Shaking Table Test On Dynamic Response of Bridge Pile Foundation Near Fault Under Strong Earthquake

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Abstract

Taking Puqian bridge as the prototype, a 1:30-scale pile-soil-fault interaction model was established. Through the shaking table test, the difference of dynamic response of pile foundation on both sides of fault under 0.15~0.60g ground motion intensity was studied. The pile acceleration, pile top relative displacement, and pile bending moment on both sides of the fault are compared respectively. Research results showed that under the action of a strong earthquake, the pile foundation on the hanging wall was greatly affected by ground motion, and “the hanging wall effect” was significant. As the ground motion intensity increased, the “hanging wall effect” of the pile foundation was more obvious. Combined with the fundamental frequency response and the test phenomenon, when ground motions intensity was strong, cracks appeared near the joint of pile top and platform, soil interface, and bedrock surface. When building a bridge pile foundation near the fault, the seismic design of the pile foundation on the hanging wall of the fault is mainly considered.

Introduction

In previous earthquakes, damage to the pile foundation is often reported. The pile foundation with excellent seismic performance and high bearing capacity is often used in bridge construction in a strong earthquake area. Pile foundation earthquake damage phenomena such as pile cap failure, pile body crack, broken pile, and so on are more common. Especially when the fault fracture zone occur, the seismic damage of the pile foundation is more serious, which seriously threatens the safe operation of bridges^[1-3]. Many major earthquakes in history have shown the destructive effects of fault rupture on pile foundation, such as Kocaeli Earthquake in Turkey, Chile earthquake and ChiChi Earthquake in Taiwan^[4-6]. Consequently, there is an urgent need to study the dynamic response of pile foundation near fault under strong earthquake.

Some scholars have studied the pile-soil dynamic interaction under earthquake by theoretical and numerical simulation methods, but there is no fault effect in geological conditions^[7-10]. Xie et al.^[11] and Li et al.^[12] studied the pile-soil-structure interaction under dynamic load, but it focuses on the dynamic response of superstructure and the effect of thrust faults. However, the shaking table test (STT) is an attractive alternative to study this problem. The study of pile-soil nonlinear interaction in STT can be obtained from researchers^[13-18]. Feng et al.^[19-22] studied the dynamic response laws of pile foundation through large-scale shaking table test. Through the 1 g STT, Yang et al.^[23] studied dynamic p-y curves for a single pile in dry and saturated dense sand, and Hamayoon^[24] studied the seismic performance of existing group-pile foundation in dry condition and soft soil respectively. There are many studies on the dynamic response of the pile foundation in liquefied soil layer under earthquake. Hui et al.^[25] established a 3-D soil-pile simulation analysis based on centrifuge test data to investigate the influence of pile response near-fault ground motion in liquefiable soil. Zhang et al.^[26] presented an STT to study the influence of lateral load and axial load on the instability of pile in liquefied soil. However, most of the existing researches only consider the seismic response of the bridge pile foundation under the action of a

single factor of earthquake or fault. The influence of fault on the dynamic response of bridge pile foundation is not considered. The interaction mechanism of pile-soil-fault under strong earthquake is not clear. Therefore, it is urgent to study the dynamic response of bridge pile foundation near fault under strong earthquake.

In this paper, the dynamic response and pile foundation damage near the fault were discussed under the ground motions intensity range of 0.15g~0.60g by STT. Focus on the difference of seismic response of pile foundation on both sides of fault. The purpose of this paper is to supplement and improve the seismic design theory of the bridge pile foundation subjected to near-fault ground motions.

Study Area And Engineering Background

The study area is a bridge pile foundation across fault near Hai'kou, Hainan Province, southern China (N20°02'45.97",E110°11'38.39"). The Puqian bridge is situated at the source of Qiongsan earthquake. There was an earthquake with magnitude 7.5 on the Richter scale in 1605 (**Fig. 1**). The bridge crosses three faults. In the region, the seismic fortification intensity is VIII degrees, and 50 years of surpassing probability 10% (2%) dynamic peak acceleration is 0.35g (0.59g). The peak acceleration value of the designed basic ground motion exceeds the fortification intensity range value (0.20g) of the general seismic measures for Class A bridges in article 3.1.4 of the " Specifications for Seismic Design of Highway Bridges " (JTG/T 2231-01—2020) ^[27]. The 38# group pile foundation is located on the hanging wall of the fault, while the 37# group pile foundation is located in the footwall of the fault. The distribution of soil layers are mucky clay, gravel, pebble soil, and slightly weathered granite.

Results

The dynamic response of near-fault bridge pile foundation under strong earthquake can be used to evaluate the stability of pile foundation, which is an important means to predict the stability of pile foundation. In this paper, acceleration, displacement, bending moment, and fundamental frequency were selected to describe the dynamic response of the model pile. If there is no special description, the solid lines in the data graph of this paper indicates the 38 - 1# pile (on the hanging wall of the fault), and the dotted lines indicates the 37 - 1# pile (in the footwall of the fault).

Acceleration response

Peak acceleration of pile. The peak acceleration (PAC) distribution of pile foundations on both sides of the fault are shown in Fig. 2. The acceleration distribution law of pile foundation on both sides of fault is similar. The PAC decreases along the pile length, which has a turning point in the muddy soil layer. The reason is that loose soil can absorb part of seismic wave energy. The porosity of the muddy soil layer is relatively large, and the particle size is small, which can absorb more energy. Under different intensity ground motion, the PAC of pile on the hanging wall of the fault is larger than that in the footwall. It reflects "the hanging wall effect" of the fault. The reason for this is that the fault filling materials are

granular particles, and their physical and mechanical states are unevenly distributed. The contact between the rock and soil on both sides of the fault and the fault filling materials is uneven, leading to the significant nonlinear difference of rock and soil around the pile on both sides of the fault.

The difference of the PAC between pile top and pile bottom is shown in Fig. 3. The PAC difference of 38 – 1# (on the hanging wall) is larger than 37 – 1# (in the footwall). Under different intensity ground motion, the difference is significantly different. In the 0.15g ~ 0.25g, the difference increases slowly. In the 0.30g ~ 0.35g, the difference is small. In the 0.40g ~ 0.60g, the difference is significantly larger. The greater the intensity of ground motion, the more obvious the difference.

Acceleration magnification fact. The PAC and acceleration amplification factor (AAF) of each measuring point of piles on both sides of the fault are shown in Fig. 4. The AAF α (shown in Eq. (1)) is the ratio of the PAC of pile top ($a_{\max}$) to the input seismic wave (a_{input}). It can reflect the properties of rock and soil layers and the magnifying effect of elevation on pile acceleration.

$$\alpha = a_{\max}/a_{\text{input}} \quad (1)$$

The PAC and AAF of the pile on the hanging wall of the fault are larger than those in the footwall. There are obvious differences in the “the hanging wall effect” of fault in different soil layers. In different soil layers, the various rule of MAC on both sides of fault is approximately the same, and there is a slight difference in the law of AAF. As the increase of ground motion intensity, the PAC increase, and the AAF decrease. Under different intensity ground motion, the PAC and AAF of the pile on both sides of the fault are quite different at the pile top and in the pebble soil (Fig. 4(a) and Fig. (d)); the PAC increases approximately linearly and the AAF stabilizes around 1 in the bedrock (Fig. 4(e)); the difference of the PAC and AAF are small in the mucky clay and gravel sand (Fig. 4(b) and Fig. (c)).

Horizontal displacement response of pile top

The relative displacement of the pile top on both sides of the fault is shown in Fig. 5. Under different input seismic intensities, the maximum relative horizontal displacement of the pile top on the hanging wall is larger than that in the footwall. With the increase of ground motion intensity, the maximum relative displacement of pile top increases gradually, and the difference of those also increases gradually. When the ground motion intensity is 0.15g ~ 0.25g, the difference of those are small, which are 0.05mm, 0.05mm, and 0.04mm. When 0.30g ~ 0.40g, the difference increases gradually, which are 0.30mm, 0.48mm, and 0.50mm. When 0.45g ~ 0.60g, the difference is large, which are 0.50mm, 0.77mm, 0.61mm, and 0.77mm. Under the pile-soil-fault interaction, the pile foundation on the hanging wall is greatly affected by ground motion.

Bending moment response of the pile

The bending moment of the pile on both sides of the fault is shown in Fig. 6. With the increase of earthquake intensity, the variation law of pile bending moment is similar. The bending moment is the largest at the interface between the muddy clay layer and g the ravel layer. And there also have a sudden change in the bending moment value on the bedrock surface. Under different intensity ground motion, the

bending moment of the pile on the hanging wall is larger than that in the footwall, which also shows the “the hanging wall effect” of the fault.

According to the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTGD62-2018) [32], the bending bearing capacity of pile foundation was 168.54 kN·m. The maximum bending moment of the pile on both sides of the fault is shown in Fig. 7 (a). The safety degree of the flexural bearing capacity of the pile is shown in Fig. 7 (b). The safety degree of flexural bearing capacity of pile β is defined as:

$$\beta = (M_{\max} - M_0) / M_0 \times 100\% \quad (2)$$

where β is the safety degree of flexural bearing capacity of pile(%), $M_{\max}$ is the maximum bending moment of pile (kN·m), M_0 is the flexural capacity of the pile (kN·m). The negative value of β indicates the surplus of bending bearing capacity, and the positive value of β indicates that it exceeds the bending bearing capacity.

In the intensity ground motion from 0.15g to 0.25g, the maximum bending moment difference is small and there is a surplus of flexural bearing capacity. In 0.30g ~ 0.40g, the difference is increases by degrees. In 0.45g ~ 0.60g, the difference increases rapidly. It is worth noting that the maximum bending moment of the pile on the hanging wall exceed the flexural capacity of the pile in 0.45g, while the maximum bending moment of the pile in the footwall not.

Fundamental frequency of the pile

The above analysis shows that “the hanging wall effect” of fault is significant under the strong earthquake-fault coupling action. Therefore, the pile foundation on the hanging wall is selected as the analysis object. The change of the fundamental frequency of the pile foundation is not obvious when the input seismic intensity is less than 0.35g. Therefore, the damage of pile foundation is analyzed when the ground motion intensity is greater than 0.35g. The Fourier spectrum of the pile on the fault wall is shown in Fig. 8.

The fundamental frequency of pile foundation before loading is 3.54Hz. In the input seismic intensity 0.35g ~ 0.60g, the fundamental frequencies are 3.57Hz, 3.48Hz, 3.26Hz, 1.78Hz, 0.93Hz and 0.84Hz, respectively. When the input seismic intensity is 0.35g ~ 0.45g, the foundation frequency of pile foundation does not change obviously. It shows that the overall stiffness of the pile foundation is not reduced, and there is no obvious damage. When the input seismic intensity reaches 0.50g, the fundamental frequency of the pile foundation decreases obviously and decreases by 49.7% (Fig. 9). In 0.50g, the foundation frequency of pile foundation decreases slowly and tends to be stable. At this time, there is a big difference between the maximum acceleration of the pile top and the pile bottom, the horizontal displacement of the pile top is larger, and the safety degree of flexural bearing capacity of pile is positive, that is, it exceeds the bending bearing capacity. At this time, under the pile-soil-fault interaction, the pile foundation is damaged by the earthquake, which is consistent with the macroscopic phenomenon of the Section *Damage analysis of the pile*.

Damage analysis of the pile

There is no obvious damage on the surface of the model pile under 0.15g ~ 0.45g seismic intensities. A slight crack was generated at the connection between the top of the pile and the cap under input seismic intensity of 0.50g. From 0.50g to 0.60g, the pile produced a slight tilt, and cracks propagation further. The dynamic failure process of the model pile is shown in Fig. 10. Results show that the dynamic failure is mainly reflected in the cracks appeared near the joint of pile top and platform, soil interface and bedrock surface. With the increase of the seismic intensities, the cracks further expand, leading to loss of bearing capacity of the model pile.

Discussion

1. In different soil layers, the PAC and AAF of the pile on the hanging wall of the fault are larger than those in the footwall. The reason may be: due to the existence of faults, the footwall foundation soil will be squeezed by the hanging wall foundation soil. In the process of shaking, the soil in the footwall tends to be denser, the damping ratio increases and more seismic wave energy is consumed. However, this phenomenon is not obvious in bedrock. The reason is that the amplification effect of bedrock on the seismic wave is small, while that of soil is larger.
2. Under the action of gradually increasing dynamic load, the soil goes through the vibration compaction stage, the vibration shear stage, and the vibration failure stage. The footwall foundation soil is squeezed. When the dynamic load is small, the vibration compaction of the footwall foundation soil may be strengthened, and when the dynamic load is large, the vibration shear of the footwall foundation soil may be inhibited. Therefore, the maximum relative horizontal displacement of pile top in the footwall is smaller than that on the hanging wall.
3. With the increase of input seismic intensity, the soil shear strain increases, the resistance of soil on the side of pile decreases, and the transmission force from soil to pile decreases gradually. The squeeze of the hanging wall foundation soil to the footwall foundation soil may restrain the increase of the shear strain of the footwall soil. As a result, the footwall foundation soil can provide greater soil resistance. Therefore, the pile bending moment in the hanging wall on the hanging wall is larger than that of in the footwall.
4. There is a difference in the seismic response of pile foundation to the effect of fault hanging wall. Taking the bending moment of pile as the main control index, 0.15g ~ 0.60g can be divided into three ranges.
 - a) The first range: the seismic intensity of 0.15g ~ 0.25g. In this range, there is little difference in seismic response of pile foundation on both sides of the fault. At this time, the foundation soil gradually tends to be dense, which provides greater constraints on the pile foundation.

b) The second range: the seismic intensity of $0.30g \sim 0.40g$. In this range, the difference of seismic response of pile foundation on both sides of fault increases gradually. At this time, micro-cracks may occur inside the pile, which weakens the propagation of seismic waves in the pile. But it is not enough to affect the integrity of the pile.

c) The third range: the seismic intensity of $0.45g \sim 0.60g$. In this stage, the seismic response of “the hanging wall effect” of the fault to the pile foundation is large, and the difference is significant. At this time, cracks appeared near the joint of pile top and platform, soil interface and bedrock surface. With the increase of earthquake intensity, the cracks further expand, and the fundamental frequency decreases obviously.

Conclusions

In this paper, the seismic response and the damage of the pile were studied under different input seismic intensities through the STT. The following conclusions were drawn.

1. Under the pile-soil-fault interaction, the pile foundation on the hanging wall of the fault is greatly affected by ground motion. When constructing the bridge pile foundation subjected to near-fault ground motions, the seismic design of the pile foundation on the hanging wall of the fault is mainly considered.
2. This paper combines the difference of dynamic response of pile foundation on both sides of fault under the seismic intensity of $0.15g \sim 0.60g$, which can be divided into three ranges: a) $0.15g \sim 0.25g$; b) $0.30g \sim 0.35g$; c) $0.40g \sim 0.60g$. With the increase of the intensity of ground motion, pile foundation on “the hanging wall effect” of the fault is more sensitive.
3. Under strong earthquake, the rock-socketed depth of the pile foundation should be increased as much as possible to avoid damage to the pile foundation caused by the magnifying effect of overburden soil on the seismic wave.
4. Under the ground motions, when designing the bending resistance of the pile foundation near the fault, the bending bearing capacity of the pile foundation at the interface of soft and hard soil and near the base rock surface should be enhanced. The design of the flexural bearing capacity of the pile foundation on the upper wall should also be considered.
5. Future research will look into the dynamic response difference of pile foundation on both sides of the fault under different types of ground motions, and further explore the mechanism of pile soil fault interaction.

Methods

A statement attesting to informed consent from all subjects. For this study, all subjects were team researchers and laboratory operators in the following figures. In this study, all subjects involved provided

informed consent to publish their identification information/images.

Test equipment. The shaking table test was carried out in the Institute of Engineering Mechanics of China Earthquake Administration. The laminar shear model box was selected ^[28]. The model box is 3.7m×2.8m×2.0m, which stacked by 15 layers of the hollow steel frame. The model box was lined with a 1 cm rubber mat to reduce the boundary effect of the box and prevent soil or water from overflowing, as shown in Fig. 11. Taking into account the model box size and test conditions, three essential similarity ratios ($C_L=30$, $C_E=1$, $C_a=1$) were determined. The similar constants of the main physical quantity are shown in Table 1. Considering artificial quality similarity criterion, the counterweight on top of cap was 100kg ^[29–30].

Table 1
Physical quantity similarity relation

Parameters	Similarity relation (prototype/model)	Similarity constant(prototype/model)
Physical dimension(L)	C_L	30
Elastic modulus(E)	C_E	1
Acceleration(a)	C_a	1
Frequency(ω)	$C_\omega = C_a^{1/2}/C_L^{1/2}$	0.18
Displacement(s)	$C_s = C_L$	30
Gravity acceleration(g)	$C_g = C_a$	1
Poisson's ratio(μ)	C_μ	1
Stress(σ)	$C_\sigma = C_E$	1
Strain(ε)	C_ε	1
Internal friction angle (φ)	C_φ	1
Cohesion (c)	$C_c = C_E$	1

Model preparation. *Model soil and bedrock.* Based on the geological exploration data of the Puqian bridge, the method of measuring the shear wave velocity of the soil is used to determine the compaction times of the soil layer^[18], as shown in Table 2. Then, the water content, cohesion, internal friction angle, compression modulus of the model soil, and compressive strength of bedrock are tested, as shown in Fig. 12. In this test, C60 concrete was selected to simulate slightly weathered granite. The compressive strength of C60 concrete is tested by the universal testing machine, and that is 56MPa. The dip angle of

the fault is 75 degrees. The fault filling materials were made of 3-5mm stone mixed with medium sand. The parameters of the model soil are shown in Table 3.

Table 2
Shear wave velocities of the soil layers (unit: $\text{m}\cdot\text{s}^{-1}$).

Name	Mucky clay	Gravel	Pebble soil	Fault fracture zone
Undisturbed soil	136	263	526	-
Model soil	138	276	539	115

Table 3
The parameters of model soil.

Model soil	Density ρ (g/cm^3)	Water content ω (%)	Compression modulus E (MPa)	Cohesion c (kPa)	Internal friction angle φ ($^\circ$)
Mucky clay	1.67	49.8	3.78	10.2	4
Gravel sand	1.94	23.2	4.68	13.3	25
Pebble soil	2.03	31.5	24	8	39

Model piles and test element. According to the test similarity ratio and the bending stiffness of the pile foundation, the model piles were made of C35 concrete and Q235 steel. The reinforcement ratio was 2.4%. The model pile was 4 four pile groups, with a length of 180cm. The model pile length was 180cm. In order to restore the actual situation as much as possible, the rock-socketed depth of pile foundation on both sides of the fault and the location of test elements are slightly different. However, this paper focuses on the influence of the relative position of fault and pile foundation on its dynamic response. In this test, acceleration, displacement, bending moment, and fundamental frequency were selected to describe the dynamic response of the pile. And the displacement meter is only installed at the top of the pile. And all strain gauges and acceleration sensors were embedded around the pile (Fig. 13).

Test operation process. The shaking model test operation processes is shown in the following Fig. 14.

1. As mentioned in the previous article, the test model pile is made according to the geometric similarity ratio and reinforcement ratio, and the test elements are arranged along the pile body after 28 days of maintenance.
2. The test model soil was prepared and C60 concrete simulated bedrock was cured for 28 days.
3. The model soil is packed and the model pile is placed, and the test element is connected with the data acquisition system.

4. The seismic waves of different intensity are loaded for 40 seconds. The data are collected every second, and the maximum value is selected for analysis.

Test conditions. The seismic wave was artificial wave, named the “5010 wave” (50 years of surpassing probability 10%), synthesized by the China Earthquake Administration. Through the correction and filtering of the matching software SEISMOSIGNAL, the peak acceleration was scaled down and controlled to 0.15g ~ 0.60g (0.15g, 0.20g, 0.25g, 0.30g, 0.35g, 0.40g, 0.45g, 0.50g, 0.55g, 0.60g). Figure 15 shows the 0.35g seismic wave. Before the shaking table test and after the loading, white noise excitation was applied to the model pile to obtain the dynamic characteristics. The excitation direction is bidirectional excitation along the horizontal plane.

Declarations

Data availability

The data used to support the findings of this study are included within the article.

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Author contributions

C.Z. carried out the shaking table test, researched the data and wrote the manuscript, Z.J.F. designed the experiments, Y.Y.K. contributed to the figures and tests, Y.H.G. established the tables, Y.X.D. and H.Y.C. conducted the idea.

Competing interests

The authors declare no competing interests.

Additional information

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Figures

Figure 1

Location map of bridge site

Figure 2

Peak acceleration of pile foundation: (a) 0.15g~0.35g; (b) 0.40g~0.60g

Figure 3

The variation law of MAC difference between pile top and pile bottom

Figure 4

The PAC and AAF of the pile on both sides of the fault: (a) TA1, UA1; (b) TA2, UA2; (c) TA3, UA3; (d) TA4, UA4; (e)TA5, UA5

Figure 5

The variation law of relative displacement of pile top

Figure 6

The bending moment of the pile under different input seismic intensities: (a) 0.15g~0.35g; (b) 0.40g~0.60g

Figure 7

The variation law of bending moment of the pile: (a) Maximum bending moment of pile; (b) Safety degree of flexural bearing capacity of pile foundation

Figure 8

Fourier spectrum of the pile: (a) Before loading; (b) 0.35g; (c) 0.40g; (d) 0.45g; (e) 0.50g; (f) 0.55g; (g) 0.60g

Figure 9

Variation of foundation frequency of pile foundation

Figure 10

Development of surface cracks in model pile.

Figure 11

Shaking table test equipment

Figure 12

Physical property tests

Figure 13

Schematic diagram of the model and layout of test components

Figure 14

Test operation process

Figure 15

5010 seismic wave