Landslides (2020) 17:677–686
 DOI 10.1007/s10346-019-01342-0
 Received: 3 October 2019
 Accepted: 23 December 2019
 Published online: 2 January 2020
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The loess landslide on 15 march 2019 in Shanxi Province, China

Abstract On 15 March 2019, a fatal deep-seated landslide occurred at the village of Zaoling in Xiangning County of Shanxi Province, China. Extending to an area of about 120 m by 85 m, with an estimated displaced mass volume of 72,000 m³, the landslide left 20 people dead, 13 injured, and 8 buildings destroyed. There were no precursory signals prior to the event, and usual triggering mechanisms for a landslide were absent. Investigation conducted immediately after the incident revealed that the landslide was initiated in a 1.0 to 1.5-m thick-softened layer located at 40 m depth along the contact between the loess and interbedded paleosol layer. This softened layer was highly saturated due to the perched water on top of the relatively impervious paleosol layer and became a critical weak zone since the shear strength of loess is very sensitive to water content. We suggest that the perched water originated from extensive long-term unsaturated seepage of rainwater and local rapid percolation along preferential channels such as sinkholes and root network. The Zaoling landslide confirms that unlike most landslides in non-loess areas, loess landslides can occur without identifiable triggering events. They can result from gradual build up of instability due to slow (in the span of hundred years) accumulation of deep soil water. Based on the lessons learned from this landslide event, suggestions are given for the planning of urban and rural development in loess areas. Due to the fact that the process leading to the development of such a landslide is largely concealed, further research should be aimed at gaining a more thorough understanding of the mechanism of this landslide type.

Keywords Loess landslide · Perched water in loess · Paleosol · Long-term seepage

Introduction

At 18:05 on 15th of March 2019 UTC + 8 (10:05 15 March UTC), a deep-seated loess landslide occurred in Zaoling Village of Shanxi Province, China. Occurring without precursory signals, the landslide covered an area of about 120 m by 85 m with total volume of displaced mass about 72,000 m³ (Fig. 1). After nearly 7 days of intense rescue operation, it was confirmed that the landslide caused 20 deaths, 13 injuries, and the destruction of 4 two- to four- story and 4 single-story buildings. Thus, this landslide is recognized as one of the most catastrophic events in recent years in the Loess Plateau of China (LPC), consequently attracting wide attention from both the public and the academic community.

The Zaoling landslide occurred without the usual triggers like heavy rainfall, earthquake, and volcanic and anthropogenic activities. In this paper, we present the cause of this landslide based on field and laboratory investigations as well as literature survey. Section 2 presents the characteristics and setting of the landslide, and then in Section 3, we give the characteristics and mechanical parameters of the strata in the landslide site. Section 4 discusses in detail the mechanism by which the slope may have failed, after

which summary and recommendations followed. We believe that this study can contribute to further understanding of the mode and mechanism by which slope fails in relatively dry areas, in particular in loess regions.

Characteristic and setting of the Zaoling loess landslide

The Zaoling loess landslide occurred in the margin of a residual loess platform (Fig. 1a). The DJI multi-rotor UAV (unmanned aerial vehicle) was employed in the field investigation of the present loess landslide. This provided a three-dimensional topographic model of the landslide site with a resolution of 2.5 cm (Fig. 2). Compared with the traditional survey and exploration methods, the modern UAV technology offers low cost, ease of operation, high efficiency, high resolution, fast and wide coverage, and fast access to difficult sites.

It can be seen that the landslide has a round-back armchair shape, with its boundaries forming an irregular trapezoid. The azimuth of the main sliding direction is 340°. The main scarp is 19–26 m high, approximately 90 m wide, and inclined by 60°–65° (Fig. 1c). The displaced mass extends from an elevation of 855 m asl down to the bottom of the valley at an elevation of 804 m asl (Figs. 1b and 2), where a distinct fan-shape deposits developed (Fig. 1d). As reckoned from the pre-failure slope surface, the maximum depth of the rupture surface is about 28 m. Following the unified loess landslide classification system, the Zaoling loess landslide is categorized as a rotational slide (Li and Mo 2019). A three-story strip-footed concrete-brick structure building remained standing on the 30 m wide and moderately sloping (15°) platform of the main landslide body, which moved about 20 m and 25 m in the horizontal and vertical directions, respectively.

The pre-failure morphology of the landslide site based on a survey conducted in 2018 is shown in Fig. 3a, where it can be gleaned that the area was characterized by convex slopes with average height of 70 m and inclination of 45°. Several rills developed on the slope surface. At the toe, a steep slope section about 40 m wide is found. Multi-temporal Google Earth images show that there have not been obvious changes in the geomorphology of the area in the last 5 years prior to the landslide event (Fig. 3b–d).

The landslide site is in the north temperate zone with a semi-arid continental monsoon climate. Based on climatological data from the weather station at Zaoling Village over the last 18 years (2000–2018), the mean annual air temperature in the area is 10.8 °C. The month with the highest average temperature (23.7 °C) has been July. January has been the coldest month with an average temperature of −4.0 °C (Fig. 4a). In early November, the daily minimum temperature drops below zero, causing the soil to freeze, and the maximum freezing depth is 75 cm in winter. In the winter–spring transition from March to April, the temperature gradually increases back to above zero. The annual average rainfall is 541.4 mm, and the summer rainfall (June to September)

Fig. 1 General view of the 3.15 Zaoling loess landslide: (a) location; (b) overview; (c) main scarp; (d) deposits (photos taken on 18th, March, 2019)

accounts for approximately 70% (Fig. 4b). The maximum monthly rainfall as recorded in the last 18 years is 309 mm, which occurred in July 2013. The 2 months (from 1 January to 15 March 2019) prior to the landslide event have been dry, with the cumulative rainfall of only 0.1 mm as recorded at Zaoling Village Weather Station. According to previous studies in similar places, the depth at which soil water content is significantly affected by evaporation is generally no more than 1 m (Li et al. 2013).

The landslide area is located at the southeastern margin of the Ordos block. As shown in Fig. 5, the nearest active fault to the landslide is the Hancheng fault, about 10.5 km away. According to the records by the Shanxi Seismic Monitoring Station, there were seven earth tremors in the landslide area in the half month prior to the landslide event. The Hancheng fault was associated with three tremors with magnitudes of -0.3 and -0.2 (both occurred on 2 March) and 0.5 (4 March). The other four tremors with magnitude of -0.5 to -0.1 occurred 41–71 km away from the landslide site on 2nd to 6th day of March in Fenwei graben. This suggests that the geological structures and earthquakes did not play immediate contributory role to the landslide.

Strata characteristics and mechanical properties

Outcrops and boreholes (locations in Fig. 2) reveal that the landslide site is mainly underlain by the late Pleistocene Malan loess (Q_3) and middle Pleistocene Lishi loess (Q_2) (Fig. 6). The

strata dip outward at an angle of 3° . The silty Malan loess composed the upper 10 m of the slope and is characterized by light yellow color and the presence of macropores and well-developed vertical cracks. The lower part of the slope is made up of silty Lishi loess with intercalations of reddish brown, silty clay paleosol layers. Within the depth of the boreholes, three paleosol layers were encountered. The toe of the rupture surface is about 45 m below the crown. About 5 m above this depth, a 1.0–1.5 m thick, wet, softened layer (SL) is found along both sides of the contact surface between L_5 loess layer and S_5 paleosol layer (Fig. 6).

According to the recent reports (Niu et al. 2009), the uppermost aquifer in the landslide region is located within a thin (usually < 2 m) locally saturated and discontinuous layer of gravels between the loess-paleosol sequence (60–150 m thick) and the bedrock (Permian mudstone with sandstone layers). The perched water was encountered in all boreholes that reached the SL (H1, H4, H6, and H7 in Fig. 2). There was no long-term monitoring of seasonal changes in the perched water level in this site. The monitoring data from other locations in the LPC with similar geological conditions show that the changes of such perched water levels are minimal under natural precipitation (Li et al. 2000; Hou et al. 2018).

Laboratory testing was conducted on samples from boreholes (H1, H2, H3, H4, H6, H7, and H8 in Fig. 2) that were drilled from

Fig. 2 Elevation model of the landslide site and layout of the field investigation

the top of the residual platform to a maximum depth of about 50 m (Fig. 7). Laser particle size analysis shows that the percentages of fines (< 0.075 mm) in both the loess and paleosols are greater than 94%. The percentage of clay-sized particles (< 0.005 mm) in loess soils is 21–27%, while in paleosols, it is greater

than 32%; S5 in particular has a mean clay content value of 36%. The dry unit weights of the loess layers are generally lower than that of the paleosol layers, with the former having a value ranging from 14.84 to 15.07 kN/m³, while the latter ranges from 15.60 to 15.74 kN/m³. The water content (w) of most of the strata is no more

Fig. 3 Topography of the slope before failure: (a) overview; and (b)–(d) Google Earth images showing local features of the slope

Fig. 4 18-year average monthly temperature (a) and rainfall (b) in the landslide area

than 18% (saturation degree no more than 70%) and does not exceed the plastic limits, while the earlier mentioned softened layer (Fig. 6) has an average water content of 24.3% and saturation degree of 83.5%. Shear tests show that the softened layer has a much lower strength with a friction angle (ϕ) of 10.6° and cohesion (c) of 33.2 kPa, compared to other strata with an average ϕ of 23.5° and c of 41.1 kPa.

Previous studies have shown that permeability coefficient of the paleosols are at least one order of magnitude lower than that of the loess layers (Gvirtzman et al. 2008; Li et al. 2013; Xing 2013; Hua and Zheng 2018). Our test results are in good agreement with previous studies as the paleosol in the landslide site possesses a permeability coefficient of 5.3×10^{-6} cm/s, which is much lower than that of the loess soil (5.8×10^{-5} cm/s).

Failure mechanism

The deep-seated landslides often develop in complex strata, with long-term gestation and diverse triggering factors (Malamud et al. 2004; Larsen et al. 2010; Gariano and Guzzetti 2016). These pose difficulties in investigating such landslides. According to previous research, heavy rainfall, earthquakes, and volcanic and anthropogenic activities are usual triggers for deep-seated landslides (Malamud et al. 2004; Gariano and Guzzetti 2016; Li and Mo 2019). Most of the deep-seated loess landslides in the world (other than LPC) are reported to be triggered by rainfall (Bazynski and Frankowski 1977; Verachtert et al. 2013; Kovács et al. 2015; Zhang et al. 2015). On the LPC, deep-seated loess landslides are however known to be triggered by a variety of processes, e.g., rainfall (35%),

Fig. 5 Regional geologic map

Fig. 6 Geological profile of Section I-I' in Fig. 2

anthropogenic activities (30%), and earthquakes (11%) (Zhang and Li 2011; Xu et al. 2017). The remained (24%) deep-seated loess landslides have not been attributed to these triggering processes, such as the landslide presented in this paper.

From the scientific viewpoint, the Zaoling landslide is highly interesting in that its cause is not immediately apparent as the days and months prior to the event were dry, and no strong earthquake occurred in the landslide area. There were no anthropogenic activities (e.g., agricultural irrigation, excavation and urban construction). In other words, the usual triggering mechanisms for a slope failure were absent. Thus, as opposed to an event-triggered (e.g., heavy rainfall event, earthquake event) landslide, the Zaoling landslide was a result of gradual build up of instability.

The original slope is convex-shaped, and the foot of the slope has steepened due to lateral erosion of gully floods (Fig. 3). The outward and slightly downward dipping strata must have enabled the perched water to migrate slowly along the top of paleosol towards the landslide site as well as favor the formation of the rupture surface (Fig. 6). It was in the winter-spring transition season, when the soil started to thaw. Thawing must have destroyed the structure and weakened the surficial layer of slope

soil, while at the same time contributed water for infiltration. This effect, however, should not be significant since the maximum frozen depth in winter is only 75 cm and is within the evaporation zone (< 1 m). The buildings on top of the slope exert an estimate load of 20–80 kPa. These buildings, however, had been built 12 years ago, and no settlements or displacements of the buildings had been observed. As such, they could not be the direct cause of the landslide.

The clue as to the main cause was found in the boreholes, where it was revealed that the rupture surface developed in the SL (softened layer) along the contact surface of the L5 loess and the S5 paleosol layers (Fig. 6). The S5 paleosol layer acted as an aquitard as it is highly dense and relatively impermeable, causing the SL to be perched with water (Fig. 7). This caused the softened layer highly saturated with low shear strength as the shear strength of loess is sensitive to water content (Derbyshire et al. 1994; Li 2018; Yates et al. 2018). This layer finally became a critical weak zone where failure of the slope was initiated. Perching of water on a relatively impermeable paleosol layer as a cause of loess slope failure has been observed in several places in the LPC (e.g., the 2010 Liulin landslide in Fig. 8).

Fig. 7 Strata structure and soil properties of the slope

Fig. 8 Perched water accumulating above the paleosol layer induced a loess landslide in Liulin County, Shanxi Province in January, 2010

The above situation then leads to the question: where did the perched water come from? Studies showed that recharge sources of deep soil water are mainly rivers, irrigation, and rainwater (Gee and Hillel 1988; Gates et al. 2011; Li et al. 2017). We conducted a geomorphology and catchment analyses of Zaoling and surrounding area based on a 3.2 m resolution digital elevation model (DEM). As shown in Fig. 9, the Zaoling residual platform is surrounded by a V-shaped gully to the north and two confluent gullies to the west and south. These gullies are ephemeral that briefly receive runoff from vicinity during and following a period of rain. The softened layer is about 20 m above the bottom of these gullies. Thus, these gullies could not be the source of the perched water. Investigation of the area reveals that agricultural and domestic water consumption and discharge on this residual platform

are limited as there is no agriculture irrigation and the domestic water is in a time-limited supply manner. Therefore, the only plausible mechanism for the recharge of the deep-seated perched water is through long-term, gradual downward rainwater migration.

Previous studies showed that rainwater can migrate through thick loess-paleosol strata to recharge deep soil water (Li et al. 2000; Gvirtzman et al. 2008). The strata above the water-resisting layer can be divided into three zones from the top to bottom (Fig. 10): (a) surface zone, (b) transition zone, and (c) accumulation zone (Gee and Hillel 1988; Zhang et al. 2014; Hou et al. 2018).

The surface zone on the LPC varies in thickness from 1 to 4 m, depending upon soil properties and precipitations (Li et al. 2013; Hou et al. 2018). The water content of the surface zone is sensitive

Fig. 9 Catchments of the landslide area

Fig. 10 Variation of water content with depth in loess-paleosol strata: (a) field monitoring in Zhengning County of Gansu Province (Zhang et al. 2014); and (b) field observation

to climate factors such as rainfall and evaporation, and varies in close correspondence with the infiltration of rainfall (Fig. 10) (Li et al. 2000; Zhang et al. 2014). Rainwater migrates downward in this zone mainly by means of saturated seepage (water flows through micro/macropores, joints, and cracks) and unsaturated seepage (water infiltrates through micropores) (Xu et al. 1993). During rainfall events, the saturated seepage occurs within the superficial layer which is normally about 20 cm or deeper depending on the existence of macropores (e.g., plant root holes) and/or cracks (Liu et al. 2008; Ghestem et al. 2011). After rainfall, the saturated seepage ceases and the water that infiltrates beyond the evaporation depth (<1 m) continues onto a long-term downward migration via unsaturated seepage (Li et al. 2016).

The transition zone is located between the surface and accumulation zones. Due to its depth, the transition zone is hardly

affected by climatic factors, and water content variation in this zone is limited throughout the year. Rainwater slowly migrates downward via unsaturated seepage into the transition zone (Li et al. 2000; Hou et al. 2018). The downward-moving rainwater can be impeded where there is presence of relatively impervious layer such as paleosol layers. This results in the formation of water accumulation zone as shown in Figs. 8 and 10 (Derbyshire 2001; Li et al. 2013).

Based on historical meteorological data (Year 2016–2018) in Zaoling Village, there were three to six rainfalls with intensity greater than 25 mm/day per year (mainly in June, July and August). These rainfalls could lead to an infiltration depth usually exceeding the evaporation zone (Li et al. 2013; Zhang et al. 2014). The rainwater from these events could therefore have been the recharge source of the deep soil water.

Fig. 11 Sinkholes around the edge of Zaoling platform: (a) spatial distribution; and (b) typical features

Zaoling platform has a typical thick loess-paleosol strata, in which three paleosol layers, S₃, S₄, and S₅, are found located at depths of 26 m, 32 m, and 40 m with average thickness of 1.8 m, 2.5 m, and 4.1 m, respectively. These layers have clay contents of 32%, 32%, and 36% and dry density of 1.560 g/cm³, 1.572 g/cm³, and 1.574 g/cm³, respectively. Among these three layers, S₅ is the thickest and densest, and is therefore the most effective in retarding water to develop an accumulation zone.

Besides the short-term saturated seepage and long-term unsaturated seepage of rainwater, sinkhole and vegetation were also found to contribute to deep-water accumulation in loess-paleosol strata (Nimmo 2012; Derbyshire 2001; Li et al. 2017). Loess

sinkholes result from mechanical and chemical erosion by short-term water percolation (Lukić et al. 2009; Peng et al. 2017) and are well developed along edges of loess platforms (Fig. 11). Most sinkholes on the LPC have diameters of 1–5 m and depths of 2–10 m (Peng et al. 2017).

During rainfall, sinkholes collect the surface runoff from its vicinity. The collected water migrates radially to the sub-ground through the channel network, which usually develops underneath the sinkholes. Due to relatively weak evaporation, soil at the bottom of sinkholes keeps moist for quite a long period, resulting in long-term infiltration of rainwater (Lukić et al. 2009; Li and Liu 2014). This is also why vegetation in sinkhole is well developed

Fig. 12 Mitigation of rainwater to form the accumulation zone in the Zaoling landslide site

Fig. 13 Residential areas located: (a) on the top of loess slopes (Xiangning of Shanxi Province); and (b) at the toe of loess slopes (Jixian of Shanxi Province)

(Fig. 11b). Thus, the sinkholes become a kind of preferential channels for recharging deep soil water (Derbyshire 2001; Tang et al. 2015).

Vegetation on slope surface enhances rainwater infiltration in several ways. (1) The canopy and litter layers dissipate the rain-drop energy to prevent the slope surface from compacting to form crust which impedes water infiltration (Man and Lin 1989; Dunne et al. 1991). (2) Vegetation canopy and fallen leaves act as sponge storing rainwater and reducing evaporation (Huang and Yan 2018). (3) Vegetation increases roughness of slope surface, reducing the velocity and amount of runoff (Man and Lin 1989; Dunne et al. 1991). (4) Root holes intersecting each other form a network favoring water percolation (Ghestem et al. 2011; Huang and Yan 2018). Field monitoring showed that slopes with vegetation coverage similar to slopes in Zaoling landslide area could receive rainwater 30% more than the bare slopes (Shen et al. 2006).

Based on the foregoing discussion, the extensive seepage of rainwater together with the contribution of sinkholes and vegetation led to the accumulation of water on top of the relatively impermeable S₅ paleosol layer (Fig. 12). The perched water made the accumulation zone a softened layer, leading to the failure of the slope.

Summary and recommendations

The Zaoling landslide is a typical deep-seated loess landslide that developed in thick loess strata of the LPC. This deep-seated landslide occurred without signs of surface deformation that could be observed on the structures or natural slopes in the area. The number of fatalities was particularly high for the fact that the failure took place suddenly at the time when most people were inside.

Based on intensive investigation including 3D terrain analysis, field survey, and laboratory testing and literature review, we found that this landslide was initiated in the softened layer along the contact between L₅ loess layer and S₅ paleosol layer located at 40 m depth. Owing to the perched water on top of the relatively impervious S₅ paleosol layer, this softened layer is highly saturated, and therefore, weak as the shear strength of loess is sensitive to water content. The deep perched water developed from extensive long-term seepage of rainwater and local rapid infiltration along preferential shortcuts such as sinkholes and vegetated slope surface.

The Zaoling landslide confirmed what has been observed from other landslides in the LPC that, unlike most landslides in non-loess areas, loess landslides can occur without obvious triggering events. As in Zaoling, they could result from gradual build up of instability due to very slow (in the span of hundred years) accumulation of soil water. Previous studies in similar loess-paleosol strata showed that the average infiltration rate was about 30 cm/a (Lin and Wei 2006; Baran et al. 2007; Hou et al. 2018). It would thus take about 130 years for rainwater on top of the platform to pass through the 40-m thick loess strata to reach the S₅ paleosol layer in the Zaoling landslide.

Loess are intermittently distributed in arid and semiarid regions in the mid-latitudes of Northern and Southern hemispheres, accounting for about 6% of the global land surface area (Li et al. 2019). Loess regions are home to billions of people and are among the main geological environments that are crucial for human survival and development. The LPC has the thickest and most complete loess strata and faces the most frequent loess geohazards in the world (MNR 2016; Li et al. 2019). With a population of more than 100 million (NDRC et al. 2010), a large number of residential areas need to be located next to the slopes due to the lack of flat space (Fig. 13). According to the open-file reports issued by the local government, there are 36,945 landslide hotspots in LPC, accounting for 12.8% of the total number (288,525 as of 2015) in the whole nation (MNR 2016). It is therefore imperative to have a clear understanding of the different mechanisms by which slope fails in loess deposits so that proper preventive and mitigation measures can be put in place.

Landslides induced by deep perched water like that in Zaoling is difficult to predict because they develop very gradually through a process that is largely concealed and occur without warning signs. As this mechanism of slope failure is dominant in the LPC, and possibly in other dry loess regions, it is important that more attention is paid to it. In areas where conditions similar to that in Zaoling are suspected, medium-deep drilling may be implemented to check out possible weak layers. Systematic investigation of the recharge and discharge of surface and groundwater may also be necessary to understand seepage conditions. Finally, a new numerical model that comprehensively accounts for all the conditions and elements that come into play in the process may need to be developed.

Acknowledgments

The authors are grateful to the students in the group, Liu Bo, Guo Dingyi and Ma Tianyu, for their help in laboratory tests and thankful to Dr. Mary Antonette Beroya-Eitner and Prof. Adnan Aydin for reviewing and editing the manuscript.

Funding information

This study was supported by the Key Program of National Natural Science Foundation of China (No. 41630640), Major Program of the National Natural Science Foundation of China (No. 41790445), and National Natural Science Foundation of China (No. 41877276).

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