Characteristics and Mechanism of Loess Landslides Induced by Strong Earthquake in The Loess Plateau of China

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Abstract. The Loess Plateau is the main loess distribution area in China with strong tectonic activity and frequent earthquakes. This paper systematically summarizes the characteristics and mechanism of loess landslides induced by strong earthquakes. The geometric characteristics of loess seismic landslide are gentle slope with 10°~25°. The motion characteristics of earthquake-induced loess landslides are high-speed and long-distance. The distribution characteristics of loess seismic landslides are also basically consistent with the distribution of earthquake active region, and mainly distribute in loess hilly and gully area or the edges of the loess tableland. Based on the mechanism of seismic instability of loess slope, we consider that there are three types of loess landslides: seismic subsidence type, liquefaction type and tension-shear coupling type.

1. Introduction
China has the loess region with the thickest soil layers, the most complicated topography and the largest distribution area in the world, where has major landforms such as loess tableland, loess ridge and hillock, valley terraces, etc. The total area of loess distribution in China is 640,000 km², accounting for approximately 6.6% of China's total land area and 4.9% of the world's total loess area. The Loess Plateau is the main loess distribution area of China and also the most developed loess area in the world. It covers Gansu, Shaanxi, Ningxia, Shanxi and partial areas of Henan provinces, with a total area of approximately 335,000 km².

The Loess Plateau is centered on the Longdong loess Plateau and the Shanbei Loess Plateau within the south Ordos platform where is surrounded by Datong, Xinding, Taiyuan, Fenwei and Yinchuan faulted basins with intense tectonic activities along the east, south and west sides of the Ordos platform, and the Longxi Loess Plateau is located in the southwest of the Ordos platform, a series of NWW regional deep faults have been developed(Fig.1a). The complicated tectonic setting and intense tectonic activities have made the Loess Plateau be one of the areas with the most intense seismic activities in China. According to historical earthquake records, seven earthquakes of magnitude 8 or above and twenty-two of magnitude 7 to 7.9 once occurred in the Loess Plateau, and almost all of earthquakes above moderate intensity occurred in the faulted basins surrounding the Ordos platform and the deep faults in the Longxi Loess Plateau. Especially the intersection of the North-South Seismic Belt and the Qilian Seismic Belt has the strongest seismicity.[1][2]

Due to the weak physical and mechanical properties of loess, it has extremely strong collapsibility and dynamic vulnerability.[3] In addition, topography of criss-cross gullies and earthquake-prone environment, the multi-factors coupling has made loess landslides and collapses have been the most prominent geological disasters in the Loess Plateau. In the moderate and strong earthquakes that...
occurred in the Loess Plateau and its surrounding areas in history, extremely severe regional geological disasters would be formed in the areas of seismic intensity VIII and above. Most of the geological disasters are slope instability hazards such as loess landslides and collapses(Fig 1b). Loess landslides feature high density, large scale, high sliding speed and long sliding distance, which are very hazardous and destructive[4,6]. In 1920, Haiyuan M8.5 earthquake caused more than 270,000 deaths, among which more than 100,000 were caused by landslides. Therefore, loess landslide was one of the most important cause of casualties (Table 1).

| Time | Epicenter | Magnitude | intensity | Major geotechnical damages | Death toll (thousand) |
|------|-----------|-----------|-----------|---------------------------|-----------------------|
| 1303 | Hongdong  | 8         | XI        | Landslide, collapse, ground motion amplification | 200 thousand          |
| 1556 | Huaxia    | 8.3       | XI        | Landslide, subsidence, ground motion amplification | 830 thousand          |
| 1654 | Tianshui  | 8         | XI        | Landslide, collapse, ground motion amplification | 31                    |
| 1718 | Tongwei   | 7.5       | X         | Landslide, subsidence       | 40                    |
| 1920 | Haiyuan   | 8.5       | XII       | Landslide, collapse, liquefaction, ground motion | 230 thousand          |
| 1927 | Gulang    | 8.0       | XI        | Landslide, collapse, ground motion amplification | 100 thousand          |

Table 1. Typical historical earthquakes damage in the Loess Plateau

2. Loess Landslides induced by Strong Earthquake in Loess Plateau

Due to the difference of topography, thickness of soil strata, hydrogeological environment and physical and mechanical properties of loess in different regions, the scales, morphological characteristics and instability modes and sliding mechanism induced by earthquake are not exactly the same. In this section, based on the previous research work, the features of loess landslides induced by a few strong earthquakes of M7 and above in the Loess Plateau are introduced.
2.1 Haiyuan Earthquake

The M8.5 earthquake that took place in Haiyuan on December 16, 1920 has induced massive and numerous loess landslides. The landslide area reached 50,000 km², including three concentrated areas. The first was the meizoseismal area of south of Haiyuan where the seismic intensity is XI–XII; the second was the vast area south of Xiji, east of Huining and north of Jingning; and the third was in Tongwei County. The total area of regional earthquake-induced landslides reached more than 4,000 km², with more than 650 landslides in Xiji County alone.

Loess landslides mostly occurred at low slopes lower than 50m or the foot of high slopes rather than high mountain ridges in Haiyuan Earthquake (Fig 2). The slopes were mostly between 10° and 20°[4], Sliding mass completely or mostly broke away from slide bed; the sliding mass had streamlined and wavy micro-topographical features, morphologically looking like deposit formed after loess disintegration and flow. The main sliding direction was approximately parallel to the overall trend of Haiyuan fault, with only a small angle, which showed that the landslide was more significantly affected by the ground motion in direction of the fault trend.

Fig 2 Landslides induced by the Haiyuan earthquake

2.2 Gulang Earthquake

On May 23, 1927, a M8 earthquake struck Gulang county, Gansu Province, with an epicentral intensity of XI. The earthquake triggered a lot of landslides, collapses, earthquake fissures and many other ground damages. Among them, the landslide hazards occurred in the loess hilly areas and caused great losses to people's lives and properties.

The landslide-concentrated areas were mostly in the epicentral area and loess covered areas nearby, mainly distributed in the level III river terrace. The landslides with an original slope greater than 25° accounted for 57.38% of the total number of landslides and that of 15°-25° accounted for 34.42%; only a small number occurred at slopes less than 15°. The scale of landslides was generally small, and sliding mass was mostly from nearly one hundred meters to several hundred meters in width and length[5].

2.3 Tongwei Earthquake

On June 19, 1718, an earthquake hit Tongwei County, Gansu, which caused landslides and house collapses in the meizoseismal area of Tongwei and Gangu. In Gangu County, the northern hill moved southward, destroying thousands of houses; the villagers and livestock in the northwest of the county were all died in the earthquake. The earthquake killed more than 40,000 people and wounded more than 40,000.

The earthquake induced a lot of loess landslides in the hilly and gully regions. A total of 512 km² sliding area appeared in the meizoseismal area, accounting for 90% of the total landslide area. The original slopes of the landslides were mostly 70m-130m in height and 11° - 18° in slope, and were mostly gentle loess ridge slopes. The thickness of sliding mass varied from more than ten meters to more than sixty meters. There were approximately 337 landslides greater than 500m in length. Among them, the largest was the huge-scale Yongning landslide, which was 8 km long and 3 km wide, sliding a total distance of 5 km and burying all the more than 2,000 households of Yongning Town[7].
2.4 South Tianshui Earthquake
On July 21, 1654, a M8 earthquake hit the area of Luojiabu between Tianshui and Lixian County, causing a large area of building collapses and inducing a large number of landslides, collapses and the formation of dammed lakes, etc., which killed more than 30,000 people.

The landslides mainly occurred in the mezoseismal area, and approximately 180 landslides of different scales developed from Lixian County to Tianshui. Among them, the landslides north of the Xihan River were larger in both number and scale than those south of the river, and the highest concentration of landslides was found along the line of Yongxing-Yanguan-Luojiabu-Tianshui\[8\]. The largest sliding mass was 4.5 km long and approximately 2 km wide.

2.5 Huaxian Earthquake
On January 23, 1556, a M8.3 devastating earthquake struck Huaxian County, Shaanxi Province, which affected nearly half of China and caused 830,000 deaths. It has been the deadliest earthquake in human history. The earthquake triggered various landslides, ground fissures, sand liquefaction and mudslides.

The earthquake triggered a large number of landslides and collapses, and several landslides of extraordinarily large scale were induced. Among them, Zhangjialing sliding mass was 2,100m long and 1,000m wide, approximately 10.5 million cubic meters in volume; Guojiagou sliding mass was 1,300m long and 550m wide, approximately 3.57 million cubic meters in volume. The surface of two landslides were steep in the upper part and gentle in the lower part\[9\].

2.6 Hongdong Earthquake
In 1303, a M8 earthquake hit Hongdong, Shaanxi Province. The epicenter was located north of the Linfen Basin; the seismic deformation zone basically extended along the seismogenic fault zone, approximately 45 km with landslides, collapses, faults, ground cracking, etc.

The largest was Huanbu landslide, approximately 1,600m long and 1,400m wide, the slope at the rear margin of the landslide is 5°-6°, while that at the front margin is only 3°, within a surface slope of 5°-10° from the front to rear margin, thus it is a gentle slope\[10\]. According to field observations and borehole revelation, ground water is well developed in this region. Soil layer liquefaction during the earthquake triggered high-speed and long-distance landslides.

3. Mechanism of Earthquake-induced Loess Landslides
Among earthquake-induced loess landslides, some feature gentle slope, loose soil, and flow-sliding soil, showing the instability characteristic of seismic subsidence and collapse; some show the instability characteristics of shearing slippage under the dynamic stress of earthquake; some of them are due to the existence of perched groundwater between mudstone and loess, and the liquefaction of water-retaining layer is the mechanism of slope instability. Thus, According to the different landslide mechanisms, earthquake-induced loess landslides are classified into three types, including subsidence type, liquefaction type and tension-shear coupling type.

3.1 Mechanism of landslides of loess subsidence type
The subsidence type landslides mostly occur in gentle loess slopes with low soil moisture content, and the micro-structure of soil mass above the landslide surface is subject to comminuting damage, showing a series of macro features, such as high speed and flow sliding\[2\].

The late Pleistocene Malan loess and Holocene loess-like soil are weakly clayey soil with a macroporous structure, featuring very weak inter-granular cohesion and low structural strength. Under the action of severe ground motion, there is action of strong dynamic stress inside the soil mass of slope. Under the repeated tension and shearing action, the porous structure, which is the weakest part inside the soil mass, is firstly destructed and collapses; the scattered soil particles fall due to gravity, filling the pores. When the destruction and disintegration of porous structure of soil mass occurs in the loess slope, the soil mass will have sudden residual deformation - seismic subsidence (Fig.3a). Under the topographical conditions of slope, seismic subsiding soil mass will easily have flow sliding along
the landslide plane due to the sliding force caused by gravity and the seismic inertia force. If the subsequent ground motion is very strong, there will also be high-speed flows such as "loess flows" that was very common in the Haiyuan Earthquake.

3.2 mechanism of landslides of loess liquefaction type

liquefaction type landslides occur either in valley terraces with high groundwater level or in the loess-mudstone structures containing perched groundwater in the ridge areas with gentle slope and feature high-speed and long-distance sliding and strong destructiveness.

As for the mechanism of loess liquefaction, the current research\cite{11} shows that, when the water content of the soil layer is higher than the plastic limit water content, the pore water pressure may increase under the coupling action of dynamic stress and water, and the corresponding effective stress in soil is reduced, shear strength of soil mass reduces, eventually resulting in sinking or flowing of a large area soil mass. In the loess slopes with higher groundwater level or perched groundwater, due to the limited soil mass with high water content in the slope and the gentle slope topographical conditions, loess slopes can maintain stable without sliding under static condition. When ground motion occurs, the structural strength of wet soil is rapidly lost and pore pressure sharply increases under the action of dynamic stress\cite{12}, finally resulting in complete loss of shear strength of soil mass and liquefaction. At this time, the internal stress of the overlying dry soil is adjusted due to the underlying soil liquefaction, stress at slope foot is even stronger. Under the continuous action of dynamic stress, the soil mass at the slope foot is sheared, the overlying soil mass drags the back edge of sliding mass and slides downward from the parent body and rapidly slide along the slope.

3.3 mechanism of seismic loess landslides of tension-shear coupling type

Due to the less rainy climate in the Loess Plateau, the slope soil mass is generally dry, and the matrix suction between soil particles is very strong, which increases the anti-skid resistance of the soil particles accordingly. Under such conditions, the subsidence and liquefaction phenomenon of slope soil mass under ground motion action is difficult to happen, and due to the strong ground motion, an arc-shaped rupture zone is formed in a certain area inside the slope, with shear failure in the mid-lower part and tension fracture near the slope top; the landslide mass slides downwards along the fracture zone, forming tension-shear coupling loess landslides.

In the process of ground motion propagating from bottom to top in the form of stress wave in the slope, the dynamic response characteristics of different slopes have great differences due to the morphological difference, soil strata structure and hydrogeological conditions of the slope. Even for the same slope, the differences of the physical and mechanical properties of soil and boundary conditions in different parts of slope, these would cause significantly different dynamic stress. In some loess slopes, shearing failure first occurs in the mid-lower part, and the shear failure area gradually expands from bottom to top with the continued action of subsequent ground motion; the front part of landslide mass drags the rear part to slip along the landslide plane, and finally the top soil mass is fractured by tension and rapidly slides downwards, forming shear-tension landslides. On the contrary, the dynamic stress at the top of some slopes is the strongest, and tensile cracks are formed at the top; under the action of subsequent ground motion, the soil mass in the mid-lower part of the slope is gradually destroyed by shearing action; with the expansion of the shear failure range, the sliding mass
is sheared out, slides out of the slide bed and slides downwards violently, forming tension-shear loess landslides.

4. Conclusion
The strong earthquake areas in the Loess Plateau are mainly distributed along the eastern, southern and western sides of the Odors platform and are extremely uneven seismicity, and the distribution of seismic loess landslide prone areas is also basically consistent with the distribution of earthquake active region. Geomorphology is an important factor affecting the development of loess seismic landslides, and loess seismic landslides are mainly distributed in loess hilly and gully area and along the edges of the Loess tableland. The geometric characteristics of loess seismic landslide are gentle slope with 10°~25° angle. The motion characteristics of earthquake-induced loess landslides are high-speed and long-distance.

According to instability mechanism, earthquake-induced loessial landslides mainly include subsidence type, liquefaction type and tension-shear coupling type. The necessary conditions for a subsidence type landslide is loose loess with developed large pores. A liquefaction type landslide often occurs in the areas with high groundwater level or slopes with perched groundwater, featuring strong destructiveness. The tension-shear coupling type landslides are the most common type among the earthquake-induced landslides in the Loess Plateau. They can be divided into shear-tension type and tension-shear type according to the damage mechanism of slip plane.

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