DESIGN AND PERFORMANCE OF A BASEMENT PALI RADICE CONTIGUOUS MINIPILED RETAINING WALL BENEATH AT THE BERKELEY HOTEL, KNIGHTSBRIDGE, LONDON

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ABSTRACT The Berkeley Hotel extension development is to include the construction of a building up to 11 storeys with four basement levels. The Hotel was constructed in the early 1970s and has two existing basement levels formed using diaphragm walls. The new basement extension is retained on three sides by a secant wall, with the southern face to be supported in the temporary condition by a combination of existing D-wall and a raking Pali Radice contiguous minipiled retaining wall. Top-down construction was adopted with plunge columns supporting the new floor slabs which together with intermediate temporary props provide the reaction for the proposed Pali Radice wall. The contiguous piles had the combined role of underpinning the D-wall and two nearby existing under-reamed piles whilst also providing earth support during the staged excavation/propping sequence. Complex constraints required the use of a 3D finite element model for design. This enabled accurate modelling of the interaction between the D-Wall and under-reamed pile loads, changes in ground and excavation profile against the behaviour of the plunge column supports under the prop reactions. An extensive instrumentation program was carried out to monitor the performance of the deep excavation and the adjacent structures.

1. Introduction

The works at the Berkeley Hotel included the demolition of the existing structure to the east of the existing south wing of the hotel and the redevelopment to provide an 11 storey high building with 4 basement levels. The proposed redevelopment location is shown in Figure 1.

Figure 1 Location of the basement extension

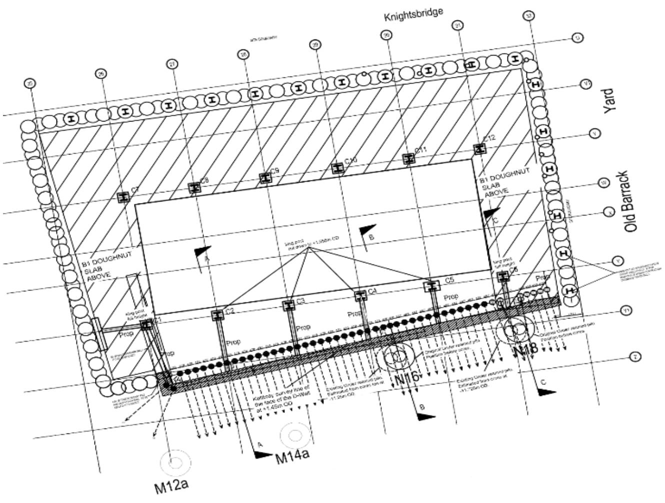
The existing hotel was constructed in 1972 and consists of six storey and two basement levels. The structure is supported by 166 no under-reamed piles transferring the loads into the underlying London Clay Formation (LCF).

The cut-off provision to support the hotel extension deep excavation for the 4 basement levels consists of a piled secant wall along three edges connected with the existing D-wall at one edge.

The length of the D-wall adjacent to the extension boundary is approximately 25lm with a top-of-wall level at around +7.80m OD. Intrusive investigation using coring methods was undertaken at a single location to determine the wall toe level. This indicated the base of the wall to be at -3.70m OD. However, given the method of D-Wall construction, the toe level profile was considered to be a risk area.

The plan footprint of the site is approximately 30m x 20m with the proposed excavation depth being over 20m from existing ground level. In addition, the rest of hotel was to remain fully operational during construction. Due to this constraint, the excavation sequence and relevant temporary works requirements needed to be carefully considered, so the work could be carried out safety, in a cost effectively manner, with minimum disruption to the hotel operation.

Figure 2 Plan of the basement extension



Wentworth House Partnership was appointed as the basement temporary works engineer after the existing building was demolished and piling mat installed.

2. Excavation support proposals

Various options were considered for stabilising the D-wall during excavation and provide earth support below the base of the D-wall.

2.1 Initial proposal for the excavation at tender stage

Secant pile walls with plunged king posts were proposed along three elevations to the north, east and west. However, in order to minimise space loss, it was preferable to consider an alternative method to a secant piled wall solution installed forward of the existing diaphragm wall.

The extension formation level was approximately 6m below the base of the existing D-wall. The original intent was to traditionally underpin and prop this wall during the excavation sequence.

From archive drawings, it was apparent that the structural RC wall from hotel was keyed into the D-walls. The hotel functional area adjacent to these works is a kitchen with extensive services. Hence, the vertical settlement of D-wall would be sensitive. To reduce the risk of unacceptable settlement, a small width of multiple pins would be required. The excavation of the basement would, as a consequence, have been delayed until the underpinning could be completed, significantly delaying the programme.

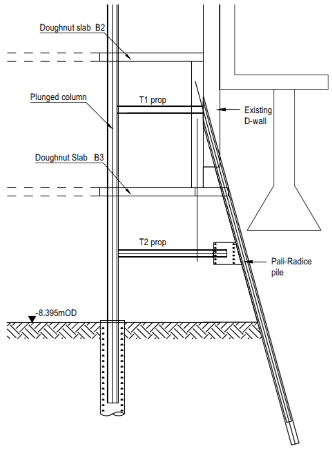
Moreover, there were two existing under-reamed piles adjacent the D-wall. The toe level of these piles was higher than the formation level. The concentrated loads from these piles adjacent to the underpinning presented the additional risk of their settlement.

2.2 Alternative proposal to replace the traditional underpinning

As stated above, conventional underpinning would have a significant impact on the construction programme, cost and risk of excessive settlement. Therefore, at tender stage, WHP engaged with Keller to develop an alternative solution. The aim was to reduce the construction programme and cost, also to minimise the D-wall movement during excavation.

The proposed solution was to install a 12.5° raked Pali Radice wall with a temporary propping system in addition to permanent floor slabs support. The Pali Radice bored through and directly permanently bonded with the existing D-wall would act as a temporary contiguous piled retaining wall and temporarily support the weight of the existing D-wall and the structure above. It was estimated it would take 6 weeks to complete the Pali Radice pile wall installation. The extent of disruption to the other works would be significantly reduced compared to the traditional underpinning option.

Figure 3. Pali-Radice and propping system to support existing D-wall



3. Pali Radice system

Mini-piled structures have been used in a variety of contexts ranging from, underpinning existing structures, strengthening the capacity of existing foundations, slope stabilisation, tunnelling and forming new embedded piling retaining walls in restricted access locations.

It is, however, Dr F. Lizzi of Fondedile Spa who is considered to have introduced the "Pali Radice" (Root Piles) technique in the 1950's. As the name suggests, the system comprises a network of minipiles constructed in the ground to act together as a unified mass of soil and sub-structure.

The Pali Radice system can be installed through and bonded to existing structures and their foundations, providing a connection between the structure and the bearing strata beneath, generally without the need for new pile caps or pile cap extensions.

The underpinning with Pali Radice piles can be considered practically inactive at the time of its construction. i.e. In this case, when the D-wall undergoes a subsequent minimum settlement, the pile will respond immediately absorbing part of the load and reducing at the same time the bearing stress on the ground. The load is therefore shared between the existing toe support and the Pali Radice system in the ratio of their relative stiffnesses.

The small diameter Pali Radice offers various advantages such as the use of specialist compact rotary rigs in restricted access sites, the ability to be constructed in very close proximity to the face of adjacent structures and in sensitive locations where excessive noise and vibration are required to be minimised.

The construction of Pali Radice involves a succession of processes, the most significant of which are drilling, placing the reinforcement and grouting.

The main steel component and the grout are designed to safely support the applied loading and bending moments induced from the structure and the retained soil mass.

Great care should be taken to ensure that the bond surface between the concrete sub-structure and the formed pile is not contaminated with spoil arising's prior to grouting. This is normally achieved by the use of an open-ended temporary drill casing left in place in the temporary condition until the grouting process has terminated.

The pile reinforcement can take the form of a single bar, cage or a circular hollow section depending of the magnitude of the applied design forces.

The site batched, colloidally mixed, sand-cement grout needs to have adequate properties of fluidity strength, stability, and durability. It also protects the steel reinforcement from corrosion.

The Keller mini rigs have the ability to rotary bore through virtually any buried obstructions including timber, remotely reinforced concrete and steel as an integral part of the pile construction process. This uses a temporary open-ended casing with a tungsten carbide tipped cutting crown. This produces a roughen surface in the cored concrete sub-structure providing mechanical bond in addition to contact adhesion.

Diamond drilling techniques are not recommended since they produce a very smooth cut surface which can lead to de-bonding in the event of any nominal grout shrinkage.

4. Ground conditions

The published geology maps showed the site to be underlain by sand and gravel of the Hackney Gravel Member overlaying the London Clay Formation.

This information was supplemented by the soil investigation work undertaken by Concept Consultants between March and November 2007.

The encountered ground conditions are typical for central London, comprising made ground (MG) overlying in turn Langley Silt (LS), River Terrace Deposits (RTD) and London Clay Formation (LCF).

MG is present between 2.5m bgl and 2.8m bgl and typically comprises reinforced concrete, sand and gravel, with subordinate inclusions of brick and concrete fragments.

The LS extend between 8.66m OD and 3.90m OD and comprises soft to stiff sandy clay with interbedded sand and silt.

The RTD extend to -0.8m OD and comprise medium dense to dense, brown, fine to coarse sand and gravel with SPT N values ranging from 15 to 42.

The LCF was encountered beneath the RTD in all boreholes. It is typically described as stiff, becoming very stiff with depth, fissured or extremely closely fissured, silty clay with occasional partings of silt and fine sand, and occasional pockets of pyrite nodules. A small number of claystone bands were encountered, which were penetrated with a chisel. Undrained Triaxial test results within the LCF c_u values between 96kPa and 359kPa.

5. Construction sequence and design

A 340mm diameter temporary casing, installed in one metre male/female threaded sections was extended down from piling platform level generally at 12.5° from the vertical and sealed off into the face of the RC D-wall. A further 280mm diameter temporary casing, with direct circulation water flush, was then used to core through the D-Wall to its underside, sealed off into the underlying London clay and left in place in the temporary condition. A 235mm diameter casing was then dry augered into the London Clay to the required pile toe level. For the underpinning of the existing under-reamed piles N16 and N18 the 280mm diameter casing was reamed down and extended to core through the under-reamed pile section with the 235mm augered clay socket then extended below to the design toe level.

With reference to Figure 4 the sequence of the works comprised the following stages:

1. Install plunged columns together with bearing piles at piling plat form level (Street level)
2. Excavate to underside of B1 slab level at and cast B1 slab
3. Excavate to underside of B2 slab level at +1.155m OD.
4. Install Guide wall for Pali-Radice piles and cast part of B2 doughnut slab along the north
5. Install Pali-Radice piles from 1.455m OD.
6. Complete doughnut B2 slab.
7. Excavate to -0.9 m OD.
8. Construct liner wall between B1 and B2
9. Install temporary props T1 at -0.8m OD and monitoring points on the steel walling beam.
10. Excavate to underside of B3 slab level at -3.745 m OD, local excavation along D-wall to -4.2m OD to clean the toe of D-wall.
11. Cast doughnut B3 slab, B2-B3 liner wall and infill between liner wall and Pali-Radice wall. Install monitoring points on B3 level
12. Excavate to - 6.0m OD
13. Install prop and RC waling at -5.77m OD. Install ties between RC waling and liner wall.
14. Excavate to final formation level -8.395m OD. Local excavation to core area.
15. Cast B4 slab, B3-B4 liner wall and infill between liner wall and Pali-Radice contig wall.

Initially, two-dimensional calculations were performed for the geotechnical design of the Pali Radice wall using the commercial software WALLAP. Given the complex geometry of the problem with a non-vertical piles, interaction with the existing basement, presence of under-reamed piles in close proximity to the wall, non-symmetry of the excavation a simple and local deeper excavations WALLAP model analyses was considered too simple and not sufficient to account for these features.

Keller commissioned A Squared Studio to undertake a 3D FEA to carry out using the Plaxis 3D software. The resistance to bending, shear and compression for the reinforced pile section was estimated in accordance with BS EN 1994 “Design of composite steel and concrete structures”.

The Pali Radice were reinforced with a 177.8mm OD x 11.5mm thick CHS section min grade 550 N/mm^2 and a full depth 25mm central bar.

The bond resistance between the pile and the D-wall was calculated in accordance with BS EN 1992-1-1:2004, “Design of concrete structures”.

6 Soil-structure interaction study

6.1 Finite element analysis

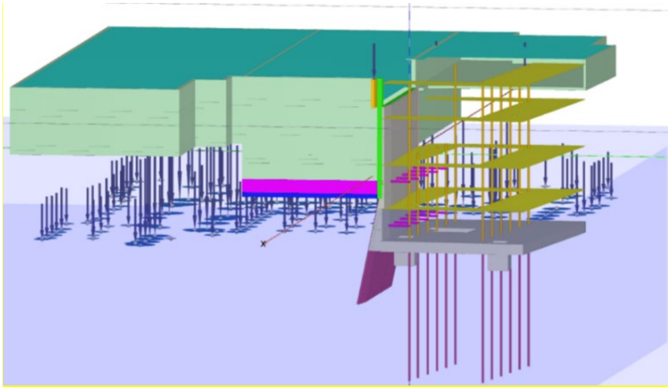
A 3D finite element model was developed to capture the staged construction of the proposed basement substructure and underpinning, with a view to incorporate the complex constraints and assess:

- SLS and ULS-DA1 C1 and C2 propping forces. Partial factors were applied to the soil shear strength characteristic parameters or the C2 analysis.
- ground and pile displacements
- structural forces acting on the Pali Radice
- factor of safety on global stability.

6.2 Finite element model

The finite element model was developed using the commercially available software, Plaxis 3D (2017). The model domain has dimensions of 150m long by 140m wide. The ground surface was modelled at +11.0m OD. The base of the domain was taken at -40.0m OD.

Figure 4 Model at B4 excavation stage



The model was composed of 369,000, ten-node, tetrahedral volume elements 4. Each node has three degrees of freedom. The mesh was refined in the vicinity of the proposed basement development and existing structure.

6.3 Constitutive models

The ground was modelled assuming the Mohr-Coulomb criterion.

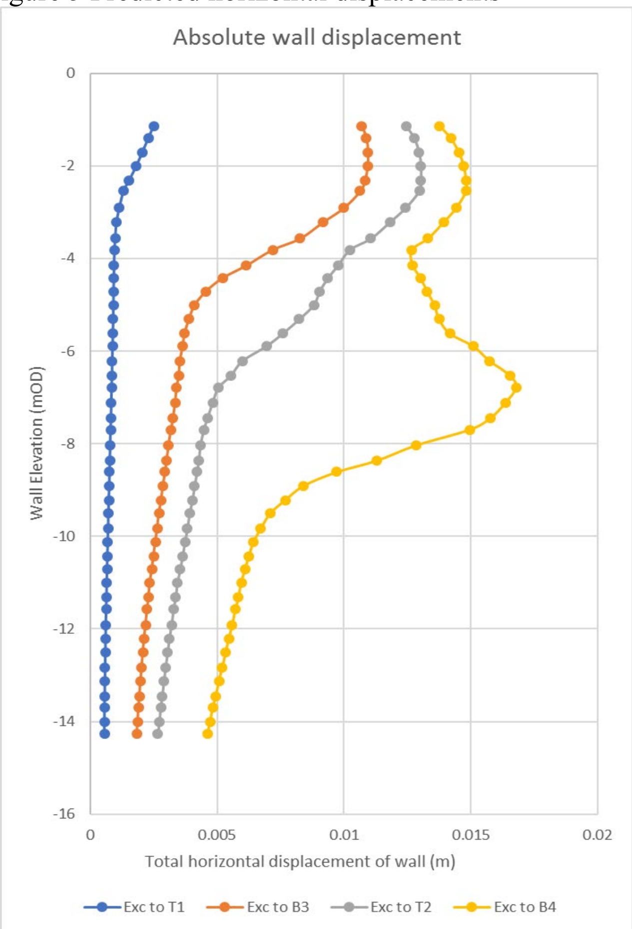
The under reamed foundations that support the existing Berkeley Hotel structure were modelled simplistically. A stiff circular plate element founded at depth was used to represent the under ream base. The assumed under ream pile foundation working load was then applied as a force directly to the plate element.

The Pali Radice underpins were modelled as embedded beam elements and were “wished in place”, with the installation movement effects not modelled. The existing diaphragm wall was modelled using volume elements assigned with a linear elastic constitutive model. The secant piles were modelled with 2D plate elements with an anisotropic elastic constitutive model. The plunge columns were modelled using beam elements. The donut slabs were modelled using linear elastic, isotropic, 2D plate elements. Temporary steel props and waling beams were modelled using one-dimensional beam elements. A linear elastic constitutive model was assigned to the elements for the analysis.

6.4 Prediction and results

Figure 5 presents the predicted envelopes representing a profile of maximum horizontal displacement that are calculated following the completion of the Pali Radice installation.

Figure 5 Predicted horizontal displacements



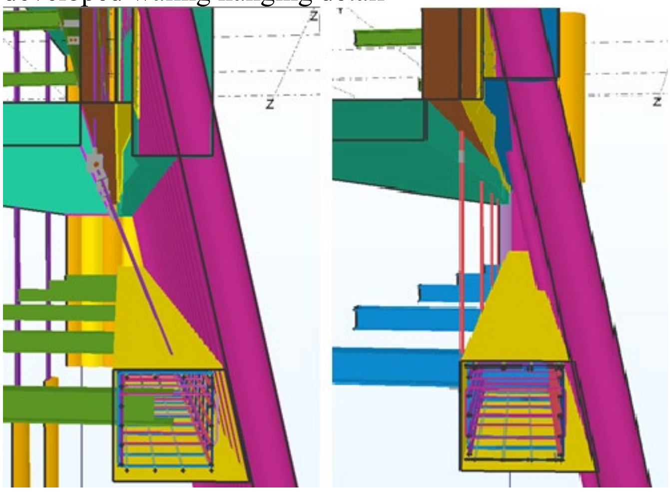
7 Temporary works technical challenges of the scheme

The alternative method of forming the excavation presented new challenges which needed to be addressed. These are discussed below.

7.1 Support to the self-weight of T2 RC waling and vertical component of propping load

Due to the top down construction sequence, the concrete waling could not be supported at bottom and it needed to be supported by hangers. The waling level was directly under the D-wall and cast against the Pali-Radice wall, so the initial proposals were to attach the waling to the D-wall or resin dowels to the underside of D-wall and extend inclined dowels into waling as shown in Figure 6(a). Through the design development this was developed into whereby the temporary props were suspended from the cast lining wall as shown in Figure 6(b). The vertical load (weight) from the waling was carried by temporary props in cantilever. This slightly increased the size of the props due to combined bending and axial loads but resulted in an efficient form of construction.

Figures 6(a) Original waling hanging details and 6(b) developed waling hanging detail



7.2 D-wall toe level differing from survey

Due to the site constraints it was only possible to carry out one concrete core drill investigation on the D-wall. The core indicated that the toe level to be at approximately at -3.7m OD.

For the check of the required bond length between the Pali Radice and D-wall the toe of the D-wall was set at -2.75m OD. During the pile installation, the piling logs show the toe level of D-wall to be varying but generally at a level of approximate -3.0m OD. After installation of Pali-Radice piles, excavation continued with the B2 slab, T1 prop and liner wall between B2 and T1 prop being constructed. As the excavation progressed and the D-wall toe was exposed the as-built toe level was found to vary between -2.2m OD and -3.3m OD. This necessitated a D-Wall to Pali-Radice pile bonded check for the most onerous condition. The outcome of this assessment indicated adequate bond was maintained as Keller had used high factors of safety in respect of the bonded connection at design stage due to the uncertainty of the D-wall toe level.

Figure 7 Variability of the D-wall toe level

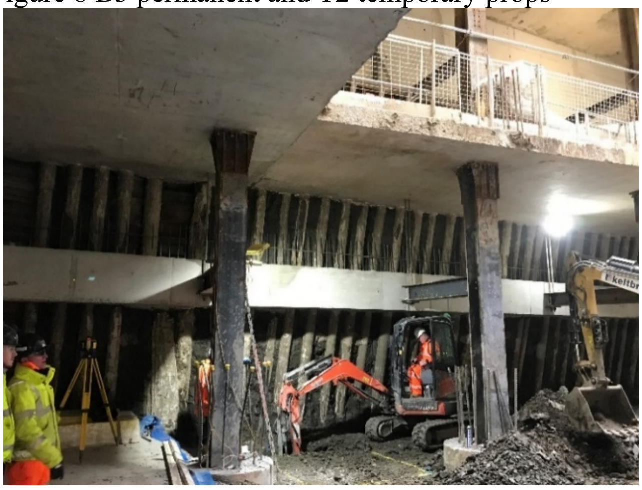
8. Basement construction and monitoring

The installation of Pile Radice wall commenced in May 2019 after the excavation reached the pile installation level and it took roughly 1.5 months to complete. Excavation below the Pile Radice installation level started after the Pali Radice were installed and the design grout strength was achieved.

After the installation of the Pali Radice piles the B2 slab was constructed. Then, soil excavation, construction of underground slabs and temporary horizontal struts were conducted alternatively using top-down method. Field monitoring are necessary to provide a means by which geotechnical and structural engineers can verify the design assumptions and the contractors can execute the work both safely and economically.

To monitor the performance of the excavation and the effects of the excavation on the surrounding structures, a variety instrumentation was installed across the construction site.

Figure 8 B3 permanent and T2 temporary props



Inclinometer tubes were installed in the diaphragm walls to measure the lateral displacement of the secant wall.

Displacement survey points were installed to monitor the displacement of the party walls and existing hotel building, adjacent buildings and the LUL line running along Knightsbridge.

The Pali Radice Contiguous wall survey points were installed during excavation stage to monitor the displacement of the wall at the temporary prop levels T1 and T2 and at B3 slab level.

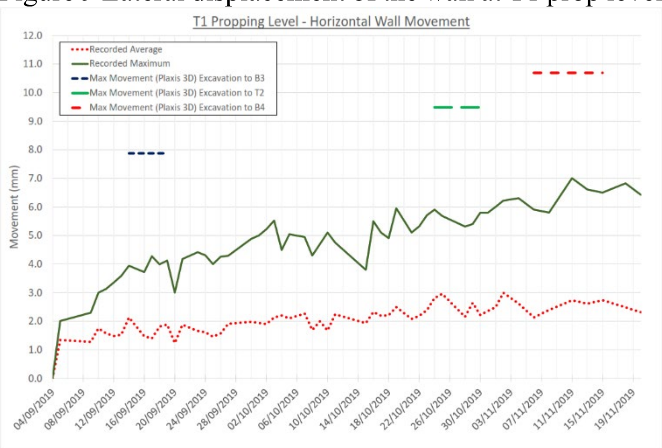
9. Lateral displacement of the Pali Radice wall

Figure 9 presents the maximum and average horizontal contiguous wall displacement measured at T1, B3 and T2 levels from when the survey points were installed and the maximum horizontal movement derived from the numerical analysis.

To permit a meaningful lateral wall movements comparison between FEA and the actual recorded movements it was necessary to artificially reset the numerical predicted movements at each stage of excavation. This is because Plaxis lateral wall movement were calculated following the completion of the Pali Radice installation while the wall movement was recorded starting from Level T1 excavation.

It can be seen from Figure 9 that the lateral general trend displacement at T1 propping level slowly increases as the excavation proceeded. Generally speaking, the measured wall deflection is contained between 2mm and 7mm for maximum and between 1.2mm and 3mm for the average. The maximum lateral displacement of wall was measured in survey point T1.2. At T1 prop level the ratio between the maximum and the lateral displacement of contiguous wall and the excavated depth calculated from T1 was only 0.092% indicating that a high lateral support stiffness have been provided to the wall.

Figure 9 Lateral displacement of the wall at T1 prop level



St John et al (1992) indicates maximum horizontal wall deflection to be typically 0.15% of the maximum excavation depth for top down construction with high support stiffness. It can be seen that data points of this project fall below the 0.15%. This shows that deformation control in this project was very successful.

The lateral movement derived from the numerical analysis follows the same trend of the measured movement. The higher deflection values derived from the numerical analysis are mainly due to the use of characteristic (moderately conservative) soil parameters in the 3D model.

10. Conclusions

This paper has provided a detailed description of the design, construction and successful performance of the Pali Radice wall system during excavation at the Berkeley Hotel, Knightsbridge, London.

The project has also provided the opportunity to solve technically challenging problems and retain substantial wall heights where the more conventional alternatives have been ruled out. The information provided in this paper can be used as a reference for similar deep excavations.

The benefit to the main works contractor can be measured in terms of immediate cost saving, reduction of the construction programme and maximization of the basement area.

11. Acknowledgements

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12. References

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