Prestressed Concrete Gable Roof Frame and Application of Vacuum Grouting — Heijokyu Izanai-kan —

プレストレストコンクリート山形梁と真空グラウト工法 — 平城宮いざない館 —


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Synopsis

The Nara Palace Site Historical Park, the construction site of this project, is one of Japan's most important historical and cultural assets. It is also designated as a Special Historical Site, and the palace is part of the World Heritage Site known as the "Historic Monuments of Ancient Nara." The buildings to be constructed, the Heijokyu Izanai-kan, are an exhibition hall located on the south side of the Nara Palace Site Historical Park. This exhibition hall consists of a guidance building and an exhibition building.

Fig. 1 Exterior View

The guidance building serves as the base for managing and operating the park and providing comprehensive usage guidance for the park and the entire Nara Palace site. The exhibition building is used for exhibiting artifacts and materials excavated at the Nara Palace site [1] [2] (**Fig. 1**). In 2018, these buildings received the JPCI (Japan Prestressed Concrete Institute) Award for outstanding structures.

Structural Data

Location: 3-5-1, Nijo Oji Minami, Nara City, Japan
Total floor area: 6755.59 m^2
Structure: Special RC moment-resisting frames
Owner: Ministry of Land, Infrastructure, Transport and Tourism, Kinki Regional Development Bureau
Contractee: Ministry of Land, Infrastructure, Transport and Tourism, Kinki Regional Development Bureau, Repair and Maintenance Department
Designer: MHS Planners, Architects & Engineers and Oriental Consultants Co., LTD. Design Joint Venture
Supervisor: Ministry of Land, Infrastructure, Transport and Tourism, Kinki Regional Development Bureau, Kyoto Repair and Maintenance Office and Kawa Architects Co., Ltd.
Contractor: Okumura Corporation

1. Introduction

The shape of the building was determined by the adoption of gable roofs as used for general buildings based on the following two points in consideration of landscape formation:

1) A two-roof plan to make the buildings appear less imposing.
2) Differentiation from the restored facilities, to which an imperial roof has been applied.

2. Design

(1) Structural Design

A representative structural plan and cross section drawings are shown in **Fig. 2**. The plan shape is regular and comprises two gable roofs and a flat roof to make the buildings appear less imposing. The plan is also characterized by deep eaves on the building periphery and set-back walls supporting the flat roof. Based on this plan, the gable side wall was made much less imposing. The plan of the structural frame has been adapted to the shape of the gables and flat roofs.

The frame structure is a moment-resisting frame with a shear wall in the X direction and a moment resisting frame in the Y direction. The spans are 4.4–17.1 m and 6.0–9.0 m in the X and Y directions, respectively. The exhibition space is arranged in the gables and flat moment-resisting frame based on the required ceiling height, and prestressed concrete (PC) beams are applied to provide a flexible exhibition space without columns. In addition, PC beams are also used in the flat moment-resisting frame apart from the exhibition room in the exhibition building.

The plan of the gable roof characterized by deep eaves is adopted for both the guidance and exhibition buildings to differentiate them from the restored facilities with imperial roofs. Because the projecting dimension of the eaves in both buildings is 3.9 m long, cantilever beams are arranged at 2.0-m intervals to enable construction by a general reinforced concrete (RC) structure. In addition, to make the edges of the eaves look as thin as possible, each cantilever is a vertical haunch beam with a depth of 900 mm and 450 mm at its root and ends, respectively. Moreover, the ends of the cantilever beams support cantilever slabs with a thickness of 200 mm through a beam arranged on the edges of the cantilever slabs, and reinforcing ribs with a thickness of 110 mm are arranged on these edges.

The ceiling of the eaves is an exposed concrete slab, and by adopting wood grain foam polystyrene formwork, it was planned to be more economical than formwork with “Honzane” (a wood grained pattern).

Moreover, by injecting extruded foam polystyrene between the eaves slab and the roof slab, it was possible to simultaneously reduce the weight and the construction labor of the formwork. The construction status of the eaves after concrete placement is shown in **Fig. 3**.

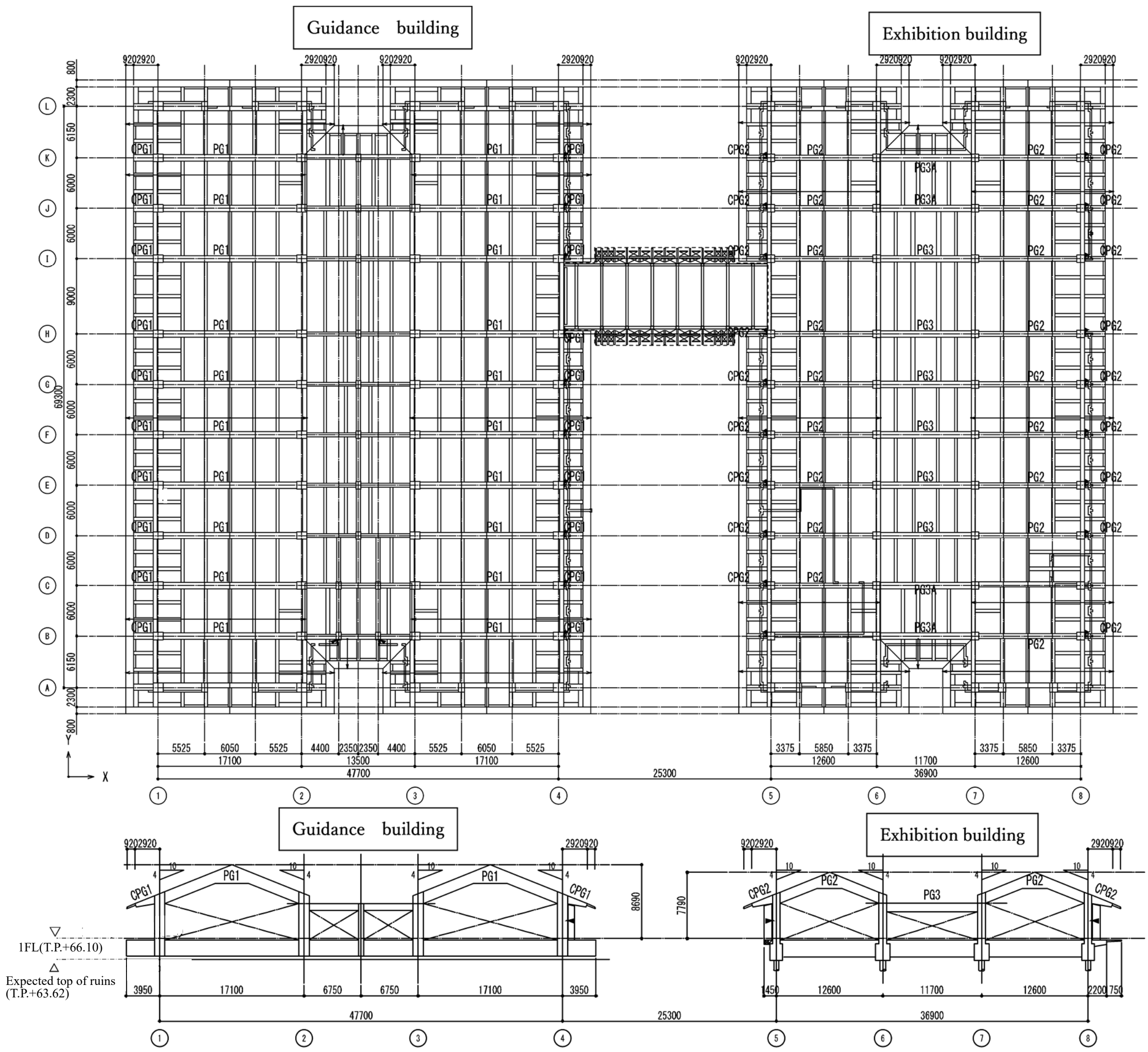

Fig. 2 Representative structural plan and cross section drawings

Fig. 3 Under the eaves (after concrete construction)

Fig. 4 Exterior View

(2) Seismic Design

The load-carrying capacity was calculated, and the seismic safety classification is Class II (the goal is to ensure that the buildings can be used without major repairs after a large earthquake, and to ensure the safety of human life and ensure functionality). In confirming that the load-carrying capacity is more than 1.25 times the required holding strength of the buildings. In general, the buildings have the function of protecting important cultural properties, and in an emergency, they become facilities with high seismic safety as a disaster prevention base.

The main design principles of the PC beams are listed below; **Fig. 4** shows the external view of a representative PC frame.

1) The indeterminate stress due to prestress is taken into consideration as the long-term stress. In the structural calculation for resisting horizontal load assuming a large earthquake, the bending strength of the PC beams was confirmed to have a trilinear restoring force characteristic considering bending cracks.
2) The PC beams were classified as Class II PC (partial prestress) for long-term bending moment, and the cross-sectional edge stress was less than the allowable tensile stress of concrete (a design that does not allow bending cracks).
3) The cantilever length continuing to the mountain-shaped beams is about 3.0 m; they were classified as Class I PC (full prestress: a design that does not allow tensile stress) for long-term bending moment. In an examination for a vertical seismic intensity of 1.0 G, it was confirmed from a safety perspective that the ultimate strength was 2.5 times higher than the long-term stress.

In this project, a mountain-shaped frame was adopted to realize a flexible display space with no intermediate columns and a gable roof design with a maximum span of 17.1 m. The thrust force of the mountain-shaped beams can be rationally processed by adopting a method to reduce the thrust force by using a tie bar such as an external cable system as a horizontal resistance member. In that case, reducing the thrust by using the conventional method of PC beams—which serve as an internal cable system—is effective. In this project, about 30% of the long-term shear force of the columns including thrust was canceled by introducing prestress, and the size of the outer columns of the guidance building could be rationally reduced. The beam size is in principle $b \times D$ = 750 mm × 1300 mm (650 mm × 1200 mm in the exhibition building). The PC steel-stranded wire has two cables of 12–12.7 mm.

By placing the dead anchor in the cantilever on the eaves side, reinforcement in the columns is facilitated, and long-term deformation of the long eaves is taken into consideration. In addition, for the tension end of the top of the beam, partial breakage of the beam cross section is avoided by providing an additional part on the top of the beam and putting it inside.

3. Construction

In this plan, two mountain-shaped special RC moment-resisting frames with PC beams are connected by a flat special RC moment-resisting frame. Therefore, if the latter frame is constructed before prestressing, there is a risk that the deformation would be restrained and an unexpected axial force would act on the beam and slab connecting the two mountain-shaped special RC moment-resisting frames.

Based on this point, in this project, concrete construction of the mountain-shaped special RC moment-resisting frames was carried out first, and after PC tension was applied, concrete construction of the flat special RC moment-resisting frame was carried out (**Fig. 5**).

For tensioning of the mountain-shaped beams, it was planned to simultaneously tension the east and west cables one by one at the same time for the two PC cable strands on the east and west sides near the top (**Fig. 5**). As a result, the prestress could be introduced into the frame with good balance without lowering the tension work efficiency, and the quality of the frame was improved by preventing unexpected distortions and cracks in the frame.

Using the conventional grout injection method in the PC grouting work for these buildings would have risked residual air in the sheath, given that the beams are mountain-shaped with a 40% slope (with a sheath slope of 15%). Thus, as an alternative, high-quality vacuum grouting was adopted, which has a proven track record in civil engineering (e.g., bridge construction work) but is still rarely used in building construction.

In the conventional grout injection method, the grout

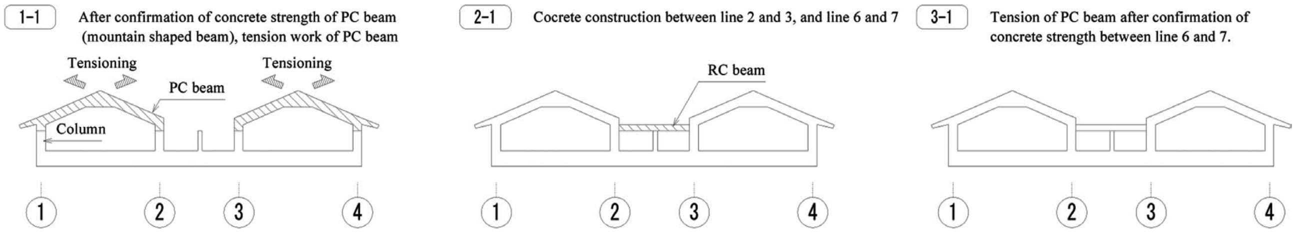

Fig. 5 PC beam tension sequence

material advances while pushing out the air in the sheath because the grout is pressurized and injected from one side. Therefore, it is difficult to eliminate residual air completely, even with an appropriate injection plan.

By contrast, vacuum grouting makes the sheath interior close to a vacuum (pressure reduction of 90% or more) by using a vacuum pump (**Fig. 6**). This makes the air bubbles due to residual air in the grout extremely small. Furthermore, this method offers simultaneous press-in and suction by using an injection pump simultaneously with the vacuum pump, resulting in reduced grout injection pressure and improved construction efficiency. Also, with conventional grouting, the grout would have flowed down the lower side of the sheath, but vacuum grouting eliminates air bubbles by propelling the grout along the PC strands. In addition, the flow of grout along the PC strands makes it possible to fill grout even between the PC strands, which would have been difficult with conventional grouting method.

In the construction using the vacuum grouting method, in addition to the management of normal grouting work, a check list of 14 items was created (e.g., the vacuum state in the sheath, and the grout progress before, during, and after grouting) and then managed visually. This ensured high grout quality with a high degree of filling.

4. Conclusion

This report describes that the procedure for introducing prestress into mountain-shaped PC beams and the grouting using a vacuum pump, which has little track record in building construction. And its quality control was provided. As this plan proceeded, the authors received much guidance from the survey staff of the Kinki Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism. Also, Okumura Co., Ltd., which was in charge of the construction work, contributed to the planning of the construction work, and this work was also supported by many other construction personnel.

Fig. 6 Grouting work using a vacuum pump

References

[1] Nakamura, M., Morita, A., Yamaguchi, J.: *Design and construction of Nara Palace Site exhibition hall in Nara Palace Site Historical Park*, Prestressed Concrete, Vol. 60, No. 4, JPCI, Tokyo, pp. 56–63, July. 2018 (in Japanese).

[2] Morita, A., Kamihama, M.: *Design and Construction of Nara Palace Exhibition Hall in Nara Palace Site Historical Park Prestressed Concrete Gable Roof Frame and Application of Vacuum Grout Method*, PCI Convention 2021 Japan Session, TECH5 Precast and/or Prestressed Concrete Buildings in Japan.

概　要

本建物は奈良県にある「国営平城宮跡歴史公園」に建設された展示場である。国営公園に設ける施設として，景観形成の上では，現代施設と復原施設の差別化を図りながらも，全体として調和の取れた落ち着きのある空間を目指すことが求められた。建物は朱雀大路に面したガイダンス棟と大池に面した展示棟の 2 棟からなり，両棟とも復原施設（入母屋屋根）との差別化を図った軒の深い切妻屋根のデザインを特徴としている。

柱のないフレキシブルな展示空間と，最大スパン17.1 m の切妻屋根のデザインを実現するため，架構形式に山形ラーメンを採用し，山形梁にプレストレストコンクリート構造を採用している。

本建物は JPCI (Japan Prestressed Concrete Institute) Award 2018 作品賞を受賞した。