Numerical Simulation of the Influence of Cutting Slope Rate on the Stability of Highway Slope in Loess Area

Pei Yuan Song¹, Yan Long Mao¹ and Heng Xing Huang²

¹Geological Engineering and Surveying Institute, Chang’an University, Xi’an, Shaanxi, 710054, China
²China Railway Wuhan Survey and design Institute Co., Ltd, Wuhan, Hubei, 430000, China

Corresponding author’s e-mail: 1075048485@qq.com

Abstract. The highway project in the loess area of northern Shaanxi is to balance the earthwork and save costs, and a large number of excavation slopes are set. In the loess area, the soil is soft. If there is a structural surface, it is easy to cause damage to the airspace, causing huge losses to highway construction and transportation on the heavy rain and other working conditions, especially the roadside slope. Taking the high loess slope of a section of Zhidan-Nanliang Red Tourism Highway as an example, the indoor parameters are used to determine the appropriate parameters. The Midas-GTS NX strength reduction method is used to analyze the slope stability under different slope cutting rates.

1. Introduction
With the further development of the western region and the further development of the “One Belt, One Road” strategy, the economic construction in the northwest region has developed rapidly. The Zhidan region relies on the advantages of red tourism to develop transportation routes between tourist areas. In the northwest region, there are many loess hilly landforms. During the construction of highway facilities, it is inevitable to encounter high slopes of excavation or filling. The stable slopes are prone to natural disasters such as landslides caused by external disturbances, causing losses to the local economy and people’s lives and property. Therefore, it is very important to take reasonable measures to ensure the stability of the excavation slope.

Zhou Zeng¹ used the geotechnical numerical analysis software SEEP/W to analyze the steady state of groundwater flow. In the transient analysis of continuous precipitation, it is concluded that the slope of 12m in Meizhou granite residual soil area does not exceed 65°. Bo Li² used the Morganstern-Price method to calculate the slope stability under different slope cutting schemes. It is concluded that when the platform width is the same, the slope rate has a greater influence on the slope stability than the slope height. Hongwei Guan³ used orthogonal test method to calculate and analyze the slope height under the same slope height condition. The slope stability and slope rate are negatively correlated with the step height, and the slope width is positively correlated with the slope width. The sensitivity is consistent with the sensitivity of the slope parameters. The influence of the berm width and the slope rate on the stability of the slope is highly significant. The height of the platform is influential but not significant. M. Rasouli Maleki [4] and other researches took the western rock wall of the Chadomalu iron mine as their research, and used the empirical method to evaluate the optimal excavation slope angle. The finite element software Phase 2D was used to calculate the optimal excavation slope angle to verify the
stability and accuracy. Wanjun Ye[5] studied the relationship between slope length, slope angle and slope flushing amount, and established an optimal design model of loess road high slope based on slope flushing loss, and carried out the optimize the design high slope of loess road. Fei Song[6] used the computational analysis method and the engineering geological analogy method to comprehensively consider the single-stage slope height and slope angle optimization design and set the platform to study the design scheme of loess high cutting slope. Ping Li[7] analyzed the relationship between slope height, slope, stability coefficient, parameter coefficient of variation and failure probability in the study area through reliability calculation systems with different confidence levels. I Otáloro[8] introduces the results of the SEEP/W simulated seepage field into the finite element calculation to analyze the variation of landslide stability with rainfall and other factors. González[9] used finite element numerical simulation to analyze the effect of groundwater on landslide resurrection. Since the 1970s, Zienkiewicz[10] first proposed the finite element strength reduction method to analyze the slope stability, a large number of numerical simulation software was developed. In the numerical calculation of rock and soil, the application of Midas-GTS NX is quite mature[11].

In this paper, the physical and mechanical parameters and shear strength parameters of slope rock and soil are determined by laboratory tests. The most suitable slope rate range is found for a high slope in northern Shaanxi by Midas-GTS NX. With the same berm width, changing the slope rate and find the correlation between the slope rate change and the stability coefficient. Under the condition of ensuring the slope height and the width of each graded slope, as far as possible to simulate different slope rates, the functional relationship between the slope stability coefficient and the slope rate of different slopes can be found. The functional relationship provides reference for the selection of high slope slope rate in other loess areas, and proposes reasonable prevention and control measures for the unstable slope to ensure that it will not form new landslide disasters under heavy rain and other conditions.

2. Regional geological background and slope situation

2.1. Regional geological background
Zhidan County is located in the loess hilly and gully region of northern Shaanxi. It belongs to the typical valley-type loess plateau. The upper part of the bedrock is covered with loess. Under the action of neotectonic movement, the bedrock surface and the ground surface gradually rise, and the loess geomorphology is constantly being washed away by water, and the undercutting action of the flowing water forms the loess geomorphology of the gully. Luohe, Zhouhe and Xingzi Rivers cross the Zhidan County and flow from the northwest to the southeast. Therefore, the overall terrain of Zhidan County is inclined from the northwest to the southeast. The county has a large area, and the main geomorphological units include three types, valley terraces, loess liang and mao and earth-rock mountains. The Luohe River and the Xingzi River have a tributary with a large flow, and a river terrace with a large area is formed by the flow of water in the basin. The area of loess liang and mao in Zhidan County is the widest, and its altitude is in the range of 1450~1650m. And there may be large isolated rafts between the tops of the loess liang. The density of gully is large, and there are many arable lands on the loess liang; The mountain is low in altitude.

Zhidan County is located in the southern part of the stablest Erdostai syncline in the North China Platform. The geological structure is simple, the bottom layer is gentle, and there is no igneous rock intrusion. The whole area is a monaxial monoclinic structure, and the overall trend is NNE, tending to NW, dip. About 10°, the fold fracture is not developed, and the structural shape is simple. Since the new generation, the region has been in a relatively stable and slowly rising state.

2.2. slope situation
The initial geomorphic unit of the unstable slope belongs to the slope of the loess residual liang-gully area. The loess liang and mao are mostly covered by loess layer, and the riverbed deeply cut the bedrock. A slight circular chair-like terrain has been seen on the trailing edge of the slope, and a slightly distorted steep ridge is visible in the rear, indicating that the high slope has begun to undergo deformation and
damage, and the gully is cut deeper on both sides of the slope. The overall terrain of the slope is high in the north and low in the south. The altitude at the trailing edge of the slope is 1466m, the elevation at the leading edge is 1373m, and the overall slope is about 50°. The overall appearance of the slope is shown in the figure:

![Figure 1. The overall situation of the slope (mirror 292°).](image)

According to the geological survey and the exposure of the borehole, the strata distributed in the slope survey area are: silt ($Q_{3}^{del}$), Middle Pleistocene loess ($Q_{2}^{eol}$), red clay ($N_{2}$) and the Lower Cretaceous Zhidan Group Luohe Formation sandstone ($K_{1}l$). The description from new to old is as follows:

1. Silt ($Q_{3}^{del}$): landslide deposits, visible pinhole structure and a small number of large holes, poor anti-scour ability, medium compressibility. The water content is low, and the borehole has shrinkage in this layer, and the maximum thickness can reach 30m.

2. Loess ($Q_{2}^{eol}$): brownish yellow, hard plastic, medium density, slightly wet, soil quality, single color, visible scattered calcareous streaks, calcium binding at the bottom. Among them, a number of pale strips of paleosol are visible, the front part of the landslide is thin, and the back part is thick.

3. Red clay ($N_{2}$): brown red, dense and hard, soil is relatively uniform, containing calcium tuberculosis and brownish black iron and manganese and organic matter markings, the bottom is light purple calcareous tuberculosis layer and sand shale Piece. Medium compression. The soil in this layer is hard when dry, and it can be seen that the surface of the core has dry cracks and is easily weathered and peeled off.

4. Mud sandstone($K_{1}l$): mainly brown-red, exposed on both sides of the road near the landslide and in the valley, thick layer, coarse to medium feldspar sandstone, muddy cementation, horizontal bedding development. Dense and hard, the cracks develop slightly.

The slope is located at the front end of the loess liang on the north side of the No. 3 Middle Bridge of Zhifanggou. The overall inclination of the slope is 116°, the width of the front edge of the slope is about 180m, the longitudinal length of the slope is about 155m, and the maximum thickness of the slope is about 32m. It is about $36.27 \times 10^4 m^3$. The vegetation on the surface of the slope is well covered, and there aren’t any good drainage measures in the slope area.

The survey data showed that a large number of heavy rainfall in July-August 2016 caused a large amount of surface water to infiltrate into the slope, resulting in slight deformation and damage in the upper part of the slope. Then, as the road was excavated, the soil at the foot of the slope began to loosen. According to the site survey and related data, the potential sliding upper part of the slope is located in the silt-loess layer, and the lower part is cut through the silt layer. Drilling shows a sharp rubbing trace on the slip surface.

3. Laboratory test analysis and parameter selection

3.1. Style and spacing
According to the results of the on-site investigation, the high slope is analyzed in an unstable state from a macro perspective. Take the original undisturbed loess pattern and use the ZJ strain-controlled direct shear instrument to test the shear strength index of the original loess. The test instrument is shown in the figure:

Figure 2. The machine of ZJ strain control direct shear.

According to the general physical and mechanical properties tests conducted, the indicators of silt \(Q^{3\text{del}}\) and medium-updated loess \(Q^{2\text{eol}}\) are shown in the table:

| Type of soil  | Proportion (Gs) | Natural moisture content(\(\omega\)) | Natural dryness and severity(\(\gamma_d\)) | Void ratio | Natural saturation(Sr) |
|--------------|-----------------|-------------------------------------|------------------------------------------|------------|------------------------|
| Silt \(Q^{3\text{del}}\) | 2.69            | 10.6                                | 16.3                                     | 0.616      | 64%                    |
| Loess \(Q^{2\text{eol}}\) | 2.7             | 18.1                                | 16.4                                     | 0.606      | 50%                    |

The undisturbed soil sample was humidified to the ratio of water content which was 8\%, 11\%, 14\%, 16\%, 18\%, 20\%, 22\%, 25\% by pre-wetting method. And each of the samples was divided into four groups to do direct shear test at normal stress of 25KPa, 50KPa, 100KPa, 200KPa, with ring cutter size 60cm3. And the relationship between shear strength index and water content can be concluded. Comparative analysis of the change of strength index of loess under different water content, the relationship between water content \(\omega\) and cohesion \(c\), water content \(\omega\) and internal friction angle \(\phi\) is obtained, as shown in the figure:

Figure 3. Relationship between cohesion and water content.  
Figure 4. Relationship between internal friction angle and water content.

It can be found from figure 3 that, as the water content \(\omega\) increases, the cohesive force of the soil decreases in three stages, and the cohesion decreases from the highest 33.2 KPa to the lowest 16.7 KPa. We can found that there is an inflection point between 8\% and 22\% in the curve. The cohesion \(c\) between the two inflection points is not obvious with \(\omega\). Outside the two inflection points, \(c\) decreases rapidly with the increase of \(\omega\), which has the same experimental results with Huili Zhao \[12\]. And it can also be found from figure 4 that the internal friction angle \(\phi\) change insignificantly as the water content \(\omega\) increases. However, the internal friction angle is stable at 15\°~25\°. Professor Ping Li \[13\] believes that
the clay content in loess is the main factor controlling the internal friction angle $\phi$. Studies by Drumright\(^{14}\) and Rohm\(^{15}\) have also shown that water content mainly affects cohesion, resulting in reduced cohesion and less effect on friction angle.

For the consolidation test of silt soil ($Q^{3del}$) and medium-updated loess ($Q^{2eol}$), the results of the two-layer soil shear strength index are shown in the table:

| Layer number | Rock and soil name | Statistical parameter | Number of valid data | Maximum | Minimum | average | Standard deviation(\(\sigma\)) | Coefficient Of variation(\(\delta\)) | standard |
|--------------|--------------------|-----------------------|----------------------|---------|---------|---------|-------------------------------|-------------------------------|----------|
| (1) Silt     | Cohesion (KPa)     | 9                     | 4.5                  | 0.7     | 2.3     | 6.55    | 0.13                          | 2.9                           |          |
|              | Internal friction angle (°) | 9                     | 13.5                | 5.9     | 9.6     | 6.16    | 0.25                          | 7.6                           |          |
| (2) Loess    | Cohesion (KPa)     | 8                     | 32.6                | 15.7    | 23.8    | 9.12    | 0.26                          | 12.6                          |          |
|              | Internal friction angle (°) | 8                     | 28.7                | 13.4    | 20.3    | 7.26    | 0.33                          | 16.7                          |          |

According to the measured moisture content of loess, the cohesive force is about 24KPa from Figure 3, and the internal friction angle is about 19° from Figure 4. Then compared with the shear strength obtained by the fast-cutting test in Table 2, the parameters of the loess layer were finally determined. Combined with local actual and engineering experience, we determine the shear strength index of red clay ($N_2$) and argillaceous sandstone ($K_1$). The overall table of all parameters is selected as follows:

| Layer number | Rock and soil name | Compression modulus (MPa) | Poisson's ratio | Natural bulk density (KN/m3) | Cohesion (KPa) | Internal friction angle (°) | Constitutive model |
|--------------|--------------------|---------------------------|----------------|-------------------------------|----------------|---------------------------|-------------------|
| (1) Silt     | 9.43               | 0.25                      | 18             | 3                             | 10.8           | mohr-coulomb               |                   |
| (2) Loess    | 8.59               | 0.25                      | 18.9           | 24                            | 19             | mohr-coulomb               |                   |
| (3) Red clay | 10.53              | 0.25                      | 19.2           | 38                            | 33             | mohr-coulomb               |                   |
| (4) Argillaceous sandstone | 1.59×10^3 | 0.25                      | 21             | 49                            | 40             | mohr-coulomb               |                   |

### 4. Model calculation and data processing

#### 4.1. Initial slope stability analysis

According to the parameters obtained in Table 3, the most dangerous sliding surface was selected from the reconnaissance report, and simulated by Midas-GTS NX finite element method. The stability coefficient of the slope was 1.0008 under natural conditions. The maximum shear strain and cloud map are as figure 5.

Through the maximum shear strain cloud map in figure 5, it can be found that shear failure has occurred in the slope, and the damage is mainly caused by shear failure along the silt-loess layer. Since the test soil is selected as the soil that has been shear-destroyed, the results of the borehole survey are confirmed, and the damage of the slope occurs inside the silt-loess layer.

This is because the surface water on the upper surface of the slope will penetrate downward along the cracks in the soil. It is found through laboratory test data that the Middle Pleistocene loess has a certain cohesive force, and the cohesive force of the silt layer is close to zero, which leads to the part. groundwater accumulates at the boundary between loess and silt, causing the pore water pressure to rise. According to the principle of effective stress:
\[ \sigma = \sigma' + \mu \]  \hspace{1cm} (1)

When the pore water pressure increases and the principal stress does not change, the effective stress decreases. Then, under the action of gravity, a soft structural surface is formed at the junction of the silt-loess layer above the slope. In the lower part of the slope, due to the large thickness of the upper silt layer, the slope is steep and the downward thrust is large. At the same time, the road cutting is carried out at the foot of the slope, resulting in the steep shape of the slope, making the stability of the slope foot is weakened. and the two effects occur at the same time, which leads to the development of the structural surface like the silt layer at the foot of the slope, destroying the silt layer and causing the entire slope to slide.

4.2. Stability analysis of different slope slope rates

Because the slope has a large amount of earthwork and a high altitude, the slope is treated according to the state of the unstable slope, combined with the slope cutting, water drainage, and other anchoring and anti-slide piles.

According to the relevant content of the landslide prevention engineering design and construction technical specifications, we design 1:1, 1:0.9, 1:0.8, 1:0.7, 1:0.6, 1:0.5, 1:0.4, seven different slope rates for slope cutting, under the condition of ensuring the slope height and the berm width at each level. Select the 1:1 slope maximum shear strain cloud map as figure 6. Check the calculation separately and obtain the corresponding slope stability coefficient as shown in the following table:
Table 4. The relationship between cutting slope rate and stability coefficient.

| Cutting Ratio | 1:1 | 1:0.9 | 1:0.8 | 1:0.7 | 1:0.6 | 1:0.5 | 1:0.4 |
|---------------|-----|-------|-------|-------|-------|-------|-------|
| Stability factor(K) | 1.7 | 1.67  | 1.5515| 1.3375| 1.1265| 1.0865| 1.0635|

Through the cloud map from figure 5~6, as the slope rate decreases, the amount of sloped soil increases continuously, and the overall shear strain of the slope decreases continuously. And the position of the most dangerous structural plane of the slope in the cloud map continuously moves downward from the silt-loess layer where the slip occurred initially to the loess-red clay layer. In order to reflect this law more intuitively, two elements located on the bottom of the silt layer(1629) and the bottom of the loess layer(2264) are selected from the model. The variation of the shear strain at the two unit nodes with the slope rate is shown in the following table:

Table 5. Maximum shear strain at the element of 1629 and 2264.

| Cutting Ratio | 1:0.4 | 1:0.5 | 1:0.6 | 1:0.7 | 1:0.8 | 1:0.9 | 1:1 |
|---------------|-------|-------|-------|-------|-------|-------|-----|
| 1629 Maximum shear strain | 1.64  | 0.82  | 0.05  | 0.03  | 0.02  | 0.008 | 0.0004 |
| 2264 Maximum shear strain | 0.87  | 0.46  | 0.33  | 0.09  | 0.05  | 0.03  | 0.01 |

From the table 5, we can find the same rule that The maximum shear strain change rate at element 2264 is less than 1629. The reason of the rule is that, when the upper silt is gradually removed, the self-weight of the upper soil is reduced. So the structural surface originally formed at the silt-loess layer is not able to slide along the previous structural plane under the sliding thrust. The infiltrated water will continue to penetrate downward along the internal fissures of the loess layer. When the infiltrated water reaches the interface between the loess and the red clay layer, the red clay becomes a relatively water-permeable layer because the permeability coefficient of the red clay is much smaller than that of the loess layer. Water gathers between the layers. The water content of the upper loess layer (Q2eol) is continuously increased. When the contact surface is softened by water, the pore water pressure is continuously increased, and the effective stress is continuously reduced, the most dangerous structural surface is formed in the layer, but when the slope rate is less than 0.7, the maximum shear strain at this point is not enough to make the soil Sliding occurs.

In addition, as the slope rate is gradually slowed down, the stability coefficient of the slope is continuously improved. When the slope rate is close to 1, the stability coefficient is greater than 1.5 and the speed of change becomes slower. When the slope rate is close to 0.4, the stability coefficient is close to 1.06, and the change speed is also slow; when the slope is at the middle slope rate, the stability coefficient changes rapidly, and there is a tendency of linear or exponential change. After combining with the previously obtained stability coefficients, removed the slope rate of 0.4 and 1.0, and we correlated analyze the remaining data. The correlation between the slope rate and the slope stability coefficient k are shown in the following table:

Table 6. Correlation table between slope cutting rate and slope stability coefficient.

| Related parameters | Stability coefficient |
|--------------------|-----------------------|
| slope cutting rate  | Correlation | Significant |
|                    | 0.966     | 0.000 |

and the linear and exponential fitting between the two variables are shown in the figure 7:
It is known from the table 6 that the correlation coefficient between cutting slope rate and stability coefficient is 0.966; and there is a positive correlation; and the significance is close to 0, indicating that the two variables have great significance. And from the figure 7, it is known that under these data points, the two fitting curves are very close, the linear and exponential equation:

\[ y = 1.6309x + 0.2096 \quad (R^2 = 0.934) \]  \hspace{1cm} (2)

\[ y = 0.5747e^{1.2046x} \quad (R^2 = 0.936) \]  \hspace{1cm} (3)

The two fittings obtained similar \( R^2 \) size and the fitting effect was good. In order to make it more convenient in the calculation, the calculation of the straight line equation can be performed in other similar cases.

5. Conclusion

According to the results of laboratory test analysis and numerical simulation analysis, the following conclusions are obtained:

(1) The slope of the study area is steep and has a high height. According to the results of site survey and numerical simulation, the shear deformation of the slope is mainly caused by the combined action of rainfall and slope foot excavation. The potential sliding surface is located in the silt-loess layer.

(2) It is found through indoor humidification test that with the increase of water content \( \omega \), the cohesive force of soil decreases in three stages, and the cohesion \( c \) between the two inflection points does not change significantly with \( \omega \), and the part outside the two inflection points, \( c \) decreases rapidly as \( \omega \) increases. As the water content \( \omega \) increases, the internal friction angle \( \phi \) does not change significantly.

(3) By simulating different cutting slope rate schemes, it is found that as the amount of sloped soil increases, the upper silt layer becomes thinner, and the most dangerous structural plane moves from the silt-loess layer down to the loess-red clay layer. The shear strain gradually becomes smaller and the slope tends to be stable.

(4) As the slope rate decreases, the slope stability coefficient \( k \) changes in a straight line in the middle part of the slope rate, which can provide data for other similar loess high slope treatment.

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