Comparison of the sand liquefaction estimated based on codes and practical earthquake damage phenomena

Yi Fang[a], Yahong Huang[b]

Institute of Crustal Dynamics, CEA, Beijing 100085, China

[a]fyyyfyyy@vip.qq.com, [b]yhhuang@aliyun.com

Abstract. Conducting sand liquefaction estimated based on codes is the important content of the geotechnical design. However, the result, sometimes, fails to conform to the practical earthquake damages. Based on the damage of Tangshan earthquake and engineering geological conditions, three typical sites are chosen. Moreover, the sand liquefaction probability was evaluated on the three sites by using the method in the *Code for Seismic Design of Buildings* and the results were compared with the sand liquefaction phenomenon in the earthquake. The result shows that the difference between sand liquefaction estimated based on codes and the practical earthquake damage is mainly attributed to the following two aspects: The primary reasons include disparity between seismic fortification intensity and practical seismic oscillation, changes of groundwater level, thickness of overlying non-liquefied soil layer, local site effect and personal error. Meanwhile, although the judgment methods in the codes exhibit certain universality, they are another reason causing the above difference due to the limitation of basic data and the qualitative anomaly of the judgment formulas.

1. Introduction

The liquefaction estimated and prediction of the sites is one of the core contents in the earthquake damage prediction [1]. The reliability and advancement of the method exert a great effect on the safety and costs of various engineering designs. Since the Tangshan earthquake (Hebei, China, 1976), numerous scholars in China have carried out in-depth researches on sand liquefaction [2]. The seismic design codes in different industries (building and railway) have corresponding sand liquefaction methods [3]. However, it is found from the practices that the existing liquefaction estimated methods are backward [2]. The study investigated the disparities between the code judgment results and practical earthquake damages found in the practical works.

By taking Tangshan earthquake with abundant resources as the example, three typical sites were chosen. Moreover, the sand liquefaction potential was assessed on the three sites by using *Code for Seismic Design of Buildings* (GB 50011-2010, hereinafter shortened as *The Code*) (Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD), 2010). The result was compared with the earthquake damages of Tangshan earthquake. The research result exerts certain significance on cognition of earthquake-inducing liquefaction mechanism and improvement of the judgment methods.

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2. Distributions of Tangshan earthquake induced liquefaction ranges and selection of the typical sites

2.1. Distribution of the seismic intensity in Tangshan earthquake and liquefaction damages

During the Tangshan earthquake, the sand blasting and watering phenomenon frequently appeared and co-existed with the ground fractures, which aggravated the earthquake damage. The liquefaction ranges started from Qinhuangdao in the east westward passing through Changli to Mafang of Sanhe county, went along Chaobai River to Miyun reservoir, and ran southward through Xianghe in Hebei province to Zhanhua county in Shandong province (Fig. 1). Moreover, the areas of serious sand-blasting and watering were mainly distributed in the south-east coastal areas of the earthquake region where the foundation failure caused by the liquefaction can be found everywhere [4].

2.2. Selections of typical sites

To favorably compare the judgment result based on the code with the practical earthquake phenomenon, three sites (Fig. 1) were selected according to the following principles. The sites need to be in the areas with the seismic fortification intensity of VII~IX, with complete data relating practical earthquake damage and boreholes, and can reflect the disparities of landform, hydrogeological and engineering geological conditions.

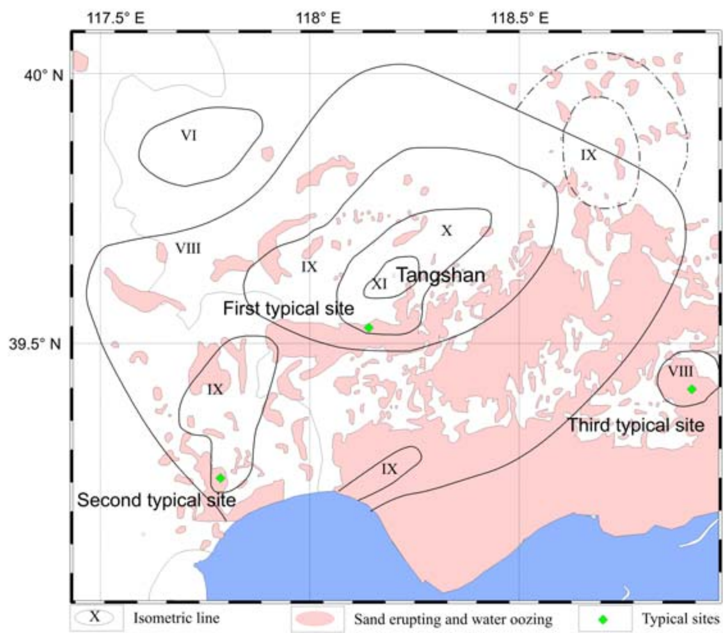

Figure 1. The distribution of Sand erupting in Tangshan earthquake, and typical sites picked in this paper

3. Comparison of the judgment results

3.1. Calculation judgment

The Code stipulates that the critical hammer count of standard penetration within the depth range of 20 m underground for liquefaction estimated can be calculated according to the following formula.

$$N_{cr}=N_0\beta[\ln(0.6d_s+1.5)-0.1d_w]\sqrt{3/\rho_c}$$

N_{cr} is the critical value of the hammering hammer number for the liquefaction. N_0 is the reference value of the hammer number. When the basic earthquake accelerations are designed as 0.10, 0.15, 0.20, 0.30 and 0.40 g, 7, 10, 12, 16 and 19 are applied, respectively. d_s is the depth of the saturated soil standard (m). d_w is the depth of the groundwater level (m). The groundwater level is the average annual water level during the base period or the highest annual water level in the near future. ρ_c is the percentage of clay content, when less than 3 or sand, should be used 3.In addition, β represents the adjustment coefficient, and it values 0.8, 0.95 and 1.05 for the first, second and third groups of the design earthquake, separately.

Because the groundwater level of various holes are the measured values during drilling without considering seasonal and yearly variable amplitude, the measured groundwater levels are generally lifted by 2 m to be used in the calculation in the practical engineering investigation. The calculation is carried out using to the surface water level when the lifted amount is less than 2 m. The calculation results are displayed in Table 1.

Table 1. The results of Liquefaction at typical sites

typical sites	Borehole	Lithology	standard penetration depth ds	Groundwater level dw	Clay content ρc	Measured value N63.5	Critical value Ncr		result		damage
							Design intensity	practical intensity	Design intensity	practical intensity	
First	zk1	thin sand nd sand	7.8	0.0	3	10	17.5	27.7	Yes	Yes	No
		thin sand	9.3	0.0	3	17	18.8	29.8	Yes	Yes	
		thin sand	12.3	0.0	3	35	21.0	33.2	No	No	
		thin sand	15.3	0.0	3	42	22.7	36.0	No	No	
	zk2	Silt sand	6.8	0.7	3	9	15.8	25.1	Yes	Yes	Yes
		Silt sand	9.3	0.7	3	16	18.1	28.7	Yes	Yes	
		Silt sand	10.3	0.7	3	18	18.9	29.9	Yes	Yes	
		Silt sand	14.3	0.7	3	30	21.5	34.1	No	Yes	
	Design intensity: Ⅷ, The first groups of the design earthquake, N0=12, β=0.8. Design intensity: Ⅹ(Ⅸ)										
Second	Zk3	Silt	18.45	0.3	12.9	22	11.7	18.3	Non liquefaction	Non liquefaction	Yes
	Zk4	Silt	4.45	0.3	12.6	5	6.7	10.4	Yes	Yes	Yes
		Silt	5.45	0.3	13.6	6	7.0	10.9	Yes	Yes	
		Silt	6.45	0.3	12.4	6	7.9	12.3	Yes	Yes	
	Design intensity: Ⅷ, The first groups of the design earthquake, N0=12, β=0.8. Design intensity: Ⅷ—Ⅸ(Ⅸ)										
Third	Zk5	thin sand	7.15	4.2	3	17	12.7	20.3	No	Yes	Yes
		thin sand	11.15	4.2	3	25	16.0	25.6	No	Yes	
		thin sand	13.15	4.2	3	34	17.2	27.7	No	No	
		thin sand	18.65	4.2	3	44	20.2	32.2	No	No	
	Zk6	thin sand	2.15	4.6	3	13	5.4	8.6	No	No	Yes
		thin sand	5.15	4.6	3	26	10.1	16.2	No	No	
		thin sand	9.15	4.6	3	25	14.1	22.6	No	No	
		thin sand	13.15	4.6	3	42	16.9	27.1	No	No	
		thin sand	19.65	4.6	3	42	20.2	32.3	No	No	
	Design intensity: Ⅶ, The second groups of the design earthquake, N0=10, β=0.95. Design intensity: Ⅷ										

The purpose of the liquefaction estimated is to predict the earthquake damage. Thus, to favorably make comparison and analysis, apart from the liquefaction calculation judgment based on the design intensity, the comparison and calculation is also conducted according to the practical influence intensity of Tangshan earthquake. Only the parameters of the intensity of VII~IX are given in the calculation formula, so the practical influence intensity of IX is taken when it is higher than IX intensity. Although it does not reach to the practical intensity, the results can still be used for the comparison and the prediction as it is higher than the design intensity.

3.2. Comparison and analysis

Table 2 shows that the sand liquefaction estimated based on the code has differences with the practical earthquake damages. The specific differences are shown as follows:

(1) Based on the design intensity, the calculation judgment results of sites 1 and 2 basically conform to the practical earthquake phenomenon: the two sites were local non-liquefied areas in the liquefaction sites. The difference lies in the different locations of the non-liquefied regions. The calculation judgment result of the site 3 was totally opposite to the practical earthquake damages, expressed as that it was a non-liquefied area based on the calculation result while it showed practical phenomena of commonly seen sand-blasting and watering.

(2) Under the practical intensity, the calculation judgment result of the sites is totally consistent with the practical earthquake phenomenon: all of the sites were liquefied areas. However, there were disparities in certain aspect. The calculation judgment results indicate that sites 1, 2 and 3 presented complete liquefaction while the practical earthquake damage of the sites were shown as non-uniform liquefaction (local non-liquefaction).

4. Discussions

The reasons causing the disparities between the sand liquefaction estimated based on the code and the practical earthquake damages mainly include five points.

(1) The seismic fortification intensity less than practical influence intensity

The higher the intensity of ground motion is, the easier the occurrence of the liquefaction to the saturated silt and sand soil layers under the same conditions. *The Code* is prepared for 500-year-resturn earthquakes but not for the rare earthquake with a return period of several thousand years (small probability event) like Tangshan earthquake. Therefore, the seismic fortification intensities of typical sites are all lower than the practical influence intensity. For example, the seismic fortification intensity of the site 1 is VIII.

While the practical influence intensity is up to X. Thus, the borehole zk5 was considered as non-liquefied region based on the seismic fortification intensity. However, during the Tangshan earthquake, the sand-blasting and watering phenomenon occurred, that is, the calculation judgment result under the practical influence intensity showed that the borehole was liquefied.

(2) Changes of groundwater buried depths

The groundwater buried depth directly influences the saturability of silt and sand soil layers: the shallower the buried depth is, the larger the possibility of liquefaction. During Tangshan earthquake, the typical sites were in the rainy season with greatly increasing rainfalls, which raised the groundwater level to a large extent. For example, the groundwater level of Laoting after the earthquake was generally less than 1 m and even close to the surface water level (Liu Huixian, 1985). However, the groundwater levels during were found to be about 5 m during the field drilling, which probably caused the inconsistency between the calculation result of local sites and the practical earthquake damage. For instance, the borehole zk9 is not liquefied both under the seismic fortification intensity and the practical influence intensity while the sand-blasting and watering commonly occurred during Tangshan earthquake.

(3) Thickness of overlying non-liquefied soil layer

During the earthquake, the liquefied soil layer did not reach to the surface through the overlying soil layer due to the large buried depth of the liquefied soil layer, so the liquefaction phenomenon was not found. For example, the calculation judgment result of the borehole zk1 displays that the liquefied soil layer was located 7 and even 14 m underground. However, the sand blasting and watering phenomenon was not observed during Tangshan earthquake, which was probably caused by thick overlying non-liquefied soil layer.

(4) Local site effects

Site conditions especially the formation lithology play an important role in the occurrence of the sand liquefaction. When soft soil is found in the formation, the earthquake damages are supposed to be aggravated to form high-intensity anomaly zones because the soft soil amplifies the seismic oscillation. For example, the site 2 is located in the coastal region of Tianjin where there exists a thick sullage soft soil layer in the shallow underground. Thus, amplification effect of the soft soil on seismic oscillation promotes the formation of the sand liquefaction of the region to some extent while the special condition is not considered in the judgment formula. Therefore, the existence of overlying non-liquefied soil layers containing sullage soft soil is probably the main reason why zk3 is judged as on-liquefied according to the calculation result while showed sand-blasting and watering in the practical earthquake.

(5) The reliability and applicability of the judgment method based on the code

Firstly, the basic data used for the judgment method based on the code are mostly taken from the shallow sand data (buried depth less than 10 m) without those from deep-seated soil and silt. Therefore, the reliability of liquefaction estimated results of the deep-seated soil and silt remains to be further investigated. Secondly, under the high-intensity condition (such as VIII and IX), the existing codes prefer to consider the non-liquefied sites as liquefied ones (Sun Rui et al., 2013), which is exactly consistent with the judgment result of zk1 (ds=7.8, 9.3) in the study. Thirdly, the curve mode of the critical standard penetration of the existing codes has certain limitations, which is one of the main reasons why the standard penetration number of the mid-compacted soil (deep soil) is large and the judgment result is shown as liquefaction. Finally, attainment of various indexes of the judgment formula shows uncertainty to some extent. For example, it is influenced by multiple factors including test equipments, methods, drilling qualities and operators' competency.

5. Summary

The following conclusions can be obtained through the above analysis.

(1) The judgement result based on codes has disparities with the damage conditions caused by practical earthquakes. The liquefied regions in the practical earthquakes are probably assessed as non-liquefied according to the judgment result based on codes. Moreover, soil layers which are judged as liquefied regions based on codes probably do show sand-blasting and watering in the reality.

(2) Multiple factors probably cause the differences between the judgment results and the practical earthquake damages. They include the disparities between the seismic fortification intensity and the practical seismic oscillation, changes of groundwater levels, the thickness of the overlying non-liquefied soil layers, local site effect and personal errors in the standard penetration test.

(3) The judgment method of sand liquefaction based on codes is obtained by summarizing the experience of the great earthquakes all over the world, which has the general applicability. It is possible that the judgment results based on codes fail to reflect the practical earthquake damage phenomena, so it remains to be further researched in the future.

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