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# Spatial Distribution Patterns of Earthquake-Induced Landslides in the Loess Region of Tongwei County, Gansu Province

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Posted Date: 12 March 2026

doi: 10.20944/preprints202603.0647.v1

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Article

# Spatial Distribution Patterns of Earthquake-Induced Landslides in the Loess Region of Tongwei County, Gansu Province

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## Abstract

This paper takes Tongwei, Gangu, Wushan and Qin'an counties involved in the 1718 Tongwei earthquake as the study area, combines with the case investigation of earthquake damage and historical landslide data, and uses the statistical analysis model to select 10 impact factors related to topography, geology, earthquakes and human activities in the study area. Finally, the relative contribution and coupling effect of different influencing factors to the spatial distribution of earthquake-induced loess landslides are discussed by principal component analysis. The results show that: (1) The loess seismic landslides in the study area are concentrated in the south-facing slope areas with elevation of 1000-1300 m, slope of 10-20°, topographic relief of 0-30 m, 1200-1600 m away from rivers, 2-8 km away from active faults, intensity of X, land use types of grass and farmland, and relatively weak lithology. (2) Further verified that the prone areas of loess landslides in the study area are the areas near rivers with an elevation of 1600-1900m and a slope of 10-20 degrees, and the areas covered by thick loess layers with a distance of 4-12 km from active faults.

**Keywords:** Tongwei earthquake; spatial distribution law; susceptibility; GIS; kernel density analysis; principal component analysis

## 1. Introduction

Earthquake-induced loess landslides are induced by a variety of factors, the scale of destruction is huge, and the occurrence is group and high sudden, which will not only cause direct disasters, but also have long-term potential risks after the earthquake, especially in the northwest plateau area of China, where strong earthquakes often trigger large-scale landslide disasters, and a strong earthquake can trigger hundreds of landslides. For example, the Tongwei earthquake in 1718 triggered more than 1300 large landslides, with a single volume of 108m<sup>3</sup> and a total area of 6.0×108m<sup>3</sup>[1]. It has caused huge losses of life and property, and in the process of seismic wave propagation, it will also cause loess collapse, fissures and secondary landslides in a long distance, expanding the scope of disaster impact[2]. Early scholars such as Wang Lanmin, Zhang Zhenzhong and Wu Zhijian also collected a large number of historical earthquake damage data to study the historical earthquake landslides in the Loess Plateau, in order to find the spatial distribution law of loess earthquake landslides and provide reasonable suggestions for national regional construction[3][4]. At the beginning of the 20th century, most scholars studied and predicted the formation mechanism of landslides in theory, which lacked technical support. Later, with the development of 3S technology, most scholars began to combine geographic information and remote sensing technology to make statistics and analysis of the spatial distribution of landslides, and moved from single-factor analysis to multi-factor analysis of landslides. Li Shanshan[5] through radar interferometry and Arc GIS technology, scholars have extracted the spatial distribution characteristics of earthquake-stricken landslides, fully excavated the advantages of remote sensing data for large-scale landslide identification, and used a variety of methods to identify loess

earthquake-stricken landslides[6].Some valuable theories are obtained, which provide new ideas for the future research. At present, the influencing factors of earthquake-induced loess landslides are mainly divided into geological environmental factors and inducing factors. Geological environmental factors are usually the internal causes of loess landslides.Barbara [7] and Phuyal [8] analyzed the sensitivity of landslide influencing factors and found that they are closely related to lithology, slope, slope height, geological structure and so on. The external inducing factors include natural and man-made inducements. Wang Gongxian et al. [9] considered that the external causes include precipitation, snowmelt, rivers, groundwater, artificial activities, earthquakes and other influencing factors. Sharma et al. also analyzed the impact of roads on the spatial distribution of loess seismic landslides. Because there are many factors affecting the occurrence of landslides, the selection of too many or too few factors will affect the accuracy of the evaluation results, so the selection of factors should be combined with the actual situation in the study area, reflecting the role of each factor in the loess landslide. By Liu Cheng Wei [10], Zhuang Jianqi [11], Peng Mu [12]and other scholars found that the distribution of loess earthquake-induced landslides is mainly affected by ground motion, faults, underlying surface properties, rivers, geology and other factors. Comprehensively considering the characteristics of geographical environment, historical and cultural environment and the characteristics of landslide development in this area, we selected 10 impact factors, including elevation, slope, aspect, land use, NDVI, topographic relief, distance to fault, intensity, lithology, distance to river, and so on, and divided them into four categories of impact factors, including topography, geology and seismic activity, and analyzed them respectively [13].Not only the influence of each of the ten factors on the spatial distribution of earthquake-induced loess landslides is studied, but also the coupling relationship between different factors is explored, which provides a systematic quantitative analysis for the spatial distribution of earthquake-induced loess landslides, and the influence mechanism of different factors and their coupling relationship on the occurrence of earthquake-induced loess landslides is deeply discussed. It provides theoretical support and practical basis for the follow-up work of disaster prevention and mitigation.

## 2. Overview of the Study Area

### 2.1. Overview of Physical Geography

In this study, Tongwei, Gangu, Wushan and Qin'an counties involved in the Tongwei earthquake are selected as the study areas, and they are collectively referred to as the Tongwei area. The study area is located in the central part of Gansu Province, with a geographical range of 104°-106° east longitude and 34°-36° north latitude, with a total area of about 8093.23 km<sup>2</sup>. The population density in this area is relatively high, with a total population of about 1.56 million in the four counties. The residential areas are relatively concentrated, and most of them are distributed along the river valleys and valleys. There are frequent seismic activities in this region, and many destructive earthquakes have occurred in history, such as the most typical Tongwei-Gangu earthquake in 1718. The magnitude of the earthquake was about 7.5, and the damage was extremely serious, causing more than 40000 to 70000 deaths and triggering large-scale landslide disasters[1,2]. According to historical data and geological survey records, the earthquake triggered more than 300 large and medium-sized landslides, and the volume of some single landslides reached 108m<sup>3</sup>, which seriously damaged the local geomorphological pattern [8]. In recent years, with the deepening of remote sensing interpretation and field investigation, thousands of loess seismic landslides triggered by the 1718 Tongwei earthquake have been identified in the Tongwei area, and it is found that these landslides are mainly distributed in the areas with dense valleys and gullies and thick loess cover. The study area is located in the intersection area of the northern margin of the West Qinling orogenic belt and the North China plate, where the tectonic background is very complex. There are a series of active fault zones developed in the area, such as Tongwei fault, north margin fault of West Qinling, Huining -Yigang fault, etc. [14], with frequent seismic activity. The regional bedrock is mainly composed of mudstone, sandstone, limestone and granite, on which there is a thick layer of late

Pleistocene loess with loose physical properties, poor structure and developed vertical joints, which is easy to produce fissure expansion and strong seismic subsidence in case of earthquake, providing a good tectonic environment for the formation of loess seismic landslides. The Tongwei area is located at the intersection of the northern margin of the West Qinling orogenic belt and the North China plate, with a complex tectonic setting. In history, the earthquakes in this area are frequent and destructive, and in recent years, there have been many moderate and strong earthquakes in this area, which has a high risk. The coupling effect of earthquake, thick loess and steep gully landform makes the study area one of the high risk areas of seismic landslides in China. The study area has a temperate continental monsoon climate with four distinct seasons. The annual average temperature is 8-11°C, and the annual average precipitation is 400-600 mm. The precipitation is mainly concentrated in the flood season from July to September[15]. Heavy rainfall often causes the softening of loess and the increase of pore water pressure, which is an important external factor triggering landslides. The main rivers are Weihe River and its tributaries such as Qingshui River and Hulu River. The slopes on both sides of the river valley are mostly developed with thick loess, which can easily induce landslides, collapses and barrier lake disasters under the combined action of earthquakes and floods. The bedrock in this area is mainly composed of mudstone, sandstone, limestone and granite, which is covered with thick layers of late Pleistocene loess. The loess is loose in physical properties, poor in structure, and developed in vertical joints. It is easy to produce fissure expansion and strong seismic subsidence in case of earthquake[16,17]. In terms of transportation, the study area is located in the middle of Lanzhou-Tianshui Economic Corridor, with Shaanxi in the east and Lanzhou in the west, so the location condition is very important[18].

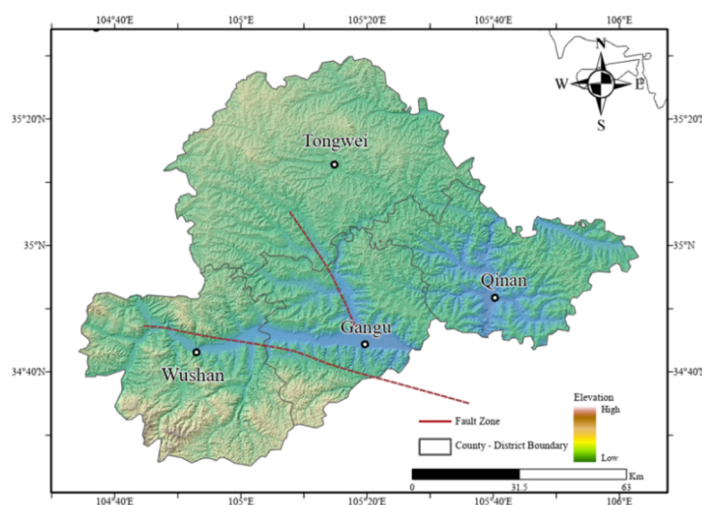
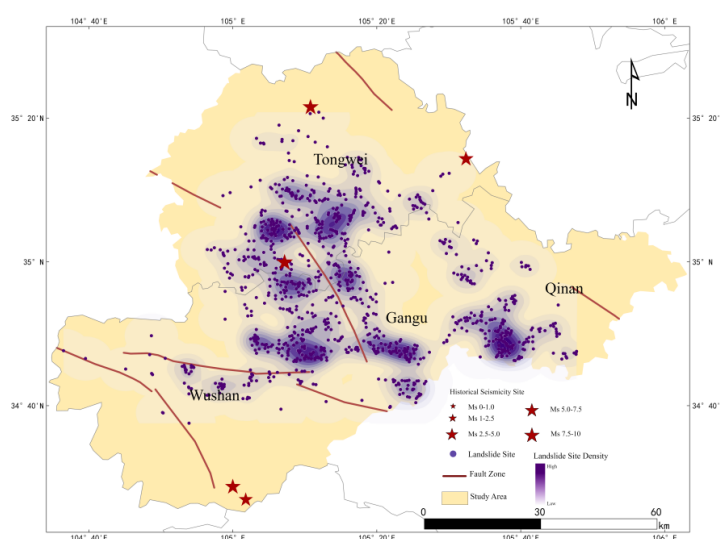


Figure 1. Location map of the study area.

## 2.2. Landslide Development Characteristics

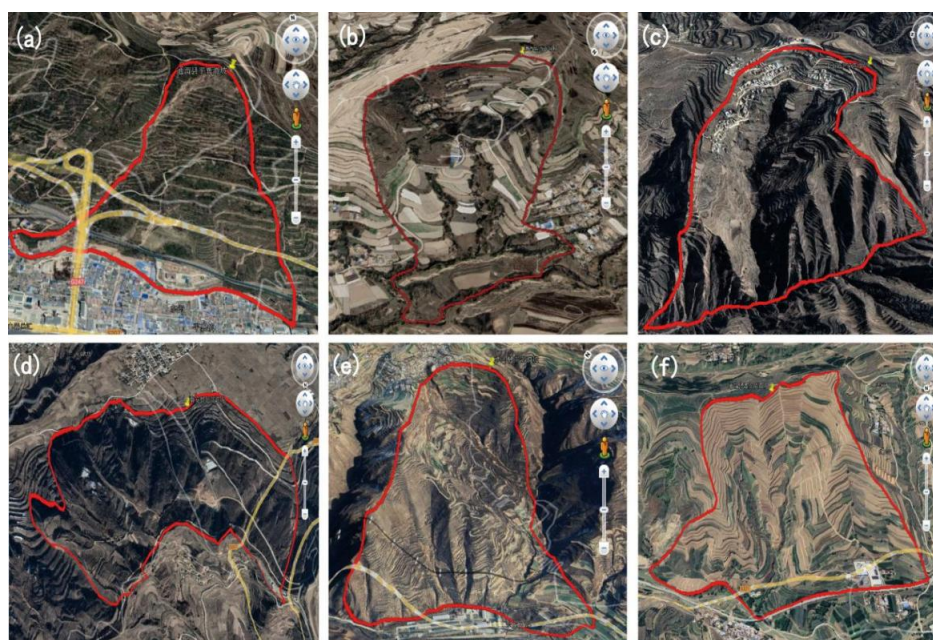
The Tongwei earthquake occurred on June 19, 1718, with a magnitude of 7.5, and the epicenter was located in the south of Tongwei County, Dingxi City, Gansu Province. According to historical records, the earthquake triggered a large number of landslides in Tongwei-Gangu area. Moreover, the seismogenic fault of the earthquake is a concealed strike-slip fault, which is very easy to destroy the original loess stratum structure and trigger landslides. Relying on the database of earthquake-triggered landslides in loess areas established by Wang yuanmin of the Institute of Disaster Prevention Science and Technology, the loess landslides triggered by the 1718 Tongwei earthquake in the database were selected, and combined with GOOGLE EARTH images for remote sensing interpretation and field investigation verification and compared with the Tongwei earthquake landslide database obtained by Xu Yueren, Qian Ziling [19] and other scholars, 1072 loess landslides in the study area were finally obtained. Because the study area belongs to the arid region of China, the landslides caused by extreme rainfall or groundwater in the selected landslide samples can be

ignored, and they are basically loess landslides triggered by the Tongwei earthquake, which further ensures the reliability of the landslide samples selected in this study. The purple area in the figure is the loess seismic landslide interpreted by GOOGLE EARTH high-resolution multi-temporal satellite images in this study, with a total area of 403.75 km<sup>2</sup> and an average area of 0.39 km<sup>2</sup>, mainly medium and large landslides. There is only one small landslide with a single landslide area less than 104m<sup>2</sup>, of which the largest single landslide area is 10.71 km<sup>2</sup> and the smallest is  $2.32 \times 10^{-2}$  km<sup>2</sup>. Through the density analysis of the loess landslides triggered by the Tongwei earthquake, two dense areas of loess landslides triggered by the Tongwei earthquake are roughly identified in the study area: one is Tongwei County and Gangu County, where landslides occurred most frequently, accounting for 75% of the total number of landslides in the whole region; the other is the areas along the Zhangxian-Tongwei Fault Zone and the Qin'an-Gangu Fault Zone, showing the characteristics of concentrated distribution along the fault zone. It is mainly developed along the fault zone, fracture zone, joint plane and weak interlayer.



**Figure 2.** Distribution of landslide hazard points and density.

After that, in order to show the landslide disaster caused by the Tongwei earthquake in 1718 more comprehensively and intuitively, the characteristics of the landslide disaster caused by the earthquake and its correlation with the surrounding geological and geomorphological environment were analyzed, and the landslide impact factors were selected, combined with the historical records and the color and texture differences of the images before and after the landslide. In this study, GOOGLE EARTH high-resolution multi-temporal satellite images were used to interpret several typical loess seismic landslides as shown in Figure 3. It can be seen from the figure that most of the loess seismic landslides triggered by the Tongwei M7.5 earthquake are long and narrow or horseshoe-shaped, and the scale is generally large. When there are multiple discontinuous faults or joint zones on the slope, the sliding surface and collapse zone of the landslide are often curved and distributed in a ladder shape. The formation reasons can be roughly divided into internal factors and external factors. The internal factors include topographic factors such as the height, slope and aspect of the back edge of the slope and geological factors such as lithology. The external factors are mainly the earthquake activity. Because of the sparse population and backward economic development at that time, the impact of human factors on the natural environment can be ignored.



**Figure 3.** Satellite images of typical landslide hazards in Tongwei area provided by Google Earth: **(a)** Geographic location: 35.21° N, 105.26°E. **(b)** Geographic location: 35.13° N, 105.34°E. **(c)** Geographic location: 34.6 ° N, 105.31°E. **(d)** Geographic location: 34.90° N, 105.68°E. **(e)** Geographic location: 35.21° N, 105.13°E. **(f)** Geographic location: 34.67° N, 104.87°E.

### 3. Data Sources and Research Methods

#### 3.1. Data Sources

The controlling factors of earthquake-induced loess landslides can be divided into three categories: topography, geology and earthquake. The selection of impact factors has a very important impact on the final evaluation results. According to the previous geographical environment of the study area, the characteristics of landslide disasters and the data of historical earthquake landslide disaster points in the study area, combined with the previous ideas for the spatial distribution of loess earthquake landslides, the internal and external causes of loess earthquake landslides are comprehensively considered. In this study, 10 factors including elevation, slope, aspect, rock properties of topographic relief strata, land use type, NDVI, distance from river, intensity and distance from fault are selected to explore their effects on spatial distribution law and scale of loess seismic landslide. The specific data sources are shown in Table 1, in which the vegetation cover index (NDVI) used in this study is calculated by comparing the reflectance of vegetation in the red band (Red) and the near-infrared band (NIR) based on the Landsat8 image obtained from the geospatial data cloud, and the calculation formula is (1):

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \quad (1)$$

**Table 1.** Data sources.

Serial number	Impact factor	Source
1	Topographic factors (elevation, slope, aspect, relief)	Topographic factors are extracted from the 30 m resolution DEM data of Open Topography.
2	Geological factors (stratigraphic lithology,	Formation lithology: 1:2000000 scale geological map; NDVI: calculated from Landsat8 image acquired by geospatial data cloud;

	NDVI, land use type, river)	Land use type: National Fundamental Geographic Information Center; River: 30 m resolution DEM data extracted from OPenTopography.
3	Earthquake factors (historical earthquake intensity, active faults)	Historical Earthquake Intensity: a Catalogue of Historical Strong Earthquakes in China from the 23rd Century BC to 1911 Active faults: the fifth generation of faults in the western region

### 3.2. Nuclear Density Analysis and Landslide Density

Kernel density analysis is an effective statistical method of landslide density in the study area. Its core idea is to apply a kernel function to each landslide point, and then add these kernel functions to estimate the landslide density in the whole area. This method can accurately calculate the density of landslide points at each location, and then generate a smooth and continuous density map to visually display the hot spots of landslides. Commonly used kernel functions include Gaussian kernel, linear kernel, neural network kernel, uniform kernel and so on. In this study, Gaussian kernel is used because it can produce a smooth density curve and is more suitable for spatial data smoothing. In ArcGIS, kernel density analysis can also generate a grid map, in which each pixel value represents the density of the landslide at that location. Through this density map, the high and low density areas of the landslide can be more intuitively displayed.

In order to better explore the law between different impact factors and the distribution of landslides, this study also calculated the landslide point density (LND) in each interval of different impact factors. LND represents the ratio of the number of landslide points in the study area to the total area of the study area, which is calculated by formula (2). It can well describe the number of landslide events per unit area, associate the landslide points with the area of the study area, visualize the landslide point density area, and provide data support for further geological disaster prevention and risk assessment. Landslide area density (LAD) is also an important index to measure the distribution density of landslides in a region, indicating the total area of landslides in unit area, which is calculated by formula (3). It reflects the spatial distribution characteristics of landslides in a specific area, and can effectively describe the spatial distribution pattern of landslides. LAD is one of the commonly used parameters in the analysis of landslide prone areas and risk assessment. In the areas with high landslide risk, the value of LAD is higher, which can provide a scientific basis for landslide disaster prevention and mitigation.

$$LND = \frac{\text{Number of landslide points}}{\text{The total area of the study area}}, \quad (1)$$

$$LAD = \frac{\text{Total landslide area}}{\text{The total area of the study area}}, \quad (2)$$

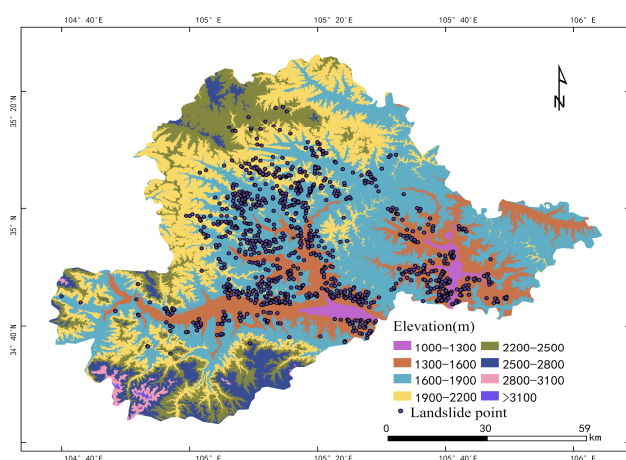
## 4. Spatial Distribution Characteristics of Earthquake-Induced Landslides in Loess Region

### 4.1. Relationship Between Different Impact Factors and Landslide Distribution

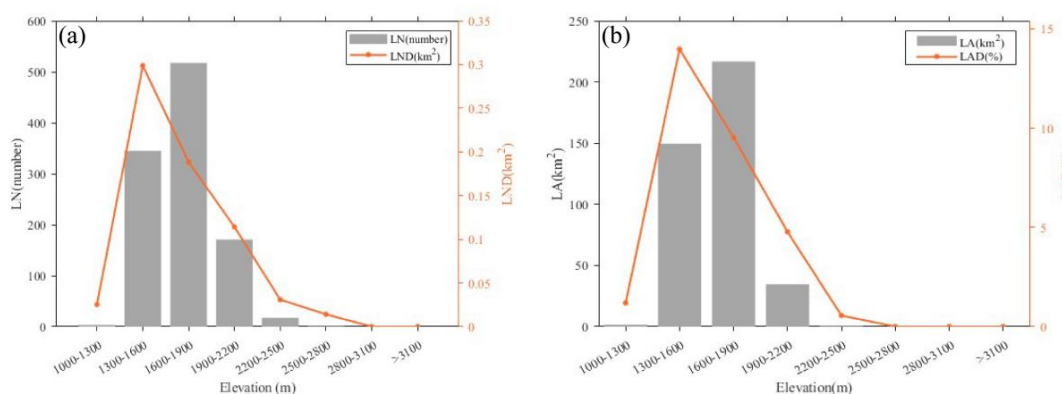
#### 4.1.1. Topographic Factors

Elevation can affect the distribution of earthquake-induced loess landslides by affecting geotechnical properties, groundwater conditions, and engineering activities [20,21]. The elevation range of the study area is 1176m-3115m, with an average elevation of 2145m, the division results are shown in Figure 4, and then the number and area data of landslides within different elevation ranges are counted. Figure 5 shows the statistical relationship between the distribution of loess seismic landslides and the elevation. It can be seen from Figure 5(a) that the landslides are mainly distributed

in the two intervals with the elevation of (1300m, 1600m] and (1600m, 1900m], and 862 landslides have occurred, accounting for 80.4% of the total number of landslides in the whole region. In the interval of (1000m, 1900m], the density of landslide points increases gradually with the increase of elevation. When the elevation is greater than 1900m, the number of landslides decreases sharply. When the elevation is greater than 2300m, there is almost no seismic landslide. Figure 5(b) shows the relationship between landslide area (LA) and landslide area density (LAD) and elevation: with the increase of elevation, the total area of landslide increases first and then decreases. The largest landslide area is found in the elevation intervals of (1300m, 1600m] and (1600m, 1900m], accounting for 90.6% of the total landslide area (366.25 km<sup>2</sup>). The maximum landslide density occurs in the (1300m, 1600m] range, at 13.97%. Above 1900m, landslide density decreases with elevation. These results suggest that elevation significantly affects landslides, with the highest incidence in the (1300m, 1600m] range, due to the region's undulating terrain, thick overburden, and strong human activity. Landslide size and density are lower at both low (1000m-1300m) and high (>2200m) elevations.



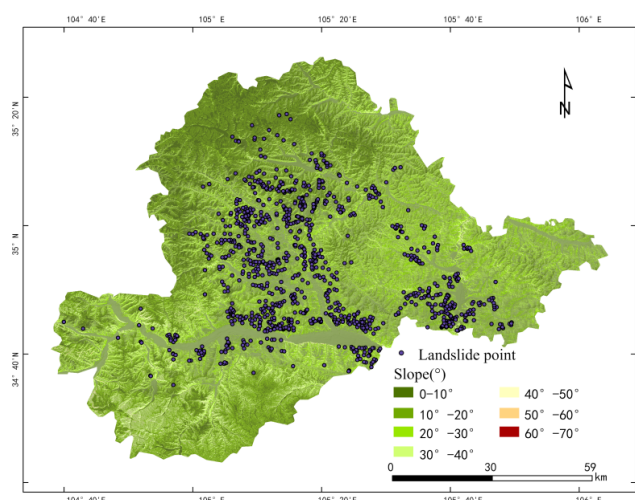
**Figure 4.** Relationship between landslide point and elevation.



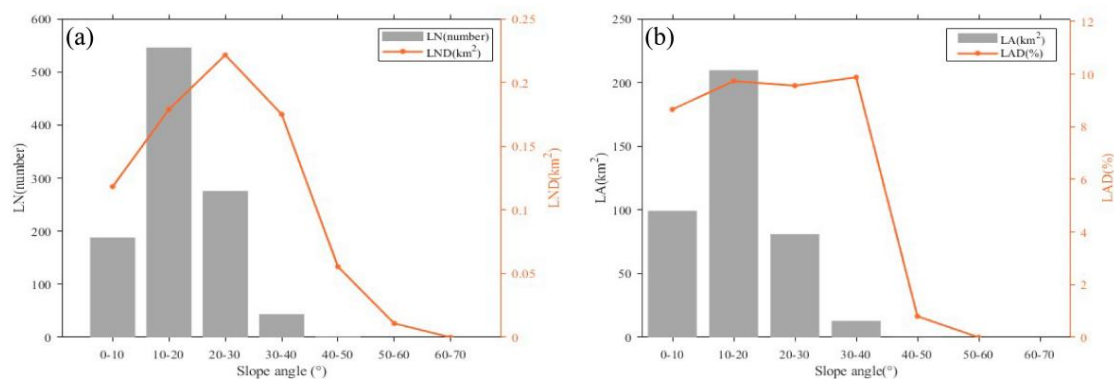
**Figure 5.** Relationship between landslide point density LND (a), landslide area density LAD(b) and elevation.

Surface stability is closely related to slope, and slope is one of the key factors determining whether the surface is stable or not. The slope in the study area ranges from 0° to 65°, so the landslide in the study area is divided into seven intervals according to the slope (Figure 6). Since the relationship between the slope and the distribution of loess seismic landslides can not be directly seen from the relationship diagram of landslide points and landslides in Figure 6, the further statistical distribution is made. According to the relationship between the distribution of landslides and the slope shown in Figure 7(a)(b), the number of landslides shows a trend of more in the middle and less at both ends, and the landslides in the area are mainly concentrated in the range of (10-20°). Landslides

in the (10-20°] slope range account for 50.9% of the total number and 52.1% of the total area. The (0-10°] and (20-30°] slope intervals follow, with landslides in these ranges making up 43.1% of the total number and 44.7% of the total area. Landslide density peaks in the (20-30°] slope range, then decreases with higher slopes. Landslide area density is mainly concentrated in the 0-40° range. Steeper slopes (40° and above) show minimal landslide distribution, as these areas typically consist of bedrock or thin loess cover. Large landslides tend to occur on medium to large slopes in gully areas with thick loess, not on extremely steep terrain, where soil mass is insufficient for large-scale landslides. Thus, steeper slopes do not necessarily correlate with higher landslide occurrence.



**Figure 6.** Relationship between landslide point and gradient.



**Figure 7.** Relationship between landslide point density LND (a), landslide area density LAD (b) and slope gradient.

The aspect indirectly determines the spatial distribution characteristics of earthquake-induced loess landslides by influencing factors such as solar radiation, soil moisture and frozen soil meltwater. In this study, eight directions of N, NE, E, SE, S, SW, W and NW were divided, and the relationship between landslide points and slope aspect was explored by using the visualization processing function of ArcgisMap (Figure 8). According to the relationship between landslide distribution and slope direction shown in Figure 9(a), although landslides are distributed in all directions, they are mainly distributed in the north-south, northwest and southwest directions, and the number of landslides is more than 135. The density of landslides in the east and southeast directions is relatively low, and the density of landslides in the southwest direction is the highest. Figure 9(b) shows the relationship between landslide scale and slope direction. It can be found that both the landslide area and the landslide area density in the south slope are higher than those in the other directions. The

total landslide area in the south slope is 82.52km<sup>2</sup>, and the landslide area density is 13.7%, followed by the southwest slope. Both landslide point density and landslide area density in the northeast, north and southeast slopes are maintained at a low level, especially in the east slope, the minimum landslide area density is only 6.9%. Therefore, in the disaster prevention and risk assessment of Tongwei County area, we should focus on the south slope, northwest slope and southwest slope.

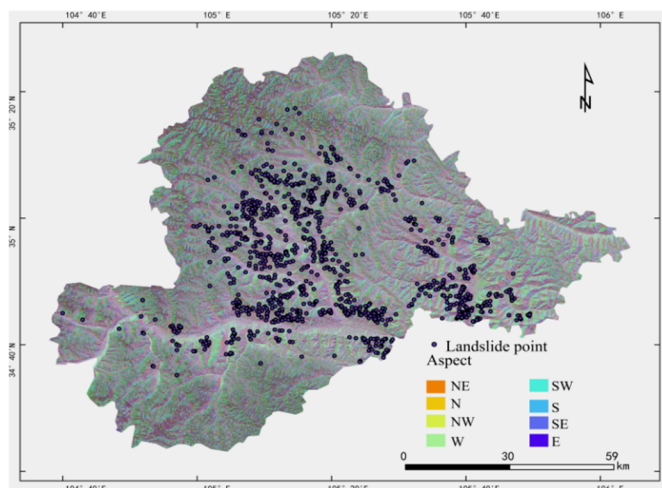


Figure 8. Relationship between landslide point and slope aspect

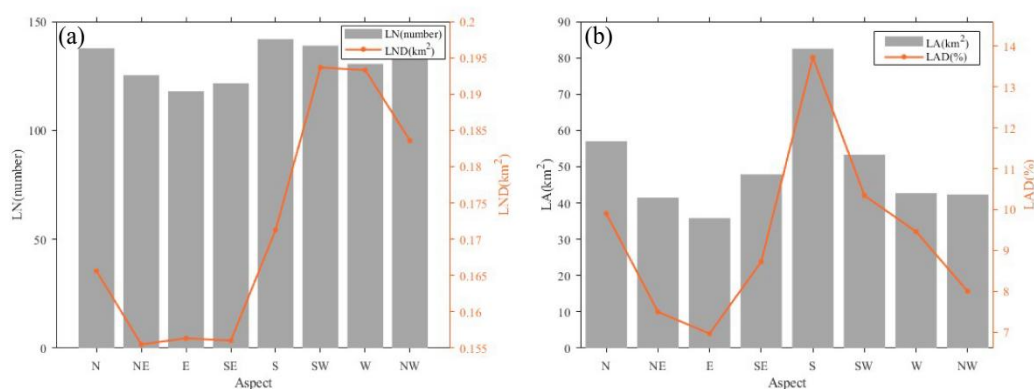
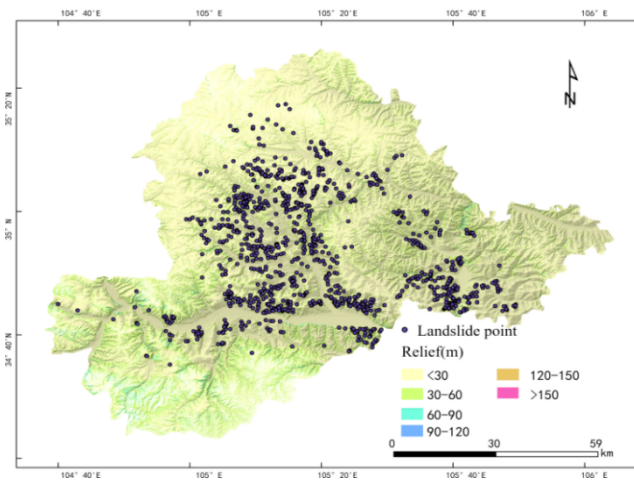
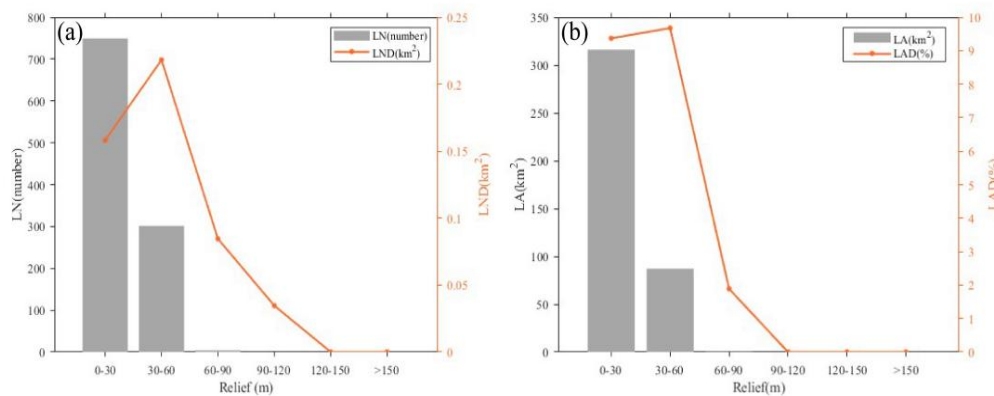


Figure 9. Relationship between landslide point density LND (a), landslide area density LAD (b) and slope aspect.

In the study of the distribution of earthquake-induced loess landslides, topographic relief is an important factor, which directly affects the stability of the slope. Figure 10 shows the relationship between relief and landslide size and density distribution. It can be seen from Figure 11(a)(b) that the low-relief area (0-30m) in the study area has a flat terrain but a wide area, so the total amount of landslides is the largest, and the total area of landslides in this area is also the largest. There are almost no landslides in the high-relief area (>60m), and there are only 4 landslides in the relative height difference of 60-90m. The low relief area has the highest total number of landslides about 749, but its landslide point and area densities are not the highest. Despite the gentle topography, small-scale seismic landslides are common due to the wide distribution and loose loess structure. In the medium relief area (30-60m), both landslide point and area densities are highest, with an area density of 9.7%. This is the highest landslide risk area, characterized by undulating slopes, valleys, and slope toes, which are prone to large-scale landslides under precipitation or seismic disturbance. Therefore, in the prevention and control of landslide disasters, special attention should be paid to the moderate relief zone.



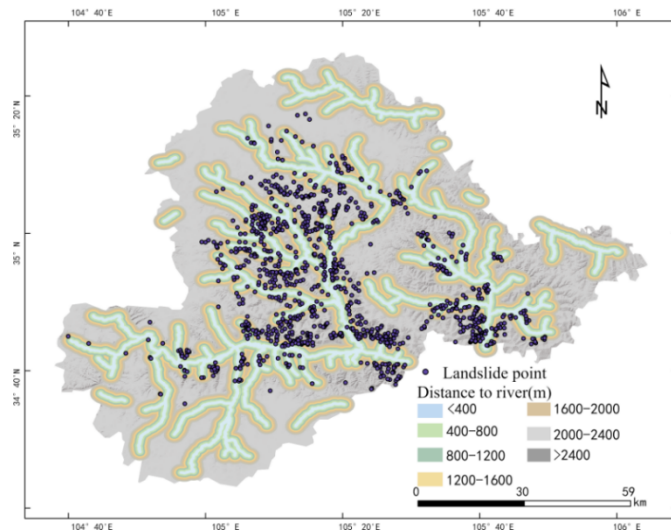
**Figure 10.** Relationship between landslide point and topographic relief.



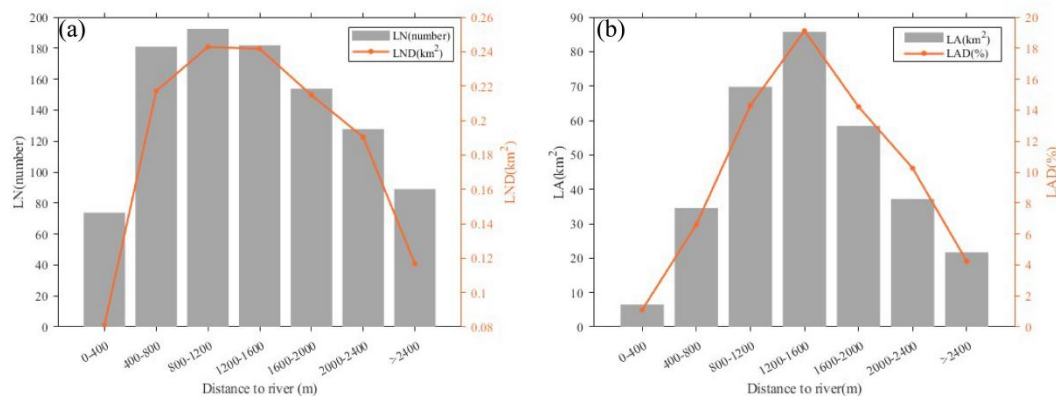
**Figure 11.** Relationship between landslide point density LND (a) , landslide area density LAD(b) and relief degree.

#### 4.1.2. Geological Factors

According to the distance of the river, the buffer zone is divided into seven buffer zones with a step of 400m, as shown in Figure 12. According to Figure 13(a), the number of landslides is mainly concentrated in the range of 1200m, accounting for 23.7% of the total number of landslides, but the density of landslides is the highest in the range of 800-1600m, and the density values of landslides are 0.217 and 0.243, respectively, which are the highest values in the whole region. With the increase of distance from the river, the number and density of landslides are gradually reduced. Figure 13(b) shows the relationship between the landslide scale and the distance from the river. The landslide area and density are highest in the distance interval (1200m, 1600m], with a total landslide area of 85.75 km<sup>2</sup>, accounting for 21.2% of the total, and a density of 19.1%. This is due to the proximity to the river, where slope foot erosion and high groundwater levels weaken stability. In the [1200m, 1600m] range, steep slopes amplify seismic effects, leading to the highest landslide density. Beyond 1600m, the distance from the river increases, reducing hydrological and erosional effects, and landslide frequency decreases. Therefore, in the prevention and control of earthquake-induced landslide disasters, the two sides of the valley and the area near the river should be taken as the key prevention and control areas.

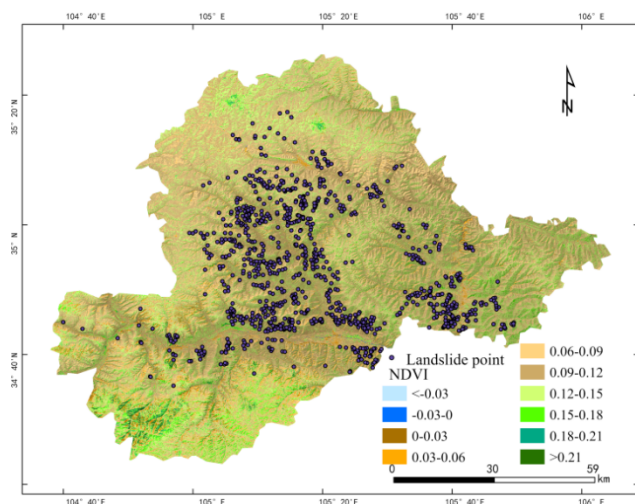


**Figure 12.** Relationship between landslide point and distance from river.

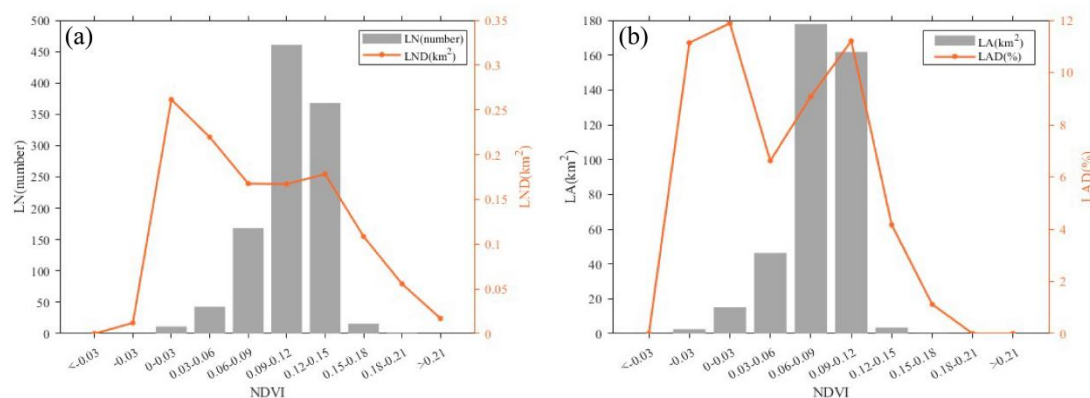


**Figure 13.** Relationship between landslide point density LND (a) , landslide area density LAD (b) and distance from river.

For the vegetation cover index (NDVI) used in this study, the value range of the final calculation results is  $[-0.184, 0.401]$ . The closer the NDVI index is to 1, the higher the vegetation coverage is. An NDVI index close to 0 indicates bare land, rocks, and sparse vegetation, while values below 0 typically represent water, snow, or clouds. The study area is mainly bare land and sparse vegetation, with most NDVI values ranging from  $[-0.03, 0.2]$ . Based on this, the area is divided into ten categories. (Figure 14). The landslide point density and landslide area density in each interval were calculated respectively (Figure 15). It can be seen from Figure 14 that the loess seismic landslides are mainly distributed in the bare land area near the river. According to the number of landslides and the relationship between LND and NDVI given in Figure 15(a), the loess seismic landslides are most concentrated in the range of  $(0.06, 0.15]$  medium NDVI, the number of landslides is the largest, accounting for 77.2% of the total number of landslides, and the density of landslides is in the range of  $(0, 0.03)$  reach a peak value of 0.26 and then decreased and maintain a high density in this interval. While in the areas with coverage less than 0.03 and coverage more than 0.15, the distribution of landslides is obviously reduced. The results shown in Figure 15(b) also show that the landslide is mainly concentrated in the medium NDVI range of  $(0.06, 0.15]$ , especially in the NDVI range of  $(0.06, 0.12]$ , and the maximum landslide area in the range of  $(0.06, 0.09]$  is  $177.87\text{km}^2$ ,  $(0.09, 0.12]$  This NDVI interval is followed by a landslide area of  $161.76\text{km}^2$ , and the landslide area density is also large. This indicates that the loess hilly and gully region with sparse vegetation is a high-risk area for earthquake-induced landslides and should be prioritized for prevention and monitoring.

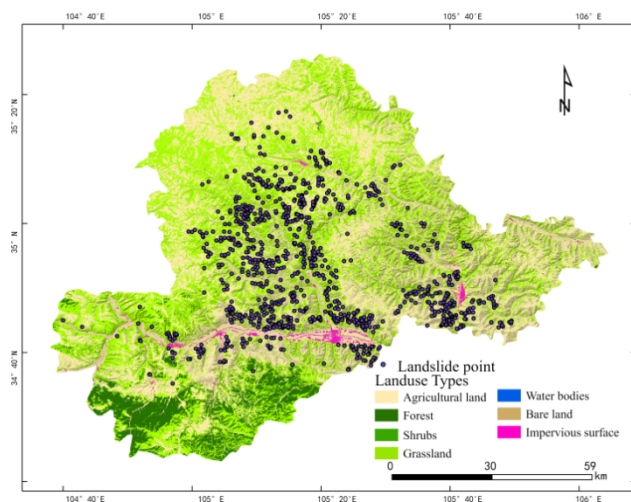


**Figure 14.** Relation between landslide point and NDVI.

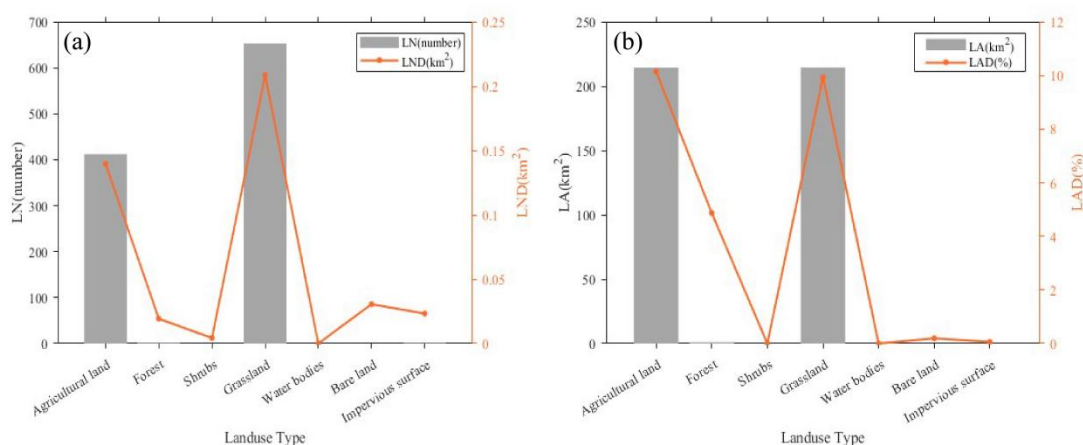


**Figure 15.** Relationship between landslide point density LND (a) , landslide area density LAD (b) and NDVI.

Land use type reflects the natural environment conditions, it can be seen from Figure 16 that most of the landslide points are distributed in farmland and bare land. Figure 17(a) and (b) respectively reflect the relationship between land use type and landslide distribution density and landslide scale. According to Figure 16, loess seismic landslides in the study area are mainly found in farmland and grassland, which account for 98.7% of the total landslides. The landslide area in these regions makes up 99.6% of the total, with the highest landslide density in grassland (0.209), followed by farmland (0.139). The landslide area density is also highest in these two regions, while farmland, due to long-term reclamation and irrigation, has destroyed the original vegetation and changed the soil structure, making the loess slope more vulnerable to strong seismic disturbance. Relatively speaking, the density of landslides in forest area is 0.019, which is significantly lower than that in grassland and farmland, indicating that higher vegetation coverage and root reinforcement can effectively enhance soil stability and have a significant inhibitory effect on seismic landslides. Shrub, water and bare land occupy a small proportion of the area, which has a limited impact on the overall pattern, but the density of landslide points in bare land is 0.031, which still shows its sensitivity to seismic disturbance under the condition of lack of vegetation cover. In addition, although the area of impervious surface (urban construction area) is small, the density of landslide points is 0.023, which indicates that human engineering activities have a potential negative impact on slope stability.

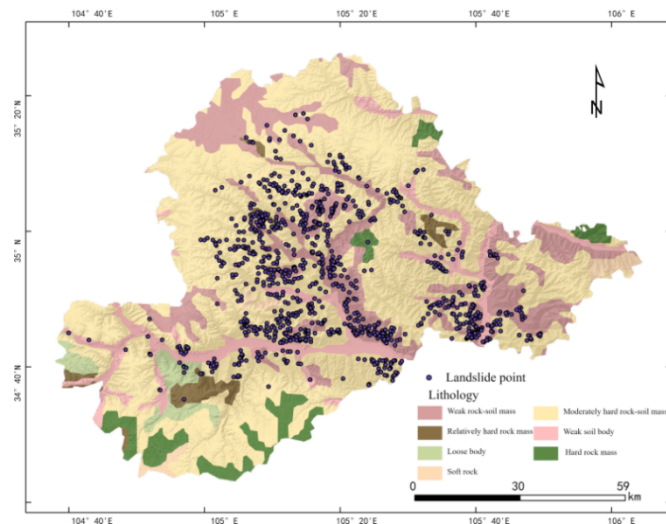


**Figure 16.** Relationship between landslide point and land use.

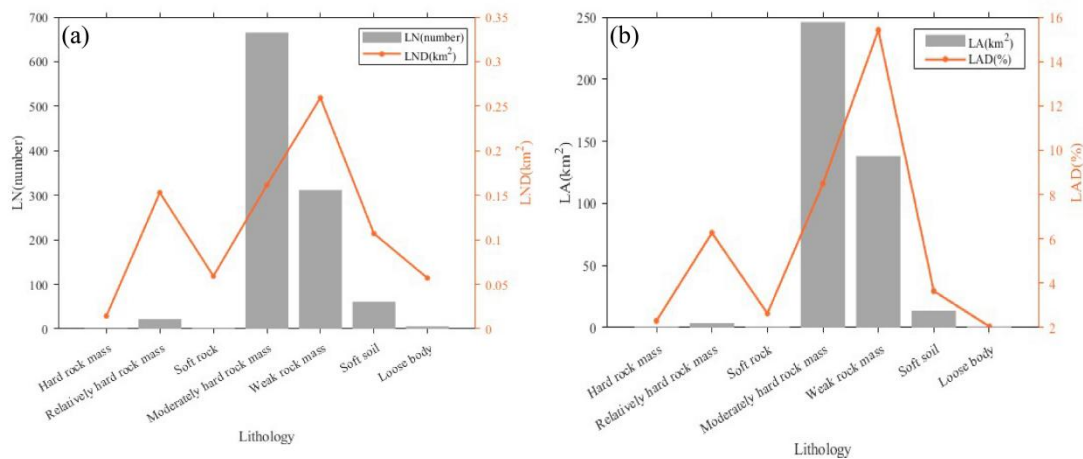


**Figure 17.** Relationship between landslide point density LND (a) , landslide area density LAD (b) and land use type.

The lithology of the study area is dominated by Tertiary and Quaternary loess, in addition to some hard granite, gneiss and soft layered rocks such as sandstone, clastic sedimentary rocks. Therefore, the study area is divided into hard rock mass, relatively hard rock mass, soft rock, medium hard soil mass, relatively soft rock and soil mass, soft soil mass and loose mass according to the hardness of different lithologies in the study area. According to the different loess characteristics in the study area, the Tertiary loess and Quaternary loess are classified as relatively soft rock and soil mass and medium hard soil mass, as shown in Figure 18. It can also be found from the statistical relationship in Figure 19 that the loess seismic landslides in the study area have significant lithological control characteristics, and their development is mainly concentrated in the dual structure slope with Quaternary loess covering Tertiary weak rock strata (mudstone and sandy mudstone). While the Quaternary loess is mainly used as the material provider and deformation body of landslides. It can be seen from Figure 19(a)(b) that the number and point density of landslides, as well as the area and area density of landslides, are concentrated in the medium hard soil mass and the relatively soft rock and soil mass. The number and area of landslides in the medium hard soil mass reach the highest value, with 665 landslides, accounting for 62.09% of the total number of landslides. This also reflects that the Quaternary loess is the main material source of the landslide. Future seismic and disaster prevention projects should prioritize the stability and seismic resistance of loess layers, conduct detailed geological surveys in key areas, and monitor slope deformation and landslide activity to reduce geological disasters.



**Figure 18.** Relationship between landslide point and lithology.

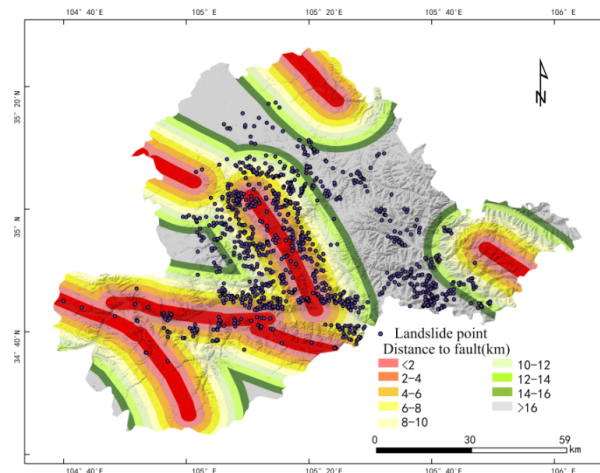


**Figure 19.** Relationship between landslide point density LND (a) , landslide area density LAD (b) and lithology type.

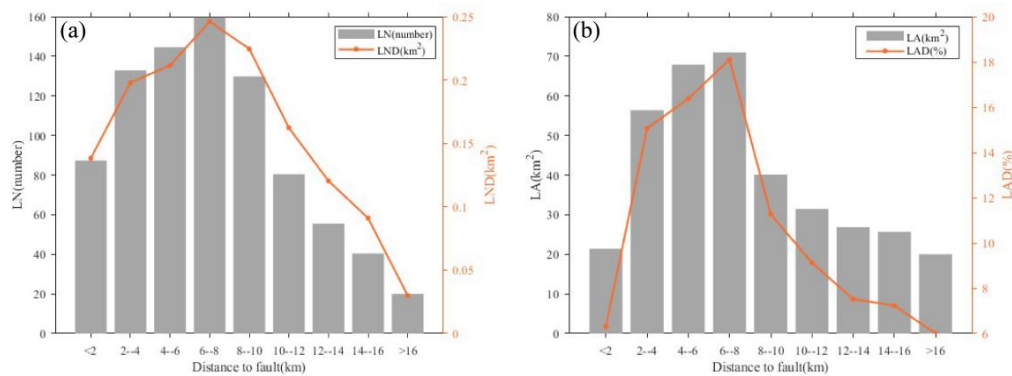
#### 4.1.3. Seismic Factors

Landslide distribution follows a clear pattern with distance from faults. Active faults affect seismic sources, ground motion, and create fault zones, scarps, and weakened areas that increase slope instability. The distance from each landslide to the nearest fault was calculated, with 9 buffer zones set at 2 km intervals. It is also evident from Figure 20 that the landslides are distributed approximately along the active fault. Figure 21 shows the relationship between landslide distribution and fault distance. It can be seen from Figure 21(a) that the probability of landslide occurrence does not show a linear attenuation trend with the distance from the fault. The results show that the number of landslides and LND are the highest in the range of 6-8km from the fault, and there are 160 landslides in this range, accounting for 14.9% of the total number of landslides. When the distance is less than 2 km, the number of landslides near the fault is less, and the density of landslides is also at a low level, LND is 0.14. When the distance is more than 8 km, with the increase of the distance from the fault, the ground motion is gradually attenuated, the damage effect is weakened, and the number and density of landslides are gradually reduced. According to Figure 21(b), both the landslide area and landslide area density reach the peak value in the range of 2-8km from the fault, especially in the range of 6-8km. This law shows that the fault activity controls the occurrence of landslides through the coupling effect of the intensity distribution of ground motion and the topographic material conditions. Landslides are rare near the fault due to poor material conditions, most concentrated in

the middle distance where strong ground motion and favorable topography-material conditions exist, and decrease with distance from the fault as seismic energy weakens.

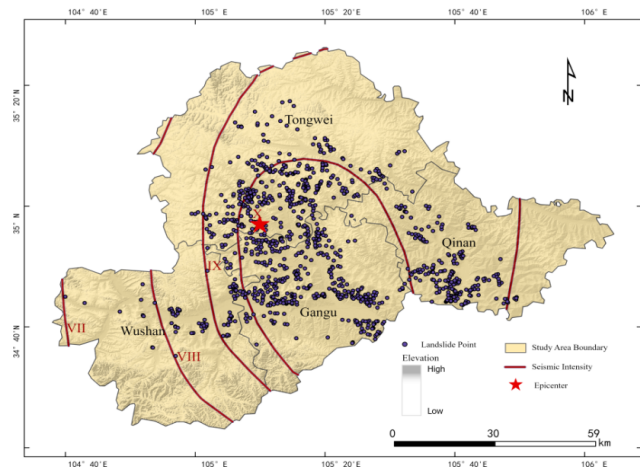


**Figure 20.** Relationship between landslide point and distance to fault.

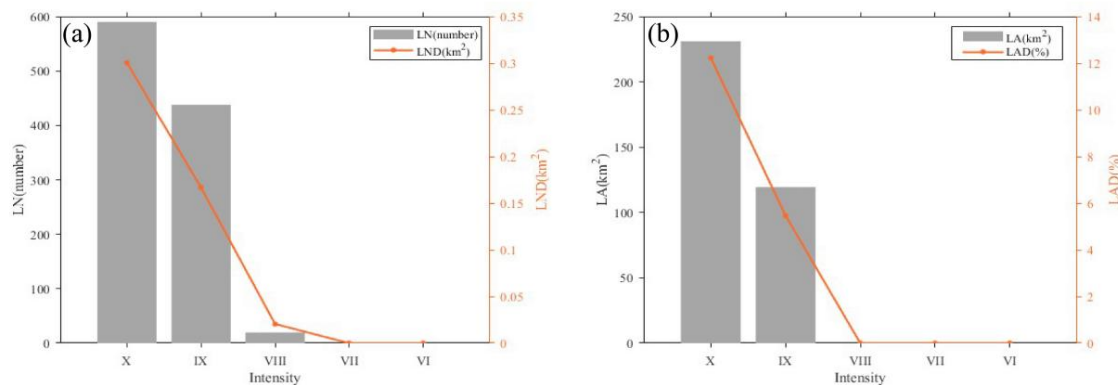


**Figure 21.** Relationship between landslide point density LND (a), landslide area density LAD(b) and distance to fault.

Seismic intensity is one of the most important reasons for loess seismic landslides. The intensity of the meizoseismal area of the Tongwei earthquake is X degree, and the study area includes X, IX, VIII, VII and a small part of VI intensity areas. It can be seen from Figure 22 that most of the landslides are located in the X intensity zone, and the greater the seismic intensity, the more the number of landslides. It can be seen from the statistical relationship between the number and density of landslides in Figure 23(a)(b) that in the area of intensity X, the ground motion is the strongest, the number of landslides is the largest, reaching 590, the density of landslide points is 0.301, and the area and area density of landslides in this intensity range are the largest. In the intensity IX region, the number of landslides has decreased, but it is still at a high level. In the area of intensity VIII, the density of landslide points decreases to 0.021, and the density of landslide area decreases to 0, which is much lower than that of intensity IX. It can be seen that seismic intensity is closely related to the frequency and density of landslides, and strong earthquakes can significantly increase the frequency and density of landslides.



**Figure 22.** Relationship between landslide point and intensity.



**Figure 23.** Relationship between landslide point density LND (a), landslide area density LAD(b) and intensity.

The distribution of loess seismic landslides is influenced by factors like topography, geology, and earthquakes. Terrain features such as elevation, slope, aspect, and relief significantly impact landslides, with the highest frequency occurring in areas of medium elevation, large slope, and relief. Earthquake intensity and proximity to active faults also play a key role, with more landslides in areas with strong earthquakes and faults nearby. Additionally, the structure and lithology of loess, particularly on sloped areas, are crucial, as landslide scale and density are closely linked to both earthquakes and slope conditions.

#### 4.2. Relative Contribution of Impact Factors

In order to evaluate the relative contribution of these 10 factors, principal component analysis (PCA) was used for multivariate statistical analysis. It generates a few new variables that can reflect the main information of the original data through the linear combination of the original multiple indicators, and replaces the original variables with fewer new variables (principal components) on the premise of as little information loss as possible. Dimension reduction is achieved by eigen-decomposing the covariance matrix or correlation matrix of the original data to find the coordinate axis in the direction of the maximum variance[22,23]. Therefore, in this study, SPSS software was used to carry out the principal component analysis of the 10 selected impact factors, and the non-numerical evaluation factors such as lithology, land use type and residential density were assigned to the levels, so as to unify the sample variables and explore the importance of different impact factors to the spatial distribution of loess earthquake-induced landslide disasters. In order to reduce the influence of multicollinearity and extract the main control factors, the principal component analysis was carried out after the standardization of ten landslide impact factors. The results after normalization are

shown in Table 2. The results of correlation matrix show that the correlation coefficients of most variables are between 0 and  $\pm 0.7$ , which is at a low level, and there is no significant collinearity problem, indicating that the sample data are suitable for principal component analysis.

**Table 2.** Correlation matrix of influencing factors.

Influencing Factor	Distance to Fault	Distance to River	Relief	Aspect	Slope	Elevation	NDVI	Land use Type	Intensity	Lithology
Distance to Fault	1.000	-0.018	0.019	-0.034	0.018	-0.090	0.076	-0.069	-0.346	0.079
Distance to River	-0.018	1.000	-0.039	0.046	-0.020	0.302	0.087	-0.154	0.19	-0.062
Relief	0.019	-0.039	1.000	0.040	0.653	-0.073	-0.207	0.262	-0.006	-0.022
Aspect	-0.034	0.046	0.040	1.000	-0.013	0.046	-0.074	0.114	-0.039	0.023
Slope	0.018	-0.020	0.653	-0.013	1.000	-0.054	-0.191	0.334	-0.03	-0.011
Elevation	-0.090	0.302	-0.073	0.046	-0.054	1.000	0.101	0.085	0.048	-0.133
NDVI	0.076	0.087	-0.207	-0.074	-0.191	0.101	1.000	-0.184	-0.012	0.006
Land Use Type	-0.069	-0.154	0.262	0.114	0.334	0.085	-0.184	1.000	0.033	0.011
Intensity	-0.346	0.19	-0.006	-0.039	-0.03	0.048	-0.012	0.033	1.000	-0.108
Lithology	0.079	-0.062	-0.022	0.023	-0.011	-0.133	0.006	0.011	-0.108	1.000

Through PCA analysis of the above data, the variance contribution and loading coefficient matrix of each impact factor are finally obtained, as shown in Table 3 and Table 4. The variance contribution rates of the 10 impact factors are counted in Table 3, and the first four factors with eigenvalues greater than 1 are the four extracted principal components. The cumulative variance contribution rate of these four components is 58.467%, contributing more than 50% of the total variance, which shows that these four principal components have retained most of the original information. The contribution rate of the first principal component is 20.126%, which contains the most variation information in the original data, and then the contribution rate of the second, third and fourth principal components is 15.607%, 11.934% and 10.799%, respectively. The loading coefficient matrix of different impact factors in Table 4 further analyzes the four principal components, revealing the correlation of the 10 impact factors of loess earthquake-induced landslides on the four principal components. The closer the value is to 1 or -1, the stronger the correlation between the component and the factor is. The load of the first principal component is higher in the relief and slope, which mainly reflects the influence of topography and surface type on the spatial distribution of earthquake-induced loess landslides. The load of the second principal component on the intensity, the distance from the fault and the elevation factor is relatively large, which reflects that the distribution of loess seismic landslides is closely related to seismic activity. The load of the third principal component is higher at the distance from the fault and the elevation, which indicates that geological factors and seismic intensity have common effects on the occurrence of loess seismic landslides. The fourth principal component is mainly controlled by slope aspect, which represents that the slope orientation in the study area has a very important impact on the stability of loess landslides caused by earthquakes. It can be seen that among the 10 selected landslide influencing factors, topographic relief, slope, slope aspect, intensity, distance from fault and elevation have the greatest impact on loess seismic landslides, which also reflects that the slope topographic characteristics and earthquake-induced activities are the most important factors controlling the occurrence of loess seismic landslides, and the other influencing factors are land use type, lithology, distance from rivers and vegetation coverage.

**Table 3.** Variance contribution table of each influencing factor.

Component	Initial Eigenvalues		
	Sum	Variance%	Cumulative %
1	2.013	20.126	20.126
2	1.561	15.607	35.733
3	1.193	11.934	47.668

4	1.08	10.799	58.467
5	0.949	9.49	67.957
6	0.89	8.905	76.862
7	0.808	8.082	84.944
8	0.668	6.678	91.623
9	0.505	5.048	96.671
10	0.333	3.329	100

**Table 4.** Loading coefficient matrix of different influencing factors.

Influencing Factor	Components			
	1	2	3	4
Distance to Fault	-0.009	-0.594	0.554	-0.085
Distance to River	-0.238	0.524	0.504	-0.07
Relief	0.807	0.077	0.19	-0.219
Aspect	0.107	0.102	0.115	0.829
Slope	0.822	0.082	0.22	-0.24
Elevation	-0.17	0.535	0.521	0.189
NDVI	-0.475	-0.043	0.298	-0.208
Land Use Type	0.599	0.163	-0.025	0.308
Severity	-0.06	0.663	-0.409	-0.179
Lithology	0.022	-0.395	-0.078	0.261

Overall, the formation and distribution of landslides in the study area are mainly controlled by topography, geographical location, tectonic activity and slope aspect characteristics. Among them, relief and slope are the most important control variables, indicating that earthquake-induced loess landslides mainly occur in the areas with large relief and steep slope, followed by elevation and distance from the river, indicating that river erosion has an important triggering effect on the occurrence of earthquake-induced loess landslides. The intensity and residential density reflect the superimposed influence of seismic activity and human activities, while the aspect effect regulates the spatial distribution characteristics of local loess landslides to a certain extent.

## 5. Influence of Multi-Factor Coupling on the Distribution Characteristics of Earthquake-Induced Loess Landslides

### 5.1. Relationship Between Elevation, Slope and Distance from the River

Based on the information of elevation, slope and distance from the river on each landslide point, the relationship between elevation and slope, slope and distance from the river is further discussed, as shown in Figure 24. It can be seen from Figure 24 (a) that the number of landslides is the largest in the area with an elevation of 1600-1900m and a slope of 10-20°, with 496 landslides in total, accounting for 46.26% of the total number of landslides in the study area, and then the number of landslides decreases gradually with the increase of elevation and slope. There are almost no landslides in the area where the elevation is more than 2500m and the slope is more than 50°. Figure 24 (b) further analyzes the relationship between the slope and the distance from the river. The lines of different colors and styles represent the distribution of landslides within different distances from the river. In general, the number of landslides within each distance range is not too different. Relatively speaking, the number of landslides in the area close to the river is higher. Especially in the range of 400-1200m from the river, the number of landslides is obviously large, the number of landslides in this area is 365, accounting for 57.48% of the total number of landslides in the river buffer zone, and then with the increase of the distance from the river, the number of landslides in each range is gradually reduced. There are only 100 landslides in the range of 2000m-2400m from the river. Based on the above analysis, it can be further determined that the loess seismic landslides in the study area are

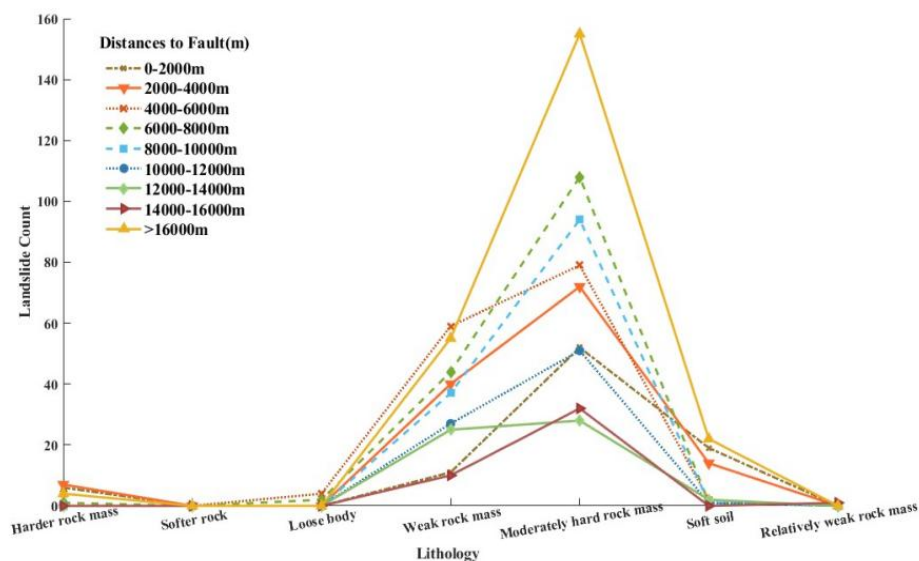
concentrated in the near-river area with an elevation of 1600-1900 m and a slope of 10-20°. In these areas, we should focus on strengthening preventive measures to reduce casualties and property losses.



**Figure 28.** Coupling relationship between elevation, slope, distance to river and landslide number.

### 5.2. Relationship Between Formation Lithology and Distance from Fault

Further analysis of the relationship between the distance from the active fault and the lithology of the stratum, as shown in Figure 25, shows that the loess seismic landslides in the study area are concentrated in the areas 4-12km away from the fault, and the lithology is moderately hard soil, relatively soft rock and soil, and soft soil. There are 625 landslides in this area, accounting for 58.31% of the total number of landslides in the study area. Because The covered area of the Quaternary loess is classified as the medium hard soil mass when the lithologic types are classified, the loess seismic landslides in the buffer zone of each active fault in this lithologic type area are the most, and the number of landslides in this lithologic type area alone is as high as 317, accounting for 29.57% of the total number of landslides. This further shows that the loess seismic landslides in the study area are mainly located on the slope surface of the near-fault area covered by the Quaternary loess, and the thick and low-strength Quaternary loess has become the main material source of these loess landslides. It can also be seen from the figure that the overall number of landslides increases first and then decreases with the increase of the distance from the active fault. In the area near the active fault, although the ground motion is very strong, the probability of landslides is low due to the difference of lithological types. Especially in areas with hard lithology, such as granite and gneiss, even if the earthquake intensity is high, these hard rock masses have high shear strength and are not prone to landslides. With the increase of the distance from the fault, the ground motion is gradually attenuated, and the frequency and scale of landslides are also reduced, especially in the areas where the lithology is relatively hard, the probability of landslides is almost zero. In the areas where the loess layer is relatively thick, such as the areas covered by the Quaternary loess, after the attenuation of the earthquake vibration, although the probability of landslides is low, there is no external force caused by other earthquakes. The number and scale of landslides are significantly reduced. Therefore, in areas close to active faults, especially in areas with thick and loose loess layers, land development should be controlled and infrastructure construction should be avoided in areas with high risk of landslides. Through reasonable planning and disaster prevention measures, the threat of loess seismic landslides to regional security can be reduced.



**Figure 29.** Coupling relationship between lithology, distance to fault and landslide number.

### 5.3. Distribution Characteristics of Multi-Factor Coupling Landslide Disaster

Based on the above analysis, it can be found that the occurrence of loess seismic landslides is not only controlled by a single influencing factor, but also triggered by the combination of multiple different influencing factors. **Error! Reference source not found.** If only a single impact factor is analyzed, the spatial distribution law of earthquake-induced loess landslides cannot be well displayed [25]. Therefore, based on the results of principal component analysis, this paper selects the factor with the highest contribution rate and larger correlation coefficient to further discuss the relationship between elevation and slope and the distance from the river, as well as the relationship between lithology and the distance from the fault, in order to improve the accuracy of the results of the spatial distribution of seismic landslides in loess. According to the statistics, the loess seismic landslides in the study area mainly occur in the area near the river with an elevation of 1600m-1900m and a slope of 10-20°, and in the area covered by a thick Quaternary loess layer with a distance of 4-12 km from the fault. Compared with the previous research results, it further narrows the most vulnerable area of loess seismic landslides, which can help the government to carry out more targeted disaster prevention engineering construction and reduce financial expenditure.

## 6. Conclusions

(1) In the study area, most of the earthquake-induced loess landslides controlled by topographic factors occurred in the south-facing slope areas with elevation of 1300m-1900m, slope of 10-20° and topographic relief of 0-30m, accounting for 80.4%, 50.9%, 69.9% and 64.8% of the total landslides in the study area, respectively. Under the control of geological factors, most of the earthquake-induced loess landslides occur in the farmland and grassland areas where the distance from the river is 800m-1600m, the NDVI index is between 0.09-0.12, and the lithology is medium hard soil and weak soil. The number, area and density of landslides in these areas account for more than 60% of the total number of landslides in the study area. Earthquake-induced loess landslides controlled by seismic factors mainly occurred in the region with an intensity of X and a distance of 2-8 km from the fault. In these areas, the strong vibration caused by the earthquake has a greater disturbance on the slope, especially in the areas close to the fault and with greater intensity, the strong earthquake vibration will seriously damage the soil structure and rock strata, resulting in an increase in the frequency and scale of loess landslides.

(2) The spatial distribution of earthquake-induced loess landslides is affected by a variety of factors, and the location and scale of landslides are not determined by a single factor. Moreover, there

is a complex coupling relationship between these influencing factors, which control the stability of the slope through interaction, mutual restriction and superposition. The principal component analysis shows that the most important factors affecting earthquake-induced loess landslides in the study area are topographic relief, slope, aspect, intensity, distance to fault and elevation, followed by land use type, lithology, distance to river and vegetation coverage. After further analysis of the relationship between elevation, slope and distance from the river, and the relationship between lithology and distance from the fault, it is further accurate that the prone areas of seismic loess landslides are mainly distributed in the area near the river (<1.2km) with an elevation of 1600m-1900m and a slope of 10-20°, and in the area covered by a thick Quaternary loess layer 4-12 km away from the fault.

(3) Therefore, the loess seismic landslides in Tongwei area should be protected and controlled from multiple dimensions, and different methods should be adopted according to the frequency and intensity of geological, topographic, cultural and historical earthquakes in different regions. Focus on the protection of slopes with low altitude, steep slope and topographic relief of about 30m, reduce the development of such areas, and remind nearby residents to stay away from these landslide-prone areas. In particular, attention should be paid to the treatment and reinforcement of slopes in farmland and grassland areas near rivers and roads. In such areas, the soil layer is relatively soft and disturbed by human beings. When an earthquake occurs, strong ground motion can easily trigger the disintegration and sliding of such slopes, resulting in a large area of loess seismic landslides with serious hazards. The study area is almost entirely located in the Loess Plateau, and most of its surface strata are mainly Quaternary loess, with loose texture and large pores, which leads to the rearrangement of loess particles and the destruction of structure when subjected to strong vibration, resulting in large-scale landslide disasters.

**Author Contributions:** Conceptualization, Xiaoxia Xu ; methodology, Xiaoxia Xu and Wujian Yan; software, Xiaoxia Xu ; formal analysis, Xiaoxia Xu; investigation, Xiaoxia Xu and Ruixin Xiao; data curation, Xiaoxia Xu; writing—original draft preparation, Xiaoxia Xu; writing—review and editing, Xiaoxia Xu ; visualization, Wujian Yan and Xiaofeng Liu; supervision, Wujian Yan; project administration, Jie Hao; funding acquisition, Wujian Yan. All authors have read and agreed to the published version of the manuscript.

**Funding:** The financial support for this project was provided by the National Natural Science Foundation of China (Grant No.42330704), and the Science for Earthquake Resilience Program of the China Earthquake Administration (Grant No. XH24044A) the Natural Science Foundation of Gansu Province (Grant Nos. 24JRRA748, 25JRRA393).

**Data Availability Statement:** The raw data supporting the conclusions of this article will be made available by the authors on request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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