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Design and construction of deep circular cofferdam in collapsed ground

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ABSTRACT: The paper describes design and construction of the large circular cofferdam in the Central Terminal Area of London's Heathrow Airport. The cofferdam is 60 m in diameter and 30 m deep. It was the principal feature in the recovery solution following the collapse of the station tunnels during construction in October 1994. It utilised 182 large diameter stepped secant/contiguous 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, 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 and large items of buried construction plant. Major cost and time savings were achieved through the Observational Method, (Peck, 1969/ Powderham, 1998) and Value Engineering (I.C.E. 1996/Powderham & Rutty, 1994) The single team approach through partnering enhanced the potential for these techniques.

1. INTRODUCTION

The Heathrow Express (HEX) Rail Link substantially improves connections between Heathrow Airport and Central London providing a sixteen minute journey from Paddington (Fig. 1). HEX is a privately owned project funded by BAA. It was fully operational by mid-1998.

In October 1994 sections of the station tunnels collapsed during construction with temporary linings. Located in the Central Terminal Area (CTA), construction of these large diameter platform and concourse tunnels was then being undertaken using sprayed concrete linings (SCL). Fortunately, there was no loss of life or injuries but there was substantial damage to the works and certain adjacent structures. Potential delay to the project at this stage resulting from the collapse was estimated to be about eighteen months. An important early decision in the recovery strategy was the formation of the Solutions Team. Its members were drawn from the main stake-holders of the project: client BAA, main contractor Balfour Beatty (BB), lead designer Mott MacDonald (MM) and the loss adjusters Brocklehurst with their consultant Ove Arup and Partners.

The task of the Solutions Team was to identify and establish the basis for a recovery solution. The risk management strategy developed needed to address the new range of ground conditions, particularly the worst credible criteria which required establishing appropriate contingency plans.

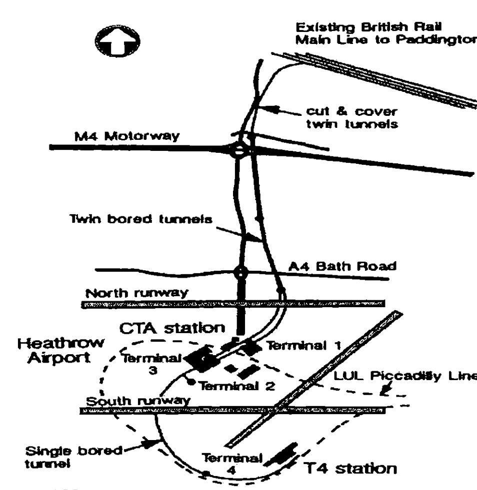

Figure 1. Heathrow express route map

2. GROUND CONDITIONS

The ground conditions in the CTA, prior to collapse, were relatively uniform with

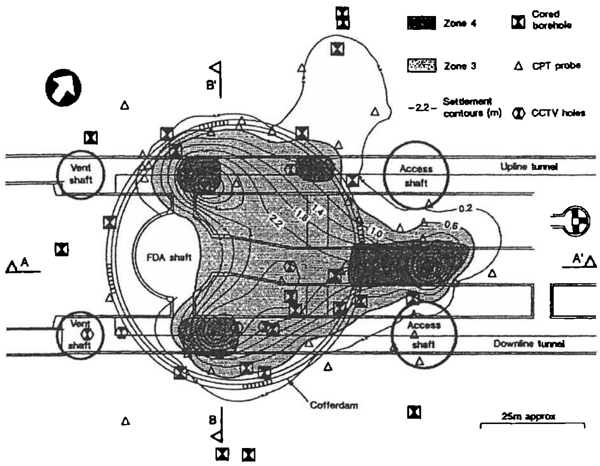

Figure 2 Settlement contours of the London Clay with predicted zones of disturbance

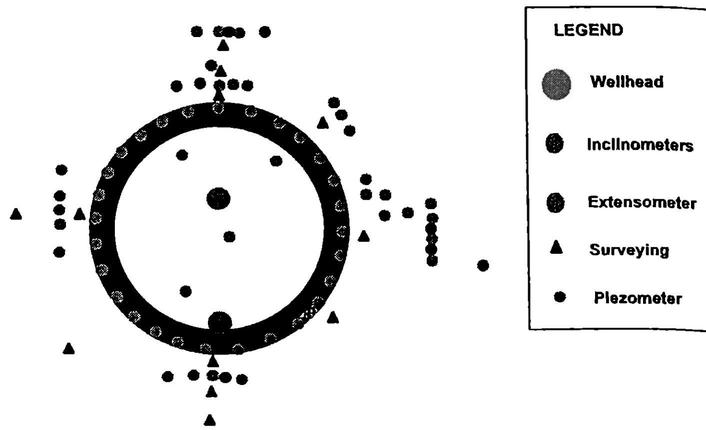

Figure 3. Cofferdam Instrumentation

approximately 6 m of Terrace Gravels overlying the London Clay which has a thickness of around 60 m at this location. The London Clay overlies the Woolwich and Reading Beds which in turn overlie the Chalk which is present at a depth of approximately 90 m below ground level.

The available data from all the various exploratory holes that identified the top of the London Clay were collated and sorted. The results were geostatistically evaluated to provide the best prediction of the surface contours on the top of the London Clay, before and after the collapse. Contours of settlement as a result of the collapse, are shown in Figure 2.

On the basis of the site investigation and predictive numerical analysis four zones were assigned within the London Clay as shown in figure 4. Zones 2 was undisturbed intact London Clay but each of Zones 2 to 4 were bounded by two sets of properties. The first represented "moderately conservative" (MC) parameters for the mass behaviour of that zone on cofferdam as a whole. The subsidiary set were "worst credible" (WC) values representing local influences that may occur where pockets of the most severely disturbed soil in that zone could result in adverse loadings on the cofferdam ring. These properties are summarised in Table 1.

3. THE COFFERDAM

A range of more conventional schemes were considered but by December 1994 a circular cofferdam was selected as the preferred option. At 60 m in diameter and 30 m deep it offered a dramatically simple solution. Larger circular cofferdams had been constructed but not in such disturbed and variable ground conditions or utilising a bored piled wall (Fig. 4). The circular cofferdam brought the following major advantages:

a) complete elimination of cross strutting maximising available space for construction operations

b) while encompassing the majority of the disturbed ground including most of the areas of greatest settlement, it minimised the total volume of excavation. This was because it was possible to arrange the two permanent ventilation shafts to the south in close juxtaposition but external to the cofferdam rather than being contained within a rectangular arrangement. In comparison with the square cofferdam option there was about 20,000 cu.m less bulk excavation. Apart from major cost savings this afforded important environmental and programme benefits, particularly since construction in the centre of a busy airport could significantly affect airport operations. The ground was also likely to be contaminated with aviation fuel which had been stored in this location. Bio-remediation was undertaken to mitigate this risk

c) 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 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 which was part of the overall risk management strategy for construction of the cofferdam and central to

Table 1. London Clay Soil Parameters

	Level	Zone 2 MC	Zone 2 WC	Zone 3 MC	Zone 3 WC	Zone 4 MC	Zone 4 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)/m		19.5	19.5	19.5	19	19	16
$\varnothing'$ (degree)		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_o (1)		1.0	0.8	0.8	0.6	0.6	0.6

d = Depth below ground level MC = Moderately Conservative WC = Worst Credible

Zone 4 extends to +95 T.D. Zone 3 extends to +93 T.D. Below +93 T.D. Zone 2 MC should be used.

The site investigation is described in more detail in Powderham & Rankin (1997).

the realisation of further potential cost and time savings.

Following careful probing and ground stabilisation measures, 182 secant piles were installed to form the outer ring. These large bored piles are 40 metres long and reduce in diameter at a depth of 20 metres to continue as "contiguous" piles. Permanent lateral support is provided by reinforced concrete rings cast directly against the piles in sequence with cycles of excavation. The ground and structure were comprehensively monitored with a range of instrumentation including electro-levels, piezometers, extensometers, strain gauges and precise spatial survey. The 255 bored piles for the base slab were installed during July 1996. Their function is to limit long term heave and control hydrostatic uplift. These piles are 0.9m in diameter and 15m long. Construction of the base slab was completed by September 1996, (Fig. 6).

4. PILED WALL CONSTRUCTION

A key feature of the cofferdam was the design and construction of the outer wall. Diaphragm (or slurry) walls are a typical option for this type of construction but the combination of heavy obstructions and potentially extensive voids were critical in eliminating this form of wall with its attendant need for bentonite slurry support for panel excavation. However, a primary consideration was the need to provide a good cut-off to the groundwater in the gravels particularly in view of its potential contamination. So 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. Depth, diameter, spacing and construction tolerances needed careful consideration in conjunction with construction methods and sequences. 1200mm diameter secant piles for the top 20m which stepped in to continue as 900mm diameter contiguous piles for the next 20m (Fig. 4) were used. The centres of the piles were set at 1060mm. Both male and female piles were reinforced generally with bar reinforcement except above the tunnels where structural steel sections construction and this was particularly relevant to effort and support was provided to the team by Stent Foundations, the piling subcontractor. The specified minimum vertical tolerance of 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 twenty metres the secant piles would reach the original level of the crown of the

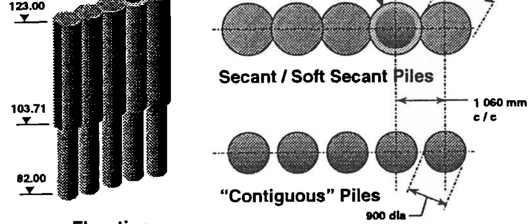

Fig. 4 Secant and "contiguous" piles

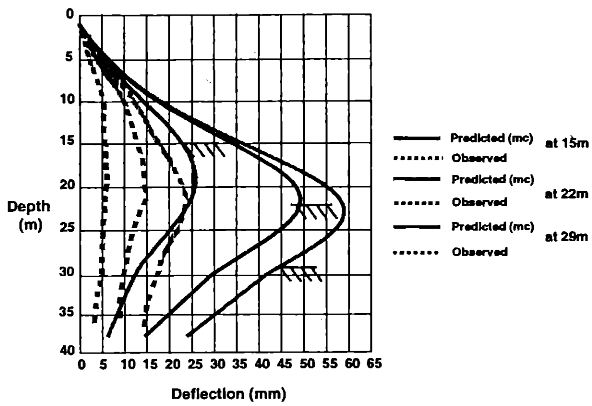

Figure 5. Cofferdam wall deflections

tunnels. It was accepted that some limited zones of ground treatment could be necessary to complete this cut-off. Pre-treatment of the ground prior to piling focussed on the highly disturbed zones above and around the collapsed tunnels.

In practice the secant piles performed extremely well overall, uniformly controlling ground movements and maintaining a very effective cut off to groundwater.

5. OBSERVATIONAL METHOD

The observational method formed an integral part of the risk management strategy for the overall design and construction of the cofferdam. Its use was envisaged right from the start of the design concept. Careful consideration was given throughout the design development to enhance compatibility with construction methods. In relating design to construction in the context of the observational method an emphasis was placed on simplicity and ease of monitoring. Such aspects as construction rhythm and symmetry have already been noted. The method was implemented on the basis of progressive modification (Powderham 1998). The situation demanded a demonstrably robust design and one that could sustain, with appropriate pre-planned 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.

There were three main aspects in this application of the method. The principal objective was to control the risk associated with such a major excavation. This focused on ground movements and wall deflections and particularly any trends towards adverse conditions. The second aspect related to contingency measures. The method would allow timely implementation of such measures to control safety. The design was robust and more conservative than one based on predictions of the most probable conditions (cf Peck 1969). There was therefore potential that the method would be able to comfortably demonstrate that contingencies were not necessary or at least minimise them and so mitigate their effect on time and cost. The added benefit of introducing design changes that would save more time was the third factor. Avoidance of contingency measures or sequential introduction of design improvements are inherent benefits of the progressive modification approach.

6. CONTINGENCY MEASURES

The critical quantities to be measured were deflection of the piled walls and the associated ground movements. These two factors relate to the flexibility of the structure and the global movements generated by the unloading created by the bulk excavation within the cofferdam. The contingency measures were to introduce thicker stiffer reinforced concrete rings in the cofferdam lining and to excavate down the sides only creating 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 mm. This was set as the limiting condition for acceptable performance of the cofferdam wall. The intention was to avoid approaching this limit by applying one or more 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. 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 m to assess trends. Detection of an adverse trend developing would then have led to implementation of contingency measures, but in the event, no adverse trends developed.

The primary instrumentation comprised inclinometers in the piles and adjacent ground along with precise levelling. The inclinometers were formed of series of beam mounted electrolevels. Secondary instrumentation involved piezometers, extensometers and spatial survey.

7. PERFORMANCE OF THE PILED WALL

The average maximum deflection of the piled walls was around 15 mm. This was at a depth of 25m below ground surface. The control of the lateral ground movements achieved compares very favourably with other case histories of deep excavations in London Clay (eg Burland & Hancock 1977 and Marchand 1993). Average deflections were about 50% less than those predicted for the most probable conditions. These trends were very evident at the 7m 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 m to 1.2 m. This change initiating a faster rate of construction was undertaken after completion of liner ring 9, all those thereafter being of the increased depth.

Another major design change was the introduction of early tunnel breakthroughs, see Fig. 6. The original design plan was to take the lining sequence completely down to base slab level thus maintaining the rhythm of construction and the ease of monitoring. However, with the performance so demonstrably robust it was elected performance so demonstrably robust it was elected to breakthrough the outer ring of piles with pilot tunnels entering the cofferdam from the adjacent shafts at a much earlier stage than originally planned in the overall construction sequence. 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 secant pile 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 allowed early progress for track work.

8. CONCLUSIONS

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

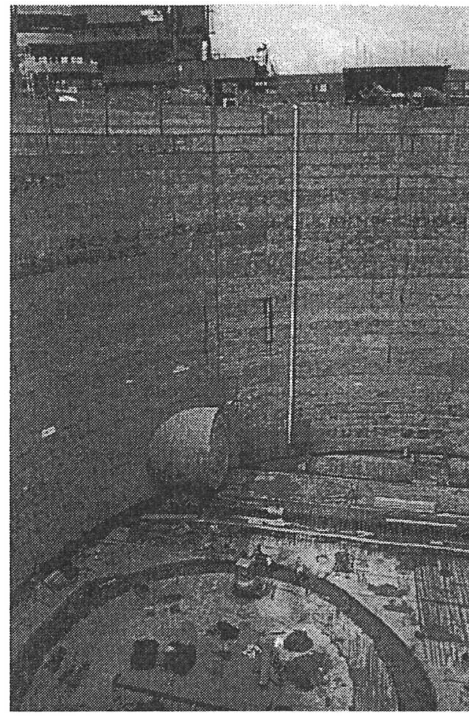

Figure 6. Base slab construction (Incorporation base of FDA shaft as VE alternative. Early tunnel breakthrough also evident).

created simplicity, symmetry and rhythm. This in turn led to efficiency of function and ease of construction and its monitoring. Recovery of the works was achieved in a demonstrably safe manner with major savings being achieved in time and cost. Overall delay to the project was reduced from eighteen to six months. 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 achieved.

9. ACKNOWLEDGEMENTS

The views and opinions expressed on the Heathrow Cofferdam case history are those of the author and are not necessarily representative of those held by BAA or MM. The author is grateful to BAA for their permission to publish this paper. In addition, the author wishes to recognise the efforts made by all individuals and parties during the investigation, ground treatment, construction and excavation of this recovery solution which has required close and effective teamwork.

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