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INTERPRETING THE HEIGHT OF LIQUEFACTION EJECTION FOLLOWING THE 2008 WENCHUAN EARTHQUAKE, CHINA

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ABSTRACT

Sand-spout and water ejection are common observations caused by liquefaction, and also are the main indicators to identify site that liquefied. Height of liquefied ejection relates with the buried conditions of liquefied soil. A simple model, adopting Bernoulli equation in hydraulics, is used to deduce the height of liquefaction ejection which correlated with liquefied soil buried depth and water table. The predicted height is compared to field investigation data from 2008 Wenchuan earthquake. It is indicated that high liquefaction ejection should deep soil buried depth or deep water tables. The height of ejection is controlled by overburden effective stress and frictional water-head loss. Analyzing of field test data of 22 liquefied sites, the liquefaction ejection predictions are generally consistent with the observations, yet variability and uncertainty exist. On the considerable inconsistency of prediction with observation, possible explanations are illustrated. To determine liquefied layers is a fundamental task which takes into account of many factors as well as in-situ test data, but the height of liquefaction ejection can assist and verify the liquefied layers.

Keywords: Wenchuan earthquake; liquefaction; water-ejecting height; Bernoulli equation

1. INTRODUCTION

Sand liquefaction is one interesting and controversial natural phenomena, but it can cause tremendous loss during earthquakes (Kramer 1996). Since 1964 Alaska, USA, and Niigata, Japan, earthquakes, liquefaction has become a meaningful topic in geotechnical engineering. In recent earthquakes, liquefaction still is the main concern from engineering point of view (e.g., Cubrinovski et al. 2011; Bhattacharya et al. 2011; Cox et al. 2013). The main affects by liquefaction express in spreading, settlement and ground fissures by water ejecting. Post-earthquake investigation is a fundamental way to gain the earthquake knowledge and experience for engineering purposes, and also is the foundation for seismic resistant design theories and analytical tools. Lessons from earthquake investigation can affiliate the practice and theory of seismic design (IEM 1979; Liu *et al.* 2002; Youd et al. 2001; Idriss and Boulanger 2015).

During past earthquakes in China, the liquefaction investigation solidifies the understanding of liquefaction and helps scientists and engineers mitigate its impact. Water-ejection and sand sprout are the main indicators to determine sites that liquefy. Liquefaction ejecting usually lags behind the shock for several seconds, since it takes time for the pore-water pressure to build up to liquefy soils and eject water and sand above ground. Water-ejecting and sand sprout are natural process of liquefaction, but these phenomena can cause emotional fear to locals. During field investigation, many locals reported that the scene of water ejecting and sand mixed with "black/yellow" mud was threatening and horrible. So, to interpret the water-ejecting caused by liquefaction is meaningful work. Generally, liquefaction ejection is a short process and ceases after a few seconds to several minutes. The liquefaction ejecting height data are difficult to obtain, mainly are from the witnesses description and marks left by ejection.

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Subjective uncertainty and variability stay large, but the ejection height data can reflect the scale and extent of liquefaction impact.

On May 12, 2008, a massively devastating M_w 7.9 earthquake hit the Sichuan Province, in China, with an epicenter in Wenchuan County. After the main shock, a team of geotechnical specialists organized by the China Earthquake Administration (*abbr*., CEA) conducted months of field investigations of liquefaction and consequent damage, leading to the identification of 118 liquefaction zones (sites) more than 2 km apart in an area about 500km long and 200km wide (Chen et al. 2009). The authors attended the liquefaction investigation. The water ejecting, during the investigation, were reported from tens of centimeters to several meters. Liu-Zeng et al. (Liu-Zeng 2017) also investigated, separately, and proposed three possibilities to explain the extremely high water ejection in the Wenchuan earthquake.

Due to a lack of adequately data of water ejection in previous earthquakes, the study of water ejection was few in published literatures. After the Wenchuan earthquake, a systemic field investigation was conducted as well as site tests. 22 ejection height data with detailed site investigation, are collected that a database is provided to study water ejection. In the paper, a simple model is used to interpret water ejection during soil liquefaction. Using a basic equation in hydraulics, the height of water ejection is predicted, and compared with observations.

2. MODELLING OF LIQUEFACTION EJECTION

The Bernoulli equation (1738) which is a basic equation in hydraulics (Zhao and He 2010), is adopted herein to develop a prediction equation of liquefaction ejection height. The Bernoulli equation can be written as (Equation 1):

$$z+\frac{p}{\rho g}+\frac{v^2}{2g}=c \qquad (1)$$

Where, z is the position head in meter; p represents the piezometric pressure; v is the liquid velocity; and c is a constant. $p/\rho g$ is called piezometric head and $v^2/2g$ denotes the kinetic energy of the unit liquid. In principle, the Bernoulli equation is a mechanical energy conservation equation. Figure 1 sketched a simple two-layer model and parameters involved in Equation 1. The model containing a non-liquefied layer lying above liquefied soil layer. An assumption of steady flow in a smooth pipe is made and suppose that liquid is incompressible ideal liquid. Taking the fluid starting from liquefied soil and ejecting up to ground surface at height H, the velocity at the starting point and ending point should be zero.

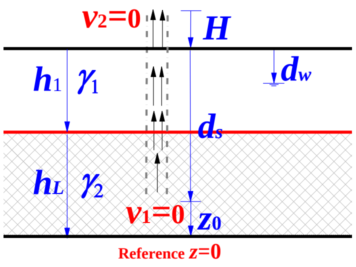

Figure 1. A simple model sketching water ejection by Bernoulli Equation

Setting the reference position, *i.e*., z=0, beneath the liquefied soil at z_0, the Bernoulli equation can be deduced into (Equation 2):

$$z_0+\frac{p_1}{\rho_L g}+\frac{v_1^2}{2g}=\left(H+h_1+h_L\right)+\frac{p_2}{\rho_L g}+\frac{v_2^2}{2g}+h_w^{'} \tag{2}$$

in which, v_1=v_2=0; z_0 and p_1 and p_2 are the dynamic pore pressure, respectively; h_i are the position defined in Figure 1; ρ_L is the density of the liquid which is taken as water density for simplicity; $h_w^{'}$ is the water-head loss due to the path friction and unknown effects.

At the highest of ejection, the dynamic water pressure p_2=0, that the ejecting height can be deduced as (Equation 3):

$$H=z_0+\frac{p_1}{\rho_L g}-\left(h_1+h_L\right)-h_w^{'}=\frac{p_1}{\gamma_L}-d_s-h_w^{'} \tag{3}$$

As soil liquefies, the pore water pressure exceeds the over-burden effective pressure, therefore, (Equation 4):

$$p_1=\gamma_1 d_w+\left(\gamma_1-\gamma_w\right)\left(h_1-d_w\right)+\left(\gamma_2-\gamma_w\right)\left(d_s-h_1\right) \tag{4}$$

Substitute p_1 into Eq.(3), the ejection height is obtained as following (Equation 5):

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$$H=\frac{\gamma_1-\gamma_2}{\gamma_L}h_1+\frac{\gamma_w}{\gamma_L}d_w+\left(\frac{\gamma_2-\gamma_w}{\gamma_L}-1\right)d_s-h_w^{'} \tag{5}$$

The ejection height depends on the thickness of the overburden layer, water table depth, depth of liquefied layer, as well as water-head loss. To be more simple, the density of soil layers are supposed to be identical, *i.e.*, $\gamma_1=\gamma_2$. Equation 5 can be transformed in to be (Equation 6): ,

$$H\approx\frac{\gamma_w}{\gamma_L}d_w+\left(\frac{\gamma_2-\gamma_w}{\gamma_L}-1\right)d_s-h_w^{'}=d_w+\left(\frac{\gamma_2}{\gamma_L}-2\right)d_s-h_w^{'} \tag{6}$$

In which the ejection height simply depends on water table depth, liquefied soil depth and water-head loss. However, the water-head loss is hard to measure in practice. According to hydraulics, the water-head loss is determined by fluid velocity, diameter of the pipe, friction of pipe walls and viscosity of the fluid, et al. These parameters are impossible to measure for liquefaction ejection. To avoid such difficulty, assume the water-head loss is proportional to d_s, *i.e.*,

$$h_w^{'}=\eta d_s \tag{7}$$

Where η is a coefficient. If the no water-head loss, i.e., η=0, then the ejection height should be the largest (Equation 8): ,

$$H\approx d_w+\left(\frac{\gamma_2}{\gamma_L}-2\right)d_s \tag{8}$$

Using Equation 8, sandy layer buried depth can be deduced as (Equation 9): ,

$$d_s\geq\frac{H}{\left(\gamma_2/\gamma_L-1\right)} \tag{9}$$

Which means that if liquefaction ejection is high that the liquefied sand should be deep. Actually, water-head loss cannot be zero that Eq.(9) gives the low bound of soil buried depth estimation. In practice, the value of η is hard to estimate. Referring to hydraulics, η values are in the order of 10^{-1} to 10^{0}.

3. LIQUEFACTION EJECTION HEIGHT ANALYSIS BY WENCHUAN EARTHQUAKE

3.1 Ejection data

Liquefaction ejection usually is ephemeral phenomenon. The height of ejection could only be obtained by description of eye-witnesses. Collecting the water ejection survey data which consist of 208 data in total (Yuan et al. 2009; Liu-Zeng et al. 2017), Figure 2 and Table 1 display the statistics of the water ejecting height following the Wenchuan earthquake. As is shown, 76% of water ejecting height stayed less than 2m. There were cases appearing remarkably high water ejection; that is, 5.8% of ejection height data were more than 5m.

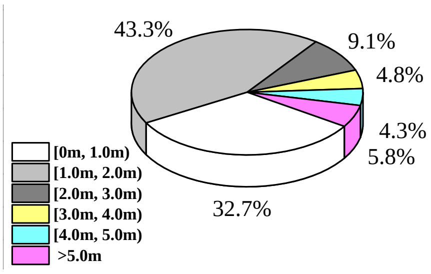

Figure 2. Statistics of liquefaction ejection height following Wenchuan earthquake

Table 1. Statistics of liquefaction ejection height data

Ejection height	Number	Data from Liu-Zeng et al.	Total	Statistics
0 m~1.0 m	13	55	68	32.7%
1.0 m~2.0 m	31	59	90	43.3%
2.0 m~3.0 m	5	14	19	9.1%
3.0 m~4.0 m	5	5	10	4.8%
4.0 m~5.0 m	1	8	9	4.3%
> 5.0 m	6	6	12	5.8%

3.2 Ejection height prediction

Using the simple model and the data collected, an explanation for water ejection height is presented. After the Wenchuan earthquake, detailed site investigation were conducted in Chengdu Plain where surface effects of liquefaction (sand boils and ground fissures) were found. Within the explored sites, 22 sites were reported with ejection heights (Table 2). The site investigation includes borehole extraction, shear-wave velocity tests and DPT test, which were used to determine liquefied layers.

Table 2. Characteristic parameters for liquefaction ejection height prediction at liquefied sites in Chengdu Plain

No.	**Locations**	**PGA(g)**	※d_{sr}**(m)**	$^{\S}d_{\mathrm{s}}$**(m)**	$^{\$}d_{\mathrm{w(}}$**m)**	$^{*}H_r$**(m)**	$^{\&}H_p$**(m) (**η**=0)**	H_p**(m) (**η**=0.5)**	H_p**(m) (**η**=1.0)**
1	Xiaojia village, Longqiao town	0.17	1.4~2.2	1.8	1.4	1.0-2.0	2.3	1.4	0.5
2	Jinxing village, Tangchang town	0.21	2.1~5.0	3.5	0.9	2.0-3.0	2.7	0.9	-0.9
3	Songbai village, Bailong town	0.24	0.8~8.3	4.6	0.8	0.5-1.5	3.1	0.8	-1.5
4	Fengle village, Guihua town	0.25	1.4~2.8	2.1	1.4	**1.0-2.0	2.5	1.4	0.4
5	Quanshui village, Juyuan town	0.24	1.0~2.4	1.7	0.9	**1.0-2.0	1.8	0.9	0.1
6	Yongshou village, Xingfu town	0.25	2.1~3.7	2.9	2.1	**0.5-1.5	3.6	2.1	0.7
7	Pilu school, Nanfeng town	0.22	2.3~8.0	5.2	1.4	~3.0	4.0	1.4	-1.2
8	Rail station, Jiangyou City	0.49	2.4~7.0	4.7	2.4	1.0-2.0	4.8	2.4	0.0
9	Banqiao School, Banqiao town	0.37	3.0~6.1	4.6	3.0	**2.0-2.5	5.3	3.0	0.7
10	Xiangliu village, Gongxing town	0.41	3.4~6.2	4.8	3.4	~10.0	5.8	3.4	1.0
11	Wudu village, Hanwang town	0.48	5.0~7.7	6.3	1.6	~1.0	4.8	1.6	-1.6
12	Linyan village, Tumen town	0.47	6.0~8.0	7.0	6.0	~1.0	9.5	6.0	2.5
13	Qifu school, Xiaode town	0.30	3.5~7.0	5.3	3.5	**1.0-4.5	6.2	3.5	0.9
14	Shihu village, Xinshi town	0.33	4.0~5.8	4.9	2.9	~1.0	5.4	2.9	0.5
15	Xinshi school, Xinshi town	0.34	2.6~3.5	3.0	1.0	**1.5-4.5	2.5	1.0	-0.5
16	Anle village, Xinglong town	0.44	4.8~6.0	5.0	4.0	>5.0	6.5	4.0	1.5
17	Guihua village, Yuquan town	0.39	2.8~3.7	3.3	0.6	~1.5	2.3	0.6	-1.1
18	Shuangquan village, Zundao town	0.49	2.5~5.0	3.3	2.5	**1.0-1.5	4.2	2.5	0.9
19	Tian’e village, Lichun town	0.24	3.1~5.1	4.1	2.4	~0.1	4.5	2.4	0.4
20	Zhenjiang village, Hefeng town	0.29	1.8~2.9	2.4	0.9	0.5-1.0	2.1	0.9	-0.3
21	Baihutou village, Jiandi town	0.46	1.2~3.2	2.2	1.2	1.0-2.0	2.3	1.2	0.1
22	Siyuan village, Shigu town	0.41	2.0~4.0	3.0	1.5	~1.0	3.0	1.5	0.0

Note：**Height collected from Liu-Zeng et al. (2017); $^{\S}d_s$ – middle depth the liquefied sandy layer in meter; ※d_{sr} – depth of liquefied sandy layers; $^{*}H_p$ – predicted water ejecting height; $^{\&}H_r$ – observed water ejecting height; $^{\$}d_w$ – water tables.

Using Eq.(6) to predict water ejection height, unit weight of the saturated soil is an important parameter. 85% of liquefied soils following Wenchuan earthquake were gravels. From laboratory tests, the dry density of soil samples extracted from borehole was measured ranging from 1.92~2.12 g/cm^3. The unit weight of saturated gravelly soil samples remolded in laboratory ranged from 20~25 kN/m^3. The liquefied gravelly layers in Chengdu plain contain many cobbles and large diameter gravels. So the unit weight of the liquefied soil is taken as γ_2=25kN/m^3. Setting η=0, 0.5 and 1.0, the water ejection heights were predicted and listed in Table 2 and portrayed in Figure 3. When η=0, i.e., water-head loss is zero, the predicted ejection height were much higher than the observations (Figure 3(c)). When η=1.0, the predictions stayed lower than the observations shown in Figure 3(a) since the water-head loss was overrated. The observations were well consistent with predictions when η=0.5 (Figure 3(b)).

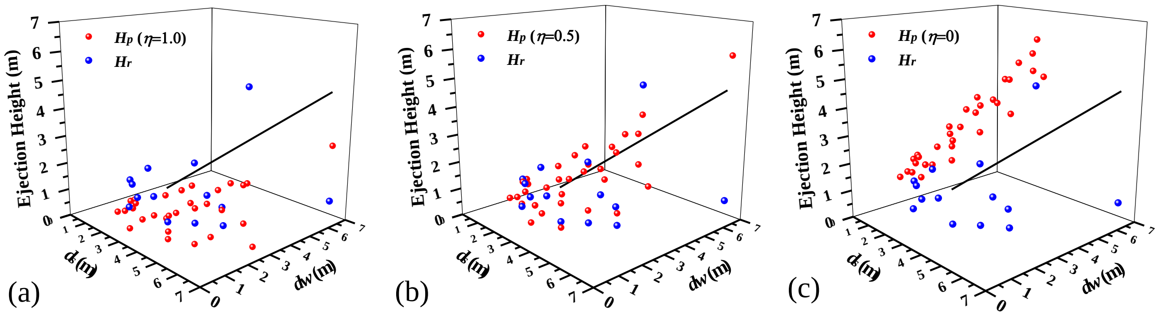

Figure 3. Comparison of predicted liquefaction ejection height with the observed

Eqation 8 indicates deep saturated sandy layer and large water table can lead to high liquefaction ejection. The height depends on the dynamic pore-water pressure generated by liquefaction so that buried condition of the saturated sand basically governs the liquefaction ejection height. On the other hand, the liquefaction ejection height can be used to test the depth of liquefied sand. In general method, the liquefied soil layers are determined by comparing CSR and CRR values (Youd et al. 2001). Using Eq.(9), the ejection height can be used to check the depth of determined liquefied sand layers.

3.3 Cases study

3.3.1 Jinxing village, Tangchang town

Grey sand was ejected in the farmland (Figure 4) right after the main shock. Ground shaking intensity was estimated to be 0.21g of PGA by a GMPE developed using the main shock accelerograms (Wang and Xie 2009). The surface ejecta contained medium sand mixed with mud. The local witness reported that in the neighboring area water ejection happened in many places and the height was about 2~3m high. However, amount of ejecta was not much, which estimated as 0.5m^3 at most.

During scientific investigation stage, site investigation such as drilling borehole, DPT test and shear-wave velocity tests were performed that the gravel layer locating at 2.1~5.0m underground was determined liquefied, i.e., d_s=3.5m. Figure 5 displayed the core sample extracted from the borehole and the liquefied layer which was marked. The local water table was d_w=0.9m. By Equation 6, the liquefaction ejection heights predicted as -0.9m, 0.9m and 2.7m respective to η=1.0, 0.5 and 0. Negative values mean water could not be ejected above ground. The prediction was underestimated the observation.

Figure 4. Sand ejecta by soil liquefaction in Jinxing village, Tangchang town

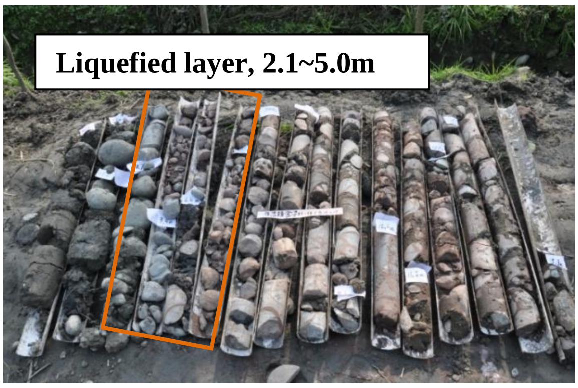

Figure 5 The extracted soil sample from the inspecting borehole in Jinxing village, Tangchang town

3.3.2 Xiangliu village, Gongxing town

The liquefaction at this site was fairly interesting that 8 pits of about 3 to 4 meters in diameter and 1 to 2 meters deep were generated by venting of water ejection (Figure 6), and scattering in 300mu of the nearby farmland (Chen et al. 2009). The site was diagnosed as gravel liquefied after detailed site drilling and tests (Cao et al. 2011). One of the interesting liquefaction behaviors, as the witness reported, was that the ejection height was extremely high as double the height of the electric pole which was estimated to be 10m approximately. The site was about 20km close to rupture faults and the PGA value was estimated to be 0.41g.

Figure 6. Large pits caused by liquefaction ejection in Xiangliu village, Gongxing town

A borehole was drilled that the gravelly soil layer between 3.4 to 6.2m was determined having liquefied. The local water table d_w=3.4m. By Eq.(6), ejection height prediction ranged from 1.0 to 5.8m with a mean value of 3.4m. That is, the prediction was much smaller than the observation. The possible explanation could be that the ground shaking intensity was amplified by a blind fault (Liu-Zeng et al. 2017). The second possibility could be that ground crack was opening and closing during earthquake and squeezed the water ejecting during liquefaction. The “clapping” effect could push the water high.

3.3.3 Tian’e village, Lichun town

The liquefaction was reported at a one-story masonry house. The house floor was protected by concrete covers. Fissures of about 2cm wide were generated and water column of about 10cm high was venting after the main shock (Figure 7). No sand sprouted out. The site was performed detailed site investigation, like CDPT and borehole tests. From the core extracted soil sample as shown in Figure 8, gravel layer between 3.1m to 5.1m was determined having liquefied. The underground water table lay d_w=2.4m. With the data, the ejection height was predicted as 0.4m, 2.4m and 4.5m respective to η=1.0, 0.5 and 0. The existing of the concrete ground of the house prohibited water ejection that water ejection was low.

Figure 7. Ground fissures caused by liquefaction ejection at Tian’e village, Lichun town

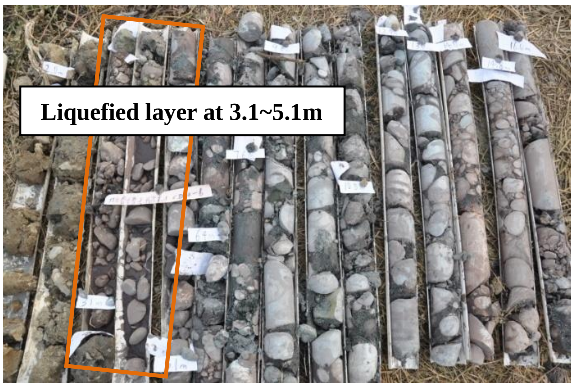

Figure 8. The extracted soil sample from the inspecting borehole in Tian’e village, Lichuan town

4. CONCLUSIONS

In this paper, a simple model is adopted to simulate the sophisticated liquefaction water ejection process using the basic equation in hydraulics. The main points can be outlined as following.

(1) The liquefaction ejection is simplified as steady flow in a pipe, and a formula was deduced to predict liquefaction ejection based on Bernoulli equation.

(2) The proposed ejection height prediction equation indicates the deep water table and deep sandy layer buried depth can cause high ejection.

(3) The liquefaction ejection height predictions are close to the observations, yet deviations and uncertainty exist. The reasons could be the description of the witnesses was not reliable and contained subjective uncertainty; the existence of structures; and buried conditions of liquefied soils were not much precise.

(4) Liquefaction ejection height, on the other hand, can reflect the buried condition of the liquefied soil that ejection height data can be used to assist to verified liquefied layer determination.

5. ACKNOWLEDGMENTS

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