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Performance Research and Application Status of Fish-Bellied Prestressed Steel Support Structure System

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ABSTRACT

With the advancement of urbanization, in the field of modern construction engineering, especially in the deep foundation pit support system, the requirements for deformation control of foundation pit are constantly improving, and the focus of foundation pit support is also more biased towards stiffness control under the condition of engineering safety. Compared with the traditional concrete support, the fish-bellied prestressed steel support system is composed of fish-bellied prestressed steel support, corner brace, brace, triangular connecting member and vertical column. As a kind of assembled large stiffness internal support system, it has obvious advantages in safety, excavation space, convenient disassembly and assembly, construction period, economy and green environmental protection, and is widely used. In order to understand the research progress of existing scholars on fish-bellied prestressed steel support, this paper first summarizes the research and application status of common assembled horizontal support and assembled vertical support structure, and summarizes the shortcomings of current research. Through in-depth research on existing literature, patents, specifications and standards, the research status of fish-bellied prestressed steel support is emphatically analyzed. The basic principle, force transmission system and application status of fish-bellied prestressed steel support system are introduced. So as to reveal the variation law of support structure stress and foundation pit displacement. Summarize the shortcomings of the system research, and give targeted suggestions and future research directions.

KEYWORDS

Foundation Pit Support; Fish-Bellied Prestressed Steel Support; Steel Purlin; Prestressing; Low Carbon and Turnover.

1. INTRODUCTION

In the field of modern construction engineering, especially in the deep foundation pit support system, fish-bellied prestressed steel purlin is playing an increasingly important role. With the continuous advancement of urban construction, various types of large-scale buildings and infrastructure projects have sprung up, and the requirements for foundation pit support have become higher and higher. However, there is still a lack of recognized evaluation index system for underground space development.

In the large foundation pit project, the support system in the foundation pit is mainly affected by the load and earth pressure of the adjacent high-rise building, and the support stiffness of the ordinary steel frame is often small. It is necessary to reduce the spacing between the supports to improve its own stiffness and support bearing capacity. Therefore, in the actual foundation pit project, the cast-in-place concrete support is often used because of the small span of the steel support. However, the cast-in-place concrete support needs to be poured on site, and it cannot be installed on site like the steel support, resulting in a large amount of wet work on site and cannot be completely prefabricated.

Innovative Prestressed Support (IPS), with its unique structural form and excellent performance, provides reliable support guarantee for foundation pit engineering[1]. It can not only effectively control the deformation of foundation pit, ensure the safety of surrounding buildings and underground pipelines, but also improve the construction efficiency and reduce the project cost. This new type of supporting structure combines advanced design concepts and represents the development direction of the current foundation pit support technology. Its successful application in practical engineering provides strong technical support for solving the problem of foundation pit support under complex geological conditions.

The core idea of the IPS system was first proposed by Kim (2004). He established the structural configuration of the system and the mechanical relationship between prestress and lateral earth pressure, which provided a theoretical framework for subsequent research[2]. Some researchers have also proposed the design method of IPS and stiffened pile composite structure, and analyzed its effect in improving the overall stiffness of the support system and controlling the displacement. However, the existing research mostly focuses on the influence of foundation pit displacement control under foundation pit support. There is still a lack of systematic method for how to realize the uniform design of supporting load under different working conditions, and there is a lack of systematic analysis of the full-scale mechanical properties of fish-bellied prestressed steel purlins (including joint force transfer mechanism and purlin-support-soil interaction). The finite element analysis is mostly two-dimensional and three-dimensional simplified model analysis, and there is a lack of systematic analysis of the fine modeling of the three-dimensional solid fish-bellied prestressed steel purlin structure.

2. RESEARCH AND APPLICATION STATUS OF COMMON ASSEMBLED

In the traditional foundation pit engineering, there are two kinds of internal support structures : steel support and reinforced concrete support. For the traditional reinforced concrete, due to the large support stiffness, it has certain advantages in controlling the deformation of the foundation pit. However, because the reinforced concrete support adopts the construction method of on-site pouring, the concrete needs to be maintained for a period of time before the excavation of the foundation pit. When there are many supports, the weight is large and the construction period is long. Blasting is needed during demolition, and the dust is easy to cause environmental pollution and cannot be recycled. The assembled internal support system has developed rapidly in foundation pit support. As a prefabricated structure, the steel support support system of deep foundation pit is a kind of support method commonly used in underground engineering, which is suitable for temporary or permanent structures. In urban construction, this technology is particularly critical to ensure the safety and stability during foundation pit excavation. By setting steel support around the foundation pit, a stable frame structure is constructed to effectively prevent soil collapse and ensure the safety of construction personnel and surrounding buildings. The internal support frame system is more complex, but the force transmission is clear, and it can be divided into horizontal support and vertical support structure.

2.1. Development of Assembled Horizontal Support System

Assembled horizontal support system is one of the rapidly developing support forms in deep foundation pit engineering. Its types can be divided into large diameter steel pipe support, fish-bellied prestressed steel support (IPS system) and steel composite assembled support. Traditional steel pipe supports are widely used in subway stations and large urban foundation pits due to their mature construction experience and large overall stiffness. However, due to their self-weight and limited turnover efficiency. The shortcomings of small stiffness, low redundancy and large overall deformation, and the small stiffness of single steel support lead to dense distribution of braces, angle braces and columns during support, narrow construction space, affecting construction efficiency, and low integrity and safety. Unstable connection nodes of each component will cause adverse effects[3].

The proposal of IPS system has significantly promoted the development of prefabricated horizontal support. As a new type of deep foundation pit support technology, the core idea of fish-bellied prestressed steel support is to significantly improve its flexural rigidity and bearing capacity by applying prestress to the purlin system, so as to achieve super-large support span and provide open space for underground space construction. The research on this technology originated in South Korea. Kim, Park and other scholars have carried out a series of pioneering work, systematically expounding its mechanical principle, component composition and design concept. The system is made of fish-bellied prestressed steel enclosures[4-5].

The steel combined support takes H-shaped steel and I-shaped steel as the basic components, and realizes rapid assembly through bolts or quick-dismantling joints. The support is an efficient and environmentally friendly green foundation pit support technology, which has the advantages of energy saving, water saving, recyclability and recycling. According to the different shapes and requirements of the foundation pit, the crescent beam, oblique support and fish-bellied prestressed system can be added on the basis of the system, and the concrete support can also be added locally to meet the requirements of various foundation pit support. The technology can effectively control the deformation of the retaining structure and reduce the displacement of the soil around the foundation pit by adjusting the axial force of the composite steel support and the prestress of the composite purlin. At the same time, combined with on-site real-time monitoring methods, it can ensure that the entire foundation pit project is always in a safe and controllable state. Compared with the traditional concrete support, the material stiffness of the prestressed composite steel support is smaller. The key is to apply a larger prestress to suppress the displacement, rather than relying on the stiffness of the material itself[6-8].

In general, the assembled horizontal support system is developing towards high stiffness, large span, reusability and intelligent monitoring, and gradually forms a diversified technical pattern with IPS system as the core and combined support of steel pipe and section steel.

2.2. Assembled Vertical Support Structure

The prefabricated vertical support structure mainly includes prefabricated concrete row piles, steel cement soil mixing piles (SMW construction method piles), prefabricated underground continuous walls, steel sheet piles and composite steel walls.

Precast concrete row piles have been applied in medium-shallow foundation pits due to their fast construction and controllable quality, but their overall stiffness and water-stopping performance are limited. The SMW method pile relies on the synergistic effect of cement soil and steel, which has good water sealing effect and economy, especially suitable for soft soil and high water level areas. It is widely used in deep foundation pit engineering in soft soil areas in China, and the technology is mature. At present, the research results of SMW pile are mainly based on the innovation of construction technology, and the design basis for reference is relatively complete.

Prefabricated underground continuous wall has more advantages in wall quality, cost and construction speed. Due to the problems of wall width and inconvenient transportation, the research and application of prefabricated underground continuous wall have only increased in recent years in China.Prefabricated diaphragm wall can improve its performance by optimizing the geometry of wall width, steel bar arrangement and material selection. The research focuses on the waterproof performance, mechanical performance, wall crack resistance and stiffness of the joints and joints of the diaphragm wall, and also involves the design of the supporting system and the improvement of the construction supporting facilities[9-10].

Steel sheet pile and composite steel wall have been widely used in water area and temporary foundation pit engineering because of their high degree of assembly, reusability and high construction efficiency. The composite steel sheet pile has a variety of structures, usually composed of component units of different sections. It is combined into the soil by means of lock connection and welding to

form a retaining system with retaining, water interception and support functions. The current related research mainly focuses on the stiffness control of components, the type of lock connection and its force transmission mechanism. At the construction level, the influence of the cross-section form of the component and the piling process on the construction quality and efficiency is emphasized[11-12].

In general, the research and application of assembled vertical supporting structure are advancing in the direction of standardization, modularization and green sustainable development. Among them, SMW pile and steel sheet pile system are relatively mature, and prefabricated underground continuous wall is still a research hotspot worthy of attention in the future[13].

For the fish-bellied prestressed steel support system, it is closely related to the vertical support structure, and the two together constitute a stable stress system. The support system effectively limits the horizontal deformation of the support structure and improves the overall stiffness and stability by applying prestress. The two are highly coordinated in structural performance and construction process, which is an important guarantee for the safety of foundation pit.

3. RESEARCH STATUS AND DEVELOPMENT DYNAMIC ANALYSIS OF FISH-BELLIED PRESTRESSED STEEL SUPPORT

3.1. Force Transmission Mechanism of Fish-Bellied Prestressed Steel Support System

The new fish-bellied prestressed steel support supporting structure system is a spatial combination system composed of a horizontal force transmission frame and a vertical stability system. The core horizontal force transmission frame of the system is composed of a fish-bellied prestressed steel purlin arranged along the contour of the foundation pit and a brace or angle brace across the foundation pit. The lateral earth pressure borne by the retaining structure is first transmitted to the purlin. As a component with both beam and truss characteristics, the steel purlin can be pre-tensioned to the upper chord beam by tensioning the upper chord steel strand, resulting in the inverted arch of the upper chord beam, effectively collecting the load, increasing its own stiffness, and transmitting it to the support node in the form of axial pressure, and then crossing the foundation pit to achieve overall static balance. The columns used in conjunction mainly bear the self-weight and maintain the lateral stability of the supporting joints. This structural configuration enables the earth pressure to be efficiently transmitted mainly in the horizontal plane, effectively reducing the peak bending moment and improving the material utilization efficiency.

3.2. Research Status of Fish-Bellied Prestressed Steel Support System

In 2004, Professor Nak-Kyung Kim, a Korean scholar, first proposed an innovative prestressed support (IPS) soil retention system. This innovative prestressed assembled fish-bellied beam internal support system is composed of waist beams, H-shaped steel straight struts and multiple steel strands. It is a prestressed large-span internal support system. The basic structure, working mechanism and theoretical research of the system are introduced. It is assumed that the pressure on each straight web member is equal and is equivalent to the earth pressure acting on the fish-bellied purlin. The mechanical analysis of the joint part is carried out. The relationship between the prestress of the steel strand of the fish-bellied beam and the earth pressure under this new system is derived, and the design method of the prestress of the steel strand of the fish-bellied prestressed steel purlin based on the balance of force is obtained. Then it is introduced into the engineering example to prove that the IPS soil conservation system can not only provide a larger working space. And can effectively reduce the amount of steel[14-16].

In 2009, Park summarized the previous research results on IPS system. It is pointed out that the distance between the support and the support is usually only 2-4 meters. The introduction of the prestressed system greatly improves the bending stiffness, and the spacing between adjacent steel pairs in IPS can reach 20 ~ 50 m[17].

Subsequently, based on the research of Kim et al., Fernandes and Xavier elaborated a structure similar to IPS based on actual cases, which combines a polygonal tendon composed of high-strength steel strands with a steel frame support plate system. The support scheme does not require the installation of devices such as bolts.

After 2012, Liu Quanlin et al.proposed an invention patent, and through the study of the prestressed fish-bellied steel support system and the composite structure of stiffening piles, the opening bearings at the junction of the two structures were analyzed, and the force transmission mechanism was studied. The stability analysis of the side wall foundation strength, bearing bolts and foundation bearing capacity of the bearing position was carried out, and the corresponding calculation method and typical engineering cases were proposed for verification[21]. The results show that the composite structure can significantly reduce the deformation degree of foundation pit in practical application. Improve stability, and have the advantages of shortening the construction cycle and reducing costs.

In 2016, Guo Liang et al.analyzed the working principle of IPS, and analyzed the influence of prestress, deformation and stiffness on the environment. The pre-stressed fish-bellied beam support system applied to the enclosure structure effectively stimulates the passive earth pressure before excavation, and the deformation outside the pit occurs first compared to the deformation inside the pit, thus significantly limiting the displacement deformation inward[25].

From 2014 to 2017, Feng T et al.established a plane strain model system to quantify the coupling effect of prestress loss and compensation on lateral displacement, and proposed a method to determine the compensation amount based on numerical inversion. According to the measured actual loss rate of the project, the quantitative identification path of ' critical loss rate ' and compensation efficiency was given. For the three-dimensional simulation of construction sequence, in 2017, FLAC3D and MCC constitutive coupling stratification / block and asymmetric load were used to verify the effectiveness of compensation tension. It is pointed out that stratification is better than block in excavation sequence and thinning the thickness of key strata can more effectively suppress deformation, and construction optimization suggestions are given accordingly[18].

In 2019, Professor Kyungnam K et al.studied the PS system for the construction of temporary retaining structures in order to reduce the interference of retaining structures during excavation. It is shown that due to the existence of prestress, the structure not only reduces the number of columns, but also reduces the deformation in the horizontal direction, which verifies that the PS synchronous beam can reduce the horizontal deflection when the tension increases[19].

In 2019, Zhuang Shichao obtained the expression of the equivalent average stiffness of the fish-bellied steel support. Combined with the stiffness of the angle brace, the stiffness expression of the fish-bellied steel support system before and after the prestressing is applied is derived. Subsequently, the expression was verified by MIDAS GTSNX, and the monitoring data of the foundation pit of Xiamen Diamond Building were compared and analyzed to verify the validity of the software model. Subsequently, in 2021, Zhuang Shichao derived a simplified expression of the stiffness of the assembled prestressed fish-bellied steel support system before and after prestressing. Through the comparative analysis of the three-dimensional finite element numerical simulation results and the theoretical derivation results, it is found that the stiffness value error of the support system between the two is small, which verifies the accuracy of the calculation formula and provides a reference for the project. However, the derived analytical formula is based on a series of simplified assumptions, so there is a certain deviation from the more detailed finite element simulation or the actual situation. Although the study optimized the main parameters of the rise-span ratio and the number of web members, it did not fully cover all the influencing factors[12-23].

In 2020, Qiang Z et al.proposed an innovative application of prestressed support system in excavation engineering. The design principle of the system is expounded, and it is emphasized that the supporting structure and the surrounding soil form a whole through the application of prestress to bear the soil pressure together. It also expounds the advantages of improving the shear strength of soil under the action of prestress and better control of soil deformation[26].

In 2020, Gu Lina conducted a numerical simulation of the IPS support scheme of a proposed foundation pit project through a three-dimensional finite element model. The research content covers parameter sensitivity analysis of soil parameters, groundwater, prestress size and other parameters and analysis of progressive collapse resistance. A more realistic and reliable three-dimensional numerical model than the traditional two-dimensional model is established. For the first time, the concept of 'redundancy ' is introduced to evaluate the progressive collapse resistance of IPS system. It is an important deepening of the safety assessment of the system to simulate local failure by 'dismantling component method[24].

In 2021, Bi et al.analyzed the bending stiffness of the fish-bellied beam. By introducing the concept of 'equivalent bending stiffness ', the fish-bellied beam was regarded as a ' reinforced beam ' under the combined action of straight web members and steel strands, and the calculation formula of its stiffness was further deduced. The influence of the curve model of fish belly, the number of steel strands, the angle and span of the end on the stiffness of the fish belly beam is analyzed, and the recommended value of the stiffness of the fish belly beam is given. The main deficiency of this study is that its simplified model does not consider the influence of prestress, and prestress is the core of the support system. At the end of the paper, the author also points out that the influence of prestress on deformation control should be taken into account in future research. At the same time, the model simplification ignores the role of secondary components such as inclined web members, and the calculation results will be smaller than the actual ones, which belongs to the safe design reserve[28].

In 2021, Guo Gan used MIDAS GTS NX software to analyze the influence of steel strand prestress applied in prestressed fish-bellied beam on the support system. At the same time, through the simulation of the structural deformation behavior during the excavation of the foundation pit soil layer by layer, the difference of the deformation control effect before and after the prestress is applied in the construction stage is studied. The optimal value of rise-span ratio and the number of upper chord beam segments are determined by simulation calculation[27].

In 2024, based on the basic theory of force method, Wang Minying deduced the formula for calculating the equivalent bending stiffness of the five-belly fish belly beam before and after prestressing, and verified the formula with the measured data of a hospital project in Nanjing. In the derivation process, not only the force of the basic structure is considered, but also the deflection increase coefficient (second-order effect) of the compression-bending member and the axial deformation of the web member are introduced, which makes the calculation model more accurate than the previous simplified model and can better reflect the real stress state of the structure. For other common forms such as three-web member and six-web member, the stiffness calculation needs further study. In addition, the derived formula is more complex, and its application convenience is not as good as the finite element software in the rapid design scenario[31].

The same year, Pang et al.used the finite element numerical simulation software MIDAS / GEN for modeling and analysis, and provided an empirical formula that can be directly used in the preliminary design for the design of fish-bellied beam support. Through scientific analysis methods, the internal mechanical relationship between a key design detail (tension point height) and the key performance of the system (node displacement and overall stability) is clearly revealed[29-30].

Summary, the research on the fish-bellied prestressed steel support structure system is multifaceted. It not only has certain research on the internal force calculation of each component under the system, but also through numerical simulation research and research methods combined with engineering practice. It is concluded that the system is not only suitable for areas with good geological conditions,

but also for deep foundation pit projects in soft soil areas. The research shows that the prestress of steel strand significantly enhances the stiffness of the whole steel support system, and the dynamic application of prestress can change the effect of active support and reduce the deformation of foundation pit. Most scholars have shown that the fish-bellied prestressed steel support system has the advantages of reducing cost, improving construction efficiency, protecting the environment and high recycling rate of components. The fish-bellied prestressed steel purlin is also called fish-bellied beam. As an important part of the fish-bellied prestressed steel support system, there are few studies on its design method and mechanical properties at home and abroad, and its mechanical properties need more extensive and in-depth research.

3.3. Stiffness Influencing Factors of Fish-Bellied Prestressed Steel Support System

The stiffness of the fish-bellied prestressed steel support system is affected by many factors, including the section size of the fish-bellied prestressed steel purlin, the arrangement of the web members, the size of the pre-tensioning force, the performance of the steel, the arrangement of the support, the stiffness of the connection nodes and the conditions of the column fulcrum.

The larger the cross section of the steel purlin, the higher the moment of inertia. The layout of web member has a significant effect on its bending and axial stiffness. The longer the web member is, the more the span is, and the better the stabilit of the support is. The initial prestress affects the initial inverted arch effect and then affects the apparent stiffness, which has a significant effect on the deformation control ability. Material properties, such as the stiffness and strength of steel and the yield strength of steel strands. The force performance of the component is affected, and the equal spacing and connection mode of the brace and the corner brace are related to the load transfer efficiency and the overall coordination of the structure. Although the column does not participate in the horizontal force transmission, it still has a certain influence on the stability of the support joint.

4. RESEARCH DEFICIENCY AND DEVELOPMENT PROSPECT OF FISH-BELLIED PRESTRESSED STEEL SUPPORT SYSTEM

As a new type of foundation pit support, the theoretical research and practical development of prestressed fish-bellied steel support structure system are not yet mature. In general, the stiffness of the prestressed fish-bellied steel support structure system is greater than that of the steel support, and the prestressed fish-bellied steel support structure system is obviously superior to the traditional concrete support in terms of material utilization, environmental protection and construction cycle. At the same time, it can actively monitor and control the deformation of the foundation pit, showing high safety and stability. In recent years, the requirements for foundation pit engineering, especially deep foundation pit engineering, are becoming more and more strict in terms of stability, displacement control, construction period and so on. However, at present, there is no very strict and good implementation specification for the prestressed fish-bellied steel support structure system. Most of the studies only focus on the control of the internal support system on the displacement of the foundation pit and the change of the soil along the depth of the foundation pit or the settlement change and safety of the adjacent building. There are few studies on the stress mechanism of the fish-bellied prestressed steel purlin itself and the deformation characteristics of each part. In the absence of a suitable design method, the fish-bellied prestressed steel purlin bears a large bending moment, which may lead to uneven stress of each straight strut, and then the displacement control can not achieve good results.

Domestic and foreign scholars have less research on the mechanical properties of fish-bellied prestressed steel purlins. If a comprehensive systematic evaluation of the mechanical properties of this type of purlin can be carried out to make up for the lack of understanding of domestic and foreign scholars, it is not only a new enrichment for the academic research of the supporting system in the

foundation pit, but also for the fish-bellied prestressed steel purlin. It also has important reference significance in different design sizes and material selections in various practical projects. Therefore, the application of prestressed fish-bellied steel support system as an internal support system has great development prospects. At the same time, it also requires us to have more refined research on the system.

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