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Review of the literature on the mechanical properties of steel and concrete embedded rock piles

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Abstract: *Steel pipe concrete embedded rock pile is widely used in river and lake engineering and bridge engineering because of its good bearing capacity. The external steel pipe can form a hoop action to restrain the reinforced concrete structure in it, which realizes the best performance of each material, the filler increases the compressive strength and stiffness of the pipe, delays and inhibits the local buckling of the pipe, and improves the ductility and resistance of the pipe under the compound action. The mechanical properties of steel pipe concrete embedded rock piles are described from theoretical analysis, numerical simulation analysis, and experimental study, including transverse bearing characteristics, longitudinal bearing characteristics, and finally, the outlook on the problems yet to be studied is presented.*

Keywords: *steel pipe concrete embedded rock pile; transverse load bearing characteristics; longitudinal load bearing characteristics; restraint effect coefficient*

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I. Introduction

The so-called steel pipe concrete Concrete-filled steel tubular (CFST) is a combination structure formed by filling the concrete into a thin-walled steel pipe, is a special form of hoop concrete, also known as concrete-filled steel pipe in foreign countries. The basic principle of steel pipe concrete is to make the core concrete in a three-way compressed state with the help of circular steel pipe on the core concrete hoop restraint, so that the core concrete has a higher compressive strength and compression deformation capacity. In addition to its superior mechanical properties such as high strength, light weight, good ductility, fatigue resistance, and impact resistance, steel pipe concrete also has superior construction properties such as labor and material saving, light erection, and fast construction [1].

As a type of deep foundation, steel pipe concrete embedded pile is widely used in port engineering and bridge engineering because of its high bearing capacity, low settlement and good seismic performance. Steel pipe concrete embedded rock pile mainly consists of two parts, i.e. steel pipe which is deeper into the bedrock externally and reinforced concrete pile core which is deeper into the bedrock internally, as shown in Figure 1, this structure form can effectively reduce the construction time of pile foundation at dry water level.

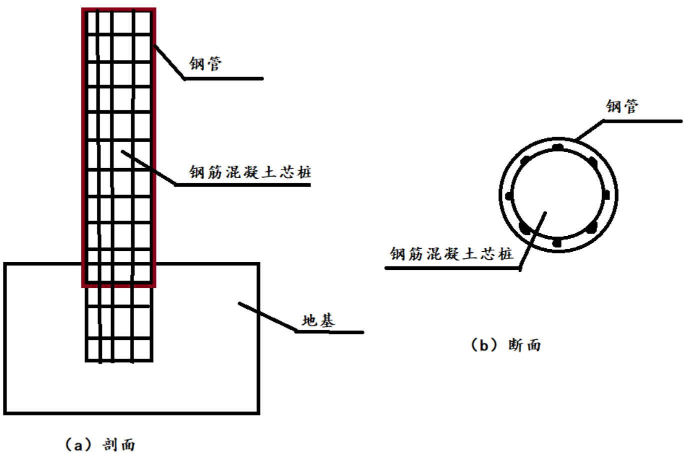

Fig. 1 Section diagram of reinforced concrete rock-socketed pile

However, due to the presence of steel pipe, the pile core concrete is in lateral compression and the steel pipe can provide uniform and continuous restraint, which is equivalent to the increase of reinforcement rate, thus the steel pipe concrete embedded pile has higher strength, ductility and greater energy absorption before damage. At present, the research tools for steel pipe concrete embedded piles are mainly experimental studies and numerical simulations.

II. Transverse load-bearing characteristics of steel pipe and concrete embedded rock piles

The main structural forms of steel pipe concrete embedded piles are: double-layer steel pipe concrete piles, rectangular section steel pipe concrete piles and circular section steel pipe concrete piles. The research on their lateral bearing capacity characteristics mainly focuses on the mechanical aspects of the combined structure such as flexural and shear resistance, while the structure shows different mechanical characteristics due to the hooping effect of the steel sheath on the pile core.

2.1 Theoretical analysis of transverse bearing characteristics of steel pipe and concrete embedded rock piles

In terms of theoretical analysis, Kozubal J et al [2] proposed a three-dimensional probabilistic method to analyze piles under horizontal loads. Two subsurface models were used in the analysis, and a reliability calculation method was proposed, which included the calculation of pile displacement. Kunyong Zhang et al [3] combined experimental research with theoretical analysis and proposed a hyperbolic function theoretical calculation method based on the foundation reaction modulus, which was used to calculate the load-displacement curve of embedded rock piles under horizontal loads. Han Linhai et al [4] established a concrete principal structure relationship model, which is applicable to steel pipe plain concrete axial compression members, and the key is to determine the principal structure relationship model of core concrete. Xiao Congzhen et al [5] found that shear damage may occur in steel pipe concrete specimens with shear-to-span ratio less than 1 through the experimental study of 58 specimens, and steel pipe concrete specimens also exhibit better ductility when shear damaged, and on this basis, a shear bearing capacity formula for steel pipe concrete columns was proposed, which contains the effects of member size, material properties and shear-to-span ratio and axial pressure. In recent years, Wu Naisen et al [6] used linear regression method to study the bending stiffness of steel pipe concrete flexural members heart static, superimposed the discount factor in the theory, and found that the degree of concrete on the overall bending stiffness in circular steel pipe concrete members is greater than that in square section steel pipe concrete members. Cai Jian et al [7] summarized the shear damage characteristics of the specimens through shear performance tests of square steel pipe concrete column specimens, fitted the data from finite element analysis simulations of square steel pipe concrete columns, comprehensively considered the effects of shear-to-span ratio and axial compression ratio, and proposed a formula for calculating the transverse shear bearing capacity. The above research results mainly focus on the factors affecting the bearing capacity of the steel pipe concrete embedded pile structure in bending and shear, and on the basis of which a principal structure model is established, a series of finite element analysis is carried out, and the corresponding design expression formula is proposed

2.2 Numerical simulation analysis of transverse bearing characteristics of steel pipe and concrete embedded rock pile

Also, finite element numerical simulation is another important research tool to study the lateral load-bearing characteristics of steel pipe concrete embedded piles.Conte E et al [8] proposed a three-dimensional finite element simulation method for reinforced concrete piles under horizontal loads. This method allows the nonlinear effects arising from pile-soil interaction to be properly considered, especially the plastic strain in the soil, concrete cracking and yielding of the reinforcement in the pile as well as the occurrence of slip and gap at the pile-pile interface are reliably simulated with the corresponding intrinsic structure model. Based on the finite element software ABAQUS, Ding Faxing et al [9] analyzed the mechanical properties of short axially compressed columns of steel pipe concrete with different cross-sectional shapes by combining the proposed stress-strain equations for uniaxially stressed and axisymmetric triaxially compressed concrete, and found that the expansion angle of the concrete plastic damage intrinsic model was 40°. Luo Yuan et al [10] used ABAQUS to analyze the shear performance of steel pipe self-stressed concrete columns and found that its shear bearing capacity was higher than that of ordinary steel pipe concrete columns when the shear-to-span ratio was the same, and the higher the stress of its own material, the higher the shear bearing capacity.

Numerical analysis of light-weight aggregate concrete-filled steel tube (LACFST) under horizontal cyclic loading by Fu et al [11] showed that the bearing capacity and ductility of the specimens increased significantly with the increase of the thickness of the steel tube. With the increase of steel and concrete strength, the load carrying capacity of the member increases and the ductility and energy dissipation properties decrease slightly. A constitutive and hysteresis model of core lightweight aggregate concrete for finite element simulation is proposed. The stress and strain changes of the steel tube and concrete internal fill were measured in the experiments, and the failure modes, hysteresis curves, skeleton curves and strain curves of the test specimens were obtained. Based on the finite element model, the effects of axial compression ratio, diameter-thickness ratio and material strength were analyzed. The above research results were carried out to investigate the mechanical response process and the factors influencing the bearing capacity of steel pipe concrete piles of different construction forms under static loading.

2.3 Experimental study of lateral load bearing characteristics of steel pipe and concrete embedded rock piles

In terms of experiments, Braford et al [12] firstly found the problem that steel pipe concrete is prone to premature instability damage during compression by steel pipe concrete column shear test, and in order to prevent premature local buckling of steel pipe, it is recommended that the length-to-diameter ratio of the specimen should not exceed 125. Wang Duoyin et al [13] studied by indoor large scale model test, which was selected by comprehensive analysis of the prototype rock and pile in the field. model ratio of 1:20, with a weight ratio of sand:gypsum:water = 5.6:0.8:1 to simulate bedrock and Plexiglas to simulate reinforced concrete piles. The mechanical properties of the piles and bedrock were tested for different lateral loads and rock flap widths, and the conclusions were concluded to have important reference value for the research and design of soft bedrock lateral bearing capacity piles. Qian Jieru et al [14] completed 35 static loading tests to establish the shear bearing capacity calculation equation of steel pipe concrete column, and the selected specimen parameters include steel pipe wall thickness, concrete strength, shear-to-span ratio and axial compression ratio, in which the relationship between axial force influence coefficient and shear-to-span ratio is shown in Figure 2. It is found that the damage form of steel tube high-strength concrete column specimen under the action of transverse force and axial pressure is related to the shear-to-span ratio and axial pressure, and the specimen with shear-to-span ratio $\lambda \leq 0.5$ applied axial pressure is shear damage, the specimen with $\lambda \geq 0.5$ not applied axial pressure is bending damage, and the specimen with $0.1 \geq \lambda > 0.5$ applied axial pressure is shear-bending damage, and the specimen has relatively large resistance to deformation.

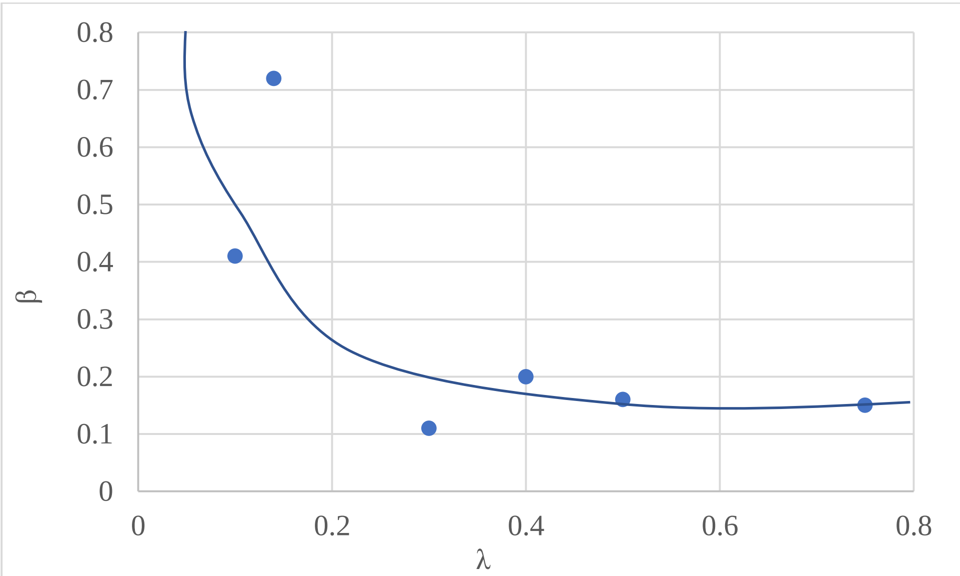

Fig.2 Relationship between axial force influence factor and shear span ratio

Fang Xiaodan et al [15] designed 26 steel pipe concrete short column specimens for experimental study, analyzed various factors affecting the shear bearing capacity of steel pipe concrete short columns, and proposed a formula for calculating the shear bearing capacity of steel pipe concrete short columns. Chen Dong et al [16] studied the shear performance of 9 carbon fibre reinforced polymer (CFRP)-square steel pipe concrete specimens and 3 square steel pipe concrete specimens, and found that the effect of the number of transverse CFRP layers on the bearing capacity of the specimens was not significant, causing little change in the shape of the initial stiffness and stress curve, but its effect was slightly greater than that of the concrete strength. The degree of influence is slightly greater than the change of specimen bearing capacity caused by the change of concrete strength. The influencing factors for the experimental study of the transverse bearing capacity of steel pipe concrete embedded pile are shown in Table 2.

Table 2 Influencing factors of transverse bearing capacity test of concrete filled steel tubular rock-socketed piles

Test type	Test content	Test parameters
Eccentric compression test of steel pipe concrete pile	Eccentricity	Eccentricity
	Geometric and dimensional effects	Aspect ratio, height to width ratio
	Material Properties	Concrete strength, steel strength, section steel content
	Structure construction	Number of CFRP layers, spiral reinforcement, ribbed
Reinforced concrete shear test	Test conditions	Shear-to-span ratio, axial compression ratio
	Geometric effects	Section shape, height to width ratio
	Material properties	Concrete strength, steel strength, section steel content
	Structure construction	Number of CFRP layers, internal steel sections, asymmetric steel sections

III. Longitudinal bearing characteristics of steel pipe and concrete embedded rock piles

Steel and concrete embedded rock piles mainly bear the vertical bearing capacity, however, the restraint effect of steel pipes with different parameters of different structures is different, and their bearing capacity is also different, and the mechanical behavior is also very complicated.

3.1 Theoretical analysis of longitudinal bearing characteristics of steel pipe and concrete embedded rock piles

Yuanfeng Wang and Bing Han et al [17] derived a formula for calculating the creep of axially compressed members of steel pipe concrete by combining the force characteristics of steel pipe concrete axially compressed members based on the successive flow theory of concrete creep and the creep theory of concrete under multi-axial stress. This formula for calculating creep not only takes into account the characteristics of creep in steel pipe concrete axially compressed members, but also reflects the effects of different factors (steel content, material strength, stress magnitude, etc.) on the creep of the members. Liu Jie [18] based on the stress-strain relationship between the internal steel pipe concrete pile core and the external hoop reinforcement, derived the equation for calculating the average restraint stress of the external hoop reinforcement on the reinforced concrete pile core, and analyzed the law of the axial compression load-deformation curve of the combined column, and gave an opinion on the design. Ou Zhijing et al [19,20] compared the calculation methods of ultimate bearing capacity of steel pipe concrete columns in domestic and foreign steel pipe concrete regulations, and on the basis of the analysis and evaluation of the calculation methods of each regulation, proposed a unified algorithm of the stability coefficient of steel pipe concrete columns, that is, the discount factor of column bearing capacity can be calculated by the double coefficient multiplication method of separated stability coefficient and eccentricity discount factor. It provides reference for the further improvement of the calculation theory of steel pipe concrete and the revision of the regulations.

3.2 Numerical simulation analysis of longitudinal bearing characteristics of steel pipe and concrete embedded rock piles

Susantha et al [21] analyzed the ultimate bearing capacity of square and rectangular steel pipe concrete and compared the ultimate bearing capacity of two different cross-sectional members through the analysis results. Liu Wei et al [22] calculated the load-deformation all-process relationship curve of steel pipe concrete when it is axially compressed by the finite element analysis software ABAQUS, and provided a core concrete intrinsic relationship model with clear mechanical concept and generality, and investigated the influence law of factors such as local compression area ratio, section steel content rate and end plate stiffness, which revealed for the first time theoretically a deeper insight into the working mechanism of steel pipe concrete The working mechanism when subjected to local pressure was firstly revealed from theoretical aspects. Chen Baochun et al [23] established a finite element model of steel pipe concrete lattice column by applying ANSYS general program, and proposed a practical algorithm for the ultimate bearing capacity of four-limbed steel pipe concrete lattice column based on the finite element parameter analysis and the evaluation of each regulation calculation method. Huang Hong et al [24] conducted an experimental study by ribbed square steel pipe concrete axial compression short columns with the cross-sectional form shown in Figure 3.

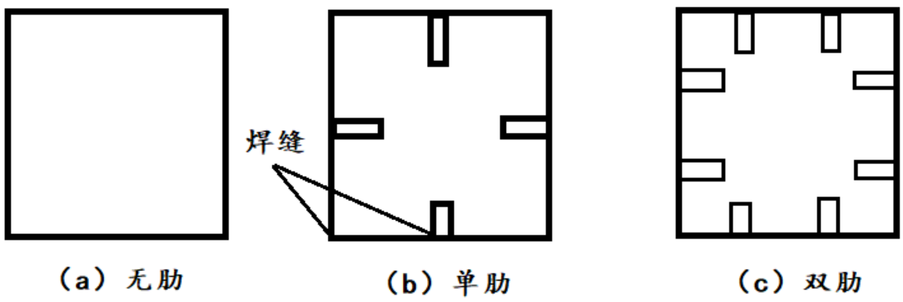

Fig.3 Schematic diagram of specimen section

The finite element software ABAQUS to calculate the load-deformation of short axially compressed columns with ribbed square steel tubes concrete, comparing and analyzing the force performance of short axially compressed columns with unribbed, single-ribbed and double-ribbed square steel tubes concrete, it was found that setting ribbed reinforcement not only improved the longitudinal stresses in the core concrete, but also significantly reduced the range of the tensile stress action zone in the steel tube wall and increased the restraint in the concrete core area. Liu et al [25] found that the increase in specimen size leads to an increase in the confinement coefficient and the decrease in nominal axial compressive strength leads to a weakening of the size effect through a three-dimensional fine-view numerical model analysis, and established a calculation method that can describe the effect of transverse confinement on the size effect. Zhang et al [26] for short columns of steel pipe concrete with a combination of freeze-thaw cycles and acid rain corrosion, the parameters of material strength, steel ratio and combination time Variations in parameters such as material strength, steel ratio and combination time have a large effect on the axial compression performance of the structure, and the results show that the effect of section size on the residual strength is smaller than other parameters, and a design equation to predict the residual strength of short CFST (Concrete-filled steel tube) columns under axial compression and the combined effect of freeze-thaw cycles and acid rain corrosion is proposed**.**

3.3 Experimental study of longitudinal bearing characteristics of steel pipe and concrete embedded rock piles

Talha Ekmekyapar et al [27] found through double-layered steel pipe concrete axial compression tests that double-layered steel pipe concrete columns have better performance than steel pipe concrete columns when the steel pipe inner barrel structure is reasonable and the inner barrel structure is consistent with the working performance of the barrel concrete, which plays an important role in reducing the damage mode of high-strength concrete. Zhang et al [28] used a high-capacity falling hammer test machine to test the static and impact forces of seven short columns of steel pipe concrete with square cross-section, the study parameters were variable height drop hammer and different load types, with the increase of impact energy, the short columns of steel pipe concrete have stronger impact resistance, and a simple method to calculate the impact strength of square steel pipe concrete columns was proposed. Zhou et al [29] found through 19 sets of specimen tests that the oblique cross combined ribs can effectively improve the axial compression force of steel pipe concrete and the composite effect of restrained concrete, and the bearing capacity of oblique bonded ribs is increased by 10%-20% and the ductility is increased by more than 30% compared with the steel pipe concrete specimens without stiffening ribs. Nour et al [30] derived an axial bearing capacity prediction model with the variables of steel pipe outer diameter, steel pipe thickness and yield strength, column length, recycled coarse aggregate replacement rate and concrete compressive strength by testing of the axial load carrying capacity prediction model and verified the correctness.5

IV. Conclusion

Through decades of continuous exploration and application of engineering practice, Chinese and foreign scholars have studied the bearing capacity of steel pipe concrete embedded piles and its influencing factors from various aspects. However, the static load capacity surplus of pile structure including steel pipe concrete embedded pile is generally high especially in longitudinal direction, but there are not many studies on steel pipe concrete embedded pile under dynamic load. Therefore, in the future, the following aspects need to be further studied.

(1) Physical model experimental aspects. Using strain gauges attached around the structure and collecting data by strain gauges is still the mainstream method for structural experiments, but the strain gauges cannot better measure the surface strain of the reinforced concrete pile core inside the steel pipe and the strain inside the reinforced concrete pile core. After the structure is cast, it is often found that the strain gauges inside have broken down or some strain gauges have been displaced under unknown circumstances. High-precision ultrasonic CT

imaging technology can be considered to detect the strain inside the structure.

(2) The principal structure model of steel-concrete embedded pile combination structure. For the steel-concrete combined structure, its mechanical properties are affected by both concrete and steel materials, and the elastic-plastic analysis of the combined structure can be carried out based on the known concrete and steel intrinsic structure models and the corresponding Poisson's ratio, using the continuous medium mechanics and fracture mechanics theories, which should be combined with theoretical and experimental methods to carry out special studies in the future.

(3) Transverse dynamic response characteristics of the combined structure. The pile foundation vertical bearing capacity is generally rich, and there is a lack of research on the aspect of relatively low bearing capacity of accidental transverse dynamic load. At present, the research on dynamic response characteristics mainly focuses on single material structure, lack of research on the modal and vibration response of the combined structure of reinforced concrete embedded rock pile, including concrete pile core, steel, foundation, etc. under dynamic load. The finite element simulations based on actual engineering situations often use simplified models due to their complexity.

(4) Study of the local interface deterioration mechanism of steel-concrete embedded piles under lateral impact loading. The combination of steel-concrete interface is related to whether the steel sheath and reinforced concrete pile core can work well together, and the current research on the interface mainly focuses on the tangential viscous force and friction, but lacks the study of the interface when the structure is subjected to lateral impact loading or repeated loading, and the local large strain to damage.

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