Research Article

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Distribution of large- and medium-scale loess landslides induced by the Haiyuan Earthquake in 1920 based on field investigation and interpretation of satellite images

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Abstract: Studying the distribution law and influencing factors of coseismic landslides has important scientific significance and engineering value for understanding the mechanism of seismic landslides and predicting the occurrence of seismic landslides. After a hundred years, these large- and medium-scale landslides induced by the 1920 Haiyuan earthquake are still well-preserved and have extremely high academic research value. About 620 loess seismic landslides induced by the Haiyuan earthquake in 1920 were investigated on site. On this basis, the shape differences between seismic landslides and gravity landslides were summarized; 605 landslides were identified by satellite images, and the Haiyuan earthquake-induced loess landslide database containing seismic information and landslide information was established. The distribution law and morphological characteristics of large- and medium-sized landslides induced by the Haiyuan earthquake were systematically counted according to the conditions of the landslide-intensive area, intensity, and fault upper and lower plates. The influencing factors of loess earthquake landslides were summarized, and the following conclusions were obtained: (1) 1,225 large- and medium-sized landslides were induced by the Haiyuan earthquake in 1920. These landslides have the characteristics of long sliding distance, large single scale, and strong disaster-causing. They are mainly distributed in three concentrated areas of Xiji, Haiyuan, and Pengyang. The landslide morphological characteristics of the three landslide-intensive areas are different because the landslide sliding mechanism caused by topography and lithology is different. (2) The landslide distribution has obvious clustering, zonation, and directivity, and has an obvious river distance effect and fault hanging wall effect. (3) The internal influencing factors such as stratum lithology, topography, fault location, and direction, and the role of water control the occurrence location and scale of landslide. The external factor of an earthquake is an important incentive and control factor for landslide occurrence.

Keywords: loess seismic landslide, 1920 Haiyuan earthquake, landslide distribution, field investigation, satellite image interpretation

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1 Introduction

Loess Plateau is one of the main areas with frequent strong earthquakes and serious geological disasters in the world. Earthquake-induced loess landslide is the main cause of casualties and economic losses in the region. In view of the wide distribution and serious disaster of loess landslide induced by the Haiyuan earthquake in 1920, a strong earthquake landslide database is established, the distribution law and development characteristics of loess landslide are analyzed statistically, and the effect of loess landslide induced by the earthquake is studied, which can lay a foundation for further research on the disaster mechanism and risk assessment of loess landslide induced by earthquake.

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On December 16, 1920, at 20:05′53″, an earthquake of M8.5 occurred in Haiyuan County, China. This earthquake is famous all over the world for its widespread, large number of casualties, heavy disaster losses, great changes in topography and geomorphology in the epicentral area, and a large number of loess landslides. It is historically called the "global earthquake." More than 270,000 people died in the Haiyuan earthquake [1]. In addition to the damage to buildings caused by the high magnitude of the earthquake, more than a thousand large- and medium-scale loess landslides are the main reason for such heavy losses. The Haiyuan earthquake induced a large and concentrated number of large- and medium-scale loess landslides, which shocked Upton Close and others, who were the first to visit the earthquake area and investigate the earthquake damage. His article published in the Journal of National Geography in the United States in 1922 described "Where the Mountains Walks" [2] and introduced the disaster scenarios of large-scale loess earthquake landslides. According to research by Zhang and Wang [3], about 100,000 deaths were directly caused by earthquake-induced landslides.

Due to the occurrence and risk of loess landslides induced by the Haiyuan earthquake, the distribution and morphological characteristics of loess landslides have been an important research topic in the field of earthquake disasters since the beginning of the Haiyuan earthquake [4,5]. Large-scale earthquake field surveys have been conducted several times by Upton Close, Weng, Lanzhou Institute of Seismology [6], Deng et al. [7], etc. In the earlier field investigation, the seismogenic structure, focal mechanism, seismic disasters, and seismic experience were systematically studied. A large number of photos of loess seismic landslides were taken, and the disasters caused by landslides were described in detail. Chen and Ye [8], Zhang and Wang [3], Jinchang et al. [9], Derbyshire [10], Wang et al. [11], Yuan [12], and Chang et al. [13] investigated part-type landslides induced by Haiyuan earthquake. The results show that the landslides are widely distributed and concentrated and have the characteristics of group, gentle slope, low slope, fast speed, and low water content. Li et al. [14], Zhuang et al. [15], Xu et al. [16], and Xu et al. [17,18] studied the influencing factors of loess seismic landslides by satellite image interpretation method. It is considered that the loess seismic landslide is controlled by the special topography, geological structure, stress relationship, and geotechnical properties of the region.

Despite a hundred years of vicissitudes of life, due to dry climatic conditions and no large-scale human destruction, large-scale loess seismic landslides are still well preserved and have high academic research value. In view of the lack of field investigation of landslides and the lack of matching between satellite interpretation results and actual investigation in previous studies, the author's team has gone to Haiyuan, Xiji, Jingning, and other earthquake-induced landslides concentrated areas seven times since 2016 to obtain many valuable field data. Through field investigation, the shape difference between earthquake landslides and gravity landslides is summarized. Satellite images are used to supplement and identify earthquake landslides that are not in the landslide concentrated area. The database of Haiyuan earthquake-induced loess landslides containing seismic information and landslide information is established. The distribution law, morphological characteristics, and influencing factors of large- and medium-scale landslides induced by the Haiyuan earthquake are systematically studied, which provides a basis for the prevention and control of earthquake landslides in the Loess Plateau.

2 Study area

2.1 Haiyuan earthquake

The macroscopic epicenter of the Haiyuan earthquake (N36.5°, E105.7°) is located near Ganyanchi in Haiyuan County, Ningxia, with a focal depth of 17 km [19]. The epicentral area extends eastward to Nikou, Guyuan City, and westward to Xingquan of Jingtai County, covering more than 20,000 km^2 of Xiji County, Haiyuan County, and Jingyuan County. The maximum intensity in the earthquake epicentral area reached XII (the maximum intensity in China). When the earthquake occurred, the mountain collapsed, the walls collapsed, the roads were cut off, and the rivers were blocked. The whole city of Xi'an and Ganyanchi in Haiyuan County was destroyed.

2.2 Haiyuan earthquake fault

The Haiyuan earthquake fault is active (Figure 1). The fault is a sinistral strike-slip fault with a steep dip angle and a tendency to southwest [20]. The middle and western segments of the fault zone are northwest (NW)-trending, and the eastern segment is NW-trending [21]. The length of the fault is 240 km. The faults are all inclined mountains, and the landform is a striking boundary between mountains and basins. There are dislocations in the trees (Figure 2), gully (Figure 3), ridges, and ridges where the fault passes. Haiyuan seismic intensity has the

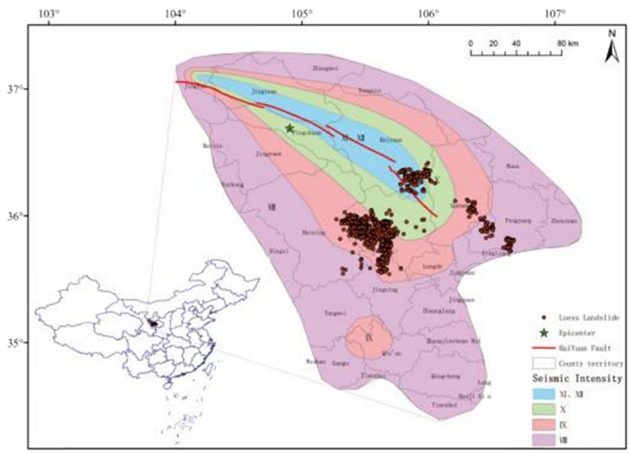

Figure 1: Landslide location and intensity distribution.

Figure 2: Fault pass through the willow tree.

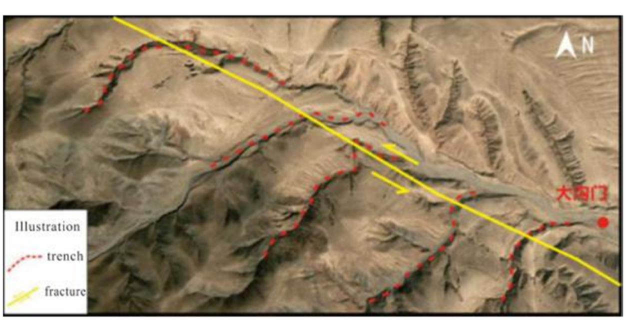

Figure 3: Fault pass through the gully.

characteristics of uneven attenuation between the north and south. The intensity on the north side of the seismic zone attenuates fast, and the intensity on the south side attenuates slowly. Although the seismogenic fault of the Haiyuan earthquake is a left-lateral strike-slip, it has a certain dip angle, and the fault generally inclines to the southwest, resulting in heavy seismic damage and slow attenuation of the hanging wall on the southwest side [21].

2.3 Regional geological conditions

Haiyuan seismic epicentral area is located in the western mountainous area of Liupan Mountain. It is greatly affected by geological movement in the northeastern margin of the Qinghai-Tibet Plateau [22]. The orogenic movement in the region is extremely strong. There are eight active faults in the region: Niushoushan-Luoshan-Guyuan fault, Yandongshan fault, Tianjingshan fault, Haiyuan fault, the eastern foot of Liupan Mountain fault, Longxian-Baoji fault, and the northern margin of Western Qinling fault. The stratigraphic division is located in the Haiyuan-Xiji stratigraphic area of the Qilian-North Qinling stratigraphic division in the Qinqikun stratigraphic area. The oldest strata are metamorphic rocks of the Haiyuan Group in Mesoproterozoic. The Caledonian granodiorite is locally exposed. The Liupan Mountain Group is exposed in the northeast of Xiji County [23]. The Cenozoic strata are widely distributed. The Quaternary strata are mainly exposed on the surface, and the lithology is mainly the silty loess of the Malan Formation of the Quaternary Upper Pleistocene. The overall terrain in the region is high in the northwest and low in the southeast, and there are many ravines, mainly the loess ridge landform. It belongs to the arid–semi-arid climate in the northern temperate zone. The annual precipitation is 200–500 mm, and the overall trend decreases from southeast to northwest. The rivers in the area mainly include the Lanni River, Hulu River, Qingshui River, and so on. The rivers are complex, and the tributaries are more developed.

3 Landslide data and method

3.1 Field investigation

In order to study the landslide induced by the Haiyuan earthquake, seven field investigations were carried out in Haiyuan, Xiji, and Jingning areas. Considering the influence of natural conditions and human destruction on small landslides, it is often difficult to preserve the original form of the landslide, and the destructive force of small landslides is relatively small. Therefore, the landslide area selected in the survey is more than 1,000 m^2. A total of 620 large loess landslides were obtained in the field investigation. The landslide investigation includes occurrence time, geographical location, sliding type, stratigraphic lithology, slope shape, slope structure type, basic characteristics of landslide, influencing factors, and stability analysis. The laser rangefinder data and satellite image measurement data are compared to ensure the accuracy of parameters.

Through investigation, abundant and detailed seismic landslide investigation data were obtained, and many novels and unique loess seismic landslide phenomena were found. The existing Haiyuan earthquake landslides have the characteristics of large-scale, rich landslide types and intact shape preservation (Figure 4). Under seismic action, these landslides tend to be low-angle slips, the surface of the landslide is gentle, the slope is small, and the sliding distance is long. Some landslides can see an obvious sliding extrusion layer (Figure 5).

3.2 Earthquake landslide and rainfall landslide

In landslide investigation, it is one of the difficulties to ensure the reliability of survey data to correctly distinguish the inducing factors of landslide and judge whether landslide is induced by earthquake or rainfall [24]. The ancient soil water-resisting layer and the tertiary layer of the lower basement in the loess area have the effect of water retention, which can form a lubricating sliding surface [25]. Rainfall landslides and earthquake landslides are mainly landslides in the loess layer and bedding landslides, which are the same characteristics of rainfall landslides and earthquake landslides. In the field investigation, through consulting historical data and inquiring about local villagers, the age and inducing factors of the investigated landslides were obtained. According to these landslides, the shape characteristics of distinguishing earthquake landslides and rainfall landslides were summarized, which provided a scientific basis for subsequent investigation and analysis.

The shape characteristics of earthquake landslides and rainfall landslides are as follows: (1) The slip surface dip angle of earthquake landslides is small. Under the action of earthquake and gravity, the slope with a lower slope can also slide, and the slip surface dip angle is generally small. (2) The occurrence location of earthquake-induced landslides is high: rainfall-induced

Figure 4: Field investigation of landslides.

Figure 5: Sliding extrusion layer.

landslides are caused by the decrease of shear strength of soil under the action of water, which are highly correlated with soil water content. Affected by topography, rainfall-induced landslides often occur in the middle and lower parts of the slope, which are low-level landslides. Earthquake-induced landslides are not restricted by topography and can occur in the middle and upper parts of the slope, which are mostly high-level landslides. (3) Large and long sliding distance of seismic landslide: seismic landslide is affected by both seismic force and high occurrence position, and its kinetic energy and potential energy are high. The earthquake-induced landslide is large, and its sliding distance is long. The sliding distance of rainfall landslides is short, and it is small. The above understanding can be verified by field investigation. There are two landslides on the same slope in Zhangjiaping Village, Pengyang Town, Pengyang County (Figure 6). The two landslides have large differences in morphology, and the left landslide occurs in the middle and lower parts of the slope. The back wall of the landslide is steep, the landslide is small in size, the sliding distance is small, and the plane morphology is in the shape of "junction." The right-side landslide occurs in the upper part of the slope, the back wall of the landslide is relatively flat, the landslide is large, the sliding distance is long, and the plane shape is "opening." The two landslides are on the same slope, and the geotechnical properties and geological conditions are the same. The reason for the different external forms of the existing landslides is that the landslide-inducing factors are different. Through interviewing a villager in a nearby village, it is known that the left landslide is the gravity landslide caused by the rainfall in 1987, and the right landslide is the landslide induced by the Haiyuan earthquake in 1920.

3.3 Satellite image interpretation

The technology of landslide identification through satellite images has become increasingly mature. Xu et al. [26,27],

Figure 6: Comparison between gravity landslide (left) and earthquake landslide (right).

Tien Bui et al. [28], Nhu et al. [29], and Shahabi and Hashim [30] have used satellite image recognition technology to record landslides, providing a large number of basic landslide data for obtaining landslide distribution characteristics and training prediction models.

Loess seismic landslides usually have the characteristics of dense distribution, clustering, large monomer scale, wide-coverage, gentle sliding body, long sliding distance, many accompanying hydrological phenomena, and strong damage. On satellite images, loess seismic landslides show the characteristics of dense distribution, strong burial damage, bright hue characteristics, significant geometric shape, and clear texture change. The loess area has less rainfall and less vegetation coverage. Most of the loess seismic landslides have little change, and the outline is clearly visible. The landslide characteristics are obvious on the satellite map. Based on the analysis of the aforementioned characteristics, the shape, texture, elevation, hue, and layout of the landslide are used. With the help of Google Earth satellite image, the study area is divided into grids, and the grids are interpreted one by one; 605 large- and medium-scale landslides with an area of more than 10,000 m^2 induced by the earthquake in 1920 are supplemented, and the landslide parameters are measured on the satellite image.

3.4 Landslide database

Using 620 landslides obtained by field investigation and 605 large- and medium-scale landslides obtained by satellite image interpretation, the basic information geographic spatial database of loess seismic landslide is established based on ArcGIS geographic information system platform. The database includes landslide point data, river vector data, digital elebation model elevation data map, underlying strata data, hydrogeological data, geomorphic unit data, and vectorized fault line data. The landslide data points include latitude and longitude coordinates, landslide length, width, thickness, area, landslide slope angle, plane shape, profile shape, main sliding direction, fault distance, and other loess seismic landslide characteristics. The establishment of the database has laid an important foundation for the study of loess seismic landslides. Using the data of the database, this article carried out a statistical analysis of loess landslides in the Haiyuan earthquake and summarized the distribution characteristics and formation law of landslides.

4 Spatial distribution of landslides

The landslide obtained by field investigation and satellite image interpretation is drawn in ArcGIS, and the landslide distribution is shown in Figure 1. The point density distribution of the Haiyuan earthquake landslide is made with 1 km as the search radius (Figure 7). From Figure 7, it can be seen that there are three dense distribution areas of the Haiyuan earthquake landslide, one is Xiji of Ningxia, Jingning, and Huining of Gansu. This area is located in the IX–X intensity area of the Haiyuan earthquake. The distribution of landslides is dense and the development characteristics are obvious. Second is Ningxia Haiyuan Jiucai Township and its surrounding areas; the region is located in the X–XII intensity area, and the regional landslide is mainly developed along both sides of the deep river. The third is the mountainous area of Hechuan Township and Pengyang County in the eastern part of Guyuan City, which is located in the IX–X intensity area, and the regional landslide distribution is relatively scattered. This is consistent with the landslide concentration area recorded in the literature. It is also pointed out that there is a landslide concentration area near Tongwei County. However, according to the latest research results of Xu et al. [18], it is confirmed by the death number density that the number of landslides induced by the Haiyuan earthquake in the Tongwei area is small, and the Tongwei area has more landslide sites in the Tianshui earthquake in 1,654 and the Tongwei earthquake in 1718. It is difficult to distinguish between field investigation and satellite image recognition. Based on the earlier two reasons, the landslide studied in this article does not involve an earthquake landslide in the region.

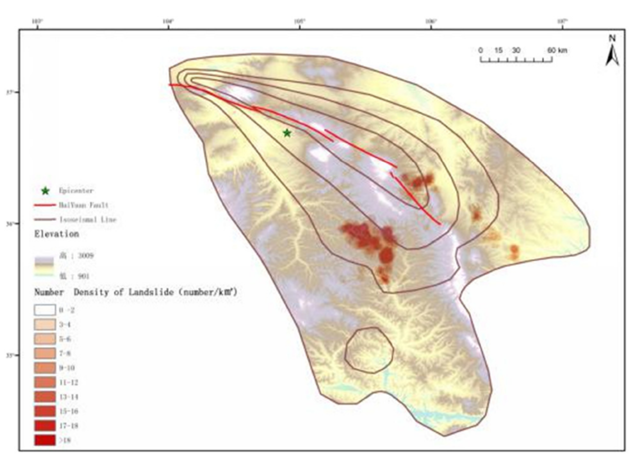

Figure 7: Distribution density and concentrated area of landslide.

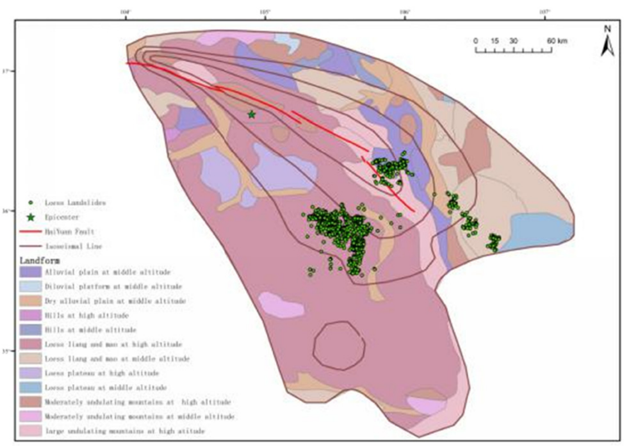

Figure 8: Landslide and topography.

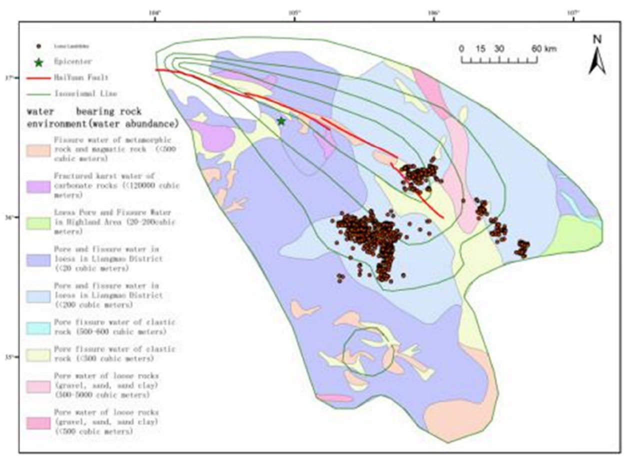

Figure 10: Landslide and hydrogeological.

Figure 7 shows that the three concentrated areas of large- and medium-sized landslides in the Haiyuan earthquake were not all concentrated in the high-intensity area with the strongest earthquake, and the concentrated areas in the high-intensity area only accounted for a part of the high-intensity area. There was no landslide in other areas of the high-intensity area, indicating that the occurrence of earthquake landslides was not only related to the seismic intensity but also affected by many factors such as topography (Figure 8), geological conditions (Figure 9), and hydrological conditions (Figure 10). Therefore, the analysis of Haiyuan earthquake landslides in 1920 needs to comprehensively consider the above-mentioned influencing factors, and the development characteristic factors such as landslide length, width, area, and original slope were counted to obtain the development characteristics of Haiyuan earthquake landslides. Statistics of landslide elevation, original slope, sliding direction, river distance, fault distance, epicentral distance, stratigraphic conditions, geomorphological conditions, and other types, and the distribution of Haiyuan earthquake landslides. The distribution law and development characteristics of the Haiyuan seismic landslide are comprehensively analyzed, and the influencing factors of the Haiyuan seismic landslide are summarized to obtain the seismic landslide effect and disaster model.

4.1 General situation

The landslide is counted according to the length, width, elevation, area, original slope, original slope direction, river distance, fault distance, epicentral distance, overlying strata, hydrogeology, and geomorphologic conditions, as shown in Figures 11–23. Figures 11–13 show

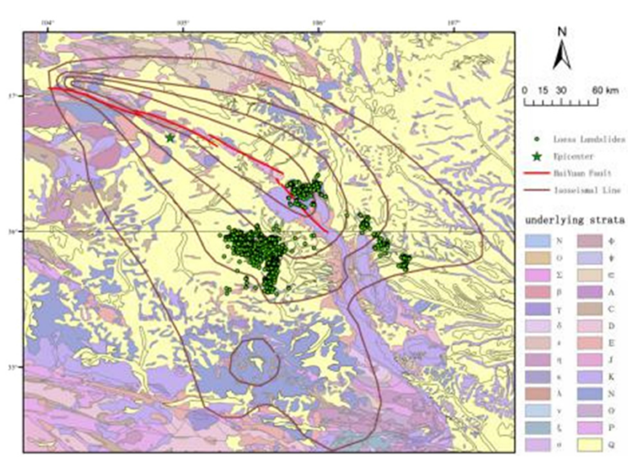

Figure 9: Landslide and geological.

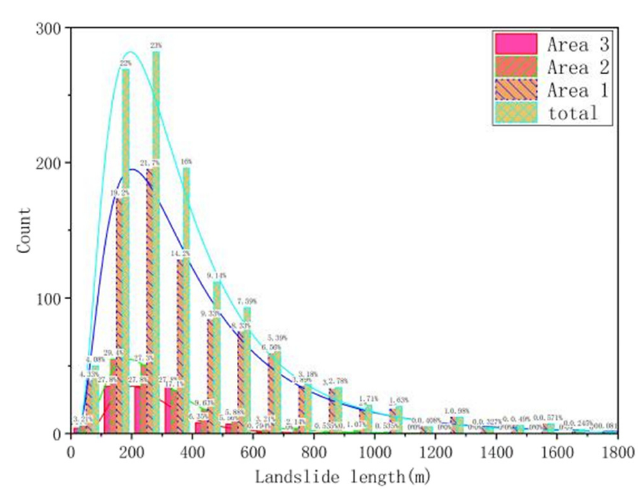

Figure 11: Distribution map of landslide length (by dense area).

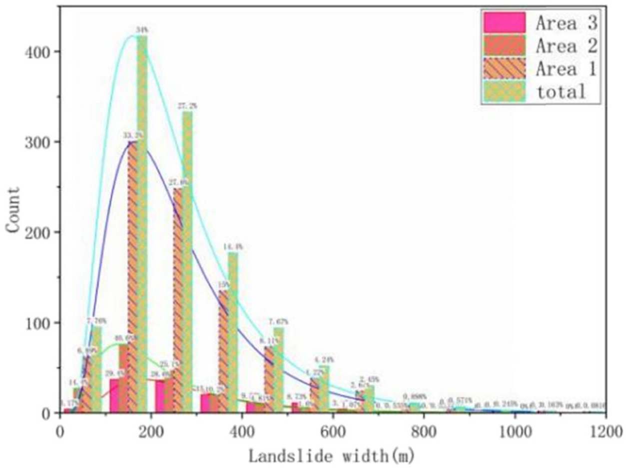

Figure 12: Distribution map of landslide width (by dense area).

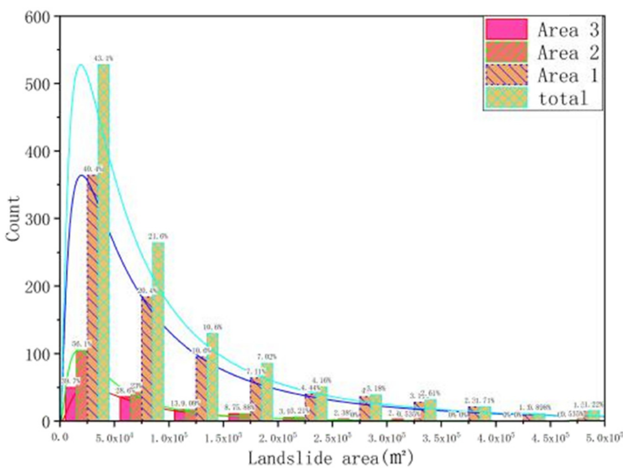

Figure 13: Distribution map of landslide area (by dense area).

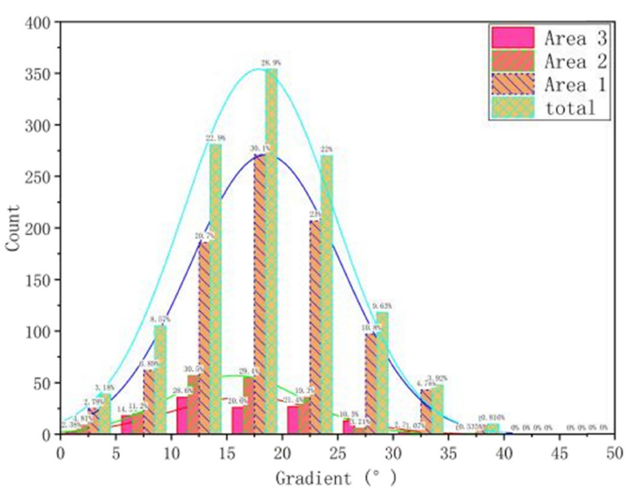

Figure 14: Original slope angle (by dense area).

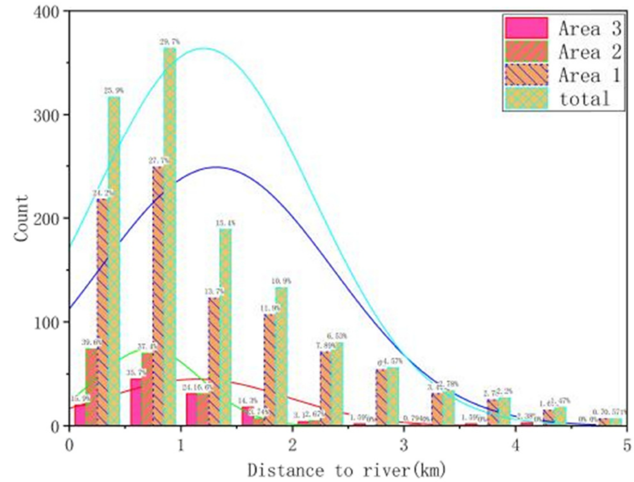

Figure 15: River distance distribution map (by dense area).

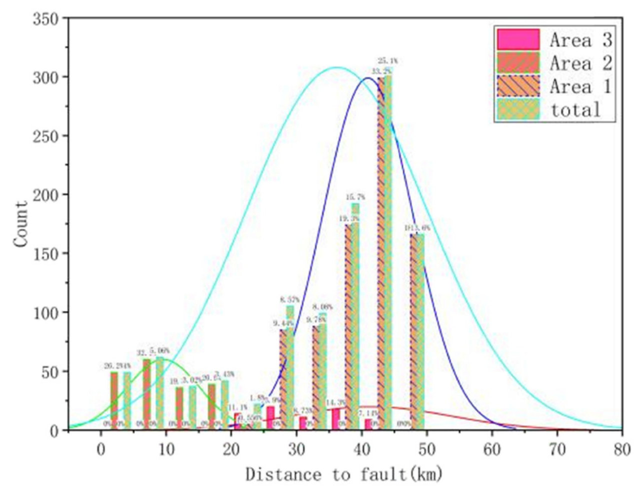

Figure 16: Fault distance distribution map (by dense area).

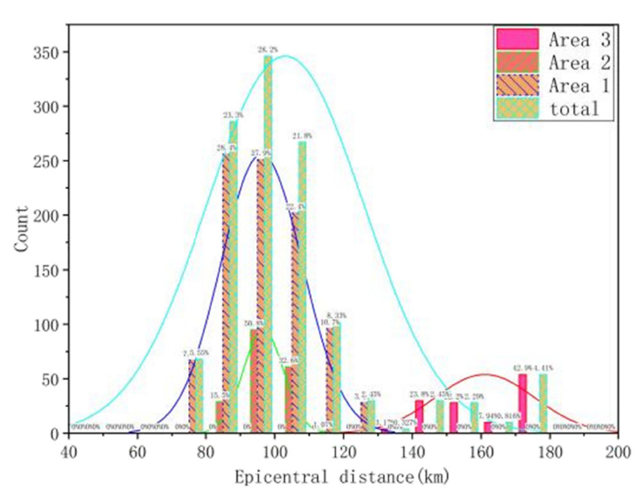

Figure 17: Distribution map of epicentral distance (by dense area).

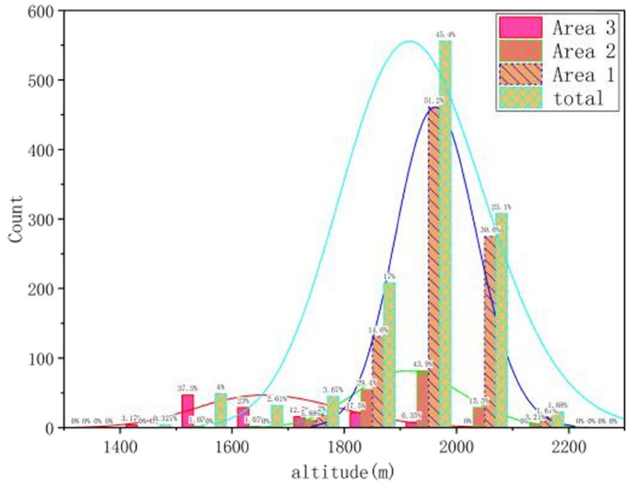

Figure 18: Height distribution map (by dense area).

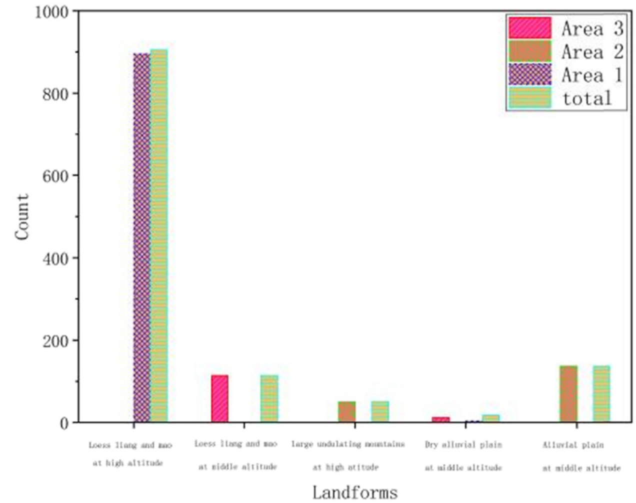

Figure 20: Topography distribution map (by dense area).

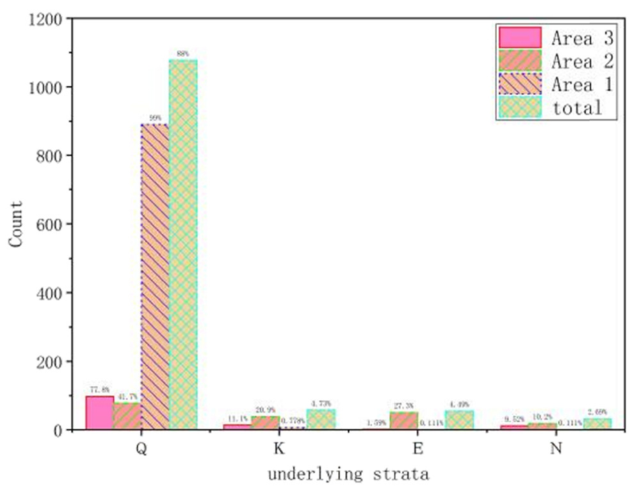

Figure 19: Distribution of underlying strata (by concentration area).

that the length, width, and area of large- and medium-scale landslides induced by the Haiyuan earthquake in 1920 conform to the lognormal distribution. On the whole, the dominant range of landslide length is 100–700 m, and the number of landslides in this range accounts for 83.03% of the total. The large- and medium-scale landslides with lengths less than 100 m only account for 4.08% of the total, and the number of landslides with lengths greater than 700 m gradually decreases. The dominant range of landslide width is 100–500 m, and the number of landslides in this range accounts for 83.27% of the total. The large- and medium-scale landslides with a width less than 100 m only account for 7.76% of the total. The number of landslides with a width greater than 500 m gradually decreases. The dominant range of landslide area is 10,000–250,000 m^2, and the number of landslides in this range accounts for 82.32% of the total. The number of landslides with an area greater than 250,000 m^2 is less and gradually decreases. It can be seen from Figure 14 that the original slope gradient of the landslide conforms to the normal distribution law, which is concentrated in the range of 5–35°. The number of landslides is very small on the slopes less than 5° and greater than 35°. This is because the slope is less than 5°, and it is not easy to landslide. In the natural state, the number of slopes with large slopes is small, so the number of landslides is small.

The landslide is close to the river (Figure 15). The dominant range from the river is 0–4 km. The number of landslides more than 4 km from the river is very small. The existence of river valleys not only ensures the soil moisture content required for landslide occurrence but also provides a movement space for landslide occurrence. The distance between the landslide and the seismogenic fault is 0–50 km (Figure 16), and the number is more in the distance of 30–50 km. The distance between the landslide and the macro epicenter is distributed in the range of 70–180 km (Figure 17). There are more landslides in the range of 80–120 km. The elevation of landslide is distributed in 1,400–2,300 m (Figure 18) and concentrated in 1,500–2,200 m. It can be seen from Figure 19 that the landslide induced by the Haiyuan earthquake is mainly loess landslide, and the landslide of Quaternary loess in the underlying strata accounts for 88% of the total number of landslides. Figure 20 shows that the landslides induced by the Haiyuan earthquake mainly occur on loess hills at high and middle altitudes, indicating that the induced landslides are mainly loess landslides. In general, the slope and sliding directions are mainly eastward and westward (Figures 21 and 22). Combined with

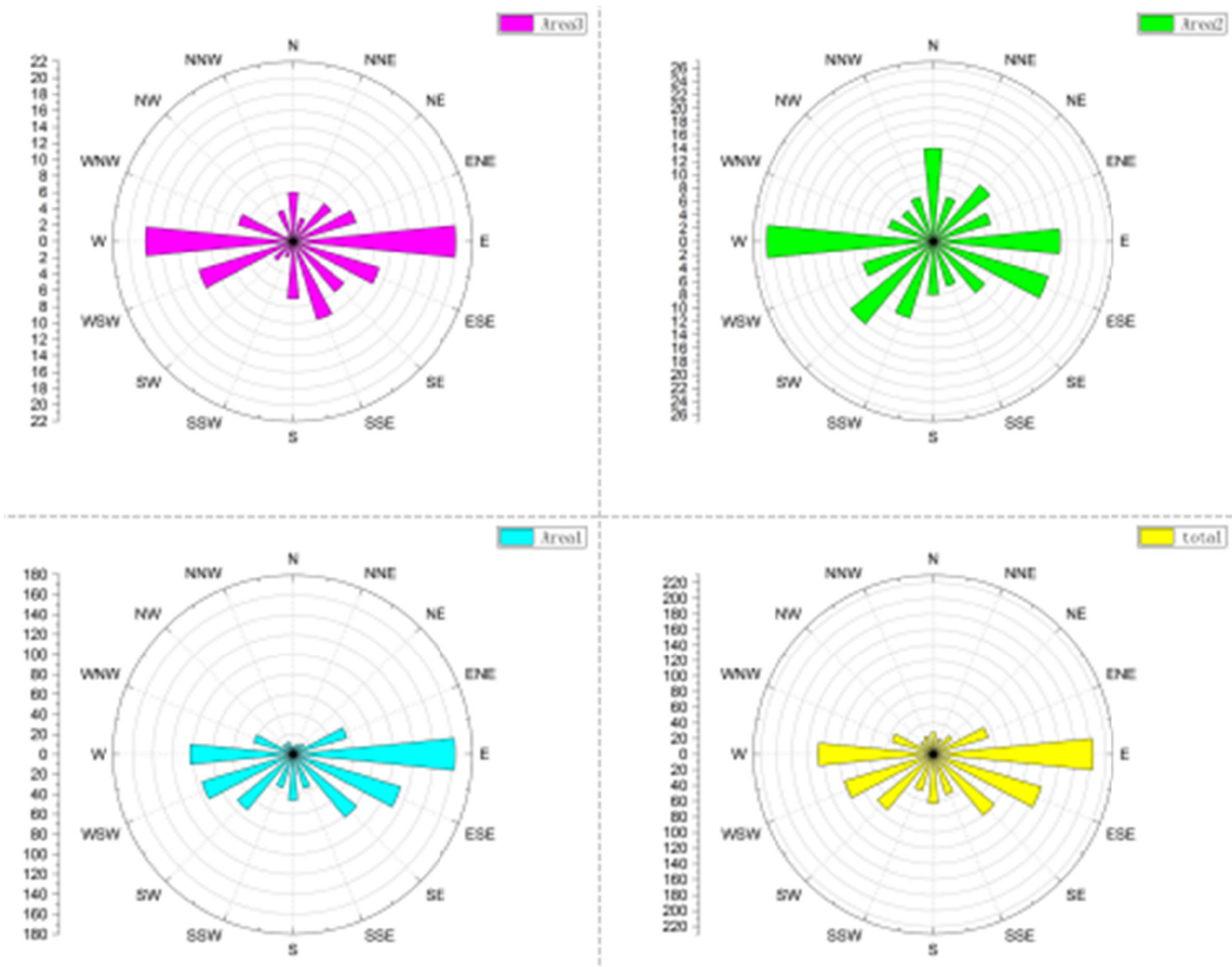

Figure 21: Original slope direction.

field investigation, several landslide-intensive areas are eroded by tectonic movement and rivers, forming a unique loess ridge, and the distribution direction of the ridge is mainly east-west.

4.2 Statistics by concentrated area

The difference in topography, geomorphology, and geological conditions of each landslide-intensive area is small, so according to the distribution law and development characteristics of landslides in the intensive area, the influence of topography, geomorphology, and geological conditions on development characteristics can be reduced. Figures 11–14 show that the length, width, area, and slope gradient of the three concentrated areas are not completely consistent. The number of landslides in concentrated area 1 is large, and the length, width, area, and slope gradient are large (Figure 23), indicating that the landslide in concentrated area 1 has a long sliding distance, a large disaster area, and large movement space. Combined with the field investigation and analysis, the loess cover in this area is thick [31], with an average thickness of about 30 m. The sliding surface has a large cutting depth, and the sliding type is mainly shear and liquefaction. The soil above the sliding surface slides as a whole, with a large speed and a long sliding distance. The sliding body and sliding bed are separated, and the coverage area is large. Many rivers are chopped up to form a weir lake, which has a strong disaster. Figures 24 and 25 are common landslide types in dense area 1. The length, width, area, and slope gradient of the landslide in intensive area 2 are relatively small. Combined with the field investigation and analysis, although this area is in an extremely seismic area, and the ground motion intensity and intensity are large, the valley is

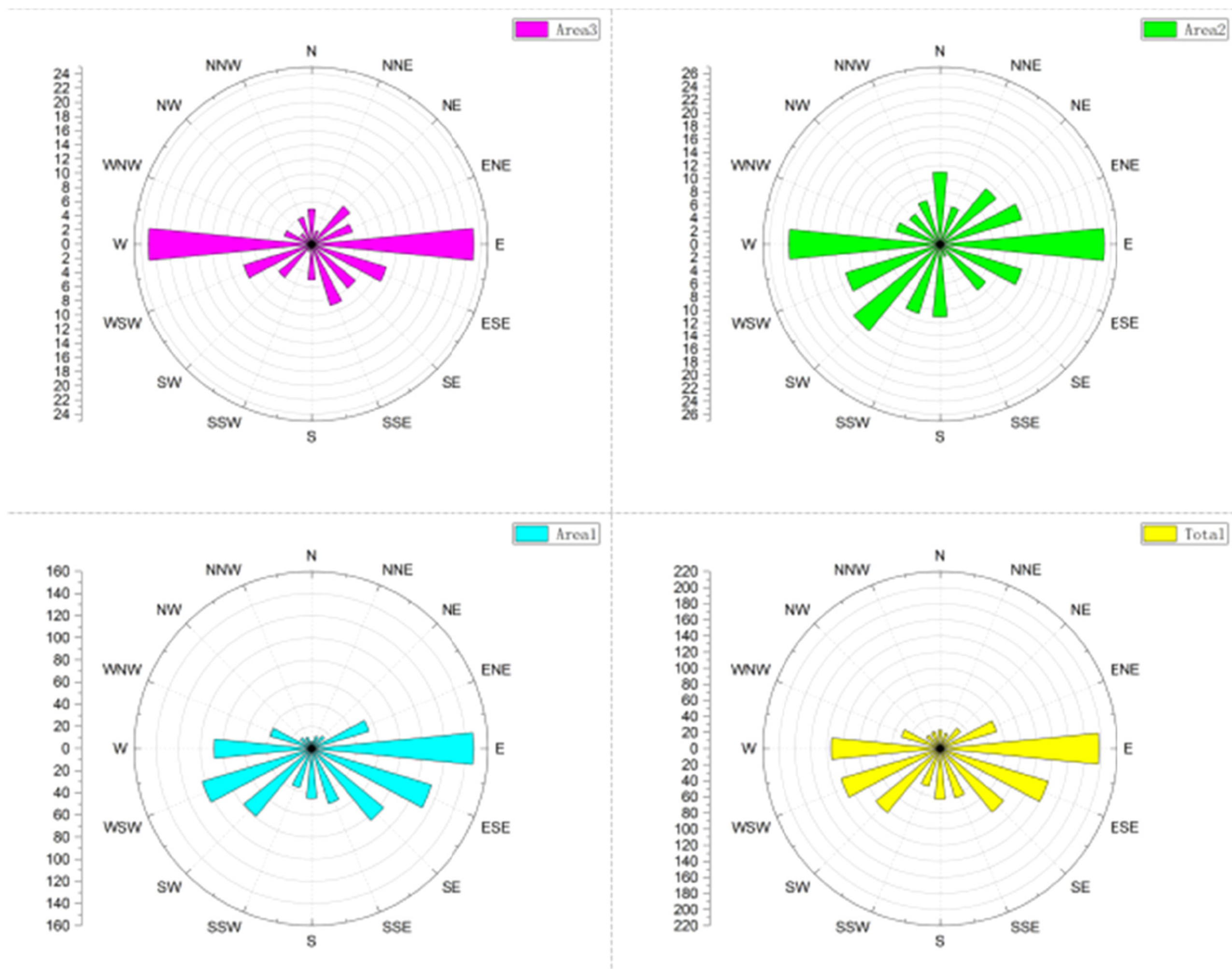

Figure 22: Slip direction.

deep, the loess overburden is thin, and the undercutting depth of the sliding surface is small, which is often thin-layer sliding. The sliding type is mainly seismic subsidence. The sliding body moves downward for some time and then stops. The vertical displacement is greater than the horizontal displacement. The sliding body and sliding bed are not separated, and the sliding distance is short. Figures 26 and 27 are the common typical landslides in the intensive area 2. The number of landslides in dense area 3 is the least, and the expected value of the logarithmic normal distribution of landslide length and area is consistent with that of dense area 1 and dense area 2, but the expected value of the logarithmic normal distribution of landslide width is larger, indicating that the proportion of landslides with larger width is more. Combined with field investigation and analysis, the loess cover in this area is thicker, and the average thickness is about 35 meters. The sliding surface has a large cutting depth, and the shear landslide is the main type. However, due to the limited seismic intensity and development space, the sliding distance is small. Figures 28 and 29 are common and typical landslides in dense area 2.

Figure 18 shows that the elevation of the landslide is concentrated at 1,500–2,200 m, and the altitude of the landslide in the three regions is not completely consistent. The altitude of the landslide in dense area 3 is smaller, and the altitudes of dense areas 1 and 2 are relatively large. The landslide is close to the river (Figure 15). The dominant interval from the river is 0–4 km, and the number of landslides more than 4 km from the river is very small. The existence of river valleys not only ensures the soil moisture content required for the occurrence of landslides but also provides the movement space for the occurrence of landslides (Cuomo, 2017). The landslide in intensive area 2 is close to the river, which is the premise of inducing some rock landslides in intensive area 2.

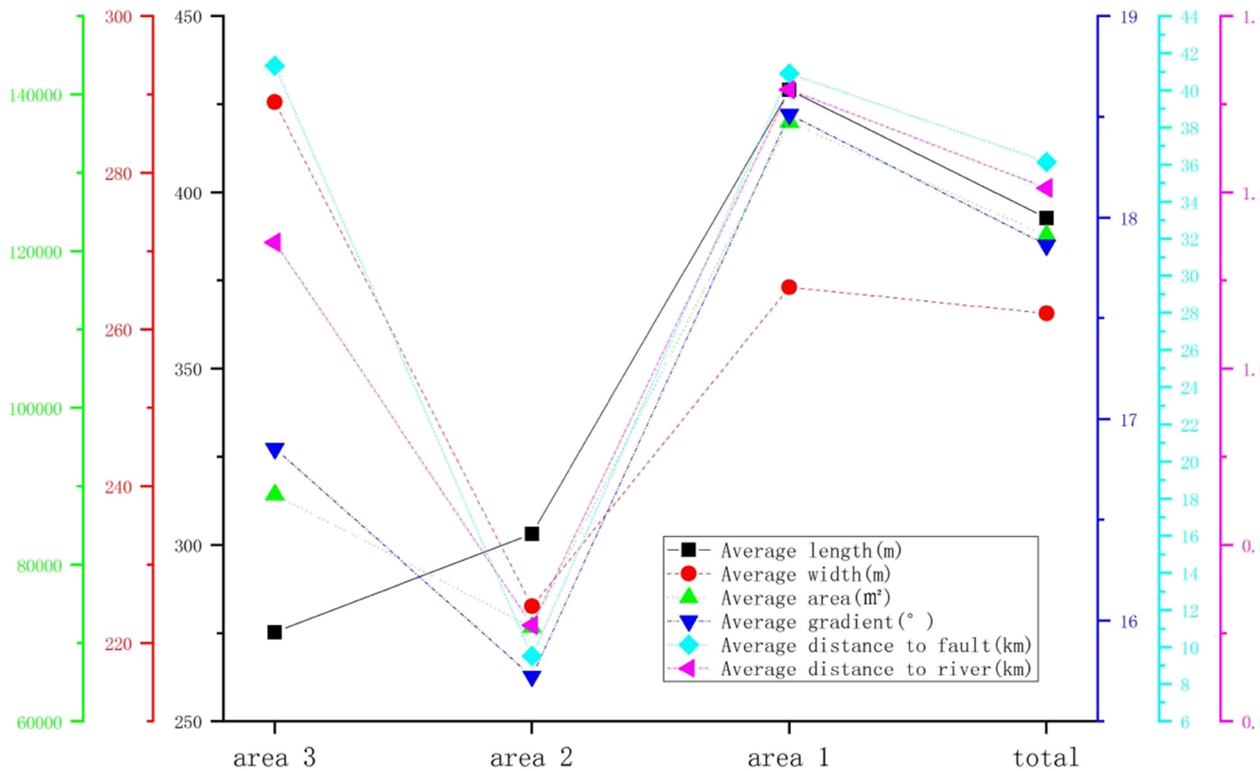

Figure 23: Average of landslide parameters (by dense area).

Figure 24: Typical landslides in dense area 1 – Lijiacha landslide in Tianping Township, Xiji County.

Figure 25: Typical landslide in dense area 1 – Shangyangwa landslide in Tianping Township, Xiji County.

It also determines that the movement space of the landslide in intensive area 2 is limited, and the sliding distance is not too long. The landslides in intensive areas 1 and 3 are far from the river, and the induced landslides can migrate for a long distance, forming a large area of landslides and causing great disasters.

Intensive area 2 is close to the fault (Figure 16), and the seismic intensity is larger. Intensive areas 1 and 3 are far away from the fault, and the seismic intensity is smaller. The distances between concentrated areas 1 and 2 and macro epicenters are similar (Figure 17). The distance between concentrated area 3 and macro epicenter is relatively far. It can be seen from the Figure that the distance between the epicenter and the occurrence of landslides is not significantly related. In the characterization of ground motion intensity, fault distance is more advantageous.

The landslides in dense area 1 and dense area 3 are mainly loess landslides (Figure 19). The number of rock landslides in dense area 2 is more, which shows that the

Figure 26: Typical landslides in dense area 2 – Erdaogou landslide in Jiucai Township, Haiyuan County.

Figure 27: Typical landslide in dense area 2 – Heiyingwan landslide in Jiucai Township, Haiyuan County.

loess cover in dense area 2 is less and the lithology of strata is diverse. Under the condition of large seismic intensity in the extreme earthquake area, the lithologic landslides outside the loess soil layer are induced, which indicates that the seismic intensity has an important effect on the occurrence of earthquakes. It can be seen from Figure 20 that the landslides induced by the Haiyuan earthquake mainly occurred on the loess ridges at high

Figure 28: Typical landslides in dense area 3 – Mingchuan Landslide, Hechuan Township, Guyuan City.

Figure 29: A typical landslide in dense area 3 – Shuiziwan landslide in the Pengyang County.

and medium altitudes, indicating that the induced landslides were mainly loess landslides. Only in concentrated area 2, there were some landslides that occurred on the rocky mountains, further indicating that the seismic intensity of the near fault was large, and there were more types of induced landslides.

Figures 21 and 22 show that there is little difference between the original slope direction and the sliding direction of the landslide, indicating that the sliding of the landslide mainly occurs along the slope direction. Both concentrated area 1 and concentrated area 3 are on the south side of the fault. The number of landslides in the SW direction is significantly more than that in the NE direction in the region, indicating that the earthquake input from the back slope of the slope is more prone to landslide disasters and has an obvious directional effect on the back slope. Concentrated area 2 runs through the north and south side of the fault, the slip direction is mainly SW and NE, and the strike of the seismogenic fault is vertical. The number of landslides parallel to the slip direction and the seismogenic fault is small, indicating that the slip direction of the landslide is affected by the propagation direction of the earthquake, and the distribution direction is directional.

4.3 Statistics by intensity area

The seismic damage of each intensity area is consistent, and the seismic intensity in the same intensity area can be approximately considered to be consistent. The statistics of landslides according to the intensity area can obtain the influence of ground motion intensity on landslide distribution. The landslide is counted according to the length, width, elevation, area, original slope, original slope direction, river distance, fault distance, epicentral distance, overlying strata, hydrogeology, and geomorphologic conditions, as shown in Figures 30–42. It can be seen from Figures 30–33 that the length, width, and area of the landslide are in line with the logarithmic normal distribution, and the original slope of the landslide is in line with the normal distribution. In addition to the intensity area VIII, the greater the intensity, the average length, area, and original slope of the landslide are reduced. Combined with the distribution number in the map, the cause of this situation is that the loess cover is thicker in the IX degree area, the number of landslides with large slopes, long sliding distances, and large areas is more, and the average value is increased. The landslides in the XI and XII intensity areas are distributed in the high-altitude mountainous areas where the loess cover is thin and the rock slope is mainly. There is no

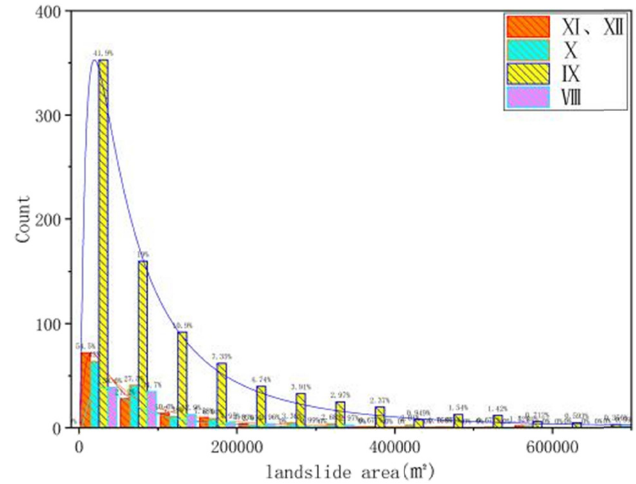

Figure 32: Landslide area distribution (by intensity).

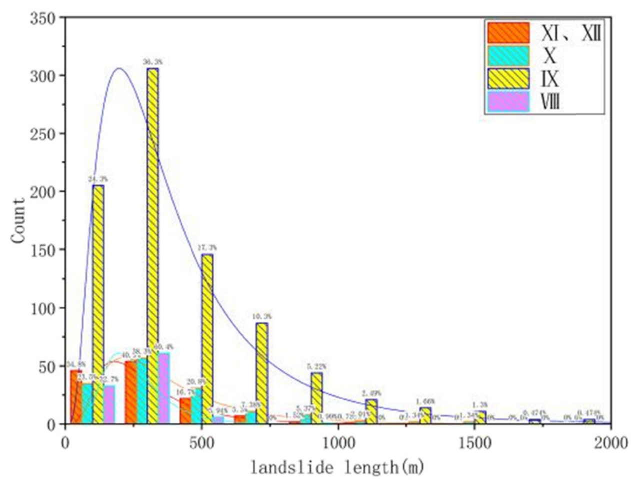

Figure 30: Length distribution of landslide (by intensity).

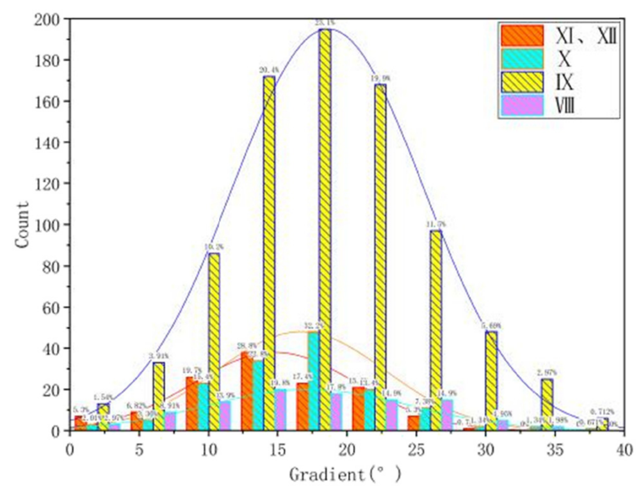

Figure 33: Original slope angle distribution of landslide (by intensity).

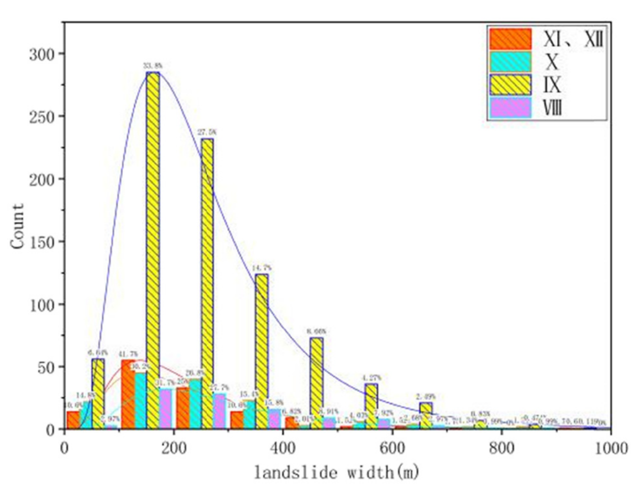

Figure 31: Distribution of landslide width (by intensity).

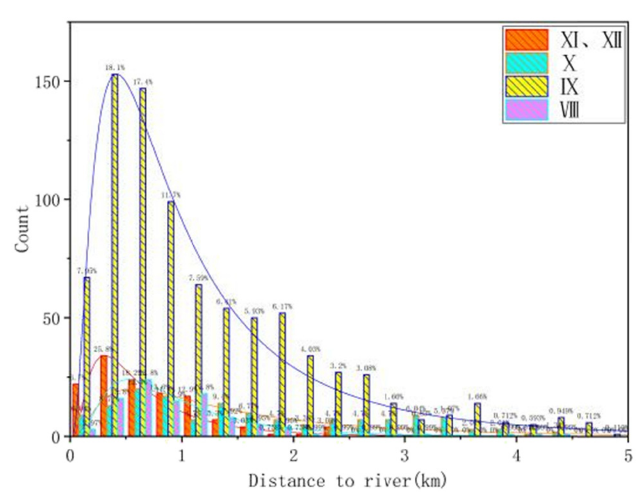

Figure 34: River distance distribution (by intensity).

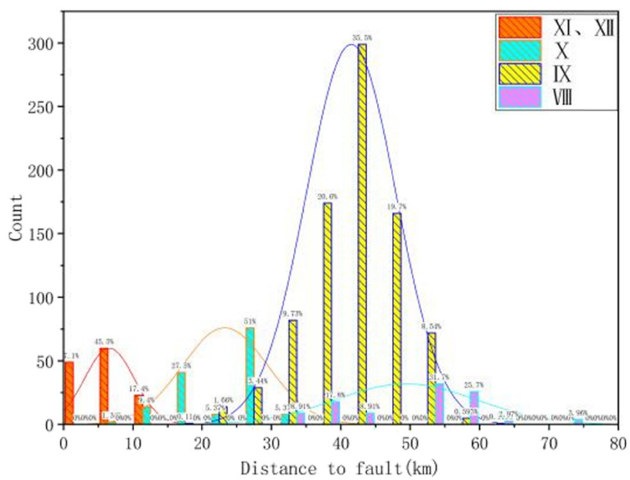

Figure 35: Fault distance distribution (by intensity).

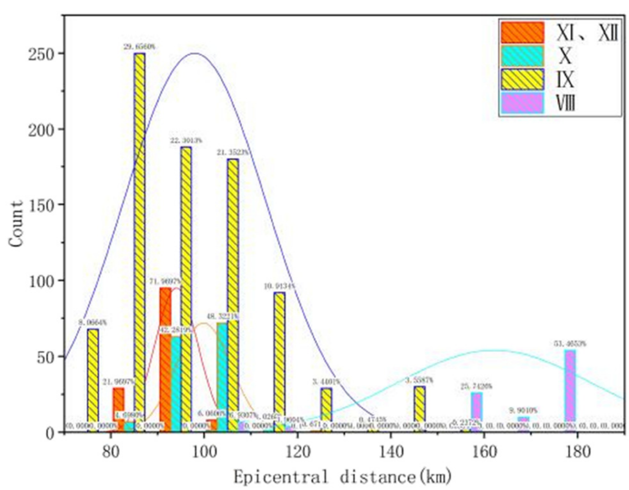

Figure 36: Distribution of epicenter distance (by intensity).

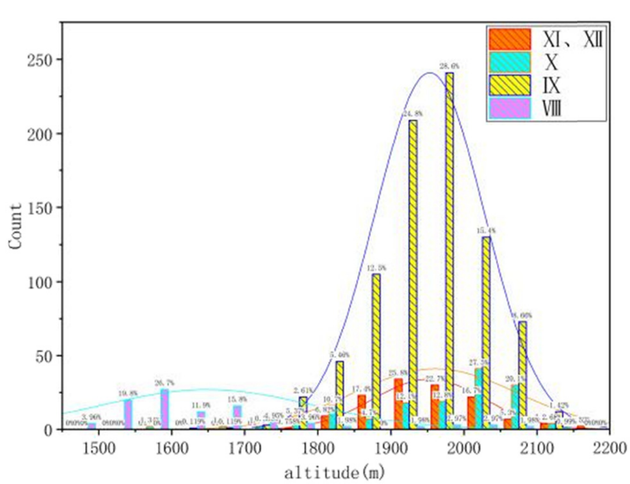

Figure 37: Altitude distribution (by intensity).

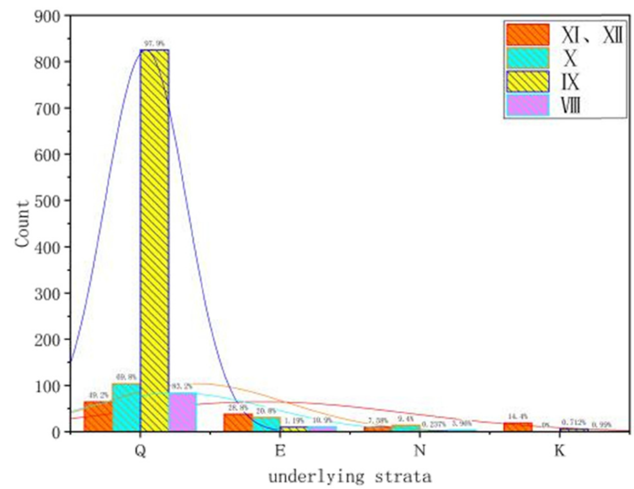

Figure 38: Distribution of underlying strata (by intensity).

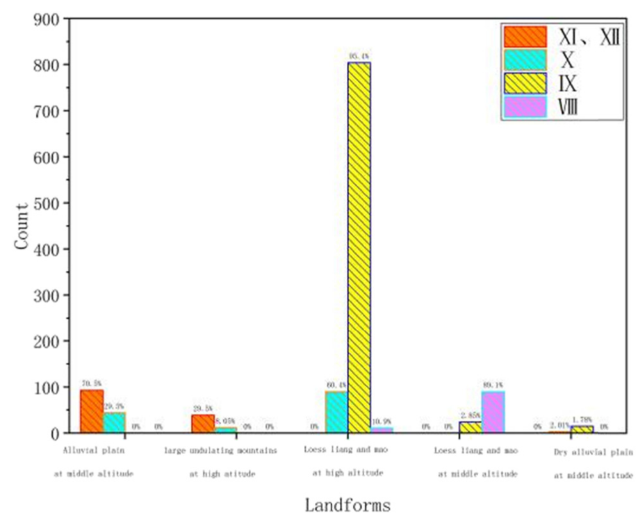

Figure 39: Geomorphological distribution (by intensity).

significant difference in the distribution of length and area of landslide in different intensity areas. The width of landslides in different intensity areas is quite different. The greater the intensity is, the smaller the average width is, and the distribution of landslide width also reflects this feature. The width of a landslide is affected by many factors such as stratum lithology, seismic intensity, and thickness of loess overburden, which can indicate important indicators of landslide such as the cutting depth of circular sliding surface and the disaster-causing range of landslide. The distribution of landslide width in different intensity areas is different, indicating that landslide width plays an important role in the study of landslide morphology. In addition to the intensity zone VIII, the greater the intensity, the greater the average slope

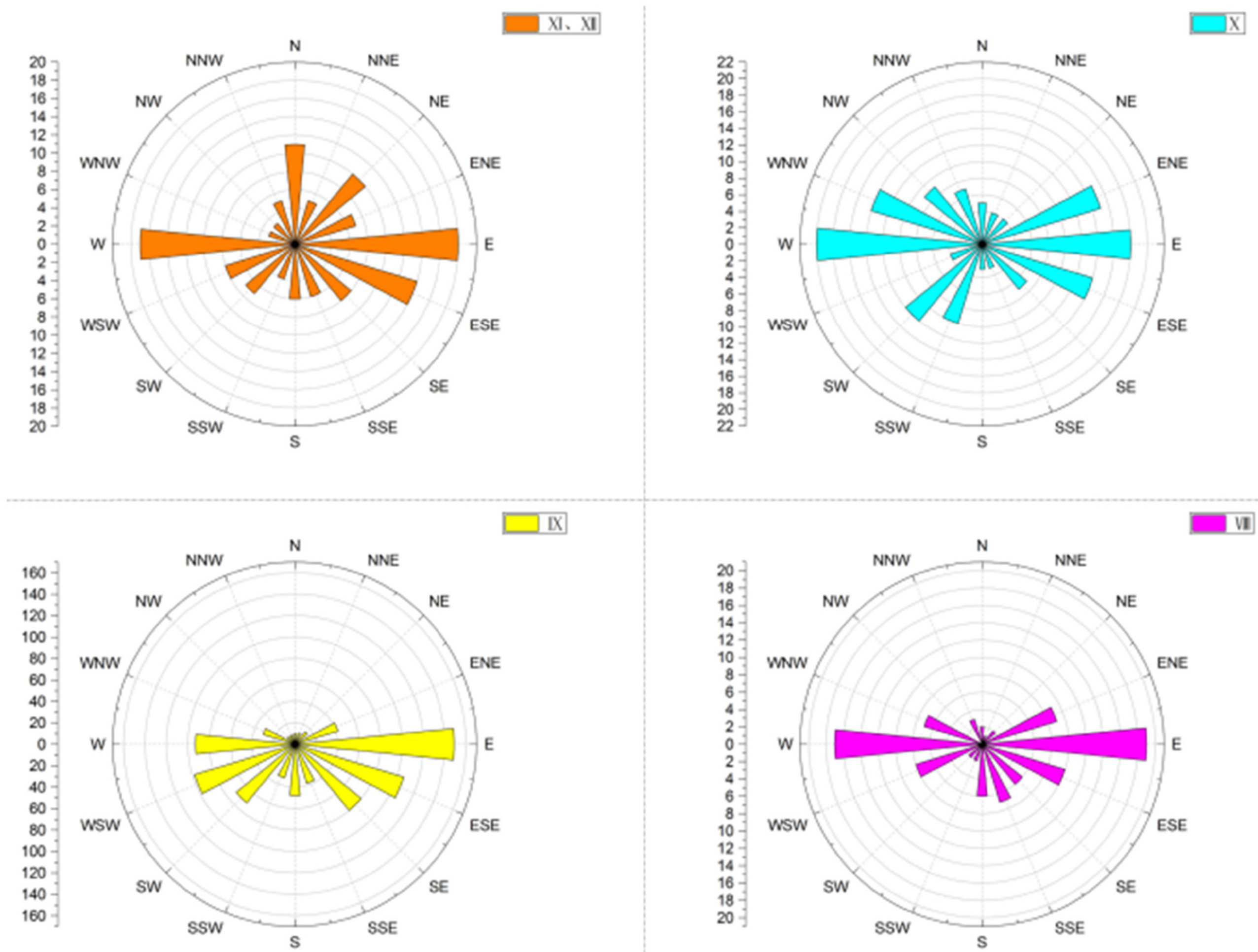

Figure 40: Original slope distribution (by intensity).

angle of landslide, and the greater the intensity, the greater the proportion of small slope angle landslides in the total number, which shows that the seismic intensity can induce the slope with small slope angle to landslide, and the smaller the seismic intensity, the main cause of slope failure with large slope angle.

It can be seen from Figure 37 that the altitudes of landslides in different intensity areas are different. The altitude of landslides in the VIII degree area is small, and that in other intensity areas is large, which is related to the average altitude of landslides in the region. The landslide in XI and XII intensity areas is closest to the river (Figure 34). The landslide in X, IX, and VIII intensity areas is closer to the river. Based on the overlying strata and geomorphology in the four intensity areas (Figures 38 and 39), the lithologic conditions of the landslide in X, IX, and VIII intensity areas are similar, and the loess landslide is the main landslide. The smaller the intensity is, the closer the landslide is to the river, and the closer the landslide is to the river. The groundwater in this area is abundant and has a certain amount of flow, indicating that water plays an important role in the occurrence of earthquake landslides. At the same time, it also shows that the intensity of ground motion has a great influence on the occurrence of landslides; XI and XII intensity area landslide has a certain number of rock landslides, which is related to the earthquake, near the river. The distance between the landslide and the fault is highly correlated with the intensity (Figure 35), indicating that the direct factor affecting the seismic intensity of the landslide is the fault distance, rather than the epicentral distance (Figure 36).

Figures 40 and 41 show that the slope direction and sliding direction are mainly east and west. In addition to intensity areas XI and XII, the slope direction and sliding direction of the original slope are similar, and the sliding direction of the landslide occurs along the slope direction. In intensity areas XI and XII, the sliding direction

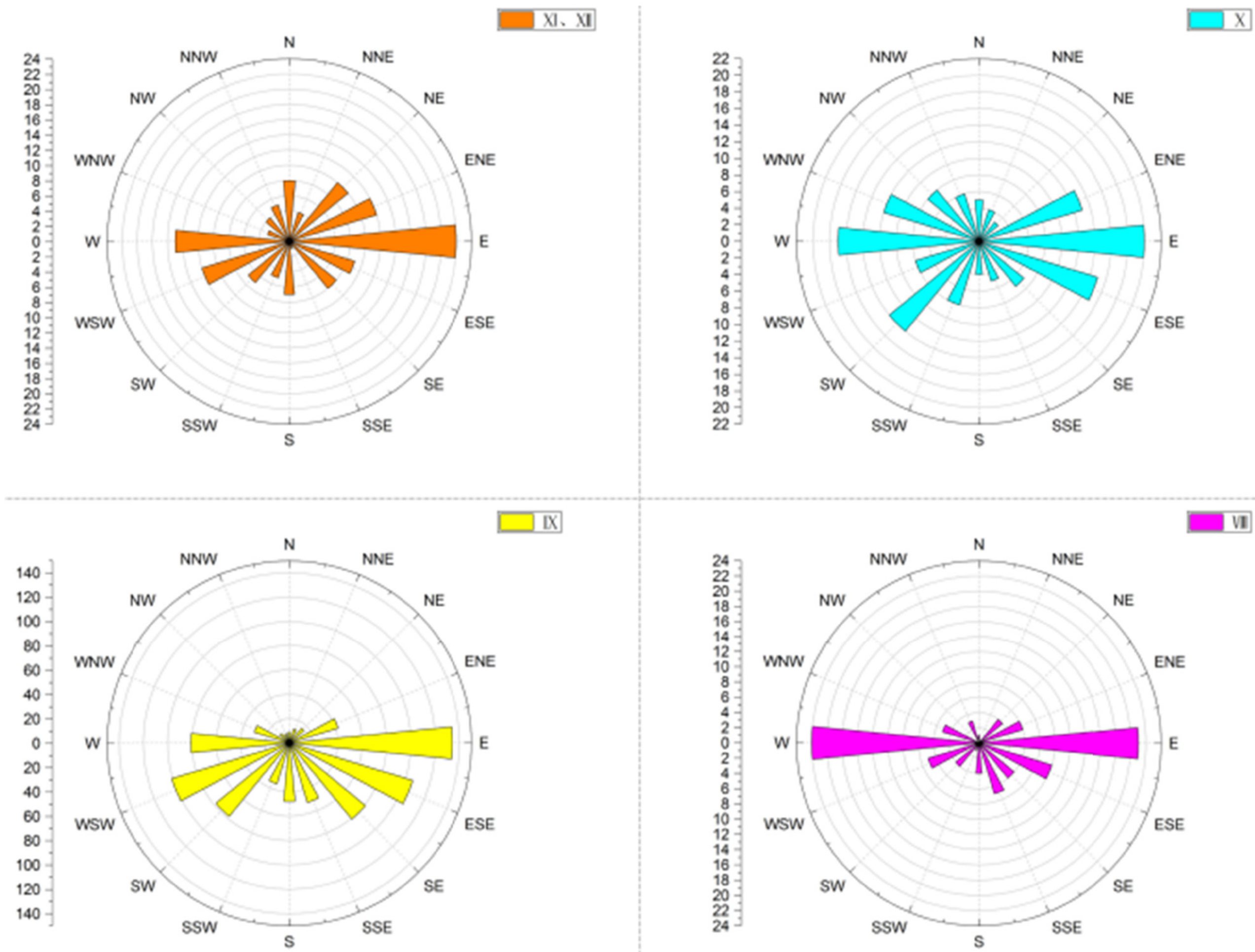

Figure 41: Landslide slip direction distribution (by intensity).

and slope direction of some landslides are not completely consistent, and the sliding direction is more vertical to the fault. The distribution direction of landslide sliding is directional, indicating that the sliding direction of the landslide is affected by the propagation direction of the earthquake.

4.4 Statistics according to hanging wall and footwall of faults

The spatial distribution of geological disasters is controlled by seismogenic faults. Some studies have found that the peak acceleration of the hanging wall of the fault is higher than that of the footwall, and the attenuation of the peak acceleration of the hanging wall is slower than that of the footwall. The landslide data are counted according to the upper and lower plates, which is convenient to explain the influence of the nature of the seismogenic fault on the distribution characteristics of the landslide. From Figures 43–55, it can be seen that the number and scale of landslides in the upper and lower walls of the fault show very different differences. The number of large- and medium-sized landslides in the hanging wall (SW) is more, and there are 1,200, accounting for 97.96% of the total, while the number of the footwall (NE) is less, accounting for 2.04%. The average length, width, area, and original slope angle of the medium- and large-sized landslides on the hanging wall of the fault are much larger than those on the footwall of the fault, and the number distribution is also significantly different, indicating that the hanging wall of the fault is subjected to strong ground motion and more catastrophic.

On the spatial distribution, the fault distance of the hanging wall landslide distribution is 20–60 km, and the fault distance of the footwall landslide distribution is 0–30 km, and the footwall landslide is closer to the fault. It shows that the seismic intensity of the footwall decays

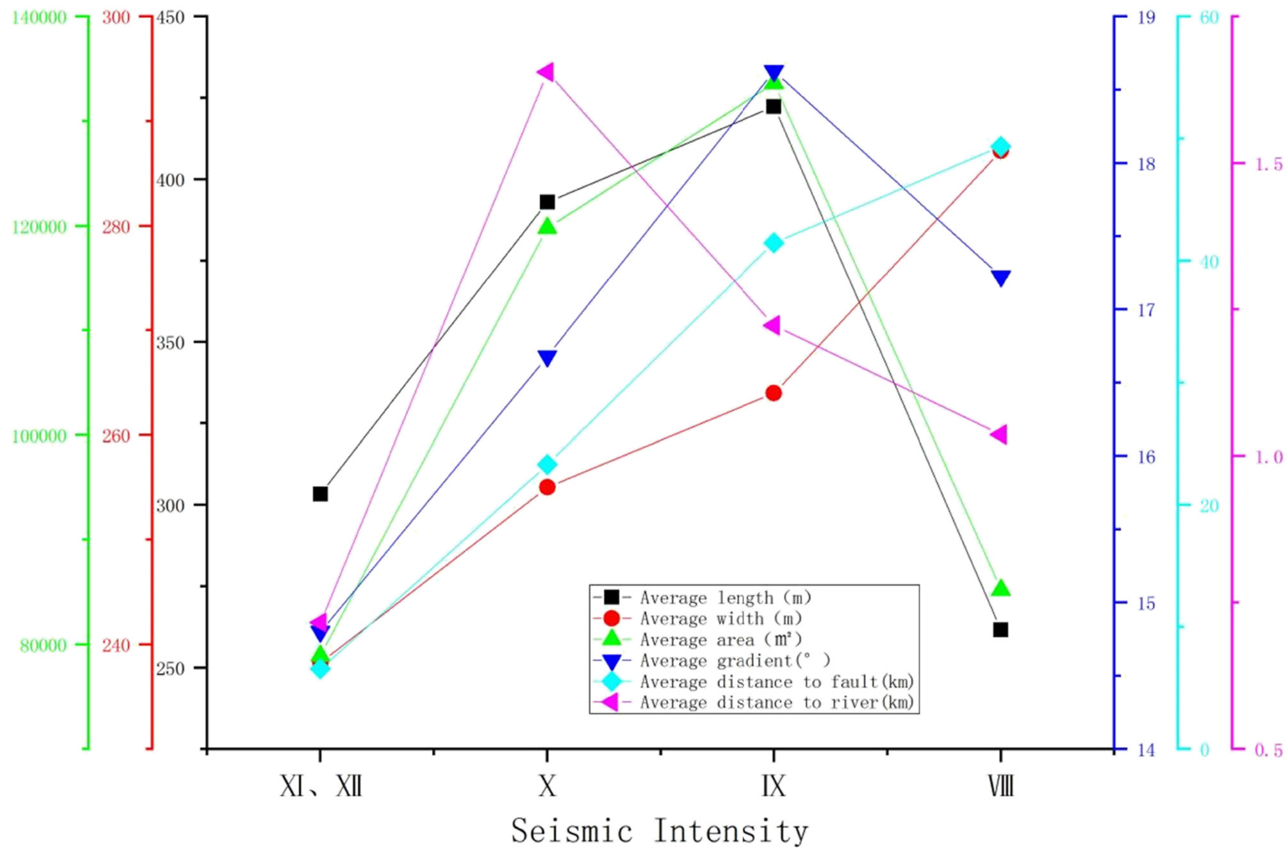

Figure 42: Average of landslide parameters (by intensity).

faster, and the seismic intensity of the loess earthquake landslide cannot be induced in a place far from the seismogenic fault. The attenuation of the hanging wall of the fault is slow. Even in a place 60 km away from the fault, the seismic intensity is still large, which can induce slope instability and cause a landslide. The landslide located in the upper wall of the fault is farther from the river, and the landslide located in the lower wall of the fault is closer to the river. It further shows that the seismic intensity of the lower wall is small, and more groundwater is

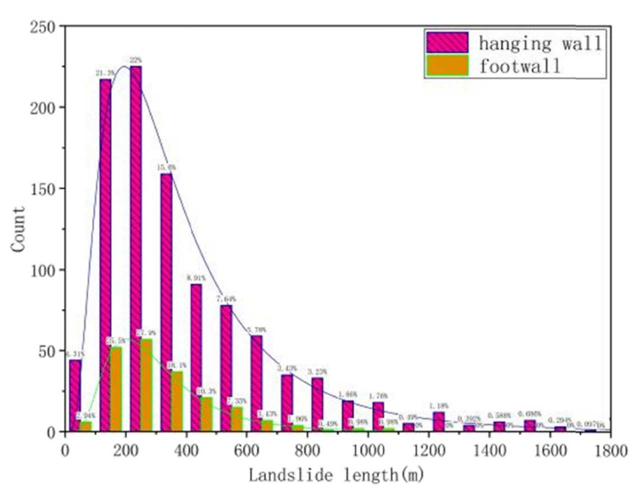

Figure 43: Length distribution of landslides (by hanging wall and footwall of faults).

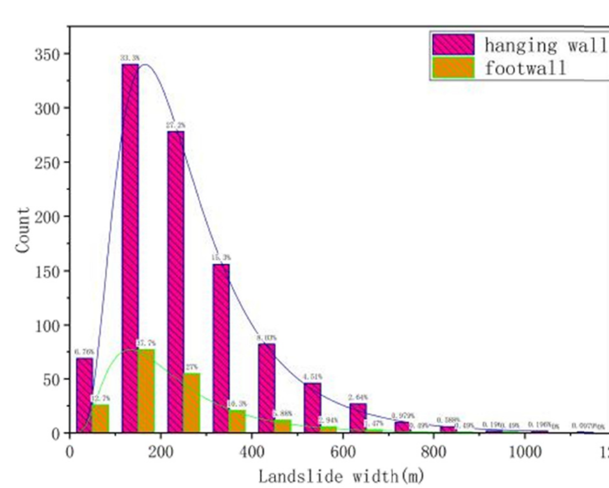

Figure 44: Distribution of landslide width (by hanging wall and footwall of faults).

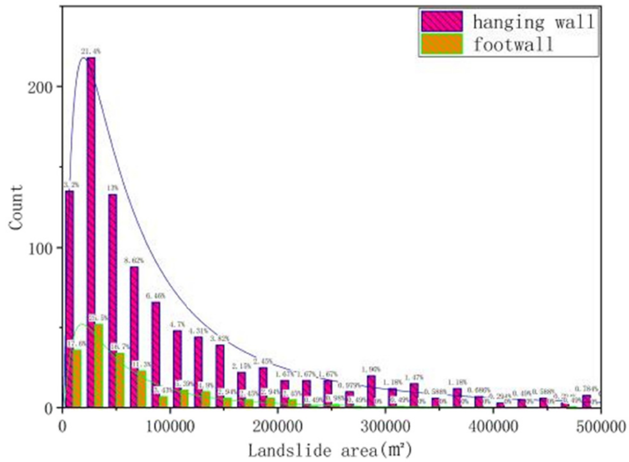

Figure 45: Landslide area distribution (by hanging wall and footwall of faults).

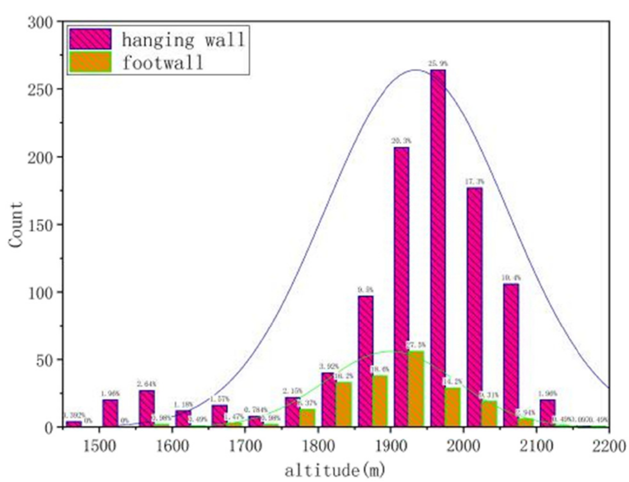

Figure 46: Elevation distribution of landslide (by hanging wall and footwall of faults).

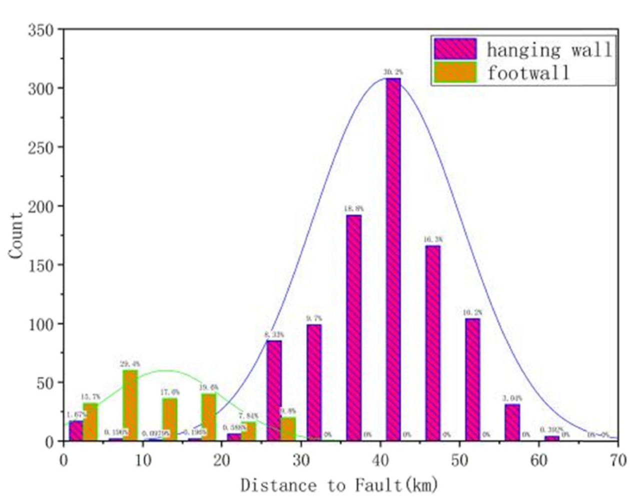

Figure 47: Fault distance distribution (by hanging wall and footwall of faults).

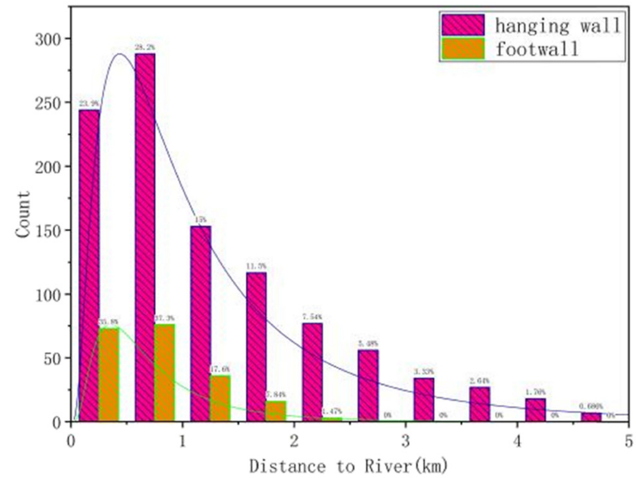

Figure 48: River spacing distribution (by hanging wall and footwall of faults).

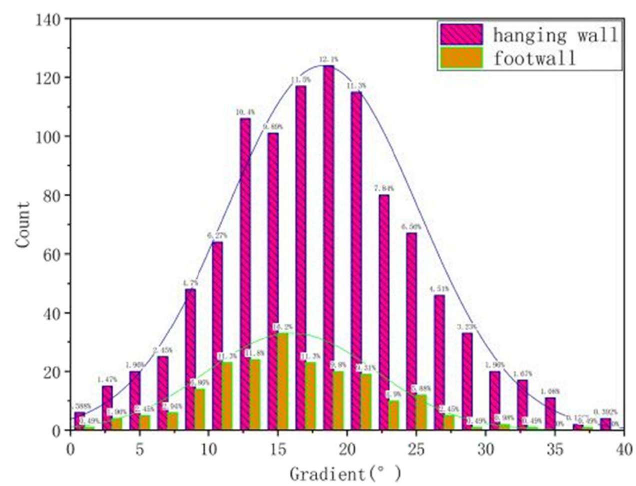

Figure 49: Original slope angle distribution (by hanging wall and footwall of faults).

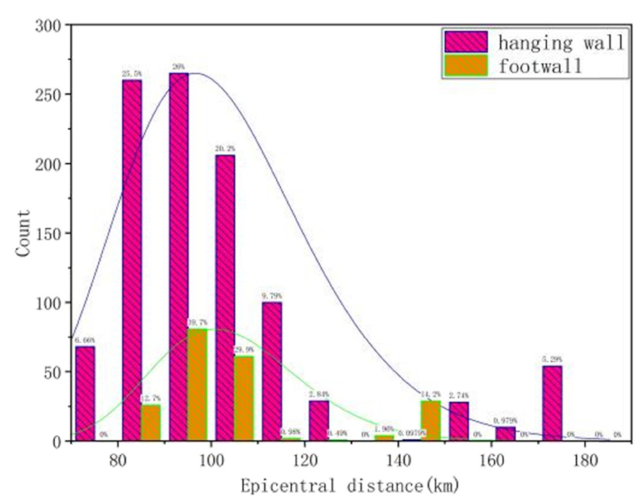

Figure 50: Epicenter distance distribution (by hanging wall and footwall of faults).

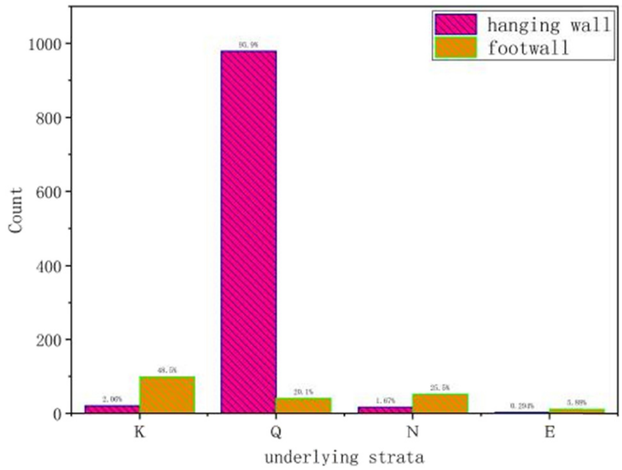

Figure 51: Distribution of underlying strata (by hanging wall and footwall of faults).

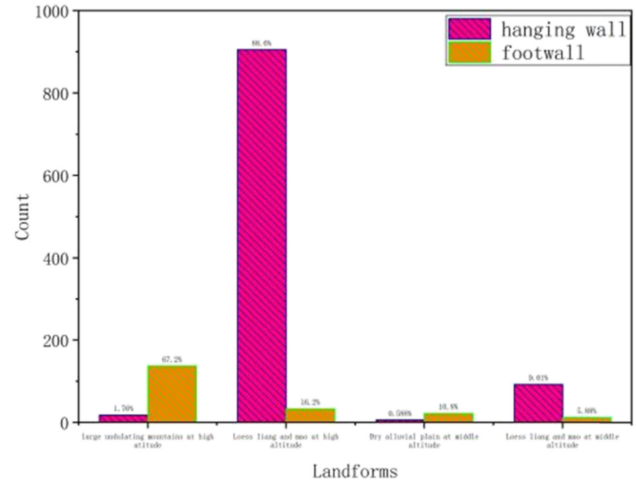

Figure 52: Landform distribution (by hanging wall and footwall of faults).

needed to weaken the rock and soil strength and lubricate the sliding surface. The distribution range of the original slope angle of the landslide on the hanging wall of the fault is wider, which is normally distributed at 0–40°, and the original slope angle of the landslide on the footwall of the fault is normally distributed in 5–30°, which further indicates that the ground motion of the landslide on the hanging wall is strong. The original slope direction of the hanging wall landslide is mainly east and west, and the sliding direction and slope direction are relatively consistent. The original slope direction of the footwall landslide is east and west, and the sliding direction is mainly NW and SE. The original slope direction of the landslide is greatly changed, and the sliding direction is closer to the vertical direction of the fault direction, indicating that the occurrence of seismic landslides has an obvious directional effect.

5 Analysis

5.1 Morphological characteristics of Haiyuan earthquake landslides

There are a large number of large and medium-sized landslides induced by the Haiyuan earthquake. There are 1,225 landslides over 10,000 m^2. The sliding distance of these landslides is long, with an average length of

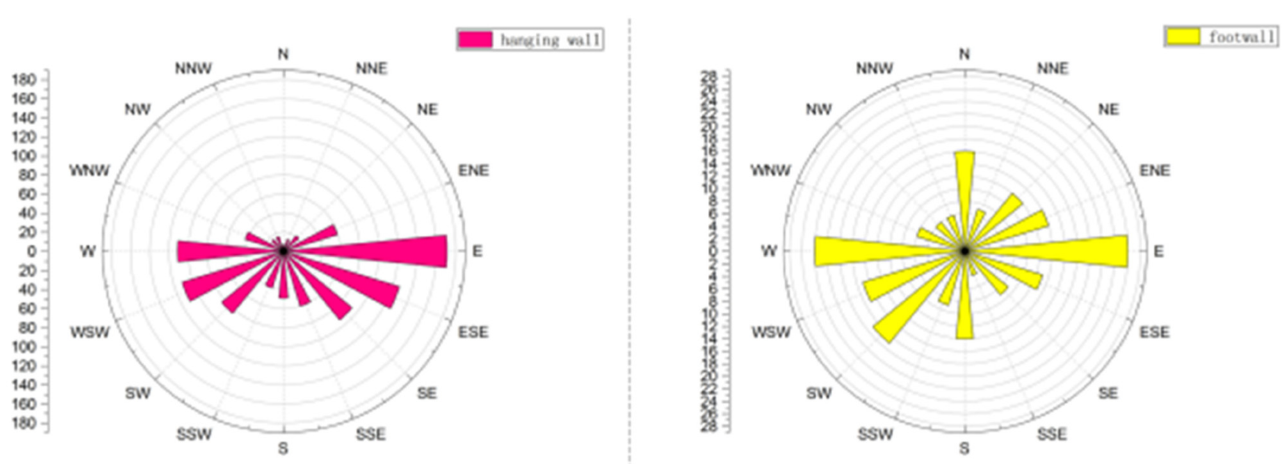

Figure 53: Distribution of original slope aspect (by hanging wall and footwall of faults).

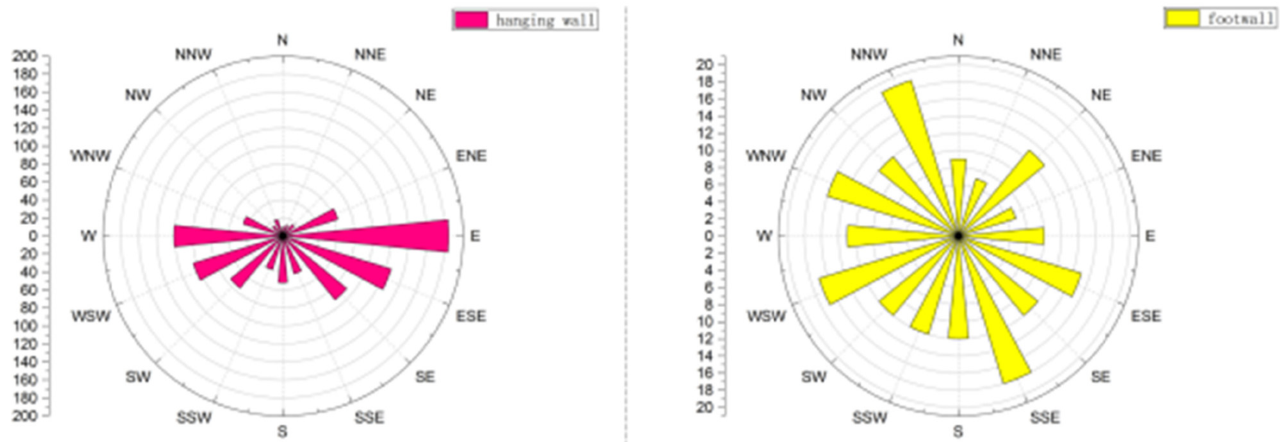

Figure 54: Slipwise distribution (by hanging wall and footwall of faults).

399.7 m. The unit size is large, with an average area of 122,000 m^2. The disaster is strong, and the total coverage area is 149.5 km^2, which is one of the important reasons for serious casualties in the Haiyuan earthquake.

There are mainly three landslide-intensive areas in the landslide, and the different sliding types of the three landslide-intensive areas lead to different morphological characteristics. The loess overburden in intensive area 1 is thick, and the sliding surface has a large cutting depth. The sliding type is mainly the shear type and liquefaction. The soil above the sliding surface slides as a whole, and the speed is large. The sliding body and the sliding bed are separated, and the sliding distance is long, and the disaster area is large. The landslide in dense area 2 is subjected to strong ground motion, but the loess cover is thin and the gully is deep, and the depth of the sliding surface is small, which is a thin layer sliding, and the vertical displacement is often greater than the horizontal displacement. The intensity of ground motion in concentrated area 3 is small, but the loess overburden is thick, and the width

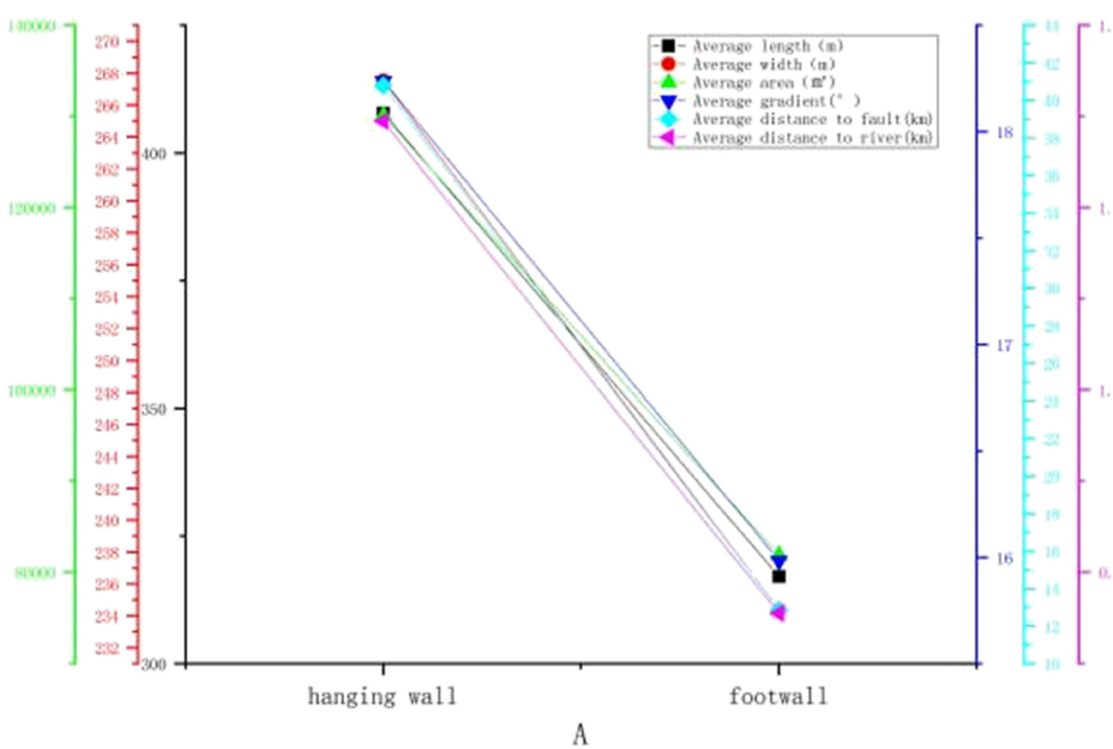

Figure 55: Average of landslide parameters (by hanging wall and footwall of faults).

of the landslide is large. The sliding distance near the river valley is small, resulting in the limited disaster area of the landslide.

5.2 Distribution law of Haiyuan earthquake landslides

(1) The occurrence of landslides is significantly grouped and has a concentrated area. Haiyuan earthquake landslide has three concentrated areas. In the concentrated area, there are a large number of landslides that are developed in groups. Outside the concentrated area, only a few scattered landslides occur. The stratum lithology of these three concentrated areas is mainly Quaternary loess, and the landform is mainly loess hill, with good lithology and landform conditions for landslide development. It indicates that the occurrence of seismic landslides is not only affected by the earthquake but also controlled by the lithology and geomorphology of the location. As long as the conditions are appropriate, a large number of seismic landslides in groups may occur, causing great harm.

(2) The river is short in distance and distributed in belts. The development position of the loess seismic landslide is close to the river, and most of the landslides are distributed within a distance of 4 km from the river. Moreover, the farther away from the river, the less the number of landslides occurs, which has an obvious distance effect. The average distance between the landslide and the river is 1,205 meters. In the concentrated area, the landslide is distributed along both sides of the river valley.

(3) The sliding direction of the landslide is affected by the vertical direction of the fault, and the hazard of the earthquake from the back slope is greater. The sliding of landslide mainly occurs along the original slope direction, but is affected by the direction of seismic propagation, the sliding direction of landslide is more perpendicular to the direction of the seismogenic fault, and the sliding direction of the landslide has obvious directionality. Compared with the earthquake input from the slope, the earthquake input from the back slope is more likely to induce landslide and has an obvious back slope direction.

(4) Fault hanging wall landslide development and large area. The spatial distribution of geological disasters will be controlled by the seismogenic fault. The fault hanging wall effect of landslide distribution is obvious. Affected by the fault, the number of landslides on the hanging wall of the fault is large, the sliding distance is long, the area is large and the disaster is strong. The number of landslides on the footwall of the fault is small, the drama is short, the area is small, and the disaster is small.

5.3 Influence factors of Haiyuan earthquake landslides

According to the analysis of the morphological characteristics and distribution of landslides, the factors affecting the landslides induced by the Haiyuan earthquake are summarized as follows:

(1) *Formation lithology*. Landslides are concentrated in three concentrated areas, and the stratigraphic lithology of these three concentrated areas is mainly Quaternary loess, while only sporadic landslides are distributed in other areas outside the concentrated area. The loess in the three concentrated areas has the structural characteristics of large pores, weak cementation, and vertical joint development, showing dynamic vulnerability and strong water sensitivity, which provides good lithologic conditions for the generation of loess seismic landslides.

(2) *Topography*. According to the slope distribution, slope direction, and geomorphological distribution of the landslide, the three landslide-intensive areas are mostly distributed in the loess hilly area, which provides the free-face conditions and topographic conditions for the occurrence of the landslide. The slope direction has an obvious dominant direction, and the slope has an interval, indicating that the occurrence of loess seismic landslide requires a certain slope, slope direction, shape, height, and good free space conditions.

(3) *Water*. According to the fact that the landslide is close to the river and distributed along the valleys, water has an important influence on the formation of loess seismic landslide. It is manifested in external erosion, side erosion, and internal corrosion and lubrication. The abundant surface water has serious mechanical erosion and side erosion on rivers and valleys, which provides a good condition for the occurrence of landslides.

(4) *Fault and its dislocation direction*. Affected by the strong movement of the seismogenic fault and the loose broken rock and soil, the landslide is distributed on both sides of the seismogenic fault, and the landslide on the hanging wall of the fault is more and the area is large, and the landslide on the footwall of the fault is less and the area is small. The dislocation direction of the seismogenic fault controls the landslide density and the sliding direction of the landslide, which has a significant impact on the occurrence of the landslide.

(5) *Seismic intensity*. Earthquake is the main reason for the occurrence of landslides in the study area. The destruction of loess structures under dynamic conditions is the prerequisite for the occurrence of landslides. The intensity of ground motion in the study area is large, and the dynamic conditions are sufficient. The intensity of ground motion decreases with the distance of the fault. The speed of attenuation also has a great influence on the occurrence of landslides.

6 Discussion

More than 50% of the landslide data in this article are derived from field investigation, which ensures the authenticity and reliability of these landslide data. The distribution model and distribution law established by these data are more reliable and true. The data obtained in this study has paid a lot of manpower and material resources. The established database can provide test methods for the development of satellite image recognition technology. With the rapid development of satellite images and remote sensing technology, many landslides no longer need to carry out field investigation of all landslides, only need to be identified on satellite images or remote sensing images, and carry out certain landslide inspections on the scene. The progress of accurate interpretation of remote sensing images is inseparable from the summary of the distribution law and morphological characteristics of a large number of landslides after field investigation. This article systematically summarizes the landslides induced by the Haiyuan earthquake in 1920, which has certain positive significance to promote the accurate interpretation of remote sensing images.

In the investigation of landslide, whether it is field investigation or satellite image interpretation, it is faced with the inducing conditions of landslide, namely earthquake-induced or rainfall-induced, which is related to the accuracy of the distribution law and morphological characteristics of co-seismic landslide. Based on field experience and landslide occurrence mechanism, this study proposes that the characteristics such as the back wall of landslides can be used to accurately distinguish between rainfall-induced landslides and earthquake-induced landslides. This view has positive significance for the establishment of an earthquake landslide database. Previous studies [32–35] have shown that the loess slope has an amplification effect on the ground motion. The seismic wave propagates from the bedrock to the slope surface. The peak acceleration has different amplification effects in different parts of the slope surface. The peak acceleration at the bottom of the slope surface is close to the input value, and the shoulder part of the middle and upper parts of the slope surface is several times the input value, which is one of the main reasons for the instability and failure of the slope caused by the earthquake. Therefore, the instability of the seismic landslide often occurs at the shoulder part, that is, the high position of the slope. At the same time, different intensities of seismic wave input and the same slope position will have different amplification coefficients, which is related to the increase in shear strain, stiffness, and damping of soil. At the same time, with the increase in input seismic intensity, the soil shows obvious nonlinear characteristics, high-frequency filtering, and low- frequency resonance, which are the main influencing factors of landslide sliding surface morphology change. From the point of view of the position of landslide development on the slope, seismic landslides are mostly high-level landslides on the slope, and the corresponding rainfall-type landslides. Affected by the distribution of groundwater level saturation line, the water content of rock mass below the slope is high. Accordingly, the existence of groundwater provides lubrication and reduces the connection.

In this article, it is found that the landslide induced by the Haiyuan earthquake has a dense distribution area, and the number of landslides developed outside the dense distribution area is relatively small, which indicates that the occurrence of earthquake landslides is more controlled by lithologic conditions and topography, and the earthquake action only plays an inducing role. In different concentrated areas, it is found that their morphological characteristics and development laws are not consistent. The statistical analysis is carried out according to different concentrated areas, and the influence of lithologic conditions in different regions on the development law of landslides is obtained, which is of great significance to explain the development mechanism of earthquake landslides, predict the occurrence of earthquake landslides, and put forward targeted prevention and control measures.

7 Conclusions

Loess seismic landslide is a typical geological disaster in the Haiyuan earthquake in 1920, which is one of the important factors causing casualties and economic losses. In this study, by a combination of field investigation and satellite image interpretation, the development law and distribution characteristics of large- and medium-scale loess seismic landslide induced by the Haiyuan earthquake in 1920 are studied, and the influencing factors of loess seismic landslide are obtained. The main conclusions are as follows:

(1) The Haiyuan earthquake in 1920 induced 1,225 medium- and large-sized landslides. These landslides have long sliding distances, with an average length of 399.7 m, large unit size, and an average area of 122,000 m^2. These landslides are highly catastrophic, and the total coverage area is 149.5 km^2. These landslides are mainly distributed in three concentrated areas of Xiji, Haiyuan, and Pengyang. The different sliding types of the three landslide concentrated areas lead to different morphological characteristics. The sliding surface of concentrated area 1 has a large cutting depth, and the sliding type is mainly shear type and liquefaction. The soil above the sliding surface slides as a whole, and the speed is large. The sliding body and sliding bed are separated, and the sliding distance is long, and the disaster area is large. The landslide in dense area 2 is subjected to strong ground motion, but the loess cover is thin and the gully is deep, and the depth of the sliding surface is small, which is a thin layer sliding, and the vertical displacement is often greater than the horizontal displacement. The intensity of ground motion in concentrated area 3 is small, but the loess overburden is thick, and the width of the landslide is large. The sliding distance near the river valley is small, and the disaster area of the landslide is limited.

(2) Affected by stratum lithology and topography, landslide occurrence is significantly grouped, and only a few scattered landslides occur outside the concentrated area. In dense area, the occurrence of landslides is close to the river valley, along the river belt distribution, and the farther away from the river, the less the number of landslides. The occurrence of the landslide has significant directionality. The seismic propagation input from the back slope direction is more likely to induce a landslide, and the sliding direction is more parallel to the vertical direction of the fault. Affected by the upper and lower hanging wall of the earthquake fault, the number of landslides on the hanging wall of the fault is large, the sliding distance is long, the area is large, and the disaster is strong.

(3) Statistics show that the internal influencing factors such as stratum lithology, topography, fault location and direction, and the role of water control the occurrence location and scale of landslides, and the seismic intensity of external factors is an important incentives for the occurrence of landslides.

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