The authors thank the reviewer and editor very much for their encouraging and constructive comments. All comments have been addressed in this revision.

1. Research is poorly described, as well as the available datasets. No description on how data were collected has been provided, nor the data types (landslides are points or polygons, vector or raster?). As it is, the paper does not contain either novel data or new ideas/insights based on data collected by previous researchers. The only statistical analyses applied to data presented consist in a percentage comparison, which is rather simplistic compared to the many possible approaches applicable to analyse the influence of a set of variables on landslides occurrence, which is evident from the specific literature worldwide.

Response:

The paper is based on a painstaking review of numerous unpublished reports presented to the local governments and published literature. The factors influencing loess failures in the Loess Plateau of China are determined from the selected failure cases. Though the discussion utilizes statistics of these factors, the main goal is achieved through demonstrating the correlations between loess failures and slope features (slope shape, angle, height, etc.), daily time period (from 10 pm to 4 am the next day), annual time periods (July to September, March to April) and human activities.

Description of data types, sources, collection and validation have been added in the revision. This is further explained in our response to the next comment below.

2. It is not clear to me where do the landslide data come from, what is their spatial, temporal and thematic accuracy, and, above all, their degree of homogeneity within all these accuracies. It is not clear what type of inventory is used (event, archive…) and which sources were used to get data. Even though the information comes from scientific literature, the authors appear not to fully handle the possible inhomogeneity of their data, and, therefore, the quality of the dataset.

Response:

The dataset is from two sources: the events recorded by the government office and the events reported in publications. Both types were originally collected through field surveys, which were normally conducted within 1 to 2 days after each event. There are standard procedures to maintain the accuracy and reliability and therefore the quality of the dataset. The data cited in the scientific literature were individually verified and sifted by referring to the original records in the relevant government offices.

A description of the origin and nature of the dataset has been added in the revision. Please find it in **Section 3 Dataset**.

3. The study area is 6.4×105 km2, twice the surface of Italy, for example. In a landslide prone area such as the loess plateau, I am expecting a much larger dataset

than a few hundreds (I take this number from a rough estimation of red dots in Figure 2). In such large areas, it is just not correct to simply draw some considerations from a small subsample of the landslides data available and extending them to areas where climatic, morphologic, anthropic, geologic conditions are (sometimes sensibly) different. In other words, to what extent the authors can extend to more than half a million square kilometre area the monthly ground temperature variations (Figure 8), or the daily temperature variations? For instance, daily temperature variations are considered for a small sample of 32 landslides. It is not stated where the sample is located, or if that location may be thought representative of all the Loess plateau. The same applies for the rainfall induced events. Comparing plots of figure 7, it is not clear why the Shaanxi has so many more failures of the other places. Is it just a larger area or it is an expression, for example, of the climatic variability inside the Loess plateau? I would have liked that the authors had pointed that out, and properly commented. If any, what areas can be represented by the Shaanxi? Why is it so different from the others in terms of rainfall thresholds? In the slope classification (Secion 2), again data are taken by a local study of Shaanxi and then applied to the whole Loess plateau. To what extent is it representative of an area that crosses two climatic zones?

Furthermore, also the temporal factor is important. For instance, temperature data come from observations that were obtained from a monitoring activity that last one year (from Nov 2004 to Oct 2005). Authors do not mention or deal with possible problems of temperature trends. Was it an average year, or it was an exceptionally cold/hot one? If available, a plot of the average temperature of the last (or even following) 10 years would have helped.

Response:

We updated **Section 2** and **Section 3** according to the reviewer’s comment.

The study area has been limited to the east of the LPC covering the regions of Northern Shaanxi and Western Shanxi provinces, considering their homogeneous background of climatic, morphologic, geologic, and anthropic conditions. Please refer to Figure 1 in the revision.

Data pertaining to rainfall are obtained from the records of 75 meteorological stations (blue 102 dots in Fig. 1), which are almost uniformly distributed across the study area. Statistical analysis shows that the variation in average annual rainfall in the past 15 years among these stations is less than 80 mm, indicating a relatively homogeneous climatic condition over the study area.

A description of the temperature data is added. As shown in Fig. 8, the average daily temperature of August is from a field monitoring from April 2014 to September 2017 in Linxian County, Shanxi, China.

4. Geography of area is not characterized. Elevations, slopes, aspects, hypsometry, should be statistically described. A little geomorphology and geology is described, but I expect something more clear and structured. There is no section on study area, with

subsections dealing with geography, geomorphology, climate, and geology. In such broad studies, a reader expects these sections to be a frame to the analyses.

Response:

Section 2: Study area describes elevations, slopes, aspects etc in the study area. It should be noted that the cracking-sliding failures are developed within the loess layer. The loess is uniform in color, mineral and chemical composition throughout the Loess Plateau and does not show any relation to the local bedrock. It overlays bedrock and continuously covers basins, slopes, hills, valleys and terraces, making the present-day topographic relief consistent with the underlying terrain. This means that there is an identical geomorphology and geology over a broad area. This is also why we do not take geology as a factor to analyze.

5. Language is often too generic. For example, words like “large dataset”, “poor stability”, “fair stability”, “good stability” shouldn’t be used in academic English of scientific papers. I also disagree with the term “cracking-sliding” as a type of failure. None of the existing landslides classifications encompass that term. Authors should find terms compliant with published nomenclature. If they are proposing a new nomenclature term, they should say that explicitly, and justify it in detail, it should be a totally different paper.

Response:

The mass movements in loess area of China are frequent and varied in forms of toppling, falling, cracking-sliding, sliding, peeling and caving. Among these modes, the cracking-sliding failure is the most common type at volumes of the order of 100 m^3. The following explanation for the cracking-sliding failure mode has been involved in the revision:

Unlike “flows” or “slides” as defined by Cruden and Varnes (1996), the cracking-sliding failures have composite failure planes, which are composed of two parts. The upper part normally develops vertically from the crown of the slope down to one to several meters deep. It is formed by tensile cracking and a slope can stand for a long time with such cracks before it fails. The lower part is generally inclined at an angle ranging from 15 to 60 degrees. The sliding, triggered by rainfall, freezing-thawing, daily temperature fluctuation, slope undercutting and earth tremors, along the lower part is thought to mobilize cracking-sliding failures. More than 1000 cracking-sliding failures were recorded in the past two decades caused on average more than 100 fatalities per year, despite small volumes of individual failures.

6. The manuscript does not follow a structure accepted for a scientific paper. (i.e. Introduction, study area and available data, methods, results, discussion, conclusion). In particular, I disagree with the idea of not writing a Discussion section. Instead, the authors have chosen to add very simple considerations while presenting some (unclear) data, which is scientifically questionable. Furthermore, the factors hypothesized to be influent for the development of “cracking-sliding” failures are presented singularly,

therefore the interaction of these factors, and their specific role or possible chains of processes inducing landsliding remains hidden and unclear.

Response:

As suggested, sections were added to present the study area and dataset. Explanations and discussions was revised accordingly.

The interaction of influential factors cannot be determined from the existing dataset and is out of the scope of this paper.

7. References are only from China, whereas loess research is not only produced in China, but also in all the other countries where loess deposit is present (as the authors point out).

Response:

We referred to and included the most relevant international publications, e.g., Smalley et al., 2011; Stacey, 1970; and Sprafke and Obreht, 2016.

Influencing factors and development patterns of cracking–sliding ~~failure~~ ~~of~~failures in loess across the east of the Loess Plateau in China

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Abstract: Loess is a porous, weakly cemented, and unsaturated Quaternary sediment deposited by the wind in arid and ~~semi-arid~~semiarid regions~~ by the wind. It~~. Loess 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-~~such as cracking–sliding ~~(Beng~~failure (“beng-hua~~)~~” in Chinese), which is a typical ~~failure~~ mode ~~because it~~that causes the largest number of casualties each year. This study investigates the ~~development pattern and~~ main influencing factors and development patterns of cracking–sliding failure of loess to help ~~in effectively preventing~~prevent its occurrence and ~~reducing~~reduce losses effectively. The following conclusions are derived: (1) cracking–sliding failures ~~are prone to occur~~mostly take place 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 10 pm to 4 am ~~the next day,~~ and ~~concentrates~~mainly in the rainy season (July to September) and in the freeze~~-~~–thaw season (March to April); and (3) ~~the more~~highly intense ~~the~~ human activities in the region~~, the greater the~~ correspond to a high possibility of cracking–sliding failures.

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

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.~~ Any yellowish, carbonate-bearing, quartz-rich, silt-dominated strata formed by aeolian deposition and aggregated by loessification during glacial times are widely accepted as loess (Sprafke and Obreht, 2016). Loess ("huang-tu" in Chinese) and its related deposits are one of the most widespread Quaternary sedimentary formations, and they are most abundant in arid or semiarid regions in inner Eurasia and North America; they are characterized by high porosity, weak cementation, and unsaturation (Samlley et al., 2011; Li and Shi, 2017).

The Loess Plateau in China (LPC) are the main regions for comprehensive development of agriculture, forestry,~~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 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).~~

~~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~~km^2, which accounts for more than one-fifth of the entire arable land of the country and ~~nourishes~~feed 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~~environments, excessive reclamation, and unreasonable engineering activities. Among ~~the~~these geohazards, cracking–sliding failure, normally with a volume of several hundred cubic meters, causes the largest number of casualties ~~(Lei, 2001) (Fig. 2). According to the historical record~~in the east of LPC (Lei, 2001). More than 1000 cracking–sliding failures were recorded in the past two decades, and they caused an average of more than 100 fatalities per year despite the small volumes of individual failures. Unlike "flows" or "slides" as defined by Cruden and Varnes (1996), cracking–sliding failures have composite failure planes composed of two parts. The upper part normally develops vertically from the crown of the slope down to one to several meters deep. The upper part forms by tensile cracking, but the slope can stand stably for a long time with such cracks.

The lower part is generally inclined at an angle ranging from 15° to 60°. Sliding along the lower part, which is triggered by rainfall, freezing–thawing, daily temperature fluctuations, slope undercutting, and earth tremors likely mobilizes cracking–sliding failures.

According to historical records, 62 cracking–sliding failures occurred in Shenmu, Mizhi, Zizhou, and other places in Northern Shaanxi Province from 1985 to 1993~~, causing~~ and caused 258 deaths and more than 40 injuries (Qu et al., 2001). In 2005, the cracking–sliding failure in Jixian County~~,~~ in Shanxi Province ~~caused~~resulted in 24 deaths and economic losses of ~~nearly~~approximately RMB 10 million. ~~The loess failure~~Failure with a volume of 2.5~~×~~ × 10^4 m^3 took place in Zhongyang County~~,~~ in Shanxi ~~Province in~~on November 16, 2009~~ caused~~, causing 23 deaths and ~~destroyed~~destroying 6 houses. In 2013, 36 loess failures ~~occurred~~were documented in Tianshui City, Gansu Province (Xin et al., ~~2014). More recently~~2013). In 2015, a cracking–sliding failure ~~occurred~~ in Linxian County, Shanxi ~~Province that~~ buried four families ~~with~~comprising nine people~~ in 2015. The above~~. All of these failures developed within the loess–paleosol sequence, with relatively uniform mineralogical and chemical compositions.

Frequent and disastrous events ~~warrant a deep~~demand an in-depth 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~~causative factors and development patterns of loess failures to reduce the occurrence of such geohazards.

~~In this~~ This study~~,~~ collects a large set of data on loess cracking–sliding failures~~ is obtained from the published literature. Based on the statistical~~, climate, and soil temperature to facilitate a detailed analysis~~,~~ of the internal and external causes of ~~cracking–sliding~~such failures~~ are summarized. Emphasis is given to~~. This study also emphasizes the influences of slope features (i.e., slope type, gradient, height, and aspect), rainfall, freezing~~ and ~~–thawing cycles, daily temperature ~~fluctuation~~fluctuations, and human engineering activities.

2 Study area

The study area is limited to the east of the LPC covering the regions of Northern Shaanxi and Western Shanxi provinces because of their homogeneous background of climatic, morphologic, geologic, and anthropic conditions (Fig. 1). The latitude of the study area ranges from 800 m to 1300 m above sea level from southeast to northwest. The study area has a typical semiarid continental monsoon climate with four distinct seasons. The average annual rainfall in this area varies from 400 mm to 700 mm. Rainfall in summer (from July to September) accounts for approximately 70% of the year (Hui, 2010; Qian, 2011; Zhu 2014). For instance, the maximum precipitation in an hour in Yan'an City can accumulate to more than 60 mm in summer (Zhu, 2014). The total rainfall in Shilou County reached 412 mm in a month from early July to early August in 2013 (Lv, 2011) and corresponded to 81% of rainfall in the same year. According to records for the past 10 years, the average annual temperature is relatively constant, ranging from 8 °C to 12 °C. However, variations in temperature in a day can occasionally be greater than 25 °C, that is, the highest temperature is recorded at noon and the lowest temperature is observed at midnight.

The study area is located in the east of the Ordos basin. The Fenwei Graben, spanning northeast to southwest, is a subsided area encountering a number of normal and strike–slip faults and covering more than 20,000 km^2 (Huang et al., 2008; Liu et al., 2013). The thickly bedded Pleistocene loess–paleosol sequence constitutes more than 70% of the study area and reaches a maximum thickness of 300 m. From top to bottom, the loess–paleosol sequence includes Late Pleistocene Malan Loess (Q_3), Middle Pleistocene Lishi Loess (Q_2), and Early Pleistocene Wucheng Loess (Q_1). The Malan Loess, with thickness ranging from 10 m to 30 m, is the most widespread. The Lishi Loess, with several interlayers to tens of interlayers of loess and paleosol, underlies the Malan Loess and forms a 60–150 m thick layer. The Wucheng Loess is sporadically exposed along some loess gullies. Remarkable landforms, such as loess platforms, ridges, and hillocks, have been formed in the study area because of intensive surficial erosion (Zhang, 1983; Zhang, 1986). Loess platforms are mainly distributed in the Luochuan area in Northern Shaanxi Province; loess ridges are mainly found in the peripheries of the Luochuan platform and eastern regions of the Yellow River; and loess hillocks are mainly located in Yan'an, Suide and in both sides of the Yellow River between Shaanxi and Shanxi provinces.

3 Dataset

A large set of data of loess cracking–sliding failure events were collected from published literature and unpublished reports to local governments. Records were originally obtained through field surveys, which were normally conducted within 1–2 days immediately after each event. A total of 1176 cracking–sliding events were recorded in the past 20 years across the study area. Of these events, 321 were published in the literature, 670 were presented in government reports, and 185 were unpublished by the local government. All of the 1176 failures were individually reviewed by verifying the reliability, accuracy, and completeness of the original records. Finally, 458 cases (red dots in Fig. 1) were selected to set up the dataset for this study.

Data pertaining to rainfall were obtained from the records of 75 meteorological stations (blue dots in Fig. 1), which are almost uniformly distributed across the study area. Statistical analysis shows that the variation in average annual rainfall in the past 15 years among these stations is less than 80 mm, indicating a relatively homogeneous climatic condition over the study area.

4 Results and discussion

4.1 Internal factors

~~Previous studies normally~~ Loess slopes are divided ~~loess slopes~~ into four types in terms of slope profile: ~~stepped, convex,~~ rectilinear, ~~and~~convex, concave~~-~~, and stepped slopes (Table 1). ~~Fig. 3 shows the classification of loess slopes in Yan'an area, Shaanxi Province, China. The~~ Concave and stepped slopes ~~account for 40% of the total number;~~are more stable than rectilinear and 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,~~ (Li and Mo, 2017; 2017). We surveyed 212 loess slopes in Lishi City in Shanxi Province and found that stepped slopes, convex slopes, rectilinear slopes, and concave slopes account for 38%, 31%, 18%, and 13% of all of the slopes, respectively (Fig. 2a). This finding is consistent with the conclusion of Qin et al. (2015), who performed a field survey on loess slopes in Yan'an City, Shaanxi Province. However, approximately one-half of cracking–sliding failures occur in rectilinear slopes. In Fig. 2b, the statistical analysis of the ~~470 occurrences of loess failures in this area~~ 458 failure cases indicates that rectilinear slopes are the most susceptible to cracking–sliding failure (~~212 occurrences, accounting for 45% of the total of 470),~~48%), followed by ~~the~~ convex slopes (~~156 occurrences, accounting for 33%), and the stepped~~28%). Stepped (13%) and concave (11%) slopes are the least susceptible ~~(51 for each; 11%, respectively)~~ to such failures~~ (Fig. 4). Generally~~.

In general, the overall gradients of rectilinear and convex slopes are steep, resulting in large internal stresses and stress ~~concentration, especially~~concentrations, particularly at the shoulder and toe ~~parts~~sections (Table 1). The ~~gentle slope at the~~ bottom part of the concave slope has a gentle gradient and has a supporting ~~effect on~~function to the steep upper ~~slope,~~part, thereby relieving the stress concentration~~ because~~; the maximum shear stress at the foot of ~~the~~ concave ~~slope~~slopes is typically only one-half ~~that~~ of the shear stress at the foot of rectilinear ~~slope~~slopes (Zhang et al., 2009). The stress distribution pattern in each step section of a stepped slope is similar to that of ~~the~~a rectilinear ~~slopes~~slope. However, the magnitude of internal stress of stepped slopes 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.~~. These findings explain that most cracking–sliding failures occur in rectilinear slopes, although these slopes are not the dominant slope type in the loess area.

In addition to ~~the~~ slope profile, the gradient, height, and aspect of loess slopes are ~~found to have close relationships with~~ closely related to the occurrence of cracking–sliding failures. Fig. ~~5a~~3a shows that ~~the~~ failure occurs mostly on slopes with gradients greater than 60~~°,~~° and that the number of failures increases ~~significantly~~ with ~~the gradient (Fig. 5a). According to the statistical analysis of the available data, 18.5% of~~gradients. Of the cracking–sliding failures~~ occurred~~, 16%, 25%, and 47% occur on slopes with gradients ranging from 61° to 70°, ~~24.9% occurred on slopes with gradients of~~from 71° to 80°, and ~~44% on slopes with~~from 81° to 90~~° gradients. This is because gradient affects the stress distribution inside the slope the most. Fig. 6~~°, respectively. Fig. 4 shows the tension ~~band, which is~~ zones that developed ~~from the transformation of the~~at slope shoulders, where radial and tangential stresses transform 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 (~~is (Stacey, 1970; Zhang et al., 2009).

Fig. ~~5b shows~~3b illustrates that slope height is another main factor that controls the occurrence of cracking–sliding failures. In ~~Huangling County of Shaanxi Province~~the study area, most ~~of the~~ cracking–sliding failures ~~occurred~~occur on slopes with heights of 5 m to 40 m~~, accounting~~ and thus account for ~~89.2~~87% of the total number of occurrences. The remaining ~~10.8% occurred~~13% take place on slopes with heights of more than ~~60~~40 m. A ~~higher~~high slope normally develops a ~~gentler~~gentle gradient because of ~~the~~ long-term weathering and erosion. By contrast, ~~slopes with lower heights are~~a low slope generally ~~steeper~~forms a steep gradient (Zhu et al., 2011), ~~being more~~thereby becoming prone to collapses.

~~As shown in Fig. 5c, the sunward~~Sunward slopes are more prone to the development of cracking–sliding failures than ~~the~~ shady slopes~~. The statistical~~ (Fig. 3c). Statistical analysis ~~of 31 loess failures in Huangling County, Shaanxi Province~~ shows that ~~62.5~~69% of the cracking–sliding failures ~~occurred~~occur on slopes with aspects ~~ranging from~~ in the range of 90° to 270°, ~~especially~~particularly 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 exists between day and night~~ exists. Furthermore, sunward~~. Sunward slopes are generally subjected to more weathering~~,~~ than shady slopes, resulting in fractured structures, which are ~~not conducive~~inconducive 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~~thereby increasing the occurrence of failures.

~~3~~4.2 External factors

~~3.~~1) Rainfall

Rainfall ~~shows a great effect on~~ remarkably influences the stability of loess slopes~~ according to the monitoring data from the Chinese government. The~~. In Fig. 5, 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~~is closely and ~~in Linxian County in July 2013 were both induced by~~positively correlated with the average monthly rainfall~~.~~

~~The seasonal variations~~ of the past 15 years. Summer 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~~) in the study area accounts for approximately 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,~~number of cracking–sliding failures in the same period corresponds to 62% of the total failures. This finding is consistent with that of Gao et al. (2012), who indicated that more than 60% of loess failures happen in Gansu Province in the rainy season. Wei (1995) 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,~~ Liu et al. (2012) presented a similar conclusion on this phenomenon in Shanxi and ~~the number of collapses accounted for 49% of the total for the year~~Shaanxi, respectively.

Rainfall induces loess ~~collapses~~ cracking–sliding failures in three ways~~:~~, namely, splash erosion, shovel runoff, and seepage. At the beginning of ~~rain~~rainfall, 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 surface further (Tang et al., 2015). In ~~the case~~cases of persistent rainfall, preferential seepage pipes ~~are~~ usually ~~formed~~develop inside ~~the~~a slope, thereby saturating the soils, reducing the shear strength, and eventually ~~leading to collapses~~causing cracking–sliding failures.

~~3.~~2) Freezing~~-~~ and~~-~~ thawing

Fig. ~~7~~5 shows that cracking–sliding failures ~~also~~ occur frequently ~~from March to April, besides~~ not only in the rainy season from July to September~~. This period is~~ but also in the winter-to-spring transition from ~~winter~~March to ~~spring. The soil~~April. Soil temperature ~~rises quickly~~increases rapidly from a value below ~~zero~~0°C to a value above ~~zero~~0°C. As shown in Fig. ~~8, the~~6, soil temperature ~~of the soil~~ remains negative, and the frozen depth can ~~go to about~~reach approximately 1.0 m ~~down~~underground from ~~December~~late November to February in the loess areas ~~of~~in China. At the end of March, the ground temperature begins to ~~rise~~increase, and the frozen layer gradually enters the thawing stage~~, and~~. By mid-April, the soil is ~~quickly~~rapidly heated up to ~~about~~approximately 8 °C~~ by mid-April~~.

Freezing and thawing mainly promote the occurrence of cracking–sliding failures via ~~the following~~ two ~~ways~~mechanisms: 1) ~~frost~~Frost heaving damages the soil structure and reduces soil shear strength. The loess itself contains a ~~great~~considerable number of large pores~~, and frost~~. 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~~Thawing causes the loess structure to collapse and ~~reduces~~reduce its shear strength. Thawed water can dissolve ~~the~~ cement ~~(~~, especially calcareous cement~~)~~, between loess particles~~,~~ (Li et al., 2017), consequently damaging the loess structure and increasing pore water pressure~~,~~ ~~thereby reducing~~; as a result, the shear strength of the soil decreases (Pang, 1986).

3~~.3~~) Daily temperature fluctuation

~~The statistical analysis of 32 cracking–sliding failure cases that caused deaths in the northern Shaanxi Province shows a~~Consistent with previous findings (Wei, 1995), our results indicate a relatively high frequency of occurrence of ~~such~~ cracking–sliding failures between 10 pm and 4 am ~~the next day~~ (Fig. ~~9).~~

7). The difference ~~of~~in temperature between day and night in the loess area is more obvious than that in other regions ~~in~~at the same latitude in China (Sun and Zhang, 2011), and ~~the difference~~ variations in air temperature in a day can occasionally reach ~~about 10~~30 °C. As shown in ~~both winter and summer (~~Fig. ~~10). A significant~~8, the soil at a 50 cm depth shows an average 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).~~difference of approximately 5 °C in summer. Thermal expansion and ~~contraction~~shrinkage occur during the ~~quick~~rapid change in ~~the~~ day~~-~~ and~~-~~ night ~~temperature~~temperatures. Under the cyclic functioning of ~~the~~ shrinkage and expansion stresses, ~~the~~a soil structure ~~is loosened~~loosens.

~~3.~~4) Human activity

~~The loess area of~~Loess areas in China ~~holds~~have a population of more than 200 million. Human engineering activities ~~are frequent~~frequently occur and mainly involve cutting slopes for buildings, excavation for cave dwellings, and construction of terraced fields~~,~~ and ~~construction of~~ roads. Cutting slopes for buildings causes the side slope to become steep. ~~The unloading~~Unloading-induced tensile fractures are usually produced on the trailing edge of ~~the slope~~slopes during the rapid adjustment of ~~the~~a stress field within ~~the~~a slope (Fig. ~~11a~~9a). When a cave is excavated, roof damage (normally caving) ~~occurs~~happens because of ~~the~~a local tensile stress concentration if the design of ~~the~~a geometric section of ~~the~~a cave is ~~improper~~inappropriate (Fig. ~~11b). The terraced~~9b). Terraced fields change the original path of ~~the~~ surface runoff and enhance rainfall infiltration.

Together with irrigation, ~~they~~ terraced fields increase the water content of ~~the~~ loess slopes and ~~raise the~~increase their phreatic level (Fig. ~~11c).~~ 9c). 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~~suitable environment for failures (Fig. ~~11d~~9d).

~~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~~More than half of the failures ~~occurred because of~~ are attributed to human engineering activities (Fig. ~~11). Among the~~10). In 2014, 9 of 16 failure cases that occurred in ~~2014 in~~ Yan’an~~, 9~~ City were ~~related to the over-~~caused by extremely steep slopes for ~~the~~ cave dwelling construction~~ of cave dwellings~~, and the 7 other ~~7~~cases were consequences of ~~the~~ improper treatment of ~~the~~ side slopes for road construction (Lei, 2001). These findings demonstrate that ~~the more~~ intense ~~the~~ human activities ~~are, the greater the~~likely result in a high probability of loess failures.

~~4~~5 Conclusions

This study investigates the influencing factors and ~~the~~ development ~~pattern~~patterns of loess cracking–sliding failures in ~~China~~the east of the LPC according to ~~the~~a large collection of field investigation data~~ from the literature.~~. The following conclusions are ~~reached~~obtained.

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

(2) Cracking–sliding failure ~~is~~ more likely ~~to occur~~occurs in rectilinear and convex slopes than in concave and stepped slopes. ~~The gradients of rectilinear~~Rectilinear and convex ~~slopes~~ slope gradients 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~~takes place on slopes with gradients of greater than 60°, and the greater the gradient is, the higher the likelihood of failures is. Cracking–sliding failure ~~is prone~~also tends 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~~of the development of cracking–sliding failure is within 180° to 270° (sunward slopes) because of the ~~obvious~~evident temperature difference between day and night and the strong weathering.

(3) The occurrence of cracking–sliding failure ~~demonstrates~~displays a ~~certain~~particular time pattern. Within a year, ~~the~~its occurrence ~~of cracking–sliding failure~~ coincides with ~~the~~

seasonal rainfall. Failures ~~are~~ mainly ~~concentrated~~occur in the rainy season, or from July to September. In addition, failures ~~occur~~ frequently take place from March to April because of freezing and thawing. Within a day, failures ~~occur~~happen mostly from 10 pm to 4 am ~~the next day~~ because of the ~~huge~~large temperature variation between day and night.

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

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References

Cruden D. M., Varnes D. J.: Landslides: investigation and mitigation. Chapter 3-Landslide types and processes, Transportation Research Board Special Report., 247, 1996.

Du J. W.: Early warning and forecasting of rainfall-induced geological disasters ~~–~~- a case study of the~~-~~ Loess~~-~~ Platea and Qin-ba~~-~~ Mountainous~~-~~ area, Sci. Press., 2010.

~~Gao H., Zhang Y. J., and Zhang X. G.: Factors on geological hazards of losee slope in Lanzhou city, Gansu Geol., 3, 30-36, 2012.~~

Hu H. T.: Preliminary investigation on the classification of landfalls, China, J. China Rail. Soc., 2, 90-100, 1985.

Hu Z. B., Pan B. T., Bridgland D., Vandenberghe J., Guo L. Y.: The linking of the upper-middle and lower reaches of the Yellow River as a result of fluvial entrenchment, Quaternary Science Reviews, 2017.

Huang Z., Xu M., Wang L., Mi N., Yu D., Li H.: Shear wave splitting in the southern margin of the Ordos Block north China, Geophys. Res. Lett., 35, 402-411, 2008.

Huang Q. B., Kang X. S., Wang Q. Y., and Li W.: Types and characteristics of loess landslides and collapses in Lvliang area of Shanxi province, China, J. Eng. Geol., 24, 64-72, 2016.

Hui X., Research on relationship between geo-hazard and rainfall in Loess Plateau of Northern Shanxi Province, Ph.D. thesis, Chang'an University, Xi'an, China, 2010.

Jin Z. X., Zhang S. W.: Distribution law of geological hazards and their application, China, J. Gansu J. Sci, 8: 123-128, 1996.

Lei X. Y.: Geohazards of Loess Plateau and their relation with human activities, Geol. Press., 2001.

Li Z. C~~. Z~~., Wei Z. G., Liu R., Zhang T. T., Wei H., and Zheng Z. Y.: Soil thermal condition over the Chinese Loess Plateau, China, Arid Land Geog., 5, 788-786, 2012.

Liu D. S.: Loess and environment, Sci. Press, 1985.

Liu J., Zhang P., Lease R.O., Zheng D., Wan J., Wang W., Zhang H.: Eocene onset and late Miocene acceleration of Cenozoic intracontinental extension in the North Qinling range-Weihe graben: Insights from apatite fission track thermochronology. Tectonophysics, 584, 281-296, 2012.

Liu J. N., Gu Y., Jin J., Ni S. H., and Shen Y.: Analysis of rainfall, floods and droughts in middle Shanxi in recent years, China, J. China. Hydrol., 2, 51-54, 2013.

Lv M.: The present situation of the loess collapse of geological sisasters in Shanxi Province and the water sensitivity analysis, Ph.D. thesis, Taiyuan University of Technology, Taiyuan, China, 2011.

Mao S. L.: The Yanchang County geology disaster distributes the rule and the stability analyses, Ph.D. thesis, Chang'an University, Xi'an, China, 2008.

Pang G. L.: A discussion on maximum seasonal frost depth of ground, China, J. Glaciol. Geocryol, 3, 253-254, 1986.

Peng, J. B., Lin, H. C., Wang, Q. Y., Zhuang, J. Q., Cheng, Y. X., and Zhu, X. H.: The critical issues and creative concepts in mitigation research of loess geological hazards, China, J. Eng. Geol., 22, 684-691, 2014.

Qian P.: Study of types for highway drainage system in loess areas in northern Shaanxi Province, Ph.D. thesis, Chang'an University, Xi'an, China, 2011.

~~Qin L. L., Qi Q., Ju Y. W.: Study on the feature governance research of loess geological disasters in Shanxi Province, China, Shanxi Archit. 6, 58-59, 2015.~~

Qu Y. X., Zhang Y. S., and Chen Q. L.: Preliminary study on loess slumping in the area between northern Shaanxi and western Shanxi – taking the pipeline for transporting gas from west to esat in China, China, J. Eng. Geol., 9, 233-240, 2001.

Qi Q.: Study on loess geological hazards characteristics and preventive measure in Shanxi Province, Taiyuan University of Technology, Taiyuan, China, 2012.

Smalley I., Marković S. B., Svirčev Z.: Loess is [almost totally formed by] the accumulation of dust, Quaternary International, 240, 4-11, 2011.

Stacey T. R.: The stress surrounding open-pit mine slope, In: Planning Open Pit Mine, 1970.

Shi L.Z.: Geological disaster risk assessment of northern Shaanxi based on GIS - take Baota District of Yanan as an example, M.S. thesis, Xi'an University of Science and Technology, Xi'an, China, 2016.

Sprafke T., Obreht I.: Loess: Rock, sediment or soil - What is missing for its definition, Quaternary International, 399, 198-207, 2016.

Sun Z. X., Zhang Q.: Analysis of climate characteristics of land surface temperature and energy in the semi-arid region in the Loess Plateau, China, J. desert Res, 5, 1302-1308, 2011.

Tang Y. M., Feng W., and Li Z. G.: A review of the study of loess slump, China, Adv. Earth Sci., 1, 26-36, 2015.

Wan Y., Xie H., Yang H., Wang Z., Liu D., Kroener A., Wilde S.A., Geng Y., Sun L., Ma M., Liu S., Dong C., Du L.: Is the Ordos Block Archean or Paleoproterozoic in age? Implications for the Precambrian evolution of the North China Craton, American Journal of Science, 313, 683-711, 2013.

Wei Q. K.: Collapse hazards and its distribution features of time and space in Shaanxi Province, China, J. Catastrophol., 10, 55-59, 1995.

Xin C. L., Yang G. L., Zhao Z. P., Sun X. H., Ma W. Y., and Li H. R.: Characteristics, causes and controlling of loess collapses in Beishan mountain of Tianshui city, China, Bull. Soil Water Conserv., 33, 120-123, 2013.

Xu L.B.: The research on the lithospheric conductivity structure of Ordos Block and its surrounding, M.S. thesis, China University of Geosciences, Beijing, Chian, 2016

Yao C.W., Li Y.H., Liu H.N., Du J.L., Wu B.Y., Peng J.: Development characteristics and spatial distribution of collapse in Northern Shaanxi, Journal of Geological Hazards and Environment Preservation, 26, 27-32, 2015.

Yan E. C., Liu G. R.: Discuss on geological model of landslide, J. Hydrogeology and engineering geology, s1, 87-90, 2004.

Yang W. Z., Shao M. A.: Researches of soil moisture in Loess Plateau, Sci. Press., 1995.

Yang Y., Li W., Ma L.: Tectonic and stratigraphic controls of hydrocarbon systems in the Ordos basin: A multicycle cratonic basin in Central China, Aapg Bulletin, 89, 255-269, 2005.

Yang S. H.: Study on the growing characteristics and rules of the geological hazards on Loess Plateau – taking Huangling County as an example, Ph.D. thesis, Chang'an University, Xi'an, China, 2010.

Yuan Y., Hu S., Wang H., Sun F.J.: Meso-Cenozoic tectonothermal evolution of Ordos basin, central China: Insights from newly acquired vitrinite reflectance data and a revision of existing paleothermal indicator data, Journal of Geodynamics , 44, 33-46, 2007.

Zhang Z.H.: The compilation principle of landscape type map of Chinese Loess Plateau, China, Hydrogeology and Engineering Geology, 2, 29-33, 1983.

Zhang Z.H.: Institute of hydrogeology and engineering geology of Chinese Academy of Geological Sciences, China, Landscape type Map and Instructions of Chinese Loess Plateau (1:500000), Beijing, Geological Press., 1986.

~~Yang W. Z., Shao M. A.: Researches of soil moisture in Loess Plateau, Sci. Press., 1995.~~

Zhang H.: Study of water migration and strength of the loess under freezing-thawing action, Ph.D. thesis, Xi'an University of Architecture and Technology, Xi’an, China, 2014.

Zhang Y. Q.: Systematic analysis on loess landslides in Heifangtai, Gansu Province, Ph.D. thesis, Northwest University, Xi’an, China, 2007.

Zhang Z. Y., Wang S. T., Wang L. S., Huang R. Q., Xu Q., and Tao L. J.: Engineering geological analysis principle~~-~~, Geol. Press., 2009.

Zhang Y.Y.: Study on the formation mechanism of loess collapse induced by rainfall in Yan’an Area. M.S. thesis, Xi’an University of Science and Technology, Xi’an, China, 2014.

Zhang H.: Study of water migration and strength of the loess under freezing-thawing action, Ph.D. thesis, Xi’an University of Architecture and Technology, Xi’an, China, 2014.

Zhu J. H.: Study on the relationship between slope geometrical morphology and landslide collapse disasters in ~~Yan’ an,~~Yan’an,. Ph.D. thesis, Chang’an University, Xi’an, China, 2014~~.~~

Zhu Y. C., Li J., and Ren Z. Y.: Change tendency and relevant analysis about cultivated land and population in Loess Plateau during about 300 years, China, J. Shaanxi Norm. University (Natur. Sci. Ed.), 3, 84-89, 2011.