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Summary of Research on Mechanical Properties of Prestressed Beam String Internal Support System in Foundation Pit Engineering

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Abstract: With the acceleration of urbanization, the number of deep foundation pit projects is increasing, and the limitations of traditional support systems in large-span and complex environments are gradually highlighted. As a new type of support form, the prestressed beam string internal support system has been more and more widely used in foundation pit engineering due to its advantages of high stiffness, large span and strong controllability. This paper systematically reviews the development history, structural composition and working mechanism of the internal support system of prestressed beam string structure, and summarizes the mechanical performance analysis, influencing factors, engineering application cases and existing problems. By integrating the relevant research results at home and abroad, the mechanical properties of the system in terms of load transfer, deformation control and stability are revealed. The effects of prestress level, geometric parameters, material properties and other factors on its performance are discussed, and its practical application effect is analyzed in combination with typical engineering cases. Finally, in view of the shortcomings of the current research, the future research direction is proposed, which provides a reference for the further development and engineering application of the system.

Keywords: Foundation Pit Engineering, Prestressed Beam String, Internal Support System, Mechanical Properties.

1. Introduction

In recent years, with the large-scale development of urban underground space, deep foundation pit engineering presents the development trend of ' large depth, large span and complex environment '. Although the traditional reinforced concrete internal support system has the advantages of high rigidity and high safety, it has the problems of long construction period, difficult demolition and serious environmental pollution. The ordinary steel support system is easy to construct, but the stiffness is low, and it is difficult to meet the deformation control requirements under complex working conditions. In this context, the internal support system of prestressed beam string structure, as a new type of support form that integrates prestressed technology and the concept of beam string structure, has gradually become a hot spot of research and application.

The prestressed beam string internal support system forms a cooperative working system between the upper rigid beam and the lower flexible cable by applying prestress to the lower cable. It has both the high stiffness of the rigid support and the controllability of the flexible cable. It can provide efficient support capacity in the large-span foundation pit, reduce the number of supports, and create a spacious space for earthwork excavation and underground structure construction. In-depth study of the mechanical properties of the system has important theoretical and engineering significance for optimizing the design of foundation pit support, improving engineering safety, and promoting the development of green construction technology.

2. Research Status at Home and Abroad

2.1. Domestic Research Progress

The research on the internal support system of prestressed beam string structure in China began in the early 21 st century. With the increase of engineering demand, the related research has developed rapidly. Zhuang et al. (2021) deduced the stiffness calculation formula of the assembled prestressed fish-bellied steel support system[8]. Through the comparison of finite element simulation and engineering cases, the accuracy of the formula was verified, which provided a theoretical basis for the stiffness design of the system. Liang Zhirong et al. (2023) applied two prestressed fish-bellied steel supports in adjacent deep foundation pit projects in soft soil areas[5]. The monitoring data show that the system can effectively control the deformation of the foundation pit, and the adjacent foundation pit has little interaction. Lu et al. (2023) analyzed the application effect of prestressed fish-bellied steel support system in deep foundation pit in combination with Xuzhou Lugang Building project, and pointed out that the system can shorten the construction period by more than 40 % and save the cost by about 20 %.[7]

2.2. Foreign Research Progress

The research on the beam string structure started earlier in foreign countries. In the 1980 s, Japanese scholars took the lead in applying the beam string structure to the building roof system, and then gradually expanded to the field of foundation pit support. Kim et al. (2004) proposed the innovative prestressed support (IPS) system[2]. By applying prestress to the steel strand, the stiffness and deformation control ability of the support system are significantly improved, and the effectiveness of the system is verified by model tests. Park et al. (2008) analyzed the influence of prestress load on the behavior of supporting wall and purlin by using three-dimensional finite element model, and pointed out that prestress compensation had a significant effect on controlling the deformation of foundation pit[4]. Roboski (2004) found that the maximum lateral displacement of the beam string support system is closely related to the length of the foundation pit by analyzing 18 foundation pit cases, which provides a reference for the span design of the system[3].

3. The Structure Composition and Working Mechanism of Prestressed Beam String Internal Support System

3.1. Structure Composition

The internal support system of prestressed beam string is mainly composed of the following parts :

Upper rigid beam : H-shaped steel, box section or composite section are usually used as the main load-bearing members to bear bending moment and axial force.

Lower flexible cables : high-strength steel strands or wire ropes are mostly used to produce prestress through tensioning to provide tensile stiffness for the system.

The web member system : connecting the rigid beam and the cable, which can be arranged vertically or obliquely, to transfer the load and maintain the geometric shape of the system.

Anchorage system : including anchorage, tensioning equipment, etc., for the application and maintenance of prestress.

Purlins and connectors : Connect the support system to the supporting pile (or diaphragm wall) to ensure effective load transfer.

3.2. Working Mechanism

The working mechanism of the internal support system of prestressed beam string structure can be summarized as 'prestressed active control + rigid-flexible cooperative force ' :

Prestressing stage : By tensioning the lower cable, the rigid beam produces an upward arch, and the initial prestressing field is established in the system. At this time, the rigid beam is subjected to bending, the cable is subjected to tension, and the web member is subjected to axial force.

Foundation pit excavation stage : With the excavation of the soil, the lateral earth pressure acts on the supporting structure and is transmitted to the supporting system through the purlin. At this time, the anti-arch effect caused by prestress can offset the deformation caused by partial earth pressure, and the rigid beam and the cable cooperate to resist the bending moment and tension, forming a working mode of ' regulating the deformation of rigid beam with cable prestress '.

Deformation control stage : the prestress level can be adjusted by secondary tension cable, and the support stiffness attenuation caused by soil creep and load change can be compensated in real time, so as to realize the dynamic control of foundation pit deformation.

4. Mechanical Performance Analysis of Prestressed Beam String Internal Support System

4.1. Load Transfer Path

The load transfer path of the internal support system of prestressed beam string is as follows :

Lateral earth pressure → supporting pile (underground continuous wall) → purlin → supporting system connector → upper rigid beam → web member → lower cable → anchorage system → foundation.

In this path, prestress, as the initial internal force, is superimposed with the load internal force generated by earth pressure to form a complex stress state. Research shows that (Feng et al., 2017), the existence of prestress can reduce the peak bending moment of rigid beam by 30 % ~ 50 %, and the cable bears about 60 % ~ 70 % of the horizontal tension, which significantly improves the mechanical performance of the system[1].

4.2. Stress Characteristic

4.2.1. Force Analysis of Rigid Beam

Under the combined action of prestress and earth pressure, the rigid beam mainly bears the combined action of eccentric compression and bending. The stress distribution of the section varies with the prestress level and the load condition. When the prestress level is high, the tensile stress may appear on the upper flange of the rigid beam, and the compressive stress on the lower flange decreases. With the increase of soil pressure, the mid-span bending moment of rigid beam increases gradually, which may be transformed into the state that the lower flange is tensioned and the upper flange is compressed. Liu Jie (2018) found through finite element analysis that the maximum bending moment of the rigid beam appears in the mid-span section, which is about 1 / 2 ~ 1 / 3 of the traditional concrete support, which is due to the anti-arch effect caused by prestress[10].

4.2.2. Cable Force Analysis

The cable is the key tensile member of the internal support system of the prestressed beam string structure, and its stress state directly affects the overall performance of the system. In the initial tensioning stage, the cable is subjected to the design prestress. With the excavation of the foundation pit, the tension of the cable gradually increases, and its increment is related to the magnitude of the earth pressure and the deformation of the system. Sun Weiwei et al. (2022) pointed out through anti-collapse analysis that the redundancy of cables is higher than that of rigid beams and web members, that is, the cable failure is more resistant to the progressive collapse of the system, but it is necessary to pay attention to the stress relaxation of cables. The loss of prestress in long-term use can reach 10 % -15 %[6].

4.2.3. Stress Analysis of Web Member

The web member is mainly subjected to axial force, and its force direction depends on the layout of the system. The vertical web member bears pressure in the pre-stressed stage, and may turn into tension or pressure increase under the action of earth pressure. The inclined web member may always bear pressure or tension, depending on the inclination angle and load distribution of the web member. Su (2019) analyzed the stability of super-long braces, and found that the stiffness and arrangement density of web members had a significant effect on the overall stability of the support system. It is recommended that the spacing of web members should not exceed 1 / 5 of the span of rigid beams[9].

4.3. Deformation Law

4.3.1. Overall Deformation Characteristics

The overall deformation of the internal support system of the prestressed beam string shows the characteristics of ' large mid-span deflection and small deformation at both ends '. The deflection curve is similar to that of the simply supported beam, but due to the influence of prestress, the initial deflection direction is opposite to the deflection direction under load. Through theoretical derivation and finite element simulation, Zhuang et al. (2021) concluded that the mid-span deflection of the system can be expressed as :

$$w = w_0 - w_p + w_q$$

Among them, W0 is the deflection caused by the initial installation error, Wp is the anti-arch deflection caused by prestress, and Wq is the deflection caused by earth pressure. When the prestress is applied reasonably, Wp can offset 60 % ~ 80 % of Wq, which significantly reduces the final deformation of the support system[8].

4.3.2. Key Node Deformation

The deformation of key parts such as the connection node between the support system and the purlin and the cable anchorage node has a significant impact on the overall performance. The measured data show that (Lu Xiaojin et al., 2023), the relative displacement at the joint can reach 10 % ~ 20 % of the mid-span deflection, mainly due to the insufficient stiffness of the joint and the deformation of the connector. Therefore, the joint design needs to consider the stiffness matching and deformation coordination, and rigid joints or additional stiffeners can be used[7].

4.4. Stability Analysis

Emid-span deflection, mainly due to the insufficient stiffness of the joint and the deformation of the connec The stability of the internal support system of prestressed beam string includes overall stability and local stability:

Overall stability : mainly affected by span, prestress level and support spacing. When the span exceeds 40 m, the out-of-plane stability of the system needs to be considered, and the stability can be improved by setting lateral support or increasing the prestress of the cable. Feng et al. (2017) showed that for every 10 % increase in prestress, the critical buckling load of the system can be increased by 15 % ~ 20 %[1].

Local stability : involving web buckling of rigid beams, out-of-plane vibration of cables, etc. Rigid beam web can prevent buckling by setting stiffeners ; cables can use spiral lines or dampers to suppress vibration and reduce resonance caused by wind load or construction disturbance.

5. Factors Affecting the Mechanical Properties of the Internal Support System of Prestressed Beam String

5.1. Prestress Level

The prestress level is the most critical factor affecting the mechanical properties of the system. The research shows that (Park et al., 2008), when the prestressing tension reaches 80 % of the design value, the stiffness of the system can reach 90 % of the maximum value ; continue to increase the prestress, the stiffness increase slows down, but may lead to cable stress overrun. The reasonable prestress level should be determined according to the magnitude of earth pressure, support span and deformation control requirements, usually taking 40 % ~ 60 % of the ultimate strength of the cable[4].

5.2. Geometric Parameter

The ratio of span to height : with the increase of span, the deflection and bending moment of the system increase significantly, and it is suggested that the span should be controlled in the range of 20 ~ 50m ; the height ratio (height / span) should be 1 / 8 ~ 1 / 12, and the system stiffness and material consumption achieve the best balance (Zhuang Shichao, etc., 2021)[8].

The spacing and inclination angle of the web members : the smaller the spacing of the web members, the more uniform the bending moment distribution of the rigid beam, but it will increase the amount of steel ; the inclination angle of the oblique abdominal rod is 45 ° ~ 60 °, and the axial force of the abdominal rod is the smallest and the force is the most reasonable (Liu Jie, 2018)[10].

5.3. Material Properties

Rigid beam material : The use of high strength steel (such as Q355B) can improve the section stiffness and reduce the size of the component. It is recommended that the elastic modulus is not less than 2.06 × 10 ^ 5 MPa.

Cable material : Low relaxation steel strand is preferred, its elastic modulus should be 1.95 × 10 ^ 5 MPa, and its ultimate strength should not be less than 1860 MPa, so as to reduce prestress loss (Sun Weiwei et al., 2022).[6]

5.4. Construction Technics

Tensioning sequence : Graded tension can reduce the initial deformation of the system. It is recommended to tension to the design value in 3-4 grades, and the interval between each grade is not less than 12h (Liang et al., 2023)[5].

Prestress loss control : the friction loss of the anchorage system, the shrinkage and creep of concrete will lead to the loss of prestress, which can be compensated by over-tension (5 % ~ 10 %) and post-tensioning.

6. Engineering Application Case Analysis

6.1. Deep foundation pit project of Xuzhou Lugang Building

6.1.1. Project Profile

The foundation pit of Xuzhou Lugang Building has a depth of 16.7 m and an area of about 19000 m2. The surrounding environment is complex, adjacent to 110 kV high-voltage cables and municipal pipelines. The ' bored pile + three prestressed fish-bellied steel support ' system is adopted, in which the second and third supports are in the form of prestressed beam string, with a span of 24 ~ 30m and a steel strand tension of 130 ~ 1650kN (Lu et al., 2023)[7].

6.1.2. Mechanical Performance

The monitoring data show that when the foundation pit is excavated to the bottom, the maximum horizontal displacement of the supporting pile is 27 mm, which meets the design control value of 45 mm. The mid-span deflection of the support system is 18.2 ~ 28.0mm, and the prestress loss rate is about 8 % ~ 12 %. Compared with the traditional concrete support, the system shortens the construction period by 45 days and saves about 26 % of the cost, reflecting good technical and economic effects.

6.2. Foundation Pit Engineering of Xiamen Diamond Building

6.2.1. Project Profile

The foundation pit of Xiamen Diamond Mansion is square, with a side length of about 82.5 m and a depth of 12.6 ~ 16.35 m. The system of ' cast-in-place pile + three pre-stressed beam string internal support ' is adopted. The support span is 20 ~

34 m, and the tensile force of steel strand is 1050 ~ 1350 kN (Zhuang Shichao, etc., 2021)[8].

6.2.2. Mechanical Performance

The comparison between finite element simulation and field monitoring shows that the error between the theoretical value and the measured value of the mid-span deflection of the system is less than 10 %, and the increment of the support axial force caused by the earth pressure is 30 % ~ 40 % of the initial prestress. By optimizing the excavation sequence (block excavation), the surface settlement around the foundation pit is controlled within 20 mm, which verifies the applicability of the system under complex working conditions.

6.3. A Deep Foundation Pit Project in Japan

6.3.1. Project Profile

The project is located in the urban area of Tokyo. The depth of the foundation pit is 18 m. The ' underground continuous wall + two IPS prestressed beam string support ' system is adopted. The span is 35 m, and the steel strand tension is 2000 kN. FLAC3D is used for numerical simulation (Feng et al., 2017)[1].

6.3.2. Mechanical Performance

The simulation results show that after the prestress is applied, the lateral displacement of the supporting wall is reduced by 40 %, and the stiffness of the supporting system is 2.5 times higher than that of the traditional steel support. On-site monitoring found that the loss of prestress in long-term operation is about 15 %. Through regular tensioning, the deformation of the foundation pit is always controlled within 15 mm.

7. Existing Problems and Future Prospects

7.1. Existing Problems

Theoretical model simplification : Most of the existing theoretical models regard the support system as a plane structure, and do not fully consider the three-dimensional space effect and soil-structure interaction, resulting in deviations between the calculation results and the actual situation.

Lack of long-term performance research: There are few studies on long-term performance such as prestress loss law and material aging, and lack of long-term monitoring data support.

The construction control is difficult: the pre-stressed tension accuracy is high, and the problems such as uneven tension and mismatch of joint stiffness are easy to occur in the field construction, which affects the performance of the system.

The research on seismic performance is weak : there are few application cases in the earthquake zone, and there is a lack of systematic research on the seismic mechanism and design method of the system.

7.2. Future Prospect

Multi-scale numerical simulation : Combining finite element and discrete element methods, a multi-scale model considering soil nonlinearity, joint flexibility and construction process is established to improve the calculation accuracy.

Intelligent monitoring and control : introduce optical fiber sensing and BIM technology to realize real-time monitoring and automatic compensation of prestress, and improve the reliability and intelligent level of the system.

Application of new materials: Explore new materials such as high-strength composite cables and self-prestressed concrete rigid beams to further improve system performance and durability.

Seismic design method: The model test and numerical analysis under earthquake action are carried out, and the design method of prestressed beam string internal support system suitable for earthquake area is established.

Standardization and normalization: The design, construction and acceptance criteria for the internal support system of prestressed beam string structure are formulated to promote the wide application of this technology.

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8. Conclusion

As a new type of support form that integrates prestressed technology and string structure concept, the internal support system of prestressed beam string structure shows significant technical advantages in foundation pit engineering. In this paper, through a systematic review of its mechanical properties, the following conclusions are drawn:

The system can effectively reduce the bending moment and deformation of the support system through the mechanism of ' pre-stress active control + rigid-flexible synergistic force ', and its stiffness is 1 ~ 2.5 times higher than that of the traditional support.

The prestress level, geometric parameters and material properties are the key factors affecting the mechanical properties of the system. Reasonable design can reduce the mid-span deflection by 60 % ~ 80 %, and the prestress loss can be controlled within 15 %.

The engineering application shows that the system can shorten the construction period by more than 40 % and save the cost by 20 % -26 %. It is suitable for deep foundation pit engineering with large span and complex environment.

In the future, it is necessary to further study the theoretical model, long-term performance, construction control and seismic design to promote the further development and engineering application of this technology.

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