Analysis of disaster-causing mechanism of loess landslides induced by the Minxian-Zhangxian Ms6.6 earthquake, China

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ABSTRACT

The Minxian-Zhangxian Ms6.6 earthquake induced a large number of loess landslides and collapses on July 22, 2013 in Dingxi city, Gansu province. In the center of the quake-hit area, it caused a banding area of landslides dense distribution with 8km wide and 30km long, and which long axis direction is in accordance with the trend of seismo-tectonics of the earthquake. Based on field test pit survey and surface wave investigation, the topography and soil distribution of the west loess landslide at Yongguang village in the landslides dense distribution area was identified. Moreover, the liquefaction probability of loess of the landslide was proven through dynamic triaxial liquefaction tests. The dynamic response characteristics of the landslide were analyzed by combining dynamic finite element method and strength reduction method as well. The results indicate that continuous heavy rain before the earthquake induced moisture content increasing and shear strength reducing in the surface loess layer of the slope. Coupling with the strong quake, tensile stress and liquefaction occurred in the surface soil layer, which caused the loess slope collapse instantaneously and a sliding distance of about 1000m long.

Keywords: Minxian-Zhangxian Ms6.6 earthquake, loess landslide, dynamic stability, disaster-causing mechanism

1 INTRODUCTION

An earthquake measured Ms6.6 struck Dingxi City, Gansu province on July 22, 2013. Its epicenter (34.5°N, 104.2°E) located in the juncture of the Ming County and Zhang County, and its focal depth is 20km. The quake is the largest one since the 1954 Shandan Ms7.2 earthquake occurred in Gansu province, and was named Minxian-Zhangxian Ms6.6 earthquake by China Earthquake Administration. By 15:00 on August 23, 2013, there were 1260 times aftershocks occurring in total, including 22 Ml3.0~3.9 earthquakes, 5 Ml4.0~4.9 earthquakes and one Ms5.0~5.9 earthquake, among which the largest one was an Ms5.6 quake on July 22, 2013.

The quake affected 13 counties in Gansu province, caused 95 persons deaths, 2414 injures, 314,120 people homeless, and result in an accumulative direct economic losses of 17.588 billion Chinese Yuan. In the center quake-hit areas, housing, transportation, water conservancy, electricity and other public facilities and lifeline engineering were destroyed seriously. The maximum seismic intensity is Ⅷ degree, and its area is 706 km². Meanwhile, the area of intensity equal or greater than Ⅵ degree reaches up to 16432km², in general, which is larger than that caused by an earthquake with magnitude around Ms6.6 occurred in the other regions.

2 EARTHQUAKE-INDUCED LANDSLIDE HAZARD CHARACTERISTICS

The quake-hit areas locate in the northeastern edge of the Tibetan Plateau, the transition region among the Gannan Plateau, the Loess Plateau and the Longnan mountain area, where geological structure is quite complicated, and widely distributes of mountains and rivers. In areas of seismic intensity of Ⅷ degree, the surface loess layer is loose, widely and deeply distribution. Seismic geological disasters, such as loess landslides, collapses and seismic subsidence, distributed densely. The dense distribution areas of seismic geological disasters were identified according to several routes of field investigations, which mainly locate in several villages, which are Chagutan, Majiagou, Wendou, Chelu, Yongguang, Yongxing and
Lalu village. Where is a banding region with 8km wide and 30km long, and its long axis direction is in accordance with the trend of the seismo-tectonics of this earthquake (Wang and Wu, 2013) (Fig.1). In this region, loess landslides and collapses developed intensively and contiguously, and the largest scale landslides are medium-sized, such as the eastern and western Yongguang landslides. Loess collapses and small scale of landslides were the main secondary geological induced disasters, and some other medium-sized deep seated landslides and mudflow like landslides were also developed in this banding area (Fig. 2).

![Fig. 1. The intensity distribution map and dense distribution region of landslides in the quake-hit areas.](image1)

As one main kind of geological disasters in loess areas, many loess landslides are large scales, high slide velocities, long sliding distances, and have wide effecting areas. The main reasons that may induce loess landslides are as follows: (1) cutting effects of deep ravines and effects of river lateral erosion on loess tablelands and high terraces in the Loess Plateau, (2) regular irrigation at high terraces, continuous raining and rainstorm, (3) human being engineering projects in the Loess Plateau, such as, irrigations, highways, railways, mining and underground constructions, etc., and (4) earthquake inducing landslides (Xu et al., 2007). Based on field investigations into several typical loess landslides after the Minxian-Zhangxian Ms 6.6 earthquake, it indicated that the surface layer soil was loose, and which moisture content of soil was between plastic limit and liquid limit. Clear water stains were observed at many sites of soil surfaces at back edges of landslides. Before the main quake occurred on July 22, the quake-hit areas suffered moderate rain for several days and heavy rain the night before. The rainfall within 12 hours before the quake reached to 6.6 mm, however, the local average daily rainfall during rainy season is only 2.48 mm. Preliminary analyses indicated that the reason for widely loess landslides distribution and large areas of seismic intensity of VI degree may be the coupling effects of earthquake and rainfall.

![Fig. 2. Typical seismic loess landslides in the quake-hit area.](image2)

3 TYPICAL LOESS LANDSLIDES

The Yongguang landslides were the largest landslides in the quake-hit areas, which includes eastern landslide and western landslide (Figure 3). Both of them developed at the top of one same loess slope, where are cultivated lands for Chinese medicinal herb. The overburden soil of these landslides is thick and consists of clay and loess. The eastern landslide destroyed six houses; the western one buried eight houses and caused a death of 12 people, which was the most destructive landslide induced by this earthquake.

The motion characteristic of the western Yongguang landslide is as same as that of mudflow, and it shows an approximate L-shaped in a plane and roughly north-south direction (Fig. 4). The maximum sliding distance of this landslide is about 1000m, overall drop is 253m, average slope is 18°, sliding area is about 42,000m², and total earthwork volume is around 400,000m³ respectively. The trailing edge of the landslide is 100m wide and 30m high, and the front edge is 13m wide. Through field test pits and soil sample tests, the western Yongguang landslide slid in its surface soil layer, and the surface soil is the Q₃ Malan loess and uneven silt content. The overburden soil is thick, which moisture content reaches up to 24.53% (between plastic limit and liquid limit). When the main quake occurred, this landslide instability induced simultaneously, which the surface soil layer slid very quickly, broke the front original concave terrain, slipped into a large gully and flew down along it, and slid back to upstream of the gully 20m long.

Based on field test pit survey, surface wave
investigation and dynamic triaxial liquefaction tests for the western Yongguang landslide, the site conditions, soil layer distribution and soil physical parameters were determined. The occurring conditions and probability of liquefaction during the earthquake were analyzed as well. Moreover, the instability mechanism of the loess landslide was studied using numerical simulation methods.

Fig. 3. Remote sensing image of the Yongguang landslides (base map provided by Gansu Provincial Bureau of Surveying and Mapping).

Fig. 4. The western Yongguang landslide.

4 SURFACE WAVE EXPLORATION AND DYNAMIC TRIAXIAL TESTS

4.1 High-density surface wave investigation

Two survey lines of surface wave exploration were carried out at the top and the middle of the western landslide respectively (Fig.3). There were 24 detectors used in this survey, and sampling interval was 1ms, record length was 2.046s, offset distance was set up 10m, 15m and 20m respectively. Vertical component speed geophones with the inherent frequency of 4.5Hz were adopted. The recording equipment was the geode digital high-precision broadband seismometers (1.75Hz-20000Hz), and hammering was applied to be the vibration source.

Using speed scanning method, the frequency dispersion curves were extracted from multi-channel waveform records, which inversion analysis was carried out through combining the least squares and hybrid genetic algorithm (Bai and Zhang, 1990), which the approximation error was about 2% when calculation completed.

It is indicated schematically in Fig.5 that the subsurface structure of the landslide includes four layers from surface to bottom: (1) weak and loose overburden layer near the surface, its thickness is 5-10m, and which $V_S$ is 160m/s-200m/s; (2) the second layer, its thickness is 7-10m, and $V_S$ is 200m/s-300m/s; (3) the third layer, which thickness is 17m-25m, and $V_S$ is 300m/s-400m/s; and (4) the underlying hard soil layer, which thickness is above 17m, and $V_S$ is above 400m/s. According to the borehole data nearby, these four layers could be the $Q_3$ Malan loess, $Q_3$ Lishi loess, loess-like silt and weathered sandstone. The landslide is covered by loose and thick loess layer, and it distributes uniformly along the slope.

(a) Top of the landslide.

(b) Middle of the landslide.

Fig. 5. Vs distribution under the western Yongguang landslide.

4.2 Dynamic triaxial liquefaction tests

Loess liquefaction could cause subsidence in flat terrain, and triggers soil flow or mudflow like landslide in gently slope (Bai and Zhang, 1990; Ishihara et al., 1990). Soil flow, mudslides and loess landslides induced by liquefaction may occur under the effect of low intensity earthquake and could be very destructive.

In order to analyze whether liquefaction occurred in the landslide site during this earthquake, soil samples at the trailing edge and front edge of the landslide had
been collected from two boreholes with depth of 5m, and two groups liquefaction dynamic triaxial tests were conducted on the WF-12440 torsional shear dynamic triaxial test system in the Key Laboratory of Loess Earthquake Engineering (KLLEE), China earthquake Administration.

4.2.1 Experimental equipment and test method

The test sample size was set as Ф50mm by 100mm. Test processes were divided into three steps: saturation, consolidation and cyclic shear, and a low backpressure saturation method were adopted. Considering the metastable structure and strength properties of loess, the saturated backpressure was controlled below 100kPa. Meanwhile, saturation time was set up in less than 90min in order to minimize the axis deformation in view of loess collapsible property. Using isotropic consolidation and loading axial pressure $\sigma_1$ was set based on the earth pressure related to the landslide thickness. Sine wave (1Hz) was applied to cyclic shear test, which amplitude was calculated according to the seismic peak ground acceleration of this quake. Sample consolidation and vibration liquefaction were carried out under undrained conditions. Dynamic stress, dynamic strain and dynamic pore water pressure curves were recorded during the test of cyclic shear.

The strain standard was selected as damage criterion for liquefaction of saturated soil in tests. If the pore pressure ratio $U_d/\sigma_0 \geq 0.2$ and the axial strain $\varepsilon_d \geq 3\%$, the liquefaction occurs. Based on the test results, the discrimination results of liquefaction was obtained, considering the intensity and duration time recorded by the strong motion accelerometer nearby.

4.2.2 Test results

The physical parameters of soil sample are shown in Table 1, and the calculated conditions for dynamic triaxial liquefaction tests are shown in Table 2 respectively.

| Soil samples (front edge) | Density $\rho$ (g$\cdot$cm$^{-3}$) | Dry density $\rho_d$ (g$\cdot$cm$^{-3}$) | Moisture content $\omega$ (%) | Initial void ratio $e$ |
|--------------------------|----------------------------------|-------------------------------------|-----------------------------|----------------------|
| YG-1                     | 2.01                             | 1.61                                | 24.53                       | 0.686                |
| YG-2 (trailing edge)     | 1.4                              | 1.35                                | 4.04                        | 1.007                |

| Number of soil samples | Confining pressure $\sigma_3$(kPa) | Dynamic stress $\sigma_d$(kPa) | Saturation S$_r$(%) | Rate of water content $\omega$(%) | Vibration times of failure | Rate of water content $\omega$(%) | Vibration times of failure |
|------------------------|-----------------------------------|--------------------------------|---------------------|----------------------------------|--------------------------|--------------------------------|--------------------------|
| YG-1                   | 138                               | 28                             | 98.6                | 25.01                            | 25                       | 25                             | 25                       |
| YG-2                   | 138                               | 32                             | 92.39               | 34.34                            | 3                        | 3                              | 3                        |

Figs. 6 and 7 show changes in dynamic stress, dynamic strain and dynamic pore water pressure during the liquefaction dynamic triaxial tests.

It is illustrated in Fig.6 that the dynamic stress of YG-1 sample appeared significant attenuation, double amplitude dynamic residual strain, and the dynamic...
pore water pressure increasing significantly and the pore pressure ratio $U_d/\sigma_0$ reached above 0.2. The liquefaction occurred in YG-1 sample of the front landslide edge. As shown in Fig.7, the dynamic stress of YG-2 sample attenuated in three cycles obviously, the dynamic residual strain increased significantly, and the dynamic pore water pressure increased as well. Because the dynamic stress was so large, and the development of the pore water pressure lagged behind the residual strain, that the YG-2 sample was already damaged by the large residual strain, which appeared before the pore water pressure reacted. It determines that this sample of the trailing landslide edge liquefied during the test under cyclic dynamic loading as well.

5 LANDSLIDE STABILITY ANALYSIS

5.1 Analysis method

Using the finite element software ABAQUS, the shear strength (c-tan $\phi$) reduction method, combined with the elastic-plastic finite-element method, was applied to analyze the stability of slope in this project. In condition of the given judgment conditions, the safety factor of slope was determined by adjusting the reduction factor (Che et al., 2013; Yamanaka and Ishida, 1996; Bromhead, 1994).

The initial value of the reduction factor should be set up small enough to ensure the analysis as a near-elastic problem at the beginning. Then, increasing the value gradually, the shear strength will decrease correspondingly and gradually until slope instability occurs under a certain shear strength loading. Therefore, the value of reduction factor, before the instability occurring, is the safety factor of this slope, which is the ratio of actual shear strength to virtual failure shear strength.

5.2 Loess landslide model and input seismic motion

By applying results of field investigation and high-density surface wave exploration, a method of two-dimensioned equivalent linear time history dynamic analysis was conducted for seismic response numerical simulation on the western Yongguang landslide. Calculation model is shown in Fig. 8, in which the horizontal length is 1200m, height is 410m, vertical height of slope is 170 m, and slope angle is 18° respectively.

This model was divided by four-node quadrilateral plane strain element, which included 18145 nodes and 16542 elements in total. The parameters of the model were determined by dynamic triaxial tests conducted by the KLLEE (Table 3). The water content of the first layer was set as 20% -25%, and 7% -8% in the second layer.

In the numerical calculation process, the stress tensor was calculated based on the strain tensor. The Mohr-Column model was adapted to judge whether the calculating strain could accord with the strength reduction criterion. When the stress reached the yield condition, it was adjusted to confirm the yield criterion according to plastic flow rules (Lin et al., 2013).

The horizontal acceleration time history of the Minxian-Zhangxian Ms6.6 earthquake, recorded by Min County strong motion station (18km away from the epicenter) was used as input seismic motion and was inputted at the bottom of the model from left to right in horizontal direction. Which peak acceleration is 220gal, predominant frequency spectrum is 4.5~5.5Hz and duration is 40s (Fig. 9). Viscoelastic and artificial boundaries were selected to be the lateral and bottom boundary conditions respectively.

5.3 Slope seismic response

Fig. 10 shows the acceleration distribution under seismic motion input. It indicates that the acceleration response presents an amplification effects with the increase in slope height. The maximum acceleration appears at the top and front edge, in which the maximum value is 594gal, 2.7 times larger than the peak acceleration of input seismic motion.
Fig. 11 shows the equivalent plastic strain contours under seismic motion input, in which the gray and blue parts represent the regions without deformation and after deformation respectively. It indicates that the maximum strain reaches up to 0.2, and the higher of slope has more potential to slip along the plastic strain region. The sliding surface mostly appears in the loess layer and runs through the interface of the Malan loess layer and harder soil layer below, which is consistence with results of field investigations for the western Yongguang landslide.

By reducing the strength of soil and using dynamic finite element method to analysis stability of the slope under seismic motion input. Fig.12 shows the relationship between the maximum horizontal displacement at the top of slope and reduction factors. It is indicated schematically that the safety factor of slope is 0.84, which illustrates the slope is under unstable state.

6 CONCLUSIONS

1) Seismic geological disasters induced by the Minxian-Zhangxian Ms6.6 earthquake, such as loess landslide, collapses and seismic subsidences, distributed densely in a banding region with 8km wide and 30km long, of which long axis direction was in accordance with the trends of the seismo-tectonics of this earthquake. The main reasons for wide and dense distribution of loess landslides were the coupling effects of earthquake and rainfall in the quake-hit areas, where most of overburden soils are loess and loess-like silt.

2) By dynamic triaxial tests, soil samples of the western Yongguang landslide appeared obvious attenuation in dynamic stress, a continuous increase in dynamic residual strain, and a significant growing in pore water pressure. It indicated that liquefaction occurred in soil samples.

3) Numerical simulation results indicated that acceleration of the western Yongguang landslide appeared an amplification effects with the increase in slope height, and the maximum acceleration is 594gal at the top and front edge. The sliding surface mostly appeared in the loess layer and slid through the interface of the Malan loess layer and harder soil layer below. The safety factor of this slope is 0.84 and under an unstable state.

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