Research on the Design of Landslide Anti-sliding Engineering Based on Inverse Parameter Calculation and the GEO-Slope Limit Equilibrium Method

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Abstract. Landslide is one of the most widely distributed and most severe geological hazards among the types of slope damage. China is among the countries most seriously affected by landslide disasters in the world. The unreasonable landslide anti-slide design will not only miss the best time for landslide treatment but also cause unnecessary engineering waste. Some may even worsen slope deformation and damage. Thus, reasonable slope protection and reinforcement and landslide anti-slide engineering design have become the current research fascination. This paper uses the Chengdu–Lanzhou Railway as the research object. This railway exhibits the typical characteristics of “four poles and three heights” in engineering geology. The main geological hazards and typical geological conditions of the Chengdu–Lanzhou Railway are systematically explained. The reasons for the determination of the principal axis section of the most unfavorable landslide and the basis for the determination of the sliding surface are summarized. Moreover, in this paper, a reasonable anti-slide engineering design is proposed. Finally, the friction coefficient of the main sliding section is calculated using the method of the coefficient of stability of the block, and the landslide thrust is calculated. Then, the stability coefficient of the landslide is verified using the GEO-Slope limit equilibrium method to determine whether the anti-slide engineering design is reasonable. This article provides a more scientific anti-skid engineering design idea and a scientific analysis method for the rationality of anti-skid engineering design.

1. Introduction

A landslide is a phenomenon in which the balance of the original slope is destroyed under certain conditions, and part of the landslide body slides along the most unfavorable sliding surface of the landslide under the action of gravity. Landslide is considered as the most destructive natural disaster with the highest proportion of geological disasters in China. It is a significant form of slope deformation and failure, and its stability is an important content of research on rock and soil mechanics.

Early research on landslide only took soil as the research object, and early stability analysis was based only on experience and simple elastic–plastic mechanics. The remarkable feature of its method is the...
use of material mechanics and simple homogeneous elasticity and elastoplasticity based on semi-empirical and semi-empirical theory. It is a theoretical research method and is used to study the stability of rock slopes. However, due to its rough mechanical mechanism or the unreasonable assumptions, the calculation results are quite different from the actual ones. After the 1980s, computers were used for the simulation of the overall destruction process of landslides. New theories, methods, and technologies were proposed, such as failure probability analysis method, information theory method, and fuzzy mathematics. The current domestic research adopting these methods for the stability analysis of landslides has been very mature. In the application of these theories, the specific direction and position of the most unfavorable sliding surface need to be analyzed. This article analyzes the typical landslides occurring in the Chengdu–Lanzhou Railway (Chengdu–Huangshenguan Section) and comprehensively describes the methods and steps of the scientific determination of the most unfavorable section in the early stage of landslide treatment. Moreover, it provides theoretical basis for the later stage of landslide treatment. The innovation of this paper is that relying on the complex engineering geology, the geology presents the typical characteristics of “four extremes and three heights” (i.e., the terrain cutting is extremely strong, the structural conditions are extremely complex and active, the lithological conditions are extremely weak and broken, and the Wenchuan earthquake effect is extremely significant; high crustal stress, high seismic intensity, and high risk of geological disasters). The cause of the landslide at this site is universal, and the landslide characteristics are special; thus, this site has a good research value. The second is to combine geological data with deep-hole displacement to determine the most unfavorable sliding surface of the landslide. The stability coefficient of landslide is calculated and checked.

2. Engineering Background

2.1. Project summary
The site is located in the alluvial fan area and the river terrace area. The terrain is relatively flat and is high in the east (on the side of the mountain) and low in the west (on the side of the Minjiang River). There are high mountains and forests, and the gullies between the mountains are deep. It has a height difference of 50–340 m and natural slope of generally 30°–60°, which is steep upward and gentle downward, and some are cliffs. The No. 1 landslide body of Zhenjiang Guan Fifth Line Extraordinary Bridge is a typical bad geological body. It is located in the D2K204 + 098–D2K204 + 300 section of the line. There are two landslide bodies in the north and south. The longitudinal slope of the landslide body is about 42°, the main axis is about 130 m, and the width of the bottom of the landslide body is about 202 m. The main axis direction of the south landslide body is NE87°, and that of the north landslide body is NW81°. From the geomorphological point of view, the landslide has the nature of collapsing and its sliding surface is relatively steeper than the general accumulation layer landslide. The rock and soil that constitute the landslide body are unevenly distributed, and the lithology of the weak rock and soil is poor, easy to weather, and easily softened by water. The structural plane NW28°/W67° constitutes the northern boundary of the landslide; NE22°/W48°, the southern boundary of the landslide; and NE28°/W24°, the bottom sliding surface of the landslide. The line passes through the front edge of the landslide body, on which the landslide has a greater impact (see Figure 1 Zhenjiangguan Station 1# landslide body panorama).
2.2 Geological overview

The stratum lithology of the construction site is mainly composed of Holocene landslide accumulation layer (Q_{4}{^\text{deq}}) silty clay, breccia soil, and rocky soil, slope avalanche layer (Q_{4}{^\text{deq}}) silty clay, fine breccia, and rough corners. Gravel soil, alluvial layer (Q_{4}{^\text{deq}}) silty clay, coarse gravel soil, pebble soil, and slope residual layer (Q_{4}{^\text{deq}}) gravel soil are the main ones. This type of lithology is characterized by loose and wet soft. The Zhenjiangguan 1# landslide body is located in the area where the Minjiang active fault and Zhenjiangguan inverted complex syncline mainly developed. Due to the influence of the Minjiang active fault, the interlayer folds developed, the stratum is inverted locally, the local is "twisted," the joints are cracked, the rock mass is fractured, and the slope stability is poor. The pore water near the work site is mainly distributed in the loose accumulation layer of the Minjiang River bed and the terraces on both banks. In this site, the soil layer is thick, and the water content is good. The remaining slopes are due to the thin surface soil layer and faster discharge. Moreover, the amount of water is extremely small, and the pore water is mainly supplied by atmospheric precipitation and is discharged to low-lying areas. Its dynamic changes are large, and the runoff path is short. During the rainy season, especially after heavy rains and torrential rains, the water level significantly rises, and the hydrodynamic pressure increases, and vice versa during the dry season. The peak ground acceleration of this site is 0.30 g, and the characteristic period of the ground motion response spectrum is 0.40 s, which is greatly affected by the earthquake. In summary, the site is a multi-unfavorable geological body with poor stratum conditions, complex geological structure, abundant groundwater, and severe earthquake impact.

3. The most unfavorable section is determined

3.1. The slip surface is determined by geological data

Landslide prevention and treatment requires on-site visit for the investigation and analysis of the features and signs of deformation, as well as for the identification of the deformation types in time to avoid passivity and errors in the survey and investigation to the greatest extent. It is also vital to the landslide surface analysis. Accurate analysis of the landslide sliding surface contributes to the prevention and control of the landslide. In this paper, taking the 1# landslide body of Zhenjiang Guan 5th Line Extra Large Bridge as an example, the basis for judgment and method of landslide sliding surface are gradually analyzed.
The main reasons for determining the sliding surface of the No. 1 landslide body of the fifth line super bridge at Zhenjiangguan Station are:

1.) According to the topography and landslide perimeter, the section is located at the center of the 1# landslide body in the north of the landslide body, which is more consistent with the obtained landslide main axis direction;

2.) According to the design situation of each section, the sections within the range of the 1# landslide body in the north landslide body are only 8# and 9# on the side of the platform of the pier section. Measures such as anchor frame beam protection are not taken;

3.) In the 1# landslide body, the depth of the bedrock is the deepest within the range of the north landslide body, which is located in the central groove of the entire north landslide body;

4.) According to the field investigation, the pile position with the largest water volume during the excavation of the anti-slide piles in the entire 1# landslide body is consistent with the obtained direction of the main sliding surface of the landslide, that is, the 29–31# piles corresponding to the main shaft section. These three piles are excavated during the process. A total of four 50 kW water pumps are used, and the water level is always at a depth of about 10 m above the bottom of the pile.

![Slide body plan of Zhenjiang Pass No.1 of newly-built railway line from Chengdu to Lanzhou](image)

**Figure 2.** Zhenjiangguan 1# sliding body plan

3.2. The slip surface is determined by geological drilling

The O"-O" main shaft section of the Zhenjiangguan 1# landslide body has two deep displacement monitoring holes and three geological drilling holes. The deep displacement monitoring holes are CX-1 and CX-2. CX-1 is located 8.3 m from the side of the 66# anti-slide pile, and CX-2 is located 8.5m from the side of the 29# anti-slide pile. In Figure 1, the layout of the deep-hole displacement monitoring is presented.
In the core identification, the core of hole CLSY-5 is determined to be 25 m and that of hole CLSY-6 is 23.61 m, which is considered to be a highly weathered zone, and the core is broken. Moreover, the core of hole CLSY-7 is extremely broken, and its recovery rate is low. Combined with the site structural plane survey position, deep-hole displacement monitoring data and geological drilling situation, the most unfavorable sliding surface position determined by each information of the spindle section is connected by the deep-hole displacement monitoring data and geological drilling situation, and the adverse sliding surface combination of the spindle section is determined.

Basis of the sliding surface determination:

1.) The trailing edge of the landslide is a gully, wherein tensile cracks and obvious signs of deformation can be observed. It has a dip angle of 67°.

2.) The highly weathered phyllite is located 26.5 m below the top of the CLSY-5 borehole, with a relatively broken rock mass, which is the fractured rock mass under the force during the formation process, forming a weak zone. The rock mass has a low shear strength and easily slips along the surface.

3.) The highly weathered phyllite is located 21–25.20 m below the top of the CX1 borehole. 21 m downward is the strongly weathered layer with a thickness of 4.2 m, which is composed of phyllite, grayish black, highly weathered, argillaceous and calcareous structure, medium thick layer structure, relatively developed rock joints and fractures, not fresh rock, relatively soft, partially crushed core by hand, and locally quartz veins. When the strength of the weathered layer is low, especially when the softening resistance is reduced by water, the rock and soil can easily slide along the layer. The rock strata are broken from 17 m down to 22 m from the top of the CLSY-06 borehole. The interface downward is highly weathered phyllite, SLATE, gray black, gray yellow, the core is short columnar, more broken. Through the comparison and analysis of the CX-1 monitoring borehole core identification and the deep-hole displacement monitoring curve, the characteristics of the sliding deformation can be initially determined at a depth of 25.20 m. Combined with the core identification, it can be determined that the interface between the soil and rock is 9.2 m.
4.) The interface between the soil and rock is 25 m from the top of the CX2 borehole. The upper layer of the surface of gravel soil is tan or gray black in color, dense, and slightly wet and has a gravel angular shape or sub-angular shape; moreover, the rock in this layer is not fresh. The following is phyllite, grayish black in color, highly weathered, has an argillaceous structure or a plate structure, joints, has well-developed fractures, has a yellowish-brown fracture surface, the local fractures are filled with fine quartz veins, the vein width is 1–3 mm. The rocks are not fresh and soft. Compared with soil, the rock top is relatively watertight, causing the groundwater to accumulate at the interface, thus soaking the soil near the contact zone. The rock strata incline towards the line, causing the residual soil of the overlying slope to be prone to sliding along the underlying rock top. The CD segment passes through hole CLSY-7 at 19.7 m and hole CISY-7 at 16.7–22.6 m, thus exhibiting an extremely broken core and low adoption rate. Through the comparison and analysis of the CX-2 monitoring borehole core identification and the deep-hole displacement monitoring curve, presented in Figure 4, the characteristics of the sliding deformation can be initially determined at the depths 8 and 25.0 m. Combined with core identification, it can be determined that 8 m is close to the interface between the backfill and brecciated soil, and 25.0 m is the interface between the soil and rock.

To determine the most unfavorable sliding surface line, the results should be combined, as presented in Figure 5.
Figure 5. Landslide profile

4. Stability factor calculation

4.1. Parameter inverse calculation of the landslide thrust

The strip stability coefficient method is commonly used to analyze slope stability. It has been proven to be an effective method in practice. In the case wherein the sliding surface can be divided into multiple bars, the bar stability coefficient method is generally used for the calculation.

Gi denotes the gravity of slider I; Ni, the positive pressure perpendicular to the sliding surface; Ti, the total sliding force on the sliding surface; and Ri, the total sliding resistance of the ith block. If there is only one bar I, the stability safety factor of the bar can be expressed as follows:

$$F_s = \frac{R_i}{T_i}$$  \hspace{1cm} (1)

Ri denotes the original resistance of the landslide, and Ri=FsiTi denotes the sliding resistance after considering the safety factor; thus, it is considered that the sliding resistance provided by the pile is expressed as follows:

$$P_i = F_s T_i - R_i$$  \hspace{1cm} (2)

When the landslide is divided into N blocks, pi-1 is the residual sliding force of the i-1 block and the i-1 block, and -1 and I are the dip angles of the sliding surface of the i-1 block and the i-1 block, respectively. Suppose the remaining interbar forces are parallel to the sliding surface of the corresponding bar, the remaining sliding force of the ith block is as follows:

$$P_i = F_s T_i P_{i-1} \Psi_{i-1} - R_i$$  \hspace{1cm} (3)

The sliding force caused by the weight of block I is as follows:
The sliding resistance of the $i$th block, including the friction resistance and cohesion resistance, caused by the deadweight force on the sliding surface is as follows:

$$T_i = G_i \sin \theta_i.$$  

(4)

The transfer coefficient is as follows:

$$\Psi_{i+1} = \cos (\theta_{i+1} - \theta_i) - \sin (\theta_{i+1} - \theta_i) \tan \phi_i.$$  

(6)

When the stability coefficient formula is defined and the safety coefficient $K$ value is the natural $K_0$ value (the thrust of the main slide section is 0), substitute it to $K = \frac{R_n + \sum_{i=1}^{n-1} (R_i \prod_{j=1}^{n-1} \Psi_j)}{T_n + \sum_{i=1}^{n-1} (T_i \prod_{j=1}^{n-1} \Psi_j)}$. The cohesive force $C$ and internal friction $\phi$ of the main slide section are calculated and then completely substituted into the thrust formula, that is, the landslide thrust can be calculated at this time.

**Table 1. Summary of the physical and mechanical parameters of the slope section**

| Material             | Severe $\gamma$ (KN/m$^3$) | Modulus of elasticity (MPa) | Poisson’s ratio | Cohesive force (kPa) | Friction angle $\phi$ ($^\circ$) |
|----------------------|-----------------------------|-----------------------------|----------------|----------------------|---------------------------------|
| Angle of coarse      | 20                          | 20                          | 0.2            | 20                   | 30                              |
| Gravel soil          | 21                          | 40                          | 0.2            | 25                   | 30                              |
| Gravel soil          | 24                          | 500                         | 0.18           | 50                   | 40                              |
| Highly weathered SLATE | 25                      | 1000                        | 0.17           | 200                  | 45                              |

4.2. Inverse calculation determines the internal friction angle of the main slide

To determine the parameters required for the calculation of the landslide thrust, the geological survey data and literature can be used as references, as well as Table 2, which presents the physical and mechanical parameters of the rock and soil in the section. In addition, the trailing edge traction section $C = 0$ kPa, the main slide section $1c = 50$ kPa, the main slide section $2C = 50$ kPa, and the stability coefficient $K = 1.15$.

The internal friction angle of the main slide section of the landslide is calculated to be 25.28°, and the residual sliding force is 2927.82 KN. Based on the above, it can be realized that the limit of stability coefficient 1.3 after the protection of no. 1 main shaft section of Zhenjiang Guan Wuxian Super large bridge. The thrust force of unbalanced landslide obtained using the balanced method is 2927.82 KN.

**Table 2. Reverse calculation of the internal friction angle of the main slide section of Zhenjiangguan No. 1 landslide spindle section**

| Number | Sliding surface angle ($^\circ$) | Severe $\gamma$ (KN/m$^3$) | Cohesive force c (kPa) | Angle of internal friction $\phi$ ($^\circ$) | Stability factor | Residual glide force (KN/m$^3$) | Calculated parameters |
|--------|---------------------------------|-----------------------------|------------------------|-----------------------------------------------|-----------------|-------------------------------|----------------------|
| Traction section | 67.00                          | 25.00                       | 0.00                   | 45.00                                         | 1.15            | 3525.91                       | Angle of internal friction in the main slide |
| 1      | 34.57                           | 25.00                       | 50.00                  | Calculated values                              | 1.15            | 6947.57                       | 25.28°               |
| 2      | 30.00                           | 24.00                       | 20.00                  | 30.00                                         | 1.15            | 7644.11                       |                     |
| 3      | 6.00                            | 20.00                       | 20.00                  | 1.51                                          | 25.28°          |                               |                     |

4.3. Stability coefficient check

Based on the most unfavorable slip surface section of the spindle section, the physical and mechanical parameters of each layer determined above were used, the limit equilibrium calculation of the GEO-Slope was performed, and the calculation results are presented in Figure 7.
Its stability coefficient is 1.153, which is 0.2% different from the stability coefficient obtained using the macroscopic deformation signs, and is in good agreement.

5. Conclusions
1.) The most unfavorable sliding surface of the landslide can be determined using the geological data and borehole data.
2.) The central position of the landslide body is consistent with the main direction of the landslide, and the main direction of the landslide is most likely to be its most unfavorable sliding surface.
3.) From the perspective of section design, the bedrock burial depth may be located in the most unfavorable sliding surface.
4.) When the anti-slide pile is excavated, the direction of the most multi-point connection may be the most unfavorable direction of the sliding surface.
5.) There are obvious tensile cracks at the back edge of the landslide. The orthogonal direction of the cracks is probably the most unfavorable direction of the sliding surface.
6.) Deep-hole displacement monitoring, monitoring the maximum range of point connecting line is likely to be the most adverse sliding surface direction.
7.) Through the core to judge the interface between soil and rock, to judge the most unfavorable direction of sliding surface.
8.) The analysis of landslide stability can initially determine the most unfavorable sliding surface, reverse-calculate the internal friction angle of landslide, and then finally check the stability coefficient using the GEO-slope.

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