TRANSPORT RESEARCH LABORATORY

## TRL REPORT 228

# MOVEMENT TRIGGER LIMITS WHEN APPLYING THE OBSERVATIONAL METHOD TO EMBEDDED RETAINING WALL CONSTRUCTION ON HIGHWAY SCHEMES

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**This report describes work commissioned by the Bridges Engineering Division of the Highways Agency under E552C/BG, Evaluation of Observational Method in Embedded Retaining Wall and Cut-and-Cover Tunnel Construction.**

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# EXECUTIVE SUMMARY

Current research on embedded retaining walls and cut-and-cover tunnels is oriented towards monitoring of performance. Increasing emphasis in the construction industry is being placed on the Observational Method where immediate feedback from monitoring is used to modify the design and construction procedures according to a pre-determined plan. This report provides guidance on suitable movement trigger limits for use in developing Observational Method options for highway retaining structures, in particular where bored pile and diaphragm walls are being constructed for retained cuttings and cut-and-cover tunnels in stiff clay. It does not cover the use of sheet pile walls which are the subject of a separate study.

A contingency action plan that sets out procedures to be followed if specified criteria are exceeded is essential for the implementation of the Observational Method. A suitable plan is presented in the report that defines a "traffic light system" of green, amber and red construction condition zones for horizontal top of wall movements. Trigger limits are established that define the upper bounds of each of these zones and provide assistance in developing design and construction methodology. In accordance with a contingency action plan, pre-determined forms of intervention are required if the trigger levels are exceeded. Modification of the design to achieve economies may be initiated if measured values are smaller than the best estimate of movement.

Suitable movement trigger limits are established for the implementation of the Observational Method for the design and construction of embedded retaining structures in stiff clay where low, moderate and high stiffness temporary support is provided during bulk excavation. These limits are derived from the results of an earlier TRL study of wall movements where retained cuttings and cut-and-cover tunnels have been constructed on highway schemes (Carder, 1995).

Care is required in the selection of movement trigger limits since factors such as the arrangement and degree of support stiffness can change during the various construction stages. The effect of a high stiffness temporary support to a wall during bulk excavation can reduce the maximum horizontal top of wall movement by some 60% to 70% compared to a low stiffness support system. It is important, therefore, to take account of changes in support stiffness in establishing a contingency action plan and setting trigger limits. It is also necessary to confirm, by monitoring the wall deflected shape, the depth at which maximum horizontal wall movement occurs.

# MOVEMENT TRIGGER LIMITS WHEN APPLYING THE OBSERVATIONAL METHOD TO EMBEDDED RETAINING WALL CONSTRUCTION ON HIGHWAY SCHEMES

## ABSTRACT

This report provides advice on suitable movement trigger limits to allow the Observational Method to be implemented for the design and construction of highway retaining structures. A contingency action plan defining trigger limits for horizontal wall movements for low, moderate and high stiffness supported retaining structures is presented. These limits are derived from the results of a TRL study of wall movements where retained cuttings and cut-and-cover tunnels were being constructed for highway schemes (Carder, 1995).

The contingency action plan will enable the use of the Observational Method to be evaluated and, where appropriate, incorporated into the design and construction methodology. This report should, therefore, be of direct interest to all engineers involved in the planning, design and construction of highway schemes.

## 1. INTRODUCTION

This report presents a set of movement trigger limits for use in developing Observational Method options for highway retaining structures, in particular where bored pile and diaphragm retaining walls are being constructed for retained cuttings and cut-and-cover tunnels. It does not cover the use of sheet pile walls which are the subject of a separate study.

In geotechnical engineering the current state of the art is such that predictions of performance are subject to a considerable degree of uncertainty. Among the reasons for this is the difficulty in predicting the construction performance of structures from a limited number of tests on soil samples. The engineering properties of the soil mass are also stress level, stress path and frequently time dependent. They are controlled by factors such as the following.

- The previous geological history.
- The proposed type and sequence of construction.
- The loads to be carried in service.

For small and medium sized structures, the inherent uncertainties referred to above are normally catered for in design by adopting conservative values of soil properties in conjunction with lumped factors of safety (Padfield and Mair, 1984) or by a factor on soil strength (BS 8002: 1994). For larger and more complex structures, however, any over-conservatism may lead to unacceptably high costs, including difficult construction sequencing and programme penalties.

Monitoring the behaviour of structures provides the most reliable means of evaluating the design judgements and methods used, from comparisons of measured and predicted behaviour. Where field monitoring forms an integral part of the overall design and construction process on a scheme specific basis, as in the Observational Method (Peck, 1969), the need for conservatism in the design assumptions can be reduced. Adoption of the method can result in significant enhancement in project value such as financial savings, operational efficiency and environmental acceptability without compromising safety.

Earlier work at TRL (Carder, 1995) established a database of measured ground and wall movements at schemes where retained cuttings, cut-and-cover tunnels and deep basements have been constructed using embedded retaining walls. This database includes results from a large number of construction schemes instrumented by TRL and others in the UK and also, where they are considered relevant to UK practice, results from elsewhere in the world. General equations have been established for the likely magnitude of maximum lateral wall movement and zone of movement of the ground surface due to installation and excavation effects for various types of embedded walls.

This report uses the findings of the earlier work to develop a set of simple design rules for horizontal wall movement that can be used to define trigger limits for use in developing Observational Method options for highway schemes.

## 2. APPLICATION OF THE OBSERVATIONAL METHOD

The key construction periods during which the Observational Method could be implemented for highway retaining structures are as follows.

- Wall installation.
- Installation of any temporary propping.
- Excavation in front of the wall.
- Installation of any permanent props.
- Removal of any temporary propping.

By its very nature it is unlikely that the Observational Method could be applied post-construction since very little action can be taken retrospectively to the design or construction methodology adopted.

The Observational Method described by Peck (1969) can be applied in two ways.

1. *Ab initio*: Where the use of the Observational Method is planned from the start of the project with the object of progressively modifying the design to minimise cost and construction time while maintaining an acceptable level of safety. It is commonly implemented either at tender preparation by the client/engineer or as an alternative proposed design by the tenderer.
2. *Best way out*: During construction when unforeseen conditions are encountered. In these situations the Observational Method may offer the only possibility of a satisfactory solution by providing the required assurance of safety.

The *ab initio* application involves developing an initial design based on *most probable* conditions, together with predictions of behaviour. Calculations based on *most unfavourable* conditions are also made and these are used to identify contingency plans and trigger values for the monitoring system. In this connection it is important to ensure that measured observations are appropriate and meaningful. The key to successful application of the Observational Method is to ensure measurements combine comprehensiveness with reliability, repeatability and simplicity.

A fundamental requirement of the Observational Method is the identification of design options that allow changes to be made during construction. If this is not possible then the implementation of the method is usually inappropriate. In addition its use can be dependent on the mode of failure of the structure. Nicholson (1994) discusses the modes of failure and identifies that the method is best applied where a gradual development of movement may lead to eventual failure of the structure. However where sudden failure might occur, such as collapse of an embedded wall or temporary prop, the method is likely to be inappropriate because there is little margin in terms of the available time to implement appropriate contingency action plans. For any highway retaining structure these limitations to the use of the Observational Method should be considered at the design stage.

# 3. MEASURING BEHAVIOUR

In order to successfully implement the Observational Method it is necessary to establish appropriate monitoring systems that can be effectively installed under construction site conditions. The behaviour of a highway retaining structure can be generally measured using several indicators.

- Lateral movement profile of the wall.
- Strains in both temporary and permanent structural elements, e.g. hence prop loads and wall bending moments.
- Soil and water pressures acting on the structure.
- Ground movements behind and in front of the wall.

Of these, the lateral movement profile of the wall is one of the most practical ways of monitoring behaviour. This is particularly the case for retaining cuttings and cut-and-cover tunnels that utilise embedded walls in urban areas where land-take is restricted and access for measurements is difficult. Furthermore wall movement measurements can be readily reviewed by site personnel and compared with pre-defined trigger limits for initiation of contingent actions and modification to the design.

Frequency of monitoring is also an important consideration in the implementation of the Observational Method. It is common practice to use rate of lateral wall displacement or rate of convergence of opposing walls to monitor behaviour during excavation and temporary and permanent prop installation (Powderham, 1994; Glass and Powderham, 1994).

Wall deformation can be measured rapidly as well as reliably using inclinometers or electro-levels cast into the wall. Absolute wall movement with respect to a fixed datum can be undertaken using surveying equipment. Depending on the required accuracy of measurements, an electronic distance measuring device (EDM) or conventional theodolite is usually capable of short-term measurements to ±2mm. For more accurate and long-term measurements a Geomensor/Mekometer EDM can read to better than ± 0.5mm. In all cases, the measuring device needs to be mounted on fixed pillars rather than a tripod to achieve reproducibility of movements. Other specialised techniques, such as tape extensometers, are described by Hanna (1985) and Dunnicliff (1988).

Prop loads have also been used for control purposes but in conjunction with wall movement measurements (Glass and Powderham, 1994). Monitoring loads in structural elements is not as easy as measuring wall movements. Load effects can also develop slowly with time and cannot be relied upon, therefore, to provide a sufficiently rapid indication of unacceptable wall behaviour during construction such that contingency plans can be implemented. Measurements such as bending moment in the wall usually require specialised expertise for interpretation and potentially this can lead to further delays in the decision making process.

For similar reasons as described above measurement of soil and water pressures may not provide rapid identification of unacceptable wall behaviour and results may be difficult to interpret. Ikuta et al (1994) describe the application of the

Observational Method to a deep basement construction in which lateral soil pressure, pore water pressure and wall displacement were measured as excavation progressed. These measurements were used to calculate maximum lateral displacement and bending moment in the wall that were compared to trigger levels related to excavation stability. The implementation of the Observational Method enabled progressive modification of the design for subsequent stages of construction particularly the decision to leave out temporary diagonal steel struts.

Monitoring ground surface movements can be essential where the effect of wall installation and excavation on adjoining structures, buildings or buried services is important. In this situation both horizontal and vertical movements of the retained ground surface are likely to be relevant and these can be measured using tensioned tape extensometers, EDM and precise levelling techniques (Dunnicliff, 1988).

# 4. IMPLEMENTATION FRAMEWORK FOR HIGHWAY STRUCTURES

## 4.1 BENEFITS OF IMPLEMENTATION

For new highway schemes it is likely that the Observational Method will be implemented in order to accommodate one or more of the following.

- Eliminate or reduce temporary propping.
- Rationalise wall design by reducing penetration or thickness.
- Change permanent prop design.

Wall installation, excavation and propping sequence, particularly in over-consolidated strata, will influence retaining wall behaviour and ground movements behind the wall. The use of temporary propping is usually the major cost element in the construction of a retained structure. Eliminating or reducing the number of temporary props not only directly reduces the material cost but it also increases working space in the excavation allowing more efficient working practices. Further benefits are an increased speed of construction and cost savings whilst maintaining an acceptable level of safety.

It is these aspects of design and construction where the use of the Observational Method can provide significant advantages. Glass and Powderham (1994) report a saving of some 90% in total weight of temporary steel work for intermediate propping for the Limehouse Link highway scheme. In addition, sections of temporary sheet pile walls used as cofferdams had embedment depths reduced from 4m to 0.5m below base slab by implementation of the Method. Design modification to the blinding base strut was also possible with a reduction in thickness from 300mm to 100mm being achieved.

The construction of retaining walls using soil berms in front of the wall to provide temporary support is another opportunity to use the Observational Method to best advantage. Carder and Bennett (1996) describe the use of soil berms to control wall movement and have evaluated their efficiency from numerical models using finite element analysis.

## 4.2 CONTINGENCY ACTION PLAN

A contingency action plan that sets out procedures to be followed if specified criteria are exceeded is essential for the implementation of the Observational Method. Contingencies might include an increase in temporary support using props or by backfilling the excavation.

Generally the range of movement that can be accepted for a particular construction condition is sub-divided into green, amber and red construction condition zones following the "traffic light" approach of Glass and Powderham (1994). The recommended contingency action plan related to each condition zone is shown in Table 1.

Similar contingency action plans as shown in Table 1 have already been adopted on some retained highway cuttings, cut-and-cover tunnels and deep basement schemes. In principle the trigger limits are set which define the boundaries between the construction condition zones and describe the magnitude and rate of convergence of opposing embedded retaining walls.

For most cantilever walls, maximum horizontal movement occurs at the wall top. However, for walls with high stiffness support during construction, such as cut-and-cover tunnels using top-down construction techniques, the maximum horizontal wall movement occurs just above excavation/formation level (Carder, 1995). It is therefore important that the design of the monitoring system is such that it can detect maximum wall movement at the appropriate wall depth. This is particularly the case in situations where wall behaviour changes as the temporary support stiffness is varied during different construction stages, as described in Section 5.

The amber trigger limit is set at the boundary of the green and amber condition zones. Movements contained within the green zone are less than the *most probable* prediction and are not a cause for concern. Whilst movements remain in this zone it is possible to progressively modify the design to achieve economies in construction without compromising safety, e.g. by reducing the number and sequence of temporary props, increasing the length of an excavation bay, reducing the thickness of a blinding strut at formation level, or speeding up construction.

## TABLE 1

General framework for contingency action plan

| Wall movement | Condition[1] | Action[1] |
|---|---|---|
| Less than the most probable movement prediction | Green zone | No cause of concern: look to achieve economies or speed up construction |
| Between most probable and upper bound movement prediction | Amber zone | Movements causing concern - increase frequency of monitoring to predict rate and whether movements would exceed the upper limit of the amber zone |
| Greater than upper bound movement prediction | Red zone | Increase reading frequency - initiate contingencies and actions such as increasing temporary or permanent support |

Note:
1. After Glass and Powderham (1994).

Horizontal wall movements in the amber condition zone are approaching the predicted upper bound movement. This usually necessitates an increased monitoring frequency, and possibly an increase in the number of monitoring points, to establish the rate of movement and the possible development of unacceptable trends and so allow the timely implementation of contingency measures. If wall movements continue to increase and exceed the red trigger limit, set at the boundary of the amber and red zones, contingency measures should be initiated. These measures are required to prevent wall movement continuing to the upper boundary of the red zone, the *most unfavourable* movement prediction beyond which damage or collapse of the structure can occur.

Typically the contingencies initiated for wall movements entering or predicted to enter the red zone are as follows:

- Modification of the design and construction method with a possibility of introducing more temporary support.
- The installation of *soft* temporary props (props installed in place but not fixed) as a precautionary measure. These props can be rapidly loaded to provide additional support if it is needed.
- The installation of *hard* temporary props (props fixed to wall) and capable of restraining further horizontal wall movement.
- Temporary backfilling of the excavation to provide more support.
- Remove surcharge/excavate some retained soil/introduce drainage to reduce earth and water pressure on retained side of wall.
- A combination of the above.

## 4.3 TRIGGER LIMITS

Careful selection of the trigger limits for horizontal wall movement is essential to implementation of the contingency action plan outlined in Table 1. These limits can be determined from a number of techniques such as:

- Wall movement predictions from numerical models, such as finite element analysis.
- Previous observations of horizontal movements on a retaining structure of similar design and constructed in similar ground conditions.
- Statistical analysis of horizontal movement from case studies on retaining structures in general, etc.

Trigger limits can be established by assuming that the horizontal movement data have a normal probability distribution from which the green, amber and red zones described in Section 4.2 and Table 1 can be defined. Figure 1 shows the principle of this assumption in which the best estimate of horizontal wall movement, derived from one of the above techniques, represents Peck's *most probable* condition for given loads, geometry and ground conditions. The best estimate of movement can be taken to represent a safe upper limit to the green condition zone. This is generally a safe assumption since in practice measured horizontal wall movements are often less than those predicted.

The upper bound of predicted wall movement can be regarded as representing the transition from the amber to the red condition zone and the trigger at which contingency action is required to avoid unacceptable movements. Within the amber zone, examination of the rate of movement is advisable to ensure that contingency action is taken early for movements predicted as rapidly entering the red zone.

One approach for determining movement values for the various trigger limits is by using the upper bound move-

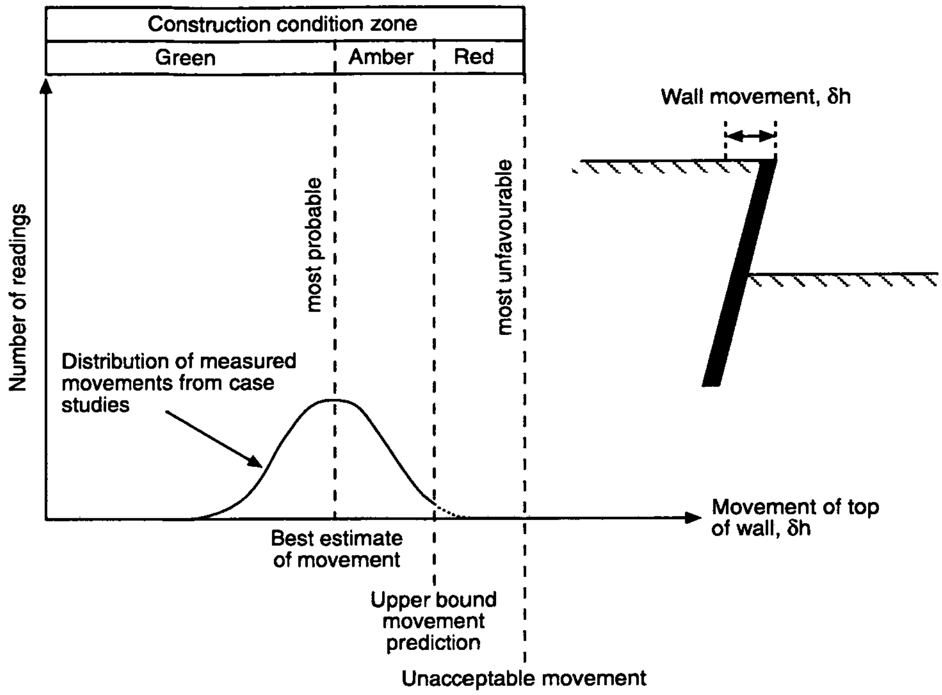

**Fig 1. Application of Observational Method to highway structures**

ments from reviews of case history studies such as those reported by Carder (1995) and O'Rourke (1981). Then using a similar philosophy to that adopted in Departmental Standard BD37 Clause 5.4.8.1 (DMRB 1.3), an appropriate value for the *most unfavourable* limit of movement (Fig 1) for a highway structure is proposed as 1.3 times the predicted upper bound movement. It is also considered that a safe assumption is to factor down the upper bound prediction by 1.3 to give an estimate of the *most probable* behaviour, i.e. the trigger limit set between the green and amber condition zones.

# 5. TRIGGER LIMIT DERIVATION FOR STRUCTURES IN STIFF CLAY

Horizontal wall movements are controlled by the stiffness of the temporary or permanent support provided. The influence of support stiffness on wall movement was investigated by O'Rourke (1981). More recently Carder (1995) has identified three categories of support stiffness for embedded walls in stiff clay.

- Low stiffness support during excavation, e.g. cantilever, temporary props of low stiffness or at low level.
- Moderate stiffness support during excavation, e.g. temporary props of high stiffness prior to permanent props at low level.
- High stiffness support during excavation, e.g. top-down construction, temporary props prior to permanent props at high level.

For the three categories of stiffness a general relationship for predicting the upper bound horizontal movement of the wall top was established from observed movements of retained cuttings, cut-and-cover tunnels and deep basements that were constructed using embedded retaining walls.

Generally the observed walls were constructed in stiff clay and designed taking into account the recommendations of CIRIA 104 (Padfield and Mair, 1984) and Departmental Standard BD42 (DMRB 2.1). These documents adopt limit state principles for the design of overall stability and structural elements and incorporate factors of safety in accordance with BD37 (DMRB 1.3). For this reason the estimate of the upper bound horizontal movement at the top of the wall based on a number of case histories (Carder, 1995) can be taken to represent the upper bound of predicted movement ($\delta h_{max}$) and, therefore, the upper limit of the amber condition zone, see Figure 1. As stated in Section 4.3 the limit of *most unfavourable* movement can be taken as 1.3 times the predicted upper bound movement (i.e. $1.3\delta h_{max}$) and represents the red zone upper limit beyond which collapse or substantial damage to the structure can occur. A safe assumption is to define the upper limit of the

## TABLE 2

Derived trigger limits for retaining structures in stiff clay with varying support stiffness

| Condition zone | Upper limit to horizontal top of wall movement $\delta h/D$ [1]<br>Low stiffness support | <br>Moderate stiffness support | <br>High stiffness support |
|---|---|---|---|
| Green | 0.30% | 0.15% | 0.10% |
| Amber | 0.40% | 0.20% | 0.125% |
| Red | 0.52% | 0.26% | 0.16% |

Note:

1. $\delta h$ = movement of the top of the wall
   D = depth of excavation.

green zone as the upper bound of predicted wall movement factored down by 1.3 (i.e. $\delta h_{max}/1.3$) which is taken to represent the *most probable* behaviour.

Using the general relationship for horizontal wall movement identified by Carder (1995) the upper bound values can be established for any embedded wall and support stiffness and, hence, the limits of the green, amber and red condition zones. Table 2 shows the resulting trigger limits for horizontal movement at the top of the wall, $\delta h$, which are calculated.

As can be seen from Table 2 the choice of low, moderate or high stiffness support significantly reduces the trigger limits. Care is required, therefore, in selecting an appropriate support stiffness for each particular construction stage and in ensuring that the choice does not violate the original design assumptions. During initial excavation to provide access for any prop installation, the structure will act as a low stiffness cantilevered wall. A change in category of support stiffness then occurs when temporary or permanent props are installed. This should be taken into account when choosing the trigger limits.

It should be noted that for embedded walls with high stiffness support during excavation the maximum wall movement is not likely to be measured at the wall top but near final excavation level (Carder, 1995). Additional monitoring of horizontal movement at low level might also be required for this type of construction.

An example of a contingency action plan and derivation of trigger limits for the main construction stages of an embedded wall propped at formation level and founded in stiff clay is given in Appendix A. Plans for other structural forms can be developed following the same principles.

To demonstrate the validity of the trigger limits derived from Table 2 a comparison has been made with the limits implemented on site during the construction of the cut-and-cover tunnel at Limehouse Link. For the purposes of this report, only the trigger limits applicable to the stages of bulk excavation and temporary prop installation have been considered. The results are presented in Appendix B and are consistently lower than the trigger limits implemented on site for the green, amber and red condition zones. The derived values are, however, more consistent with actual measured values of maximum horizontal wall movement recorded during construction.

# 6. SUMMARY AND CONCLUSIONS

In this report a simple framework based on movement trigger limits has been established to allow the development of Observational Method options for the design and construction of highway retaining structures. The main points of the framework are as follows.

(i) A contingency action plan following the "traffic light" approach of Glass and Powderham (1994) that defines green, amber and red construction condition zones is recommended. The contingency action plan allows decisions to be made regarding the feasibility of using the Observational Method for specific highway schemes and, where appropriate, to be incorporated into the design and construction methodology.

(ii) For embedded retaining wall construction, selection of trigger limits between construction condition zones is generally best based on horizontal wall movement data. However, environmental factors such as sensitivity of nearby existing structures to construction, health and safety of construction workers, site working practices and phasing of works should also be taken into account when setting trigger limits. These factors may have risk implications which necessitate monitoring of other factors in addition to horizontal wall movement.

(iii) Care is required in the adoption of trigger limits since factors such as the arrangement and degree of support stiffness can change during construction stages. For embedded walls that are cantilevered or have low stiffness support during excavation, the maximum wall movement is likely to occur at the top. For embedded walls with high stiffness support during excavation the maximum wall movement is likely to occur near final excavation level. In this situation an additional set of trigger limits might be required to monitor and control movement at this depth as well as at the wall top.

(iv) Numerical values are proposed in Table 2 for the trigger limits between construction condition zones for horizontal top of wall movements for structures with low, moderate and high stiffness support during excavation and founded in stiff clay. These limits are based on the results of a TRL study of wall movements on schemes where retained cuttings and cut-and-cover tunnels have been constructed (Carder, 1995). The effect of a high stiffness support to the wall during excavation is to reduce the maximum horizontal top of wall movement by about 70% compared to a low stiffness support system.

## 7. ACKNOWLEDGEMENTS

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DESIGN MANUAL FOR ROADS AND BRIDGES (DMRB)

Volume 1: Section 3 General Design
BD 37 *Loads for Highway Bridges. Use of BS 5400: Part 2* (DMRB 1.3)

Volume 2: Section 1 Sub structures
BD 42/94 *Design of embedded retaining walls and bridge abutments (unpropped or propped at the top)* (DMRB 2.1)

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# APPENDIX A: EXAMPLE OF A CONTINGENCY ACTION PLAN FOR A HIGHWAY RETAINING STRUCTURE

## A.1 INTRODUCTION

To demonstrate the application of the contingency action plan based on movement trigger limits shown in Table 2 of the report, an embedded retaining wall construction sequence is considered that is typical of that employed for many highway retaining structures.

## A.2 DESIGN AND CONSTRUCTION SEQUENCE

Consider an embedded retaining wall structure, propped at formation and founded in stiff clay, designed in accordance with CIRIA 104 (Padfield and Mair, 1981) and BD42 (DMRB 2.1). The embedded retaining wall is formed from 17m deep, 1.5m diameter contiguous bored concrete piles with a permanent prop at formation level resulting in a finished retained wall height of 8m. The width of the excavation between opposing walls is 25m. Excavation in front of the wall takes place initially to 2m depth before installation of a row of temporary steel props. Bulk excavation continues below temporary props to final dig level approximately 9m below original ground level. After construction of the permanent prop, at carriageway level, the temporary props are released and removed.

## A.3 CONTINGENCY ACTION PLAN

The contingency action plan and movement trigger limits can be defined taking into account the wall/excavation geometry and prop system stiffness for each construction stage as follows.

### A.3.1 Installation of wall

Installation of an embedded wall can cause movement of the adjoining ground. Carder (1995) identifies maximum surface horizontal movements ranging from 0.04% of the pile depth for contiguous piling to 0.08% of the pile depth for secant piled walls. Maximum surface settlements are about half of the horizontal movement. In all cases the zone of movement extends no more than 1.5 times the pile depth.

The Observational Method only needs to be employed at wall installation stage if there is a risk to nearby buildings or buried services. Trigger limits based on ground movement measurements at critical distances from the wall need to be established.

For example, if surface movements immediately adjoining the contiguous piling are critical, the anticipated upper bound of horizontal ($\delta h$) and vertical ($\delta v$) ground surface movements are estimated as:-

$\delta h = P \times 0.04\% = 17 \times 1000 \times 0.04/100 = 6.8\text{mm}$

$\delta v = P \times 0.02\% = 17 \times 1000 \times 0.02/100 = 3.4\text{mm}$

where P is the overall penetration of the piles.

These values may form the upper trigger limits of the *amber* zone, with trigger limits for the *green* and *red* zones being determined by dividing and multiplying by 1.3 respectively. However these values for ground movements at installation stage have little relevance in terms of the performance of the new structure and should be established in terms of the risk implications to nearby buildings or buried services.

### A.3.2 Initial excavation to 2m depth

The initial excavation will be unsupported with the wall acting as a free cantilever as there is sufficient embedment for fixed earth support to operate at the wall toe. Behaviour will therefore lie in the "low support stiffness" category and from Table 2 the upper trigger limits for horizontal top of wall movement for the zone conditions green, amber and red can be derived as follows.

*Green - best estimate of movement*
$\delta h = D \times 0.3\% = 1 \times 1000 \times 0.3/100 = 3.0\text{mm}$

*Amber - upper bound of predicted movement*
$\delta h = D \times 0.4\% = 1 \times 1000 \times 0.4/100 = 4.0\text{mm}$

*Red - most unfavourable movement*
$\delta h = D \times 0.52\% = 1 \times 1000 \times 0.52/100 = 5.2\text{mm}$

where the depth of the excavation (D) has been reduced by 1m to allow for the 1m deep excavation on the retained side of the wall used to provide temporary access for pile trimming.

Although excessive wall movement is unlikely at this stage, it can be readily prevented by excavation to the same depth on both sides of the wall. Indeed this is quite often undertaken in order to construct formwork to cast-in-place a capping beam to the wall.

### A.3.3 Bulk excavation below temporary props

Bulk excavation to formation level at 9m below original ground level will be undertaken below temporary steel props. As described in Section 5, a moderate support stiffness is considered appropriate for this stage of construction. From Table 2 the upper trigger limits for horizontal top of wall movement for the zone conditions green, amber and red are as follows.

*Green - best estimate of movement*
$\delta h = D \times 0.15\% = 9 \times 1000 \times 0.15/100 = 13.5\text{mm}$

*Amber - upper bound of predicted movement*
$\delta h = D \times 0.2\% = 9 \times 1000 \times 0.2/100 = 18.0mm$

*Red - most unfavourable movement*
$\delta h = D \times 0.26\% = 9 \times 1000 \times 0.26/100 = 23.5mm$

If horizontal movements remain in the green zone then it is possible to reduce the number of temporary props or to leave some props unloaded. If movements progressively increase into the amber zone this will cause concern and it is necessary to instigate an increased frequency of monitoring to predict rate of movement and anticipate whether movements will continue to increase into the red zone. If movements enter the red zone then contingency measures such as increasing temporary propping are necessary to prevent eventual collapse or structural distress.

It is important to note that if movements are so small that temporary props are not needed at all, the trigger limits on movement calculated assuming moderate stiffness support are still appropriate. Adoption of trigger limits for cantilever structures (low stiffness support during excavation) will violate the original design criteria as insufficient wall embedment will exist for stability. The significant differences in wall bending moments and shear forces will also need to be assessed if the construction sequence is modified to that of bulk excavation without temporary propping.

The thermal movement of temporary steel props needs to be considered when applying the trigger limits. When fixed in place, thermal expansion or contraction of the temporary prop can cause movement of the wall which may be of a similar magnitude to that caused by loading effects and soil pressures (Yeow, 1994). It is important, therefore, to make allowance for thermal effects on horizontal wall movements when deriving the trigger limits to implement the Observational Method.

For this example, the expansion of the temporary steel prop is calculated assuming a coefficient of thermal expansion of steel of $12 \times 10^{-6}$ per °C, a change in prop temperature of 20°C, and a prop length of 25m. On this basis a value of 6mm is calculated so that, if expansion occurs uniformly, the maximum induced wall movement at each end of the prop is 3mm. It must be noted that the change in temperature needs to be calculated from the datum at which the prop is loaded and that the change in black steel may be of the order of twice that of the ambient temperature.

If the temperature of the prop falls by 20°C from its installation datum, then wall movements towards the excavation may therefore increase by 3mm and trigger limits should be increased accordingly. The significance of these thermal effects, in terms of movement towards the excavation, is clearly reduced if temporary props are loaded in cold weather, although increased prop load capacity may then be necessary.

### A.3.4 Installation of permanent prop and release of temporary props

Installation of the permanent prop and removal of the temporary props will not effect the support stiffness category and, as the maximum excavation depth has remained unchanged, movements can be controlled using the same trigger limit values as indicated in Section A3.3.

Additional horizontal movements of the top of the wall towards the excavation will occur on temporary prop release. Some movement will also occur at carriageway level as load is taken up by the permanent prop: the magnitude of this movement will depend on the nature of the wall/prop connection (Powrie and Li, 1991; Potts, 1993).

At this stage the permanent works are complete and, provided a safe design has been employed, measurements may be discontinued. If however horizontal movements at the top of the wall are approaching the upper bound of predicted movement and nearly into the red condition zone, continued monitoring of wall movement should be undertaken to demonstrate that wall movements in service will remain below the most unfavourable prediction.

Continued but less frequent monitoring of wall movement in the longer term may help to provide valuable feedback of the performance of the structure and the validity of the trigger limits for the implementation of the Observational Method on other highway schemes.

# APPENDIX B: THE LIMEHOUSE LINK CUT-AND-COVER TUNNEL

## B.1 INTRODUCTION

Limehouse Link is a major cut-and-cover tunnel built to connect the City of London and London's Docklands. The Observational Method was implemented under a value engineering clause which allowed the design of the tunnel to be progressively modified during construction resulting in significant savings in construction programme and costs (Glass and Powderham, 1994). The method allowed a reduction in temporary support of the retaining walls during bulk excavation. In addition design changes were introduced progressively during construction whilst horizontal movements remained consistent with Peck's *most probable* condition.

## B.2 TRIGGER LIMITS

Trigger limits were set which related to the magnitude and rate of convergence of opposing tunnel walls. The trigger limit of 20mm (wall movement) was set at the boundary of the green and amber condition zones as described in Table 1. Movements contained within the green zone were not a cause for concern and allowed the design to be modified by initiating a construction sequence without mid-height props and the additional possibility of increasing the length of the excavation bay and/or reducing the thickness of the blinding strut.

The trigger limit of 25mm marked the boundary between the amber and red zone. Measurements recorded in the amber zone signified that wall movements were causing some concern. This initiated the contingency of increased frequency of monitoring to assess whether the wall movement would exceed the second trigger limit before the blinding strut or base slab were cast. The rate of movement was important to identify the development of unacceptable trends and so allow the timely implementation of contingency measures.

The contingencies initiated for wall movements entering or predicted to enter the red zone were either:

- the use of temporary *hard* props (props fixed to wall) would be resumed, or
- during construction without temporary props, installation of *soft* props would be triggered as a contingency measure. Modification of the design would then involve assessments to reintroduce more temporary support on the basis of wall monitoring results.

The construction method and cycle time were then selected so that there was sufficient flexibility to allow for the taking and assessment of measurements of horizontal wall movement. The design/construction methods were then modified using actual measurements.

## B.3 COMPARISON WITH DERIVED TRIGGER LIMITS

The geometry of the cut-and-cover tunnel cross-section varied along the route of the scheme including the sequence and arrangement of temporary support during excavation. Typically, however, the embedded retaining walls were formed from reinforced concrete diaphragm panels some 22m in depth below ground level. A top-down method of construction was generally adopted for the cut-and-cover tunnel sections where the Observational Method was employed. A variable sequence of construction was implemented, however, with temporary props being initially installed at 2.5m depth (above soffit level of the permanent roof slab) and at 10m depth (above soffit level of the permanent base slab). Total excavation depth was some 13m below ground level. As work progressed the temporary props were gradually left out of the construction sequence. The reduction in propping during construction is considered to correspond to a reduction from high stiffness to moderate stiffness support.

For the purposes of this report, trigger limits applicable for bulk excavation and temporary/permanent prop installation only are considered. The trigger limits implemented on site are compared in Table B1 with those derived using the approach given in this report.

The trigger limits implemented on site corresponded to a maximum horizontal movement of the wall monitored from measurements of tunnel convergence. These values are compared with top of wall movements for both high and moderate stiffness support during excavation calculated from Table 2 and also with the movements calculated just above formation level. The latter values were based on the findings of Carder (1995) who showed that for walls with high stiffness support the maximum horizontal wall movement at depth is about 0.15% of the excavation depth. Using this relationship as the upper bound of predicted wall movement just above formation level, the trigger limits for the various construction conditions can be calculated.

There is reasonable consistency between the implemented and derived trigger values with the derived values being slightly lower. These trigger values can be compared with the maximum horizontal wall movements measured on site which were generally less than 11mm. No allowance has been made in the value of the derived trigger levels for thermal movement of the temporary props as described in Appendix A. This would be necessary if these values were to be used for a specific scheme.

# TABLE B.1

Comparison of implemented and derived trigger limits for bulk excavation and temporary prop installation

| | Trigger limit defining upper limit of wall horizontal movement (mm) | | | |
|---|---|---|---|---|
| Condition zone | Implemented (movement from tunnel convergence) | Movement just above formation (High stiffness support)[1] | Top of wall movement[2] | |
| | | | High stiffness support | Moderate stiffness support |
| Green | 20 | 15 | 13 | 20 |
| Amber | 25 | 20 | 16 | 26 |
| Red | 35 | 25 | 21 | 34 |

Notes:

1. From Fig 9 of Carder (1995).
2. From Table 2 with D = 13m.

# MORE INFORMATION

The Transport Research Laboratory has published the following other reports on this area of research:

TRL172 Ground movements caused by different embedded retaining wall construction techniques.
D R Carder. Price Code E.

TRL213 The effectiveness of berms and raked props as temporary support to retaining walls.
D R Carder and S N Bennett. Price Code E.

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