Comparison of Current Chinese and Japanese Design Specification for Bridge Pile in Liquefied Ground

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Abstract—Firstly, this study briefly presents the current situation that there exists a vast gap between current Chinese and Japanese seismic design specification for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground; The Chinese and Japanese seismic design method and technical detail for bridge pile foundation in liquefying and lateral spreading ground are described and compared systematically and comprehensively, the methods of determining coefficient of subgrade reaction and its reduction factor as well as the computing mode of the applied force on pile foundation due to liquefaction-induced lateral spreading soil in Japanese design specification are especially introduced. Subsequently, the comparison indicates that the content of Chinese seismic design specification for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground, just presenting some qualitative items, is too general and lacks systematicness and maneuverability. Finally, some defects of seismic design specification in China are summarized, so the improvement and revision of specification in the field turns out to be imperative for China, some key problems of current Chinese specifications are generalized and the corresponding improvement suggestions are proposed.

Keywords—liquefying soil, laterally spreading ground, seismic design specification for bridge pile foundation.

I. INTRODUCTION

IN the past 30 years, a number of devastating earthquakes have occurred successively throughout the world, which has caused a lot of damage and collapse of pile bridges. Damage Investigation and research shows that, pile foundation liquefaction coupled with the superstructure damage is one of the main causes [1]-[6]. The upper bridge structural failure results from the liquefaction or the loss of stability of the liquid side [3]-[6]. Therefore, scholars from various countries have reflected on their own bridge seismic design specifications, and have undertaken a series of seismic revision for liquefaction design of bridge foundation [7]; compared with the old standard, the new revised standards or technical guidelines have changed comprehensively and deeply in terms of pile design, design techniques, design procedure or detailed requirements for the construction details, with the most representative seismic design of bridge pile foundation in Japan [8]. Currently, seismic design of bridge pile foundation generally refers to "Code for Seismic Design of Highway Engineering" and "Railway Engineering

Seismic Design Code" [9]-[11], in which the specification for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground is too general, only giving some qualitative terms, lacking of detailed and effective technical details, and strong operability, and showing that the seismic design of pile foundation is not taken seriously enough. In contrast, the Japanese specification for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground is more detailed, and their technical level is more advanced [12]. This gap is caused by two reasons, on the one hand, the research on seismic performance of bridge foundation in our country (especially the seismic performance of bridge pile foundation in liquefiable ground) is still not deep enough, and there is a lack of understanding of the potential threat of damage to the pile [13]; on the other hand, our current seismic design of bridge pile foundation liquefaction specification was developed mainly based on Tangshan and Haicheng earthquake damage that happened in the 1970s. There has been no wide use of pile due to the limited economic level. In spite of much liquefaction, there are fewer seismic liquefaction damage examples since the use of pile is limited [1]-[5], [13]. Thus, the seismic design of bridge foundation liquefaction research has not been paid enough attention to. Nowadays, bridge construction and development in China has enjoyed a rapid pace, especially in large-span road bridges, railway bridges, cross-sea bridges and the city large overpass, extensive use of pile foundation for viaduct constructions; meanwhile, China is an earthquake-prone country, over half of which is the region with intensity VII degree or above, and most bridge area is of weak soil liquefaction, especially in the Yangtze River Delta, Pearl River Delta, three city groups (Beijing, Tianjin and Tangshan) and the economically developed coastal zone where this feature is more significant [13]. According to China's investigation on the intensity VII degree earthquake damage, the bridge pile seismic performance is better when the foundation liquefaction does not occur; however, if the foundation liquefaction or earthquake liquefaction damage lateral expansion flow happens, the pile will be severely damaged, and so is the upper structure coupling. For example in Tangshan earthquake, 15 of the 18 collapsed bridges were damaged due

to liquefaction and then caused the superstructure damage. Whereas, our current project seismic design code in terms of seismic bridge pile foundation in liquefied ground is far behind Japan in the same specification, lacking the technical details in the effective design, and can't go with the current bridge construction development pace, which may make some of the new bridges immediately become seismic strengthening targets. Because of this, in order to ensure that our road infrastructure develops steadily and rapidly, referring to the Japanese bridge foundation design code, and further updating and revising the specification for liquefaction and lateral flow of liquefied seismic design of bridge pile foundation are of importantly practical significance. This paper makes a brief analysis and comparison of current Chinese and Japanese seismic design specification for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground, and points out China exists problems in seismic liquefaction design of bridge foundation and the technical details that need improvement. The starting point of this paper is to learn from each other and adopt advanced experience and technical measures.
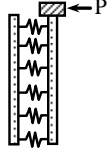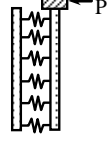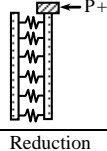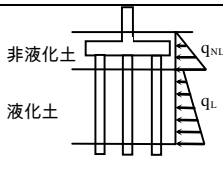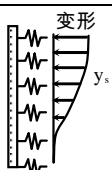
II. CHINA'S LIQUEFIED SEISMIC DESIGN OF BRIDGE FOUNDATION

China's "Highway Engineering Seismic Design Code" (JTJ004-89) [9] started to be revised in the mid-80s, and was promulgated and implemented in 1989. In 2008 the published "Road Bridge Seismic Design Rules" (JTGTB02-01-2008) [10] did not cover the specification for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground, but only putting that pile penetrates deep enough into the dense and stable layer of liquefied soil as one of the responses to seismic liquefaction; while taking into account of a variety of bridge damages resulting from the earthquake effect (such as the subsidence and slope pile caused by liquefaction, abutment slip, etc.), the Code, still sees seismic action as a control load of bridge seismic response analysis, without analyzing the seismic performance of pile; the specification does not cover the design content of bridge pile foundation in liquefaction-induced lateral spreading ground, either. Our national current "Railway Engineering Seismic Design Code" (GB50111-2006) was promulgated and implemented in 2006, giving reduction method for the liquefied soil mechanical indexes, and putting forward some instructive specification in terms of bridge pile foundation in liquefaction-induced lateral spreading ground. However, it lacks the necessary technical details of the design, and still treats the pile as an effective treatment and prevention of liquefaction and liquefaction lateral expansion flow on the bridge site from the seismic damage. Code JTJ004-89, Code GB50111-2006 also does not cover the technical details of the seismic design of bridge pile foundation in liquefaction-induced lateral spreading ground.

III. JAPANESE SEISMIC DESIGN SPECIFICATIONS FOR LIQUEFACTION HIGHWAY BRIDGE FOUNDATION

According to the liquefaction and lateral expansion of liquefaction conditions, the vast majority of the Japanese current seismic engineering design of the bridge foundation has detailed specifications and instructions, and takes fully account of the influence of the liquefaction or lateral expansion of liquefied ground flow on the pile working performances. The difference lies in the Coefficient of soil reaction in different codes. In the following, the focus is the introduction of Japanese technical details for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground in Seismic Design of Highway Projects [14] and Railway Engineering Seismic Design Code [15]. The basic viewpoints of the design are shown in Table 1.

TABLE I
BASIC DESIGN OF BRIDGE PILE AT LIQUEFIABLE GROUND AND
LATERAL SPREADING GROUND IN JAPAN STANDARD

Site type	Load form	Japan Highway Bridge Design Code (JRA, 2002)	Japan's Rail Infrastructure Design Standards (RTRI, 1999)
liquefaction Site	Inertial force		
	Ground Movement	No consideration	
	Ground Reduction	Liquefied strength ratio, soil depth, earthquake magnitude decide. F_L is Safety factor for the resistance to liquefaction	Reduction coefficient of soil reaction is decided by the value of soil depth
Lateral spreading ground	Inertial force	No consideration	No consideration
	Ground movement		
	Ground Reduction	—	Soil liquefaction：1/1000 Non-liquefied soil: No reduction

In Japanese Highway Bridge Design Specifications (JRA, 2002), in the level of facilities for the liquefaction, pile under lateral loads in the design uses seismic coefficient method which can reflect the effects of soil liquefaction and can be shown by soil available anti-seismic coefficient. But the effect liquefied soil deformation on the pile can not be considered.

Coefficient of soil reaction is decided by the equations（1）- （5）which is suitable for venues in the sand pile filled with concrete.

$$k_h = k_{h0}(B_H / 0.3)^{-3/4} \quad (kN/m^3) \tag{1}$$

$$B_H = \sqrt{(D / \beta)} \tag{2}$$

$$\beta = (k_h D / 4EI)^{1/4} \tag{3}$$

$$k_{h0} = \alpha E_0 / 0.3 \quad (kN/m^3) \tag{4}$$

$$E_0 = 2800 N \quad (kN/m^2) \tag{5}$$

In the above equation,

B_H is the standardized pile width (m)；

D is pile diameter (m)

β is eigenvalue

EI is flexural stiffness of pile (kN·m^2)

α is constant

E_0 is soil modulus (kN/m^2)；

N is N of SPT

JRA specification also gives the soil resistance reduction factor of foundation soil liquefaction, and defines it as the liquefaction resistance factor F_L, liquefied dynamic shear strength ratio R_L, soil depth Z, a function of earthquake magnitude, which is shown in Table 2.

TABLE II

REDUCTION FACTOR OF SUB GRADE REACTION FOR JAPANESE HIGHWAY BRIDGES SPECIFICATION

F_L Range	Soil liquefaction Layer depth Z (m)	The values of dynamic shear strength of liquefied R_L			
		$R_L \leq 0.3$		$R_L > 0.3$	
		I level Level Ground motion	II level Level Ground motion	I level Level Ground motion	II level Level Ground motion
$F_L \leq 1/3$	$0 < x \leq 10$	1/6	0	1/3	1/6
	$10 < x \leq 20$	2/3	1/3	2/3	1/3
$1/3 < F_L \leq 2/3$	$0 < x \leq 10$	2/3	1/3	1	2/3
	$10 < x \leq 20$	1	2/3	1	2/3
$2/3 < F_L \leq 1$	$0 < x \leq 10$	1	2/3	1	1
	$10 < x \leq 20$	1	1	1	1

In the string earthquakes in 1980's and earthquake in Osaka and Kobe in 1995, the destructive effects of expansion of fluid flow on the pile side is the focus of research and prevention. The destructive effects of soil liquefaction on pile lateral expansion flow in coastal area in Osaka and Kobe earthquake were first recognized. After the earthquake, Japan quickly revised highway bridge design code, in which specific provisions on this issue are made, upgrading checking the soil fluid flow caused by expansion of lateral pile load and other new content. In expansion flow field in the liquid side of the seismic design of highway bridge foundation, the role in the pile of earth pressure is considered, without considering

inertia force and the upper structure of the soil reaction force reduction, but the calculation method of soil liquefaction side of the expansion flow acting on the pile on the side of the thrust is given in detail. The calculation model is shown in Figure 1, the equations (6) - (8) are used for soil liquefaction by the lateral expansion effect resulting in non-liquefied soil and the structure of soil liquefaction lateral thrust, if it is necessary, the impact of soil sliding flow needs to be considered without considering the level of soil resistance.

$$q_{NL} = c_s c_{NL} K_p \gamma_{NL} Z (0 \leq Z \leq H_{NL}) \tag{6}$$

$$q_L = c_s c_L [\gamma_{NL} H_{NL} + \gamma_L (Z - H_{NL})]$$
$$(H_{NL} \leq Z \leq H_{NL} + H_L) \tag{7}$$

$$P_L = \int_0^{20} (1 - F_L)(10 - 0.5 z) dz \tag{8}$$

In the above equation,

q_{NL} is the side thrust a pile suffered in non-liquefaction of soil per unit area (kN/m^2), q_L is the side thrust a pile suffered in liquefaction of soil per unit area (kN/m^2).

c_s is correction factor from coastline to pile

c_{NL} is correction factor of side thrust in non-liquefaction of soil

c_L is correction factor of side thrust in liquefaction of soil

K_p is passive earth pressure coefficient

γ_{NL} is severe of non-liquefied soil

γ_L is severe of liquefied soil

Z is depth of calculation

H_L is thickness of liquefied soil

F_L is liquefaction resistance coefficient

In the specification, it is clearly stated that the calculation model of the lateral expansion of the soil fluid flow acting on the pile on the side of the thrust is from analytical results of the deep pile of coastal bridge and research results liquefaction side of the expansion flow on bridge foundation Mechanism of the relevant parts in the 1995 Osaka and Kobe earthquake which are shown in Figure 1, Figure 2

Besides, the Specification clearly states the two types of soil layer that can determine the impact of lateral flowing of soil on bridge pile. The first type is soil layers whose distance from its banks' horizontal level is less than 100m, and the expansion water level elevation on both sides of the bank revetment is not less than 5m; the second type is sand land layer which has been determined as potential to be liquefied; the thickness is not less than 5m and water of the temporary level distributes horizontally and continuously. The specification on "the expansion water level elevation on both sides of the bank revetment is not less than 5m" derives from Osaka and Kobe Earthquake. In the earthquake, soil being liquefied and lateral flowed outside, leading to the displacement of the bridge pier, are those coastal areas whose bank revetment water level elevation before and after were

below 10m. The specification on the lateral expansion of the scope of soil flow, which is potentially to be liquefied and subsequently impact the bridge pile, derives from Osaka and Kobe Earthquake, in which the extent of lateral expansion flow of soil liquefaction led the displacement of the bridge pile (100m from the shoreline). The specification on "soil layers which is potentially liquefied are those sand land layer not less than 5m in thickness" also derives from Osaka and Kobe Earthquake in which the soil was liquefied and lateral flowed outside leading to the displacement of the bridge pile. Suppose the soil within 100m from the shoreline is potentially liquefied, but the liquefaction soil layer is discontinuous horizontally, then it can be regarded as a lateral flow of soil liquefaction phenomenon not affecting the bridge pile.
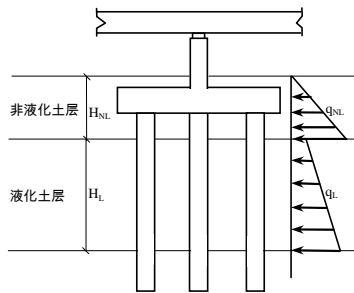

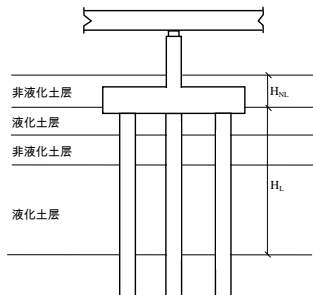Fig. 1 Calculation model for liquefaction lateral spreading

Fig. 2 Influence range of lateral spreading due to liquefaction to pile foundation for multi-liquefaction layer

As for the anti-seismic design on the upper part of bridge structures, the Japan Specification on Highway Bridge Anti-seismic Design only provides design for bridges most easily affected by earthquake (such as arch bridge, suspension bridge, rigid frame, cable-stayed bridge). In Japan's Anti-seismic Design on Highway Bridges, upper part of bridge structure is generally viewed as not having a controlling force in earthquake, and thus attention is only paid to the lower part of the structures. This point also shows, from one aspect, Japan's attentions paid to the anti-seismic design of bridge pile.

TABLE III
MODIFIED COEFFICIENT OF DISTANCE FROM SHORELINE TO PILE

Distance from shoreline to pile (m)	Modified coefficient(c_s)
$s \leq 50$	1.0
$50 < s \leq 100$	0.5
$100 < s$	0

TABLE IV
MODIFIED COEFFICIENT OF LATERAL SPREADING FORCE IN THE NON-LIQUEFACTION LAYER

Liquefaction index	Modified coefficient (c_{NL})
$P_L \leq 5$	0
$5 < P_L \leq 20$	$(0.2P_L - 1)/3$
$P_L > 20$	1

IV. JAPAN STANDARDS ON ANTI-SEISMIC RAILWAY BRIDGE PILE DESIGN IN LIQUEFIABLE GROUND

In Japan Standard on Railway Facilities (RTRI, 1999), the design of pile in horizontal loads is mainly controlled by the inertia force from the upper part of structure. Despite the fact that the anti-seismic design of pile does not consider the soil liquefaction and deformation, it applies the additional inertia force relating to the liquefaction degree to substitute the soil deformation's effect on the pile. Foundation soil reaction coefficient k_h can be estimated by Equation (9). (Suitable for site concrete pouring sand pile).

$$k_h = f_{rk}(0.6\alpha E_0 D^{-3/4})$$
$$E_0 = 2500N \tag{9}$$

In the equation, f_{rk} refers to soil's resistance force factor. (1.0) ;

α is a constant (if E is estimated by N, then α =2kN/m^2) ;

D refers to pile diameter (m) ;

E_0 refers to elastic modulus (kN/m^2)。

In the Standards, the reduction of reaction coefficient of foundation soil is taken as the function for anti-liquefaction strength coefficient (F_L) and liquefied soil depth (Z)

The anti-seismic pile design under the force of lateral spreading liquefaction ground applies the seismic deformation method, considering both the liquefied soil thickness and the movement of side wall to estimate the displacement of soil liquefaction and lateral expansion flow, and counter-force to the pile through foundation soil. In the liquefied lateral spreading soil, the foundation soil reaction is 1/1000 of its initial reaction, which is different from the foundation soil reaction adopted by liquefied soil. In Japan Specification (JRA, 2002) and Standard (RTRI, 1999), anti-seismic pile design all applies foundation soil reaction (foundation soil reaction coefficient) to resist inertia force of the upper part of

the structure, and adopts different appraisal method to appraise foundation soil reaction.

VI. CHINA STANDARDS ON ANTI-SEISMIC BRIDGE PILE DESIGN IN LIQUEFIABLE GROUND: PROBLEMS AND SUGGESTIONS

By comparing China's and Japan's respective Standard on a number of technical details of bridge pile anti-seismic design in liquefiable ground, we can find some existing problems in China's Standard about technical specifications on bridge pile anti-seismic design in liquefiable ground and lateral spreading ground, which are mainly reflected in the following points.

(1) Anti-Seismic Design in Liquefiable Ground

China Standard on the specification of anti-seismic bridge pile design is too general, stating only a number of qualitative terms, which shows inadequate attention paid to the basic anti-seismic design of pile foundation and other similar light constructions. In contrast, Japan Standard has systematically states the reduction approach of foundation soil reaction in pile design in liquefiable ground. In regarding of this, it is necessary to amplify this approach when further revising China Standard on anti-seismic pile design in liquefiable ground and lateral spreading ground. Of course, with the further studies in earthquake liquefaction ground both at home and abroad in recent years, China's relevant standard has also gradually transited to a new phase in which the actual physical and mechanical processes and probability computation in earthquake liquefaction ground are considered. It is also necessary, in the future revision of China Standard, to put forward feasible computation method for anti-seismic design in liquefiable ground. This is also a major problem China faces in the current design of bridge pile in liquefiable ground.

(2) Seismic design of bridge pile foundation in liquefaction-induced lateral spreading ground

There are several earthquakes in China which caused widespread liquefaction, such as Haicheng earthquake and Tangshan earthquake. Soil liquefaction-induced lateral spreading is one of the key causes leading to the damage of the pile and bridge. However, there are few provisions about the design requirement and method of the pile foundations in the liquefaction-induced lateral spreading ground, toward which Japan pays comparatively more attention by adopting effective technological measures.[19] Although China has a long history of major earthquakes, especially in the past 40 years, during which the devastating earthquakes become more and more and most of them are strong earthquakes with light source or light source directly beneath ground. But, for various reasons, we did not well analyze the historical seismic record and the recent earthquake data. Unlike China, Japan concluded an empirical formula for the estimation of the liquefaction displacement according to the analysis of the historical earthquake data. In addition, there are relatively few studies on the soil dynamic performance after liquefaction and the calculation method of the liquefaction displacement.[20] That liquefaction-induced lateral spreading ground causing destructive damage to the pile

foundation and bridge has been widely accepted in the engineering and academic communities. [21] With our current level of research in this field, the accumulation of data about the quake damage and reference to the successful practice of Japan, revising our seismic design of bridge in China are beneficial. [22] At the same time, it is urgent for China to carry more and deeper studies on the calculation of the displacement in the liquefaction ground and the resistance of the liquefaction-induced lateral spreading. [23]

(3) Seismic Design of Pile Foundations at the boundaries of different soil level in the liquefiable ground

The analysis of the examples of actual seismic damage and response [24] shows that in earthquake, the radical change in the soil stiffness at the interface of different layers leads to the increase in bending moment and shear of the pile body, which causes the damage of the pile foundation easily. It is concluded from the finite element analysis of the dynamics of the pile foundation in the liquefiable ground during the Kobe earthquake that 1) the force the quake exerts on the pile is equivalent to the combination of the horizontal force on the top of the pile and the force of the soil movement; 2) the soil movement causes the internal force of the pile to be highest at the changing area of the soil stiffness; 3) the stronger the quake motion is, the greater the influence exerted by the soil movement on the internal force of the pile is. [3],[6]and [25]However, the calculation method of the internal force of the pile in the quake in general project cannot reflect the actual situation of the internal force at the interface of the soft and hard soil. Amendments to the existing norms and regulations based only on the qualitative conclusions have some blindness and randomness. [26] Bridge seismic design code in Japan does not address this part, either. It can be said to be the blind area for many countries in the bridge seismic design code. In order to ensure the seismic safety of bridge foundation, it is proposed that China has to include specific requirement on the detailed construction of the pile foundation its seismic design specification for bridge pile foundation in liquefiable ground.

(4) Check of the vertical bearing capacity of pile foundation in liquefiable ground

The check of the vertical bearing capacity of pile foundation in liquefiable ground has to include the checks both during the main quake and after quake when the shear strength of soil has not yet resumed. [27],[28]During the earthquake, the axial force of the pile is unstable, and it even changes into a pull-up force; even if it sinks, it occurs intermittently and the seismic subsidence is not strong. But considering the special nature of the mechanical properties of liquefied soil, the friction around the pile has to be properly reduced when checking the vertical bearing capacity of pile. After the quake, in spite of the disappearance of the quake, the strength of liquefied soil has not been resumed, and the pore pressure even continues to rise, and as a result, the pile will continues to sink and most of the seismic subsidence may occur after the shock. Therefore, it is necessary to check the after-shock bearing capacity of the pile. [29],[30]However, so far apart from some seismic design specifications in China make such a request, most of the seismic

design provisions have no specific requirement on this. In view of this, for the conditions of the liquefiable ground, it is suggested to take this issue into consideration by trying two-stage analysis—in-shock and after-shock and the comprehensive analysis to check the vertical bearing capacity of pile foundation in order to improve the seismic design specification for the pile foundation and enhance the seismic safety of the bridge with an operation life.

VII. Conclusion

Through the comparison and contrast between current Chinese and Japanese seismic design specification for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground, it is found that there exists a gap between Chinese seismic design specification and the Japanese one. Given our current level of specification and its weakness, it is imperative to draw the successful experience of Japan, in order to revise and improve our seismic design specification for bridge pile foundation in liquefiable and liquefaction-induced lateral spreading ground. It is of great significance for further enhancing the seismic performance of our bridges and the safety in earthquake.

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Biographies

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