A coupled excavation and rainfall-induced loess landslide in Liuwanjia Village, Yan’an China: Case study of Middle Pleistocene loess slopes

Zhongjie Fan1,2,3,5, Zhenjiang Meng4, Hongyu Ren1,2, Jianbing Peng4, Xiangjun Pei3, Linyao Dong1,2, Jun Du1,2 and Hongya Zhang1,2

1Changjiang River Scientific Research Institute of Changjiang Water Resources Commission, Wuhan 430010, Hubei, China;
2Research Center on Mountain Torrent and Geologic Disaster Prevention, Ministry of Water Resources, Wuhan 430010, Hubei, China;
3Chengdu University of Technology, State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu 610059, China;
4Department of Geological Engineering, Chang’an University, Xi’an 710054, Shaanxi, China
5Email: stephenf88@163.com

Abstract. Loess Plateau is one of the natural test sites to carry out the research of hazards induced by human activities. The loess landslide at Liuwanjia, Yan’an City, Shaanxi Province of China was observed to occur after continuous excavation and rainfall. The Liuwanjia landslide was selected as a case study and then detailed field mapping, 3D laser scanning and laboratory tests were carried out to study the formation characteristics and mechanism of this type of landslide. Based on the analysis of field investigation, excavation was a direct causing factor and the rainwater was a significant influencing factor in the formation of the landslide. The unloading fissures caused by excavation were preferential paths for infiltration of rainwater. Soil compression in the slope induced by excavation and the infiltration of rainwater played an significant role in the formation of local failure. Finally, the formation mechanism of Liuwanjia landslide has been discussed.

1. Introduction
Loess Plateau, the main loess region in China, has reported a quite high density of landslides due to the unique structural properties of loess, causing significant casualties and economic losses every year[1]. According to the incomplete statistics, a large number of catastrophic landslides were caused by engineering excavation[2]. For example, the Maohuoliang Landslide in Zhongyang city on November, 2009 reported 23 deaths and the Baoqiao Landslide in Xi’an Bailuyuan in 2011 caused 32 deaths[3]. Such catastrophic loess landslides are caused by certain external inducing factors except for the unique topographic and geological conditions. Due to the joint surface control and different soil properties, stress distribution inside the excavated slopes is relatively complex, thus making it difficult to predict excavation-induced landslides accurately. Moreover, it’s unavoidable to carry out engineering activities on slopes for living space due to terrain limitation in the mountainous Loess Plateau, such as excavation at slope toe[4]. Thus, it becomes an important issue to carry out a thorough study on loess landslides triggered by excavation.
Several approaches have been reported to study the triggering factors, formation characteristics and failure mechanism of landslides triggered by excavation[5-7]. The distinctive physical and mechanical properties of loess, such as loose texture, vertical joint development and susceptibility to collapse on wetting, have been a concern as a combined factor with the excavation that triggered landslides in some previous studies[8-9]. However, loess slopes are often observed to fail if subject to large-scale excavation conditions, but keep stable under small-scale excavation conditions[10]. It still lacks systematic study in terms of the influence of excavation scale on loess landslides. In addition, the average stress in slope reduces due to the performed excavation, the stress conditions of soil in excavation slope has its traits compared with the general loading cases[11]. Further researches are needed to be performed to explore the mechanical mechanism of excavation-induced loess landslides.

In this paper, a Middle Pleistocene loess landslide is selected as a case study. Detailed field mapping, 3D laser scanning and laboratory tests were carried out to study the formation process and mechanical mechanism of the case study. The results of this study can provide basis for the prediction and prevention of excavation-induced loess landslides.

2. Study area
Liuwanjia landslide occurred on the slope in east of Liuwanjia Village, Qiaogou Town, Baota District, Yan’an City in June, 2018. It is adjacent to the west bank of Yanhe Basin and about 5 km away from the center of Yan’an City (see Figure 1). It is originally planned to build the Intermediate Court of Yan’an City. After the slope toe was damaged, the construction team turned to excavate the middle slope, but destroyed the postmedian slope again and caused the landslide. Although the landslide buried some construction plants, it caused no injury and death because of the short sliding distance.

The Liuwanjia landslide locates in the northeast region of Yan’an City, where has the Yan River, Nanchuan River and tributaries (Figure 1). Influenced by river cutting and tectonic movement, the research area has higher elevation in west compared to northeast and surrounding areas compared to the central area. Based on the DEM with 5 m resolution of Yan’an, the landform map of Yan’an can be obtained (Figure 1). On this DEM, the Profile I-I’ presents the topographic features of the landslide region. The slope elevation ranges from 920-1187 m and the relative height difference is 270 m. The whole slope is composed of extremely steep upper, flat middle and steep bottom. The cross sectional position of the landslide is shown in Figure 1b. The elevation of slope toe is about 940 m and the elevation of slope upper is about 1000m. The slope angle differs between 27°-55°.

![Figure 1. The location and main longitudinal section of Liuwanjia landslide.](image-url)
Outcropping strata in the landslide region are mainly Quaternary loess deposits and mudstone of Jurassic deposits ($J_2$) (Figure 2). The former is mainly composed of Middle Pleistocene loess ($Q_2$), Late Pleistocene loess ($Q_3$) and Holocene loess ($Q_4$). The Holocene loess is distributed in a small region in northeast slope, while the Middle Pleistocene loess and Late Pleistocene loess have a wide and deep distribution in the research area. Several layers of ancient soils exit in the Middle Pleistocene loess. Mudstone of Jurassic deposits is observed in the newly excavated slope toe. No intensive tectonic reworking was found in the research area.

3. The landslide event

3.1. Landslide dimensions

Based on the field investigation, the landslide dimensions is revealed as follows: it toward southwest 230° caused $4.9 \times 10^5 \text{ m}^3$ slip masses (relative height: about 50 m; width: about 150 m; mean thickness: 40 m; sliding distance: 20 m). It buried $2.3 \times 10^3 \text{ m}^2$ area of the construction plant, about 2 m thickness and a total volume of $4.6 \times 10^3 \text{ m}^3$.

3.2. Terrain conditions

The three-dimensional terrain before the landslide can be drawn according to the aerial survey data in 1980s and the three-dimensional terrain after the landslide can be obtained by the 3D laser scanning, whose resolution are both 1 m. The depositional gradient is relative flat, but steepens suddenly after the excavation. This creates dynamic conditions for the slope instability. Slope profiles before and after the landslide can be gained from the corresponding three-dimensional terrains. Slope profiles before the excavation, after the slope toe excavation, after the middle slope excavation and after the landslide were compared (Figure 3).
Figure 3. Three-dimensional terrain prior to excavation and after Liuwanjigou landslide occurrence.

3.3. Triggering factors

Figure 3 indicates that a large-scale of excavation have been carried out before the landslide occurrence. In order to reveal the influence of excavation, the historical images of Google Earth were used to analyze the excavation process (see Figure 4). The slope toe of the landslide started to be excavated one year prior to the occurrence of the landslide. In addition, the sectional change of the Liuwanjia landslide in the process of excavation can also be illustrated in Figure 5. It can be seen from Figure 4 and 5 that the excavation was firstly executed at the toe of the slope (Figure 4b). The excavation face was observed to bloat outward which indicated a signal of failure trend. In the second stage, excavation was carried out in the middle part of the slope, which kept the slope toe from further instability (Figure 4c). A steep slope (>60°) was created above the excavation site as a result of a large-scale excavation on the middle slope. With continues excavation, the steep slope was observed to slide in a sudden and buried a part of the construction plant (Figure 4d and Figure 5).
As the entire excavation process lasted almost one year. The influence of rainfall was also taken into consideration in this analysis. According to the meteorological date from Yan’an Meteorological Station (Figure 6), the maximum monthly precipitation is 223 mm in the year of 2018. As shown in Figure 6, the precipitation increased markedly from April to June. It indicates that the rainfall, coupled with excavation, has played an significant role in the formation of the Liuwanjia landslide.

4. The formation mechanism of the Liuwanjia landslide

A series of drained reduced triaxial compression (RTC) tests have been conducted to analyze the mechanical response of the soils in the slope under excavation (Figure 7). The tested soil samples are Pleistocene loess collected from the Liuwanjia landslide. It should be noted that the soil samples in the RTC tests were preliminarily consolidated to $K_0$ state, and then the stress was adjusted to simulate the unloading conditions under excavation.

As shown in Figure 7a, the soils manifested strain softening characteristics with respect to the increasing axial strain. Strain softening is regarded as an important cause of progressive failure of soil slopes[8], indicating that excavation-induced loess landslides are prone to form progressively. In addition, Fan et al. have measured the water permeability of the loess in the study area[3]. The results show that the loess had a very poor water permeability and the rainwater can only permeate into a quite limited depth of the loess slopes. It indicates that some preferential paths for infiltration, such as the unloading fissures in loess slopes caused by excavation, should appear when the loess slopes were subjected to rainfall and excavation at the same time. Thus, the preferential paths for infiltration were the prerequisite in the progressive formation process for the loess landslides triggered by excavation and rainfall.
The entire process of excavation consists of a circulation of slope cutting period and the lockout between each slope cutting period. The results of the RTC tests showed that the volumetric strain of the soils tend to be compression at the beginning of the tests (Figure 7b), indicating that the soils of the Liuwanjia landslide were compressed at the beginning of each excavation period. Notably, if the rainwater permeates into the loess slope through the unloading fissures in the same time and therefore increase the saturation of the soils nearby, the aforementioned compression of the soils induced by excavation would cause excess pore-water pressure in the soils. As a result, local failure would be generated and then extend to a general failure.

Based on field investigations and the analysis of laboratory tests, the formation process of Liuwanjia landslide can be summarized as follows.

1) Slope toe excavation began, causing soil creeping and lowering slope stability
   During the excavation of the slope toe, the original slope gradient is changed, which changes the internal stress field accordingly. As a result, the slope toe forms a shearing strain concentration area and deforms, finally causing local deformation failure in the slope toe.

2) Middle slope excavation began, increasing slope stability
   The post-slope toe is cut immediately, which weakens the sliding force and stops further instability of the slope.

3) Middle slope excavation continued, steepening the slope face
   The continuous middle slope excavation steepens the slope gradually and changes the distribution of stress in the slope. The tractive deformation of slope toe increases the tensile stress at slope top and develops several tension fissures (unloading fissures) near the slope top. The development of tension fissures is related with over intensive tensile stress and loess joint development. During this period, slope deforms homogeneously.

4) Local failure formed and extend to a general failure
   Influenced by excavation and rainfall, local failure formed in the loess slope and extended backward and upward continuously, accelerating the slope deformation. The local failure caused a traction zone[12]. This traction zone destroyed the slide-resistance zone at the rest of the slope and finally caused landslide initiation.

5) Rainfall continuously infiltrated and caused slip mass deformation
   According to the field survey, the slip mass was observed to deform significantly after the landslide initiation, which has strong relations with the rainfall. With the infiltration of rainwater along the cracks of the slip mass, the transient seepage field inside the slope changed and thus decreased the matrix suction of soil mass and form hard spots in the strain softening zone[13]. Consequently, the sliding mass deformed continuously.

5. Conclusions
Detailed field mapping, 3D laser scanning and drained RTC tests were carried out to study the formation process and mechanical mechanism of the Liuwanjia landslide subjected to continuous excavation and rainfall. The influence of triggering factors were analyzed based on field investigation. Results show that both internal and external dynamic conditions were important influencing factors of the formation of Liuwanjia landslide. Topographic features determined the main direction of landslide. Geological condition was the basis of internal slope failure. Human activities were the key cause of slope instability. Rainfall was an important influencing factor of landslide stability.

The formation and evolution of Liuwanjia landslide was the collaborative consequence of internal and external factors. The poor water permeability of loess was internal factor and slope excavation was external factor. Excavation was a direct causing factor that changed internal stress distribution and induced unloading fissures in the slope. The overall formation process of the Liuwanjia landslide indicates that the slope deformation is a gradual process from local failure to general failure rather than an instant overall failure. Results of RTC tests shown that the soil compression in the slope induced by excavation can generated local failure in the slope when coupled with the infiltration of
rainwater along the unloading fissures. Thus, the rainwater was a significant influencing factor in the formation of Liuwanjia landslide.

The formation process of Liuwanjia landslide can be described as follows: slope toe excavation begun→middle slope excavation and stability increased→excavation continues and slope steepened→fissures developed on slope top→rainfall infiltration→local failure generated and extended→shear failure zone affect the slide-resistance zone→slide-resistance zone failed and slope lost stability→rainfall infiltration caused continuous slope deformation.

In conclusion, prompt support for the loess slope under excavation shall be paid enough attentions in the practice. Some countermeasure, such as displacement monitoring, prediction and calculation of potential sliding surface, should be carried out before excavation, which can increase the engineering safety during construction.

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