Study on seismic damage model of PHC pipe pile embedded in clay soil

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Abstract. In this study, attempts were made to modify the C-Park-Ang damage model for its applicability to PHC pipe pile embedded in clay soil. According to the fibre beam element theory and the common node method, the finite element (FE) model of PHC pipe piles considering pile-soil interaction was established by the ABAQUS/Standard software program. The non-linear FE analysis was then performed to study the effect of length-diameter (L/D) ratio, axial compression ratio ν0 and configuration of transverse and longitudinal reinforcement on the energy combination coefficient βc of damage model through monotonic and reversed cyclic lateral loading. The modified equation of energy combination coefficient βcm of PHC pipe pile is obtained by non-linear regression and the modified seismic damage model of PHC pipe pile is proposed.

1. Introduction

Park-Ang damage model [1] had attracted more and more attention all over the world since it was proposed in 1985 for its combination of maximum deformation and the effect of reversed cyclic loading. In 2005, Fu et al. [2] modified the original Park-Ang damage model by introducing the exponential modification term into both displacement term and energy term. In 2010, Chen et al. [3] proposed the C-Park-Ang damage model with the energy combination coefficient βc, modifying the deficiency of the original Park-Ang damage model that the damage index does not equal 1.0 in the failure state and not equal 0 in the elastic stage under monotonic loading. In 2017, Xu and Yan [4] modified the deficiency of boundary convergence and dissociation of C-Park-Ang damage model. The influence of P-Δ effects on lateral displacement of members was addressed by theoretical derivation and the displacement term of C-Park-Ang damage model was thus modified.

However, the modified damage models mentioned above assume a rigid foundation of the structure, and do not consider the effect of pile-soil interaction on the structural damage under earthquake. The seismic response and failure modes of PHC pipe piles in pile-supported wharf are affected by pile-soil interaction, which are different from the engineering structure of buildings. The applicability of the damage models mentioned to PHC pipe piles in pile-supported wharf is thus uncertain. Therefore, the modification of damage model by considering the pile-soil interaction and the restraint conditions and failure modes of PHC pipe piles in pile-supported wharf is needed in order to better assess the seismic damage of PHC pipe piles in pile-supported wharf.
2. Modification method of C-Park-Ang damage model

2.1 Original damage model

This study modifies the C-Park-Ang damage model expressed as equation (1), which can better satisfy the convergence conditions in values.

\[ D_c = (1 - \beta_c) \frac{\delta_u}{\delta_a} + \beta_c \frac{E}{F_y(\delta_a - \delta_y)} \]  \hspace{1cm} (1)

\[ \beta_c = \left(0.023 \frac{l}{h} + 3.352 n_0^{0.35}\right) 0.818 \frac{\rho_{ax} f_w}{f_c} + 0.039 \]  \hspace{1cm} (2)

\[ k = \frac{1 - \frac{s}{2d_s}}{1 - \rho_{cc}} \]  \hspace{1cm} (3)

where \( D_c \) is damage index; \( \delta_u \) is maximum deformation under earthquake; \( \delta_a \) is ultimate deformation under monotonic loading; \( E \) is accumulated hysteretic dissipated energy; \( F_y \) is calculated yield strength; \( \delta_y \) is calculated yield deformation; \( \beta_c \) is energy combination coefficient; \( l \) is length of specimen; \( h \) is height of specimen section; \( n_0 \) is axial compression ratio; \( k \) is effectively confined coefficient; \( \rho_{ec} \) is ratio of transverse steel parallel to the direction of loading; \( f_w \) is calculated yield strength of transverse steel; \( f_c \) is uniaxial compressive strength of concrete; \( s \) is clear vertical spacing between circular spirals; \( d_s \) is diameter of spiral between bar centers; \( \rho_{cc} \) is ratio of area of longitudinal steels to area of core of section.

The distribution interval of shear span ratio (i.e. \( l/h \)) of the specimens used in the non-linear regression of energy combination coefficient \( \beta_c \) in the original C-Park-Ang damage model is 2.0-7.0. For PHC pipe piles in pile-supported wharf, the effect of shear span ratio \( l/h \) on energy combination coefficient \( \beta_c \) can be replaced by the ratio of converted length of pile to diameter (defined as \( l_{eq}/D \)) after the PHC pipe pile is equivalent to a cantilever pile fixed at the bottom by the fixed point method proposed in the literature [5]. However, due to the long free length above the mud surface of PHC pipe piles, \( l_{eq}/D \) is greater than 7.0 and the energy combination coefficient \( \beta_c \) obtained exceeds 1.0, which obviously does not correspond to the range of energy combination coefficient (0-1.0). The applicability of the original equation of energy combination coefficient \( \beta_c \) in evaluating the seismic damage of PHC pipe piles in pile-supported wharf is needed to be studied. Therefore, it is necessary to modify the original equation of energy combination coefficient \( \beta_c \) by considering the restraint conditions and failure modes of PHC pipe piles in pile-supported wharf.

2.2 Modification method of PHC pipe pile damage model considering pile-soil interaction

In order to modify the energy combination coefficient \( \beta_c \), it can be assumed that the \( D_c \) of PHC pipe pile in the ultimate failure state equals 1.0 and the expression of \( \beta_c \) can be calculated and obtained as follows (4):

\[ \beta_c = \frac{F_y \left( \delta_u - \delta_y \right) \left( \delta_u - \delta_m \right)}{\delta_u E - F_y \delta_m \left( \delta_u - \delta_y \right)} \]  \hspace{1cm} (4)

where the parameters have the same meanings as the equation (1).

In this study, monotonic and reversed cyclic lateral loading are applied on the head of PHC pipe pile to obtain the ultimate deformation \( \delta_u \) of PHC pipe pile under monotonic load and maximum deformation \( \delta_m \) under earthquake, accumulative hysteretic dissipated energy \( E \), yield strength \( F_y \), yield deformation \( \delta_y \), respectively. The corresponding \( \beta_c \) value of PHC pipe pile is then calculated according to equation (4). Finally, the non-linear regression of modified energy combination coefficient \( \beta_{cm} \) is carried out by analysing the effect of \( l_{eq}/D \) ratio, axial compression ratio \( n_0 \) and configuration of
transverse and longitudinal reinforcement on the energy combination coefficient and then the modified
damage model suitable for assessing seismic damage of PHC pipe piles in pile-supported wharf is
obtained with $\beta_{cm}$.

3. Finite element model
In this study, the element B21 in ABAQUS 6.14 software is used to simulate PHC pipe pile and the
length of each element is set as 0.5m. In the .inp file, the keyword *rebar is used to insert longitudinal
steels into the core concrete of the beam element section according to their actual positions in the PHC
pipe pile and the longitudinal steels are then prestressed through the keyword *initial condition. In
order to simulate the uniaxial stress-strain relationship of reinforced concrete structural elements under
monotonic and cyclic loading, the constitutive model of PQ-Fibre subroutine programmed by
Tsinghua University is used. The partition of fibre points and the layout of prestressed reinforcement
in beam cross section are shown in figure 1.

![Figure 1. Fibre point partition and prestressed reinforcement layout of the beam cross section of PHC pipe pile.](image1)

The $p-y$ soil springs of soft clay are used to simulate the pile-soil interaction in the horizontal
direction. The soil springs are arranged at intervals of 0.5m below the mud surface. Considering the
actual restraint of pile in the pile-supported wharf, the rotation freedom of pile head and the vertical
freedom of pile bottom are restricted. The vertical concentrated force and the horizontal displacement
load are applied to the pile head to realize the axial load and the horizontal seismic load, respectively.
The FE model of PHC pipe pile is shown in figure 2.

![Figure 2. FE model of PHC pipe pile.](image2)

![Figure 3. Process of cyclic loading.](image3)
4. Modification of Damage Model

4.1 Calculation conditions and loading mode

4.1.1 Calculation conditions. The effect of length-diameter ratio \( l_{eq}/D \), axial compression ratio \( n_0 \) and configuration of transverse and longitudinal reinforcement on energy combination coefficient \( \beta_c \) of damage model is studied under 30 calculation conditions shown in table 1. The embedded depth of each pile and the undrained shear strength of clay soil remain the same as 20m and 20kPa, respectively. The relevant design parameters of PHC pipe piles are shown in table 2.

4.1.2 Loading mode. The displacement loading is adopted according to the literature [6]. In the monotonic loading mode, the pile is subjected to loading in stages and the amplitude of load are 20\%, 50\% and 80\% of yield displacement of piles, respectively, before yielding and after yielding the pile is subjected to loading in stages and the amplitude of load is equal to integer times of the yield deformation. When the horizontal reaction force of the pile head is less than 85\% of the horizontal bearing capacity, the monotonic loading stops. At this time, the displacement of the pile head is considered as the ultimate deformation \( \delta_u \) under monotonic loading.

The cyclic loading mode is roughly the same as the monotonic loading mode. The only difference is that each stage repeats 3 times in the cyclic loading mode. When the horizontal reaction force of the pile head is less than 85\% of the horizontal bearing capacity, the cyclic loading stops. At this time, the displacement of the pile head is considered as the maximum deformation \( \delta_m \) under cyclic loading. The process of cyclic loading is shown in figure 3.

4.2 Effect of \( l_{eq}/D \) on energy combination coefficient of PHC pipe piles

According to the literature [5], the fixed point depth from mud surface \( t \) and free length of piles equal the converted length of the piles \( l_{eq} \). The calculated results by fixed point method are summarized in table 3.

| No. | \( D \) (mm) | Type | \( n_0 \) | Free Length (m) | No. | \( D \) (mm) | Type | \( n_0 \) | Free Length (m) |
|-----|-------------|------|---------|-------------|-----|-------------|------|---------|-------------|
| 1   | 800         | A    | 0.2     | 5           | 16  | 1000        | C    | 0.6     | 5           |
| 2   | 800         | AB   | 0.2     | 5           | 17  | 1000        | C    | 0.8     | 5           |
| 3   | 800         | B    | 0.2     | 5           | 18  | 1000        | C    | 0.2     | 2           |
| 4   | 800         | C    | 0.2     | 5           | 19  | 1000        | C    | 0.2     | 8           |
| 5   | 800         | C    | 0.4     | 5           | 20  | 1000        | C    | 0.2     | 11          |
| 6   | 800         | C    | 0.6     | 5           | 21  | 1200        | A    | 0.2     | 5           |
| 7   | 800         | C    | 0.8     | 5           | 22  | 1200        | AB   | 0.2     | 5           |
| 8   | 800         | C    | 0.2     | 2           | 23  | 1200        | B    | 0.2     | 5           |
| 9   | 800         | C    | 0.2     | 8           | 24  | 1200        | C    | 0.2     | 5           |
| 10  | 800         | C    | 0.2     | 11          | 25  | 1200        | C    | 0.4     | 5           |
| 11  | 1000        | A    | 0.2     | 5           | 26  | 1200        | C    | 0.6     | 5           |
| 12  | 1000        | AB   | 0.2     | 5           | 27  | 1200        | C    | 0.8     | 5           |
| 13  | 1000        | B    | 0.2     | 5           | 28  | 1200        | C    | 0.2     | 2           |
| 14  | 1000        | C    | 0.2     | 5           | 29  | 1200        | C    | 0.2     | 8           |
| 15  | 1000        | C    | 0.4     | 5           | 30  | 1200        | C    | 0.2     | 11          |
Table 2. The relevant design parameters of PHC pipe piles.

| No. | D (mm) | Type | Thickness (mm) | Clear Vertical Spacing between Circular Spirals (mm) | Circular Spirals Diameter (mm) | Configuration of Longitudinal Reinforcement % | Distribution Diameter of Longitudinal Steel around the Core Perimeter (mm) | Effective Prestress of Concrete (MPa) |
|-----|--------|------|----------------|---------------------------------------------------|-------------------------------|---------------------------------------------|-------------------------------------------------|-------------------------------------|
| 1   | 800    | A    | 130            | 80                                                | 6                             | 0.53                                        | 690                                             | 4.57                                |
| 2   | 800    | AB   | 130            | 80                                                | 6                             | 0.73                                        | 690                                             | 6.16                                |
| 3   | 800    | B    | 130            | 80                                                | 6                             | 1.05                                        | 690                                             | 8.47                                |
| 4   | 800    | C    | 130            | 80                                                | 6                             | 1.46                                        | 690                                             | 11.10                               |
| 5   | 1000   | A    | 130            | 80                                                | 8                             | 0.58                                        | 880                                             | 4.97                                |
| 6   | 1000   | AB   | 130            | 80                                                | 8                             | 0.81                                        | 880                                             | 6.75                                |
| 7   | 1000   | B    | 130            | 80                                                | 8                             | 1.13                                        | 880                                             | 8.97                                |
| 8   | 1000   | C    | 130            | 80                                                | 8                             | 1.39                                        | 880                                             | 10.65                               |
| 9   | 1200   | A    | 150            | 80                                                | 8                             | 0.55                                        | 1060                                            | 4.73                                |
| 10  | 1200   | AB   | 150            | 80                                                | 8                             | 0.76                                        | 1060                                            | 6.36                                |
| 11  | 1200   | B    | 150            | 80                                                | 8                             | 1.14                                        | 1060                                            | 9.04                                |
| 12  | 1200   | C    | 150            | 80                                                | 8                             | 1.40                                        | 1060                                            | 10.73                               |

When the embedded depth is 20m, undrained shear strength of clay soil is 20KPa, axial compression ratio is 0.2, the relationship between the energy combination coefficient $\beta_c$ and the length-diameter ratio $l_{eq}/D$ of C-type PHC pipe piles of 800mm, 1000mm and 1200mm is shown in figure 4, respectively.

It is shown that when the configuration of transverse and longitudinal reinforcement, embedded depth, axial compression ratio of PHC pipe piles and undrained shear strength of clay soil are fixed, the energy combination coefficient $\beta_c$ of PHC pipe piles increases with the increase of length-diameter ratio $l_{eq}/D$. Besides, a positive linear correlation is observed between $\beta_c$ and $l_{eq}/D$.

Table 3. Calculated results by fixed point method.

| No. | D (m) | Type | $l$ (m) | $l_{eq}$ (m) | $l_{eq}/D$ | $\beta_c$ |
|-----|-------|------|---------|-------------|------------|------------|
| 1   | 0.8   | A    | 5.339   | 10.339      | 12.923     | 0.022143   |
| 2   | 0.8   | AB   | 5.339   | 10.339      | 12.923     | 0.015289   |
| 3   | 0.8   | B    | 5.339   | 10.339      | 12.923     | 0.009368   |
| 4   | 0.8   | C    | 5.339   | 10.339      | 12.923     | 0.008857   |
| 5   | 0.8   | C    | 5.339   | 10.339      | 12.923     | 0.031045   |
| 6   | 0.8   | C    | 5.339   | 10.339      | 12.923     | 0.063475   |
| 7   | 0.8   | C    | 5.339   | 10.339      | 12.923     | 0.104670   |
| 8   | 0.8   | C    | 5.339   | 7.339       | 9.173      | 0.006276   |
| 9   | 0.8   | C    | 5.339   | 13.339      | 16.673     | 0.011744   |
| 10  | 0.8   | C    | 5.339   | 16.339      | 20.423     | 0.016423   |
| 11  | 1.0   | A    | 6.022   | 11.022      | 11.022     | 0.026094   |
| 12  | 1.0   | AB   | 6.022   | 11.022      | 11.022     | 0.015670   |
| 13  | 1.0   | B    | 6.022   | 11.022      | 11.022     | 0.011248   |
| 14  | 1.0   | C    | 6.022   | 11.022      | 11.022     | 0.014097   |
| 15  | 1.0   | C    | 6.022   | 11.022      | 11.022     | 0.021853   |
4.3 Effect of $n_0$ on energy combination coefficient of PHC pipe piles

When the embedded depth is 20m, free length is 5m, undrained shear strength of clay soil is 20kPa, the relationship between the energy combination coefficient $\beta_c$ and the axial compression ratio $n_0$ of C-type PHC pipe piles of 800mm, 1000mm and 1200mm is shown in figure 5, respectively.

It can be seen that when the embedded depth, free length, configuration of transverse and longitudinal reinforcement of PHC pipe piles and undrained shear strength of clay soil are fixed, the energy combination coefficient $\beta_c$ of PHC pipe piles increases with the increase of axial compression ratio $n_0$. Besides, a positive exponential correlation is observed between $\beta_c$ and $n_0$.

![Figure 4. Effect of length-diameter ratio $l_{eq}/D$ on energy combination coefficient $\beta_c$.](image1)

![Figure 5. Effect of axial compression ratio $n_0$ on energy combination coefficient $\beta_c$.](image2)

4.4 Effect of configuration of transverse and longitudinal reinforcement on energy combination coefficient of PHC pipe piles

For the evaluation of transverse confinement of circular spirals in reinforced concrete structural elements, some scholars believe that the effect of transverse confinement is not only related to the relative number of circular spirals, but also to the number and distribution of longitudinal steels and the layout of circular spirals. Sheikh and Uzumeri [7] put forward the concept of effectively confined concrete based on the analysis of a large number of test results and then established the confined concrete model, which was adopted by the European Seismic Code [8]. Therefore, the effectively confined coefficient $k$ is used in this study to reflect the confinement of the core area of PHC pipe piles and $k\rho_{cys}\sigma_c$ is used to measure the transverse confinement of PHC pipe piles. The effectively confined coefficient $k$, $k\rho_{cys}\sigma_c$ and energy combination coefficient $\beta_c$ are summarized in table 4.

When the embedded depth is 20 m, free length is 5m, undrained shear strength of clay soil is 20kPa, axial compression ratio is 0.2, the relationship between the energy combination coefficient $\beta_c$ and $k\rho_{cys}\sigma_c$ of PHC pipe piles of 800mm, 1000mm and 1200mm is shown in figure 6, respectively.

It can be observed that when the embedded depth, free length, axial compression ratio of PHC pipe piles and undrained shear strength of clay soil are fixed, the energy combination coefficient $\beta_c$ of PHC pipe piles decreases with the increase of $k\rho_{cys}\sigma_c$. Besides, a negative exponential correlation is observed between $\beta_c$ and $k\rho_{cys}\sigma_c$.

![Figure 6. Effect of $k\rho_{cys}\sigma_c$ on energy combination coefficient $\beta_c$.](image3)
4.5 Modified Damage Model

According to the analysis of section 4.2-4.4, it can be seen that the length-diameter ratio $I_e/D$, axial compression ratio $n_0$ and configuration of transverse and longitudinal reinforcement (evaluated by $k_{psf_{yw}/f_c}$) are the main factors affecting the energy combination coefficient $\beta_c$ of PHC pipe piles. A modified equation for energy combination coefficient $\beta_{cm}$ of PHC pipe piles suitable for pile-supported wharf can be obtained by non-linear regression, which is expressed as follows (5):

$$\beta_{cm} = \left(0.0003 \frac{l_e}{D} + 0.3029 n_0^{2.2864}\right) 0.7033 \frac{\rho_{psf_{yw}}}{\rho_c} + 0.0087$$  

(5)

Where $\beta_{cm}$ is modified value of $\beta_c$; $l_e$ is converted pile length, equals the sum of the fixed point depth $t$ of the piles from the mud surface (calculated according to the literature [5]) and the free length of the piles; $D$ is diameter of PHC pipe pile; the other parameters have the same meanings as the equation (2). The unit of $k_{psf_{yw}/f_c}$ is 1% when equation (5) is used to calculate the energy combination coefficient $\beta_{cm}$.

Figure 7 compares the regression value $\beta_{cm}$ of the equation (5) with the calculated value $\beta_c$ of numerical simulation. The correlation coefficient $R$ between the two kinds of $\beta$ is up to 0.97, which shows that the correlation is good.

Table 4. Calculated results of transverse constraints and $\beta_c$.

| No. | $D$ (m) | Type | $\rho_c$ | $k$ | $k_{psf_{yw}/f_c}$ | $\beta_c$ | No. | $D$ (m) | Type | $\rho_c$ | $k$ | $k_{psf_{yw}/f_c}$ | $\beta_c$ |
|-----|--------|------|---------|-----|-----------------|----------|-----|--------|------|-----|-----------------|----------|
| 1   | 0.8    | A    | 0.010   | 5.339| 0.01889         | 0.022143 | 16  | 1.0    | C    | 0.028 | 6.022          | 0.03466  | 0.041006 |
| 2   | 0.8    | AB   | 0.014   | 5.339| 0.01897         | 0.015289 | 17  | 1.0    | C    | 0.028 | 6.022          | 0.03466  | 0.074745 |
| 3   | 0.8    | B    | 0.020   | 5.339| 0.01908         | 0.009368 | 18  | 1.0    | C    | 0.028 | 6.022          | 0.03466  | 0.007994 |
| 4   | 0.8    | C    | 0.028   | 5.339| 0.01924         | 0.008857 | 19  | 1.0    | C    | 0.028 | 6.022          | 0.03466  | 0.013748 |
| 5   | 0.8    | C    | 0.028   | 5.339| 0.01924         | 0.031045 | 20  | 1.0    | C    | 0.028 | 6.022          | 0.03466  | 0.015807 |
| 6   | 0.8    | C    | 0.028   | 5.339| 0.01924         | 0.063475 | 21  | 1.2    | A    | 0.011 | 6.804          | 0.02977  | 0.020595 |
| 7   | 0.8    | C    | 0.028   | 5.339| 0.01924         | 0.104670 | 22  | 1.2    | AB   | 0.015 | 6.804          | 0.02990  | 0.012416 |
| 8   | 0.8    | C    | 0.028   | 5.339| 0.01924         | 0.006276 | 23  | 1.2    | B    | 0.023 | 6.804          | 0.03013  | 0.009769 |
| 9   | 0.8    | C    | 0.028   | 5.339| 0.01924         | 0.011744 | 24  | 1.2    | C    | 0.028 | 6.804          | 0.03029  | 0.009755 |
| 10  | 0.8    | C    | 0.028   | 5.339| 0.01924         | 0.016423 | 25  | 1.2    | C    | 0.028 | 6.804          | 0.03029  | 0.020692 |
| 11  | 1.0    | A    | 0.012   | 6.022| 0.03409         | 0.026094 | 26  | 1.2    | C    | 0.028 | 6.804          | 0.03029  | 0.035763 |
| 12  | 1.0    | AB   | 0.016   | 6.022| 0.03425         | 0.015670 | 27  | 1.2    | C    | 0.028 | 6.804          | 0.03029  | 0.059384 |
| 13  | 1.0    | B    | 0.022   | 6.022| 0.03447         | 0.011248 | 28  | 1.2    | C    | 0.028 | 6.804          | 0.03029  | 0.006843 |
| 14  | 1.0    | C    | 0.028   | 6.022| 0.03466         | 0.010497 | 29  | 1.2    | C    | 0.028 | 6.804          | 0.03029  | 0.011455 |
| 15  | 1.0    | C    | 0.028   | 6.022| 0.03466         | 0.021853 | 30  | 1.2    | C    | 0.028 | 6.804          | 0.03029  | 0.014840 |

Based on equation (1) and (5), the modified damage model for PHC pipe piles in pile-supported wharf can be proposed. In order to evaluate the predictive effect of the modified damage model, the corresponding damage indices of PHC pipe piles are calculated and shown in table 5. According to table 5, the mean value, standard deviation and coefficient of variation of $D_c$ are 1.0040, 0.0341 and 3.40%, respectively. The mean percentage of $D/D_c$ and $D_c/D$ is 88.12% and 11.88%, respectively, where $D=\left[1-\beta_{cm}\delta m/\delta u\right]$ and $D_c=\beta_{cm}E/[F(y/\delta u-\delta y)]$. Thus, the contribution of displacement term and energy term in the C-Park-Ang damage model can not be neglected, which also proves the necessity of using the double-parameter damage model to predict the seismic damage of PHC pipe piles.

Figure 8 shows the distribution of the modified damage indices under ultimate failure state. It can be seen that the mean value of damage indices is closer to 1.0 with low degree of scatter.
Table 5. Energy combination coefficient $\beta_{cm}$ and corresponding damage indices $D_c$

| No. | Regression Value of $\beta_{cm}$ | $D_c$ | $D_o/D_i$ (%) | $D_y/D_i$ (%) |
|-----|---------------------------------|------|---------------|---------------|
| 1   | 0.014624                        | 0.9649 | 91.56         | 8.44          |
| 2   | 0.014608                        | 0.9959 | 89.77         | 10.23         |
| 3   | 0.014585                        | 1.0402 | 87.90         | 12.10         |
| 4   | 0.014552                        | 1.0586 | 84.60         | 15.40         |
| 5   | 0.029608                        | 0.9912 | 79.36         | 20.64         |
| 6   | 0.058529                        | 0.9863 | 78.66         | 21.34         |
| 7   | 0.103059                        | 0.9972 | 73.73         | 26.27         |
| 8   | 0.013980                        | 1.1120 | 80.58         | 19.42         |
| 9   | 0.015123                        | 1.0271 | 86.87         | 13.13         |
| 10  | 0.015695                        | 0.9963 | 90.48         | 9.52          |
| 11  | 0.011998                        | 0.9251 | 91.99         | 8.01          |
| 12  | 0.011979                        | 0.9775 | 91.41         | 8.59          |
| 13  | 0.011954                        | 1.0040 | 92.11         | 7.89          |
| 14  | 0.011932                        | 1.0105 | 90.31         | 9.69          |
| 15  | 0.020683                        | 0.9956 | 90.32         | 9.68          |
| 16  | 0.037400                        | 0.9924 | 88.43         | 11.57         |
| 17  | 0.063369                        | 0.9902 | 88.48         | 11.52         |
| 18  | 0.011667                        | 1.0286 | 90.11         | 9.89          |
| 19  | 0.012198                        | 0.9899 | 90.84         | 9.16          |
| 20  | 0.012464                        | 0.9797 | 91.12         | 8.88          |
| 21  | 0.012415                        | 0.9390 | 89.02         | 10.98         |
| 22  | 0.012398                        | 0.9999 | 90.24         | 9.76          |
| 23  | 0.012368                        | 1.0159 | 91.41         | 8.59          |
| 24  | 0.012347                        | 1.0208 | 89.18         | 10.82         |
| 25  | 0.022552                        | 1.0067 | 89.84         | 10.16         |
| 26  | 0.042154                        | 1.0144 | 86.82         | 13.18         |
| 27  | 0.072336                        | 1.0106 | 87.31         | 12.69         |
| 28  | 0.012089                        | 1.0533 | 87.28         | 12.72         |
| 29  | 0.012606                        | 1.0070 | 91.22         | 8.78          |
| 30  | 0.012864                        | 0.9905 | 92.52         | 7.48          |

5. Conclusion
The ultimate deformation $\delta_u$ of pipe pile under monotonic loading and maximum deformation $\delta_m$ of pipe pile under cyclic loading, accumulated hysteretic dissipated energy $E$, yield load $F_y$ and yield deformation $\delta_y$ are obtained by applying horizontal monotonic and cyclic loading to the head of PHC pipe pile, respectively. Then by assuming $D_c=1.0$ corresponding to the ultimate failure of pipe pile, the energy combination coefficient $\beta_c$ is evaluated. Moreover, the effect of different parameters of
length-diameter ratio \( l_{eq}/D \), axial compression ratio \( n_0 \), configuration of transverse and longitudinal reinforcement (evaluated by \( k_{ps}f_{yw}/f'_c \)) on the energy combination coefficient \( \beta_c \) of pipe pile is analyzed. The following conclusions are therefore drawn from this study:

1) With the increase of length-diameter ratio \( l_{eq}/D \), the energy combination coefficient \( \beta_c \) of PHC pipe piles increases correspondingly and a positive linear correlation is observed between \( \beta_c \) and \( l_{eq}/D \);

2) With the increase of axial compression ratio \( n_0 \), the energy combination coefficient \( \beta_c \) of PHC pipe piles increases correspondingly and a positive exponential correlation is observed between \( \beta_c \) and \( n_0 \);

3) With the increase of \( k_{ps}f_{yw}/f'_c \), the energy combination coefficient \( \beta_c \) of PHC pipe piles decreases correspondingly and a negative exponential correlation is observed between \( \beta_c \) and \( k_{ps}f_{yw}/f'_c \);

4) Based on the above analysis of the factors affecting the energy combination coefficient \( \beta_c \) of PHC pipe piles, a modified equation for calculating the energy combination coefficient \( \beta_{cm} \) of PHC pipe piles is obtained by non-linear regression. The mean value of damage indices under the ultimate failure state calculated by the modified calculation equation is closer to 1.0 with low degree of scatter.

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References
[1] Park, Y. J., Ang, A. H. S. (1985) Mechanistic seismic damage model for reinforced concrete. Journal of Structural Engineering, 111: 722-739.
[2] Fu, J. F., Wang, M., Bai, S. L. (2005) Identification and modification of the Park-Ang criterion for failure of RC Structures. Earthquake Engineering and Engineering Vibration, 25: 73-79.
[3] Chen, L. Z., Jiang, H. J., Lu, X. L. (2010) Modified Park-Ang damage model for reinforced concrete structures. Journal of Tongji University (Natural Science), 38: 1103-1107.
[4] Xu, L. H., Yan, X. T. (2017) Parameters modification of deformation and energy based double parameters damage model for RC column. Journal of Tianjin University (Science and Technology), 50: 1314-1320.
[5] JTS 167-4-2012. Code of pile foundation of harbour engineering. Beijing: China Communication Press, 2012.
[6] JGJ/T101-2015. Specification for seismic test of buildings. Beijing: China Architecture and Building Press, 2015.
[7] Sheikh, S., Uzumeri, S. M. (1982) Analytical model for concrete confinement in tied columns. Journal of Structural Engineering, 108: 2703-2722.
[8] Eurocode 8. Design of structures for earthquake resistant. Brussels: European Committee for Standardization, 2005.