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Influencing factors and development patterns of cracking–sliding failure of loess in China

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Abstract. Loess is a porous, weakly cemented, and unsaturated Quaternary sediment deposited in arid and semi-arid regions by the wind. It is widely and thickly distributed in China, making the Loess Plateau the largest bulk accumulation of loess on the Earth. However, the fragile geoenvironment in the loess areas of China causes frequent and various geohazards, among which, the Cracking-sliding (Beng-hua) is a typical failure mode because it causes the largest number of casualties each year. This study investigates the development pattern and main influencing factors of cracking–sliding failure to help in effectively preventing its occurrence and reducing losses. The following conclusions are derived: 1) cracking–sliding failures are prone to occur in rectilinear slopes, convex slopes, slopes with gradients greater than 60°, slopes with heights of 5 m to 40 m, and sunward slopes with aspects of 180° to 270°; 2) cracking–sliding failures occur mostly from 9 pm to 4 am the next day, and concentrates in the rainy season (July to September) and freeze-thaw season (March to May); and 3) the more intense the human activities in the region, the greater the possibility of cracking–sliding failures.

Keywords: loess, cracking–sliding failure, influencing factors, development pattern

1 Introduction

Loess (Huangtu in Chinese) is a porous, weakly cemented, and unsaturated Quaternary sediment deposited in arid and semi-arid regions by the wind. It is distributed in Asia, Europe, North America, and South America. In China, loess is distributed roughly along the north of Kunlun and Qinling Mts., south of the Altai and Helan Mts., and the Greater Khingan Range, forming a loess strip that stretches from NWW to SEE (Lei, 2001), with a total area of 6.4×10^5 km^2 covering 6.67% of the land area of China (Peng et al., 2014) (Fig. 1). The thickness of the loess deposit in China usually ranges from tens to hundred meters. In the area surrounded by the Liupan, Baiyu, and Huajia Mts. and Lanzhou City, the thickness of loess falls between 200 m and 300 m. In the area from the east of Liupan Mt. to the west of Luliang Mt., the thickness falls

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between 100 m and 200 m. The thickness is below 50 m at the northern foots of Qilian, Tianshan and Altun Mts., and the North China Plain (Lei, 2001).

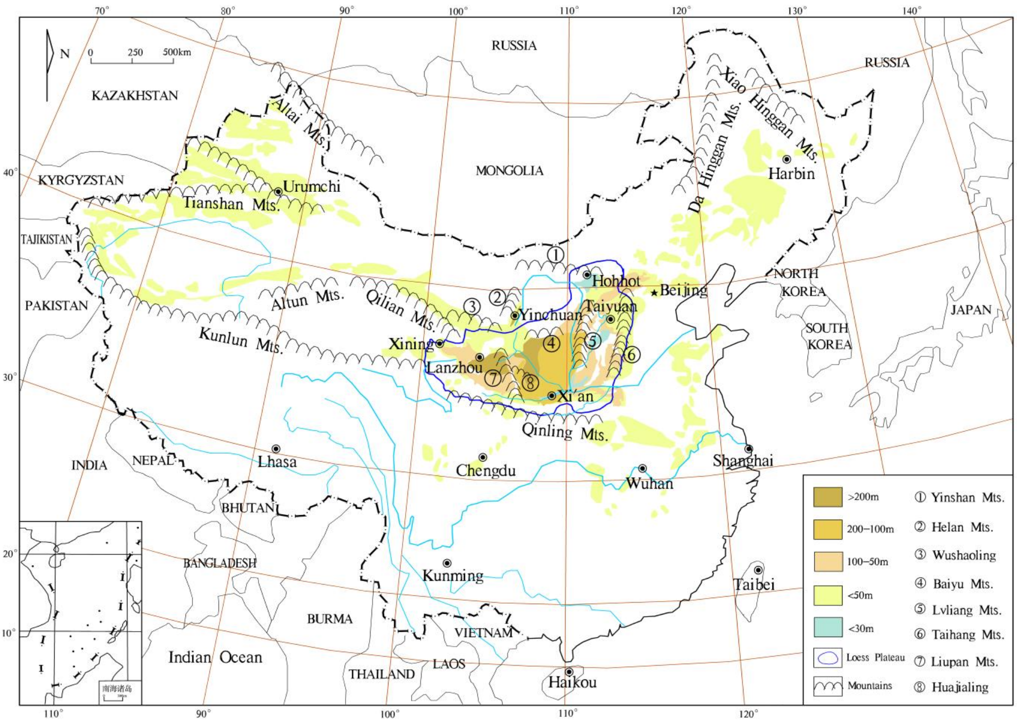

Figure 1. Thickness distribution of loess in China.

Loess consists mainly of silt particles and small amounts of sand and clay particles. Both the content of clay minerals in the loess and the degree of loess consolidation gradually increase with age (from Q_3 to Q_1) (Liu, 1985). The existence of dense pores and joints leads to a loose structure, cracking–sliding, toppling, and other types of failures triggered by some factors, such as rainfall, freezing and thawing, and daily temperature fluctuation.

The loess areas in China are rich in farming, forestry and animal husbandry, and industrial resources, with an arable land area of 173,000 km, which accounts for more than one-fifth of the arable land of the country and nourishes more than 200 million people (Zhang, 2014). However, geohazards, such as cracking–sliding, toppling, falling, sliding, peeling, and caving failures, occur frequently because of the fragile geological and natural environment and the excessive reclamation and unreasonable engineering activities. Among the geohazards, cracking–sliding failure causes the largest number of casualties (Lei, 2001) (Fig. 2). According to the historical record, 62 cracking–sliding failures occurred in Shenmu, Mizhi, Zizhou, and other places in Northern Shaanxi Province from 1985 to 1993, causing 258 deaths and more than 40 injuries (Qu

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et al., 2001). In 2005, the cracking–sliding failure in Jixian County, Shanxi Province caused 24 deaths and economic losses of nearly RMB 10 million. The loess failure with a volume of 2.5×10^4 m^3 in Zhongyang County, Shanxi Province in November 16, 2009 caused 23 deaths and destroyed 6 houses. In 2013, 36 loess failures occurred in Tianshui City, Gansu Province (Xin et al., 2014). More recently, a cracking–sliding failure occurred in Linxian County, Shanxi Province that buried four families with nine people in 2015. The above events warrant a deep understanding of the factors that cause loess failures and a clear view of the development pattern of loess failure to prevent the continuing deterioration of the morbid environment in the loess area of China and to reduce the occurrence of such geohazards.

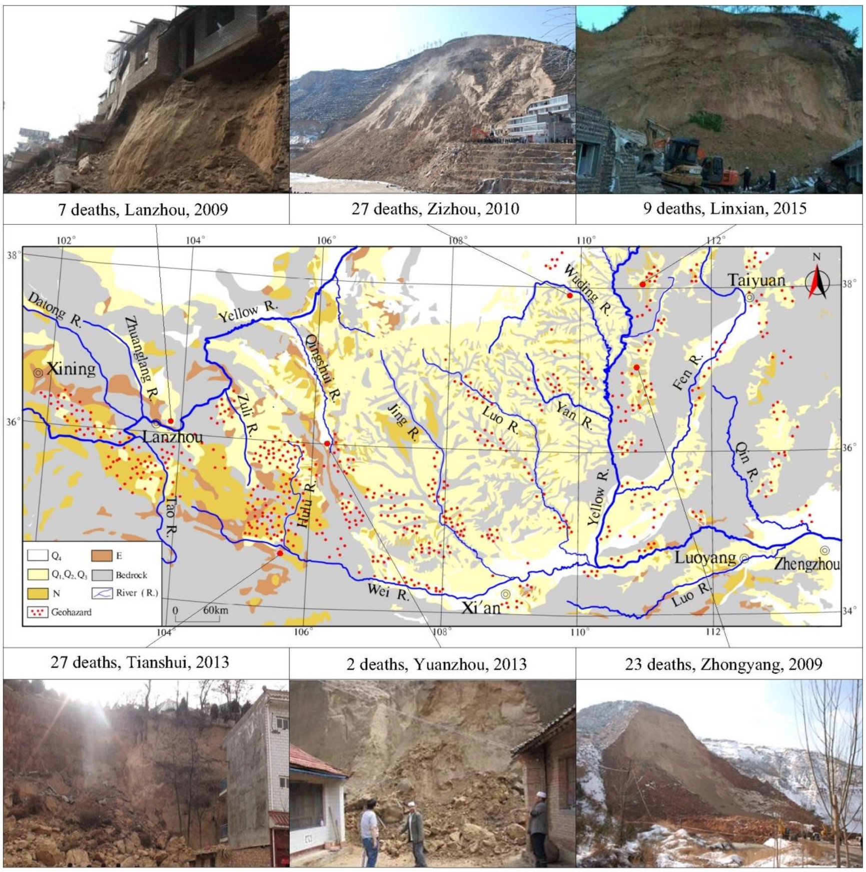

Figure 2. Distribution of cracking-sliding failures of loess in China.

Note: Q_4 - Holocene loess; Q_3 - Late Pleistocene; Q_2 - Middle Pleistocene; Q_1 - Early Pleistocene; N - Neogene; E - Paleogene; Bedrock - Cretaceous and Pre-Cretaceous strata.

In this study, a large set of data on loess cracking–sliding failures is obtained from the published literature. Based on the statistical analysis, the internal and external causes of

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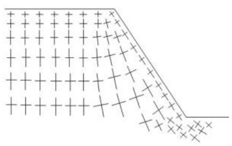
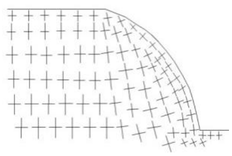
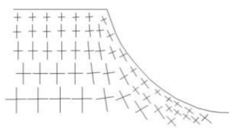
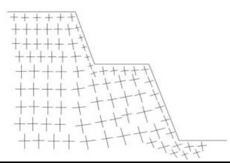
cracking–sliding failures are summarized. Emphasis is given to the influences of slope features (i.e., slope type, gradient, height, and aspect), rainfall, freezing and thawing, daily temperature fluctuation, and human engineering activities.

Table 1. Classification of loess slopes. Note: # - susceptible to cracking-sliding failure

Slope type	Characteristics	Characteristics	Susceptible#?
Rectilinear		The profile of the slope is straight or nearly straight; the slope gradients are fairly large and are constant from the top to the bottom parts; the stability is low.	Yes
Convex		The slope profile is gentle at the top and steep at the bottom parts; the slope shoulder shows convex; the stability is generally poor.	Yes
Concave		The slope profile curves inward; the gentle slope in the lower part has a supporting effect on the steep slope in the upper part; given the same slope height and average slope angle, it is more stable than other slopes; the stability is fair.	No
Stepped		The slope profile is stepped, while each step is linear; the average gradient of the overall slope is generally small; the stability is good.	No

2 Internal factors

Previous studies normally divided loess slopes into four types in terms of slope profile: stepped, convex, rectilinear, and concave (Table 1). Fig. 3 shows the classification of loess slopes in Yan'an area, Shaanxi Province, China. The stepped slopes account for 40% of the total number; convex slopes follow with a percentage of 30%; rectilinear slopes are fewer, accounting for 20%; and the number of concave slopes is the least, accounting for only 10%. However, the statistical analysis of the 470 occurrences of loess failures in this area indicates that rectilinear slopes are the most susceptible to cracking–sliding failure (212 occurrences, accounting for 45% of the total of 470), followed by the convex slopes (156 occurrences, accounting for 33%), and the stepped

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and concave slopes are the least susceptible (51 for each; 11%, respectively) to such failures (Fig. 4). Generally, the overall gradients of rectilinear and convex slopes are steep, resulting in large internal stresses and stress concentration, especially at the shoulder and toe parts (Table 1). The gentle slope at the bottom of the concave slope has a supporting effect on the steep upper slope, relieving the stress concentration because the maximum shear stress at the foot of the concave slope is typically only one-half that of the rectilinear slope (Zhang et al., 2009). The stress distribution pattern in each step section of a stepped slope is similar to that of the rectilinear slopes. However, the magnitude of internal stress is much less than that of the rectilinear slopes because of the small height of each step and the gentle overall gradient of the whole slope.

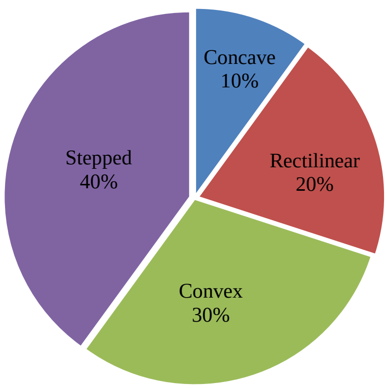

Figure 3. Percentage distribution of loess slopes in Yan'an area, Shaanxi Province. (Data source: Qin et al., 2015).

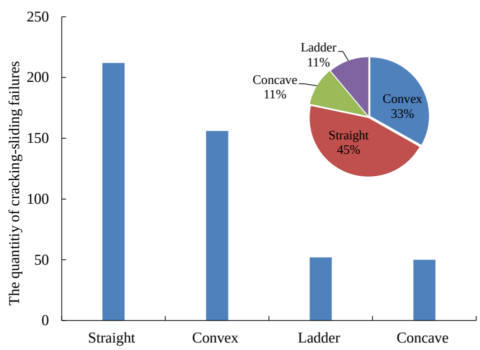

Figure 4. Relationship between cracking-sliding failures and slope types in Yan'an area. (Data source: Qin et al., 2015).

In addition to the slope profile, the gradient, height, and aspect of loess slopes are found to have close relationships with the occurrence of cracking–sliding failures. Fig. 5a shows that the failure occurs mostly on slopes with gradients greater than 60°, and the number of failures increases significantly with the gradient (Fig. 5a). According to the statistical analysis of the available data, 18.5% of the cracking–sliding failures occurred on slopes with gradients ranging from 61° to 70°, 24.9% occurred on slopes with gradients of 71° to 80°, and 44% on slopes with 81° to 90° gradients. This is because gradient affects the stress distribution inside the slope the most. Fig. 6 shows the tension band, which is developed from the transformation of the radial and tangential stresses into tensile stresses at the shoulder of a slope. The steeper the slope is, the wider the tension band would be; in addition, tension cracks are more likely to form near the shoulder part, resulting in cracking–sliding failures (Zhang et al., 2009).

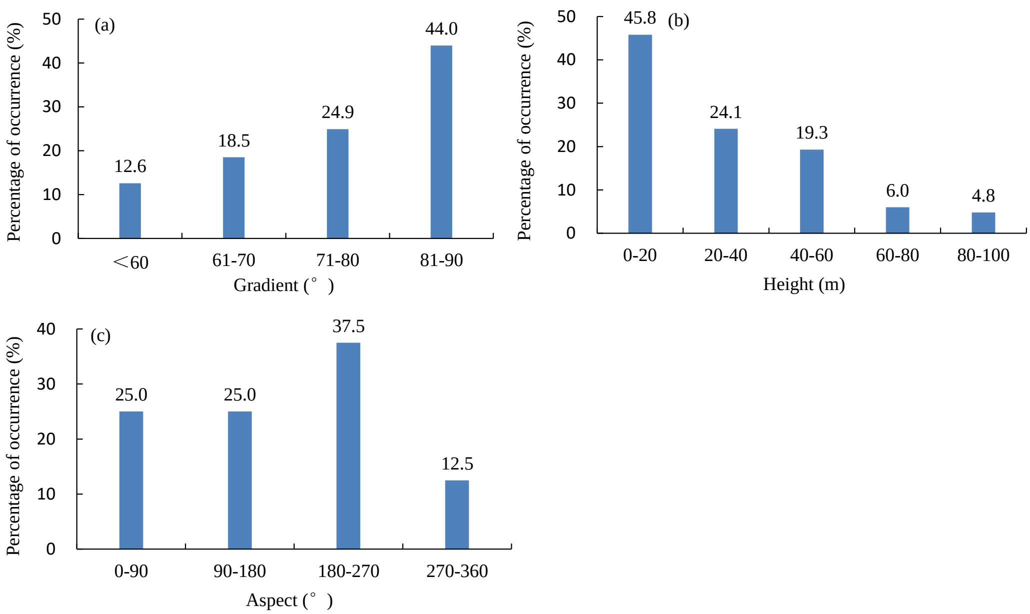

Figure 5. Effect of slope features on cracking-sliding failures of loess. (Data source: Qin et al., 2015; Yang, 2010; Mao, 2008)

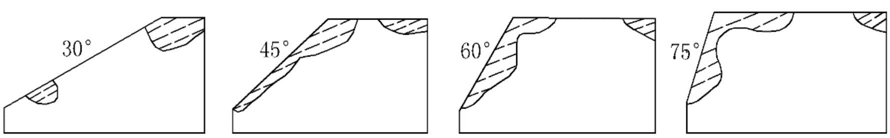

Figure 6. Development of tension band in slopes of different gradients. (Zhang et al., 2009)

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Fig. 5b shows that slope height is another main factor that controls the occurrence of cracking–sliding failures. In Huangling County of Shaanxi Province, most of the cracking–sliding failures occurred on slopes with heights of 5 m to 40 m, accounting for 89.2% of the total number of occurrences. The remaining 10.8% occurred on slopes with heights of more than 60 m. A higher slope normally develops a gentler gradient because of the long-term weathering and erosion. By contrast, slopes with lower heights are generally steeper (Zhu et al., 2011), being more prone to collapses.

As shown in Fig. 5c, the sunward slopes are more prone to the development of cracking–sliding failures than the shady slopes. The statistical analysis of 31 loess failures in Huangling County, Shaanxi Province shows that 62.5% of the cracking–sliding failures occurred on slopes with aspects ranging from 90° to 270°, especially within 180° to 270°. This may be because of the fact that sunward slopes receive long sunshine hours and the soil temperature is relatively high during the day. Therefore, a large temperature difference between day and night exists. Furthermore, sunward slopes are generally subjected to more weathering, resulting in fractured structures, which are not conducive to slope stability. Furthermore, people usually reside on the sunward slopes, and dense human engineering activities exert a large degree of disturbance on the slope body, which increases the occurrence of failures.

3 External factors

3.1 Rainfall

Rainfall shows a great effect on the stability of loess slopes according to the monitoring data from the Chinese government. The number of loess failures triggered by persistent rainfall accounts for about 65% of the total number of the failures in the Loess Plateau (Du, 2010). From 1974 to 2003, 25 loess failures caused by rainfall occurred in the urban area of Lanzhou (Gao et al., 2012). In Shanxi Province, the collapses caused by rainfall accounted for more than 62% of the total in the same period (Huang et al., 2016). The cracking–sliding failures that occurred in Shilou County in August 2013 and in Linxian County in July 2013 were both induced by rainfall.

The seasonal variations of rainfall are significant in the Loess Plateau, although the annual average rainfall in this area is low (400–800 mm). Rainfall is mainly concentrated from July to September, accounting for about 60% of the annual rainfall (Qian, 2011). In Yan'an City, the maximum precipitation in one hour can accumulate to as much as 62 mm in summer (Zhu, 2014). From early July to early August in 2013, the total rainfall in Shilou County reached 412 mm (Lv, 2011), accounting for almost 80% of the annual amount. Fig. 7 shows the relationship between the number of loess collapses and the rainfall in three provinces, namely, Shanxi, Shaanxi, and Gansu. The number of loess failures indicates a close positive correlation with the rainfall. From July to September, the rainfall in these three provinces accounted for an average of 57% of the total rainfall for the year, and the number of collapses accounted for 49% of the total for the year.

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Rainfall induces loess collapses in three ways: splash erosion, shovel runoff, and seepage. At the beginning of rain, soil particles with poor adhesion are separated and broken under the impact of raindrops. When the potholes formed by the splash erosion are filled with water, a layer of water flow forms and triggers small soil particles to move. Along with the continued rain, this water flow converges into the slope runoff to further erode and destroy the slope (Tang et al., 2015). In the case of persistent rainfall, preferential seepage pipes are usually formed inside the slope, saturating the soils, reducing the shear strength, and eventually leading to collapses.

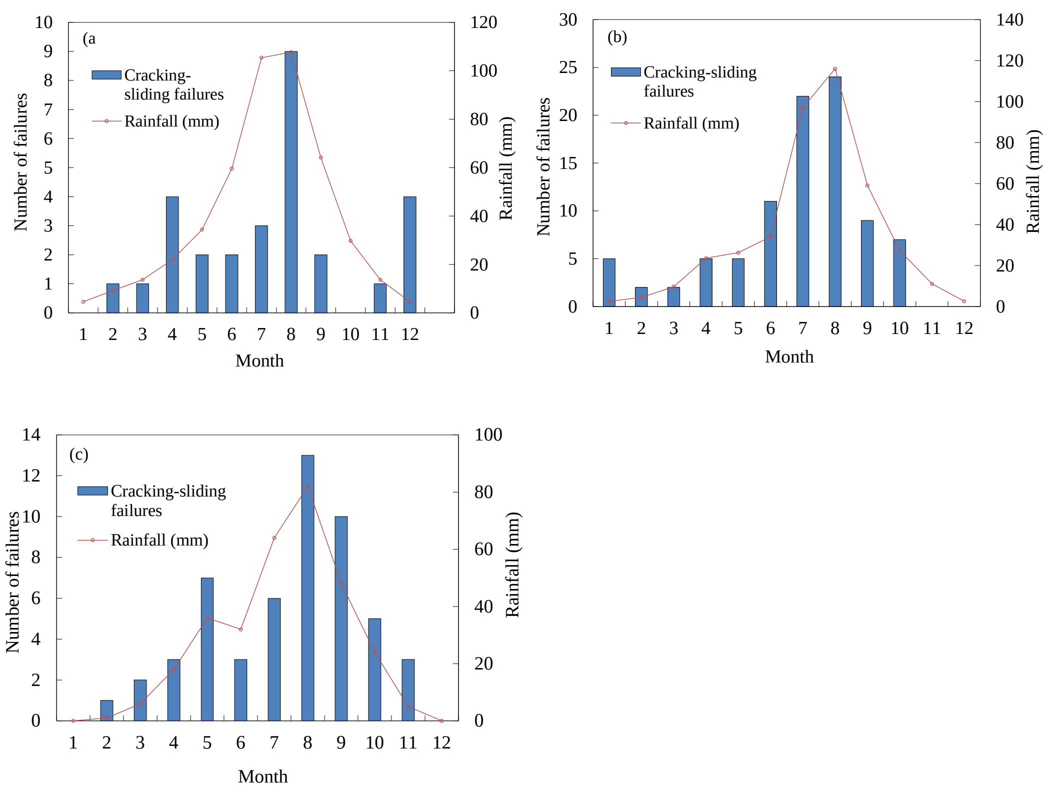

Figure 7. Relationship between loess failures and rainfall: (a) Shanxi; (b) Shaanxi; and (c) Gansu Provinces. (Data source: Wei, 1995; Gao, 2012; Liu et al., 2012).

3.2 Freezing-and-thawing

Fig. 7 shows that cracking–sliding failures also occur frequently from March to May, besides the rainy season from July to September. This period is the transition from winter to spring. The soil temperature rises quickly from a value below zero to a value above zero. As shown in Fig. 8, the temperature of the soil remains negative and the frozen depth can go to about 1.0 m down from December to February in the loess areas of China. At the end of March, the ground temperature

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begins to rise and the frozen layer gradually enters the thawing stage, and the soil is quickly heated up to about 8 ℃ by mid-April.

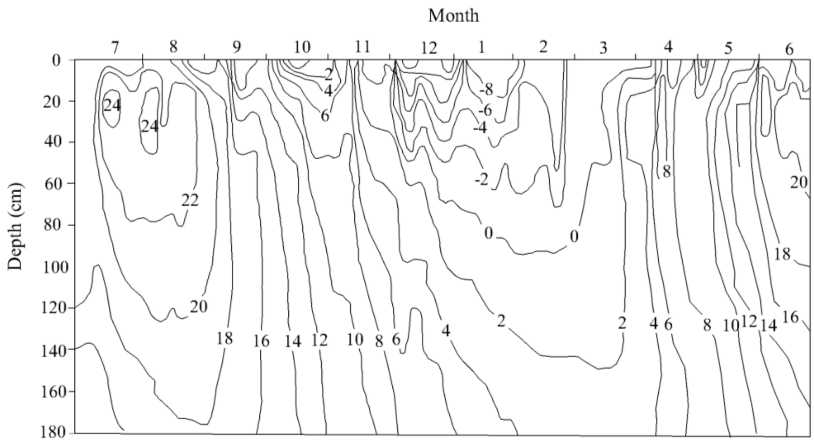

Figure 8. Monthly variation of ground temperature in loess slopes. (Yang and Shao, 1995).

Freezing and thawing mainly promote the occurrence of cracking–sliding failures via the following two ways: 1) frost heaving damages the soil structure and reduces soil shear strength. The loess itself contains a great number of large pores, and frost heaving further increases the distance between soil particles, reduces the dry density of soil, and loosens the structure, thereby reducing its cohesion and internal friction angle; and 2) thawing causes the loess to collapse and reduces its shear strength. Thawed water can dissolve the cement (especially calcareous cement) between loess particles, damaging the loess structure and increasing pore water pressure, thereby reducing the shear strength of the soil (Pang, 1986).

3.3 Daily temperature fluctuation

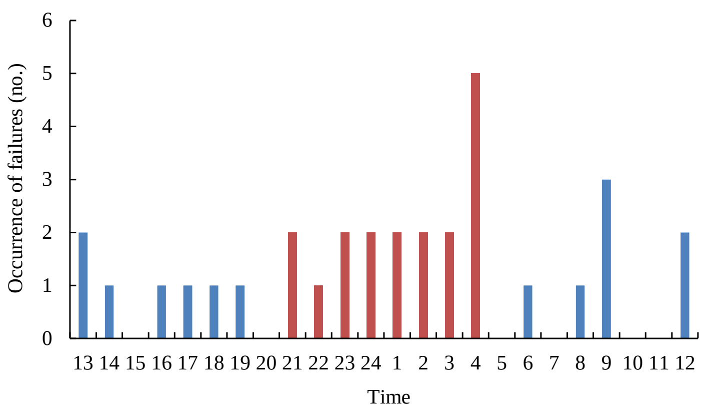

Figure 9. Temporal distribution of cracking-sliding failures in a day. (Data source: Wei, 1995).

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The statistical analysis of 32 cracking–sliding failure cases that caused deaths in the northern Shaanxi Province shows a high frequency of occurrence of such failures between 9 pm to 4 am the next day (Fig. 9).

The difference of temperature between day and night in the loess area is more obvious than that in other regions in the same latitude (Sun and Zhang, 2011), and the difference can reach about 10 ℃ in both winter and summer (Fig. 10). A significant daily temperature variation of soils within 80 cm depth was observed based on the monitoring in the Loess Plateau from November 2004 to October 2005 (Sun and Zhang, 2011). Thermal expansion and contraction occur during the quick change in the day-and-night temperature. Under the cyclic functioning of the shrinkage and expansion stresses, the soil structure is loosened.

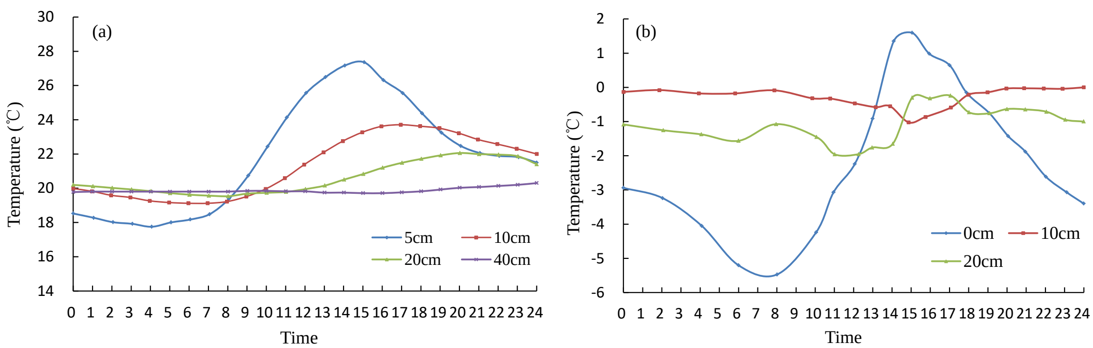

Figure 10. Variation of soil temperature in loess areas of China: (a) summer; (b) winter. (Data source: Li et al., 2012; Zhang, 2014).

3.4 Human activity

The loess area of China holds a population of more than 200 million. Human engineering activities are frequent and mainly involve cutting slopes for buildings, excavation for cave dwellings, construction of terraced fields, and construction of roads. Cutting slopes for buildings causes the side slope to become steep. The unloading-induced tensile fractures are usually produced on the trailing edge of the slope during the rapid adjustment of the stress field within the slope (Fig. 11a). When a cave is excavated, roof damage (normally caving) occurs because of the local tensile stress concentration if the design of the geometric section of the cave is improper (Fig. 11b). The terraced fields change the original path of the surface runoff and enhance rainfall infiltration. Together with irrigation, they increase the water content of the loess slopes and raise the phreatic level (Fig. 11c). The majority of traffic lines in the loess area stretch along valleys and bank slopes. Slope cutting and excavation during road construction result in a large number of high and steep side slopes, which provide a breeding environment for failures (Fig. 11d).

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An investigation of the cracking–sliding failures, which occurred within five years in Shanxi Province and within one year in Huangling County, Shaanxi Province, shows that more than half of the failures occurred because of human engineering activities (Fig. 11). Among the 16 failure cases that occurred in 2014 in Yan'an, 9 were related to the over-steep slopes for the construction of cave dwellings and the other 7 were consequences of the improper treatment of the side slopes for road construction (Lei, 2001). These demonstrate that the more intense the human activities are, the greater the probability of loess failures.

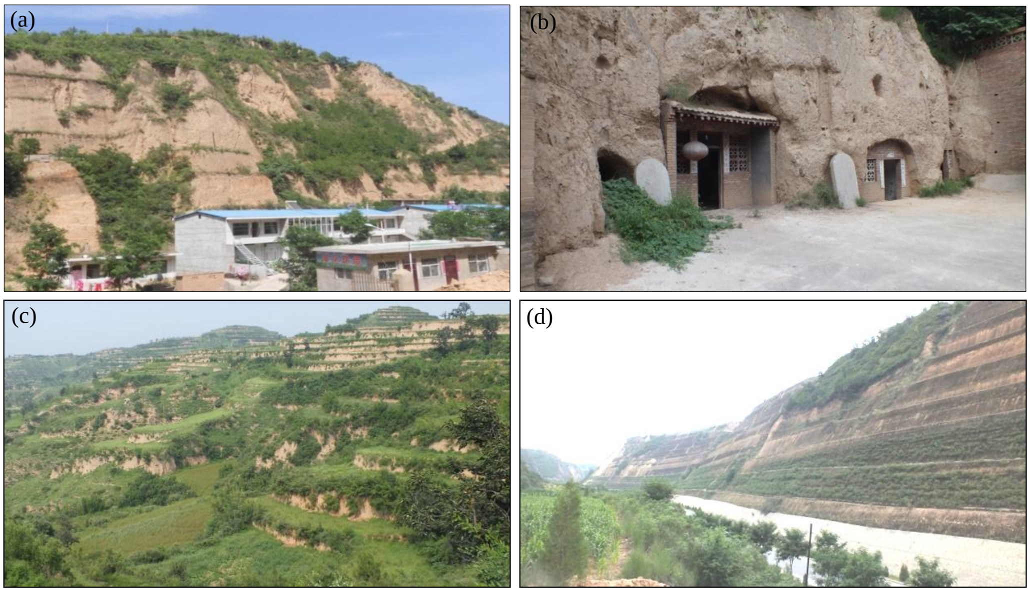

Figure 11. Typical human engineering activities in loess areas of China: (a) cutting slope for buildings; (b) excavation for cave dwellings; (c) construction of terraced fields; and (d) construction of roads.

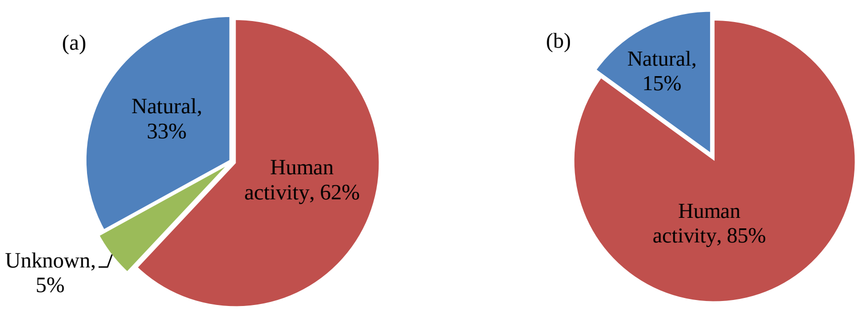

Figure 12. Responsibility of human engineering activities for loess failures: (a) Shanxi Province; and (b) Huangling County, Shaanxi Province. (Data source: Yang, 2010).

4 Conclusions

This study investigates the influencing factors and the development pattern of loess cracking–sliding failures in China according to the large collection of data from the literature. The following conclusions are reached.

(1) The influencing factors of cracking–sliding failure are divided into internal and external causes. Internal causes include the features of loess slopes (e.g., slope geometry, height, gradient, and aspect), while external causes include rainfall, freezing and thawing, temperature fluctuation, and human engineering activity.

(2) Cracking–sliding failure is more likely to occur in rectilinear and convex slopes than in concave and stepped slopes. The gradients of rectilinear and convex slopes are generally steep, the stress concentrations are obvious, and the slope stability is poor. The stress concentration in concave and stepped slopes is minimized, and the stability is fair. Cracking–sliding failure is more likely to occur on slopes with gradients greater than 60°, and the greater the gradient is, the higher the likelihood of failures. Cracking–sliding failure is prone to occur on slopes with heights of 5 m to 40 m. Slopes below 5 m have low internal stress and high stability. Slopes above 40 m are generally gentle with low stress concentration. The dominant aspect for the development of cracking–sliding failure is within 180° to 270° (sunward slopes) because of the obvious temperature difference between day and night and strong weathering.

(3) The occurrence of cracking–sliding failure demonstrates a certain time pattern. Within a year, the occurrence of cracking–sliding failure coincides with the seasonal rainfall. Failures are mainly concentrated in the rainy season from July to September. In addition, failures occur frequently from March to May because of freezing and thawing. Within a day, failures occur mostly from 9 pm to 4 am the next day because of the huge temperature variation between day and night.

(4) The more intense the engineering activities, the greater the possibility of loess failures. Human engineering activities in loess areas include cutting slopes for buildings, excavation of cave dwellings, construction of terraced fields, and construction of roads. These engineering activities usually lead to a quick change of the features and stress field of slopes. The high and steep side slopes so formed tend to develop unloading-induced tensile fractures, increasing the possibility of loess failures.

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