THE OBSERVATIONAL METHOD – LEARNING FROM PROJECTS

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ABSTRACT

Simplicity is at the heart of the observational method.[1,2] Its basis is straightforward and it is an inherently natural approach to address uncertainty. The focus on prediction, monitoring, feedback, and teamwork also creates a strong opportunity for learning. Applications typically involve underground construction and temporary works. The objectives are to save cost or time while maintaining an acceptable level of safety. Application of the method was pioneered by Terzaghi and the principles were formally set down by Peck[3] in his 1969 Rankine lecture. Possible modes of failure must be carefully assessed and controlled – particularly those of a sudden or brittle nature, or those that could lead to progressive collapse. Safety is essential and a high degree of certainty in project performance and schedule is generally required. The observational method overcomes the limitations of conventional design by evaluating feedback from actual conditions. This paper describes how simple measurements were central to resolving complexity and controlling risk. It presents three recent case histories featuring the 'progressive modification' approach which removed barriers that may have prevented the opportunity to apply the observational method.

THE PROGRESSIVE MODIFICATION APPROACH

The observational method facilitates design changes during construction and establishes a framework for risk management. It is not surprising that proposing changes tends to create concerns regarding safety and certainty. However, it is unfortunate that the method may be inappropriately associated with uncomfortably low safety margins coupled with the potential cost and delay of contingency measures. Progressive modification permits technical or contractual constraints to be addressed by accommodating the concerns of all parties involved in the project. Such constraints have discouraged wider and more frequent application of the observational method.[4] The overall performance is measured and evaluated including soil/structure interaction, construction methods, communication, and teamwork. The objective is to demonstrate the basis for introducing design changes sequentially during construction that create cost or time savings – or to avoid unnecessary contingencies. The latter particularly applies to 'best way out' cases where phased construction allows feedback and re-evaluation of predictions for each subsequent phase. This requires additional design work, monitoring and supervision but this should be absorbed in the overall benefits.

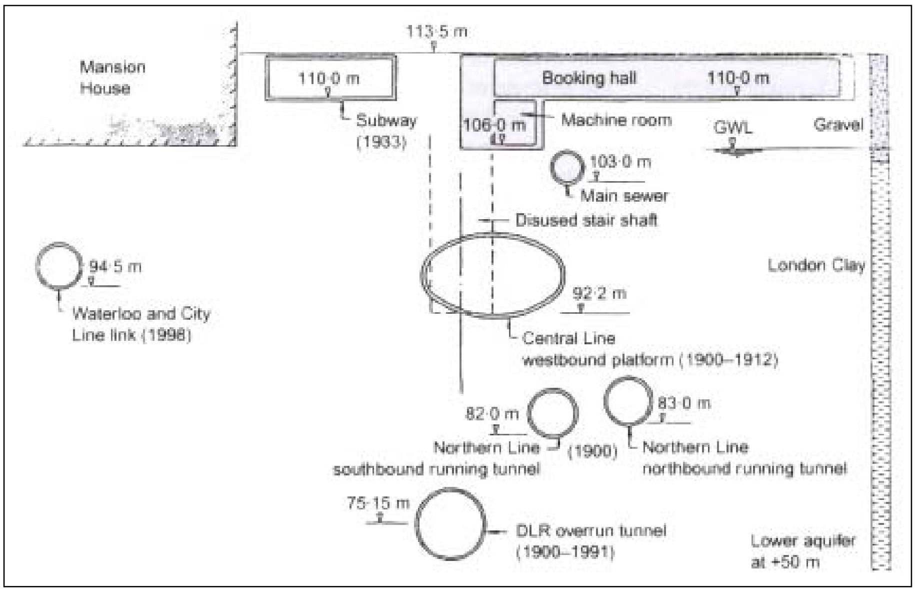

Fig.1 Tunnelling works beneath Mansion House

The basis of the approach is to:

a. commence construction with a design providing an acceptable level of risk to all parties
b. maintain or decrease this level of risk
c. progress construction in clearly defined phases
d. implement appropriate changes progressively and demonstrate acceptable performance through observational feedback.

Most potential for savings relates to temporary works or construction method and sequence. There may also be substantial savings in permanent works, for example through avoiding inappropriate protective works or providing the basis for innovation in future construction.

For two of the case histories – the Limehouse

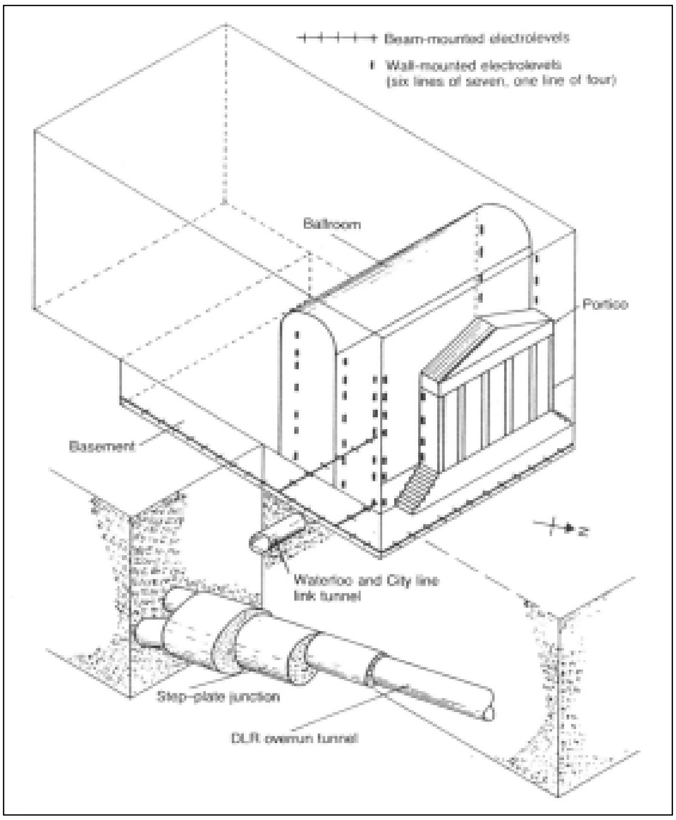

Fig.2 New tunnels within zone of influence and electrolevels on building

Link and the Heathrow cofferdam – progressive modification produced savings through design improvements that accelerated construction. The Mansion House case history presents a different scenario. The focus was on re-establishing the confidence of the building owners by clear control of safety and avoiding damage to the building. The progressive approach would permit an acceptable level of safety to be demonstrated, ideally without resort to any contingency measures. These are planned design changes that involve penalties of cost and time. In 'best way out' applications, like the Mansion House, success relates to the avoidance of unnecessary contingencies. Progressive modification, with its basis on defined construction phases, provides a way forward to achieve this. For Mansion House it was the cumulative effect of excavation on the building that was being progressively modified and evaluated through phased construction.[5]

OBSERVATIONS

Observations need to embrace all critical information necessary to manage risk but should be as simple and concise as practicable. A motivated site team with a clear brief and supported by an appropriate system for instrumentation and monitoring is essential. Achieving the right balance should not be underestimated since there are usually varying views on the amount and type of instrumentation required, and responsibilities need to be clearly established.

THE MANSION HOUSE

In mid-1989 concerns over damage to the Mansion House arose following construction of a small diameter tunnel directly beneath the building (Figs. 1 and 2). This imposing masonry building is the official residence of the Lord Mayor of London with a Grade 1 heritage listing. It was built over the period 1739-53 to the design of George Dance the Elder (Fig. 3). Since then it has undergone extensive modifications including major structural alterations. The building, measuring about 60m by 30m in plan, now has five storeys with a vaulted masonry arch basement under the northern two-thirds (Fig. 4). Much of the alterations related to or affected the foundations. Construction of tunnels for the London Underground Central Line, which started in 1901, led to some substantial underpinning at the northern end of the building. The Docklands Light Railway (DLR) extension from London's Tower Hill to Bank Station involved a range of bored tunnelling works beneath the Mansion House. The parliamentary undertaking required the approval of the City Engineer before tunnelling within the zone of influence of the building could commence. The first phase of this tunnelling was the passenger link tunnel to the Waterloo and City Line and the associated settlement appeared to be exceeding the long-term prediction.[6] All remaining tunnelling within the contractual zone of influence was stopped and a detailed evaluation of the implications to the building was initiated. Prior to the proposal to use the observational method, a wide range of alternatives to protect the building in advance of the tunnelling had been considered:

a. shielding the foundations of the building from the imposed settlement trough from tunnelling by constructing a structural curtain wall
b. localized foundation strengthening, such as underpinning and ground treatment
c. building strengthening such as a system of structural ties
d. elimination of the settlement effects on the building by compensation grouting.
e. complete underpinning of the building combined with a global jacking system to compensate for the imposed settlements.

All these preventative methods would introduce new risks of damage to the building and involve substantial cost and delay. At the request of the DLR, a specialist team was formed to undertake an independent assessment and propose a way forward. This team reported to the project director of the DLR and to the City Engineer and his consultants. The objective was to develop a solution based on the least risk to the building and prevention of any unacceptable damage. The study led to the application of the observational method based on the progressive modification approach.

Risk control

The observational method provided a basis to limit risk of damage to an acceptably low level.[7] A comprehensive assurance of safety was required, and it was necessary to consider the long-term implications as well as short-term effects. A progressive approach, requiring approval by all parties, was adopted with phased sequences of tunnelling. It was expected that design changes, if

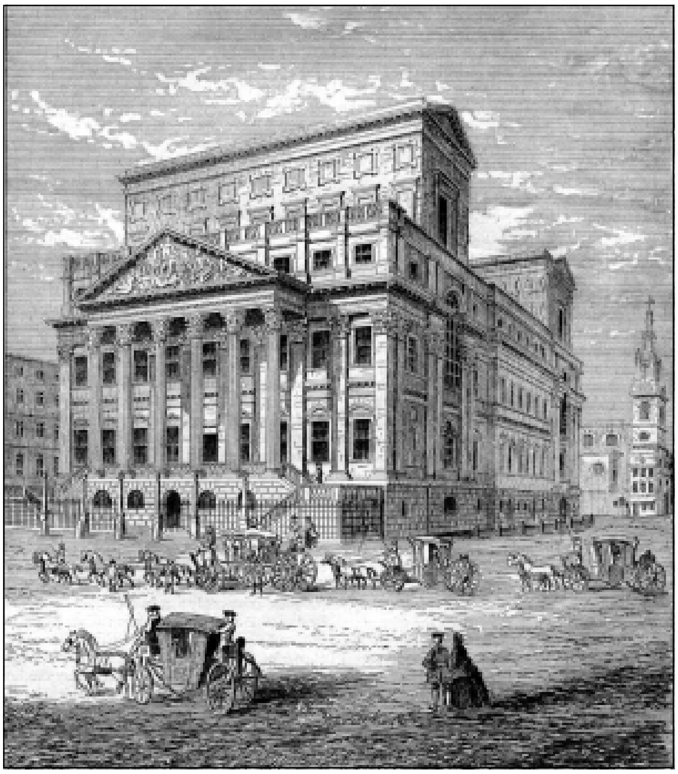

Fig.3 Mansion House in the 1750s

necessary, would be implemented after a given phase to control the level of risk. The phases comprised the Central Line passenger link, the overrun tunnel, and the enlargements for the step plate junction. The latter involved three stages which were constructed by hand with cast iron linings, enlarging from the pre-cast concrete lined overrun tunnel.

The observational method was implemented on the following basis: An assessment of the building and its foundation conditions was made that included a detailed condition survey and a comprehensive review of historical records. Detailed consultations were held with the main contractor to review tunnelling methods and performance. Particular attention was given to the sequence of tunnelling and the level of risk relating to each phase. The passenger link tunnel was realigned to leave only the overrun tunnel and the step-plate junction within the contractual zone of influence.

Assessing the most probable conditions for tunnelling was relatively straightforward but far more complex for the Mansion House and its foundations. The most unfavourable conceivable deviations from these conditions would be higher volume losses from tunnelling and a high sensitivity of the building to settlement. In particular, this would involve planes of weakness developing in the masonry structure and a response to settlement to be induced in a bending rather than shear mode of deformation.[8]

Initial predictions for surface settlements were based on greenfield conditions.[9] Assessment of the actual behaviour of the building anticipated under the most probable conditions indicated an acceptably low level of risk of damage. The main response was expected to be by free-body rotation. Any response to deformation, with development or extensions of cracks, was predicted to be predominately in shear.

A key requirement was to monitor and record the detailed response of the building and identify any adverse trends. The principal system consisted of arrays of horizontally and vertically aligned electrolevels supplemented by precise levelling. In total, 101 electrolevels were attached to the building. There were 55 in the basement in four horizontal strings, the rest were attached individually to the external masonry and aligned vertically. Secondary instrumentation included a water-levelling system and spatial surveys. Details of the instrumentation, its performance and interpretation of the readings are given by Forbes et al.[10] and Price et al.[11]

The overall soil-structure interaction was extremely complex. It was therefore considered inappropriate to rely on powerful analytical techniques to model both the ground and the building as a basis for implementing protective measures. There were too many significant unknowns; Burland et al.[12] make apt comments in this regard. The effects of the tunnelling sequence in the zone of influence would be cumulative. The objective was to maintain the risk at an acceptably low level during each phase of tunnelling. Three zones of risk were identified as shown in the flow chart, Fig. 5. This led to the ‘traffic light’ system of green, amber and red zones for categorising risk levels in the observational method. It proved a clear and simple way of communicating risk status to all parties. It was then used for Limehouse Link[13] and the Heathrow cofferdam and subsequently adopted in the CIRIA report on the observational method.[5] The overrun tunnel, which presented the lowest risk, was undertaken first.

The basis for risk control is shown in Fig. 5. Two alert thresholds were set with specific actions. These thresholds relate to the boundaries between ‘negligible’, ‘very slight’ and ‘slight risk’ of damage to the building. The boundaries were obtained by consideration of both angular distortion and horizontal tensile strain (Fig. 6). The latter was relevant because the building was theoretically subjected to a hogging deformation on the limb of the settlement trough. Since the risk assessment accounted for both effects, it was considered necessary, and indeed practical, to monitor only the angular distortion. This provided a single, relatively simple control measure. The three zones of levels of risk, green, amber and red, were established with thresholds set for angular distortions of 1/2000 and 1/1000. Entering the red zone would bring a definite hold on the next phase of tunnelling. Then, pending comprehensive assessment of the effects on the building, the need for installing one or more of a range of preventative works would be assessed. These consisted of various

Fig.4 Mansion House in 1990

forms of underpinning and ground treatment, including compensation grouting, and structural strengthening. In addition, the ability to install emergency strengthening in the form of steel ties was assessed in advance. Such strengthening had been installed at the southern end of the building during Victorian times. Should any preventative works have been required, the instrumentation would have been used to monitor their installation and performance.

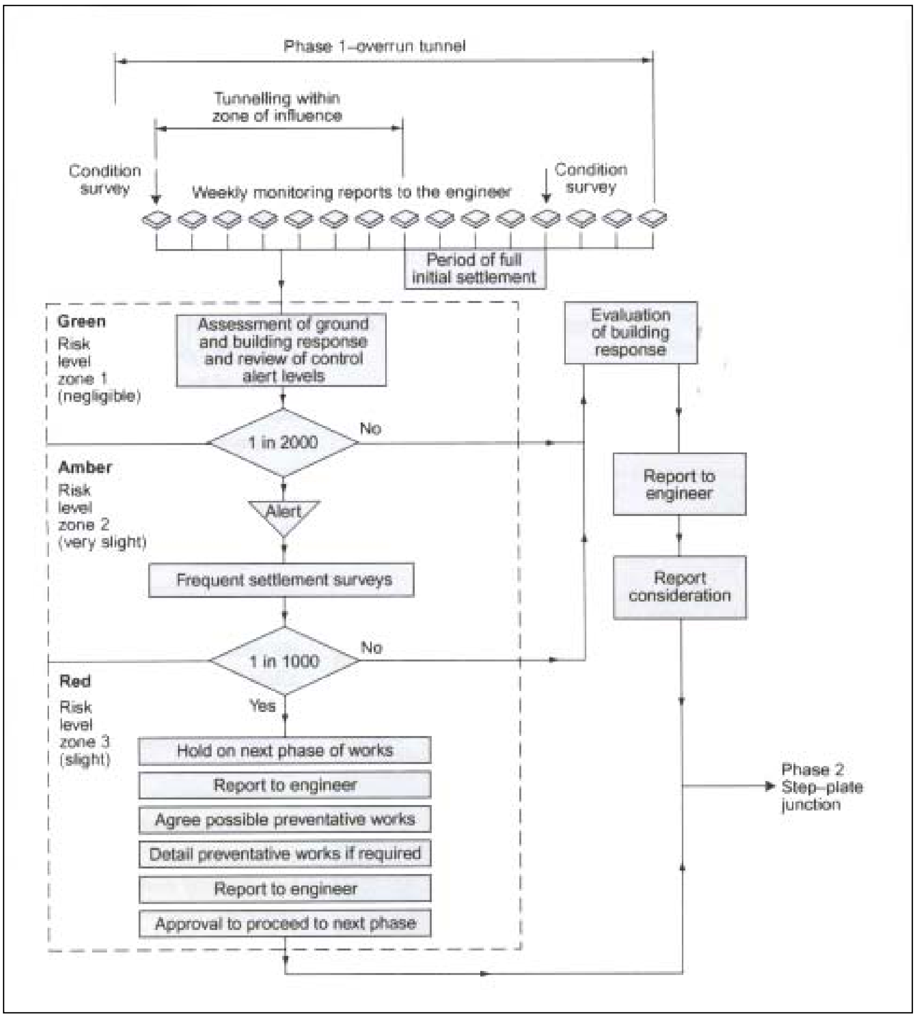

Fig.5 Basic flow chart for risk levels and responses

Results

Tunnelling was completed in the proposed sequence without further delay to the programme. No damage to the building associated with the remaining phases of tunnelling was evident. The deformation of the building was very small. The angular distortion was less than 1/7000. Most of the settlement was accommodated by free-body rotation as predicted. The maximum recorded settlement at the north-west corner of the building up to February 1991 was 20 mm. Less than half of this was attributable to short-term effects from tunnelling within the contractual zone of influence. The remainder derived from ongoing global settlement, mainly from consolidation of the clay. The electrolevel system performed particularly well and its high sensitivity proved very effective in enabling the short-term response to be separated from longer term effects. This was most important in the assessment of risk to the building since these latter effects were causing only free-body movement. This settlement did not present a risk of damage to the structure or fabric of the building. No damage to the building was recorded. This was checked by detailed condition surveys including analytical photogrammetry which would have revealed even small extensions to existing cracks.

It had thus been possible through the application of the observational method on a progressive basis to show that the risk of damage was maintained within acceptable limits. The substantial cost and delay in implementing major protective works to the foundations were avoided. The estimate for the curtain wall was £3 million, and that for the full underpinning scheme was £13 million.[14]

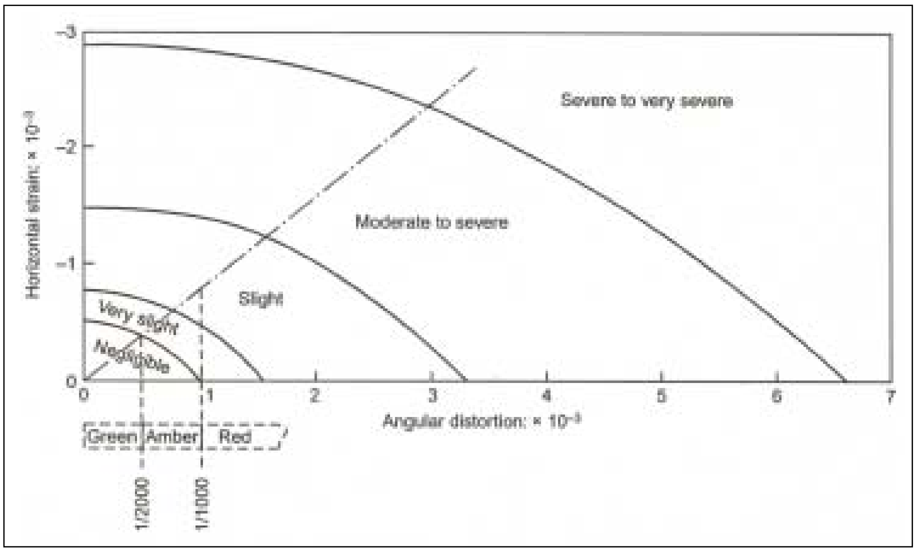

Fig.6 Relationship of angular distortion and horizon extension strain

LIMEHOUSE LINK

Limehouse Link is a major cut and cover highway tunnel in London’s Docklands. Here the observational method was applied to eliminate the substantial temporary steel strutting system for the diaphragm walls.[13] It was used in

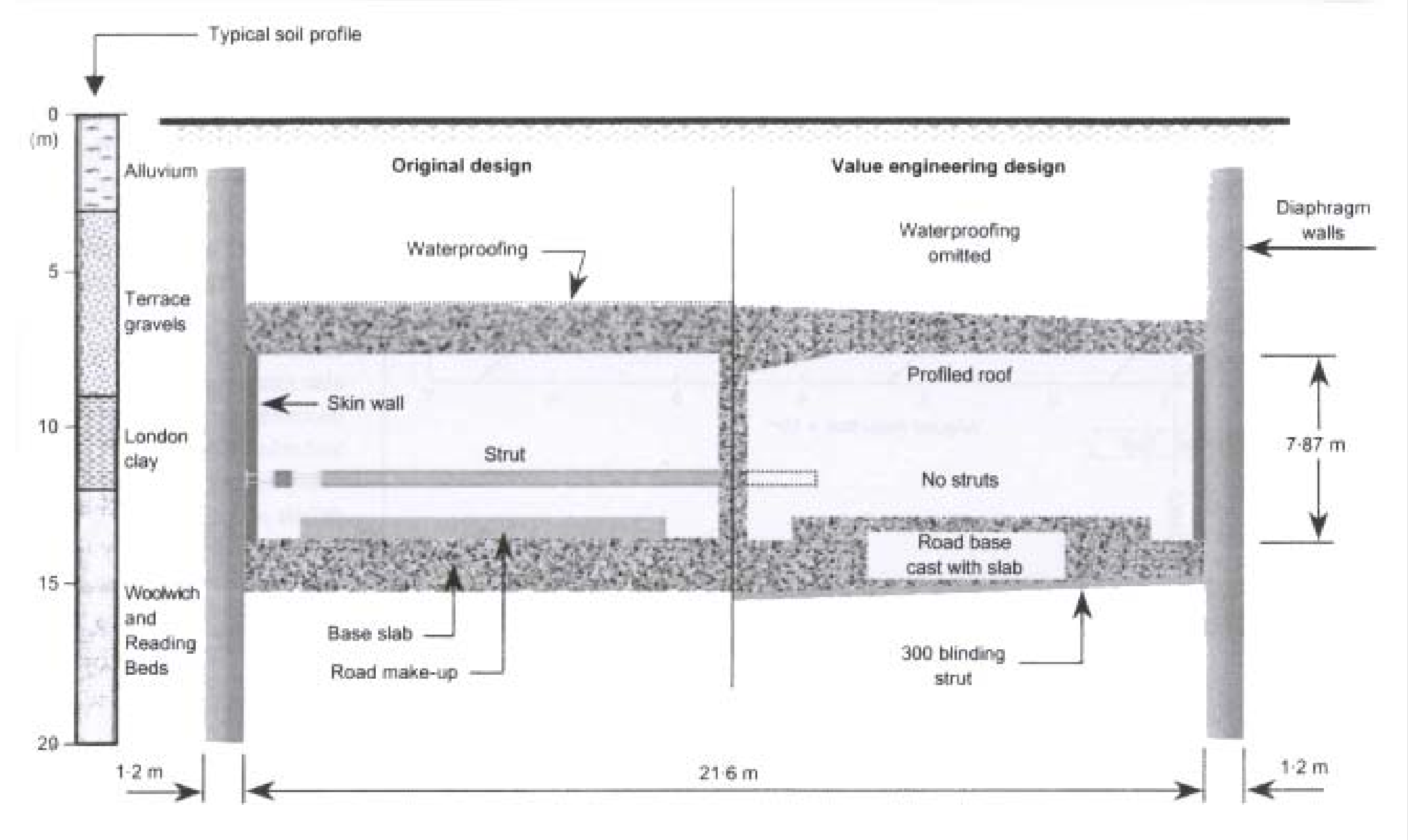

Fig.7 Cross-section—top-down construction

conjunction with another powerful technique – that of value engineering.

The £250 million project involved complex subsurface construction in a congested urban site with significant physical, environmental and planning constraints. Work started on site in November 1989 but soon encountered problems that caused delay and increased costs. A variation agreement between the London Docklands Development Corporation and the contractor Balfour Beatty-Amec was subsequently negotiated. This included the addition of a value engineering clause to the contract in March 1991.

The value engineering clause facilitated the introduction of the observational method and created opportunities to introduce design changes that increased the speed of construction and substantially decreased cost. Operational safety was also enhanced. The principal need was to reduce delay to the programme. In this sense it was a 'best way out' application of the method. In other respects, the application by progressive modification was similar to that developed for the Channel Tunnel cut and cover construction and drew advantageously upon the progress achieved there.[6] Similar concepts applied, particularly those relating to possible failure modes including brittle behaviour.

Ground Conditions

The ground conditions were variable and challenging. The surficial soils consist of man-made fill and alluvium above River Terrace gravels. These overlie the London clay, Woolwich and Reading beds, and Thanet sands. The relative location of the tunnel with respect to a typical soil profile is shown in Fig. 7. There were also numerous major obstructions, including mass and reinforced concrete and heavy timber piling. Further details of the ground conditions are given by Stevenson and De Moor.[15]

Implementation

The observational method was introduced on a progressive basis starting with a trial section using 'soft' struts[13] (Fig. 8). The 'soft' strut was simply an existing strut installed with a predefined gap at one end. This gap was set significantly less than the allowable wall movement. It was thus possible to demonstrate adequate performance by monitoring gap closure and avoiding the complications of strain or load measurements in the struts.

The main tunnel sections utilised top-down construction with diaphragm walls. Beneath the roof slab, the excavation was initially taken forward in short sections of 3 to 4 metres per day with 300 mm thick blinding to act as a low level strut. This provided an extra safeguard in conjunction with the three-dimensional effects of soil arching. Control centred on the simple observation of wall movement (Fig. 9). Spatial surveys established that sway effects of the tunnel were not a significant factor in lateral wall movement. The trial section successfully demonstrated that wall movements were acceptable without the intermediate struts. Inclinometers placed in the walls enabled measurement of typical lateral wall movements from the start of excavation from ground level to the intermediate strutting level. This had to be accounted for in setting the zonal limits shown in

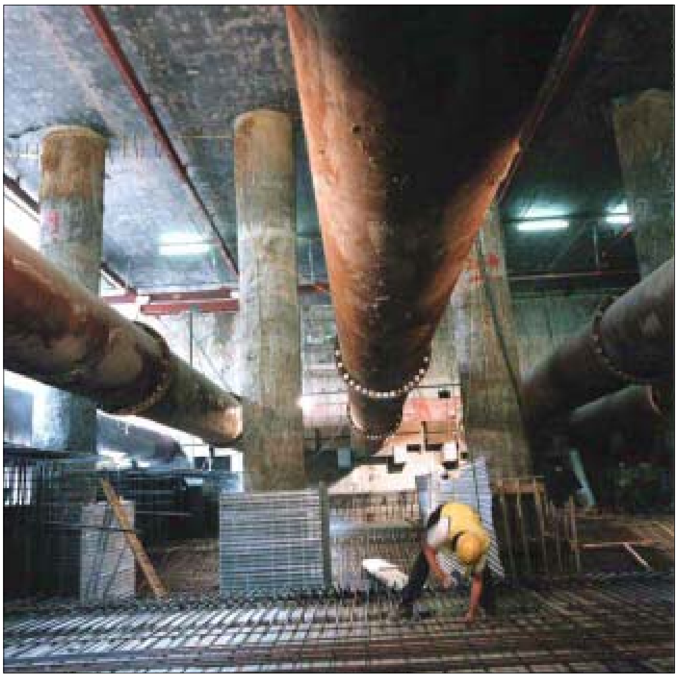

Fig.8 First trial section with 'soft' struts

Fig. 9. So, larger machines could be used making excavation faster and more economical. Observations were compared with those of previous sections, and when the results were found to be satisfactory, the bay length was progressively increased. A similar investigation of the need for the enhanced blinding led to its reduction to a standard 100mm thickness. The absence of the temporary struts also made fixing reinforcement and concreting operations easier and safer.

Activity was extended to a total of nine excavation fronts along the 1.7km tunnel. This included two sections in Limehouse Basin where the observational method was implemented to eliminate the mid-height struts in the deep steel piled cofferdam. Here it was only partially successful. The attempt to eliminate these struts extended the progressive modification approach beyond its useful limit. In practice, the risk control was too onerous. However, observational feedback provided a basis to substantially increase excavation rates. Sheet pile embedments were also reduced by more than 80%. This created cost and time savings together with a substantial environmental benefit from noise reduction.

Overall success at Limehouse Link amounted to a saving of nearly 5000 tonnes of temporary support. This comprised 5400m of strutting and 2700m of associated walings. From being significantly delayed the project was completed 5½ months ahead of schedule.

HEATHROW COFFERDAM

The Heathrow Express Rail Link provides a new direct connection between the airport and Central London. It required major underground works at Heathrow Airport. The project suffered a severe setback following the collapse of the tunnels in the Central Terminal Area (CTA) on 21 October 1994.[16]

Fortunately, there were no injuries or loss of life but the works and adjacent structures suffered extensive damage. The potential delay to the project was estimated to be of the order of eighteen months.

The key element in the recovery solution for the CTA was the large circular cofferdam (Fig. 10). The design had to address conditions that included highly disturbed ground, water filled voids, major obstructions together with spatial and environmental constraints. Apart from the collapsed tunnels, other obstructions were mass and reinforced concrete and large buried construction plant. A robust risk management strategy was developed. The worst credible ground conditions were addressed by pre-planned contingency measures.

Ground Conditions

The ground conditions in this area, prior to collapse, were relatively uniform with approximately 6m of Terrace Gravels

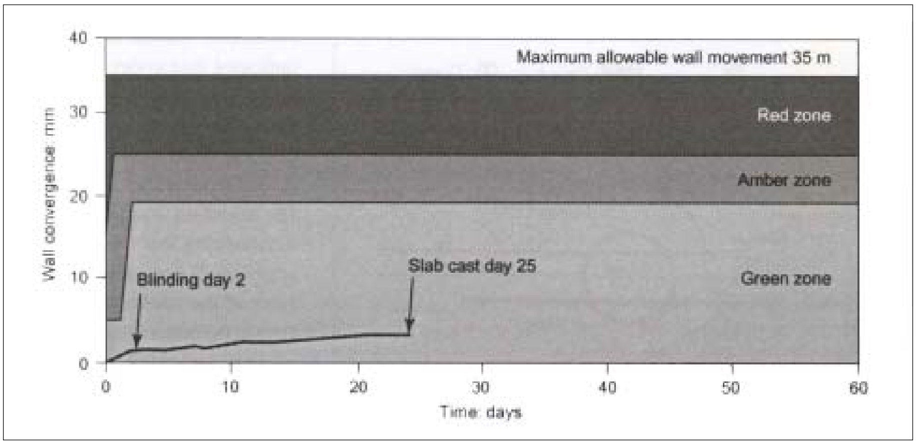

Fig.9 Limehouse Link—typical diaphragm wall convergence. Zonal limits are for one wall only. Wall convergence is the sum of two walls.

Fig.10 Cofferdam construction, April 1996

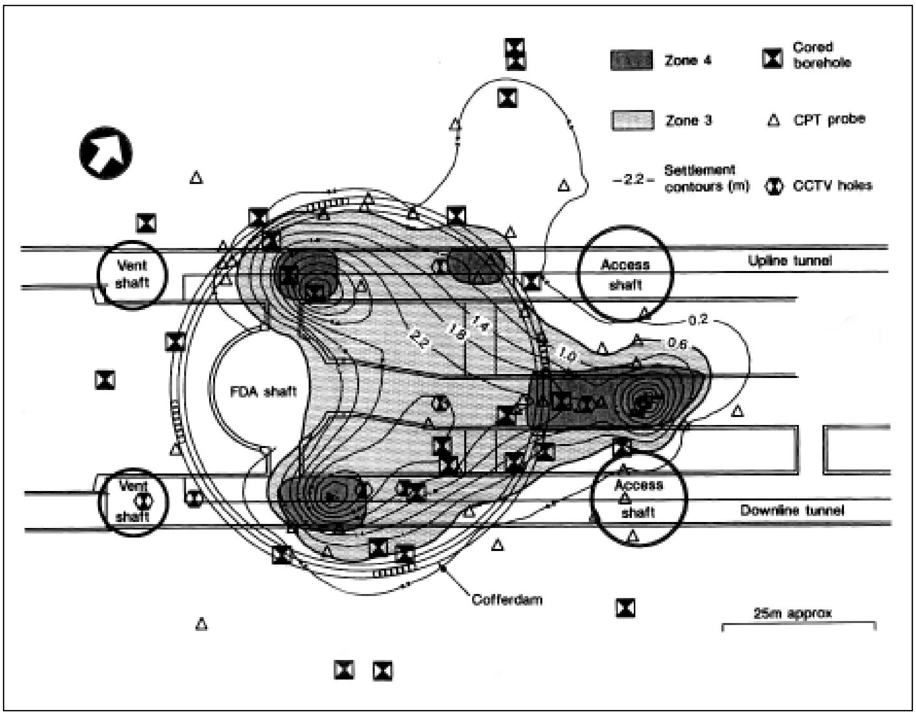

Fig.11 Settlement contours of London Clay with predicted zones of disturbance

overlying some 60 of London Clay. In turn, the Woolwich and Reading Beds overlie the Chalk which is present at a depth of approximately 90m below ground level.

Post collapse, on the basis of detailed site investigation and predictive numerical analysis, four zones were assigned within the London Clay as indicated in plan Fig. 11. Zone 1 was undisturbed London Clay, Zone 2 was generally within the active zone of the cofferdam, Zone 3 was for settlement of the London Clay greater than 0.6m, and Zone 4 represented area collapse. More details of the ground conditions, design parameters and zoning are given by Powderham and Rankin, 1997. [16]

The Cofferdam

A circular cofferdam was selected as the preferred option. At 60m in diameter and 30m 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. 12). The circular cofferdam allowed complete elimination of cross strutting thus maximising space for construction operations. It also minimized excavation volumes – compared, for example, to a square cofferdam it required about 20,000 cu.m less bulk excavation. Following careful probing and ground stabilisation measures, 182 secant piles were installed to form the outer ring of the cofferdam. These large bored piles are 40 metres long and reduce in diameter at a depth of 20 m to continue as individual “contiguous” piles. The symmetry facilitated a uniform, step by step sequence of construction for the cycles of excavation and the casting of the inner reinforced concrete liner (Fig. 13). This rhythm greatly helped monitoring of ground and structural movements so that trends, and in particular any adverse ones, could be detected at an early stage. This was very compatible with the application of the observational method. In contrast to the previous case histories, the method here integral to the whole concept of design and construction of the cofferdam. So from the start, a design was developed that could be progressively modified during construction and was easy to monitor.

Implementation

There were three main aspects to this application of the method. The principal objective was to control the risk associated with such a major excavation. The simple parameter of wall movement was central to the overall strategy. The second aspect related to contingency measures. The method needed timely implementation of such measures to control safety. Since the design was robust, it was hoped that the method would demonstrate that contingencies were not necessary. The third aspect was the potential for introducing time-saving design changes.

Contingency Measures

The two contingency measures were to stiffen the reinforced concrete lining of the cofferdam and to excavate only down the sides thus creating a substantial time lag before bulk excavation. Construction of the reinforced concrete liner rings would then progress significantly ahead of the main excavation within the cofferdam. This would provide additional support prior to bulk removal of overburden and thus limit wall movement.

Parametric studies had indicated that under the worst case conditions, a deflection in excess of

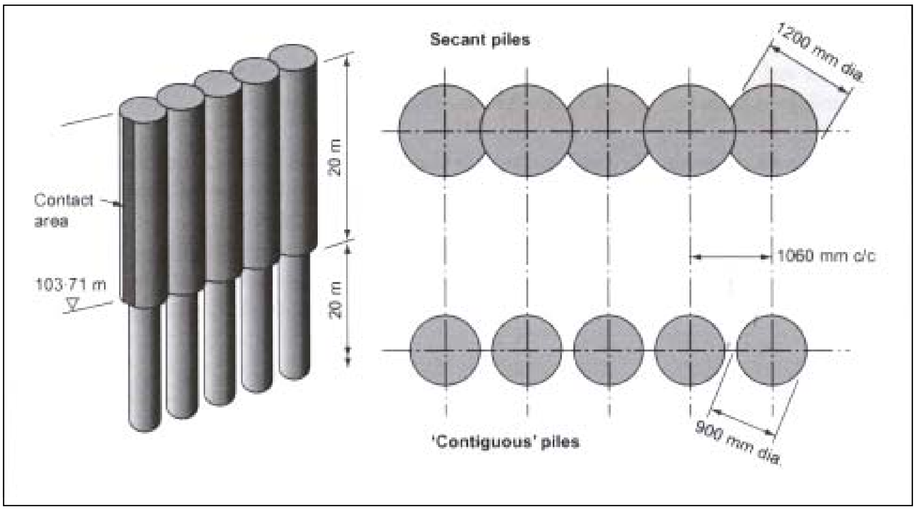

Fig.12 Secant/’contiguous’ piles

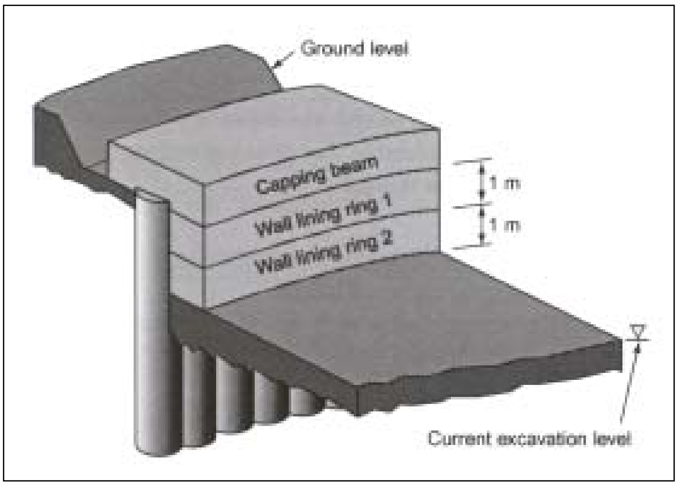

Fig.13 Construction sequence for wall lining: (1) excavate for current wall lining ring; (2) cast lining ring; (3) repeat sequence down to base slab level

75 mm could develop in the 900mm diameter “contiguous” piles. The intention was to avoid approaching this limit by applying, if necessary, one or more of the contingency measures. Success depended on early and reliable identification of deflection trends. The primary instrumentation comprised inclinometers in the piles and adjacent ground and precise levelling. The inclinometers were series of beam mounted electrolevels. Secondary instrumentation involved piezometers, extensometers and spatial survey (Fig. 14).

Performance

The average maximum deflection of the piled walls was around 15 mm which was considerably better than the worst case scenario. Figure 15 shows the overall maximum deflections recorded. The control of lateral ground movement compares favourably with other case histories of deep excavations in London Clay (eg Burland & Hancock[17] 1977 and Marchand[18] 1993). Average deflections were about 50% less than those predicted for the most probable conditions assessed prior to construction. By an excavation depth of 7m, comfortable deflection trends were evident. This enabled beneficial design changes to be introduced. The first change was to increase the depth of excavation and liner ring construction from 1m to 1.2m. This change, permitting a faster rate of construction, was made from liner ring 10 onwards.

Another significant design change was the incorporation of early station tunnel breakthroughs (Fig. 16). The original design plan was to take the lining sequence completely down to base slab level thus maintaining the rhythm of construction and monitoring. Early tunnel breakthroughs were achieved well ahead of bulk excavation within the cofferdam. In addition to advancing bored tunnel construction, this allowed early progress for track work. The line was opened on 25th May 1998, only 6 months late. The cofferdam was a key element of this success and the use of the observational method made a major contribution in savings estimated at £1.25 million.

RISK MANAGEMENT

The observational method is essentially a risk management system. Yet concerns about increased risk are usually among the first to be expressed when introduction of the observational method is proposed. However, it is the experience of the author that application of the method leads to increased safety. This may be achieved, for example, by:

a. avoiding inappropriate contingencies
b. eliminating heavy and constricting temporary works and creating freer working space
c. focusing awareness on the importance of teamwork, good communication, clear procedures, control during construction, and the need for planned contingency measures.

Starting with a design based on estimations of the most probable conditions may not be acceptable. The associated level of risk perceived by some parties to the contract may be too high. Concerns may arise from lack of case history data or confidence in the quality of information and proposed parameters. Without an alternative strategy, use of the observational method may not be approved. For Mansion House and Heathrow Express cofferdam design concerns were raised. At Limehouse Link contractual conditions were also an issue. The constraints in all three case histories were overcome by using the observational method through progressive modification.

VALUE ENGINEERING

The strong compatibility between the observational method and value engineering was demonstrated at Limehouse Link.[19] Both techniques are directed at creating savings in cost or time.[5,20] They also demand an enhanced relation of design to construction and require similar contractual conditions. The inclusion of a value engineering clause in a construction contract can facilitate the introduction of the observational method. The Heathrow

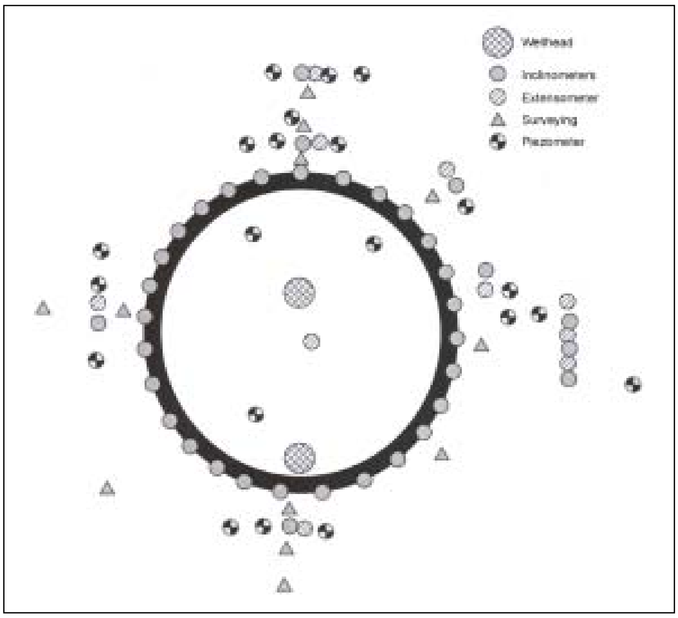

Fig.14 Cofferdam instrumentation

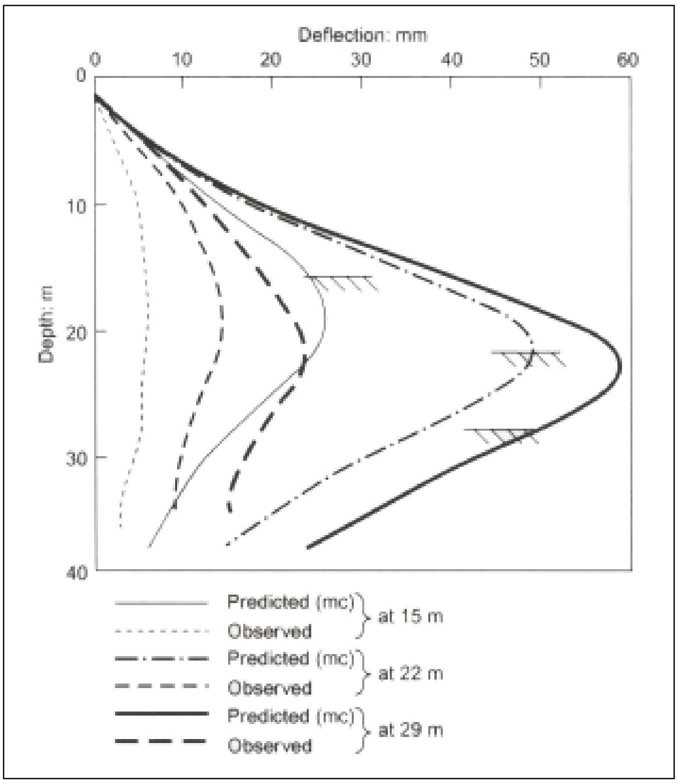

Fig15 Wall deflections

Fig.16 Early tunnel breakthrough

Express cofferdam was another application where the two techniques were combined.[21,22,23] The New Engineering Contract[24] (NEC), adopted for this project, facilitates change and, with the single team culture, made the conditions very conducive to application of the observational method. Published in 1995, this form of contract seeks to establish a fair balance of risk between the parties.

CONCLUSIONS

The observational method can very successfully achieve its main objectives – savings in cost or time or the assurance of acceptable safety. However, there are important limitations. The overall conditions to apply the method must be suitable. The key requirements[1] must be understood and carefully applied. It is important to identify trends and to separate key construction induced events from background or secondary effects. The rigour demanded by these requirements is onerous. They impose time and cost penalties that at least need to be balanced by the benefits achieved. The direct benefits to a project can be very considerable. The observational method also promotes innovation through:

i) Stronger connection of design to construction
ii) Increased safety during construction
iii) Improved understanding of soil/structure interaction
iv) Improvements in the use and performance of instrumentation
v) Higher quality case history data
vi) Greater motivation and teamwork

The benefits of innovation for the Heathrow cofferdam, for example, were assessed against the Egan[25] targets.[26]

Although the observational method has its limitations it is still significantly under used. Traditional contractual conditions can separate design from construction and impede a team approach to the management of risk. The paper has described how, using simple but critical measurements, an incremental approach can overcome contractual and technical constraints. Progressive modification thus offers the opportunity maximise potential benefits while maintaining and demonstrating the required level of safety.

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