Journal of Applied Sciences

ISSN 1812-5654

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Journal of Applied Sciences 13 (22): 5342-5348, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.5342.5348

Influence of Pile-Pier Reinforcement Ratio on the Development of Plastic Zone of Bridge Structure

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Abstract: In this study, using elastic-plastic fiber unit model for a continuous beam bridge structure and foundation to analyses the nonlinear seismic response of pier and pile foundation considering pile-soil interaction and the different types of seismic wave on the pile foundation and the pier' dynamic response, focusing on the development of plastic zone and dynamic response of structure under different pile-pier reinforcement ration conditions. The results show that, with the pile pier reinforcement ratio increases, the response plasticity of pile and pier show a different trend; so pile-pier reinforcement ration is an important factor of dynamic characteristics for the bridge pier supported by group piles system; the pier reinforcement ratio not only impact on development of the plastic zone of the pier but also impact on the pile. In addition, different types of seismic waves on the structure are different, the long-period seismic waves maximum, followed by inland direct seismic waves, plate boundary seismic wave minimum.

Key words: Bridge structure, ground motion, plastic zone, reinforcement ratio, pile-soil interaction

INTRODUCTION

View of the structural characteristics of the bridge is "top-heavy", inspired by the earthquake inertia force is mainly concentrated in the superstructure of the center of mass but mainly borne by the substructure, moreover the pile is weaker than pier and easier to enter the plastic state in earthquake. For example, in the 1999 Kobe earthquake in Japan, the Japan Society of Civil engineering count the destruction of the 3rd and the 5th Hanshin Expressway (JRA, 2002) and over half of pile foundation needs to be fixed and pile testing and repair is very difficult, post-disaster have serious implications for the reconstruction and economic development and therefore need the reasonable control of the generation site and the development process of the plastic hinge zone bridge seismic design. Plastic energy dissipation mechanism is selected, as far as possible the expected plastic hinge is easy to check and repair parts.

In recent years, the ratio of reinforcement on the seismic performance of the bridge has become focus of the research, such as Watson (Waston *et al*., 1994) use Mander model of the confined concrete numerical regression to analysis of the cross-sectional moment curvature and proposed calculation formula for pier columns curvature reinforce dosage. Chang and Mander (1994) give an equivalent mechanical calculations for the length of the plastic hinge model and developed program to non-linear analysis of the reinforced concrete pier. Liu and Fan (1998) use approximate Watson theoretically to analysis of the relationship between the column curvature ductility of reinforced concrete with reinforcement ratio. Wang *et al*. (2011) use repeatedly by low cycle load test to study the seismic performance of the columns of the piers under the ordinary composite stirrups and the new S-Clip tendons, found that the stirrup reinforcement ratio and method could influence the longitudinal reinforcement performance and damage of reinforced concrete structures. Li *et al*. (2007) analyzed what would be the shear capacity of the box girder impact of a variety of shear span ratio, different stirrup ratio, different longitudinal ordinary web reinforcement ratio and different vertical prestress. Found that changing the web vertical ordinary reinforcement and stirrup reinforcement ratio have no significant effect on the carrying capacity and failure pattern of component. Fu (2012) found that due to the lower plastic hinge of specification requirements minimum constraints stirrup, under the same reinforcement conditions, the capacity of pier shear used china code calculated is lower than in other countries. Zhuo and Fan (2002) use the different experimental research and nonlinear regression analysis to proposed a new formula for ductile pier plastic hinge zone minimum constraints stirrup.

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However, in previous studies, scholars mainly derivate the theory of the plastic hinge and computing but for the impact of reinforcement ratio on the plastic zone only have the analysis of a single component, longitudinal reinforcement ratio of the pile and pier the ratio of the bridge structure to carry out of the plastic zone affects relatively few. Definition the longitudinal reinforcement ratio of pile-section with the ratio of longitudinal reinforcement ratio of pier-section is the pile-pier reinforcement ratio (Zhao, 2005). On the basis of existing research, based on the general-purpose finite element analysis software of the bridge structure, used the common continuous highway bridges bridge as the engineering background to create a continuous bridge pier pile group foundation model, analysis of elastic-plastic seismic response of the structure under different types of seismic wave. Changing the pile-pier reinforcement ratio to focus on carry out the trend of plastic zone of the pier supported by group pile foundation under different pile-pier reinforcement ratio, in order to provide a reference for bridge seismic design and seismic performance evaluation.

ENGINEERING AND MODEL

Engineering background: A continuous bridges across 40 m long, pier and pile are used HRB335 rebar and C40 concrete, pier is rectangular and height 10 m, pile is a bored pile and length 28.5 m, engineering site type is 2, pier and pile shown in Fig. 1, site soil distribution shown in Fig. 2. Using Midas Civil to establish space power computing model of the pier supported by group pile foundation, pier and pile use the beam unit, platform use plate unit and plate elements and beam elements are rigidly connected. Transform the quality of the superstructure loads about 6900 kN (Lu *et al.*, 2011) as the mass to load the top of the pier, supports constraint of bridge in axial direction use bilinear ideal elastic-plastic spring to simulate, supports constraint of transverse to bridge is negligible. It takes centralized system of particles pile to simulate pile-soil interaction. The interaction of pile and soil stiffness and damping of the spring as well as part of the vibration of the equivalent soil quality added to the pile node corresponding position.

Longitudinal reinforcement rate of the chosen continuous bridge piers and pile are 0.994 and 1.042%, respectively, in order to study influence of the different pile-pier reinforcement ratio to plastic zone carried out of pier supported by group pile foundation under the strong earthquake, according to the Guidelines for Seismic Design of Highway Bridge (CCRDI, 2008) (JTG/T B02-01-2008), in accordance with the 8-degree earthquake fortification level of the pier and pile foundation design. Another the selected longitudinal reinforcement ratio of pier section are 1.141 and 1.345%, respectively longitudinal reinforcement ratio of pile section are 1.306% and 1.707%, three different reinforcement ratio pier and pile-section were analyzed. Numerical calculation model using different reinforcement ratio pier and pile model portfolio, A1,..., C3, 9 group model, model pier-pile reinforcement ratio as shown in Table 1. According to Code for Design of Concrete Structures (GB50010-2011)

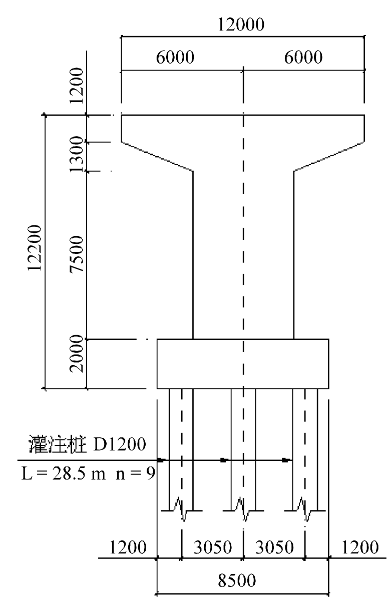

Fig. 1: Size of the pier and pile

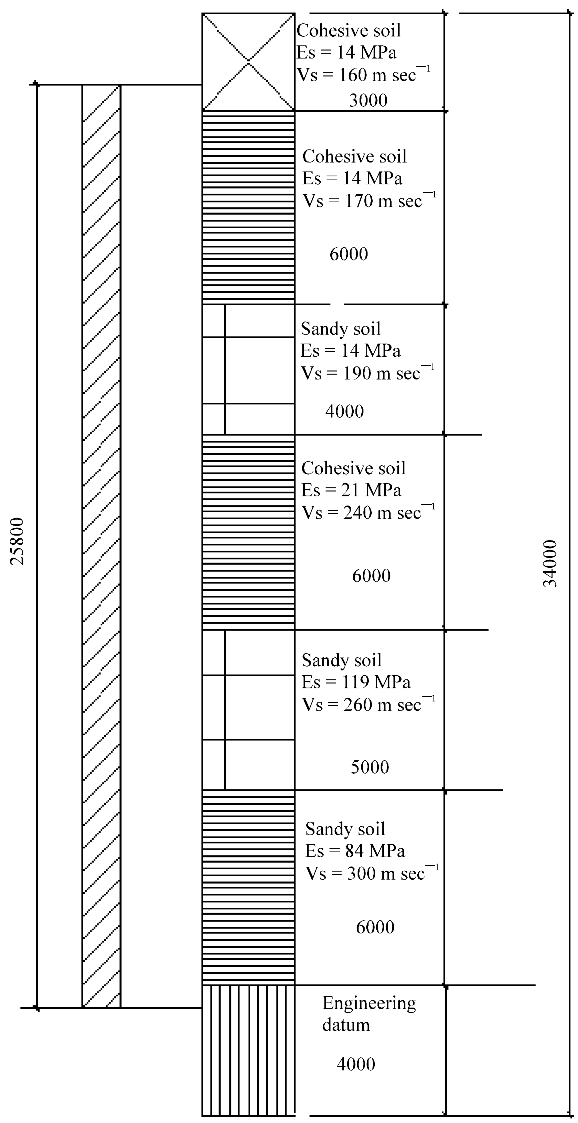

Fig. 2: Soil distribution map

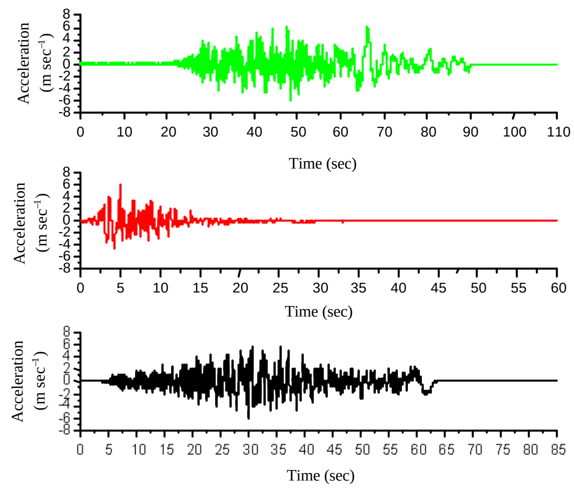

Fig. 3(a-c): Accelerations time-history curves of seismic accelerations (a) TCU115 seismic wave, (b) T2-II-3 Seismic wave and (c) T1-II-3 Seismic wave

(Ministry of Housing and Urban-Rural Development, 2011) uses UCFyber to calculate flexural capacity of groups pier section and pile-section, the values shown in Table 1.

Model parameters: The creation of group pile model is determined by the stiffness of the spring to simulate pile soil together. The effect of the soil around the pile foundation use the p-y spring to simulate that which can better simulate the pile-soil reaction elastic-plastic development process. Very 1m along the depth of pile set a p-y spring.

Using fiber element model to analysis the damage of reinforced concrete bridge pier supported by group pile foundation, concrete constitutive model take the pressure concrete envelope curve (envelope curve) formula that is propounded by Kent and Park (1971) and consider concrete binding ductility (Nagoya *et al*., 2006). Reinforcement constitutive model the bilinear-kinematic hardening (kinematic hardening) curve and consider the axial the steel stress-strain relationship. Transfer between the various load paths and strain-hardening interval asymptote section is curve (CCRDI, 2008).

Selection of seismic waves: According to Japanese Specification for Highway Bridges to get structure's earthquake responses under 3 different seismic waves, select plate boundary type seismic waves T1-II-3, inland direct seismic waves T2-II-3, as well as long-period seismic waves TCU115. In order to study the influence of pile-pier reinforcement to plastic zone, according to the Code for Seismic Design of Buildings (GB50011-2010) (Ministry of Housing and Urban-Rural Development, 2010) to take acceleration peaks level of three different types of seismic waves adjusted to 620 Gal to meet the 9 degrees rare earthquake design requirements, acceleration time-history curves of seismic waves shown in Fig. 3. Made the response spectrum curve of three seismic waves at the damping ratio of 0.05 that shown in Fig. 4. As can be seen from Fig. 4, the plate boundary type of seismic wave for cycle is 0.25~1.5 sec. Structure takes a greater response and acceleration response with increased structural natural periods of slow decline. For inland direct seismic wave, acceleration response

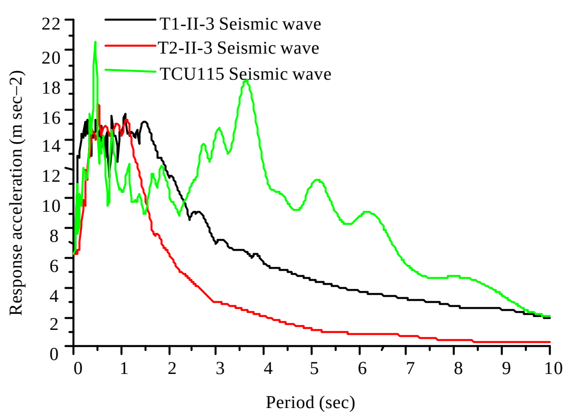

Fig. 4: Response spectrums of the loading seismic waves

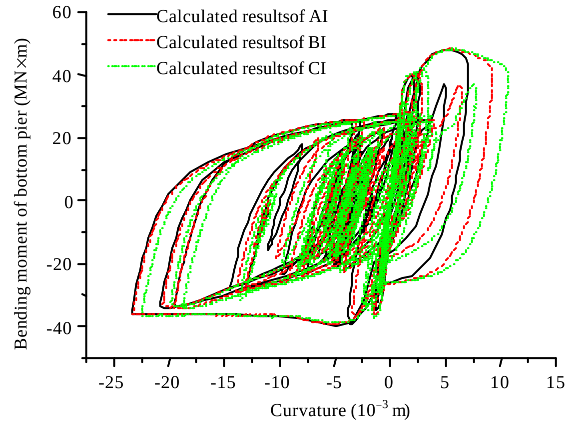

Fig. 5: Flexural moment and curvature hysteretic of the section of the bottom of the pier

spectrum predominant period platform shorter, faster than inland direct seismic wave acceleration response rate of decline with increasing structural natural periods. The long-period seismic waves have acceleration response spectrum characteristics of excellent cycle platform longer and the response of the structure is significantly larger than the plate boundary and inland direct seismic waves.

Plastic range to carry out the process of analysis under rare earthquake: Analysis of indicators: In the bridge structure's seismic design, Guidelines for Seismic Design of Highway Bridges using allowable plastic rotation and allow displacement to evaluate the bridge's seismic performance while the Japanese Specification for Highway Bridges mainly adopted to allow plastic rate as analytical indicators. Two evaluation methods are basically similar, Chinese specification take the project site considered for the seismic design of pile foundation and damage assessment lacking. This article mainly reference to the Japanese code and the curvature of the maximum response plasticity rate defined with rod (Liu and Guo, 2003) to analyze the development of plastic zone of bridge structure under rare earthquake and their seismic performance. Maximum rate of reaction plasticity, allowing plastic rate and displacement ductility factor can be calculated as follows:

$$\mu_{max} = |\theta_{max}| / \theta_y \quad (1)$$

$$\mu_a = 1 + \frac{(\delta_u - \delta_y)}{(\alpha \delta_y)} \quad (2)$$

Where:

$\theta_{|max|}$ = Absolute maximum reaction curvature of the concrete elements and θ_y is yield curvature

α = Deformation of the reinforced concrete member safety factor, for inland direct ground vibration take 1.2, plate boundary earthquake with 2.4 the value of long-period seismic waves according to 2.0; For reinforced concrete members

δy = Yield displacement and δ_u is ultimate displacement. There could be calculated as follows:

$$\delta_y = \theta_y L^2 / 3 \quad (3)$$

$$\delta_u = \delta_y + (\theta_u - \theta_y) L_p (h - L_p / 2) \quad (4)$$

Where:

L_p = Length of equivalent plastic hinge. It could be calculated as:

$$L_p = 0.2L\text{-}0.1D \quad (5)$$

where, the length of the member L; D is a circular cross-sectional diameter, the rectangular cross-section length of the short side $0.1D \le L_p \le 0.5D$.

Analysis of seismic response characteristics: To further study the different reinforcement ratio of pile impact on the seismic response of structures, select A1, B1, C1 to comparative to study, due to space limitations, we choose bending moment - curvature hysteresis curve of three sets of numerical model under T1-II-3 seismic waves shown in Fig. 5-6.

Can be seen from Fig. 5-6, on T1-II-3 seismic waves, with increases the reinforcement of the pile, the pier

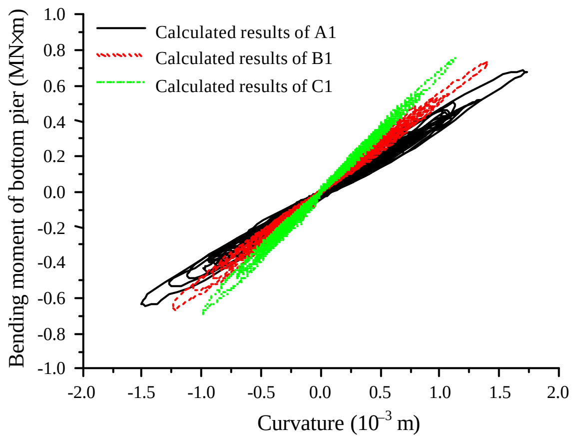

Fig. 6: Flexural moment and curvature hysteretic of the section of the top of the pile

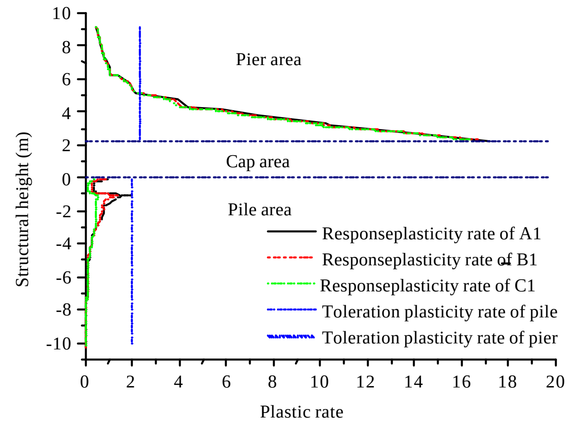

Fig. 7: Curvature distribution of A1, B1, C1 structure under TCU115seismic waves

sectional moment and curvature hysteresis curve tended to increase, indicating that the shear and knot slip of rebar sticking is small, the pier deformation and energy dissipation capacity enhanced and the pile section curvature hysteresis curve show a decreasing trend, the impact of the shear and knot slip of rebar is more significant. Earthquake excitation of pile is smaller.

Thus, the reinforcement ratio is greater effect reaction of the bridge supported by pile group. In different types of seismic waves, the maximum response curvature of pier at the bottom is take at model that combined by the minimum reinforcement ratio of pile-pier. With reinforcement ratio of pile increasing, the maximum reaction curvature of the pier at the bottom also increased, degree of plasticity of the structure transferred to the pier. While in the case of the same reinforcement, under TCU115 seismic waves, the maximum curvature of the pier at the bottom is most significant, followed by T1-II-3 seismic waves, the T2-II-3 seismic waves on the structural dynamic response is minimal. So in the bridge seismic design of earthquake-prone region, an appropriate increase the reinforcement ratio of the pile-pier to improve the energy dissipation capacity of the bridge columns, reducing the pile foundation by seismic excitation.

Structure of the plastic zone to carry out the degree of analysis: Under strong earthquakes, the group piles foundation reaches the yield and near destruction. Transform the reinforcement ratio of pier and pile foundation has greater impact on bridge seismic performance and the role of different types of seismic waves, the development of plastic zone of the pile foundation and piers is different. In order to study the reinforcement ratio of pile and pier impact on structural plastic zone, according to the numerical simulation results

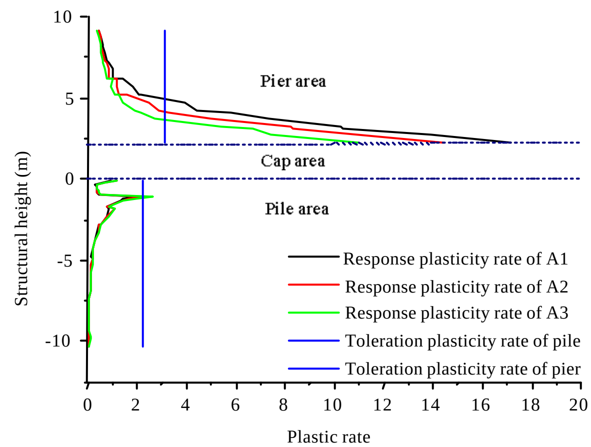

Fig. 8: Curvature distribution of A1, A2, A3 structure under TCU115seismic waves

and Eq. 11-12, under TCU115 earthquake wave, calculate the maximum rate of reaction plastic pier and allowing plastic rate of representative pile and pier length along the change in height, the structural contrast shown in Fig. 7-9.

As can be seen from Fig. 8, under TCU115 seismic waves, the pier at a height of 4.808 m the maximum reaction curvature reaches yield curvature and began yield at A1 numerical model, yield extent with pier height decreases while gradually increasing, at the bottom reaches the maximum, the length of the plastic zone is 4.808 m and the pile plastically zone length 0.577 m; when the pile reinforcement ratio increased by 14.78%, as B1 numerical model, the length of plastic zone of the pier tended to increase to 4.813 m while the length of plastic zone of the pile is reduced to 0.245 m; when the pile

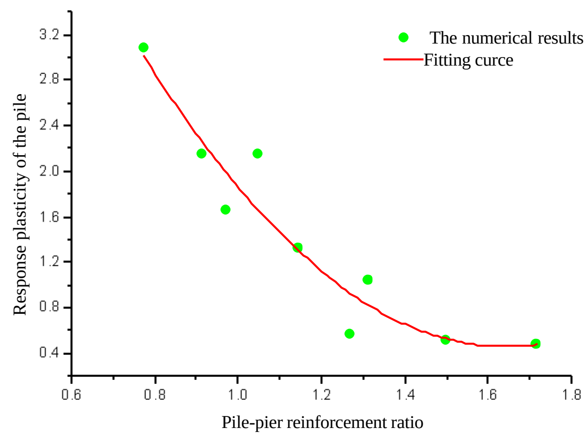

Fig. 9: Response plasticity of the pile

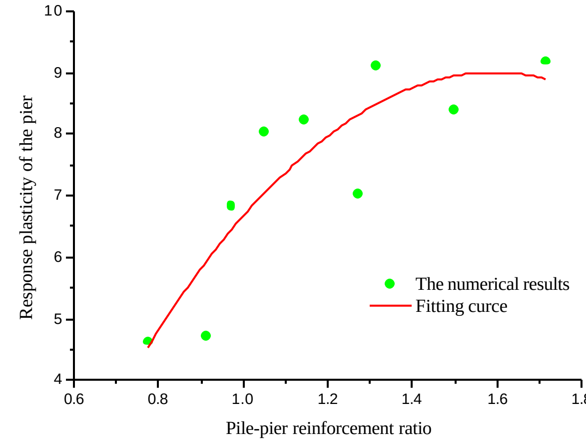

Fig. 10: Response plasticity of the pier

foundation reinforcement ratio increased to 1.707%, as C1 numerical model, pile is elastic stage but the length of plastic zone of the pier tended to increase to 4.816 m. As can be seen from Fig. 9, with reinforcement ratio of pier increasing, the development of pier plastic zone takes a decreasing trend while the plastic zone of pile foundation tended to increase. When the reinforcement ratio of pier was 1.141%, as A2 numerical model, the maximum plastic zone of the pier is 4.202 m, the pile was 0.615 m; when the reinforcement ratio of pier increased by 17.88%, the development of plastic zone of the pier structure increased 0.83 %, the pile increased 4.72%.

Thus, with reinforcement ratio of pile increasing, the development of plastic zone of the pile and pier have different trend. The plastic zone transfer to the pier and it take the major earthquake ground motion. With the reinforcement ratio of pier changing, it take great impact on plastic zone of the pier and pile, indicating the reinforcement ratio of pile changes have a lesser affect the extent of the plastic zone of the bridge structure than the pier reinforcement ratio. In general bridge seismic design, we should take the reinforcement ratio of pier as bridge seismic performance master factors and the reinforcement ratio of pile as the main factors of the pile foundation seismic performance.

Furthermore, in order to explore the pile-pier reinforcement ratio impact on plastic zone of the bridge structure, refer to the numerical results and Eq. 11 can calculate the value of reaction plasticity rate of pile and pier under different pile-pier reinforcement ratio of different numerical model onT1-II-3 seismic waves that shown in Fig. 9-10.

Can be seen from Fig. 9-10, with pier-pile reinforcement ratio increasing, reaction plasticity rate of pile take to decrease and reaction plasticity rate of pier take to increase, indicating that in the earthquake, with the pile-pier reinforcement ratio increasing, the pile withstand ground motion gradually decreases but pier withstand ground motion gradually increasing, piers become the main energy dissipation components, plastic zone the transfer to the pier by the pile. In shows pile-pier reinforcement ratio take great impact on the development of plastic zone of the bridge structure. If the pile takes yield in the earthquake, even if the pier has little damage, bridge basically no repair possible. When the pile-pier reinforcement ratio close to 1, curvature demand rate of pier is 6.38 while the curvature demand of pile foundation is 1.72, were less than member to allow the plastic rate and bridge structure is in a safe state. In general bridge seismic design, we should be based on the reasonable control of the pile-pier reinforcement ratio than the plastic collapse of the structure occurs at easy-to-repair parts, trying to make the bridge columns become a major capacity dissipation member.

SUMMARY

This study is mainly to study development of plastic zone of single-column rectangular piers and group pile under the different types of seismic waves. Comparison development plastic zone bridge pier supported by group pile foundation under different reinforcement conditions under. as well as analysis the different types of seismic waves impact on the dynamic response of the bridge. Get the following conclusions:

- With the pile-pier reinforcement ratio increasing, reaction plasticity rate of pile tended to decrease, reaction plasticity rate of pier tended to increase, showing the pier hinge is greater than pile hinge trend; pier takes main energy dissipative components. Pile-pier reinforcement ratio takes impact on development of the plastic zone of bridge structure. For general structural seismic design, it take reasonable control of the reinforcement ratio of pier and pile that the pier and pile of plastic to carry out the extent to tend to the ideal state, even if the bridge is damaged, but also to facilitate the inspection and repair

- If only reinforcement ratio pile increased degree of plasticity carry on the pier increasing trend but this trend is not obvious but the pier reinforcement ratio changes relatively large impact on the pile. In general bridge seismic design, it should take reinforcement ratio of pier as a bridge seismic performance master factors and the pile foundation reinforcement ratio as the main factors of the pile
- Different types of ground motion on the bridge structure are different. For the purposes a continuous bridge model that Calculated in this article, the long-period seismic waves maximum, followed by inland direct seismic waves, plate boundary seismic wave minimum. In addition, the reaction plasticity maximum values of the structure appear in different seismic waves, it should be integrated to be evaluated during the bridge seismic design

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