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Analysis of Historical Strong Earthquake Impacts on Landslides at the Gansu Segment in the Bailongjiang River Basin, China

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Abstract: Strong earthquake not only triggers a large number of landslides, but also changes the structure of the geological body and groundwater seepage field, and disturbs the stability of rock mass. Repeated strong earthquakes aggravate the stability of geological environment, and generate beneficial conditions for landslides, such as avalanches, landslides, ground fractures, etc. A data set of historical strong earthquakes and landslides at the Gansu segment of Bailongjiang River Basin in China has been compiled, and then the present landslides distribution in high intensity areas of three Ms8.0 historical earthquakes has been examined by ArcGIS. The results showed that: with the decrease of seismic intensity, the landslides quantity, density and size in high intensity areas of three earthquakes were overall attenuated gradually apart from local anomalies in individual intensity area, which revealed that the landslides were affected strongly by the three earthquakes. The Wudu earthquake in 1879 had greater impacts on landslides in the study area than the Wenchuan earthquake in 2008, and the Tianshui earthquake in 1654 had minimal impacts, which indicated that the seismogenic period and epicentral distance were the key factors of historical earthquakes impact on landslides.

Keywords: *Historical earthquakes, Seismic intensity, Landslides, Distribution characteristics, Bailongjiang River Basin, Impact analysis*

1. Introduction

The occurrence of landslides is controlled by many factors, including the geological dynamic environment, structural setting, geography, morphology, lithology, hydrology, climate and human engineering activities [1]. The seismic action is one of the key factors triggering landslides [2], and its action strength is much stronger than other predisposing factors, such as rainfall and gravity [3]. In addition, the earthquake with *Ms*5.3 could induce landslides [4]. Various types of landslides triggered by earthquake which include avalanches, landslides, ground fissures, ground subsidence and soil liquefactions, and they were distributed mainly in areas with frequent strong earthquakes and complex terrain, especially in the ridge, river bank and edge of the slope [5-7]. The study of landslides triggered by Wenchuan earthquake and Ninger earthquake showed that the landslides distribution had close relationship with the magnitude, intensity, epicenter and peak ground accelerate of earthquakes, and the landslides density and size decayed gradually with the decrease of seismic intensity [8-10]. Strong earthquake not only triggers a large number of landslides, but also changes the structure of the geological body and groundwater seepage field, and also disturbs the stability of rock mass [11, 12]. The magnitude is the quantitative index that describes the energy released by earthquake. The higher the magnitude is, the greater energy earthquake released, yet causing more serious damages and having stronger influence on the geological environment. For instance, the collapse deposits triggered by the *Ms*8.0 Huaxian earthquake in 1556 and the *Ms*8.0 Wudu earthquake in 1879 still preserved in the seismic areas [13, 14]. Repeated strong earthquakes aggravate the situation of geological environment, and offer triggering conditions for landslides such as avalanches, landslides, ground fractures, etc.

The present studies mainly focus on the landslides triggered by only one earthquake but not those affected by superimposed effect of repeated strong earthquakes. The Gansu segment in Bailongjiang River Basin was taken as the study area. The landslides distribution in the high intensity areas of the three historical strong earthquakes is examined to analyze the impacts of strong earthquakes on landslides, so as to provide a reference for monitoring, early warning and assessment of regional landslides.

2. Study Area

The Gansu segment in Bailongjiang River Basin is located in the southeast of Gansu province, and the intersection area of the Chinese North-South Seismic Belt and the East-West Qinling Orogenic Belt. It belongs to the mountain of erosion-denudation, and lies between latitude N32°60' to 34°40' and longitude E103°00' to 105°50', covering an area of about 2.36×104 km^2, the elevation ranges from 600m at the southeastward to 4800m at the northwestward in the study area, including Diebu County and Zhouqu County in Gannan State, Wudu District, Tanchang

County, Kangxian County and Wenxain County in Longnan City (Fig. 1). Due to strictly control by the regional tectonic, the area has a complex geological setting, strongly cutting of terrain, sufficient development of folds and faults, wide distribution of weak and soft rocks, active tectonic movement, frequent seismic actions and strong human engineering activities, which has become one of the highest landslides susceptibility areas in China [15]. The direction of the main structure line presents NWW, and the fractures mainly belong to compressive fractures. Weak and soft rocks mainly include phyllite, thin-bedded limestone, siltstone, thin-bedded glutenite and layer of Quaternary sand gravel, etc. The development level, outbreak frequency, damage extent and threat of landslides in the study area all rank the top in China [16].

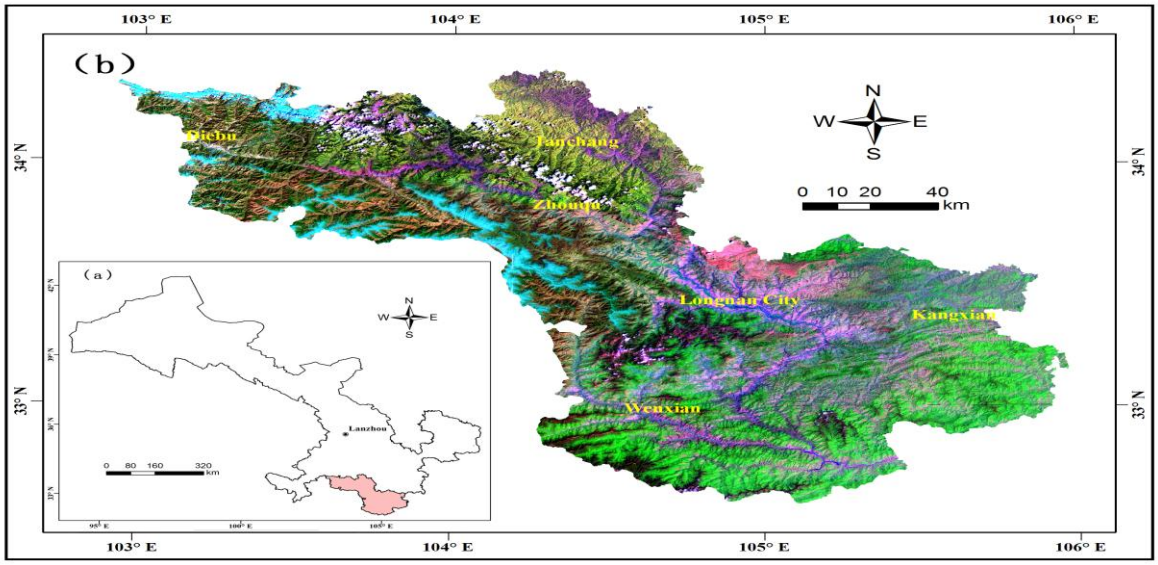

Figure 1 *Location of the study area in Gansu province: (a). Region of Gansu Province; (b). The study area*

3. Materials

3.1. Historical Strong Earthquakes

Seismic activities were active in the study area, and the region has been regarded as the earthquake monitored area [17]. According to the records of Chinese Historical Earthquake Catalog (the 23th Century BC-1911 AD), Chinese Modern Earthquake Catalog (1912-1990) and Chinese Earthquake Networks (http://www.ceic.ac.cn/), the historical report of earthquakes affected the study area dates back to 186 BC, by the end of 12 May in 2008, 37 earthquakes with the magnitude exceeding 5.0 were recorded (Fig. 2), including 24 earthquakes of *Ms*5.0 to 5.9, 8 earthquakes of *Ms*6.0 to 6.9, 2 earthquakes of *Ms*7.0 to 7.9, and 3 earthquakes of *Ms*8.0 which were the Tianshui earthquake in 1654, the Wudu earthquake in 1879 and the Wenchuan earthquake in 2008 respectively. The earthquake epicenters mainly distribute in depth of 10 to 25 km, so they are all shallow earthquakes in the upper crust.

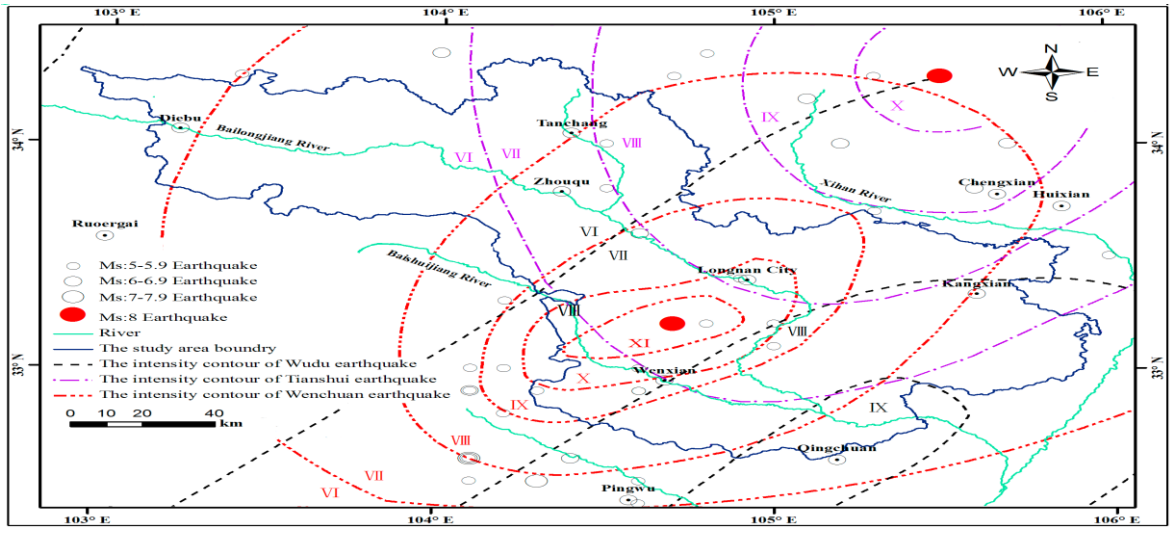

Figure 2. *Epicenter distribution of the earthquakes affected the study area*

3.2. Landslides

According to the geo-hazards data at 1:10 000 scale of the study area (Geological Environment Monitoring Institute of Gansu Province, from 2001 to 2009) and the investigation data of the geo-hazards triggered by the Wenchuan earthquake in Gansu province (Gansu Provincial Department of Land and Resources, 2008), 3445 geo-hazards are counted, including landslides, ground fissures and land subsidence. There are 2182 landslide cases (Fig. 3), which accounted for 63.3% of the total geo-hazards in the study area. So landslides are the main type of geo-hazards induced by earthquake.

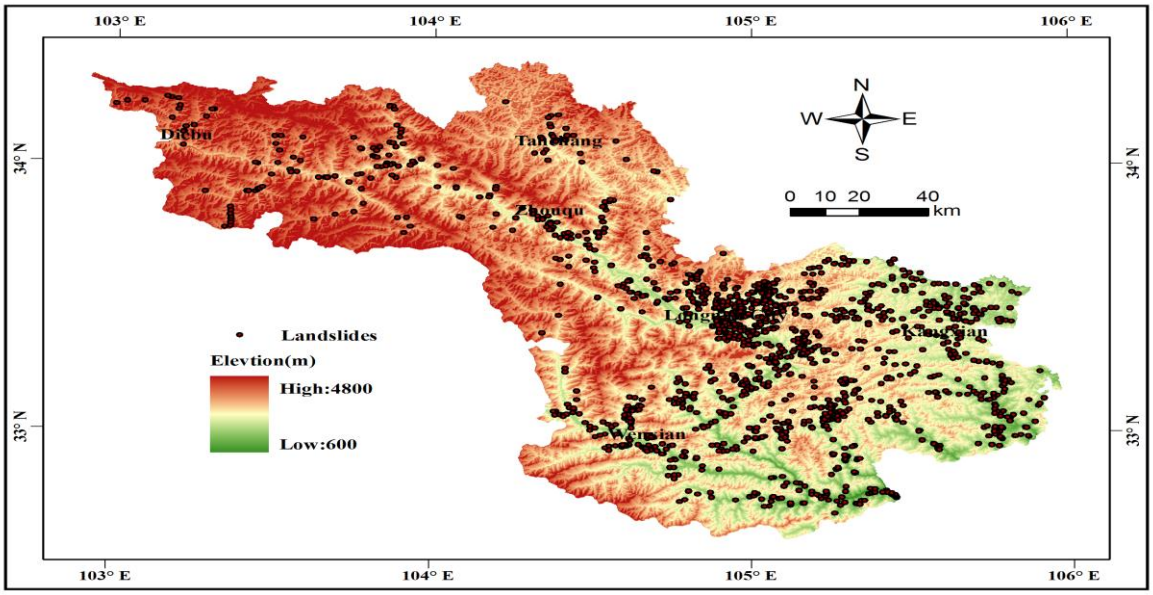

Figure 3. *Distribution of landslides in the study area*

The landslides were mostly distributed in Wudu District of Longnan City (especially around the city and in Beiyuhe River Basin) in the central part of the study area, followed by Wenxian and Kangxian Counties, and less in Zhouqu, Tanchang, and Diebu Counties. Based on the topographical features, the landslides were mainly distributed in both sides of large river within a certain range, including Bailongjiang River, Baishuijiang River and Minjiang River.

4. The Landslides Distribution and Historical Strong Earthquakes

Generally speaking, the impact of earthquake on geological environment presents positive correlation with the earthquake magnitude and intensity. The maximum earthquake magnitude in the study area was *M*s8.0, which releasing energy was much higher than smaller magnitude earthquakes, and the impact on geological environment was unmatched by others. So the historical strong earthquakes may be represented by the *M*s8.0 earthquakes.

With the increase of epicentral distance, the seismic intensity is attenuated gradually. The landslides distribution in high earthquake intensity areas may reflect the level of the earthquake impact on geological environment. In this paper, the landslides distribution in high intensity areas of the *M*s8.0 earthquakes is analyzed by using ArcGIS.

4.1. The *M*s8.0 Tianshui Earthquake in 1654

A devastating *M*s8.0 earthquake occurred in the southern part of Tianshui prefecture in 1654, and the epicenter was located between Luojiabao and the town of Yanguan. The intensity of meizoseismal area reached XI, and the seismogenic fault was striking NEE-trending [18]. Though the earthquake epicenter was not in the study area, the district of intensity VIII extended to the southern part of Wudu District and the western part of Tanchang County, also the district of intensity VII extended to the southern part of Wenxian County (Fig. 2). The earthquake triggered large numbers of geo-hazards, including collapses, landslides, ground fissures and sand liquefactions [19]. The distribution of landslides in high intensity areas showed that (Fig. 4) the landslides were mainly distributed in the district of intensity VIII, up to 1069 cases, which accounted for 49% of the total landslides in the study area, followed by the district of intensity VII, and least in the district of intensity VI, only 367 cases. The highest landslides density was in the district of intensity VIII, up to 25.45 cases per 100 km2, followed by the district of intensity VII, and the lowest in the district of intensity VI, reduced to 3.67 cases per 100 km2. Most of the extra-large and large-size landslides distributed in the district of intensity VII, the medium-size landslides mainly in the district of intensity VIII, and the small-size landslides almost in the districts of intensity VII and VIII.

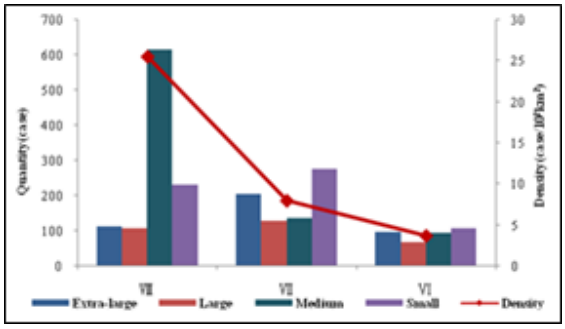

Figure 4. *Landslides in the 1654 Tianshui earthquake zone*

4.2. The *Ms*8.0 Wudu Earthquake in 1879

The epicenter of the *Ms*8.0 Wudu earthquake in 1879 was located between the Wudu District and Wenxian County, and the epicentral intensity was XI [14]. The district of intensity VIII extended to Tanchang County, and the district of intensity VII extended to Diebu County (Fig. 2). The earthquake induced large numbers of secondary geo-hazards, including collapses, landslides and ground fissures. Some collapses and landslides triggered by the earthquake still preserved in the study area at present [19]. The distribution of landslides in high intensity areas showed that (Fig. 5) the landslides were mainly distributed in the district of intensity X, up to 629 cases, which accounted for 29% of the total landslides in the study area, followed by the districts of intensity VIII and VII, IX, and less in the districts of intensity XI and VI, only 38 and 17 cases, respectively. The highest landslides density was in the district of intensity X, up to 33.11 cases per 100 km^2, followed by the districts of intensity IX, VIII and VII, lower in the district of intensity XI, only 4.22 cases per 100 km^2, and the lowest in the district of intensity VI, just 2.13 cases per 100 km^2. Most of the extra-large and large-size landslides were distributed in the districts of intensity X, IX and VIII, the medium-size landslides mainly in the districts of intensity X and IX, and most of the small-size landslides in the districts of intensity VIII and VII. However, the landslides in the district of intensity XI were almost extra-large and large-size, all of the landslides in the VI district were medium and small-size.

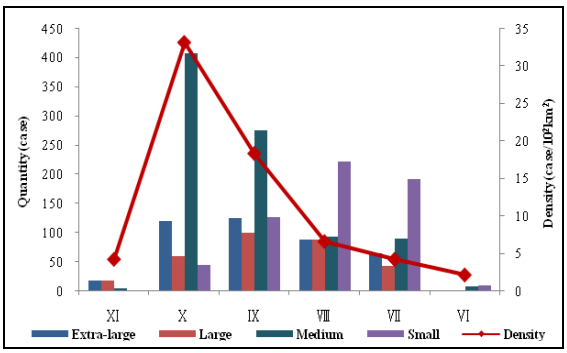

Figure 5. *Landslides in the 1879 Wudu earthquake zone*

4.3. The *Ms*8.0 Wenchuan Earthquake in 2008

A devastating *Ms*8.0 earthquake stroked Wenchuan County and Beichuan County of Sichuan province on May 12, 2008, and the epicenter was located in Caijia Village of Yingxiu Town. The epicentral intensity reached XI, and the seismogenic fault showed striking NE-trending [20]. Though the earthquake epicenter was not in the study area, the district of intensity IX extended to the southeastern part of Longnan City, the district of intensity VIII extended to Wudu District, Wenxian County and Kangxian County, and the districts of intensity VI and VII stretched to Diebu County and Tanchang County (Fig. 2). Large numbers of collapses, landslides and ground fissures were triggered [19]. The distribution of landslides in high intensity areas showed that (Fig. 6), the landslides were mainly distributed in the district of intensity VII, up to 1395 cases, which accounted for 64% of the total landslides in the study area, followed by the district of intensity VIII, and less in the districts of intensity VI and IX. The highest landslides density in the district of intensity VII, up to 20.22 cases per 100 km^2, followed by the districts of intensity VIII and IX, and the lowest in the district of intensity VI, only 2.12 cases per 100 km^2. All sizes of landslides were mainly distributed in the district of intensity VII, but the landslides were extra-large size in the district of intensity IX, and were almost medium and small-size in the district of intensity VI.

In summary, with the decrease of seismic intensity, the landslides quantity, density and size in high intensity areas of the three historical strong earthquakes attenuate gradually apart from local anomalies in individual area.

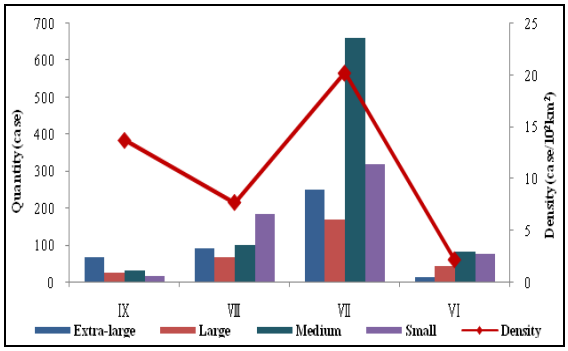

Figure 6 *Landslides in the 2008 Wenchuan earthquake zone*

5. Results and Discussion

5.1. Abnormal Distribution of Landslides in High Intensity Areas of Historical Strong Earthquakes

5.1.1. Landslides in the District of Intensity VII of the Ms8.0 Tianshui Earthquake

With the decrease of seismic intensity, the landslides quantity and density in high intensity districts of the Tianshui earthquake decreased obviously, and the medium and small-size landslides reduced gradually.

The extra-large and large-size landslides were mainly distributed in the district of intensity VII, but less in the district of intensity VIII.

The occurrence of landslides is certainly controlled by seismic intensity, but it's also closely related to other factors, such as the different intensity area, the structure setting, lithology, topography, meteorology, hydrology and human engineering activities, etc.

The district of intensity VII covered the most part of Tanchang, Zhouqu, Kangxian Counties and Wudu District, which included long reach of Bailongjiang River, and a wide range of influence (the district of intensity VII with an area of 0.94×10^4 km^2, the district of intensity VIII with an area of 0.42×10^4 km^2). The river erosion is extremely heavy; human engineering activities are strong and frequent. The natural geological process and human engineering activities (including river erosion, road construction, the excavation of soil) have disturbed the stability of rock mass, damaged the steep slopes, so the landslides can be easily triggered compared with the district of intensity VIII.

Furthermore, five earthquakes (once *M*s6.5, others *M*s5.0 to 6.0) occurred in the district of intensity VII. Though the magnitudes were low, these earthquakes were certainly affected the fragile geological environment as the predisposing factor of landslides. For example, the slope in the critical state will slump under influence of small vibration [21]. Compared with the district of intensity VII, five earthquakes also occurred in the districts of VIII and VI, but these earthquakes' magnitude are less than *M*s6.0, and the epicenters of three earthquakes were adjacent to the boundary of the district of intensity VII, so the abnormal distribution of landslides in the district of intensity VII may relate to these historical earthquakes with smaller magnitude.

5.1.2. Landslides in Magistoseismic Area (XI) of the Ms8.0 Wudu Earthquake

With the decrease of seismic intensity, the landslides quantity, density and size in high intensity areas of the Wudu earthquake were decayed gradually with the exception in the magistoseismic area.

Theoretically, the landslides should be extremely developed in the magistoseismic area due to serious destruction of earthquake to the rock mass. However, the landslides in the magistoseismic area showed obviously anomalous distribution with small quantity and low density. In other words, these landslides are almost extra-large and large size, less medium-size, not small-size, which reflects the high-strength destruction on geological environment in the meizoseismal area. Though these landslides quantity was less, their sizes were huge, much larger than others. The distribution characteristics of the landslides quantity, density and size comprehensively reflect the seismic intensity.

5.1.3. Landslides in the District of Intensity VII of the Ms8.0 Wenchuan Earthquake

The landslides size in high intensity areas of the Wenchuan earthquake was decreased gradually with the decrease of seismic intensity, but the landslides quantity and density were anomalous obviously. The landslides were mainly distributed in the district of intensity VII, and the density was higher. By contrast, not many landslides were distributed in the districts of intensity IX and VIII and the density was lower accordingly.

Analyzing the reasons of these phenomena, the district of intensity VII covered the most parts of Wudu District of Longnan City, which has high population density and frequent human activities. Meanwhile, the area was the district of intensity VII of the Tianshui earthquake and the meizoseismal area of the Wudu earthquake, which has been repeatedly battered by the three strong earthquakes, and the geological structures were damaged seriously. There were large numbers of slopes in a critical state, which provided advantageous conditions for the subsequent landslides.

Furthermore, eight earthquakes (once *M*s7.2, twice *M*s6.5, others *M*s5.0 to 6.0) occurred in the district of intensity VII. However, three earthquakes of the magnitude less than *M*s6.0 occurred in other districts, which indicated that the abnormal distribution of landslides related to these weaker earthquakes.

These factors, including geological structure, lithology, landform, etc., offered beneficial conditions for the formation of landslides. As a key factor to trigger landslides, the driving loadings of earthquake are much stronger than other predisposing factors, such as rainfall and gravity. Though the abnormal distribution of landslides happened in individual region due to these factors, with the decrease of seismic intensity, the landslides quantity, density and size were attenuated gradually, from extra-large, large size and medium-size in the district of intensity XI to medium and small-size in the district of intensity VI, which indicated that the distribution of landslides was affected obviously by the three historical strong earthquakes.

5.2. Influenced Intensity of the Three *M*s8.0 Earthquakes on Landslides

The grade of earthquake's destruction on geological environment is closely related to the magnitude, intensity and epicenter location, etc. [11]. The influenced intensity of the three earthquakes on geological environment was different because of the different seismogenic period and epicentral distance. For one earthquake, the landslides distribution in different intensity areas is obviously different, which shows certain distribution regularities. But for several earthquakes with the same study area and different intensity area, the landslides distribution

characteristics in the areas of the same intensity and higher intensity could reflect the influenced intensity on landslides of different earthquakes in a certain extent.

The developmental degree of the present landslides in the areas of intensity VII and higher intensity of the three earthquakes were calculated (Fig. 7): all sizes of landslides were mostly distributed in Wudu earthquake zone, followed by Wenchuan earthquake, and the least in Tianshui earthquake zone. The landslides density in Wenchuan earthquake zone is the highest, reached to 14.49 cases per 100 km^2, followed by Tianshui earthquake, and the lowest in Wudu earthquake zone, only 9.50 cases per 100 km^2.

The landslides density has close relationship with the landslide effect area. The Wudu earthquake zone extends for 2.28×10^4 km^2, almost covers the entire study area, and thus the density is relatively low, but the area of intensity VII of Wenchuan earthquake and Tianshui earthquake are roughly the same, and both of them are 1.36×10^4 km^2, and the landslides density of Wenchuan earthquake was significantly higher than that of Tianshui earthquake. It's clear that Wenchuan earthquake has stronger impact on landslides than that of Tianshui earthquake.

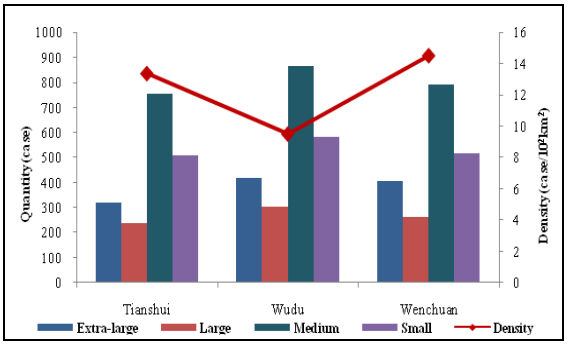

Figure 7. *Landslides distribution in the areas of intensity VII and higher intensity of the three earthquakes*

To determine the influenced intensity of Wudu earthquake, the developmental degree of landslides in the areas of intensity VIII and higher intensity of the three earthquakes were analyzed (Fig. 8): the landslides were mainly distributed in Wudu earthquake zone, up to 1778 cases, followed by Tianshui earthquake zone, and the least in Wenchuan earthquake zone, only 575 cases. All sizes of landslides were mainly distributed in Wudu earthquake zone, and the extra-large landslide sizes in Wenchuan earthquake zone were more than that of Tianshui earthquake, while other landslide sizes were less than that of Tianshui earthquake. The landslide density was the highest in Tianshui earthquake zone, reached to 25.45 cases per 100 km^2, followed by Wudu earthquake, and the lowest in Wenchuan earthquake zone, only 8.58 cases per 100 km^2. The distribution regularities of landslides quantity and size indicated that Wudu earthquake impact on landslides is greater than Wenchuan earthquake, and Tianshui earthquake impact was the lowest.

The landslides density in Wudu earthquake zone was higher than that of Wenchuan earthquake. As in the Tianshui earthquake zone was the highest because the area contains Longnan City and the surrounding areas, where landslides concentrated. Comprehensive analysis, the influenced intensity of Wudu earthquake was significantly higher than that of Wenchuan earthquake, and the intensity of Tianshui earthquake was minimal.

In conclusion, the Wudu earthquake had greater effects on landslides in the study area than the Wenchuan earthquake, and the impact of Tianshui earthquake is the smallest, which indicated that the seismogenic period and epicentral distance were the key factors of historical earthquakes impact on landslides.

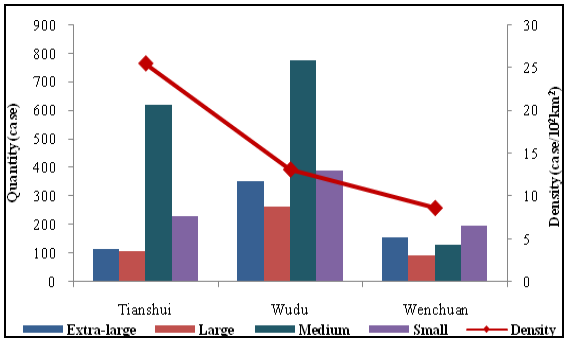

Figure 8. *Landslides distribution in the areas of intensity VIII and higher intensity of the three earthquakes*

6. Conclusions

The distribution of landslides in high intensity areas of the three *Ms*8.0 historical earthquakes in the Gansu segment of Bailongjiang River Basin are analyzed by ArcGIS, the results show that:

(1) The occurrence of landslides is significantly affected by the historical strong earthquakes. With the decrease of seismic intensity, the landslides quantity, density and size are obviously decayed, at the same time, the landslides sizes are transferred gradually from extra-large, large and medium-size in the district of intensity XI to medium and small-size in the district of intensity VI.

(2) The Wudu earthquake has greater effects on landslides in the study area than the Wenchuan earthquake, and the Tianshui earthquake has minimal impacts, which indicates that the seismogenic period and epicentral distance are the key factors of historical earthquakes' impact on landslides.

(3) The distribution regularities of landslides in the high intensity areas of historical strong earthquakes are complex due to the combined influence of many factors, including the

geological environment, topography, human engineering activities, and small magnitude historical earthquakes. The influence of historical earthquakes with smaller magnitudes in degree and scope will be further studied.

7. Acknowledgements

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