DAMAGE PATTERNS AND FAILURE MECHANISMS OF BRIDGE PILE FOUNDATION UNDER EARTHQUAKE

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ABSTRACT:

This paper gives a briefly summary on seismic damage of bridge pile foundations from major earthquakes since 1960s. The typical damage patterns and causes of pile foundation failure with no liquefaction-induced and liquefaction–induced are discussed. Some commentaries and protection measures on seismic design of pile foundation are also given in this paper.

KEYWORDS: failure mechanism, bridge pile foundation, liquefaction-induced, lateral expanding

INTRODUCTION

Pile foundation is a widely applied deep foundation type for civil structure. It is easily fit for complex geologic settings and all kinds of load conditions, especially for soft soil foundation. Pile foundation is widely used in bridge engineering, for its large bearing capacity, well stability and small differential settlement compared to other foundation types.

According to the damage statistics of bridges in the past strong earthquakes over last thirty years, the structures with pile foundation have a better aseismic performance than those without pile foundation, but damages were also found in pile foundation. However, compared to superstructure, there were fewer reports about earthquake damages of pile foundation, the reason of which may be that pile foundations are embedded underground, which make their damages hard to be found.

Since 1960s, several major earthquakes, such as the 1975 Haicheng, 1976 Tangshan and 1995 Hyogoken-Nanbu (Kobe) earthquakes etc., gave excellent indications of bridge pile failure performance, and enrich our understandings about the bridge pile foundation during earthquake loading.

1. EARTHQUAKE DAMAGE OF BRIDGE PILE FOUNDATION

Lots of factors will cause damage of bridge pile foundation under earthquake, such as soil conditions, excessive inertia force caused by superstructure and incorrect design of piles. According to the damage statistics of pile foundation, its failure modes are complex, but soil displacement and sandy soil liquefaction are the most common ones, while the amplification effect of ground motion and excessive deformations of piles are also included. According to the investigation and research of historic strong earthquakes over recent several decades, the damage patterns of bridge pile foundation can be summarized as follows[1][6]:

(1) Crushing failure of pile shaft, or integral settlement of pile and pier due to shear failure. This failure pattern was observed in the 1995 Hyogoken-Nanbu and 1976 Tangshan earthquake. As shown in figure 1

(2) There is no obvious lateral movement or signs of settlement for pile, but many crowded zonal cracks with different width around pile surface can be found. This kind of pile failure pattern can be found in Tangshan and Niigata earthquakes, 1964. As shown in figure 2.

Fig.1 Crushing failure , Hyogoken-Nanbu earthquake

Fig 2 Gaps with differential wide opened around the piles, Tangshan earthquake

(3) Detachment between pile cap and pile head due to shear and bending failures in pile head, and the inadequate (or nonexistent) structural connecting measures. It can be found in the Hyogoken-Nanbu earthquake. As shown in figure 3 and figure 4.

Fig3~4.detachment failures between pile head and pile cap, Higashi bridge, Hyogoken-Nanbu earthquake

(4) Failure of the welded joint of pile cap due to buckling damage of piles.
(5) Girder falling due to the movement of pier supported by pile foundation. As shown in figure 5.
(6) Failure of inclined pile. Bank soil moves to the center of river, which will cause torsional deformation in abutment. Such damage pattern can be found in Tangshan earthquake.

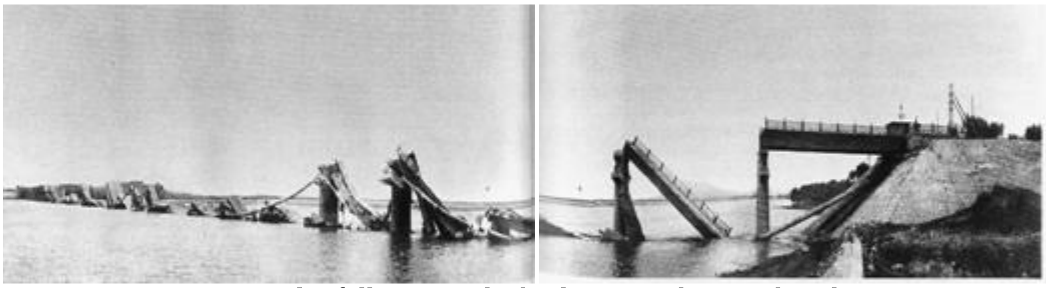

Fig.5 girder falling, Luanhe bridge, Tangshan earthquake

(7) Pier deformation, girder falling or pier penetrating bridge deck due to pile settlement or lateral bending deformation under earthquake loading, both of which are the result of pile not located on steady soil or its insufficient design length. As shown in figure 6 and figure 7.

Fig.6 pile body sinking, Copper highway bridge, Alaska earthquake, 1964

Fig.7 piers penetrate bridge deck, Struve Slough bridge, Loma Prieta earthquake, 1989

2. FAILURE PATTERNS OF BRIDGE PILE FOUNDATION WITH NO LIQUEFACTION-INDUCED PHENOMENA

Seismically-induced bridge pile failures can be described as damage with no liquefaction-induced and liquefaction-induced phenomena. Meanwhile, pile failure modes with no liquefaction-induced phenomena can be described as follows [2]:

(1) Failure caused by inertial force of superstructure. The main positions of damage are joints between pile head and pile cap or the top of pile. The main failure modes are tension, compression and compression-shear failure.

(2) Pile Failure due to excessive bending moment and shear force at the interface between soft and hard soil layer. The 'm' method [9] or the p-y curve method, which is used to calculate pile internal forces, can not reflect actual situation at the interface of different soils.

(3) Pile settlement due to its insufficient vertical bearing capacity. Friction force of soft soil decreases when

thixotropy of soft soil occurs under earthquake loading.
(4) Retaining wall and soil slope around pile foundation or ground load will make nearby soil instable when earthquake occurs, which consequently makes pile subject to lateral compression and excessive bending moment, leading to its failure.

3. FAILURE PATTERNS OF PILE FOUNDATION WITH LIQUEFACTION-INDUCED PHENOMENA

Soil liquefaction was primary cause of bridge foundation distress. Pile damage with liquefaction-induced phenomena can be classified as damage without soil lateral spreading and with soil lateral spreading. The large lateral deformation of ground induced by liquefaction under earthquake loading is one of the main reasons of the damage of structures. To some extent, it is the most main form of earthquake damage of bridge in the liquefiable zone.

3.1.Pile damage without soil lateral spreading[2]

In the case of liquefiable but no soil lateral spreading condition, there appears various phenomena when earthquake occurs, such as sand erupting, water oozing, detachment between pile cap and soil etc.
If the distributions of load, quality of liquefied soil and thickness of liquefied soil are non-uniform, the bridge foundations often produce a quite large uneven settlement under earthquake action. In the case of uniform distributions, pile maybe failed at the interface between liquefied soil and un-liquefied soil or at pile head with little uneven settlement.

3.2. Failure mechanisms of pile with soil lateral spreading

Bridges are often located at the impact band of rivers, where there exist a lot of liquefiable sand and silty layers with gentle slope (0^0~5^0), where lateral spreading easily happen under earthquake loading. When soil liquefies under earthquake loading, its shear resistance will decrease, therefore, liquefied layer with its nonliquefiable overburden layer maybe slide to river along the interface between liquefied layer and its overburden layer. Many bridges collapsed in this mode. This kind of failure mode can be found in Tangshan earthquake and the 1975 Haicheng earthquake in China.
After the investigation of previous earthquakes, Huishan Liu[3] also gave a summary on seismic damage of liquefiable pile foundation under lateral spreading soil condition. Damage to bridge pile with lateral soil spreading was attributed to several mechanisms:
(1) Shear failure and bending failure of piles in the middle and bottom of liquefied layers because of lateral compression of piles induced by soil movement. As shown in figure 8.

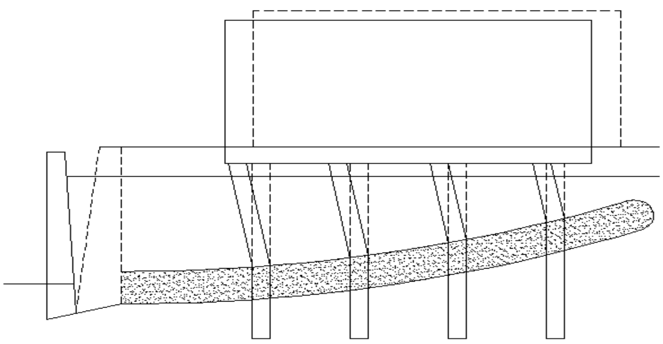

Fig.8

(2) Flexure-shear failure caused by seismic inertial force while pile head is fixed. As shown in figure 9.

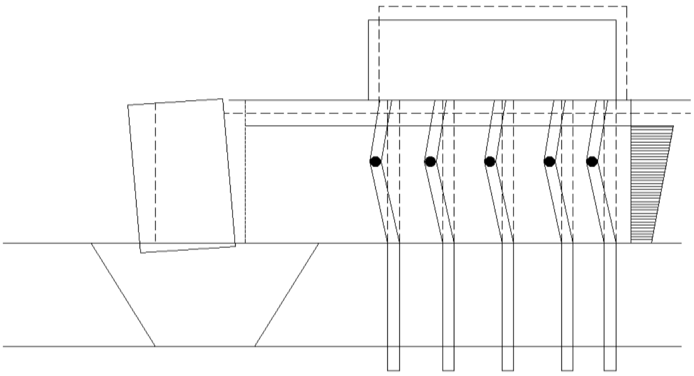

Fig.9

(3) Due to uneven settlement of superstructure, great horizontal displacement and additional bending moment are generated in tall structure. With this additional bending moment, the interior side pile bears tensile stress, so earthquake damage of piles can be relieved and there maybe exist only one plastic hinge for side pile. As shown in figure 10.

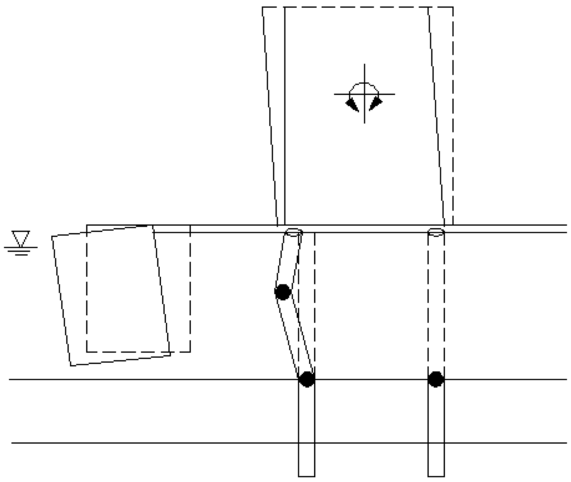

Fig.10

4. FAILURE MECHANISMS OF BRIDGE PILE FOUNDATION

4.1 Force of pile shaft under earthquake loading

The force of pile shaft under earthquake loading can be classified as two types: 1) additional dynamic stress, which is induced by soil-pile-superstructure interaction. 2) additional static stress, which is the consequence of the lateral deformation of pile shaft. When soil produces lateral movement under earthquake loading, pile will produce lateral deformation due to the lateral thrust of soil.

When soil doesn't produce lateral movement under earthquake loading, piles only bear additional dynamic stress that is induced by soil-pile-superstructure interaction. If soil produces lateral movement under earthquake loading, piles bear additional dynamic stress and additional static stress that is produced by soil lateral movement. In most cases, the latter plays a more important role than the former.

Structurally, pile is connected with superstructure through pile cap. Pile movement must be coordinated with soil movement, which results in dynamic stress in pile. On the other hand, the seismic inertial force of superstructure is transmitted to pile through pile cap, which also results in dynamic stress in pile. Therefore, the dynamic stresses that the pile bears under earthquake loading include the two parts above.

4.2. Failure mechanism of pile

The failure mechanism of pile is related to the force conditions of pile under earthquake loading, so the failure mechanism can be subcategorized to three types[4]:
(1) The failure caused by additional dynamic stress that is induced by vibration. Such failure mode generally occurs when the ground motion level is high, the quality of pile is poor, and the soil layer is weak. Under such conditions, the reaction forces to piles from surrounding soil are relatively small, the deformation of piles are relatively large, and relatively big additional dynamic stresses are generated in pile shaft.
(2) The failure caused by additional static stress that is induced by soil lateral movement. Such failure mode usually occurs at bank-side site. It provides two conditions for such failure mode to take place: ①the soil of bank-side site is usually very weak, and is easy to produce large permanent deformation under earthquake loading; ②Due to the slope of bank-side site, when earthquake occurs, soil element will produce static shear stress whose direction will be the same as the bank slope, thus, soil lateral movement will be generated along the stress direction. The statistics of previous earthquake damages indicate that such failure mode tend to take place at relative low ground motion level.
(3) The length of pile penetrating into steady soil layer is not enough or pile tip don't arrive at steady soil layer, so pile foundation is easy to lose bearing capacity due to liquefaction of sandy soil under earthquake loading.

5. COUNTERMEASURES AND SUGGESTIONS ON BRIDGE PILE DESIGN

Liquefaction-induced large deformation of soil is the most main reason for bridge pile damage, so prevention measures to pile must be taken in seismic design.

5.1. Site selection and survey of engineering geology[7]

(1) In bridge route design, the destruction to natural balance condition of site should be avoided because it causes high and steep free face during construction.
(2) The purpose of survey is to ascertain the thickness and buried depth of liquefiable soil layers, grade of soil interface, ground slope, history of river channel, and retaining structures of bank etc..
(3) With regards to the region with large-area liquefiable soil, the principle, which is "bypass rather than pass through", should be abided by, in order to thoroughly eliminate potential dangers to the bridge structure.

5.2. Aseismic construction measures of pile

Generally, liquefiable soil layer shouldn't be used as bearing layer for pile. However, in liquefiable soil area, driving pile not only can make sand layer tighter and stronger, but it can also reach steady soil layer by passing through the liquefiable soil layer. According to the earthquake reconnaissance investigation, the pile foundations used in liquefiable soil area had good performance under earthquake loading, so pile foundation is a suitable choice for liquefiable foundation[2][5][7][10].
In liquefiable soil area, end resistance, lateral resistance and horizontal resistance of piles are very small or even close to zero. If pile foundation is used in liquefiable soil area, the following requirements need to be satisfied:
(1) Pile shaft should penetrate into steady soil layer, and the length of pile should be determined by calculation and must be no less than $4.0/\alpha$ (α , relative flexibility factor of pile). For the piles with medium diameter, the penetrating length should be no less than 7~14 times of the diameter. When the soil of steady layer is gravel soil, sandy gravel, coarse middle sand or hard clay, the penetrating length should be no less than 0.5m.
(2) Fixity of pile head needs to be strengthened. According to the investigation of earthquake damage and relevant reports, whether piles are located in liquefiable soil or not, the maximum bending moment and shear force will be generated in pile head, so the failure modes, such as misplacement, pulling out, and fracture of steel etc, easily take place. The junction between pile cap and pile head is the most vulnerable position under earthquake loading, so strengthening the fixity of pile head is an important measure to relieve earthquake damage of piles.

(3)It is necessary to pave compacted gravel soil or sand cushion with the depth of 200~300mm under pile cap.
(4) In order to make up for the deficiency of calculation method, the reinforcement of pile should be strengthened nearby the interface of liquefiable soil layer. From the top of pile to the location which is 2~3 times of pile diameter below the liquefiable interface, the amount of longitudinal reinforcements and stirrups of pile should be the same as that of the top of pile.
(5) When it has the possibility of soil lateral spreading, special attentions should be given to shear design and construction requirements of pile shaft.

6. CONCLUDING REMARKS

Predicting the behavior of bridge pile foundation under earthquake loading is a very complex problem involving consideration of design ground motions, superstructure response and soil-pile-superstructure interaction. Thus, lessons from historic earthquake are beneficial to pile seismic design. According to the failure patterns and failure mechanisms of bridge pile foundation described above, the following conclusions can be obtained:
(1) Failure modes of bridge piles are complex, but soil expanding and sand liquefaction are the most common ones, while the amplification effect of ground motion and excessive deformation of pile are also included.
(2) The analysis on failure patterns and failure mechanisms of bridge piles indicate that, the failure probability of bridge piles in the slope or bank-side site is higher than that of pile with large displacement induced by earthquake liquefaction.
(3) When soil large displacement with liquefaction-induced occurs, bridge piles bear horizontal stresses, which include dynamic stress induced by inertial forces of superstructure as well as additional stress induced by soil lateral movement. In most cases, the latter plays a more important role than the former.
(4) With regards to site selection for engineering, it is necessary to keep the site clear of the region with large-area liquefiable soil. Even if not, the location of piles must be far from bank slope, especially far from abrupt slope.
(5) With regards to the pile foundations in the liquefiable soil, it is necessary to take active preventive measures such as enhancing horizontal bearing capacity of piles, strengthening the fixity between pile head and pile cap, foundation consolidation etc.

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