The study on sand liquefaction of the Songyuan M5.7 Earthquake in China

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Abstract

A large scale sand liquefaction phenomenon which is typically and rarely was found in the epicenter of Songyuan M5.7 earthquake on May 28, 2018. To find out the liquefaction damages and site characteristics, a field survey and experimental testing (including boring sampling, Standard Penetration Testing (SPT), Cone Penetration Testing (CPT), Scanning Electron Microscope (SEM), X-Ray Diffraction (XRD) and X-ray Fluorescence (XRF) were performed. The formation conditions and influence factors of sand liquefaction in this earthquake were analyzed. The liquefaction covered a total area of 80km2, which mainly reflected in sandboils and water sprouts in paddy field, and no serious structural destruction occured. Ground motion, geomorphic conditions and groundwater level are the main controlling factors of the liquefaction distribution due to a single soil layer structure in this area. The depth of liquefied sand layers were mainly within 10m, and deep layer liquefaction under 18m was found out by drilling, which exposed the ascending channel of liquefied sand in clay layer. Cone Penetration Testing has unique advantage in liquefied sand layer identification and physico-mechanical parameters acquisition, it can apply to field investigation after earthquake. And the loess liquefaction is first found in northeast of China. Furthermore, there is a risk of serious liquefaction damage in Songyuan city. The liquefaction hazard in this area should be special study in earthquake disaster mitigation planning and engineering reconnaissance and design projects.

Keywords: Songyuan Earthquake; sand liquefaction; field survey; Cone Penetration Testing; Loess liquefaction

1. Introduction

As one kind of highly destructive earthquake-induced geological disasters, liquefaction can cause serious damage to foundation and engineering structure. In previous earthquakes include 1966 Xingtai (China), 1976 Tangshan(China), 1989 Loma Prieta (USA), 1995 Kobe(Japan),1999 Chi-Chi(Taiwan,China), 1999 Izmit (Turkey), 2008 Wenchuan (China), 2011 Christ-Church(New Zealand), 2018 Petrobo(Indonesia) and so on, serious disasters like ground sliding, buildings collapsing and lifeline engineering failure were induced by liquefaction. These phenomena have attracted the attention of many researchers. New findings about liquefaction mechanism, liquefaction evaluation and liquefaction disaster reduction are emerging[1-6].

To find out the distribution of liquefaction and identify the influencing factors. Post-earthquake investigation is an essential measure for liquefaction research. It mainly includes two aspects: The first part is to determine liquefied and unliquefied field to get the liquefaction region according to ground damages. Then, collecting the ground motion data and conducting some essential test like drilling, screening test, standard penetration test, cone penetration test, wave velocity test to get quantitative data for detailed calculation and analysis. Many researchers obtained detailed liquefaction damage information and experience in engineering seismic damage by liquefaction macro-phenomena investigation. These achievements played an important role in promoting the development and practice of earthquake engineering. Nevertheless, there are still some limitations in previous investigations:1) Liquefied sites in preliminary post-earthquake investigation were identified by macro-phenomena such as sandboil, deep soil liquefaction with no macro-phenomena were often neglected. 2) In-situ special soil liquefaction phenomena such as loess are rare in northeast of China.

At May 28,2018, a earthquake of magnitude M5.7 occurred in Songyuan city, Jilin province, China. The earthquake was felt at most of Jilin province and part of Liaoning province and the Nei Monggol Autonomous Region. The epicenter of this earthquake was located in Yamutu village, which is part of the Songhua River alluvial terrace. The soil layer under the surface is mainly composed of fine sand and the water level is shallow. Compared to previous earthquakes, liquefaction phenomena widely occurred this time. To find out liquefaction distribution and related disasters, a field survey and experimental testing including boring sampling, standard penetration testing(SPT), cone penetration testing(CPT), scanning electron microscope(SEM), X-ray diffraction(XRD), X Ray Fluorescence(XRF) were performed soon afterwards. This paper provides the basic introduction of the Seismic characteristics in Songyuan and an overview of post-earthquake investigation. Firstly, the historical earthquake situation and ground motion distribution of this time are given. Observations of the liquefaction phenomena and field comparison test on liquefied and non-liquefied sites are then presented in this paper. Subsequently, a series of experiment on liquefied loess to confirm this new finding in north northeast of China are introduced. In general, there are not only some known liquefaction damages including sandboils and waterspouts but also some interesting phenomenon that has not been found before. Just like the deep soil layer liquefaction and special soil liquefaction. The results of this paper can give a better understanding for liquefaction disaster prevention in Songyuan city, and provide fundamental information for future research.

Songyuan city is located in southern Songliao Basin, which has complex faults structures. It is one of the only two cites of VIII seismic fortification intensity in northeast of China. A series of M>5.0 earthquakes happened in its history. According to the Dajin chorography, an destructive earthquake estimated at magnitude 6¾ occurred in this area at February, 1119. It is the largest earthquake in Songyuan. Figure 1 is the isoseismal map of this earthquake. The estimated epicentral intensity is Ⅷ to Ⅸ. Thousands of people died of the “subsidence”, accounting for around one-tenth of the total population of Zhaozhou and Longzhou. The earthquake region is located in the songhua river basin, Holocene sand layers are widely distributed. The shallow sand layers are saturated and loose, which are susceptible to liquefaction under earthquake action. However, there are no large-scale landslides, ground cracks and other subsidence inducements in this area, in consideration of the perspective of regional geomorphic features. It is suggested that the large-scale surface subsidence was induced by the sand liquefaction from Tahu Town to Nongan Town.

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2. Seismic characteristics in Songyuan

2.1 Historical earthquake

Use the decimal system of headings with no more than three levels. Songyuan city is located in southern Songliao Basin, which has complex faults structures. It is one of the only two cites of VIII seismic fortification intensity in northeast of China. A series of M>5.0 earthquakes happened in its history. According to the Dajin chorography, an destructive earthquake estimated at magnitude occurred in this area at February, 1119. It is the largest earthquake in Songyuan. Figure 1 is the isoseismal map of this earthquake. The estimated epicentral intensity is Ⅷ to Ⅸ . Thousands of people died of the "subsidence", accounting for around one-tenth of the total population of Zhaozhou and Longzhou. The earthquake region is located in the songhua river basin, Holocene sand layers are widely distributed. The shallow sand layers are saturated and loose, which are susceptible to liquefaction under earthquake action. However, there are no large-scale landslides, ground cracks and other subsidence inducements in this area, in consideration of the perspective of regional geomorphic features. It is suggested that the large-scale surface subsidence was induced by the sand liquefaction from Tahu Town to Nongan Town.

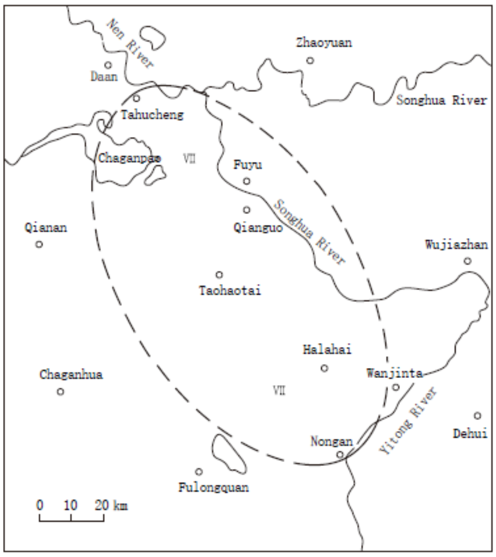

Fig.1 Isoseismal map of Qianguo Earthquake in 1119[7]

In recent years, seismic activity about magnitude from 4 to 5 is frequent in Songyuan area. The historical earthquake occurred in swarm sequence[8]. Since 2006, several earthquakes have happened here, including the 31 March 2006 M5.0 Qianan earthquake, the 2013 M>5.0 Qianguo earthquake swarm, the 23 July 2017 M4.9 Ningjiang earthquake, and the 28 May M5.7 Songyuan earthquake. It's necessary to note that the 2013 M>5.0 Qianguo earthquake swarm started from 31 October 2013 M5.5 Qianguo earthquake to the end of 2014, and that includes M5.0-5.9 earthquakes 5 times, M4.0-4.9 earthquakes 7times. These earthquake toppled buildings and caused farmland to liquefaction, tens of thousands of people have been affected[9]. Due to the widely distributed sand layers and the shallow buried underground water. Therefore, liquefaction disaster in this region is particularly serious.

1.2 Basic information of the M5.7 earthquake

The earthquake sequence is mainshock-aftershock. Focal mechanism solution shows it is a strike-slip earthquake. The seismogenic faults of this quake is presumed as Fuyu-Zhaodong faults. Figure is the seismic intensity distribution map from seismic intensity survey. The maximum intensity is Ⅶ, that covers an area of 157 km2. The long axis of the Ⅶ region is distributed along the NE direction, 9.2km long. The short axis is

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4.8km long. The Ⅵ region covers an area of 880 km2. The long axis is 24km long and the short axis is 16km long. The intensity distribution is north-south asymmetry, the decay rate of intensity is faster to the south west than to the north east.

According to China Strong Motion Network Centre, strong motion records of peak ground acceleration (PGA) over 100gal were recorded at the Daliba and Fenghua station near the epicenter. Epicentral distance of the former is 16km, which horizontal PGA is 159gal, vertical PGA is 189gal. The latter is located in 24km away from the epicenter, which horizontal PGA is 189gal, vertical PGA is 48gal. Figure 2 illustrates the distribution of strong motion records at the nearby stations.

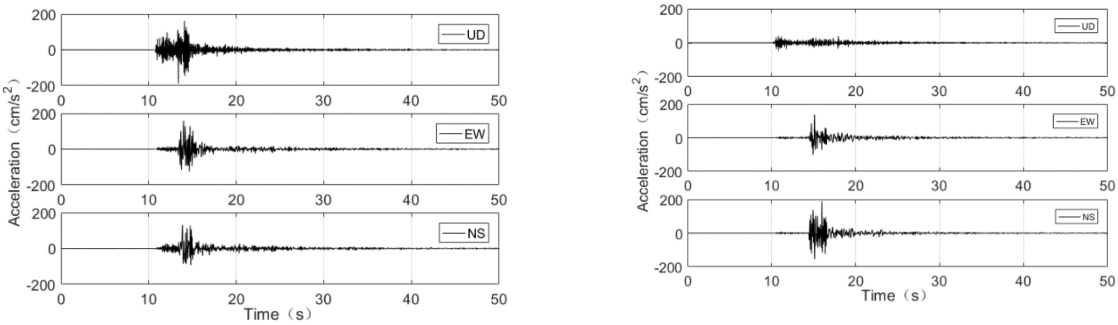

Fig.2 The figure of strong motion records of Daliba and Fenghua station

2. Field investigation and liquefaction macro phenomenon

2.1 Distribution and range of liquefaction

By the investigation, large scale liquefaction appeared in the region of seismic intensity of Ⅶ of this earthquake. A small number of liquefaction sites were found in the region of seismic intensity of Ⅵ. Figure 3 illustrates the distribution of the observed liquefied sites. All liquefied site were found in the countryside, the main macro phenomenon are sandboils and waterspouts. Most of the liquefaction occurred in rice field, a small amount of liquefaction caused damage to buildings. About two hundred of liquefied sites were detected, most of those distribute in left bank of the Songhua river. The right bank only has one liquefied site. The liquefaction zone is centered Yamutu village, Ningjiang district. East from the Songhua river, west to Langjia village, Qianguo county. North from the Guojia village, Qianguo county, south to the Jiangjia village, Ningjiang district. Its length and width are both about 9km, the area is approximately 80km^2.

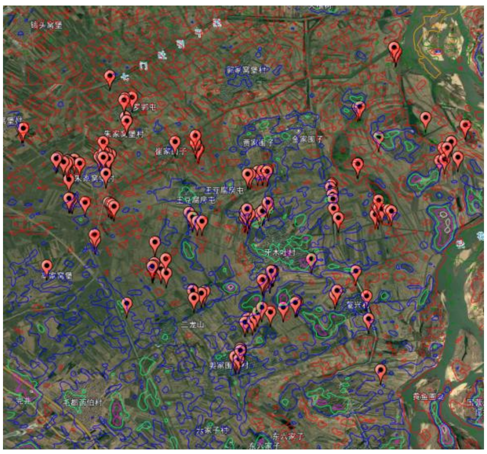

Fig.3 Distribution of liquefaction in Songyuan Earthquake

2.2 Liquefaction macrophenomena

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During this earthquake, the most obvious macrophenomena are sandboils and waterspouts. Those mainly occur in rice field, other part were found in forest, dry farmland and residential area. Among all the liquefied sites, the rice field sites are the most serious. The features of these sites are long liquefied duration time, deep liquefied hole and large scale eructation. The post-earthquake duration time of waterspouts ranges from several minutes to several hours. Water spraying can still be found 4 days after the earthquake at an rice field in Jiangjia village. This indicates that the pore water pressure in the underground soil layer had not completely dissipated. The accumulation patterns of liquefied ejecta are mainly embody as centralized shape(Figure 4a) and string beads shape(Figure 4b). The diameters of centralized shape liquefied ejecta are mostly greater than 1m.The maximum diameter is about 10m.The volume of the ejecta is about 10m^3.The string beads shape liquefied ejecta embodies as a combination of multiple central forms. The maximum extension length is more than 20m.The diameters of liquefied hole are from 20cm to 4m. The maximum depth of the liquefied hole is 4m.

（a）

（b）

Fig.4 Typical sites of liquefaction(a. Central eruption,direction 28 ； b. beaded eruption,direction 354°)

The liquefaction did not cause extensive damage to buildings. There are only two sites which are found in the village committee office of Jiangjia (Figure 5a,Figure 5b) and an house in Cuijia(Figure 5c,Figure 5d), both of them are one-storey masonry structure. Liquefied sand spout from the concrete floor joints in the village committee square of Jiangjia, the coverage area is about 30m*40m.The sand also spout from the corner of office building foundation, but just has slight damage to the building. The only one serious building damage is the house in Cuijia. The interior floor is full of liquefied sand. This masonry house has no ring beam and construction column. Liquefaction caused building settlement and wall crack. There are two types of liquefied sand in this earthquake: yellow fine sand and gray fine sand.

（a）

（b）

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(c)

（d）

Fig.5 Construction damage induced by liquefication

2.3 Field test investigation

On the basis of the survey mentioned above, drilling investigation was carried out in the epicenter region of the earthquake. Through sampling drilling to the typical soil layer, the data of soil layer burial, physical and mechanical indexes of soil in liquefied and non-liquefied sites were obtained. The standard penetration test (SPT) and cone penetration test (CPT) measurement in the earthquake site were conducted. The results of the tests will provide valuable data for the research and modification of liquefaction estimation methods[10-16].

Figure 7 illustrates the distribution of all the field test sites. All of those sites are located in Ⅶ degrees region. Six drilling sites were selected in the earthquake sites, including three sites with surface spray sand eruption and three sites without sand eruption. The footage of each drilling hole is about 20m.Typical soil layer samples were taken and standard penetration were carried out. Thirteen cone penetration test (CPT) sites were selected, including four sites with surface spray sand eruption and nine sites without sand eruption. Meanwhile, six of them coincide with the drilling sites. The CPT probe is an JMS-15A-3 with cone bottom of 43.7mm, cone tip area of 15cm^2, friction cylinder surface area of 300cm^2 and the cone angle of 60°. The weight of CPT truck is 20 tons. A great deal of work on the methods of determining liquefaction by CPT have been done. And good results are been got in engineering practice [12-14]. In the CPT data analysis process, the soil layer with high resistance at the cone tip and low lateral friction resistance is judged as sand layer, the soil layer with low cone tip resistance and low lateral friction resistance is classified as liquefied soil layer. This judgement is under the premise that the site is located in the liquefaction region.

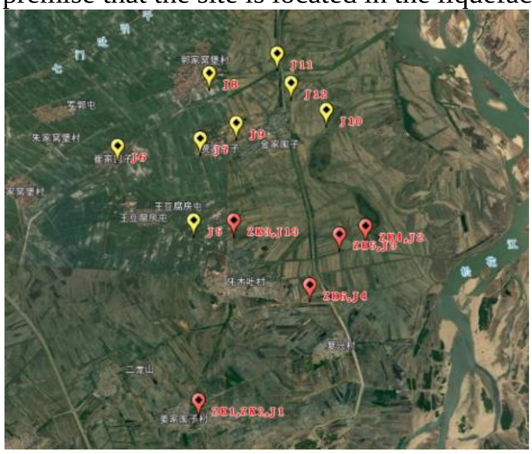

Fig.7 Distribution of drilling and CPT(ZK-Drilling point;J-CPT point)

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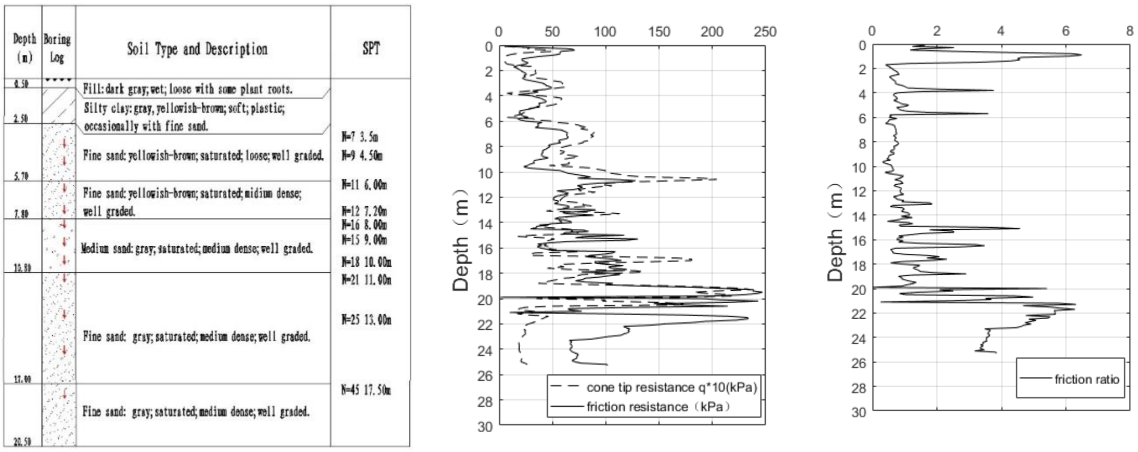
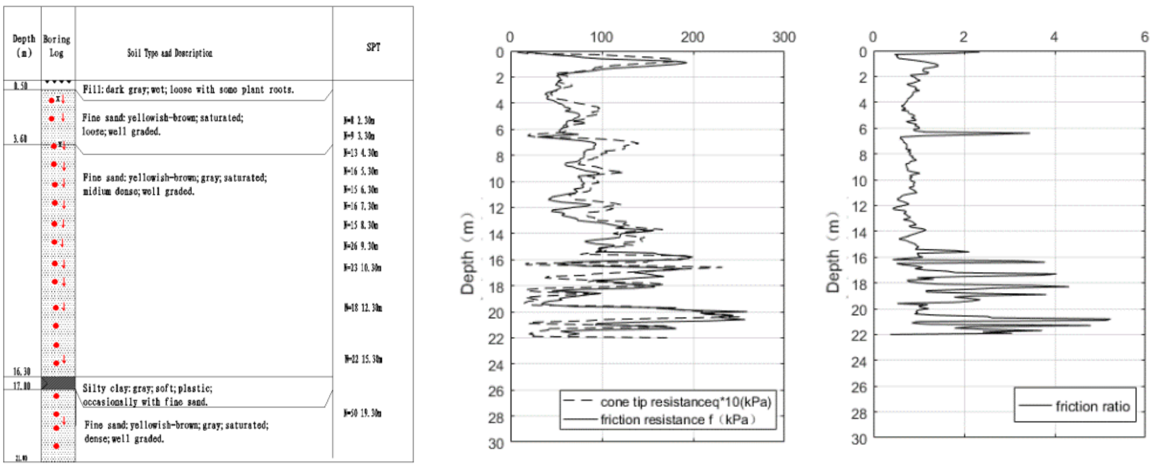
Figure 8 shows the test results of a sand spraying site, which is located next to a rice field with full water. It can be seen from the drill hole histogram (Figure 8a) that the soil layer structure of this site is relatively simple. The underground water level depth is 2.5m. From 0m to 2.5m underground, there is a clay confining bed with humus plant roots. Under this layer, there are saturated yellow fine sand, gray fine sand and gray medium sand, from top to bottom. Under the depth of 20m, there is also a clay confining bed. The CPT profile (Figure 8b) has good correspondence with drilling profile. The characteristics of cone tip resistance and lateral friction resistance of each soil layer are clear, and the liquefied layer from 3m to 4m are exposed. The CPT result, combined with drilling data and SPT data, prove the reliability of the CPT discriminating principle of soil layer and liquefaction layer.



(a) (b) (c)

Fig.8 Borehole profile and CPT data of liquefaction site （a Drill column b Blow counts of SPT c The data of CPT）



(a) (b) (c)

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（d）

Fig.9 Borehole profile and CPT data of un-liquefaction site(a Drill column b Blow counts of SPT c The data of CPT d Deep liquefaction channel)

Figure 9 shows the test results of a non sand spraying site, which is located next to dry farmland. The buried depth of underground water level of this site is greater than the above sand spraying site, which is about 5m. From 0m to 0.5m underground, there is a clay layer with humus plant roots. Under this layer, there are also saturated yellow fine sand, gray fine sand and gray medium sand, from top to bottom. From 16.3m to 17m underground, there is a gray-black silty clay layer. Under the silty clay layer, there is a fine sand layer including yellow sand and gray sand. Field drilling and sampling results show that the yellow fine sand layer at the depth of 6-7m appears as slightly liquefied. This phenomenon is also reflected in the CPT profile (Figure 9b). And more notably, deep liquefaction is observed on this site. Due to the liquefaction of the lower sand layer, an upward channel of liquefied sand leave at the clay layer in the depth of 17m. Drilling samples reveal this phenomenon directly (Figure 9d). Meanwhile, as it is shown in Figure 9b, the CPT cone tip resistance and lateral friction resistance of sand layer in the depth of 18-19m are relatively low. These results fully prove that deep sand liquefaction occur in this site, and the depth is between 18 and 19m.

3. Special soil liquefaction

3.1 Macrophenomena of special soil liquefaction

A special type of liquefaction ejecta is found during the post-earthquake field investigation, gray-black soil particles similar to silty clay. Figure 10 shows the field appearance of the special soil liquefaction in Wangjia village. The diameter of the ejecta in surface of the ground is about 6 m, the thickness is about 15cm. This soil is in the form of round particles, the size is about 3~5mm, soft, with large viscosity, and it can be rolled into clay strips. There are many fine hard particle in this special soil, and Fe-Mn nodules are found.

Fig.10 The field appearance of the special soil liquefaction in Wangjia village.

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According to the surface phenomenon and field evaluation, this soil is not common sand. Bo, Shen et al. indicated that there is a sub-clay or loess layer distributed in this area and it is buried in shallow underground. Moreover, historical earthquake damages and laboratory experiments demonstrated that saturated loess is easily to liquefy under Ⅶ degree earthquake intensity. In order to make judgments about the type of liquefied soil, SEM, XRD, XRF were performed. These tests preliminary estimate that this soil is loess. That is to say, loess liquefaction occurs in the epicenter region of Songyuan M5.7 earthquake.

3.2 Micro-morphology and composition analysis

The morphology of the soil is characterized by scanning electron microscope(SEM). The test sample is post-liquefaction soil taken from the ground surface. By using the Hitachi SU8020 field emission scanning electron microscope, pores and soil matrix particles of the sample are detected. Figure 11 shows the 200,800,2000 magnifications images. The scanning result indicate that: a)Soil particles are not only composed of rounded sand particles but also flat clay particles, and the proportion of flat clay particles is high. b)The primary structure of the soil was destroyed, the ratio of small void and medium void is larger than big void, the particle cement form is contact-basal cementation. It is accord with the micro-morphology change of liquefied loess (Wang, Liu et al.2000).

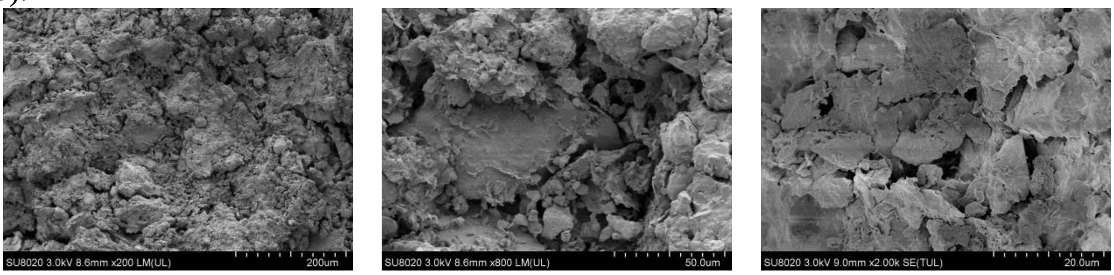

Figure 11 The SEM images of the liquefied soil sample(a.200 times b.800 times c.2000 times)

Liu summarized the material composition of Chinese loess, indicated that there are 3 main mineral compositions of loess: quartz, feldspar and carbonate. To find out material and mineral composition the liquefied soil, XRD and XRF tests were performed. Figure 12a shows the mineral compositions of the liquefied soil. The soil is composed of quartz(53.48), albite(22.51%), orthoclase(5.52%) and kaoline(3.23%), illite(15.26%). Figure 12b and Figure 12c show the element and elemental oxide compositions of the liquefied soil, respectively. Table 1 is the comparison of physical and chemical indicators between the liquefied soil and Malan loess. By the physical property, the liquefied soil is a kind of silty clay, it conform with the characteristics of loess. In terms of chemical composition, the proportions of SiO_2 and Al_2O_3 are in the interval. The proportion of Fe_2O_3 is higher and CaO is lower. These are because that the liquefied soil sample is taken from the ground surface, during liquefaction and ejection, the Fe^{2+} is oxidized to Fe^{3+}, the FeO translate into Fe_2O_3, the content of Fe_2O_3 increase. Meanwhile, the carbonate is dissolved, so the content of CaO decrease. In general, physical and chemical indicators of the liquefied soil meet the standard of loess.

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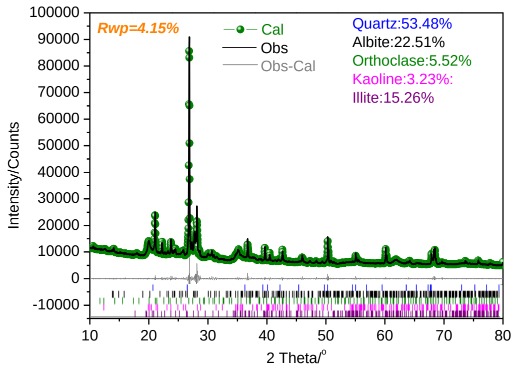
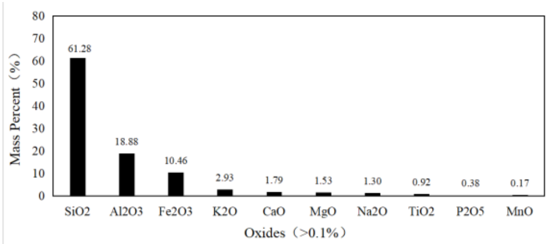
Table 1 Comparison of physical and chemical indicators

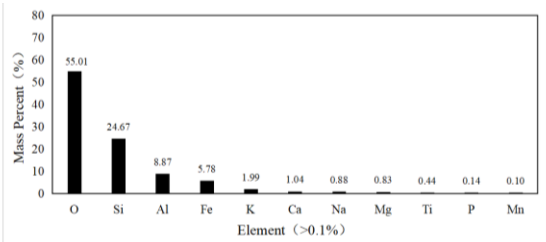
soil	**chemical component content (%)**				**physical property**	
	SiO_2	**Al_2O_3**	**Fe_2O_3**	**CaO**	**plasticity index**	**clay content (<0.075mm)(%)**
Liquefied Soil sanmple	61.3	18.9	10.5	1.8	13	20.5
Malan loess (by Liu.)	>60		3~6	7.5~10.5	7.6~15.7	7.0~30.4



(a)



(b)



(c)

Figure 12 The mineral compositions and element and elemental oxide compositions of the liquefied soil(a.mineral b. oxide elemental c.element)

3.3 Discussion

According to the preliminary investigation and laboratory test results, we infer that the special soil found in liquefied site is loess. This is the first time loess liquefaction found in northeast of China. However, due to time and financial constraints, drilling is not conducted in this site, no undisturbed soil samples are obtained. The information of occurrence condition, natural density and moisture content is incomplete. The mechanism and influencing factors of the special soil liquefaction still need further study.

4. Conclusions and discussions

Through the seismic site investigation, drilling, CPT and other work, the seismic damage and site characteristics in the epicenter area of the M5.7 Songyuan earthquake are obtained. The phenomenon of liquefaction in this earthquake and its influencing factors are preliminarily explained.
1.The main feature of the liquefaction is the surface damage of rice fields, There was no large-scale building destruction. The soil layer is relatively simple in the earthquake region, the distribution of liquefaction is mainly controlled by ground motion, landform and groundwater level.
2.Deep liquefaction. Shallow liquefaction mainly occurs in the soil layer above 10m.The occurrence of shallow liquefaction is easy to cause the surface damage like sandboils and waterspouts, which are easy to distinguish. The deep liquefaction is often neglected in field investigation. In this paper, we reveal an upward

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channel of liquefied sand in the clay layer buried at the depth of 16.3~17m,which are caused by the liquefaction of the lower sand layer. It proves that significant deep liquefaction occur at the depth of 18~19m.This phenomenon is rare in previous field investigation. Moreover, the success rate of discriminating deep liquefaction is low using the present code method. More work should be done on the discrimination methods of deep liquefaction.

3.Determination method of field liquefaction. This survey shows that, liquefaction can also occur in sites without the surface macrophenomena. Traditional field investigation methods are difficult to distinguish. Efficient and feasible methods should be explored. Compared with drilling and SPT,CPT has the unique advantage of speed and accuracy. It can be applied in post-earthquake investigation to provide reference for sand liquefaction distinguish. However, due to the lack of seismic data, the criterion and experience of this method need more study and accumulation.

4.Special soil liquefaction. The loess liquefaction is first found in northeast of China. The mechanism and influencing factors of the special soil liquefaction still need further study. However,it indicates that this region has the risk of unique earthquake disasters of special soil like loess. In addition to the sand liquefaction, we should pay attention to the special soil liquefaction.

5.High liquefaction risk in Songyuan. Songyuan city is one of the only two cites of VIII seismic fortification intensity in northeast of China. The seismic activity in this area is frequent and characterized by earthquake swarm sequence. And the site soil layer structure is thick loose sand, the groundwater is shallow buried. Earthquake damage and the investigation shows that there is a high risk of larger liquefaction damage in Songyuan city. Therefore,specialized research for the liquefaction disaster in Songyuan is needed in earthquake disaster reduction planning and construction engineering design projects.

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