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Seismic Damage Analysis of Pile Foundation on Liquefiable Sandy Soil Foundation

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Abstract

Under the action of cyclic dynamic loads caused by earthquakes, the sandy soil foundation will liquefy, which may easily lead to damage to the pile foundation. For example, the soil liquefaction will cause pile foundation subsidence, the failure of the connection between pile cap and cap, and the beam drop caused by pile foundation moving sideways with soil. There are many influencing factors of foundation liquefaction, and the influence of many factors on foundation liquefaction is highly nonlinear. The author analyzes the liquefaction principle of sandy soil foundation and combines the seismic damage data of pile foundation with the experimental data of large-scale shaking table. Then this paper describes the damage and failure characteristics of pile foundation on liquefied sandy soil foundation.

Keywords

Earthquake Hazard; Liquefaction of the Soil; Pile Foundation.

1. Introduction

Earthquake is sudden. Earthquake disasters have always been the largest proportion of natural disasters, which humanity has ever experienced, that produce serious secondary disasters and cause huge losses to society. Because of Its unpredictability and high frequency. China is a country with many earthquakes, just between the Pacific seismic belt and the Himalaya-Mediterranean seismic belt. Through protracted and unremitting researching and discussion on the seismic performance of pile foundation since the 1960s, Seismic damage of pile foundation has been extensively investigated and analyzed. The seismic performance of pile foundation and the causes and types of failure have been accumulated, and the understanding has been gradually improved. It can be roughly divided into non-liquefied foundation and liquefied foundation, the latter is more complex mechanical mechanism. In the Kobe earthquake in 1995, the liquefaction caused the collapse of urban roads, the slip of river and bank slope, and the collapse of houses.

In fact, The geological composition of earthquake-prone areas in China is mostly sandy soil, which is prone to liquefaction under earthquake action. For example, The 6.8 Ms earthquake in Xingtai in 1966, the 7.8 Ms earthquake in Tangshan in 1976, the 8.0 Ms earthquake in Wenchuan in 2008, and the 7.1 Ms earthquake in Yushu in 2010 . All of them have serious liquefaction phenomena in alluvial soil sites and multiple filling soil sites to varying degrees, including sandblasting water, site lateral movement and settlement, and buildings tilt and settlement [1].

2. Liquefaction of Sand Under Earthquake Action

As the soil, especially saturated and loose sandy soil, under the action of vibration load, the excess water pressure in the soil gradually accumulates and the effective stress decreases. When the pore water pressure accumulates to the total stress, the effective stress becoms zero.

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Then the soil particles are in a suspended state, showing a phenomenon similar to liquid properties and completely losing the shear strength, which is called soil liquefaction. Sand blasting and mud water gushing out of ground cracks are common liquefaction phenomena. They can cause the ground to settle and buildings to tilt. And Underground pipes and tanks may float up. At the same time, river banks have shifted sideways, Bridges have collapsed, dikes or banks have slipped, underground structures and dock facilities have been damaged. In order to reduce the social losses caused by secondary disasters, it is necessary to analyze the factors affecting liquefaction, evaluate the potential liquefaction risk of specific sites, and put forward corresponding effective measures for disaster reduction.

2.1. Earthquake Liquefaction Mechanism of Sand

Under a certain seismic load, whether or not sand liquefaction occurs and the degree of liquefaction occurs are mainly determined by the physical properties of sand and environmental conditions. A large number of studies have found that particle size, density, clay component content, geological time when soil layer was formed, earthquake history, saturation degree and field conditions, such as soil layer thickness, groundwater level burial conditions, drainage conditions and permeability, will all affect sand liquefaction [2]. In addition, the form and amplitude of the load can also affect the liquefaction of sand. It is generally believed that there are two different types of liquefaction mechanisms.

2.1.1. Vibration Liquefaction

The stability of sand is mainly provided by the friction between soil particles. Under the action of earthquake transverse wave, the soil mass shows irreversible volume compression under the shear action of one-way loading. Then resulting in the increase of pore water pressure and the decrease of effective pressure, this phenomenon of Flow deformation is called Flow Slide. Under round-trip load, dense sand always presents volume compression at low shear strain level, and volume expansion at high shear strain level. Therefore, liquefaction may occur in the period of low shear strain level, and the shear resistance regains in the period of high shear strain level. Such a series of interstitial liquefaction results in Cyclic Mobility.

2.1.2. Seepage Liquefaction

When the pore water pressure in a saturated soil rises to equal or exceed its overlying pressure due to the change of groundwater head, the saturated soil will float or "boil" phenomenon, and all the bearing capacity will be lost. This process is independent of the density of sand and volume strain, so it is often considered as "permeability instability phenomenon" . However, from the point of view of the mechanical behavior of the object, sand boiling also belongs to the category of soil liquefaction.

2.2. Influencing Factors of Sand Liquefaction

Whether liquefaction of sandy soil is triggered by vibration is mainly related to soil properties, stress conditions before earthquake, vibration characteristics and other factors. There are many factors affecting ground liquefaction, and the influence of many factors on ground liquefaction is highly nonlinear [3]. At present, it is difficult to use statistics, simplified models, single elastomer theory, plastic theory or even elastic-plastic theory to accurately identify ground liquefaction and assess the damage degree.

2.3. Liquefaction Evaluation

Soil liquefaction evaluation includes the evaluation of soil liquefaction sensitivity, trigger and effect. Soil composition and environmental factors affecting soil liquefaction trigger sensitivity are mainly: mineral composition, particle shape, gradation and fabric, density, effective overlying pressure, saturation.

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2.3.1. Liquefaction Evaluation Method

There are many kinds of identification methods for sand liquefaction in the world, which can be roughly divided into two kinds: one is based on laboratory test, and the other is based on the empirical method of field testing. However, due to the complexity of the problems affecting the liquefaction of sand, each method has certain application scope and limitations. Seed Simplification Method is the first proposed method of free site liquefaction identification, and it's also one of the generally accepted methods at present. On the basis of the field investigation, the empirical criterion and formula, such as the standard penetration test, are established to judge the liquefaction of sand layer.

(1) Seed Simplification Method

Seed Method is a discriminant method based on the ratio of seismic shear stress [4]. The liquefaction possibility is evaluated by comparing the magnitude of the shear stress and the critical shear stress of liquefaction during the earthquake. The simplified Seed method takes into account the effects of earthquake magnitude, peak surface acceleration, bulk density of soil, relative density and burial depth on the liquefaction of sandy soil. The horizontal seismic shear stress required for liquefaction of saturated sand is simulated according to laboratory tests, and the liquefaction resistance of saturated sand is determined. However, due to the complexity of distinguishing the stress state and geometric boundary of soil, the reliability analysis of sand liquefaction method mainly depends on two aspects: one is the reliability of liquefaction test, and the other is the reliability of soil seismic response analysis results.

(2) Standard Penetration Test Method (SPT)

SPT is widely used to estimate the relevant parameters of soil and to evaluate the liquefaction of sand. However, there are many differences in the empirical relationship between determining soil property parameters [5, 6]. The correction of the number of strikes on the standard penetration includes groundwater level correction, rod length correction, overlying earth pressure correction and energy correction [7]. The engineering industry code is based on the empirical formula established on the basis of domestic seismic field data, constantly enriching the database and revising the discriminant.

2.3.2. Evaluation Index of Liquefaction

Wang [8] Based on the soil property data of intensity Ⅷ ~ Ⅸ, silt and less viscous soil in 7 liquefaction sites, proposed the following evaluation criteria for the liquefaction possibility of silt/less viscous soil: clay (particle size $\leq 5\mu m$) content $\rho_c < 15 \sim 20\%$, plasticity index $PI > 3$, water content $w_c > 0.9LL$. However, Chen et al. [9] reviewed the 1994 Northridge earthquake in the United States, the 1995 Hanshin earthquake in Japan, the 1999 Kocaeli earthquake in Turkey, the 1999 Taiwan earthquake, the 2008 Wenchuan earthquake in China, the 2010 Maule earthquake in Chile, and the 2010 ~ 2011 Darfield field in New Zealand It is concluded that clay content is not a reliable index to evaluate the liquefaction possibility of fine grained soil. The fine soil with low liquid limit and high water content is prone to liquefaction. It is suggested that the plastic index(PI)and the ratio of water content(w_c) to liquid limit(LL) should be used to evaluate the liquefaction possibility of fine grained soil.

3. Pile Foundation Earthquake Damage

3.1. Earthquake Damage Characteristics of Pile Foundation

In these earthquakes, a large number of bridge pile foundations are damaged in complex forms, such as pile foundation subsidence caused by soil liquefaction, failure of the connection between pile cap and cap, and beam fall caused by pile foundation lateral movement with soil.

According to many earthquake damage investigations and related literature reports, the damage forms of building pile foundation in liquefied soil or non-liquefied soil are different. But

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the pile head parts of both reach the maximum bending moment and shear force, and the joint of cap and pile is the most damaged part of earthquake. The main reason is that weak links are formed in the area and the shear strength is insufficient. However, when there is a liquefied soil layer, the damage types of piles in the liquefied soil are various and involve liquefaction or lateral expansion.

3.1.1. Failure of Piles on Foundation Without Lateral Expansion

In the case of liquefaction of the whole layer of foundation fill, groundwater spouts can be seen everywhere, with the ground sinked after the earthquake. The damage of the upper structure is light, all of them settle and tilt uniformly, and the pile foundation generally protrudes out of the ground after the earthquake. There are horizontal cracks in the whole section of piles at the interface of liquefaction layer and non-liquefaction layer [10, 11].

3.1.2. Failure of Pile on Foundation with Lateral Expansion

Taking the Great Hanshin Earthquake as an example [12], the lateral expansion of liquefaction in the coastal and water-facing areas of Kobe City and artificial islands caused a horizontal displacement of more than 1m in the coastal protection wall. The seismic damage of pile and superstructure is mainly manifested as: the lateral pressure of flowing soil makes the pile body shear or bending damage at the bottom and middle of the liquefied layer; Failure of pile top embedment; The uneven settlement of the superstructure is caused by the fracture of the pile body.

3.2. Earthquake Damage Mechanism of Pile Foundation

3.2.1. Force of Pile under Earthquake Force

The stress of pile under earthquake load can be divided into two categories: one is the stress of pile under the interaction of soil - pile - structure, which is called additional dynamic stress; The other kind is the lateral displacement of a large amount of soil, the pile deformation under the lateral push of soil, the stress is called the additional static stress.

When the pile is set in the soil without lateral displacement during the earthquake, it’s only bearing the additional dynamic stress caused by vibration. When the pile is set in the soil with lateral displacement during earthquake, the pile not only bears the additional dynamic stress caused by vibration but also the additional static stress caused by lateral displacement of soil [13, 14]. In many cases, the latter has a more significant effect on the pile than the former.

From the perspective of structure, since the pile body is buried in the soil and connected to the superstructure through the pile cap. When the earthquake occurs, the movement of the pile should be coordinated with the surrounding soil [15] , and the deformation of the pile body will cause additional dynamic stress; When the superstructure is transmitted to the pile body through the pile cap with the inertial force of earthquake motion, additional dynamic stress is also generated [16]. Therefore, the soil pile-structure should be taken as a whole during an earthquake, and the additional dynamic stress borne by the pile foundation is caused by the inertial load of the superstructure or the interaction of soil motion [17].

However, the pile foundation can also effectively avoid the mechanical resonance of the superstructure. The high permeability of the concrete pile causes the excess pore water pressure caused by the earthquake to dissipate rapidly. The liquefied sand can filter the high-frequency vibration [18] and amplify the low-frequency vibration, which effectively inhibits the liquefaction of the foundation. Therefore, the drainage and damping coupling effect of concrete pile [19] can improve the deformation compatibility of soil during earthquake.

3.2.2. Failure Mechanism of Pile

The failure mechanism of pile is related to the stress condition of pile during earthquake. Combined with the earthquake damage condition of pile foundation, the failure mechanism of pile foundation can be divided into the following three kinds.

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(1) Damage occurred under the action of additional dynamic stress caused by seismic waves

When the ground motion level is high or the pile foundation construction quality is poor or the foundation soil is weak, the additional dynamic stress caused by seismic waves will cause the damage of the building structure. During the earthquake, the reaction force of the surrounding soil on the pile is small, but the deformation of the pile is large, which leads to the additional dynamic stress of the pile. At the same time, pile group has obvious pile group effect compared with single pile, the additional dynamic stress on the top of pile is more obvious and the time history benefit is slightly delayed [20].

(2) The fracture occurs under the action of additional static stress caused by lateral displacement of soil

The fracture under the action of additional static stress caused by lateral displacement of soil mostly occurs at the shore site. Because the shore site provides two conditions for the failure of this mechanism: first, the soil layer of the shore site is generally very weak, which will produce large permanent deformation during the earthquake; Second, because there are certain slopes on the ground of the shore site, the static shear stress on the horizontal surface of the soil element in the soil is consistent with the direction of the slope, so that the lateral displacement of the soil mass is consistent with the direction of the slope during the earthquake.Moreover, due to the large difference in the degree of softness and hardness of rock and soil mass, the bending moment of pile body at the interface of soil layer and the soil layer near the bedrock surface is larger. The earthquake damage experience shows that the pile foundation may be damaged by this mechanism even if the ground motion level is low [21].

(3) Damage caused by soil liquefaction, pile foundation collapse and loss of bearing capacity

The collapse of pile foundation due to soil liquefaction and loss of bearing capacity can be divided into two failure modes [22] : The first type is that the soil between piles is liquefied before the tip soil, which leads to the reduction of pile bearing capacity. The liquefied soil between piles is extruded laterally, and the pile body moves downward. The second category is that the bearing capacity of the pile is not lost, but the pile foundation as a whole deep foundation. Due to the liquefaction of soil under the base and outside the pile, the pile foundation will produce overall instability, subsidence and even tilt.

4. Conclusion

Under the action of seismic load, the effective stress of saturated sand soil or silt soil is zero, and the soil particles are in a suspended state. This phenomenon is called "liquefaction", and its mechanism can be divided into two processes: vibration liquefaction and seepage liquefaction. The liquefaction soil is accompanied by the special phenomenon of sand floating and water flowing from cracks, and all the bearing capacity is lost.

Pile foundation will have special damage performance under earthquake action:

(1) Whether the building pile foundation in liquefied soil or non-liquefied soil, the pile head is always a dangerous part of large bending moments and shear forces.

(2) The interface of the liquefaction layer is the dangerous part of large bending moment and shear force, and the middle of the liquefaction layer is more dangerous to bend.

(3) Liquefaction without side expansion is generally less harmful to piles than liquefaction with side expansion, and the superstructure is also less harmful.

(4) The bearing capacity and lateral friction resistance of soft soil and liquefied soil caused by vibration can lead to excessive subsidence of piles.

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References

[1] CAO Z, YUAN X, CHEN L, et al. Summary of liquefaction macrophenomena in Wenchuan Earthquake . Chinese Journal of Geotechnical Engineering, 2010, 32(04): 645-50. (In Chinese).

[2] XU X. Study on the micromechanism of sand liquefaction and its evaluation. (MS.,Zhejiang University, China 2012).

[3] REN H, LU X, LI P. Advances in liquefaction research on saturated soils . Journal of Earthquake Engineering and Engineering Vibration, 2007, 06): 166-75.(In Chinese).

[4] CHEN G, WU Q, SUN S, et al. Advances in Soil Liquefaction Triggering Procedures during Earthquakes: Retrospect and Prospect . Journal of Disaster Prevention and Mitigation Engineering, 2021, 41(04): 677-709+33.(In Chinese).

[5] HAO S, ZHANG B, CHEN M. Comparative Analysis on the Discrimination Methods of Sand Liquefaction at a Project Site in Shanghai . Water Power, 1-5.(In Chinese).

[6] ZHU G. Mechanism,Determination and Hazard Evaluation of Seismic Liquefaction. Engineering and Technological Research, 2019, 4(02): 233-4.(In Chinese).

[7] LU K, LI Z, YUAN X, et al. Influence Factors of Standard Penetration Test in China and Over the World. Journal of Seismological Research, 2020, 43(03): 582-91+604.(In Chinese).

[8] WANG W. Mechanism of Soil Liquefaction . SHUILI XUEBAO, 1981, 05): 22-34.(In Chinese).

[9] CHEN G, JIN D, CHANG X, et al. Review of soil liquefaction characteristics during major earthquakes in recent twenty years and liquefaction susceptibility criteria for soils. Rock and Soil Mechanics, 2013, 34(10): 2737-55+95.(In Chinese).

[10] SONG Y, ZHOU S, ZHAO W, et al. Analyze the Influence of Non-liquefied Soil Inter-layer on Bearing Capacity and Deformation of Pile Foundation. Electric Power Survey & Design | Electr Power Survey Design, 2019, 04): 51-4.(In Chinese).

[11] HUANG C. Shaking table model test and numerical simulation of the soil-pile-pier system in liquefied and non-liquefied soil layers. (MS., Beijing Jiaotong University, China 2012.).

[12] LIU H. Discussion on Seismic Design of Pile Foundation-Inspiration from the Great Hanshin Earthquake in Japan. Earthquake Resistant Engineering and Retrofitting, 2000, 03): 27-32.(In Chinese).

[13] KUMAR A, CHOUDHURY D, KATZENBACH R. Effect of Earthquake on Combined Pile-Raft Foundation. Int J Geomech, 2016, 16(5): 16.

[14] GARALA T K, MADABHUSHI G S P, DI LAORA R. Experimental investigation of kinematic pile bending in layered soils. Geotechnique, 2022, 72(2): 146-61.

[15] SONG J, DU X, XU C, et al. Research on the dynamic responses of saturated porous media-pile foundation-superstructure system. Rock and Soil Mechanics, 2018, 39(08): 3061-70.(In Chinese).

[16] LU C W, GUI M W, LAI S C. A NUMERICAL STUDY ON SOIL-GROUP-PILE-BRIDGE-PIER INTERACTION UNDER THE EFFECT OF EARTHQUAKE LOADING. Journal of Earthquake and Tsunami, 2014, 8(1).

[17] LI X, XIAO Y, XU Y M, et al. Structural behavior of double-CFT-pile foundations under cyclic loads. Soil Dynamics and Earthquake Engineering, 2020, 128.

[18] LI P Z, YANG J P, LU Z. Shaking table test and theoretical analysis of the pile-soil-structure interaction at a liquefiable site. Structural Design of Tall and Special Buildings, 2018, 27(15).

[19] ZHANG J, CUI X Z, LAN R Y, et al. Dynamic Performance Characteristics of Pervious Concrete Pile Composite Foundations under Earthquake Loads. Journal of Performance of Constructed Facilities, 2017, 31(5).

[20] ZHANG C, FENG Z, MENG Y, et al. Shaking table test on the difference of dynamic time-history response between single pile and pile group foundation. Rock and Soil Mechanics, 2022, 43(05): 1326-34.(In Chinese).

[21] LING X, GUO M, WANG D, et al. Large-scale shaking table model test of seismic response of bridge of pile foundation in ground of liquefaction. Rock and Soil Mechanics, 2006, 01): 7-10+22.(In Chinese).

ISSN: 2710-0588

[22] JIANG K. Study on dynamic response of underground structure in liquefied and unliquefied foundation.(MS., Hefei University of technology, China 2016.).