Stability analysis of Shijiaping landslide and its effect on the safety of a 750KV substation in Tianshui, China

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Abstract

As a part of Lanzhou East-Tianshui-Qian county electric power transmission project, one 750KV substation engineering was planned to build in Gangu County, Tianshui, China. However, field investigation revealed that an ancient Shijiaping landslide is situated on the left bank of the substation site. In order to assess the suitability of the substation site and ensure its safe operation, the evaluation of landslide stability and its effects on the site was performed. By using limit equilibrium method and numerical calculation, the results were drawn, which indicated that in natural state, the Shijiaping landslide is stable at present, yet creeping may occur in rainstorm season due to the softening of underlying mudstone. In the most adverse condition as the combination of rainstorm and earthquake, the landslide would be unstable. However, the landslide does not pose threat to the safety of the transformer substation site, for there is on chance for the occurrence of long run-out landslide. The results in the paper played an important role in guiding the siting of the substation and the transmission line.

Keywords: transformer substation, Shijiaping landslide, stability

1. Introduction

As a part of Lanzhou East-Tianshui-Qian county electric power transmission project, one 750KV substation engineering was planned to build in Gangu County, Tianshui, China. With the development of modern large-scale high-voltage transmission line laying projects, calls for strictly controlled foundation displacement of superstructures is becoming more and more important. Yet there exist many ancient landslides in northwest China, whose stability exerts great influence on the construction of the transmission lines. Related projects had been studied(Cui et. al., 2007; Li et al., 2007; Ren, 2012; Li, 2014) and yielded some profound results.

Fig.1 Location of Shijiaping Landslide

The planned substation was to be built at 300 meters away from north of Shijiaping, Xinxing town, Gangu county. It is 11.5km away from Gangu county (Fig.1). The traffic is convenient, the Gangu-Tongwei highway passes through on the 30 meters to the west of substation.

The landform in the studied region is mainly loess mountain ridge and fluvial terrace. Ancient landslides and debris flows are relative highly developed, which has reformed the geomorphology of this area. The substation is located on the loess deposit, near the substation there is the Sandu River with an incision depth of 30m. According to geological survey, this region belongs to geohazard incidental zone, Shijiaping large-scaled landslide is on the west of the substation. Meanwhile, this area situated in Ⅷ degree seismic intensity area. Hereby, the stability of the landslide will have a great influence on the safety operation of the substation.

The purpose of the paper is to answer whether the landslide would affect the safety of the substation. Site investigation, drilling, test pitting and trenching were carried out. Based on the above investigation, the engineering geological conditions of the site was evaluated. Limit equilibrium method and numerical stimulation were used to calculate the stability of Shijiaping landslide.

2. Geological settings

2.1 Climate

The study area belongs to warm temperate zone, with a subhumid climate. The annual average temperature is 10.2°C, extreme maximum temperature is 36.3°C while extreme minimum temperature is -19.2°C. The rainfall, about 480.8mm per year, presents an uneven distribution in a year. Annual average evapotranspiration is recorded as 1481.5mm. Geohazards such as landslides, rockfalls, debris flows are easily triggered by rainfalls with short duration and heavy intensity. As a typical seasonally frozen region, the maximum depth of permafrost is 51cm.

2.2 Tectonics

The convergence part of Longxi vortex structure incorporates with Qilv arcuate fold belt at this region, and structural features are relative complex (GDMG, 1971). Major structural traces are structural belt with NW direction and arcuate compressive belt with NNW direction. The dominated regional trend from northwesterly, which is parallel to Weihe River. Folds and faults are fairly developed, however, most structural traces are covered by thick wide-spread loess. Neotectonic movement in this region has resulted in strong uplift of crust and downward erosion of rivers.

2.3 Strata

All the systems in Cenozoic, ranging from the Paleogene to Quaternary, are represented in this region. The Paleogene rocks are essentially amaranthine shaly sandstone with pelitic texture and calcite cementation, it is sporadically exposed on both sides of Sandu riverbed and the gullies. The Neogene rocks are red clastic rocks with loess overlies them, which form the skeleton of loess mountain ridge. Outcrops are occasionally observed on gullies, heavy eroded mountains and Sandu River banks. The Quaternary rocks themselves are loose accumulations, they include black clay(Q_2), the Malan loess(Q_3^{pr}), first terrace and flood plan($Q_4^{al\text{-}pl}$), redeposited loess(Q_4^{1al}), gravity accumulation(Q_4^{2del}) and alluvial-pluvial sand and pebble(Q_4^{3al+pl}).The gravity accumulation spreads over the gullies and alluvial-pluvial fans, the materials mainly consist of deposits from landslides, rockfalls and debris flows, which is characterized by a mixed lithology with messy structure and different thickness(GPIHEG,2007).

2.4 Hydrogeology

The main stream in the study area is Sandu River, larger branches include Zaojiaoshu gully, Bailin gully, Ma'er'yu gully and Gongjiachuan gully. The Sandu River is rich in salt, its water quality is poor and inappropriate for irrigation. Lithology of phreatic aquifer is featured by glutenite with a buried depth over 20 meters, and the aquifer depth is about 2-4m. Groundwater flows from north to south, which is parallel to the strike of river valleys, both on the east of the site and right side of the Sandu River there is nonexistence of groundwater on the surface. The Sandu River is charged by rainfalls, and the rainfall intensity directly influence river level. The salinity of groundwater is relatively higher, and the TDS reaches 3.89g/L, which belongs to saline water. As to its pH value, it belongs to neutral water with pH value of 7.48. The water hardness is computed as 8.419meq/L, which belongs to hard water.

2.5 Earthquake

Five earthquakes have been recorded historically due to their significant regional influence. The basic earthquake intensity of this area is Ⅷ degree, which belongs to meizoseismal area. The PGA of this area is 0.20g, and characteristic period of the seismic response spectrum is 0.45s.

3. Characteristics of Shijiaping Landslide

The Shijiaping landslide lies at the left bank of Sandu River, east of the site. The slope body is about 1500m in length, and the maximum width is about 1500m, its level difference is 180m approximately. The front part of slope body is gently with a gradient of 10°, while its back part is steep, with a gradient of 17° . At the backscarp, the slope angle is generally 65° ~70° . Which presents an obvious armchair shaped structure, as Figure 2 shows.

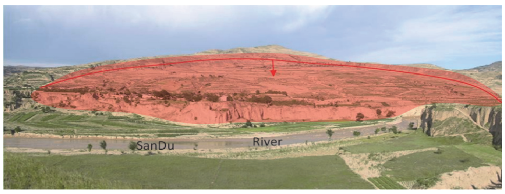

Fig.2 Overall sketch of Shijiaping landslide

Field investigations revealed that sinkholes and gullies are highly developed in landslide body. There are sinkholes parallel to the trailing edge and sidewall of the landslide, as Figure 3 illustrates. The sinkholes almost string-shaped distributed along the gullies, trailing edge and sidewalls of the landslide. Moreover, several rockfalls have been observed on the frontal parts near southern sidewall of the landslide.

The strata of landslide body contain Neogene rocks and Quaternary accumulations. The outcropped Neogene strata are mainly in gullies of the landslide body and partial areas along banks of Sandu River sporadically. The rocks are mainly mudstone with thickness more than 50cm. In the upper mudstone layer, vertical joints are highly developed. The rock would soften when it absorbed water, and cracked after losing water, i.e., it has the feature of water-expanding and dry dehydration. The Quaternary strata rocks are mainly the Malan loess, redeposited loess, silty clay, gravel soil, calcareous cemented conglomerate and flood plain deposits. Additionally, black clay with humus outcrops could be observed at local area. The Malan loess is thicker with a maximum thickness of 40m, vertical joints and sinkholes are highly developed in this layer. Mudstone interbedded with silty clay is also found in landslide accumulation. Six interlayers can be found from the borehole and trial pit exploration. Striation and mirror surface, as Figure 4 shows, could be easily observed, which implies that the landslide has suffered several slides.

Fig.3 Sinkholes in the leading edge and backscarp of Shijiaping Landslide

In the landslide accumulation body, groundwater is mainly perched groundwater in colluvial deposits and pore-phreatic groundwater in sand gravel layer. It is directly supplied by rainfalls. Relative water-resisting layer comprises of mudstone, due to the existence of perched groundwater, partial soil becomes saturated and its strength is relatively low. Consequently, hole collapse and necking have occurred during drilling.

Fig.4 Mirror surface and striation in drill cores

4. LEM stability analysis of Shijiaping landslide

Field geological survey and exploration reveal that the landslide terrain has been steady due to alterations of human activities, and no sliding events have been recorded since 100 years before. Besides, obvious deformation traces are nonexistent in trailing edge of the landslide. Therefore, it is believed that the landslide stays in stable state at present. However, with the increase of sinkholes, and downward erosion of gullies, accompanied by collapses of Sandu River banks, the landslide body would be severely fragmented and then its mechanical properties would be degenerated as well. Therefore, unexpected complex geological conditions would occur and thus exert an adverse effect on the stability of the whole slopes. To evaluate the safety of this substation site, limit equilibrium method (LEM) and finite difference method (FDM) (Chen et. al., 1995, Chen, 2003) were utilized to analyze the stability of the landslide.

Three kinds of state were considered in the calculation, natural state, rainstorm state, earthquake state and rainstorm simultaneous with earthquake state. Calculation methods of Morgenstern-Price, Janbu and Bishop are adopted respectively. I-I′ and II-II′ profiles were chosen to conduct the calculation (Figure 5 and Figure 6). With regard to I-I′ profile, two-stage sliding surfaces, the H1-1 and H1-2 slices are both calculated. There is only the perched water in landslide body without an unified underground water level, therefore, the impact of groundwater on slope stability can be ignored during calculations.

In natural state, the intensity of rainfall is weak, with a small permeability coefficient of the soil, the impact of rainfall is ignored when performing the calculation. In rainstorm state, the most unfavorable factors are taken into account, and the landslide accumulation is considered as saturated soil. Due to the existence of perched water and nonexistence of unified groundwater table, in addition, seepages of groundwater in toe of the slope are not seen. Therefore, seepage influence is excluded when performing stability calculation under the four state. When considering earthquake, a Ⅷ degree of the local basic seismic intensity is set for calculation. The factor of safety (FOS) under different conditions is listed in Table 1.

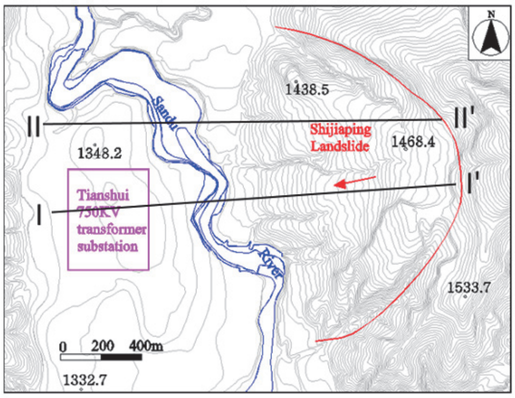

Fig.5 Topography of Shijiaping landslide

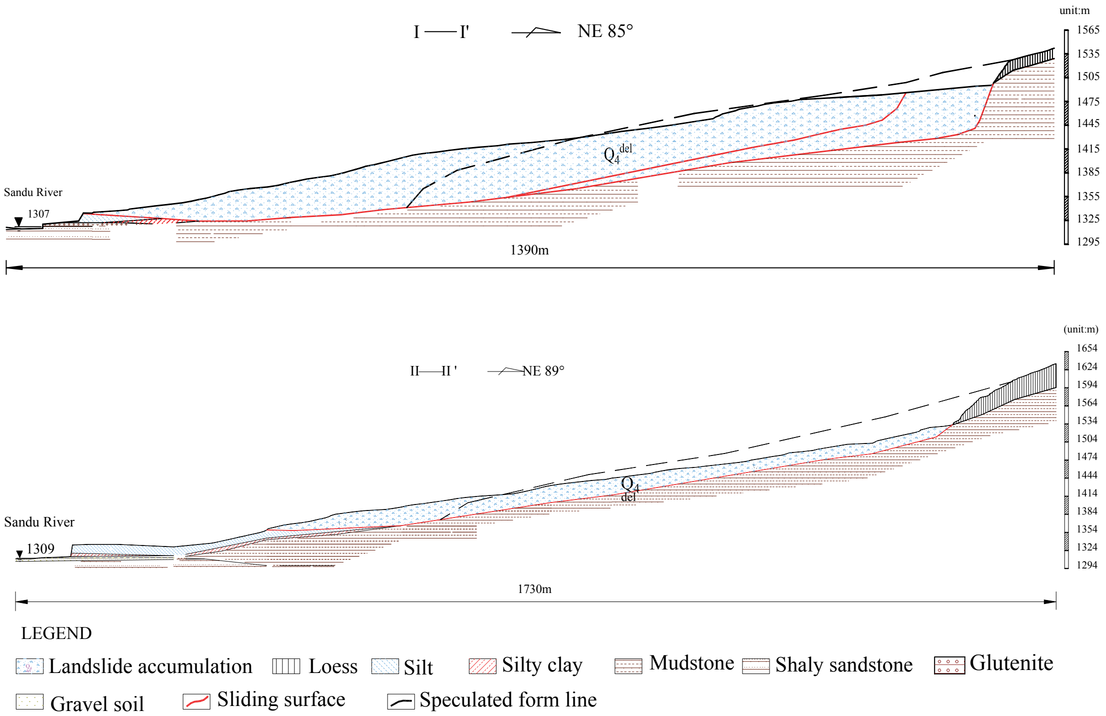

Fig.6 Engineering geological profiles of Shijiaping landslide

5. Numerical stimulation stability analysis

5.1 Modelling and boundary conditions

(1) Studied regions

Figure 7 showed the 3D terrain of the rectangular region to calculate, which includes the Shijiaping landslide and substation site. The east-west length is 2720m, and its south-north width is 2330m, the vertical scope range from surface to a certain distance of bed rocks (1100-1690m). Fig.8 illustrates 3-dimensional mesh plot of the model including 166320 elements and 93500 nodes.

(2) Boundary and initial conditions

A simple boundary condition was configured for calculation, which implies that a roller boundaries are placed on the four lateral sides of the model, while all the base nodes on the bottom are fixed in both vertical and horizontal directions, and the surface nodes are set free.

(3) Parameters and model configuration

The type of Shijiaping belongs to loess-mudstone landslide, its slide mass could be regarded as elasto-plastic materials. Therefore, the Mohr-Coulomb constitutive model is assigned to perform the calculation. The parameters used in the calculation were listed in Table 2.

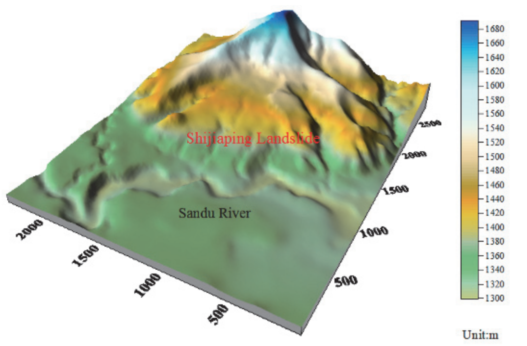

Fig.7 3D topographic map of Shijiaping landslide(unit:m)

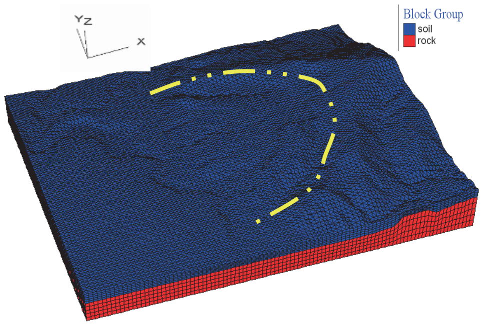

Fig.8 Mesh plot of Shijiaping landslide model

5.2 Design of numerical stimulation

The numerical stimulation is designed corresponding to cases in LEM stability calculation. According to the influences of different triggered factors in the evolution of landslide, deformation characters of the slope are stimulated under the condition of natural state, rainstorm state, earthquake state and rainstorm accompanied with earthquake state.

5.3 Results

(1) Stress analysis

Figures 9~12 illustrate the vector plots of principle stress in I-I', II-II' profiles under the condition of natural state and earthquake state.

As the figures demonstrate, the slope shape exerts directly influence on directions of principle stress in the slope, the direction deflects significantly near the slope surface, the minimum principle stress approaches to horizontal direction, while the direction of maximum principle stress is parallel to slope surface. Under the condition of natural state and rainstorm state, the minimum principle stress presents as compressive state. While in the situation of earthquake, earthquake & rainstorm, the minimum principle stress turns to tensile. Moreover, influenced by horizontal seismic force, the direction of principle stresses has changed significantly.

Table 1 Calculated factor of safety (FOS) of Shijiaping landslide under different conditions

Profile No.	Calculation method	Natural state	Rainstorm state	Earthquake state	Rainstorm & earthquake state
H1-1	Morgenstern-Price	1.73	1.266	1.292	0.945
	bishop	1.747	1.278	1.307	0.956
	Janbu	1.71	1.251	1.276	0.934
H1-2	Morgenstern-Price	1.900	1.394	1.389	1.019
	bishop	1.887	1.384	1.384	1.015
	Janbu	1.851	1.357	1.354	0.993
H2	Morgenstern-Price	2.006	1.442	1.486	1.068
	bishop	2.023	1.454	1.498	1.077
	Janbu	1.996	1.435	1.479	1.063

Table 2 Parameters used in the stimulation

Lithology	Elastic modulus (GPa)	Poisson's ratio ν	Density (KN/m3)	C (kPa)	Φ (°)	Tensile Strength (MPa)
accumulations	0.03	0.37	17.64	28.2	12.3	-
slip soil	0.08	0.35	18	38	15	-
mudstone	13	0.22	20	38.68	16.46	0.086
covering layer	0.02	0.38	16	20	25.7	-

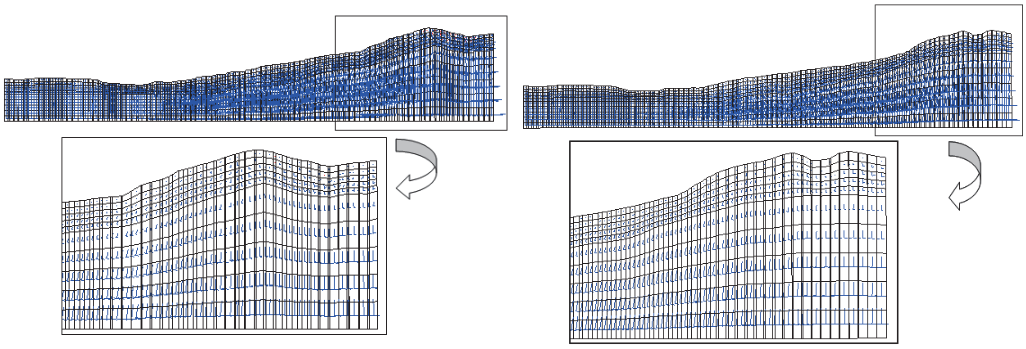
Section I-I'   Section II-II'

Fig.9 Principle stress plots in natural state

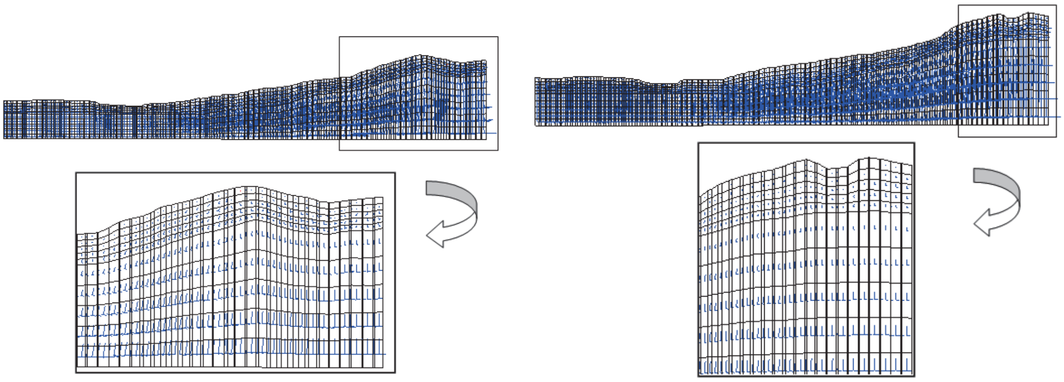
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Fig.10 Principle stress plots in rainstorm state

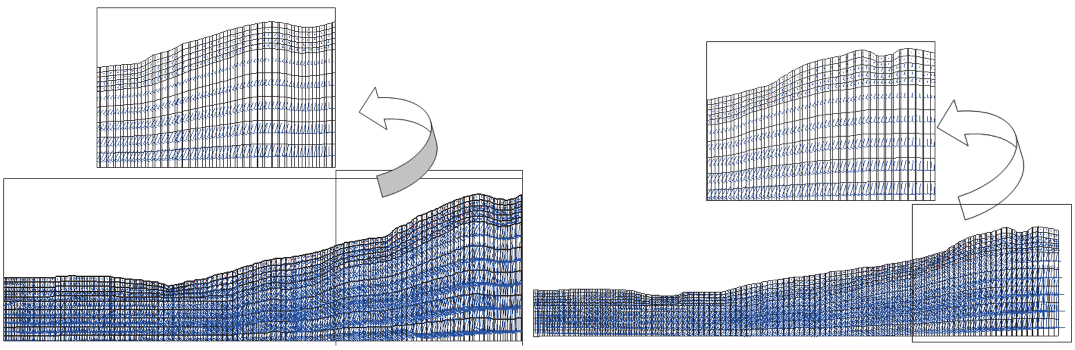
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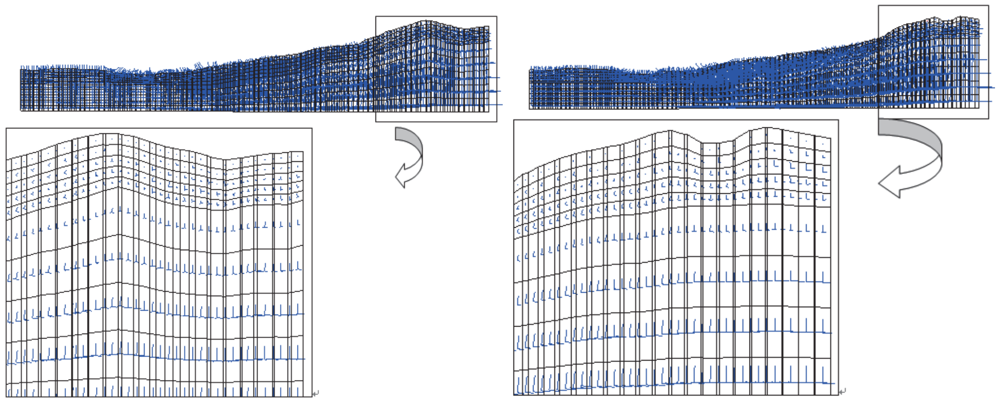
Fig.11 Principle stress plots in earthquake state



Section I-I' Section II-II'

Fig.12 Principle stress plots in earthquake & rainstorm state

(2) Deformation analysis

Figures 13~16 demonstrate displacement vector plot of I-I' profile and II-II' profile under different conditions.

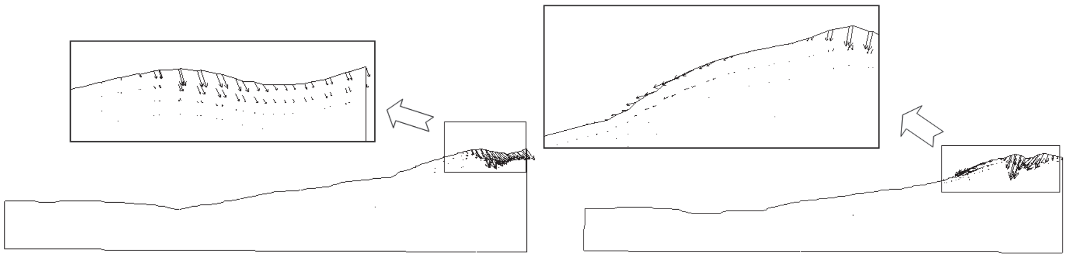


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Fig.13 Displacement vector plots in natural state

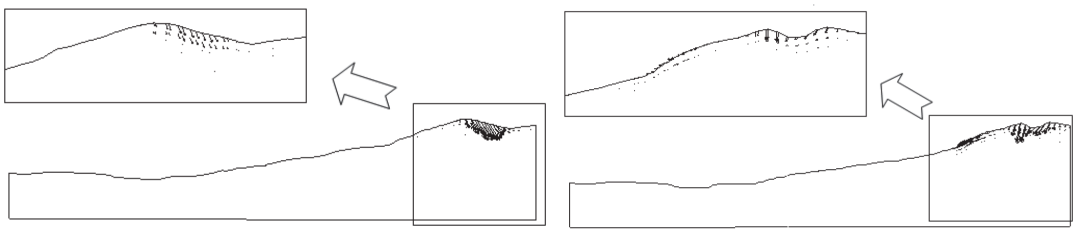

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Fig.14 Displacement vector plots in rainstorm state

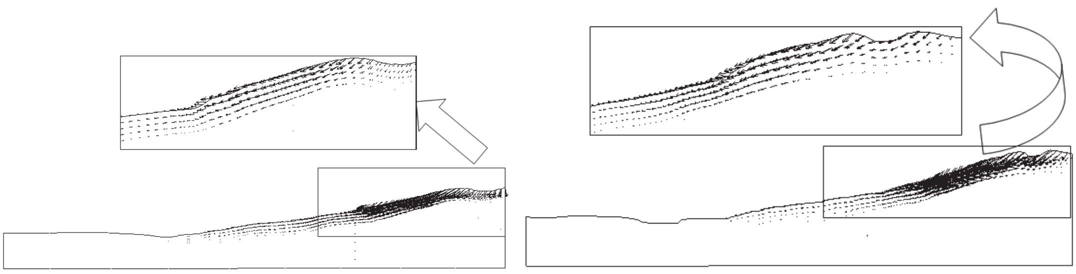

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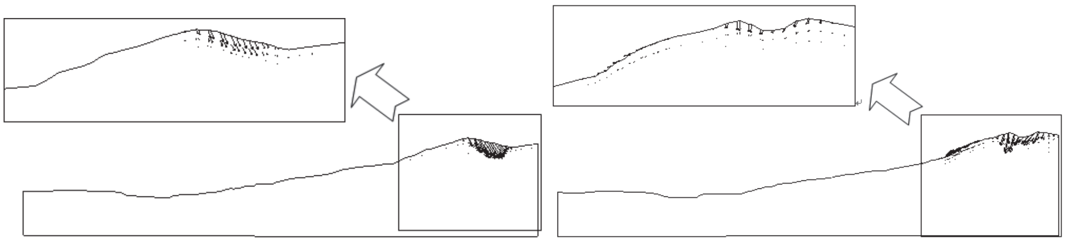
Fig.15 Displacement vector plots in earthquake state



Section I-I' Section II-II'

Fig.16 Displacement vector plots in rainstorm & earthquake state

As the figures illustrate, in natural state, due to the impact of slope shape, maximum displacement occurs at trailing edges. In I-I' profile, maximum displacement trends toward outside of the slope, which exerts no adverse effect on the slope stability. However, maximum displacement in II-II' profile trend toward inside of the slope, which puts an adverse influence on slope stability. In the situation of earthquake, the trend of displacement in the slope alters, and both the maximum displacements in I-I' profile and II-II' profile are parallel to their respective slop surfaces, and trend toward the inside of slope, which is unfavorable for the stability of the trailing edges.

6. Conclusions

Both from the perspective of geological microscopic assessment and quantitative calculation, it is concluded that the Shijiaping landslide can maintain its stability at present in natural state, which implies that the landslide could not fail thoroughly. However, as the strength of underlying mudstone decreases when soften in water, creeping would occur in the slope. Besides, under the condition of rainstorm and earthquake, the landslide would be unstable. Due to a gentle surface of the slope, there are little chance for Shijiaping landslide evolved into a remote landslide if it revives or partially fails. In summary, the landslide puts no direct threat to the site of substation.

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References

Chen,Z.Y., Zhou, J.X., Wang,H.J.(1995): Soil Mechanics [M]. Beijing: Tsinghua University Press.

Chen,Z.Y.(2003): Analysis of Soil Slope Stability [M], Beijing; China Water & Power Press.

Cui, F.P., Hu, R.L., Tan, R.J., Yang, K., Yu, J.Q., Zhang, M., Wang, L.C., Li, X. (2007): Study on formation mechanism and stability evaluation of Badashan landslide group in Qinghai Province, Chinese Journal of Rock Mechanics and Enginee ring, Vol.27, No.4,pp.848-857.

Gansu Division of Mines and Geology (GDMG)(1971):Regional Report of Geologic Survey on Qin'an (1:200000).

Gansu Prospecting Institute of Hydrogeology & Engineering Geology (GPIHEG) (2007): Risk Assessment Report on Engineering Geologic Hazard of Tianshui Transformer Substation of 750 KV.

Li, Y.Q., Yang, X.F., Li, Y.S., Su, X.Q. (2007): Stress-deformation characteristics of an ancient landslide at Dagang transformer substation site, Hydro-Science and Engineering ,No.3, PP.57-61.

Li, L., Xu, F.X., Zheng, Y.Q.(2014): Characteristics and stability study on landslide deformation of a 500kV transformer su bstation in Shiyan, China water Resources, No.4, PP. 59-60, 67.

Ren, S.L.(2012): Reinforcement scheme and stability aanalysis for the side slope, Shanxi Architecture, Vol.38, No.19, pp.61-63.

Sun,Y.K., Mu,H.C., Yao, B.K.(1988): Analysis of Rock Slope Stability [M], Beijing: Science Press.

Tang,D.X., Liu, Y.R., Zhang, W.S., Wang,Q. (1999):Geotechnical Engineering [M]. Beijing: Geological Publishing House.