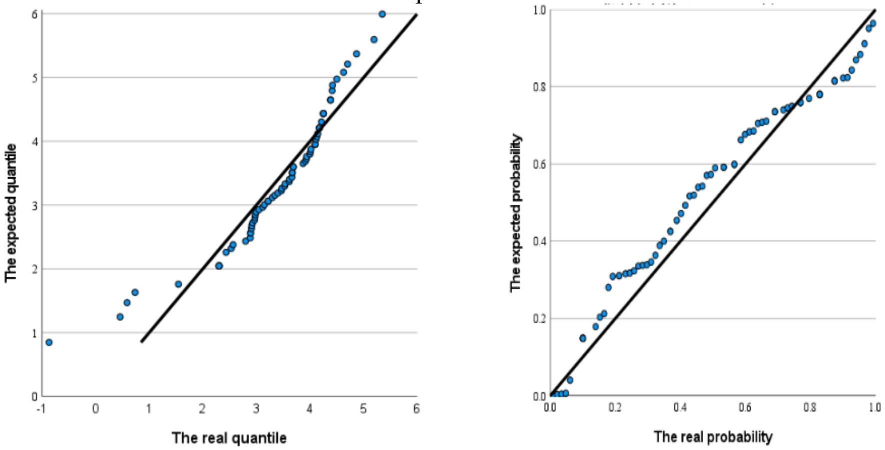


Fig. 1. Histogram of peak cohesive strength distribution in natural deposited material.

We used the Kolmogorov-Smirnov (K-S) test to check the normality of the cohesion values and the log values of cohesion from the database.

The significance level for the normality test of cohesion is 0.001, which is less than 0.05. This indicates that the peak cohesion of the deposit samples overall does not follow a normal distribution. The significance level for the normality test of the logarithm of cohesion is 0.05, which is equal to 0.05. This suggests that the peak cohesion of these deposit samples approximately follows a log-normal distribution. As can be observed from the normal quantile plot and probability plot shown in Figure 2, extreme values, both far below and far above the mean, affect the overall fit of the distribution. These comparisons highlight that narrowing the study scope to a smaller spatial scale can enhance the fit of the database and reduce prediction deviations.



(a) (b)

Fig. 2. Normal quantile-quantile plot for cohesive strength sample statistics.

Probability Density Function of Logarithmic Values of Natural Cohesion in Accumulative Strata:

$$f[(\ln(C)] = \frac{1}{1.07\sqrt{2\pi}} e^{-\frac{[ln(C)-3.42]^2}{2.3}} \tag{1}$$

3.2 Internal Friction Angle

In the dataset, the natural peak internal friction angles of the accumulative bodies are primarily distributed between 15° and 45°. The average value is 27.45°, with a median of 25.1° and a standard deviation of 12.06. The internal friction coefficients of the accumulative bodies in the samples range from 0.21 to 1.0, with an average value of 0.57, a median of 0.44, and a standard deviation of 0.37. The overall distribution is depicted in Figure 3.

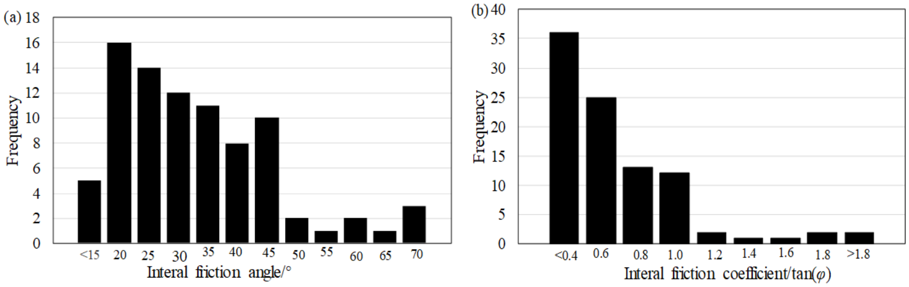


Fig. 3. Histogram of (a) natural state internal friction angle and (b) coefficient of internal friction for the sediment body.

We employed the Kolmogorov-Smirnov (K-S) test to assess the normality of the internal friction angle \phiϕ and the logarithmic values of the tangent of the internal friction angle \tan(\phi)tan(ϕ) in the database. The significance values for the normality test of the internal friction angle and coefficient were 0.026 and 0.027, respectively, both less than 0.05. Thus, neither the peak internal friction angle nor the internal friction coefficient of the samples follows a normal distribution. In Table 2, we present the probability density values for the internal friction angle and coefficient from the database.

Table 2. Probability density table for internal friction angle and coefficient of internal friction

Interval Number	Friction Angle /°	Frequency	Estimated Probability	Friction Coefficient	Frequency	Estimated Probability
1	0~15	5	6.58%	0.2~0.4	30	39.47%
2	15~20	16	21.05%	0.4~0.6	22	28.95%
3	20~25	14	18.42%	0.6~0.8	8	10.53%
4	25~30	12	15.79%	0.8~1.0	11	14.47%
5	30~35	11	14.47%	1.0~1.2	2	2.63%
6	35~40	8	10.53%	1.2~1.4	1	1.32%
7	40~45	10	13.16%	>1.4	2	2.63%
8	45~50	2	2.63%			
9	50~55	1	1.32%			
10	55~60	2	2.63%			
11	60~65	1	1.32%			
12	65~70	2	2.63%			

In summary, both cohesion and internal friction angle in this study's database do not follow a normal distribution, which is inconsistent with the research conclusions of Li Yuanyao[24] and Luo Chong[25]. The latter two focused on the landslide slip-zone soil of the Three Gorges Reservoir area and Wanzhou district. Their findings indicate that both cohesion and internal friction angle in their databases follow a normal distribution. By analyzing the three databases, we believe the variations in overall distribution arise from the following aspects:

(1)The data in this study are sourced from publicly available papers, leading to greater spatial and temporal variations than in the other two databases.

(2)The shear strength indices in our database derive from in-situ tests of varying sizes, while the other two databases do not disclose the test sizes in their studies.

(3)There's a variation in the stone content among the three databases. In this study, the stone content ranges from 2% to 90%, whereas in Li Yuanyao's database, it ranges from 10% to 40%. Luo Chong did not disclose data on stone content. However, their study described the slip-zone soil primarily as gray-white clay, suggesting minimal stone content.

(4)The sources of shear strength data differ. Neither Li Yuanyao nor Luo Chong specified if their shear strength parameters were derived from a combined analysis of survey, design, and construction data. In contrast, all shear strength values in this study's database come from in-situ tests.

3.3 Factors Affecting Shear Strength

Due to the nature of in-situ tests, it's impossible to quantitatively regulate properties of the samples such as moisture content and particle size distribution. Consequently, we cannot conduct controlled experiments under a single condition like in laboratory tests, nor can we decouple and analyze the various influencing factors. Therefore, the following analyses are conducted with a focus on a single dimension of shear strength. When analyzing one factor, the other factors are not kept consistent.

3.3.1.Moisture Content. The relationship between the moisture content of the depositional body and its shear strength is depicted in Figure 4. Under natural conditions, both the internal friction angle and cohesion decrease as moisture content reduces. This contrasts with the optimal moisture content phenomenon observed in granular soils. This is because, under natural conditions, the compaction of depositional bodies is generally less than that of laboratory-tested samples subjected to compaction tests or on-site layered rolling. When the natural compaction remains constant and the moisture content increases, the free water layer on the soil particle surface thickens, reducing the cohesion and internal friction angle between soil particles. Additionally, an increase in moisture content will soften the contact surfaces between granular particles and soil particles, and between granular particles themselves. Therefore, regardless of the gradation conditions of the depositional body, its shear strength always increases with the rise in moisture content.

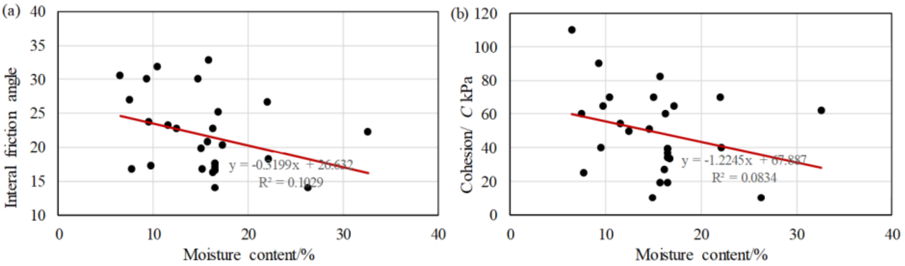


Fig. 4. Relationship between (a) internal friction angle and (b) cohesion of sedimentary deposits with moisture content.

3.3.2.Soil Density t. The relationship between the water content of the depositional body and its shear strength can be seen in Figure 5. In its natural state, the internal friction angle of the depositional body generally decreases with an increase in soil density, while its cohesion generally increases with an increase in soil density. The underlying mechanisms influencing the shear strength of the depositional body due to soil density are relatively complex, involving factors such as moisture, compaction, and the proportion of coarse to fine particles. A comprehensive explanation of its principles has not yet been well articulated.

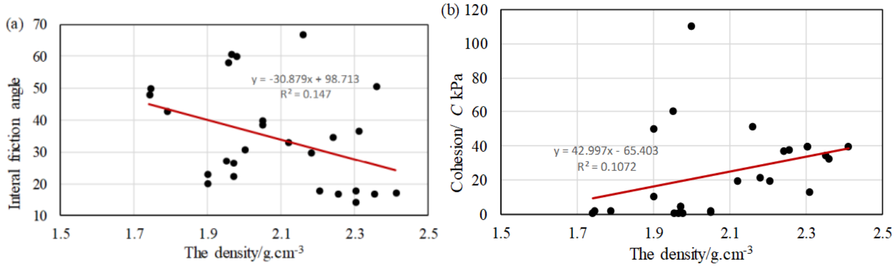


Fig. 5. Relationship between (a) internal friction angle and (b) cohesion with soil density

4 Conclusion

In this study, by collecting and organizing in-situ tests of depositional strata in the southwestern region of China from public literature, a database containing shear strength parameters, moisture content, particle size distribution, and sample size was established. Based on this database, the overall distribution pattern of the shear strength of the depositional body was analyzed, and the probability density functions of cohesion and internal friction angle were presented both in formulaic and tabular forms. In addition, this study analyzed the variation in in-situ shear strength of the depositional body with moisture content, soil density, and particle size distribution. Combining the above analyses, the following conclusions are drawn:

(1)The peak in-situ shear strength of the depositional body in the data of this study exhibits a non-normal distribution, and the cohesion shows a weak logarithmic normal distribution.

(2)Both the peak in-situ internal friction angle and cohesion of the depositional body decrease with increasing moisture content.

(3)Compared to the natural state, the average reduction percentages of the saturated depositional body's peak in-situ internal friction angle and cohesion are 11.79% and 39.46% respectively.

(4)The peak in-situ internal friction angle of the depositional body decreases with increasing soil density, while the cohesion increases with increasing soil density.

(5)The peak in-situ internal friction angle of the depositional body increases with increasing stone content in the soil, while the cohesion decreases with increasing stone content.

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