Earthq Eng & Eng Vib (2009) 8:219-229 **DOI**: 10.1007/s11803-009-9033-4

Liquefaction macrophenomena in the great Wenchuan earthquake

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Abstract: On May 12, 2008 at 14:28, a catastrophic magnitude M_s 8.0 earthquake struck the Sichuan Province of China. The epicenter was located at Wenchuan (31.00ºN, 103.40ºE). Liquefaction macrophenomena and corresponding destruction was observed throughout a vast area of 500 km long and 200 km wide following the earthquake. This paper illustrates the geographic distribution of the liquefaction and the relationship between liquefaction behavior and seismic intensity, and summarizes the liquefaction macrophenomena, including sandboils and waterspouts, ground subsidence, ground fissures etc., and relevant liquefaction features. A brief summary of the structural damage caused by liquefaction is presented and discussed. Based on comparisons with liquefaction phenomena observed in the 1976 Tangshan and 1975 Haicheng earthquakes, preliminary analyses were performed, which revealed some new features of liquefaction behavior and associated issues arising from this event. The site investigation indicated that the spatial non-uniformity of liquefaction distribution was obvious and most of the liquefied sites were located in regions of seismic intensity VIII. However, liquefaction phenomena at ten different sites in regions of seismic intensity VI were also observed for the first time in China mainland. Sandboils and waterspouts ranged from centimeters to tens of meters, with most between 1 m to 3 m. Dramatically high water/sand ejections, e.g., more than 10 m, were observed at four different sites. The sand ejections included silty sand, fine sand, medium sand, course sand and gravel, but the ejected sand amount was less than that in the 1976 Tangshan earthquake. Possible liquefaction of natural gravel soils was observed for the first time in China mainland.

Keywords: Wenchuan earthquake; post-earthquake investigation; liquefaction; macrophenomena

1 Introduction

Liquefaction is one of the most significant, interesting, complex and controversial topics in geotechnical earthquake engineering (Kramer, 1996). Many research efforts have been devoted to obtaining a better understanding of this phenomena and great progress has been achieved (Seed and Idriss, 1971; Seed, 1979; Robertson and Fear, 1995; Youd *et al.*, 2001; Ku *et al.*, 2004; Lin *et al.*, 2007). Post-earthquake investigations are a fundamental way to gain earthquake knowledge and experience for engineering purposes. It also provides the basis for seismic resistant design theories and analytical tools. In previous earthquakes in China mainland, e.g. Heyuan (1962), Xingtai (1966), Tonghai (1970), Haicheng (1975) and Tangshan (1976), detailed post-earthquake investigations have facilitated the development of earthquake engineering and seismic resistant techniques in China (Hu, 1988; Liao, 1989; IEM, 1979; Liu *et al*, 2002).

At 14:28 May 12, 2008, a devastating earthquake of magnitude M_s 8.0, the epicenter of which was located at Wenchuan (31.0°N, 103.4°E), struck the Sichuan Province, causing severe loss both to human lives and the national economy. This was one of the most catastrophic earthquakes that occured in China since the 20th century. During the post-earthquake in-situ investigation, liquefaction phenomena were widely observed. Other than ground shaking, liquefaction was responsible for the most severe damage to civil engineering structures and facilities.

At the initial stage of the event, the extent and distribution of liquefaction was controversial and scarcely reported. Since mid-July 2008, i.e., two months after the earthquake, a specific team organized by the Institute of Engineering Mechanics, CEA conducted a detailed field investigation of liquefaction phenomena. Subsequently, more liquefied sites were detected during the investigation, which covered Chengdu, Mianyang, Deyang, Leshan, Meishan, Suining and Ya'an areas. Liquefaction-induced damage was also widely observed on liquefied sites, e.g., ground fissures, ground subsidence, cracks in roads, settlement/

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Supported by: National Natural Science Foundation of China Under Grant No.50638010; the Foundation of Ministry of Education for Innovation Group Under Grant No. IRT0518

Received March 31, 2009; **Accepted** April 10, 2009

differential settlement of buildings, etc. The liquefaction macrophenomena and preliminary analysis presented in this paper reveal new features of liquefaction behavior that were remarkably different from those observed in previous earthquakes, which could be helpful in further research and provide a basis for reviewing existing theories of soil liquefaction.

2 Liquefaction distribution

Figure 1 presents a distribution map of the observed liquefied sites. Note that these sites are located within a long narrow belt-shaped region that is almost parallel to the orientation of the active fault (Longmenshan fault) that generated the earthquake. This distribution feature may be closely related to the local hydrological and geotechnical site conditions, however, further investigation is needed to verify this assumption.

So far, 118 liquefied sites have been detected. One liquefied site is defined as a typical village or town within which one or more liquefied points were observed. Thus, at least a 2-km distance exists between two adjacent liquefied sites. The total liquefied area (the rectangle as shown in Fig.1) is estimated to be approximately 500 km long and 200 km wide in regions of seismic intensities of VI and more covering Chengdu, Deyang, Mianyang and some sites in Suining, Ya’an, Meishan and Guangyuan. Note that liquefaction has never before been reported in regions of seismic intensity of VI in China. However, in this event 10 liquefied sites in regions of seismic intensity of VI in Chengdu, Meishan, Leshan, Ya’an and Suining (Fig. 1) were observed.

In the meizoseismal areas of seismic intensities of X and XI, soil liquefaction was not frequently observed due to local geological site conditions. From the distribution map (Fig. 1), most observed liquefied sites were concentrated in a rectangular area approximately 160 km long and 60 km wide. The long side of the rectangle is consistent with the longitudinal direction of the isoseismals. Areas with major liquefaction include Chengdu, Deyang and Mianyang.

The region within the red circle in Fig. 1 shows the distribution of the liquefied sites in the Chengdu area, which covers seismic intensities of VI, VII, VIII and IX. However, most liquefied sites concentrated in the subarea of Dujiangyan had a seismic intensity of VIII.

The region bounded by the green circle in Fig. 1 illustrates liquefaction in the Deyang area, which was the most seriously affected among the three major liquefied areas. Liquefied sites located in Mianzhu City, Shifang City and Deyang City had seismic intensities of VII, VIII and IX. However, most of the liquefied sites were in regions of seismic intensity of VIII.

Liquefaction behavior in the Mianyang area, i.e., the least significant among the three, is shown in the region bounded by the yellow circle in Fig. 1. Most of the liquefied sites were distributed in Xianyou District and Jiangyou City, with seismic intensities of VII and VIII. From a geological point of view, the Mianyang area is mainly hilly land, thus liquefaction phenomena was relatively rare.

3 Liquefaction macrophenomena

3.1 Sandboils and waterspouts

Sandboils and waterspouts forming at the ground surface provide qualitative evidence that the ground had indeed liquefied as a result of shaking, and the height and

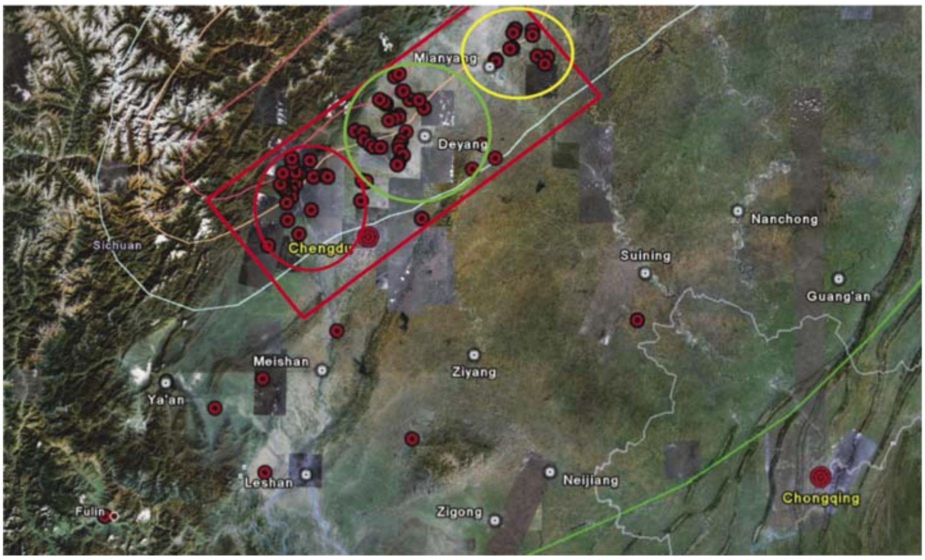

Fig. 1 Distribution map of liquefied sites (Red points represent the observed liquefied sites and the colorful lines represent the boundaries of different intensities (China scale); the big colorful circles bound the liquefied sites in Chengdu, Deyang and Mianyang areas, respectively)

amount of water/sand ejection can reflect the depth and thickness of the liquefied soil layer. Figure 2 statistically presents the number of liquefied sites versus the height of water/sand ejections. Obviously, the heights at most liquefied sites are within 1 m to 3 m. However, there are four sites with water ejection height of more than 6 m. These sites are located in Chengdu, Mianyang, Ya'an and Deyang areas, respectively, with the closest distance between two adjacent liquefied sites at more than 30 km. Using the liquefied site in Xiangliu Village of Mianzhou City as an example, the water ejection had a height of about 15 m, or double the height of the electric pole (Fig. 3). Such phenomena of high water/sand ejection have seldom been observed in previous earthquakes. Preliminary analysis indicates that they may have been caused by deep soil liquefaction.

In addition, most sandboils and waterspouts caused by liquefaction had a duration of several minutes or less, much shorter than that in the Tangshan earthquake. Such phenomena seem to be related to local site conditions. The geotechnical investigation indicates that thick gravelly soil layers are common in Chengdu Plains. With a high permeability of this gravelly soil layer, the accumulated pore water pressure could be quickly dissipated. Nevertheless, in some places the duration of water spouting was rather long. For example, in Xinlian Village of Leshan City located more than 200 km from the epicenter, water spouting of 1 m high and sand ejection of fine sands and gravels occurred just following the earthquake, and water spouting lasted over three months (Fig. 4). The long duration of water spouting may be explained by the re-distribution of water pressure or flowing of the underground water due to the ground fissure. However, the mechanisms of these behaviors are unclear and a detailed investigation by borehole should be conducted.

Figure 5 shows sand boils and aligned sand boils following the earthquake. Compared with previous cases (Hu, 1988; Liao, 1989; IEM, 1979; Liu *et al*, 2002), the sand amount ejected in this event was generally not remarkable. The site investigation shows that a thick pure sand layer can hardly be detected, but loose gravelly sandy soil layers exist universally. In the 1976 Tangshan earthquake, for example, the sand that was ejected was buried in a vast area of farmland, since the local soil in the Tangshan area contains thick pure sandy layers. However, there are also some typical sites with a relatively large amount of sand ejection. In Siyuan Village of Shifang City, for example, an initially empty swimming pool of 50 m × 20 m × 2 m was filled with ejected sand and water 1 m deep after the earthquake (Fig. 6). Moreover, a crack of about 50 m long occurred on the ground close to the swimming pool. Sand also ejected from the crack during the earthquake.

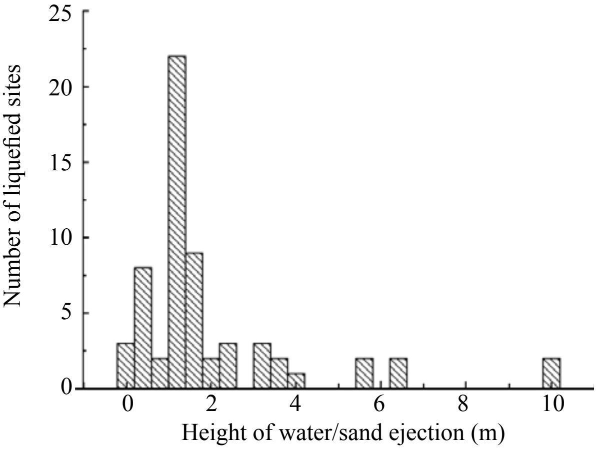

Fig. 2 Statistics of the height of water/sand ejection versus the number of liquefied sites

Fig. 3 Liquefied site with a high water ejection of about double the height of the wire pole and a visible ground failure (Photo by WM Wang)

Fig. 4 Yellow ejected sand and water in Xinlian Village of Leshan City, where water spouting lasted more than 3 months (Photo by LW Chen)

Fig. 5 Large sand boil (left) and aligned sand boils along the crack in the ground (right) in Mianyang area (Photo by ZZ Cao)

Fig. 6 Previously empty swimming pool filled with ejected sand and water of about 1m in depth after the earthquake (Photo by ZZ Cao)

3.2 Ground subsidence

The ground usually subsides following sandboils and waterspouts caused by liquefaction. During the post-earthquake in-situ investigation, typical ground subsidence was observed in ten villages. For example, in Xiangliu Village of Mianzhu City, eight pits of 3 m to 4 m in diameter and 1 m to 2 m in depth were found throughout the farmland areas (Fig. 7). In the Caidikan Village of Meishan City on the 14th of May (i.e., the third day after the main shock), water spouting suddenly started and lasted about one minute. Subsequently, a large pit of 2 m in diameter and 2 m deep appeared (Fig.8). Pits or ground subsidence created by liquefaction can result in severe destruction to adjacent structures. Figure 9 illustrates a large pit created by liquefaction that destroyed an adjacent house.

Fig. 7 Large pits of about 3 to 5m in diameter (left) and ground failure (right) were created by water/sand ejection in Xiangliu Village (Photo by WM Wang)

Fig. 8 Pit of 2 m in diameter caused by water spouting in CaidikanVillage (Photo by ZZ Cao)

Fig. 9 Large pit of about 3 m in diameter destroyed a house (Photo by ZZ Cao)

3.3 Ground fissures

Ground fissures were observed at 70% to 80% of the liquefied sites with various lengths from tens to thousands of meters (Fig. 10). In Fig. 10 (a), sand was ejected from the ground fissure created by liquefaction. Figure 10 (b) shows similar examples in Dujiangyan City, where a ground fissure of about 30 m long and a maximum width of 0.5 m was created just adjacent to the sand ejection point (Fig. 10 (b), left). Ground fissures can be dangerous to structures or aggravate structural damage, e.g., tilt and settlement of buildings, etc. Alternatively, liquefaction may have a positive shock absorption effect on structural damage as observed after the Tangshan and Haicheng earthquakes (Hu, 1988; IEM, 1979; Liu *et al*, 2002). However, this phenomena was not detected in this investigation.

The liquefied sites are identified by the macrophenomena discussed above, e.g., sandboils and waterspouts. However, liquefaction detection is a sophisticated technique; in some cases it cannot be assumed that a site without visible sandboils and waterspouts was a non-liquefied site. For example, in Xinglong Town of Mianzhu City, there was no evidence of water spouting but many wells were filled with sandy soil just after the event, indicating that the underground soil had liquefied. Therefore, the actual liquefied area may be much larger than observed.

4 Materials ejected and possible liquefied soils

Various sand categories, including silty sand, fine sand, medium sand, course sand and even gravelly sand have been visualized from the ejected materials following the earthquake.

4.1 Silty sand and fine sand

Generally, 50% to 60% of the ejected materials are silty sand and fine sand (Fig. 11). For example, in Xinglong Village of Banqiao Town, the yellow fine sand ejected from a ground crack generated by liquefaction. The crack penetrated a house and resulted in damage to both the house and its foundation (Fig. 11; left).

(a) Ground fissure and sand ejected

(b) Ground fissure and visible sand ejected

Fig. 10 Ground fissures caused by liquefaction and the sand ejected during the earthquake (Photo by LW Chen)

Fig. 11 Grey and yellow fine sand ejected to the ground following liquefaction behaviors (Photo by JS Bo and ZZ Cao)

4.2 Medium sand and course sand

During the investigation, it was noticed that 20% to 30% of the ejected materials are medium sand and course sand (Fig. 12). Figure 12 is an example from Bilu Preliminary School. The classrooms of the one-story brick-concrete structures were jeopardized by liquefaction and torn down afterward.

Fig. 12 Medium sand was ejected to the ground in Bilu Preliminary School and caused the destruction of the classrooms (Photo by ZZ Cao)

Fig. 13 Gravelly sand of 3 cm to 15 cm in diameter ejected to the ground (Photo by SY Li and ZZ Cao)

4.3 Gravelly sand

One typical observation of liquefaction is gravel ejected to the ground. Figure 13 shows evidence of this behavior, which was observed for the first time in China mainland. About ten sites with gravelly sand ejected were found during the post-earthquake investigation. The corresponding ejected material contained gravels an average of 3 cm to 15 cm in diameter. The phenomena indicate that even a site of gravel can liquefy. In previous earthquakes, for example of the 1994 Hokkaido-Nansei-Oki earthquake, the soil containing large cobbles of 20 cm to 30 cm in diameter had been liquefied. This behavior also occurred in the 1995 Kobe and 1999 Chi-Chi earthquakes. The susceptibility of gravelly soil needs to be evaluated properly for seismic resistant design with suitable and feasible methods.

In Baihutou Village of Mianzhu City, a well of 3 m deep was filled with ejected material containing large-diameter gravels (Fig. 14) after the earthquake. The diameter of gravel varies from several centimeters to tens of centimeters. Figure 14 shows the material sampled from the well.

4.4 Possible liquefied soils

During the post-earthquake investigation, most ejected materials were found to be silty sand and fine sand. Thus, the liquefied soils were initially thought to be silty sand layers and fine sand layers. However, the special site conditions in the Chengdu Plains did not correspond to this assumption. According to geological and geotechnical documents (He, 1992), the soil profiles of the Chengdu Plains contain thick alluvial and diluvium gravel layers with thicknesses ranging from meters to tens of meters. Pure thick sandy layers were not found, even though pure sand ejection was common. It can be concluded that the gravelly soil liquefied. The evidence of gravelly sand ejection supports this observation. In addition, the relatively short time of the occurrence of sandboils and waterspouts provided more evidence to support this theory. Due to the high permeability of the gravelly soils, the pore water pressure dissipated quickly. Therefore, currently available methods to evaluate liquefaction potential (Harder and Seed, 1986; Harder, 1997; Seed and Idriss, 1971; Shibata and Teparaska, 1988) are not applicable for the Chengdu Plains.

5 Liquefaction behavior under aftershocks

In Guoyuan Village of Deyang City located in a region of seismic intensity of VII, waterspouts and sandboils were observed on the day following the main shock. However, the same phenomenon re-occurred during an aftershock of magnitude M_S6.4 (Fig. 15).

Generally, the liquefied soil layer tends to be denser during the consolidation afterward. Thus, the possibility of liquefaction re-occurrence would be much lower (Youd, 1984). In the 1979 Montenegro earthquake (*M* 7.1), for example, buildings on one liquefied site almost remained intact during the main shock due in large

Fig. 14 Gravel sand sampled from the well in Baihutou Village of Mianzhu City (Photo by ZZ Cao)

Fig. 15 Liquefaction reoccurrence following the aftershock (left) and subsidence of the house adjacent (right) (Photo by WM Wang)

part to the absorption effect offered by the liquefied soil layers at the site (Li *et al*, 1992). However, these buildings were seriously damaged by an aftershock one month later. This observation can probably be explained as follows: the liquefaction caused by the mainshock made the site much denser and stiffer, and as a result, the predominant period of the effective input motions became closer to the vibration periods of the buildings.

6 Liquefaction-induced damage to structures

In the post-earthquake investigation, liquefaction-induced damage to structures and infrastructures observed included factories, roads, bridges, and farmlands, etc. Figures 16, 17 and 18 show some examples. In Fig. 16, for example, sand ejection and water spouting occurred around a teaching building of Zhongxing Middle School in Dujiangyan City. Consequently, the entire building subsided, resulting in deformation of the window frames. In Fig. 17 (left), sandboils and waterspouts occurred close to a bridge and caused it to subside and become unusable. Severe liquefaction is shown in Fig. 17 (right), with the water ejection height of 1 m, and 10 cm to 16 cm lateral spreading at a country road in Dujiangyan City, resulting in road damage. At the liquefied sites, poorly constructed houses without any consideration of seismic resistant design collapsed, and confined masonry houses/buildings subsided or tilted. For example, at Banqiao School, the main teaching building that was almost intact was torn down due to the settlement and tilt of the structure and foundation caused by liquefaction (Fig. 19). Another typical example is the Jianyou Railway Station (Fig. 20). Apparently, the station was intact after the earthquake (Fig. 20 (a)). However, a detailed investigation found that its foundations subsided due to subsoil liquefaction (Fig. 20 (b)), and ejected sand was visible inside the station and caused ground cracks.

A typical feature of liquefaction behavior was its

Fig. 16 Liquefaction-induced settlement/differential settlement caused the deformation of the window frames in Zhongxing Middle School in Dujiangyan City (Photo by LW Chen)

Fig. 17 Liquefaction-induced destruction to bridge (left) and road (right) (Photo by ZZ Cao and FC Meng)

Fig. 18 Liquefaction- along with ground shaking, induced destruction to factories (Photo by ED Guo)

Fig. 19 Sand ejected in the school yard (left) and liquefaction-induced destruction/tilt of the main teaching building (right) of Banqiao School. (Photo by LW Chen)

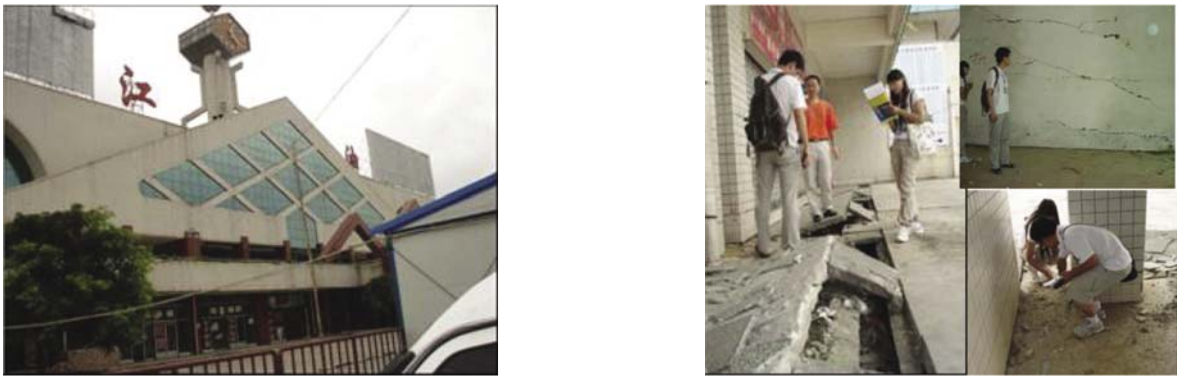

Fig. 20 Liquefaction-induced destruction of Jiangyou Railway Station along with ground shaking, including ground cracks and foundation settlement (Photo by WM Wang and L Dong)

impact on structural damage. For example, in Baijiang Village of Deyang City, sandboils and waterspouts were observed at the base of a house (Fig. 21). The house, which was a 2-story brick structure, was seriously damaged and tilted with differential settlement (Fig. 21 (a)); its floor had been removed because of the severe destruction. However, other houses in the neighborhood were almost intact (Fig. 21 (b)). Similar features were observed at some other liquefied sites during the field investigation. Note that most of the ground fissures generated by liquefaction were not uniformly distributed.

(a) Differential settlement caused by liquefaction

(b) Houses in the neighborhood of the house in (a) are almost intact

Fig. 21 Liquefaction-induced structural damage along with ground shaking in Baijing Village of Deyang City (Photo by L Dong)

7 Conclusions and discussion

Through detailed in-situ investigation of liquefaction following the great Wenchuan earthquake, the following conclusions can be drawn:

(1) The area that liquefied in this event was vast, involving an area of about 500 km long and 200 km wide including Chengdu, Deyang, Mianyang and some sites in Suining, Ya'an, Meishan and Guangyuan. The most affected areas were Chengdu, Deyang and Mianyang areas, involving a rectangular area of 160 km long and 60 km wide. Compared with previous earthquakes in China mainland, the spatial distribution of liquefaction following the Wenchuan earthquake was not uniform. The non-uniformity is particularly associated with the complex geological and hydrological site conditions of the affected area. The liquefied sites were distributed in various regions of different seismic intensities, but most were located in regions of seismic intensity VIII. Note that even in regions of seismic intensity VI, liquefaction behavior at ten different sites was observed. The phenomena of liquefaction occurring in low-intensity regions have not been reported in historic earthquakes in China mainland.

(2) The heights of water ejection range from centimeters to tens of meters. In most cases, the heights of water/sand ejection were 1 m to 3 m. For extremely high water ejection, i.e., more than 10 m, the controlling mechanism and a reasonable explanation needs to be explored. Site conditions are certainly an important factor related to these phenomena. In addition, the duration of sandboils and waterspouts was several minutes for most cases, which is shorter than in the Tangshan earthquake. The different site conditions in the affected areas of the two earthquakes should be further investigated. Many ground fissures and cracks were visualized on the liquefied sites in this event, resulting in structural damage. The relationship between liquefaction and ground fissures needs to be studied further.

(3) The amount of sand ejected was generally less than in the Tangshan earthquake. However, the type of sand varied, including silty sand, fine sand, medium sand, course sand and gravel. This was the first time natural gravel was observed to liquefy in China mainland. From the site investigation, the actual number of sites that sustained gravelly sand liquefaction could be much greater than observed. New research should be conducted to address these issues.

(4) The liquefaction behavior caused by the aftershock in Guoyuan Village of Deyang City is also an interesting issue, noteworthy of further research. Furthermore, research on the factors that influence the liquefaction resistance of soil needs to be extended and corresponding evaluation methods should be developed.

(5) Liquefaction behavior following the earthquake caused damage to farmland, roads, bridges, residential houses, factories, schools, etc. that outweighed its energy-absorption benefits. Preliminary analysis reveals that liquefaction induced structural damage may be closely related to ground fissures and the non-uniformity of the liquefaction distribution within the liquefied site.

(6) Liquefied sites were determined from macrophenomena such as sandboils and waterspouts. Some incorrectly identified non-liquefied sites certainly exist. New reliable methods to identify liquefied or non-liquefied sites need to be developed. The technique of liquefaction detection is a sophisticated task, but distinguishing liquefied sites from non-liquefied sites is of considerable benefit to engineering practice.

The preliminary analyses in this paper reveals new phenomena of the liquefaction behavior in this earthquake and new liquefaction issues worthy of further research are identified. Further clarification of some of the new phenomena observed in this event is necessary and the mechanisms for these new characteristics should be identified further by borehole investigation. Relevant investigations are being conducted and further results can be expected.

Acknowledgement

The authors gratefully thank Prof. Jingshan Bo, Prof. Zhenghua Zhou, Prof. Endong Guo, Prof. Aiwen Liu for providing photos and documents. Also the authors thank the Sichuan Earthquake Bureau and the local governmental institutions for their cooperation and kind help. All their help is sincerely appreciated.

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