Heathrow Express Cofferdam: Innovation & Delivery Through the Single-Team Approach – Part 1: Design & Construction

Partnering, value and risk management, and technical innovation rescued this project from substantial delay and cost overruns following a major setback during construction.

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The Heathrow Express (HEX) Rail Link is an important new connection between Central London and Heathrow Airport. It provides a frequent, direct service between the airport terminals and London's Paddington Station with a journey time of fifteen minutes (see Figure 1). The line runs 19 kilometers along existing track before branching off for an additional 6 kilometers below ground to the Central Terminal Area (CTA). It required major underground construction at Heathrow Airport. These works suffered a major setback following the collapse of the tunnels in the CTA.

Tunneling work began at the mainline end near the M4 Motorway in December 1993, building 600 meters of cut and cover between the main rail line and M4, followed by the start of the main bored tunnel in August 1994. The original target date for the opening of the Heathrow Express was December 1, 1997, some 40 months later. The bored tunneling route south of the M4 included 3 kilometers of running tunnels to the CTA, a series of station caverns underneath the CTA and a further

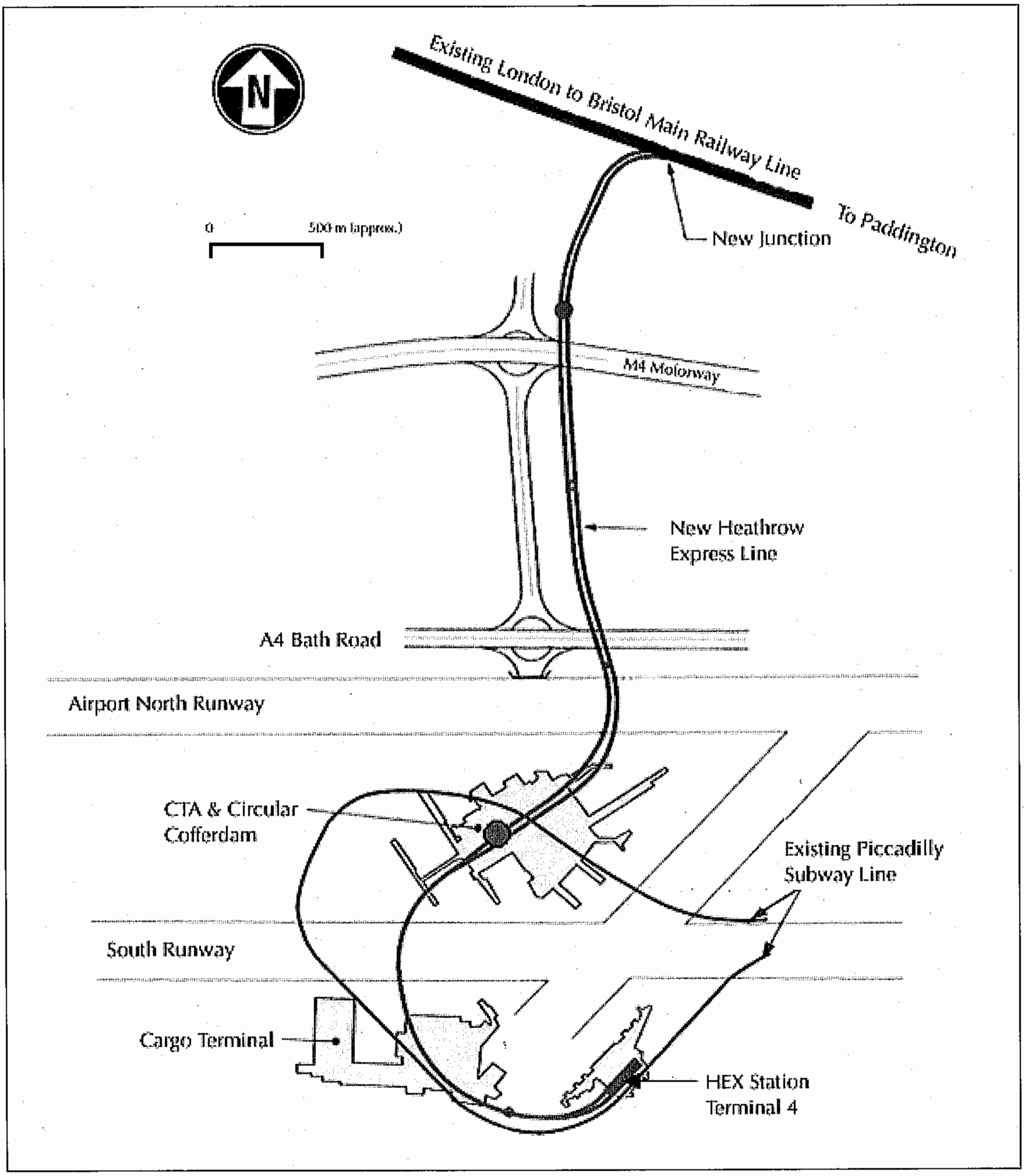

FIGURE 1. The location of Heathrow Express at the airport.

length of running tunnel from the CTA to Terminal 4, which has a smaller station area. The collapse occurred when the station tunnels below the CTA gave way in October 1994.[1] Figure 2 shows the progress of construction as of the collapse. The primary linings for these large-diameter platform and concourse tunnels were sprayed concrete linings (SCLs). Tunnel invert was at a depth of around 30 meters below ground surface. Fortunately, there were no injuries or loss of life; however, substantial damage to the works and some adjacent structures occurred. At this stage, potential delay to the project resulting from the collapse was estimated to be about eighteen months. The need to safely

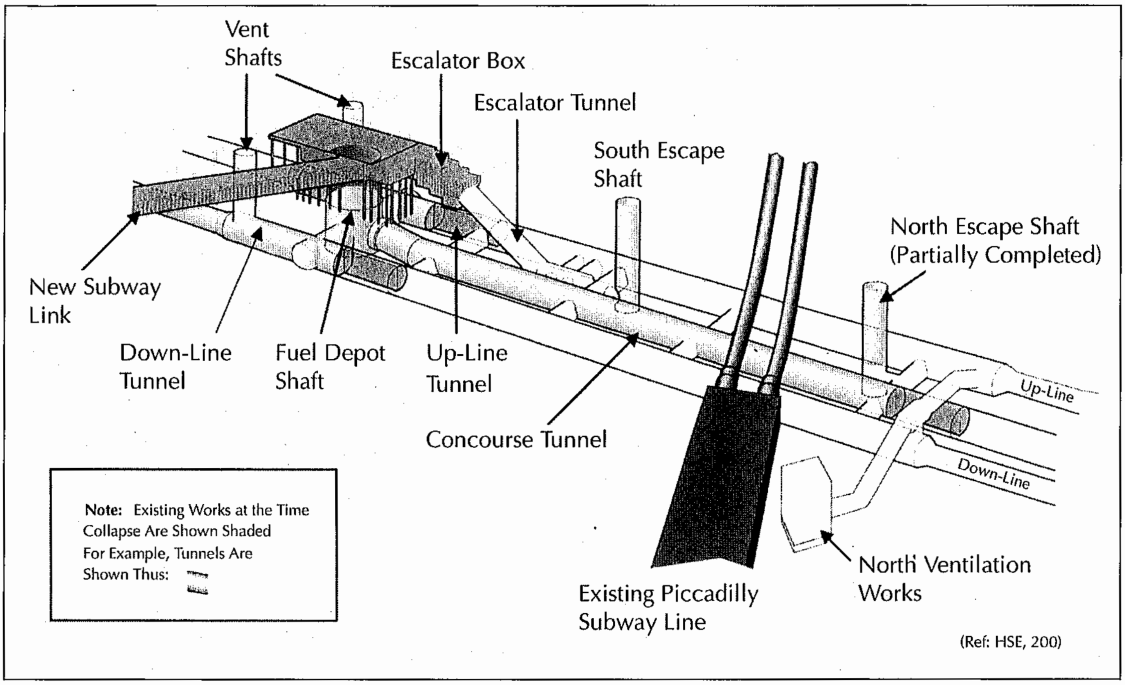

FIGURE 2. Progress of the work at the CTA Station in October 1994.

repair the damaged works and reconnect the tunnels with minimal impact on the opening date was fundamental to the recovery plan. The CTA cofferdam was the key element in this strategy and its successful completion allowed the line to be opened on May 25, 1998, only six months late overall.[2] The total project cost for the HEX Rail Link as a whole was £450 million ($760 million). An important early decision in the recovery strategy was the formation of a Solutions Team. The owner developed a single-team approach to the project's management and the formation of this team naturally flowed from that. The Solutions Team members were selected from the main stake-holders of the project: the owner, main contractor, lead designer and the loss adjusters (who also included their consultant on the team).

Contractual Conditions

The New Engineering Contract (NEC) for the tunneling project was specifically adopted by the owner to facilitate a less confrontational approach to construction.[3] The NEC emphasizes the principles of trust and cooperation within a contractual framework. In a recent article, Sir Michael Latham sought enhanced performance in a healthier U.K. construction industry through teamwork and undertaking projects "in a spirit of mutual trust and co-operation, and trading fairly and nurturing the supply chain."[4] This philosophy has been adopted by the Construction Task Force and set forth in a recent report.[5] This task force, chaired by Sir John Egan, provided the stimulus for the recent initiatives of the Construction Best Practice Program and Movement for Innovation. The key emphasis on teamwork and creating a "win-win" approach has also led to the process of partnering:

> "Partnering has emerged in a number of forms, partly to reverse the suicidal fall into institutionalized conflict with appalling relationships between contracting parties in the construction industry, and more recently as a means of securing more work by creating a competitive advantage."[6]

The Construction Task Force's report, "Rethinking Construction," emphasizes the need to measure performance. Teamwork and

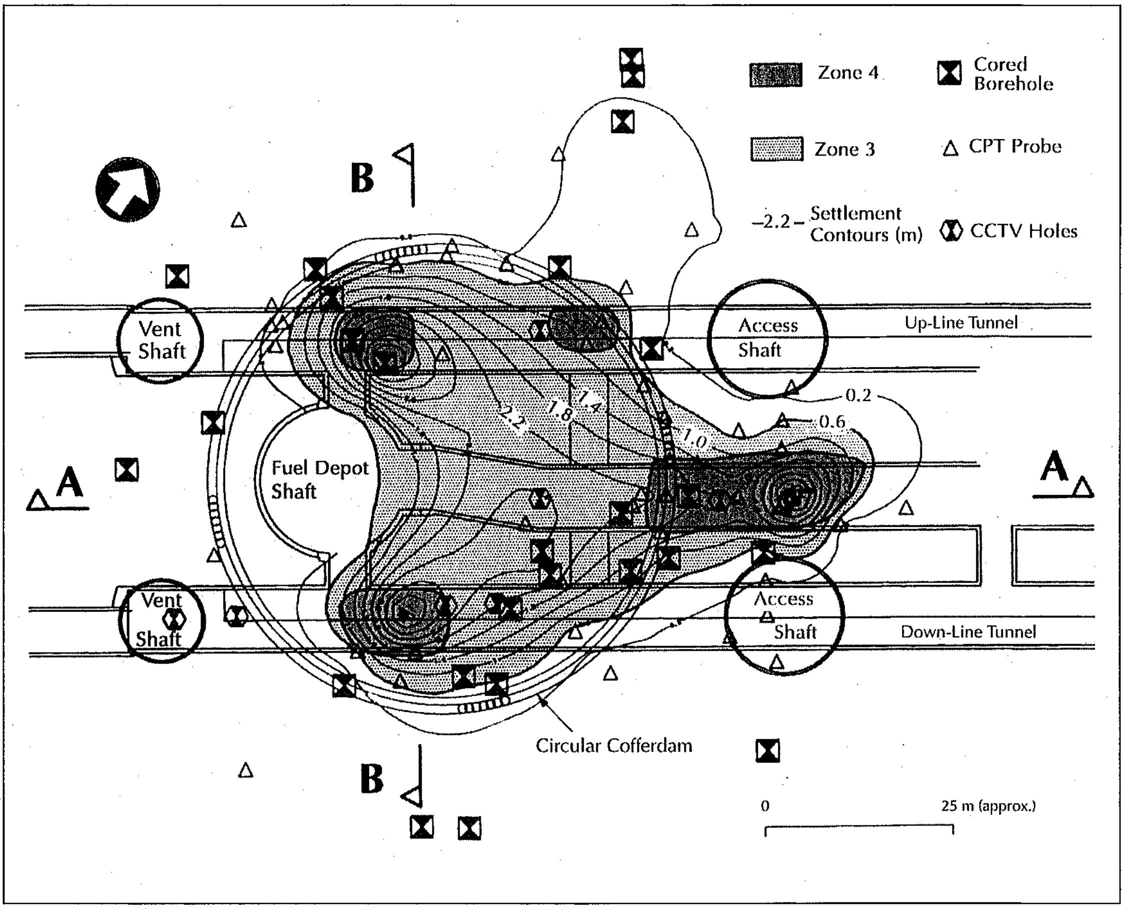

FIGURE 3. Settlement contours of London Clay with predicted zones of disturbance for the circular cofferdam option.

good communication are key factors for improved and innovative construction industry practices. Below-surface work has always presented particular challenges and risks. Improved management of such risks leads to better overall performance and enhanced business opportunities. There is a strong link between innovation and improved business performance and the HEX cofferdam has been evaluated against the Egan performance targets.[2] These targets are to reduce capital cost and construction time by 10 percent, increase the predictability of outcomes by 20 percent, reduce defects and accidents by 20 percent and increase productivity, turnover and profits by 10 percent. The HEX cofferdam achieved positive results in all of these categories. For example, the predictability of the performance and delivery of the cofferdam was developed through the robustness and simplicity of the overall design concept that was further enhanced during construction through the application of the observational method.[7,8]

Site Investigation

A site investigation to evaluate the changed conditions was initiated very soon after the collapse. The ground conditions in the CTA, prior to collapse, were relatively uniform, with approximately 6 meters of Terrace Gravels overlying the London Clay (which has a thickness of around 60 meters at this location). The London Clay overlies the Lambeth Group, which generally consists of heavily over-consolidated clays and sands. This layer, in turn, overlies the Chalk (which is present at a depth of approximately 90 meters below ground level).

The recovery strategy required early establishment of a ground model. This effort involved an iterative approach and, as new information became available, it enabled the development and the refinement of the model. Original ground horizon levels were carefully assessed and compared with those after the failure. The focus was the top of the London Clay that had originally been about 6 meters below the ground surface. The new ground horizon levels were mainly assessed from a series of shallow boreholes. A series of deep boreholes was also drilled to assess the condition in and adjacent to the collapsed tunnels. Detailed core logging was used, with emphasis placed on visual descriptions. Investigation and design development were proceeding in parallel and it was important not to create unnecessary delay with a prolonged program of laboratory testing.

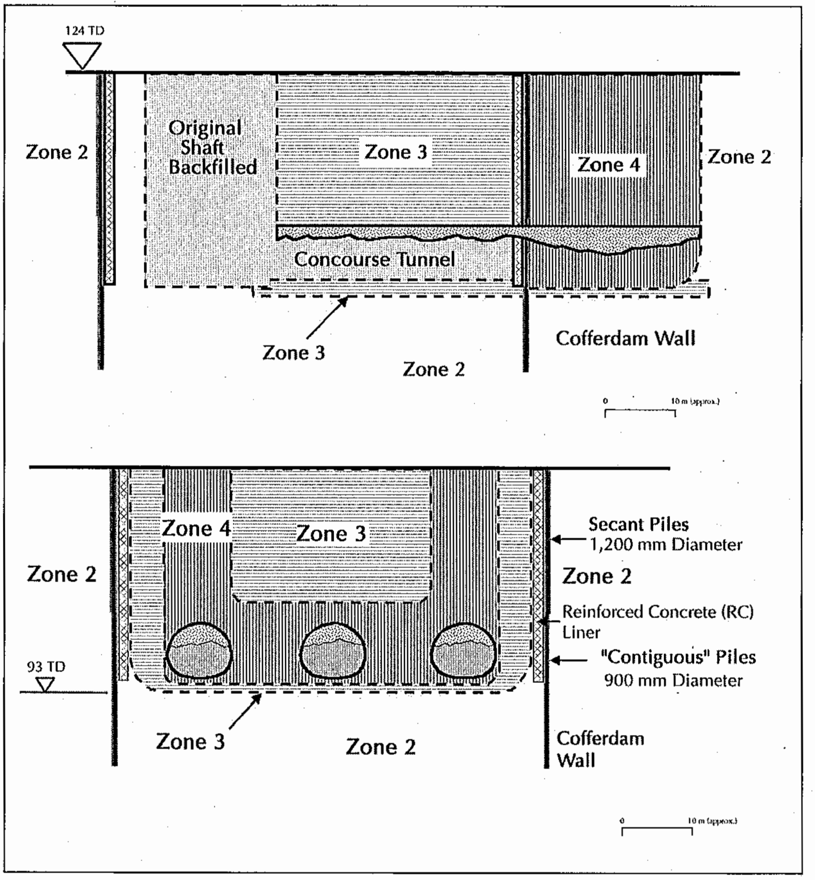

FIGURE 4. Cross-sections showing predicted zones of disturbance.

Two sets of data (pre- and post collapse) for the top of the London Clay were collated. To achieve the best estimate of the contours for these two London Clay horizons, the data were statistically evaluated through an interpolation process known as *kriging*.[9] The differences between the two kriged surfaces were plotted as contours of settlement as a result of the collapse (see Figure 3).

This process revealed that there were four localized areas of highly disturbed ground. In view of the large collapsed volume (approximately 6,000 cubic meters) and the subsequent amount of excavation required, it was considered that there would likely be significant time-dependent softening initiated as a result of the collapse. The excavation of the cofferdam would also create a further reduction in stresses leading to a prediction for soil strengths much lower than for typical conditions in London Clay.

On the basis of the site investigation and predictive numerical analysis, four zones were assigned within the London Clay (see Figures 3 and 4). Zone 1 was undisturbed, intact London Clay that was considered to lie beyond the active wedge of soil on the outside of the cofferdam. So the performance of the cofferdam would be principally influenced by Zones 2 through 4. Each of these zones were assigned two sets of bounding soil properties. The first represented "moderately conservative" (MC) parameters for the mass behavior of that zone on the cofferdam as a whole. The subsidiary set was assigned "worst credible"

TABLE 1.
London Clay Soil Parameters at the Heathrow Cofferdam Site

		Zone 2		Zone 3		Zone 4	
	Level	**MC**	**WC**	**MC**	**WC**	**MC**	**WC**
cu (kPa)	118-108 mTD	50 + 7 d	30 + 7 d	30 + 7 d	0 + 7 d	0 + 7 d	10 +1.5 d
	108-93 mTD	105 + 3.5 d	85 + 3.5 d	85 + 3.5 d	55 + 3.5 d	55 + 3.5 d	(=0.25 σ'_v)
γ_B (kPa)		19.5	19.5	19.5	19	19	16
Ø′ (°)		25	25	25	25	25	21
c′ (kPa)		10	5	5	0	0	0
Strain (%)		<0.1	0.2	0.2	0.5	1	N/A
Eu/cu		700	500	500	350	150	150
k_h (m/sec)		(1×10^{-8} to 1×10^{-10})		(1×10^{-7} to 1×10^{-9})		(1×10^{-3} to 1×10^{-7})	
k_v (m/sec)		$k_h \times 10^{-1}$		$k_h \times 10^{-1}$		$k_h \times 1$	
k_o (l)		1.0	0.8	0.8	0.6	0.6	0.6

Notes: TD = Tunnel Datum (= ordnance datum + 100 m); d = Depth Below Ground Level; MC = Moderately Conservative; WC = Worst Credible; mTD = meters TD; Zone 4 extends to +95 TD; Zone 3 extends to +93 TD; below +93 TD Zone 2 MC should be used.

(WC) values, representing local influences that might occur where pockets of the most severely disturbed soil in that zone could result in adverse loadings on the cofferdam ring. These properties are summarized in Table 1.

Basis of Solution

Early brainstorming workshops by the Solutions Team produced a wide range of schemes (including micro-tunneling and jacked tunnels), but the team quickly came to the conclusion that a large cofferdam should be a key feature of the recovery solution. The use of a cofferdam fulfilled the basic requirement of encompassing most of the disturbed ground and the majority of the damaged subsurface structures. These structures included reinforced concrete piled surface slabs and the escalator box, the original 20-meter-diameter 30-meter-deep fuel depot shaft and three partially constructed large-diameter SCL platform and concourse tunnels. The shaft and tunnels had been filled with around 13,000 cubic meters of concrete as an emergency measure for the short-term stabilization of the collapse. There was clearly a need for a robust design for the cofferdam that would have to be built in highly disturbed ground. A range of configurations for the cofferdam were considered, including a 65-meter square (see Figure 5). Initial options favored a top-down construction sequence based on this square configuration or various arrangements of rectangular plan layouts. However, the top-down construction method posed the following major disadvantages:

- It required early decisions to be made for the layout of the final internal structure and the associated design. These decisions applied particularly to the floor layout and levels as well as internal columns and piles. Being on the critical path for design development and approval, these design requirements risked delaying the project substantially.
- Although any permanent slabs might have been able to provide a measure of temporary lateral support during construction, a substantial amount of additional temporary strutting would still likely be needed.

- A prime reason for such a large cofferdam was to enable safe access and removal of major obstructions. Top-down construction could severely inhibit such access. The presence of major obstructions throughout the 30-meter depth would conflict with the construction of the permanent lateral supporting slabs.

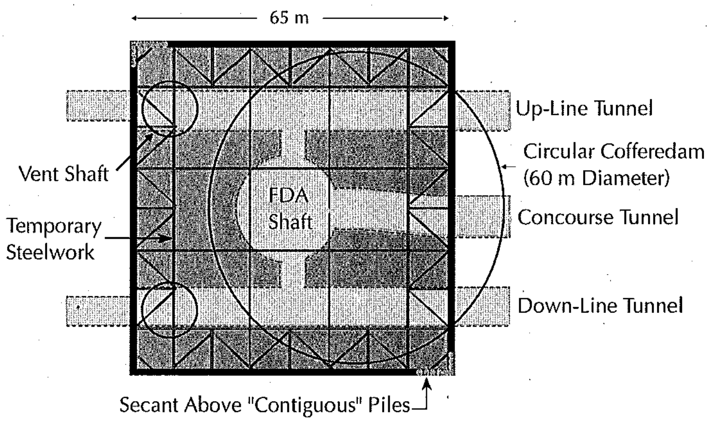

FIGURE 5. Square cofferdam option (not implemented).

Although top-down construction is often the preferred method for large excavations in urban environments, it was rejected here in favor of a bottom-up sequence for those reasons. However, with a rectilinear shape, bottom-up construction would maximize the amount of temporary strutting required. For example, the amount of structural steelwork estimated for the 65-meter square cofferdam was about 5,500 tons. Apart from the cost and project implications, this steelwork would also present significant restrictions to access and working space. Ongoing concept development therefore concentrated on ways to reduce the need for such strutting. The type of construction for the outer wall of the cofferdam needed to be decided early in the concept development since the whole process for project progress demanded close integration of the design with construction methods.

Circular Cofferdam

In December 1994, a circular cofferdam was selected as the preferred option. At 60 meters in diameter and 30 meters deep, it offered a dramatically simple solution. Larger circular cofferdams had been constructed, but not in such disturbed and variable ground conditions or utilizing a bored piled wall (see Figure 6).[10] The circular cofferdam brought the following major advantages:

- It completely eliminated the need for temporary cross strutting, thus maximizing available space for construction operations.
- It minimized the total volume of the excavation because it was possible to arrange the two permanent ventilation shafts to the south close but external to the cofferdam rather than being contained within a rectangular arrangement. Since these two shafts were in the relatively undisturbed Zone 2, the circular cofferdam still encompassed the majority of the disturbed ground, including most of the areas of greatest settlement.
- In comparison with the square cofferdam option, about 20,000 cubic meters less bulk excavation was required. Apart from major cost savings, this reduction afforded important environmental and program benefits, particularly since construction in the center of a busy airport could significantly affect airport operations. The ground was also likely to have been contaminated with aviation fuel that had been stored in this location. Since expensive bioremediation would be needed to deal with the contaminated soil, less excavation would save time and money.
- The symmetry of the solution allowed a uniformly progressive step-by-step sequence of construction for the cycles of excavation and the casting of the inner reinforced concrete liner supporting the piles. This rhythm and symmetry greatly facilitated the progressive monitoring of ground and structural movements so that

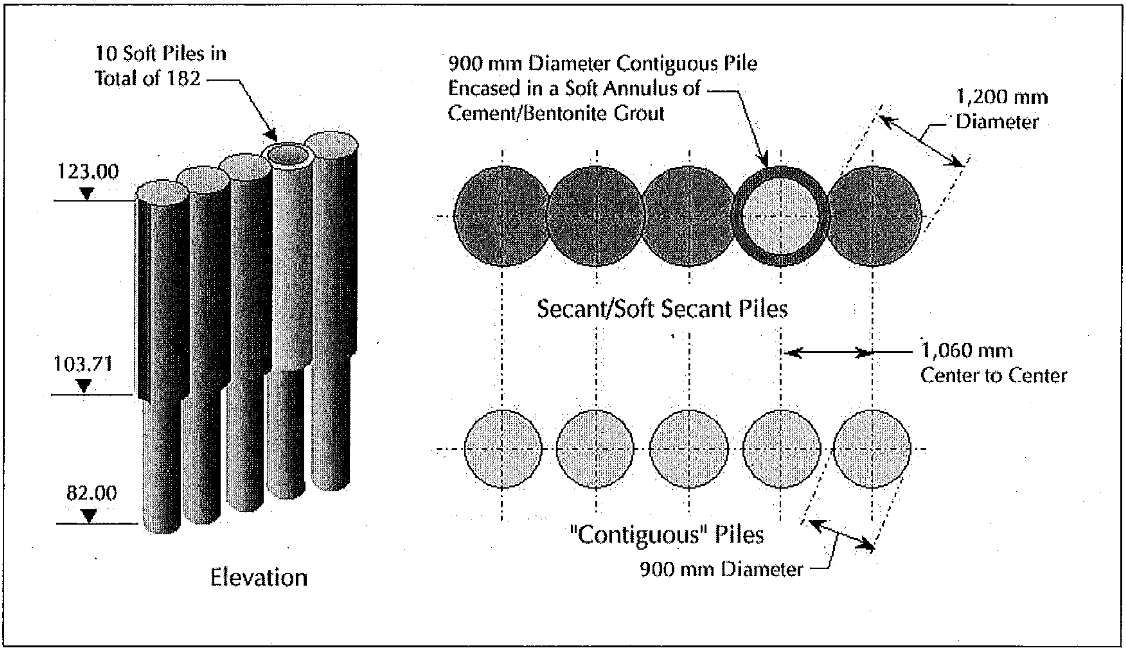

FIGURE 6. Views of the secant and "contiguous" piles.

the associated trends and, in particular, any adverse ones could be detected at an early stage. This latter aspect was also highly compatible with the application of the observational method that was part of the overall risk management strategy for the construction of the cofferdam and central to the realization of further potential cost and time savings.

The circular cofferdam utilized 182 large-diameter stepped secant/contiguous piles for the outer wall and 255 large-diameter bored piles for the base slab. The design and construction had to deal with disturbed and unstable ground (including gravel beds and London Clay), water-filled voids and major subsurface obstructions. There were also severe space limitations and environmental issues to address. Obstructions to piling and excavation included mass and reinforced concrete (near the surface and in the original access shaft and tunnels at depth) and large items of a buried construction plant.

Piled Wall Construction

The site conditions created particular requirements for the construction methods that would have to be used. A fundamental aspect of the cofferdam was the design and construction of the outer wall. Diaphragm (or slurry) walls are typically adopted for this type of construction but the combination of heavy obstructions (see Figure 7) and potentially extensive voids were critical in eliminating this form of wall with its dependence on bentonite slurry support for panel excavation. However, a primary consideration was the need to provide a good cut-off to the groundwater in the Terrace Gravels above the London Clay, particularly in view of its potential contamination. Therefore, groundwater inflow had to be controlled along with the need to fully retain any loose, disturbed ground caused by the collapse. The outer wall also needed to be reasonably stiff and robust. Large-diameter piles secanted to an appropriate depth offered the potential to satisfy all the criteria. Secant piles were therefore adopted as the basis for the development of the wall design. Depth, diameter, spacing and construction tolerances then needed careful consideration in conjunction with construction methods and sequences.

Given the challenges presented by the disturbed ground and obstructions that (apart from reinforced concrete structures) included

FIGURE 7. Piling obstruction from construction machinery buried in the concourse tunnel.

large items of a buried construction plant entombed in mass concrete, emphasis was placed on keeping the bored piling plant reasonably within its operating range. Thus, the team decided to utilize 1,200-millimeter-diameter secant piles for the top 20 meters that stepped in to continue as 900-millimeter-diameter "contiguous" piles for the next 20 meters (see Figure 6). (In practice, the term "contiguous" piles is something of a misnomer since they generally do not touch each other because of necessary construction tolerances and the use of temporary liners. The so-called "contiguous" piles in the lower half of the cofferdam were even further apart because of the step change in diameter from the secanted section above — these stepped piles being at nominal centers of 1,060 millimeters.) Both primary and secondary piles were reinforced generally with bar reinforcement except above the tunnels where structural steel sections were used. It is essential to relate design to construction and this approach was particularly relevant to the piled wall where considerable interactive effort and support was provided to the team by the piling subcontractor. The piles were installed using an oscillator and casing through an accurately constructed reinforced concrete guide wall. The specified minimum vertical tolerance for these piles of 1 in 150 was satisfied and was generally achieved close to 1 in 200.

The principal function of the secant piles was to provide a barrier to groundwater and continuous support to any zones of weakened soil. At a depth of 20 meters, the secant piles would reach the original level of the crown of the tunnels. The vast majority of the disturbed ground would be encountered over this depth and the secant piles would thus form an effective barrier. It was accepted that some limited zones of ground treatment would be necessary to complete this cut-off. Pre-treatment of the ground prior to piling focused on the highly disturbed zones above and around the collapsed tunnels. A program of permeation and grouting was initiated to infill any remaining voids in these zones and to minimize the risks

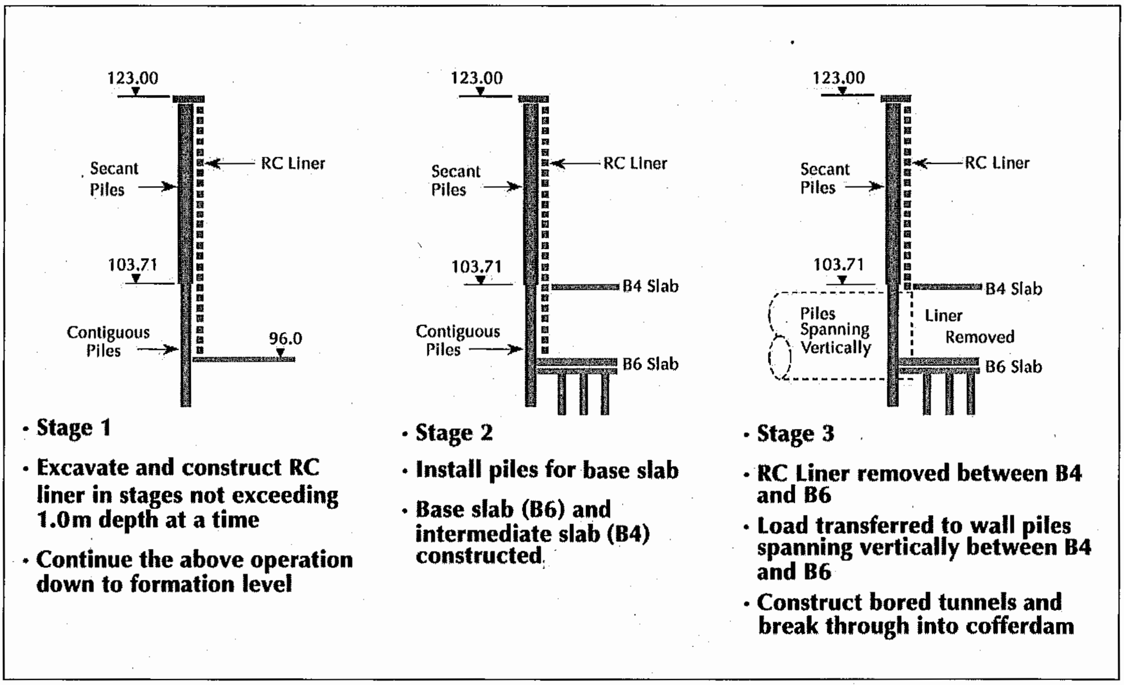

FIGURE 8. Base scheme for the construction sequence.

and potential delays arising from the need for additional contingency ground treatment during excavation. In practice, the secant piles performed extremely well overall, uniformly controlling ground movements and maintaining a very effective cut-off to groundwater.

Design Development

Following approval of the design concept for the cofferdam (which included location, diameter and wall type), the design effort focused on detailed design development linked to the needs of construction. Given the importance of regaining lost construction time, a fast-track design and construction approach was required. This approach was greatly aided by the formation of an integrated single team, including the establishment of site-based designers during construction.

A key advantage of the circular cofferdam was its inherent integrity and simplicity of form. It provided a robust base scheme consisting of an outer ring of piles, reinforced concrete liner, piled base slab and an intermediate slab at level B4 (see Figure 8), which allowed the design and construction to be independent from whatever internal structure above the B4 level was eventually developed (thus avoiding delay from the associated design development and approval process). This benefit was mainly due to the circular geometry that eliminated the need for any permanent cross strutting above this level but also because the piled foundations would allow a wide range of options for vertical loading. The secanted section of the piled wall essentially had a temporary function since the inner reinforced concrete liner was designed to take all of the permanent ground loading. The secanted section stopped at the B4 level, just above the crown of the bored tunnels. The "contiguous" piles extending below this level were designed to span between the B4 and B6 slabs. The internal piles beneath the base slab (B6) were required to control ground heave and to provide vertical stability against uplift. Because these effects were dominant, there was high downward capacity for vertical loads in the permanent condition and good flexibility in their location.

Observational Method

Application of the observational method formed an integral part of the risk management strategy for the overall design and construction of the cofferdam. Its potential was identified right from the start of the design concept. Careful consideration was given throughout the design development to enhance compatibility with existing construction methods. The observational method addressed the performance of the cofferdam during construction. The critical observations were the lateral deflections of the piled wall. These deflections had to be assessed with regard to overall ground movements and the potential effects on adjacent structures. Emphasis was placed on simplicity and ease of monitoring. The observational method was implemented on the basis of progressive modification.[8] This approach enhances the application of risk management through a step-by-step implementation and starts with a design on-site that is acceptably safe to all parties. The particular conditions at Heathrow demanded a demonstrably robust design and one that could sustain, with appropriate preplanned contingency measures, the worst credible ground conditions. However, given the particular need to safely recover as much of the delay caused by the collapse as possible, the observational method also offered major opportunities. Here, progressive modification could generate further time savings by introducing advantageous design changes on the basis of acceptable feedback from measured performance during construction.

The application of the method was characterized by three main aspects:

- The first was the principal objective to control the risk associated with such a major excavation. This objective focused on wall deflections and ground movements and particularly on any trends towards adverse conditions.
- The second aspect related to contingency measures. The method allowed timely implementation of such measures to maintain and control safety. The design was robust and more conservative than one based on predictions of the most probable conditions.[7] There was therefore the expectation that the method would be able to acceptably demonstrate that contingencies were not necessary, or at least to minimize them and therefore mitigate their effect on time and cost.
- The third factor was the added benefit of introducing design changes that would create extra time savings. Avoidance of contingency measures or sequential introduction of design improvements are inherent benefits of the progressive modification approach.[8]

Contingency Measures

The primary instrumentation for the cofferdam consisted of inclinometers in the piles and on the adjacent ground, along with precise leveling (see Figure 9). The inclinometers were formed of series of beam-mounted electrolevels.[11] Secondary instrumentation involved piezometers, extensometers and a spatial survey.

The critical quantities to be measured were the deflection of the piled walls and the associated ground movements. These two factors related to the flexibility of the structure and the global movements generated by the unloading created by the bulk excavation within the cofferdam. Two principal contingency measures were developed to address trends that indicated the likelihood of an unacceptable wall deflection. These measures were to introduce thicker and stiffer reinforced concrete rings in the cofferdam lining and to excavate down the sides, which created a substantial time lag between the main central excavation. Construction of the reinforced concrete liner rings would then progress significantly ahead of the bulk excavation, thus providing early support and limiting wall movement. Parametric studies had indicated that under the worst-case scenario maximum bending moments could develop in the contiguous piled section with a deflection of around 75 millimeters, which was set as the limiting condition for acceptable performance of the cofferdam wall. The intention was to avoid exceeding this limit by applying one or both of the above contingency measures at a sufficiently early stage in the excavation process. To successfully implement such a process (if necessary) would need early and reliable identification of deflection trends.

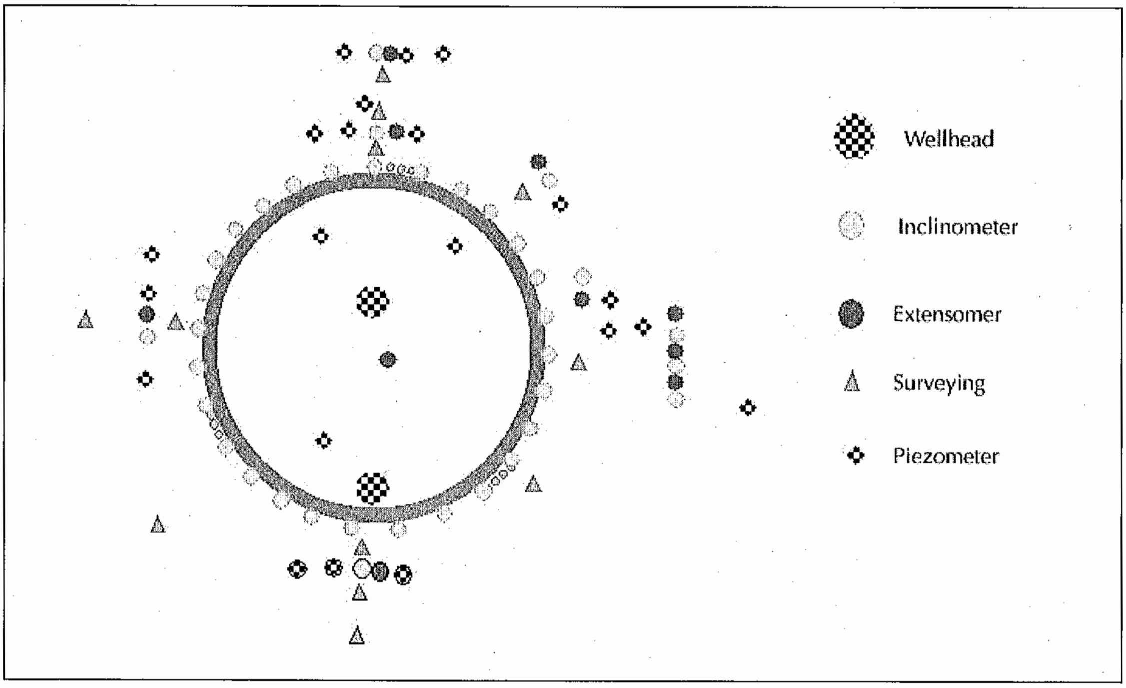

FIGURE 9. Instrumentation for the cofferdam.

While the performance of the cofferdam was continuously monitored throughout the construction process, a detailed review was set for when the excavation depth reached 7 meters to assess trends. Detection of an adverse trend developing then would have led to the implementation of contingency measures. In practice, no adverse trends developed and, in fact, further benefits were gained.

Measured Performance & Design Improvements

The comparison between average predicted and measured deflections of the cofferdam wall are shown in Figure 10. The observed values were overall maxima for the various construction stages. The performance was notably better than the range of predictions generated for moderately conservative soil parameters. Although the cofferdam offered an attractive structural simplicity, the variable soil/structure interaction together with the construction sequence presented great complexity. It was a challenge to produce an appropriate model for numerical analysis and the various analyses indicated that there was an average maximum deflection of around 60 millimeters. In practice, the average maximum deflection of the piled walls was around 15 millimeters. The control of the lateral ground movements that was achieved compares very favorably with other case histories of deep excavations in London Clay.[12,13] Average deflections were about 50 percent less than those predicted for the most probable conditions. These trends were very evident at the 7-meter depth review and enabled a variety of advantageous design changes to be implemented. The first change was to increase the depth of excavation and liner ring construction from 1 to 1.2 meters. This change, which allowed a faster rate of construction, was undertaken after completion of the liner ring No. 9, all those thereafter being of the increased depth. This change also reduced the total number of rings from 29 to 22.

Another major design change was the introduction of early tunnel breakthroughs (see Figure 11). The original design plan was to take the lining sequence completely down to the base slab level, thus maintaining the rhythm of construction and the ease of monitoring (see Figure 8). However, with the performance so demonstrably robust, it was

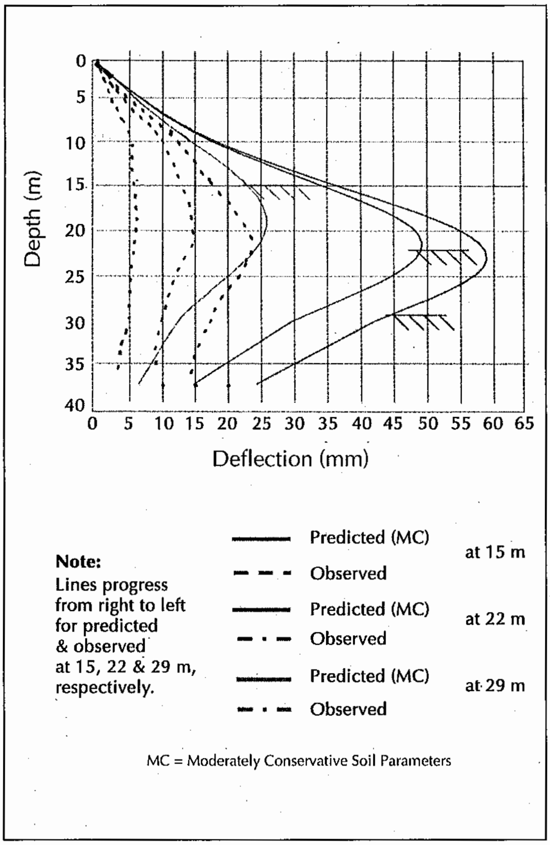

FIGURE 10. Cofferdam wall deflections.

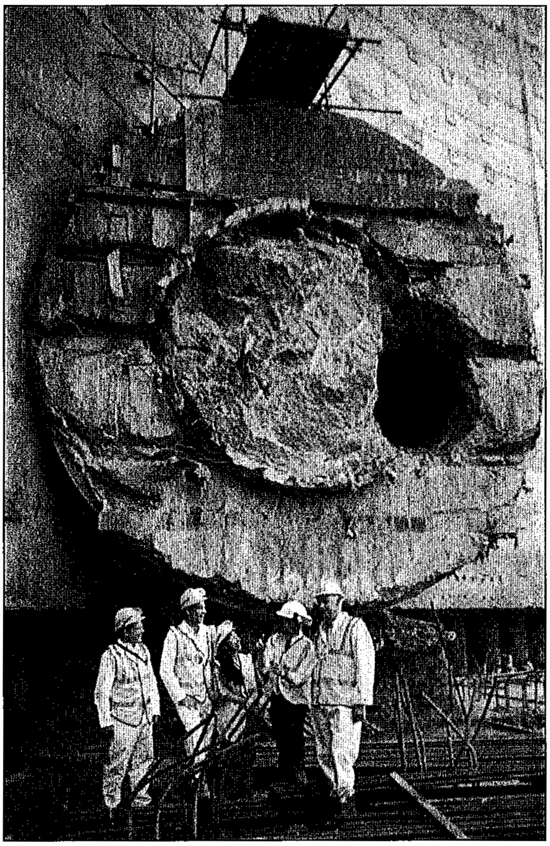

FIGURE 11. Early tunnel break-through.

decided to break through into the cofferdam from the adjacent shafts at a much earlier stage than originally planned. The effects of the breakthroughs were carefully monitored by implementing each of them progressively in defined stages. The pilot tunnels were sequentially enlarged to full size and temporarily plugged with mass concrete to maintain ring action around the wall of the cofferdam. Early tunnel breakthroughs were thus achieved substantially ahead of excavation within the cofferdam. Apart from advancing tunnel construction adjacent to the cofferdam, this change allowed for an early start on track work.

Development of Technical Innovations

The HEX tunnel collapse might be considered as providing a major opportunity for implementing innovative measures to rescue the rail link project. In practice, this rationale was only partly true since it was never an option to adopt experimental or untested methods that could have jeopardized an acceptable completion time for the project. The key elements of the operation — the physical device of the cofferdam to recover the collapsed area and the application of the observational method — were both tried and tested technologies. Their innovative features were their form and the circumstances under which they were applied, including the application of methods of construction (such as piling, where the speed, accuracy and depth achieved was novel). Key technical innovative elements were:

- the scale and geometry of the cofferdam and its means of construction in a tightly constrained space;
- the nature of the piled wall construction for the cofferdam and the nature of ground conditions through which it was installed;

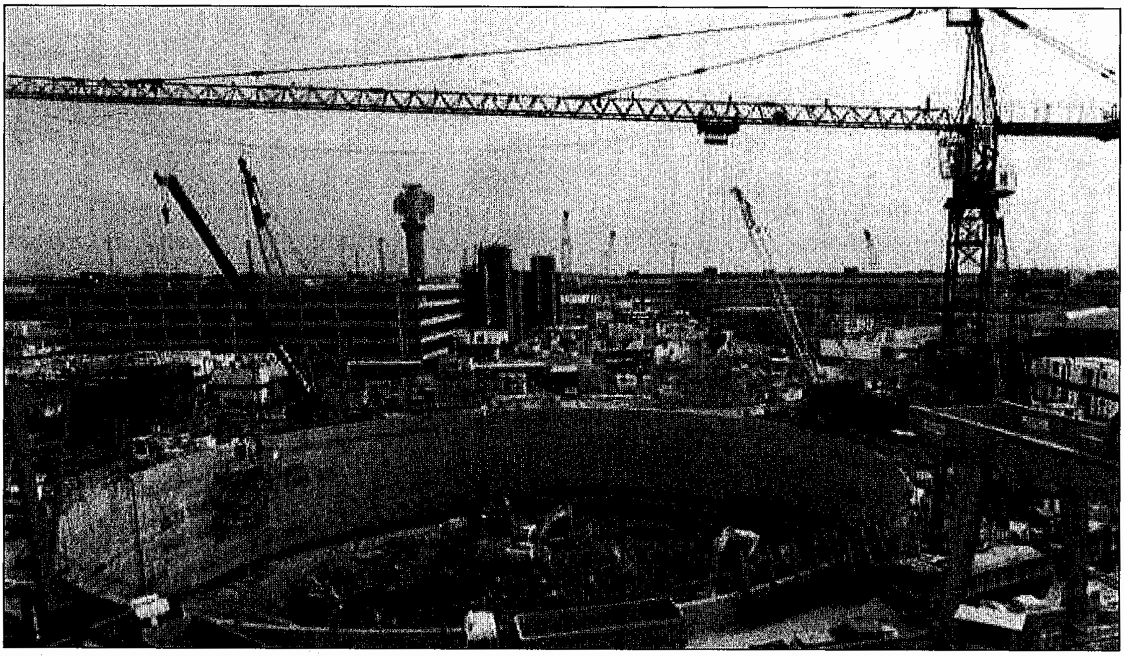

FIGURE 12. A view of the cofferdam during construction in April 1996.

- application of the observational method through progressive modification to manage risk and maximize potential benefits; and,
- deployment of an electronic data management system.

The scale of the cofferdam within the CTA is illustrated in Figure 12. The design had to address criteria that included substantially disturbed ground, water-filled voids, major obstructions and significant spatial and environmental constraints. Apart from the collapsed tunnels, other obstructions were mass and reinforced concrete and a large buried construction plant. The risk management strategy developed needed to address the new range of weakened ground conditions, particularly the worst credible criteria that required establishing appropriate contingency plans. The Solutions Team members were already very familiar with the project and the objective was to establish an agreed basis for a recovery solution as soon as possible. All tunneling work required comprehensive review, particularly work utilizing SCLs. The CTA, where the collapse occurred, demanded particular focus.

After the soil in the area was stabilized using ground treatments (which included void filling and grouting), 182 secant piles were installed to form the outer ring of the cofferdam. These large-bored piles were 40 meters long and reduced in diameter from 1,200 to 900 millimeters at a depth of 20 meters to continue as discrete "contiguous" piles. Permanent lateral support was provided by reinforced concrete rings cast directly against the piles in sequence with cycles of the excavation. The ground, cofferdam and adjacent structures were comprehensively monitored with a variety of instrumentation. The 255 bored piles for the base slab were installed from the base of the excavation during July 1996 and construction of the base slab was completed by September 1996.

Conclusions

The cofferdam marked a comprehensive success in an integrated approach to design and construction on a high-profile project. The owner merits particular recognition as the initiator for such a positive team environment.

The circular shape adopted for the cofferdam created simplicity, symmetry and rhythm. These design features in turn led to the efficiency of function and ease of construction and its monitoring. Recovery of the works was achieved in a demonstrably safe manner with major savings achieved in time and cost. Overall delay to the project was reduced from eighteen to six months. The success provided a further strong example of the synergy between value engineering and the observational method.[14-17] One of the value engineering alternatives is shown in Figure 13. The NEC facilitates design changes during construction. This ability, combined with the creation of the single-team culture, made the conditions very conducive for the application of the observational method. Progressive modification brought additional comfort and control in addressing the variable ground conditions and the uncertainties in soil/structure interaction. Contingencies were avoided and a range of design improvements were introduced during construction that delivered substantial time savings. The main outcomes of the single-team approach for the HEX as a whole are noted by Rust D'Eye.[18]

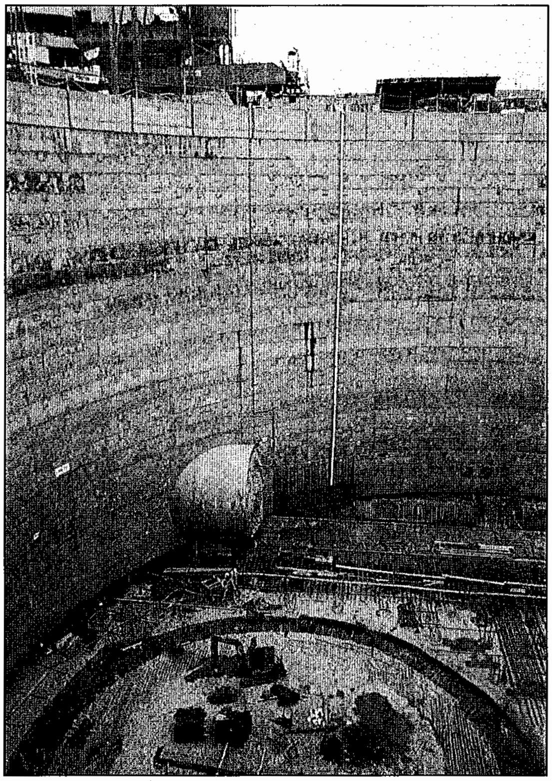

FIGURE 13. Base slab construction incorporating the base of the original shaft as a value engineering alternative.

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