On the Mechanism for a Long-Travel Loess Landslide Triggered by the 1920 Haiyuan Earthquake in China

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Abstract

During the 1920 Haiyuan earthquake, numerous catastrophic landslides were triggered in the loess area on the northwest of China, killing about 200,000 people. Among them a landslide occurred in Dangjiacha area of Xiji County, Ningxia (termed as Dangjiacha landslide in this paper) was investigated in detail. This landslide originated on a slope of about 20 degrees, and the displaced soil mass from the source area traveled about 3200 m, damming a valley. Field survey revealed that standing groundwater exists within the landslide on the source area, and the loess on the source area was in great void ratio. Therefore, it is reasonable to infer that liquefaction failure within the water-saturated loess layer was the main reason for this long-travel landslide, rather than the assumption that these earthquake-triggered rapid landslides were due to the suspension of silt in air. To examine this assumption, ring shear tests were performed on the samples taken from the source area of Dangjiacha landslide. Undrained ring shear tests on the water-saturated loess soils applied to monotonic/cyclic shearing showed that the loess soil is highly liquefiable, and shear failure can be triggered during cyclic loading. In additional, undrained ring shear tests had also been performed on the dry sample "saturated" by air to examine whether landslide with high mobility can be triggered or not, with the involving of air. The results revealed that the increase of pore-air pressure with increase of shear displacement was small such that no significant reduction in the shear resistance was observed.

Keywords: Earthquake, loess landslide, long-travel movement, liquefaction, groundwater, air-pressure

Introduction

Rapid landslide with large runout distance is a challenging geo-disaster problem to both geologists and geotechnical researchers. Many researches had been performed in attempt to have a better understanding on this kind of landslide. Although different assumptions were raised for the mechanism of different landslides, they can be basically summarized as five categories (Baerbel K. Lucchitta, 1979): (1) flow involving debris and air (Varnes, 1978; Kent, 1966); (2) flow involving debris alone (Howard, 1973; Hsu, 1975); (3) flow involving debris and water (Plafker and Erickson, 1978); (4) sliding on a cushion of air (Shreve, 1968); and (5) sliding on a cushion of steam (Habib, 1975).

During the 1920 Haiyuan earthquake (M = 8.5), a great deal of catastrophic landslides was triggered in the loess area on the northwest part of China (Fig. 1), killing about 200,000 people (Close and McCormick 1922), and forming many landslide-dams (Zhu 1989a, b; Derbyshire 1991; Derbyshire etl 2000; Dijkstra et al 1994). By now, many researches have been performed and different assumptions had been raised for better understanding these earthquake-induced loess landslides. Basically, it has been widely accepted that earthquake-induced landslides mainly are caused by the soil liquefaction (Seed, 1966). For example, Ishihara et al. (1990) investigated those large-scale landslides triggered by an earthquake in the suburb of Dushanbe, the capital of the Tajikistan Republic (January 23, 1989, M = 5.5), and concluded that liquefaction occurred in those landslides mass due to the high collapsibility of the porous loess soil. However, for those loess landsides triggered by the 1920 Haiyuan earthquake, different assumptions had been raised in attempt to interpret the rapid long-travel movement of many catastrophic landslides. Some researchers believed that these landslides were due to the suspension of silt in air, i.e., displaced loess sliding on a cushion of air (Ter-Stepanian 1998). Keefer (1984) studied the landslides triggered by 40 major earthquakes throughout the world and classified

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Fig. 1. location of loess landslides area on the map of China

them in 14 categories. In his classification loess landslides were classified as "Rapid Soil Flows". Varnes (1978) also regards these landslides as dry loess flow in his landslide classification, acknowledging the air's involving in the movement. This explanation sounds reasonable, because the loess plateau is in a semi-arid environment, and loess is rich in great void space. In addition, it had also been pointed out that soils composed mainly of fine grains are not considered to liquefy during earthquakes under any kind of cyclic loading (Yoshimi, 1991). However, recently Zhang et al (1995) and Zhang & Sassa (1996) performed a detailed study on the geomorphologic characteristics of these loess landslides. They found that slopes in the source areas of these loess landslides were gentle and most landslides occurred on the concave slopes. Hence, he inferred that these loess landslides with high mobility were mainly resulted from liquefaction phenomena during the earthquake.

Therefore, from the above investigations, it can be concluded that the understanding on the rapid long-travel movement of these loess landslides remains unclear. Nevertheless, recently we had a detailed survey on a large scale landslide occurred in Dangjiacha area, Xiji county, Ningxia (Hereinafter, we call this landslide as Dangjiacha landslide) that occurred during the 1920 Haiyuan Earthquake. Laboratory experimental examining on the loess samples taken from the source area of this landslide had also been performed. This paper intends to show some field survey and laboratory findings, evidencing that liquefaction phenomenon occurred on the groundwater-saturated loess layer should be the main reason for these loess landslides with rapid large runout movement.

Dangjiacha Landslide

Locating approximately 25 km southwest of Xiji city, Dangjiacha landslide was one of the most catastrophic ones triggered by the 1920 earthquake. Fig. 2 shows an airphoto of the landslide area. The landslide was composed of two big blocks, and both of them originated on the same side of a mountain ridge. In 2002 and 2003, we surveyed this landslide. Using a total station, the longitude sections along line A-B-C-D and A'-C' had been measured and presented in Fig. 3. The landslide mass of the left side block originated on a slope of about 20 degrees, and almost all of them slip out of the source area, while those from the right side block moved certain of distance, and stopped. The block on the left side of the landslide (hereinafter term as left side block) has a maximum width of about 520 m, and length of 2000 m, while the one on the right side has a maximum width of 400 m, and length of 1500 m. The volume of displaced landslide mass from these two blocks was estimated as 1.5×10^7 m^3. Most of the displaced landslide mass moved southwards for a distance of 2000 m, before turning westwards for a further 1100 m and damming the whole valley. The impounded lake is about 5 km long and 380 m wide, the largest one among the recorded impounded lakes formed by the same earthquake event.

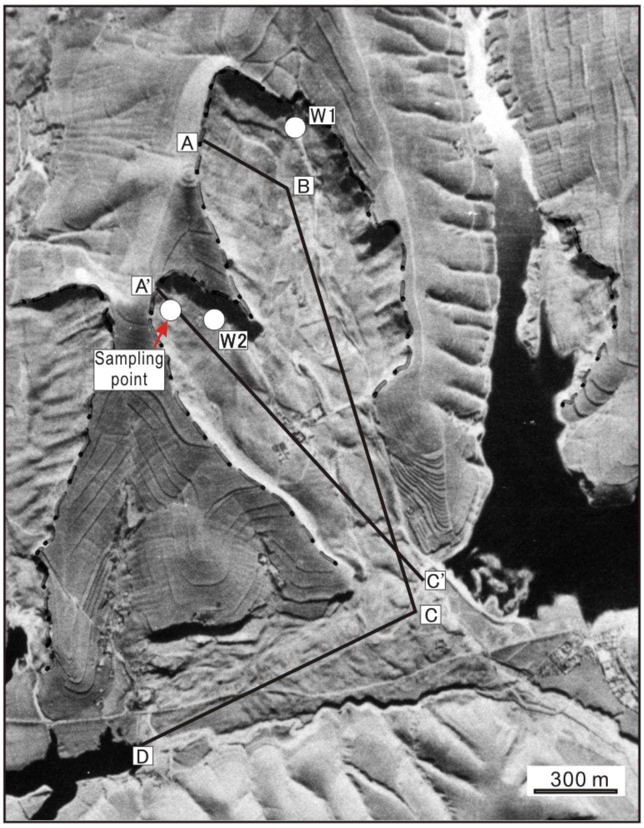

Fig. 2. Dangjiacha landslide in Xiji, Ningxia, triggered by the 1920 Haiyuan Earthquake

It was clarified that standing groundwater exists within the landslide on the source area (see Points W1 and W2 in Fig. 2), even 80 years after the 1920 earthquake. Point **W2** is a well supplying water for several families with a water table 22 m below the present ground surface; while **W1** is a very shallow well. To examine the location of aquifer, we dug a pit near **W1**. Groundwater appeared when the depth reached about 2 m below the ground surface (Fig. 4c). It is worth noting that the digging was performed on the winter time (March 20, 2005), and a 30 cm thick frozen layer was found about 20 cm below the ground surface, indicating the high water content nature. Sample was taken from the main scarp of right slide block (See Fig. 3a).

Although the ground water state is different from that of 80 years ago due to the changes in climate and topography, it is reasonable to believe that the displaced landslide mass was rich in groundwater before the earthquake. In addition, the in situ soil layers on the source area were in great void ratios ranging from 1.13 to 1.31, indicating the high liquefaction potential during earthquake. Therefore, it is reasonable to infer that liquefaction failure occurring within the water-saturated loess layer was the main reason for this long runout landslide. This is demonstrated by the following ring shear test results.

Undrained ring shear test results

Characteristics of loess sample

Theoretically, it is desirable to use the undisturbed samples to study the strength variation; here disturbed samples were used in all the tests, due to the difficulties in sampling and transportation. These samples were taken from the source area of right slide block. The samples ranged from fine sand to silt sizes with a specific gravity of approximate 2.72. The grain size distribution is illustrated in Fig. 5. As shown, the sample mainly consists of silt-size grains. The in-situ void ratio was 1.17 near the sampling area.

Ring shear apparatus

Ring shear apparatus has been widely used in the analysis of slope stability due to its advantage of large shear displacement (Bishop et al 1971; Sassa 2000). Recently, a series of undrained ring shear apparatus (DPRI-4, 5, 6, and 7) had been developed and improved in Disaster Prevention Research Institute (DPRI),

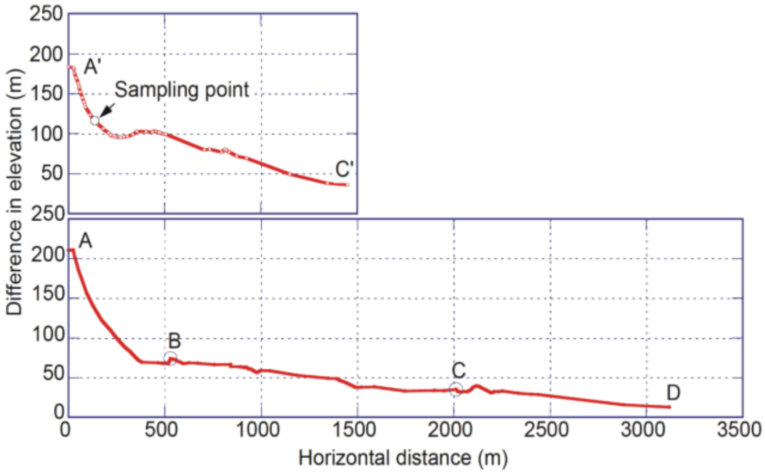

Fig. 3. Longitudinal sections of the Dangjiacha Landslide

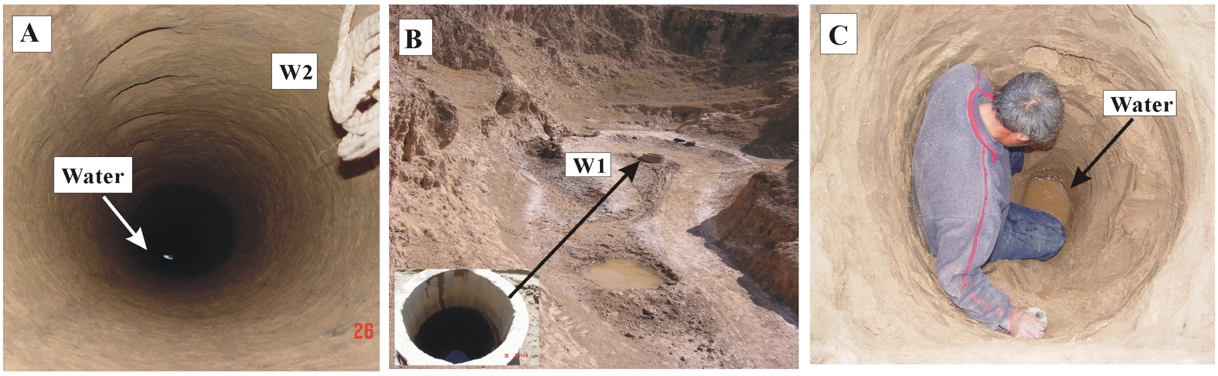

Fig. 4. Wells on right slide block (A) and on the left side block (B), as well as the investigation pit (C) near W1

Kyoto University, after the 1995 Hyogoken-Nambu earthquake, Japan (Sassa et al 2004). In the present research, DPRI-5 and DPRI-7 were used. DPRI-5 has a shear box sized 120 mm in inner diameter, 180 mm in outer diameter, and 115 mm in height, and a maximum shear velocity of 10 cm/s; while DPRI-7 has large transparent shear box (270 mm inner diameter, 350 mm outer diameter, and 115 mm height), and can produce a high shear velocity of as much as 300 cm/sec. Both of them enable simulation of many different kinds of static and dynamic loadings under undrained condition. Using these ring shear apparatus, test can be carried out either by shear-torque-controlled or shear-speed-controlled method. In this study, DPRI-5 was used for all the tests on water-saturated samples, while DPRI-7 for the fast shear tests on dry samples with initial air pressure. Additional details on the design and construction of these apparatus, as well as the operation method, can be found in Sassa et al (2003, 2004).

Test results for water-saturated loess sample

Because all of the samples were consolidated under the same initial normal stress, dry-deposition method (Ishihara 1993) was used to prepare the samples to different initial densities. The oven-dried sample was poured into the shear box freely in several layers, and each layer was tamped differently to achieve different initial densities.

All samples were fully saturated by means of CO_2 and de-aired water. After saturated, the sample was consolidated at a given normal stress. Because the purpose of this study is to examine the basic liquefaction characteristics of loess soil, a normal stress of 200 kPa was used in all the tests. After the consolidation, the sample was then sheared by increasing the shear stress at a loading rate of 0.098 kPa/sec under undrained condition. In this study, all the samples were sheared to steady state (Poulos 1981), i.e., the shear resistance became constant. It is noted that, after the shear failure, the applied shear torque will be greater than the

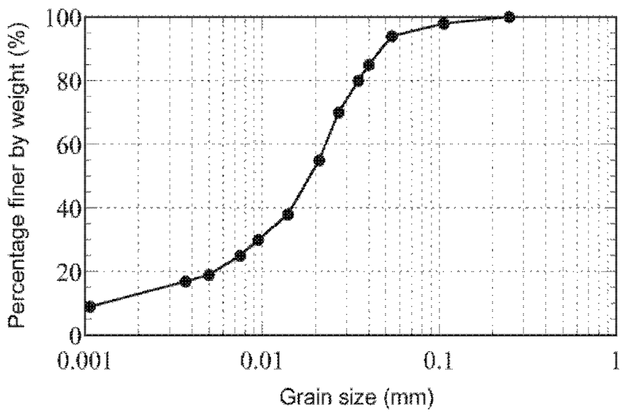

Fig. 5. Grain size distribution of loess sample from the source area of right slide block

resistive shear torque offered by the shear resistance of soil within the shear box (measured by means of two retaining torque arms on the upper confining rings). The difference between the applied shear torque and the resistive one accelerates the rotating movement of the lower part of the shear box to the available maximum shear speed.

The results of one test on water-saturated loess sample, whose initial void ratio was 1.06, are shown in Fig. 6, where the normal stress and pore-water pressure, as well as the shear resistance, are plotted against the shear displacement (Fig. 6a). Fig. 6b depicts the effective-stress path. From Fig. 6a, it can be seen that the pore-water pressure increases with increase of shear displacement, and finally elevated to a great value (about 85% of the applied normal stress); while the shear resistance decreased to a small value (about 10 kPa) at the shear displacement of about 1000 cm, and thereafter, almost kept the same, i.e., steady state had been reached.

Cyclic loading test had also been conducted on the water saturated loess sample using the ring shear apparatus of DPRI-5. After saturated, the sample was consolidated under the normal stress of 200 kPa, and shear stress of 80 kPa. After the consolidation, a cyclic shear loading with the amplitude of shear stress being 60 kPa and frequency being 0.25 Hz was applied to the sample under undrained condition. Fig. 7 presents the test results, where the normal stress, shear resistance and pore-water pressure are plotted versus time. Shear failure was triggered during the first cycle, and thereafter, pore-water pressure increased continuously, and shear resistance decreased consequently until a small value (about 7.6 kPa). From Fig. 6 and Fig. 7, it can be concluded that the water-saturated loess samples are high liquefiable, when they are subjected to monotonic or cyclic shearing under undrained condition.

Test results for dry loess soil with entrained air pressure

As stated above, because the landslide area is located on arid region, and loess is also rich in great void, it is reasonable to assume that the low permeability of loess prevents air from readily escaping, and then liquefaction can be triggered (Ter-Stepanian, 1998). However, this assumption has never been examined by laboratory tests. Here to clarify the possible effects of entrained air on the high mobility of displaced landslide mass, a series of fast shearing tests was conducted on the loess sample in natural water content (measured as 8.5%). During test, the sample with some natural loess blocks was first placed into the shear box without tamping, such that the specimen can be in very loose state with great void spaces. After sample was normally consolidated, the shear box was switched into undrained condition, and then the sample was sheared by increasing the shear speed quickly. In this series tests, the shear speed was increased to 2 m/s within 4 seconds. Fig. 8 shows the test results, where it can be seen that air pressure increases with shear displacement. However, the increment is very small such that no significant reduction on the shear resistance was resulted in.

Discussion of the test results

The steady state of loess

Based on the concept of critical void ratio defined by Casagrande (1936), and on the supportive results obtained from undrained monotonic loading tests on saturated sand, Castro (1969, 1975) introduced a steady state line. Thereafter, the steady state approach of analyzing liquefaction susceptibility was postulated and

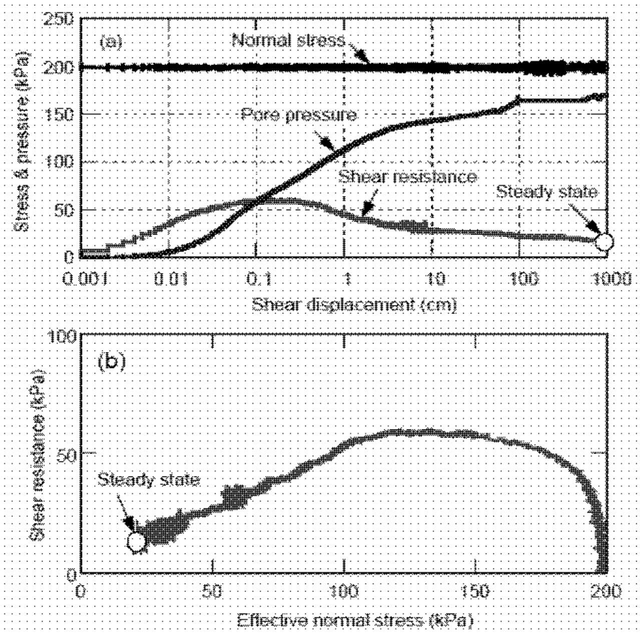

Fig. 6. Undrained response of water-saturated loess sample to monotonic shearing. (a) Normal stress, shear resistance and pore-water pressure versus shear displacement; (b) Effective stress path

widely used in practice. The important assumption in this analysis is that the sand has a unique steady-state line in void ratio-effective stress space; this line can be determined from the results of undrained tests on loose specimens of sand, and only those sands with their initial normal stress and void ratio locating above the steady state line can suffer from liquefaction flow failure (Castro 1969; Castro and Poulos 1977; Poulos 1981). Basing on this concept, the liquefaction potential of loess was examined.

A series of monotonic shear tests was performed on water-saturated loess samples at different initial void ratios. Probably due to the small value of applied initial normal stress (200 kPa) and the sample preparation method, the void ratios of tested samples ranged from 0.9 to 1.1. Each sample was sheared to steady state. The steady state points for all the tests are plotted on a e versus $\log(\tau_s)$ plane, shown in Fig. 9. As expected, the data plots in a relatively narrow band, and a well fit regression line was obtained.

The essential criterion of steady state approach is that saturated soil with void ratio and shear stress located below the steady state line has no susceptibility to suffer liquefaction failure. Field survey revealed that the in situ void ratios of loess layer near the sampling point are ranging from 1.13 to 1.31, while the loess layer around the aquifer investigation pit has a smaller void ratio of approximate 0.80, i.e., in denser state. From this tendency, it is inferred that the sample area was not in saturated state during the 1920 earthquake event time. However, considering the possible effect of landslide topography and the climate changing (this area is becoming drier), it is reasonable to believe that ground water existed at least as high as the pit area during the earthquake time. The great difference in the void ratio of soil layer may be due to the fact that loess is high compressible with increase of water content. This can be seen from Fig. 10, where the results of one test performed to examine the compressibility are presented. The oven-dried sample was set into the shear box and consolidated under the normal stress of 200 kPa. Thereafter, water was applied to saturate the sample from the bottom of the shear box. During this period, the void ratio continued to decrease until a constant. The void ratio decreased from 1.54 to 1.02. Therefore, it is reasonable to believe that if the normal stress be greater (say corresponding to the thickness of displaced landslide mass on the source area of about 100 m), the void ratio should be smaller after the sample was saturated.

Role of air in the movement

In the analysis of landside mobility, a parameter of travel angle (ϕ_a) has been widely used (Scheidegger 1973; Cruden & Varnes 1996). ϕ_a is defined as $\tan\phi_a = H/L$, where H is the height of landslide, i.e., the difference in elevation between the crown and the tip of the landslide; L is horizontal distance of the landslide. This value of $\tan\phi_a$ is also called apparent friction, and ϕ_a apparent friction angle. Low apparent friction angle means high mobility. This apparent friction angle can also be obtained from undrained ring shear test results.

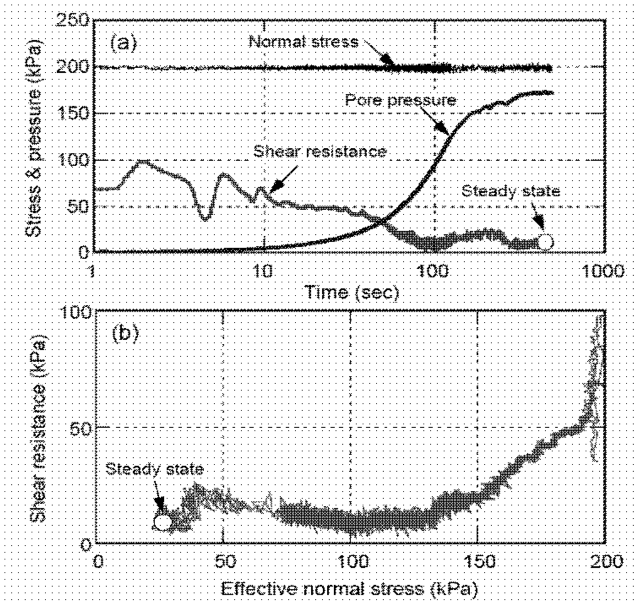

Fig. 7. Undrained response of water-saturated loess sample to cyclic loading in ring shear test. (a) Time series data of normal stress, shear resistance and pore-water pressure; (b) Effective stress path

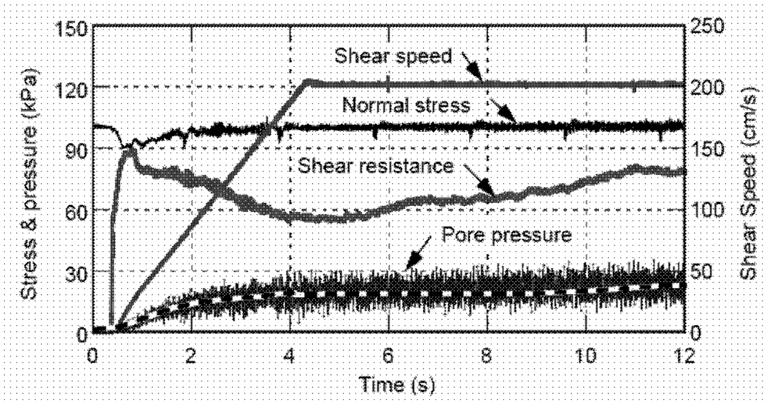

Fig. 8. Undrained response of air-saturated loess sample to monotonic shearing

Sassa (1996) pointed out that the mobilized friction angle at steady state (ϕ_m) for those saturated samples subjected to undrained shearing ($\tan\phi_m = \tau_s/\sigma_i, \tau_s$: shear strength at steady state; σ_I: Initial consolidation normal stress) is approximately equal to the travel angle for most landslide with high mobility. Therefore, the ring shear test provides a workable approach for the prediction of landslide mobility.

Basing on the concept of mobilized friction angle, here the effect of possible entrained air on the landslide movement is examined. A series of undrained fast shear tests was performed on loess samples that were normally consolidated under the initial effective normal stress (σ_i) of 50 and 100 kPa, respectively. In these tests, the observed pore-air pressures are ranging from 20–27 kPa. However, the mobilized friction angles are different (Fig. 11). The test with $\sigma_i = 100$ kPa has its mobilized friction angle not less than 30 degrees during the whole shear process. However, the test with $\sigma_i = 50$ kPa showed significant reduction in ϕ_m with a minimum value of approximate 13 degree. This value is a typical one for those rapid long-travel landslides (Sassa 2004). From Fig. 11, it can be concluded that when the initial normal stress is small, high mobility can be triggered within the loess layer entraining air. Namely, high mobility can be triggered by the involvement of air within those small landslides. However, for this deep seated landslide, the increased pore-air pressure does not contribute significantly to the high mobility. Therefore, it is difficult to give a acceptable explanation by the contribution of air-pressure for this large catastrophic landslide.

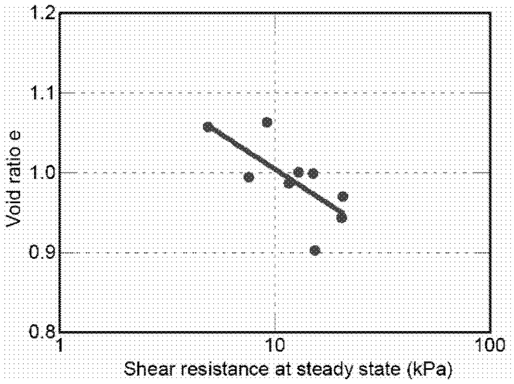

Fig. 9. Shear resistance at steady state versus void ratio for water-saturated loess samples

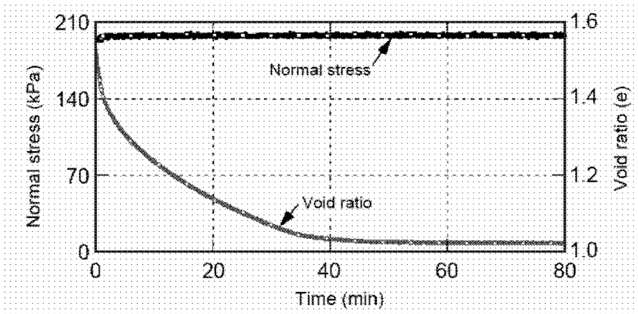

Fig. 10. Consolidation of loess sample during the saturating period by water

Conclusions

This paper presents the results of field survey and experimental investigation on the Dangjiacha landslide triggered by the 1920 Haiyuan Earthquake. Basing on the findings of field survey and results of undrained ring-shear tests on the loess samples taken from the source area of the landslide, the mechanism of this landslide with high mobility are discussed. Following conclusions can be drawn.

1. Dangjiacha landslide was a liquefied one with high mobility and large runout distance, which dammed a valley completely, showing some typical flow characteristics.
2. Field survey and laboratory examining on the variation of density of loess soil demonstrated that standing ground water existed on the source area, and the loess layer near the sliding surface was in saturated state.
3. The loess samples from the landslide source area are highly liquefiable. The water-saturated loess sample can be liquefied, and then suffer large runout movement under the possible shear stress corresponding to the thickness of displaced landslide mass from the source area and the slope angle.
4. Loess in naturally dry state with entrained air in the void showed reduction in shear strength in some extent due to the increase of pore-air pressure during the fast shearing. Although the generated pore-air pressure can make the shallow landslide to move with high mobility, it is not great enough for the initiation and maintaining of high mobility of the displaced landslide mass of Dangjiacha landslide. Therefore, the high mobility of Dangjiacha landslide. was due to the liquefaction failure with the water-saturated loess layers, not the involvement of air in the movement.

References

Bishop, A.W., Green, G. E., Garge, V. K., Andersen, A. and Brown, J. D. (1971) A new ring shear apparatus and its application to the measurement of residual strength. *Géotechnique* **21**(1), 273–328.

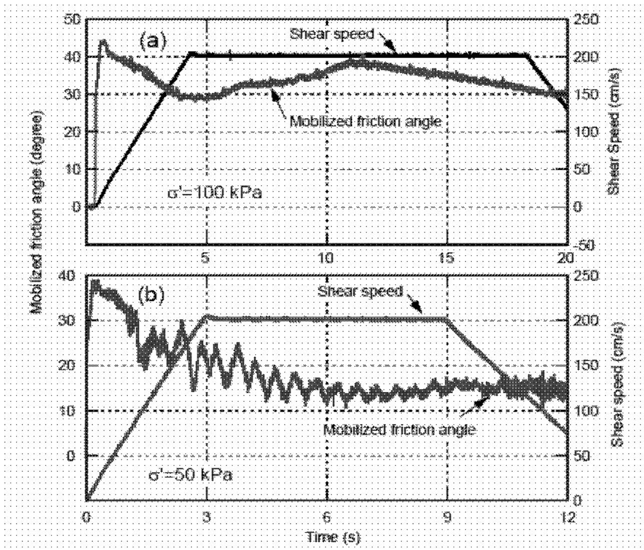

Fig. 11. Results of tests on air-dried loess samples that were consolidated under the initial stress of, (a) 100 kPa, and (b) 50 kPa, respectively

Casagrande, A. (1936) Characteristics of cohesionless soils affecting the stability of slopes and earth fills. *Journal of the Boston society of civil engineers*, reprinted in Contributions to soil mechanics, 1925 to 1940, Boston Society for Civil Engineers, 257–276.

Castro, G. (1969) *Liquefaction of sands*. Ph.D. Thesis, Harvard University, Cambridge, Massachusetts.

Castro, G. (1975) Liquefaction and Cyclic Mobility of Saturated Sands. *ASCE, Geotechnical Engineering Division* **101**(6), 551–569.

Castro, G. and Poulos, S.J. (1977) Factors Affecting Liquefaction and Cyclic Mobility. *ASCE, Geotechnical Engineering Division* **103**(6), 501–516.

Close, U. and McCormick, E. (1922) Where the Mountains Walked. *The National Geographic Magazine* **41**(5), 445–464.

Cruden, D.M, and Varnes, D.J. (1996) Landslide types and processes. In *Landslides: Investigation and Mitigation* (A.K. Turner & R.L. Schuster eds), 36–75.

Derbyshire, E. (1991) Landslides in the Gansu Loess of China. *Loess-Geomorphological Hazards and Processes, Catena Supplement* **20**, 119–145.

Derbyshire, E., Meng X.M. and Dijkstra, T.A. (2000) *Landslides in the Thick Loess Terrain of North-West China*. Wiley, 352p.

Dijkstra, T. A., Rogers, C. D. F., Smalley, I. J., Derbyshire, E., Li Y.J., and Meng, X.M. (1994) The loess of north-central China: Geotechnical properties and their relation to slope stability. *Engineering Geology* **36**, 153–171.

Habib, P. (1975) Production of gaseous pore pressure during rock slides. *Rock Mechanics* **7**: 193–197.

Howard, K.E. (1973) Avalanche mode of motion: implications from lunar examples. *Science* **180**, 1052–1055.

Hsü K.J. (1975) Catastrophic debris streams (Sturzstroms) generated by rockfalls. *Geol. Soc. Am. Bull.* **86**, 129–140.

Ishihara, K. (1993). "Liquefaction and flow failure during earthquakes." *Géotechnique* **43**(3), 351–415.

Ishihara, K., Okusa, S., Oyagi, N. and Ischuk, A. (1990). Liquefaction-induced Flow Slide in the Collapsible Loess Deposit in Soviet Tajik. *Soils and Foundation* **30**(4), 73–89.

Keefer, D.K. (1984) Landslides Caused by Earthquakes. *Geological Society of America Bulletin* **95**, 406–421.

Kent, P.E (1966) The transport mechanism in catastrophic rock falls. *J. Geol.* **74**, 79–83.

Lucchitta, B.K. (1979) Landslides in Valles Marineris, Mars. *J. Geophys. Res.* **84**, 8097–8113.

Plafker, G., and Ericksen, G.E. (1978) Nevados Huascarán avalanches, Peru. In: B. Voight, Editor, *Rockslides and Avalanches. 1. Natural Phenomena*, Elsevier, Amsterdam, p.277–314.

Poulos, S.J. (1981) The Steady State of Deformation. *ASCE, Geotechnical Engineering Division* **107**(5), 553–561.

Sassa, K. (1996) Prediction of earthquake induced landslides. Special Lecture of 7th International Symposium on Landslides, "*Landslides*", Rotterdam: Balkema, **1**, p.115–132.

Sassa, K. (2000) Mechanism of flows in granular soils. *Proceedings of GeoEng2000*, Melbourne, 1, p.1671–1702.

Sassa, K. (2004) Preface. *Landslides: Journal of the International Consortium on Landslides* **1**(3), 169–171.

Sassa, K., Wang, G., and Fukuoka, H. (2003). Performing undrained shear tests on saturated sands in a new intelligent type of ring shear apparatus. *Geotechnical Testing Journal*, ASTM, **26**(3), 257–265.

Sassa, K., Fukuoka, H., Wang, G., and Ishikawa, N. (2004) undrained dynamic-loading ring-shear apparatus and its application to landslide dynamics. *Landslides: Journal of the International Consortium on Landslides* **1**(1), 9–17.

Scheidegger, A.E. (1973) On the Prediction of the Reach and Velocity of Catastrophic Landslides. *Rock Mechanics* **5**, 231–236.

Seed, H.B. (1966) Landslides During Earthquakes due to Soil Liquefaction. *Journal Soil Mechanics Foundations Division, ASCE* **94**(5), 1055–1122.

Shreve, R. L. (1968) The Blackhawk Landslide. *Geological Society of America, Special Paper* **108**, 1–49.

Ter-Stepanian, G. (1998) Suspension force induced landslides. *Proceedings of 8th Congress of IAEG*, Vancouver, Canada. Balkema, Rotterdam, **3**, p.1905–1912.

Varnes, D.J. (1978) Slope Movement Types and Processes. *"Landslides — Analysis and Control"*, Special Report, No. 176, Transportation Research Board, National Academy of Sciences, USA, p.11–33.

Yoshimi, Y. (1991) *Liquefaction of Sands*. Gihoudo Press, Co. Ltd. Tokyo, p.182 (in Japanese).

Zhang, D., Takeuchi, A. and Sassa, K. (1995) The Motion Characteristics of Loess Landslides Induced by the Haiyuan Earthquake in Ningxia Province, China. *Journal of the Japan Landslide Society* **32**(1), 12–17 (in Japanese).

Zhang, D. and Sassa, K. (1996) Study of the Mechanism of Loess Landslides Induced by Earthquakes. *Journal of the Japan Society of Erosion Control Engineering* **49**(2), 4–13 (in Japanese).

Zhu, H. (1989a) The Geological Characteristics of Landslides Induced by Earthquakes in China. *Proceeding of the Japan-China Symposium on Landslides and Debris Flows*, p.161–168.

Zhu, H. (1989b) Some Types of Seismic Landslides in the Loess Area in China. *Proceeding of the International Field Workshop on Loess Geomorphological Processes and Hazards*, p. 64–71.