

A Review of Research on Prestressed Fish-Belly Steel Bracing Systems

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Abstract: Prestressed fish-belly beam steel bracing has emerged as a reusable and space-efficient support solution for deep excavations. This paper reviews research and engineering applications reported from 2008 to 2025, with emphasis on mechanical behavior, deformation control, stability, stiffness matching, construction technology, monitoring, and structural optimization. Existing studies show that prestressing can mobilize passive earth pressure, increase the apparent stiffness of the bracing system, reduce retaining-wall movement and ground settlement, and improve construction efficiency while limiting material waste. Nevertheless, current design practice remains fragmented. Prestress is commonly introduced through steel strands whose anchorage slip may cause force loss; unified methods for in-plane stability, combined stiffness, failure-mode identification, and capacity calculation are still incomplete. Future research should therefore focus on self-balanced prestressed steel wales, reliable anchorage and compensation, failure-mode-based design, multi-objective optimization, standardized reusable components, and digital monitoring throughout construction.

Keywords: Prestressed Fish-Belly Beam, Steel Bracing, Deep Excavation, Deformation Control, Structural Optimization, Green Construction.

1. Introduction

With the continued acceleration of urbanization in China, the development of underground space has intensified. Deep excavations are now widely used for high-rise buildings, urban rail transit, utility tunnels, and other underground infrastructure. As the core structural system that safeguards excavation and controls deformation of the surrounding environment, an excavation bracing system directly affects project safety, quality, economy, and construction efficiency.

Conventional internal bracing generally consists of reinforced-concrete struts or ordinary steel struts. Reinforced-concrete bracing provides high stiffness and capacity, but it also requires a long construction cycle, has substantial self-weight, involves extensive casting work, and is difficult to demolish and recycle. Ordinary steel bracing is lighter, faster to install, and reusable, but its relatively simple section forms can develop local stress concentrations and inadequate global stability under large lateral loads. Increasing section size or adding more struts raises material consumption and cost and can obstruct the excavation workspace.

The assembled prestressed fish-belly beam steel bracing system was developed to address these limitations. Its modular construction and large unobstructed horizontal spans can improve site access, shorten the programme, and reduce cost. Research has primarily examined excavation deformation under this form of support, whereas fewer studies have addressed the structural design method and mechanical performance of the bracing system itself. Inadequate design can lead to prestress loss, local component failure, buckling, or shear failure at joints. Existing systems often rely on steel strands both to introduce prestress and to provide additional support; the stressing operation is relatively complicated, and anchorage slip can reduce strand force.

A promising direction is the self-balanced prestressed steel wale. Unlike a conventional prestressed wale, it does not

require additional members between web members to resist horizontal components, and the compression in the web members can be balanced by tension in connecting members. The central research tasks are to identify failure modes under different design parameters, quantify the corresponding load-carrying capacity, and establish practical methods for failure-mode classification and capacity calculation.

2. Development Status

Research on prestressed fish-belly beam bracing has progressed from three-dimensional numerical modelling of prestressed earth-retention systems to full-scale field applications, analytical models, stability design, hybrid bracing, automated optimization, and EPC-based construction management. The main technical themes are prestress-induced deformation control, stiffness enhancement, in-plane and out-of-plane stability, construction and monitoring, and the environmental and economic benefits of modular reuse.

The published record also shows a gradual change in emphasis. Early work verified system behavior through finite-element models and field measurements. Later studies established design and construction procedures and investigated prestress compensation, stiffness, and stability. Recent work increasingly combines analytical calculation, numerical simulation, real-time monitoring, parametric optimization, and lifecycle management. The following review organizes the literature into four periods while retaining the original citation sequence.

3. Research Progress

3.1. Early Numerical and Field Studies (2008-2013)

In 2008, Park, Jong-Sik et al. [1] developed a three-dimensional finite-element model to examine the mechanical response of an earth-retention system under prestressing. The

model predicted retaining-wall deformation and axial loads in system components, and the results were validated against field monitoring. Parametric sensitivity analyses further evaluated lateral wall and pile deformation, pile bending moment, and lateral earth-pressure distribution.

In 2009, Jong-Sik Park et al. [2] investigated a new earth-retention system using prestressed wales. They described its basic principles, working mechanism, design process, advantages, and limitations and evaluated its field performance. The measured results demonstrated favorable application in urban excavation.

In 2011, Wang et al. [3] reviewed emerging underground-engineering technologies, including large-diameter super-long piles, uplift-resistant piles, excavation deformation and environmental control, sustainable support, large-section pipe-roof box culverts, modern pneumatic caissons, and three-dimensional digital technology. Pan et al. [4] presented an engineering application of the innovative prestressed support (IPS) fish-belly beam system, explaining its mechanism, construction process, and technical features. The case indicated potential reductions in cost and programme duration together with greener construction.

In 2013, Liu [5] used an excavation case to demonstrate that high-pressure jet-grouting can significantly influence an adjacent excavation under construction by increasing the horizontal load on retaining piles. Recalculated retaining-structure displacements agreed closely with field measurements. Tugen Feng et al. [6] used ABAQUS to simulate an excavation supported by prestressed fish-belly beams and quantified the effects of prestress loss and compensation on lateral deformation. Their results identified a critical loss ratio and showed that compensation adjusted to this threshold could control lateral movement effectively.

3.2. Engineering Application and Design Development (2014-2018)

In 2014, Li et al. [7] summarized the configuration and mechanical analysis of built-up steel bracing. Monitoring in a silty-soil excavation showed a parabolic lateral-displacement profile resembling cantilever excavation; back-analysis attributed this behavior mainly to connections that did not develop equal strength, leading to recommendations for greater bracing stiffness. Xie [8] explained the mechanism of prestressed fish-belly beam composite steel bracing and documented its first application in Guangzhou, where it reduced cost and duration and improved safety and environmental performance. Zhang [9] developed a deformation-control framework for deep excavations and described how prestress should be applied, adjusted, and linked to control criteria and contingency plans.

In 2015, Li et al. [10] examined the Jinghui Plaza excavation in Jiaxing and used monitoring of deep-soil displacement, road settlement, anchor-pile force, and external groundwater level to support information-based construction. The study found rapid prestress decay in anchor piles in soft soil, effective displacement restraint by steel bracing, and good water cutoff performance from SMW piles. Pei et al. [11] clarified two theoretical issues for prestressed support in large excavations: prestress should be applied before lower-layer excavation to mobilize passive earth pressure, and the lateral elastic restraint provided by columns may eliminate the need for a separate global-stability check and related strength reduction for ultra-long cross-lot struts.

In 2016, Liu [12] developed a stability-design procedure for

assembled steel internal bracing in large-span excavations based on GB 50017-2003, covering both overall and individual-member stability. Bai et al. [13] compared Chinese and Japanese design methods for steel excavation bracing and identified their similarities and differences. Using field data, Guo et al. [14] examined IPS behavior from the perspectives of prestress, deformation, and stiffness control. Prestressing before excavation mobilized passive pressure and directed the retaining structure slightly outward, thereby suppressing inward movement. Measured deep horizontal movement remained below 10 mm, while surface settlement remained below 18 mm. The system also supplied a comparatively uniform reaction over the full span and mitigated the stress concentrations found in conventional internal bracing.

In 2017, Lu [15] reported an IPS application beside sensitive utilities. Monitoring confirmed effective deformation control, provided that the support layout and excavation sequence were carefully coordinated. Tugen Feng et al. [16] established and validated a FLAC3D model for the IPS system. Parametric analysis led to recommendations for excavation location, lift thickness, and zoned excavation sequence. Prestress compensation strongly affected mechanical performance, whereas changes in excavation sequence produced more limited improvements.

In 2018, Ou et al. [17] proposed a cross-shaped assembled excavation-support system intended for rapid, safe, low-cost, recyclable, and environmentally responsible construction. Field tests in Nanning agreed well with calculated results. Qi et al. [18] documented construction procedures, technical requirements, quality-control points, and deformation monitoring for prestressed built-up steel bracing. Liu [19] investigated the load-transfer mechanism and deformation control of IPS fish-belly beam steel bracing by combining modal finite-element analysis with an engineering case. In the same year, Liu [20] optimized a large-area excavation at Guangzhou South Station using prestressed fish-belly steel bracing and MIDAS/GTS. Comparison with the original scheme confirmed the rationality and advantages of the optimized green-support solution.

3.3. Stability, Deformation Control, and Analytical Models (2019-2021)

In 2019, Kyungnam Kim et al. [21] evaluated the horizontal deflection of a prestressed synchronized wale under tensile action and found that its mechanical performance was adequate when deflection was kept within the 5 mm safety limit. Prestressed fish-belly bracing must satisfy strength, individual-member stability, out-of-plane stability, and in-plane stability. Because design standards did not specify the in-plane effective length of built-up members with lateral elastic restraint, Su [22] combined theoretical analysis and three-dimensional modelling to propose a practical method for ultra-long cross-lot struts. Liu [23] combined MIDAS/GTS analysis with field measurements. The computed maximum system displacement was 28.26 mm, maximum horizontal displacement 14.7 mm, maximum ground settlement 9.6 mm, and maximum bracing axial force 5,896 kN. The adjacent metro tunnel experienced maximum horizontal and vertical movements of 2.32 mm and 5.343 mm, respectively; all calculated and measured values remained below alarm thresholds.

In 2020, Zhang Qiang [24] described the operating principle and construction sequence of an innovative prestressed combined support system through a metro network operations

and management center project. Wang et al. [25] reviewed emerging Chinese excavation and underground-engineering technologies related to energy efficiency, environmental impact, intelligent control, and ultra-deep excavations. Xu [26] simplified the fish-belly beam as a first-degree indeterminate beam-string model and derived an analytical solution for force and deformation. The prestress that produced zero upper-chord deflection was defined as the rational prestress. MIDAS/GTS simulations agreed with the analytical solution while prestress remained at or below this value, but diverged when prestress continued to increase.

Also in 2020, Wang et al. [27] developed a large-span support system combining beam strings and built-up steel trusses. Compared with conventional fish-belly bracing, the new system simplified joints, improved plan layout and support stiffness, enhanced global stability, and facilitated prestressing. Du et al. [28] reviewed applications in two deep excavations in soft soil and reported short construction periods, good economy, and recyclability, while also identifying challenges in deep, thick soft-soil deposits.

In 2021, Bi and Xu [29] introduced the concept of equivalent flexural stiffness for fish-belly beam steel bracing. By simplifying the web members, treating the beam as fixed at both ends, and solving the load-deformation relationship with the displacement method and MATLAB, they showed that the strengthened beam follows a quartic-parabolic deformation pattern under uniform loading. Their parametric analysis considered the fish-belly curve, number of strands, end angle, and span. Zhang [30] validated a MIDAS/GTS model against monitoring and showed that prestressing significantly reduced retaining-pile deformation. Hua [31] similarly verified effective deformation control in a complex surrounding environment. Liang [32] systematically discussed the technical basis and deep-excavation application of assembled prestressed fish-belly beam bracing, while Ma [33] summarized the construction sequence, practical control points, and precautions needed to improve performance and shorten the programme.

3.4. Integrated Design and Recent Applications (2022-2025)

In 2022, Yang et al. [34] investigated stiffness coordination between concrete bracing and fish-belly beam steel bracing in hybrid systems. Starting from allowable design strength, they derived a stiffness-ratio relationship and proposed a method for calculating combined structural stiffness and selecting prestress compatible with the steel strands. Post-construction monitoring supported the reliability and practicality of the method. Yi [35] reported a super-large deep excavation in Shanghai where assembled prestressed fish-belly beam bracing performed well in soft soil and met deformation and stability requirements. Ji [36] developed a Python-based planar-region partitioning algorithm for H-section steel truss bracing, linked it to ABAQUS preprocessing, and combined it with ISIGHT to automate optimization of the internal bracing layout.

In 2023, Lu et al. [37] described the system configuration and mechanism through the Xuzhou Land Port Building project. Analysis of support selection, construction, and monitoring showed that the system controlled excavation deformation and maintained safety while shortening the programme and reducing cost.

In 2024, Wang et al. [38] compared support alternatives for a Sam's Club excavation adjacent to Wuxi Metro Line 1.

Prestressed fish-belly steel bracing was selected to replace conventional concrete bracing. Finite-element simulation and real-time field monitoring confirmed safety and reliability, together with substantial savings in time and cost.

In 2025, Song et al. [39] studied a deep excavation for a building in Xuzhou from an engineering-procurement-construction management perspective. They proposed coordinated optimization of site and support layout, fish-belly beam configuration, tower-crane location, prestress application, and construction-stage division, demonstrating the growing integration of structural design and construction management.

4. Existing Challenges and Research Needs

Despite extensive engineering application, the design of the bracing system itself remains less mature than excavation-deformation analysis. Failure-mode identification and capacity calculation need to cover member buckling, local yielding, joint shear, anchorage behavior, and interactions among upper chords, web members, ties, and wales. Design procedures should also distinguish in-plane and out-of-plane instability and define effective lengths for built-up members under elastic restraint.

Prestress introduction and retention are another central issue. Steel-strand systems may experience anchorage slip, relaxation, staged construction effects, and temperature-related force variation. Reliable anchorage, measurable prestress transfer, active compensation, and acceptance criteria are needed so that the design force can be maintained throughout excavation and removal.

Hybrid systems require a unified treatment of stiffness coordination. Concrete struts, fish-belly steel bracing, retaining walls, columns, and soil springs interact as a single time-dependent system. Future methods should integrate structural capacity, excavation sequence, spatial layout, soil-structure interaction, and serviceability limits instead of checking each component in isolation.

Finally, the evidence base is still dominated by individual projects and deterministic simulations. Standardized full-scale tests, long-term monitoring, uncertainty analysis, and comparable performance datasets are needed. Digital sensing, model updating, automated optimization, and lifecycle assessment can support safer prestress control, more efficient material use, and higher rates of component reuse.

5. Conclusion and Outlook

Research in China and abroad shows that prestressed fish-belly steel bracing has evolved from a specialized structural support into an integrated solution combining mechanical analysis, deformation control, modular construction, monitoring, and green reuse. Prestressing mobilizes passive soil resistance and increases apparent system stiffness, while the large-span arrangement improves construction access and reduces demolition waste. Field applications have repeatedly demonstrated effective control of retaining-wall movement and ground settlement.

The next stage of development should shift from project-specific verification toward unified, failure-mode-based design. Particular priorities include self-balanced prestressed steel wales, low-slip anchorage and active compensation, rational stiffness matching in hybrid systems, standardized reusable joints and members, and digital monitoring linked to

continuously updated numerical models. These advances would improve the safety, efficiency, economy, and sustainability of underground-space development.

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