The Low Viscosity Loess Liquefaction and its Microstructure Analysis

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Abstract. Low viscosity powder loess is widely distributed in loess plateau areas of northwest China. It has a high liquefaction potential. The mechanism of low viscosity loess water action is studied using CT scanning. CT scanning results showed that initially, water in loess will tend to rise as a whole. Then, cement salts around the loess grains melt and form large holes. Finally, deformation collapse and damage can occur. In this study, low viscosity loess is compared with sandy loess and clayey loess obtained from Lanzhou, Guyuan, and Tongguan. Based on the results of dynamic triaxial torsion tests, the low viscous powder loess dynamic loading time was shorter and more easily liquefied than sandy loess and clayey loess. Electron microscope scanning of loess microstructures showed the chemical element ratios around the loess particles produced cemented material (such as Ca/Fe). The chemical elements around loess particles and the pore diameter/grain ratio were selected to evaluate liquefaction resistance in loess. In addition, loess particle size distribution and the pore/grain ratio also influenced the liquid level. It is an effective innovative method to judge the liquefaction strength of low viscosity silt based on microcosmic parameters.

1. Introduction
Loess plateaus in the east QiLian mountain and the west LiuPanshan mountain range of northwest China have experienced frequent seismic geological disasters that have spread loess over wide areas. There have been many loess liquefaction and destruction events caused by a rise in underground water that has occurred due to seismic loading. For example, Guyuan (Shi-Bei-yuan) loess (sandy loess) liquefaction caused by the Haiyuan earthquake induced a large loess landslide in 1920[1]. The Tian-Chuan loess liquefaction event was caused by the Wenchuan magnitude (ML=8.0) earthquake in 2008[2]. Extensive liquefaction causes about 1.0 m of lateral spreading at the toe of a landslide[3]. Many studies have discussed the mechanisms of loess liquefaction events[4-9]. The landslide rupture mechanism [10] studied in an analysis of the seismic landslide event caused by the 1999 Kocaeli (Izmit)-Turkey earthquake. Numerical analyses have been conducted to study clay foundation liquefaction using an effective stress[11] and liquefiable loess foundation liquefaction[12-13]. Numerical analysis of seismically induced liquefaction in earth embankments has also been conducted[11]. The seismically induced landslide during the Kocaeli (Izmit)-Turkey earthquake has
been studied[10]. The SiBeiYuan tableland loess liquefaction characteristics and influencing factors of landslide research have also been examined [14]. Loess is primarily divided into three types in foundation engineering: low viscosity loess, sandy loess, and clayey loess. The influence of loess types on structural stability needs to be researched, and further tests need to be conducted. Large data sets have shown that loess, particularly low viscosity loess, liquefies very easily under certain vibratory conditions. Even when a loess foundation is subjected to mechanical engineering vibrations, this type of vibration induced foundation subsidence and fissures in the Lanzhou west foundation[15].

In recent studies, researchers have investigated loess microstructures and their microstructures parameters. A dynamic triaxial-loading liquefaction test indicated that loess microstructure characteristic parameters had an obvious influence on the degree of loess saturation and liquefaction[16,17,14]. In this study, microscopic pore water level changes are analyzed using a variety of chemical elements, and a liquefaction test is performed to explore loess liquefaction.

2. Method
An investigation of the Shibeiyuan landslide showed that saturated loess or loess with high water content had high liquefaction and destructive potential, which could have caused the liquefaction and flow slides during this strong earthquake. Understanding the behavior and mechanisms of these events is very important to understand liquefied slope failures that travel long distances in areas with high amounts of loess. Analytical results have revealed that the liquefied stress ratio decreases and pore pressure response is stronger with increasing clay content.

Figure 1 shows Ningxia Guyuan’s Shibeiyuan tableland loess liquefaction sliding mass due to the Haiyuan earthquake. Its flow slide reached 2000 m and more than 200 people died. An important investigation area is the Shi Beiyuan loess liquefaction. The structural strength of the specimen decreased, leading to a decrease in the liquefaction stress ratio [14].

Figure 1. Shi Beiyuan loess liquefaction slide in Ningxia Guyuan (2005)

As Figure 1 shows, the 1920 Haiyuan magnitude 8.5 earthquake induced a large number of fluidized loess landslides characterized by low slope angles, long run-out distances, and fluidized movement. The mechanism of these landslides has aroused considerable interest, although additional research is needed to more fully understand the behavior of the loess and the failure mechanisms. Excess pore pressure can accumulate under seismic loading and plastic deformation can develop rapidly within a shearing zone, resulting in loess liquefaction and a reduction in shear strength. In the Shibeiyuan landslide, the steady state strength was near zero, and the large deformation was related to the low angle, long distance, and fluidized movement[18,19]. The initial induction factors of liquefaction is a key to understanding loess water interactions.

2.1 Test analysis of loess water interactions
There are two possibilities that induce loess liquefaction that involve microstructure factors. 1) First, water action starts in the weak points of original cracks. When the liquid water level rises up to original cracks, “weak grain” collapse happens, and then total liquefaction occurs. 2) Second, the course of the water action causes the entire water level to rise first, then crack grains fail and liquefaction happens. More specifically, a suction action occurs throughout the region, then cracks
points break and total liquefaction occurs. CT scanning will be used to analyze the mechanisms of loess water interactions and to infer scenarios that may occur during the liquefaction process.

2.1.1 CT scanning test of the stages of liquefaction

A dynamic loading test indicated that the Longxi loess saturation degree was more than 90–95% (Wang et al., 2000). However, the sandy loess saturation degree was only 75–85%. To determine the reason for this, the loess liquid water level rise was analyzed using a CT scanning test. Static microscopic scans (CT) were designed to test the water absorption of loess samples.

In this test, an undisturbed loess sample was placed in an exposure beaker, then an amount of water was added to make approximately 10% of the sample contain water. Water rise level images were recorded at one second intervals using CT scanning. Computation time began after the water was put into sample. Figures 2(a) and 2(b) show the loess samples after suction. The liquid level line appears at 43 minutes and 30.01 seconds (expressed as 43′ 30.01") in Figure 2(a). Fig 2(b) shows the water level at 43′ and 31.02". The water level was located at the circle marked on the loess sample and, on the whole, the liquid level generally rose. The water layer rise speed was 1.5 cm/s. The water rose to a certain height due to loess water suction. Figures 2(c) and 2(d) are photos of the duration at 43′32.94" and 43′33.28", respectively. Loess voids and cementing around voids occurred intense hydration reaction, in which cements were dissolved and broken and pore sizes increased (Fig. 2(c)). Liquefaction began after the liquid levels rose as whole. Salts around large voids dissolved and became voids of certain sizes. Water continuously entered these areas until the voids were broken and disintegrated (Fig. 2(d)). In the third stage, small voids continued to suction water after being broken (Fig. 2(e)). The time duration was 43 minutes and 33.44 seconds. The water level still increased until more voids collapsed. The processes of increasing suction and collapsing voids caused a gradually circulation, and the liquid level continued to increase. Cement salts around the particles dissolved, scattered, and later recrystallized around particles. Large particles rearranged under the dynamic stress effect. In this end of the process, there were further changes in the degree of saturation and then excessive saturation, loess flow, and collapse occurred.

![Figure 2](image1)

These results indicate that loess liquefaction occurred as the water in the loess samples rose quickly, and then samples became saturated and the effective stress between particles broke, causing
liquefaction to occur. This could be due to the different processes of suction and disintegration by different kinds of loess microstructure. This process caused a rise in the liquid level, and then the strength of microstructure was broken. The liquefaction experiments and microstructure parameters are more closely examined below.

### 2.2 Liquefaction experiments under dynamic loading

As Figure 3, the samples selected places. The test samples selected from Gansu Lanzhou (LZ), Ningxia Guyuan (GY), and Shanxi Tongguan (TG) had been covered by sand loess, low viscosity silt, and clayey loess. The three kinds of loess were selected for the dynamic loading liquefaction test, including sand loess (from Guyuan, Gy, 6 meters), low viscosity loess (from Lanzhou, LZ, 5 meters), and clayey loess (from Shanxi, SX 4 meters). These are the main types of loess used in foundation engineering applications in western China.

![Figure 3. The Natural loess samples selected places (spots are Lanzhou, Guyuan, Tongwei’s loess regions)](image)

As shown in Table 1, the percentages of sand, powder, and clay in the three kinds of loess were the following: Guyuan loess contained 33%, 53%, and 16%, respectively; Lanzhou low viscosity loess contained 13%, 76.5%, and 10.5%, respectively; and Shanxi loess contained 6.5%, 62.1%, and 31%, respectively. The dry density was 1.43, 1.24, and 1.41 for Guyuan, Lanzhou, and Shanxi loess, respectively. The natural void ratio for the loess from the three areas was 0.896, 1.2, and 0.933, respectively, and the plasticity index was below 10 for all three types. According to these indices, the samples were divided into sand loess, low viscosity silt, and clayey loess.

The liquefaction test equipment used was a WF-12440 dynamic triaxial torsional shear apparatus (produced by WFI company in the UK). The loess samples had equal pressure consolidation with a consolidation value of $K_c = 1$, and the confining pressure used was 100 kPa. Each sample size was 300 mm × 500 mm, and the shaking frequency was 100 KPa of dynamic stress applied 100 times at one second intervals. Due to the strong water sensitivity of saturated loess, the consolidation time was limited to two hours to avoid collapse deformation of the samples. When the residual strain increased dramatically to 3%, loess deformation changed from stable to a large deformation. The critical threshold for deformation from a previous study was 3% [20,21,22]. Hence, a 3% strain was used as the critical threshold for liquefaction deformation in this study.

The test result liquefaction curve of the three samples are shown in Figure 4 and Table 1.2. The turning point of the pore pressure can be considered the critical point for liquefaction deformation. The index included a critical pore pressure and critical loading time to judge the strength of different samples and their grades in the test.

The test curve in Figure 4 shows the critical pore pressure and loading time of three kinds of loess.
Low viscosity loess (LZ) is 117.9 kPa and 15.84 s, the sandy loess from Guyuan (GY) is 148.3 kPa and 64.17 s, and the clayey loess (SX) is 150 kPa and 145.15 s. This indicates that the first liquefaction phenomenon occurred in the low viscosity loess (LZ), and the dynamic loading time was only 15.84 s. With an increase in the critical pore water pressure to 117 kPa, the dynamic strain rose to 3%, after that it was nonlinear. When the dynamic strain rose to 3%, sand loess (GY) and clayey loess (SX) had loading times as large as 64.17 and 145.15 seconds, respectively, and pore water pressures of 148 kPa and 150 kPa, respectively. The liquefaction order was low viscosity loess (LZ), sand loess (GY), and then clayey loess (SX).

![Liquefaction load dynamic pore water pressures and deformations of the three kinds of loess](image)

**Figure 4** Liquefaction load dynamic pore water pressures and deformations of the three kinds of loess

3. **Microscopic influence factor analysis of loess liquefaction**

The CT scanning test analysis results indicated that the loess liquefied due to the natural suction of the loess materials inducing the water level in the samples to rise. The factors contributing to this phenomenon were specific chemical elements in the cements and the particle sizes. The details of the analysis are discussed below.

3.1 **The first factor: the ratio of chemical elements**

Undisturbed loess has a chemical composition consisting of inorganic minerals with chemical formulas of Mg₃(Al₂Si₃O₁₀), (OH)₂, Na₂KAl₅Si₇O₂₁, CaAl₂Si₂O₈, KAl₃[Si₈AlO₁₈], and (OH, Fe)₂. Undisturbed loess can be decomposed under dry conditions of weathering and form alkaline cement-like compounds, such as CaCO₃, MgCO₃ and SiO₂, among others. CaCO₃ alkaline salt can produce a strong hydration reaction. An electron microscope energy spectrum was used to monitor the chemical element content surrounding the voids. The analysis included Ca, Mg, Fe, and other elements, and the ratios of Ca/Mg, Ca/Fe, and K/Al were calculated.

In alkaline conditions, when the ratio of Ca/Mg is higher than the highest content of Ca, the easier it is for a hydration reaction to occur. When the ratio of Ca/Fe is high and the mean content of Fe is lower, Ca compounds more easily experiences water hydration. The ratio of K/Al will easily dissolve, because K⁺ will dissolve and migrate with water, the Al will be stable because of precipitation.

Table 2 shows that in low viscosity loess, the content of Ca/Fe, Ca/Mg, and K/Al are 3.1, 66, and 1.9, respectively. The higher the content of water soluble salt, the more easily it absorbs water and is dissolved. The ratio values of the sand loess are 4.03, 97, and 1.28, respectively. The first two values are higher, but the content of K is less. Water soluble salt easily absorbs water, but does not easily dissolve. The ratio values of clayey loess are 2.09, 12.6, and 0.43, respectively. These values are all low, meaning that clayey loess does not easily absorb water and dissolve.
3.2 The second factor: microstructure parameters of particles

Some micro-factors, like the size of loess voids and particles, also have an influence on water pressure rise. Figure 5 shows the microstructure of the three types of loess. The microstructure characteristics for the Lanzhou low viscosity loess (type I, Fig. 5(a)), are powders that are loosely accumulated. The microstructure properties of the low viscosity loess are trellis pores and low strength cements with powder particles. The sand loess from Guyuan (type II, Fig. 5(b)) are a powder and sand particle accumulations, and the clayey loess from Shanxi (type III, Fig. 5(c)) is a dense granular accumulation. The high cementation strength is related to the clay content of the dense packing structures, as shown in Figure 5(c), followed by the sand and silt accumulation structure shown in Figure 5(b). The lowest cementation strength is a loose powder accumulation structure, as shown in Figure 5(a).

![Image](5a.png) Lanzhou (5b) Guyuan (5c) Shanxi

Figure 5. Types of natural loess microstructures in loess samples

Image processing software was used to extract the diameters of the voids and particles values from the loess microstructure pictures. After grayscale image processing, the sizes of the pores and particles displayed were measured. Averages were taken to obtain the value of \( \frac{K_x}{K_L} \). The ratio of voids to particle diameters \( \frac{K_x}{K_L} \) was selected as an evaluation index.

As Figure 6 illustrates, for Lanzhou loess (LZ), the curve trend of the particles size are in proximity with the void diameters. This means that the particles accumulated loosely and the compactness was lower. The two curve values for the Shanxi loess (TG) are very different because of the strong bonding among particles that formed many voids among the collection of particles. These kinds of voids are smaller than the size of mass particles. The Guyuan loess (GY) is between the LZ and TG loess.

![Image](6a.png) (6b) (6c)

Figure 6. The pore diameter/particle size change curves of the three loess samples

| Table 1: The physical and mechanical parameters of three typical types of loess |
|------------------------------------------|--------|------|------|---------|--------|
| Loess types                            | Microstructure kinds | Natural dry density g/cm\(^3\) | water content /% | void ratio | plastic index |
| Low viscosity loess /LZ                | Loose powder accumulation | 1.13 | 7.65 | 0.896 | 8.4 | 13.0 | 76.5 | 10.5 |
| Sandy loess /GY                        | Powder and sand accumulation | 1.24 | 8.96 | 1.20 | 11.1 | 33 | 53 | 16.0 |
More specifically, the water pressure and soil deformation research technologies in China. The article McKenzie's text on liquefaction of clay accumulation includes the chemical elements. It was confirmed that the chemical elements were one of the leading factors influencing liquefaction. However, finding microcosmic parameters with strong correlation is the primary reason that the particle size of silt and the natural suction degree (Ca/Mg, Ca/Fe, and K/Al) were much lower than the Lanzhou loess loess, which consists of low viscosity loess, sandy loess, and clayey loess, respectively. The liquefaction test showed that the lowest liquefaction critical threshold was found in the Lanzhou low viscosity loess, which can reach a high degree of saturation degree and therefore, have a serious liquefaction risk. The sandy loess had a middle risk of liquefaction. The clayey loess only showed mild liquefaction.

As Figure 6(a) shows, the similar numerical values for particles and voids in the Lanzhou sample indicates that the loose accumulation between particles formed big voids (the biggest particles are 30 to 70 μm), and the voids are 30 to 60 μm. Figure 6(b) shows the sand loess in Guyuan, and its curve of particles and voids display significant differences. The particle sizes are from 20 to 50 μm, and the void sizes are from 30 to 50 μm. The sand loess (SX) is made up of big particle sizes, and its Kx/KL is 0.85. Its accumulation degree is larger than that of the Lanzhou loess, so it will produce a medium liquefaction. In Figure 6(c), the void curve of the Shanxi loess is much lower than the particle curve, and the primary particle size is 10 to 30 μm, and the void size is 10 to 30 μm. The strong accumulation structure will make it slightly liquefy.

### 4. Conclusion

1) In this study, three kinds of loess were chosen to do liquefaction test: Gansu Lanzhou (LZ), Ningxia Guyuan (GY), and Shanxi Tongguan (TG) loess, which consisted of low viscosity loess, sandy loess, and clayey loess, respectively. The liquefaction test showed that the lowest liquefaction critical threshold was found in the Lanzhou low viscosity loess, which can reach a high degree of saturation degree and therefore, have a serious liquefaction risk. The sandy loess had a middle risk of liquefaction. The clayey loess only showed mild liquefaction.

2) By CT test to loess samples, it is showed that the loess water action was due entirely to loess suction. The primary reason for liquid level rise was due to the void size of silt and the natural suction of cements (capillary phenomenon). These led to a rise in the water content of loess up to certain saturation degree, a rise in pore water pressure that broke cements, and a reduction in the effective stress, then, the loess was liquefied.

3) The loess microstructure quantization parameters relative to strength of liquefaction energy. It was confirmed to evaluate loess liquefaction resistance. The microstructure quantization parameters is including of the chemical elements ratios around loess particles (Ca/Mg, Ca/Fe, and K/Al), and the pore diameter/grain ratio (Kx/KL).

### 5. Discussion

Loess liquefaction test can measure the increase of soil pore water pressure and soil deformation strength. In the past, many traditional parameters such as pore ratio were studied to determine the factors influencing liquefaction. However, finding microcosmic parameters with strong correlation is one of the leading research technologies in China. The article’s electron microscopy analysis results

| Clayey Loess/SX | Cementation of clay accumulation | Critical pore pressure /kPa | Liquefaction potential/Ⅶ | Liquefaction destroy loading time /S | Ratios of chemical elements |
|----------------|---------------------------------|-----------------------------|---------------------------|-------------------------------------|-----------------------------|
|                |                                 | 1.41                        | 9.27                      | 0.933                               | 9.7                         |
|                |                                 |                             |                           |                                     | 6.5                         |
|                |                                 |                             |                           |                                     | 62.1                        |
|                |                                 |                             |                           |                                     | 31.0                        |

The ratio results of the three kinds of samples are 0.75, 0.85, and 0.64, respectively. The Shanxi loess produced slight liquefaction and is the lowest among three samples. The value of Kx/KL are for voids particles. The smaller the value, the closer the particle and void curves. More specifically, the particles had a higher intensity.

Table 2 The microstructure quantitative parameters of three typical types of loess

| Loess types  | Critical pore pressure /kPa | Liquefaction destroy loading time /S | Ratios of chemical elements |
|--------------|----------------------------|-------------------------------------|-----------------------------|
| Low viscosity loess | Completely liquefied     | 117.9                               | 15.84                       |
| Sandy loess  | Medium liquefied          | 148.3                               | 64.17                       |
| Clayey Loess/SX | Mild liquefaction         | 150                                 | 145.15                      |

- **Ca/Fe**
- **Ca/Mg**
- **K/AL**
- **Kx/KL**
indicated that primary factors involved in natural suction were void size of the loess and cements around particles. The loess particle size distribution and the pore/grain ratio is influenced the liquid level. These two indices were able to predict the preliminary strength trend of liquefaction. It is an effective innovative method to judge the liquefaction strength of low viscosity silt based on micromesoscopic parameters.

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