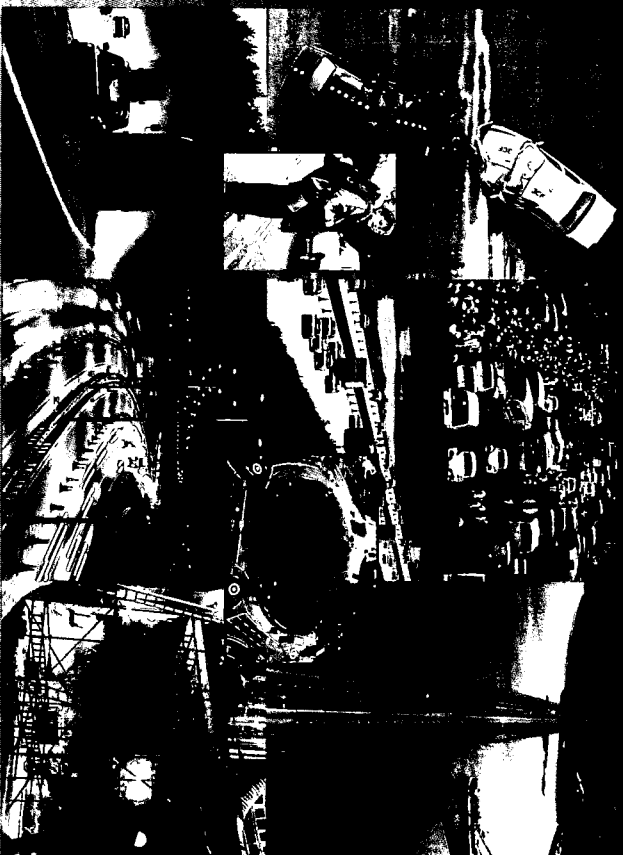


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**Ground movements caused by  
different embedded retaining wall  
construction techniques**

by D R Carder

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**TRL REPORT 172**

**GROUND MOVEMENTS CAUSED BY DIFFERENT EMBEDDED  
RETAINING WALL CONSTRUCTION TECHNIQUES**

by **D R Carder**

**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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Transport Research Laboratory  
Old Wokingham Road  
Crowthorne, Berkshire, RG45 6AU

Highway Agency  
St Christopher House  
Southwark Street, London SE1 0TE

1995  
ISSN 0968-4107

# CONTENTS

|  | Page |
|--|------|
| Executive Summary  | 1    |
| Abstract   | 3    |
| 1. Introduction  | 3    |
| 2. Methodology   | 3    |
| 3. Walls founded in stiff clay and instrumented by TRL       | 4    |
| 3.1 Surface ground movements caused by wall installation     | 4    |
| 3.1.1 Bored pile walls                                       | 4    |
| 3.1.2 Diaphragm walls  | 6    |
| 3.2 Movements caused by excavation in front of the wall      | 8    |
| 4. General experience with walls founded in stiff clay       | 10   |
| 4.1 Surface ground movements caused by wall installation     | 10   |
| 4.2 Movements caused by excavation in front of the wall      | 10   |
| 5. General experience with walls founded in other soil types | 14   |
| 5.1 Surface ground movements caused by wall installation     | 14   |
| 5.2 Movements caused by excavation in front of the wall      | 17   |
| 6. Summary and conclusions                                   | 19   |
| 7. Acknowledgements  | 19   |
| 8. References  | 19   |

## EXECUTIVE SUMMARY

Increasing emphasis in the design and construction of embedded retaining walls is being placed on the Observational Method where immediate feedback from monitoring is used to modify the design and construction procedures to provide more economic structures. The essentials of the Method include establishing the limits of behaviour which are acceptable together with predictions of the most probable behaviour and contingency plans if monitoring reveals behaviour is outside acceptable limits. For this reason likely patterns of wall and ground movements need to be identified in advance at the design stage. The only source of this data, other than from numerical analysis, is from previous case history studies.

In this report, a database has been established from measurements of ground and wall movements at sites where bored pile and diaphragm retaining walls were being used for the construction of retained cuttings, cut-and-cover tunnels and deep basements. Results were obtained from a large number of instrumented highway and building schemes in the UK and also, where they are considered relevant to UK practice, from elsewhere in the world. The variation of surface ground movements with distance during wall installation and bulk excavation are separately reported.

Movements of the ground surface due to wall installation in stiff clay varied according to the construction technique employed. Maximum horizontal movements ranged from

0.04% of the pile depth for contiguous piling to 0.11% of the trench depth for counterforted diaphragm walls. In general, maximum settlements were about half of the horizontal movements and in all cases the zone of possible movement was considered to extend to no more than 1.5 times the trench/pile depth.

A summary of the magnitude and extent of horizontal and vertical movements at ground and wall surface caused by excavation in front of walls founded in stiff clay is given. Final recommended upper bound values of horizontal surface movement were 0.125%, 0.2% and 0.4% of the excavation depth depending on whether high, moderate or low stiffness support was used during bulk excavation. Upper bound values of surface settlement varied between 0.1% and 0.2% of the excavation depth over the same range of support conditions. Generally the extent of possible movements was up to 4 times the excavation depth. With top-down construction in particular, the maximum horizontal movement of the wall during bulk excavation is not likely to be measured at the top. The magnitude of this movement and the depth at which it occurs is investigated.

Although data on embedded wall construction in ground conditions other than stiff clay are not so abundant, the magnitude of measured surface settlements was found to be particularly variable.

# GROUND MOVEMENTS CAUSED BY DIFFERENT EMBEDDED RETAINING WALL CONSTRUCTION TECHNIQUES

## ABSTRACT

A database has been established of the pattern of ground and wall movements measured at sites where bored pile and diaphragm retaining walls were being used for the construction of retained cuttings, cut-and-cover tunnels and deep basements. Results were obtained from a large number of instrumented highway and building schemes in the UK and also, where they are considered relevant to UK practice, from elsewhere in the world. The variation of surface ground movements with distance during wall installation and bulk excavation are separately reported. The zones of movement which develop are related to the type of wall construction, the ground conditions and the stiffness of the support system used during excavation in front of the wall. The results are of value both in establishing the most probable movement and acceptable limits when using the Observational Method to control construction and also in assessing the effects of construction on neighbouring buildings and buried services.

## 1. INTRODUCTION

Increasing emphasis in the design and construction of embedded retaining walls is being placed on the Observational Method where immediate feedback from monitoring is used to modify the design and construction procedures to provide more economic structures. The principles of the Observational Method were first described in detail by Peck (1969). The essentials of the Method include establishing the limits of behaviour which are acceptable together with predictions of the most probable behaviour and contingency plans if monitoring reveals behaviour is outside acceptable limits.

In monitoring embedded retaining wall behaviour, instrumentation tends to concentrate on techniques for determining deformation and movements of the structure and ground. For this reason likely patterns of wall and ground movements need to be identified at the design stage from either numerical analysis or previous case histories. Because of the sensitivity of analyses to the soil parameters adopted and the difficulty in accurately modelling the complexity of the construction sequence and the soil-structure interaction, the most reliable source of these data is generally considered to be from case studies where the same construction technique has been used in similar ground conditions.

In this report a database has been established from the monitored movements at schemes where retained cuttings, cut-and-cover tunnels and deep basements were being constructed using embedded retaining walls. This database includes results from a large number of highway and building 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. The latter were the subject of earlier reviews by Peck (1969) and Clough and O'Rourke (1990).

In addition to being an essential pre-requisite of design and construction using the Observational Method, the results in this report are expected to be of value in assessing the magnitude of ground movements near to wall construction and its effect on neighbouring buildings and buried services.

## 2. METHODOLOGY

For permanent works, bored pile or diaphragm (slurry trench) techniques are usually used to form walls of reinforced concrete. The construction procedures used for the installation of the wall are expected to have a considerable influence on the ground movements and stress regime close to the structure both immediately after installation and in the longer term during underpass or cut-and-cover tunnel construction. For this reason the variation of surface ground settlements and horizontal movements with distance caused by wall installation are separately assessed following the non-dimensional method of Peck (1969), which divides both movements and distances by the depth of augered hole or trench. This differs from the analyses of ground movements during the subsequent stages of construction which are treated non-dimensionally by dividing by the depth of excavation in front of the wall. It must be noted that only cast-in-place piles/panels fall within the scope of this study: driven piling techniques have not been included.

Embedded walls can be free standing and act as cantilevers, supported by anchoring back, or by provision of structural props. For retained cuttings, support is often provided by a permanent structural slab spanning between the walls on each side and cast just below carriageway level. In this case, temporary support in the form of either props or berms is required to prevent excessive movements when excavating to formation level and constructing the permanent slab. On release of the temporary props, rotation of the wall can then

occur about the permanent carriageway slab. With cut-and-cover tunnels the roof slab is normally designed to act as a permanent prop with construction being top-down. Top-down construction is also widely used in deep basement construction with the floor slabs acting as permanent props. In this report the type and effectiveness of support is related to the surface ground movements and distances from the excavation calculated non-dimensionally by dividing by the maximum depth of excavation in front of the wall. The distance from the excavation has been taken as that from the front face of the wall for the bulk excavation stage so that movements at zero distance represent wall movement rather than ground movement.

In summary, wherever possible the measurements of movement in the proximity of the wall were non-dimensionally evaluated for the following cases:

- After wall installation
  - Bored pile walls
  - Diaphragm walls
- Shortly after underpass/tunnel/basement construction
  - 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.

It must be noted that movement measurements have been separately quoted for the wall installation and the main construction stages, i.e. overall movements have to be obtained by summation of the two effects.

Because of the extensive information available from field studies carried out by TRL (Symons and Carder, 1992; Carder, 1994) on bored pile and diaphragm walls founded in stiff clays, data from this source were separately analysed as the first phase of the study. The second and third phase of the study involved researching a broader database from all sources of construction in stiff clay and other ground conditions respectively and attempting correlations with the TRL data.

### **3. WALLS FOUNDED IN STIFF CLAY AND INSTRUMENTED BY TRL**

The ongoing programme of field monitoring carried out by TRL on the behaviour of embedded retaining walls founded

in stiff clay was initiated in the early 1980's when the secant pile walls of the cut-and-cover tunnel at Bell Common (M25) were instrumented. Since then a number of construction schemes have been instrumented and the site locations, wall form, construction sequence and ground conditions are listed in Table 1. Also given in the table are the source references for each site.

For the purposes of this study only ground movement data have been extracted for the sites listed in Table 1. More detailed information on other aspects such as ground and water pressures, wall bending moments, prop loads and heave of the ground below excavation level can be found from the source references.

## **3.1 SURFACE GROUND MOVEMENTS CAUSED BY WALL INSTALLATION**

### **3.1.1 Bored pile walls**

The horizontal ground movements caused by installation of bored pile walls are shown non-dimensionally in Fig 1. At the contiguous bored pile sites, movements were generally small and within the indicated upper bound line. On this basis only small movements were measured at distances greater than 1.0 times the pile depth, although the possible zone of movement extended to 1.5 times the pile depth. A maximum horizontal movement of 0.04% of the pile depth was measured at the ground surface close to the piles.

Also shown in Fig 1 are the results from two sites where secant bored pile techniques were employed. At Bell Common tunnel the primary piles were cased through the Older Head and Claygate Beds to a depth of about 6m; secondary piles were then bored using casing to full depth with the cutting edge on the casing breaking out the concrete of the primary piles. A similar approach was used at Hackney Wick M11 with primary pile casing to about 4.5m depth through the Terrace Gravel. In both cases the magnitudes of the measured movements were unexpected and outside of the trend of movements for contiguous bored piling. At Bell Common, approximately 30% of the surface movement during tunnel construction occurred during wall installation. A maximum horizontal movement of 0.08% of the pile depth was measured close to the piles and the zone of possible movement extended to 1.5 times the pile depth. Unusually at Hackney Wick M11, localised surface movements of the ground away from the piles were measured and this was considered to be a 'displacement effect' as the full depth casing for the secondary piles could only be driven using a very heavy oscillator. It is worth noting that at depth some lateral stress relief still occurred during pile installation at this site, implying subsurface movement towards the piling.

Surface settlement data for the same sites are shown in Fig 2. Generally surface settlements were much smaller than

**TABLE 1**

**BORED PILE AND DIAPHRAGM WALLS INSTRUMENTED BY TRL**

| SITE LOCATION               | WALL TYPE   | CONSTRUCTION SEQUENCE  | GROUND CONDITIONS  | SOURCE REFERENCES  |
|-----------------------------|---|--|--|--|
| <b>(a) BORED PILE WALLS</b> |   |  |  |  |
| Bell Common (M25)           | Secant (1.18m piles at 1.08m centres)                                     | Cut-and-cover tunnel, roof simply supported and acts as prop                                       | London Clay overlain by 7m Older Head and Claygate Beds    | Tedd, Chard, Charles and Symons (1984); Symons and Tedd (1989) |
| Rayleigh Weir (A127)        | Contiguous (1.5m piles at 1.7m centres)                                   | Partly excavated before using temporary props spanning underpass, permanent prop below carriageway | London Clay overlain by 3m made ground                     | Darley, Carder and Alderman (1994)                             |
| Walthamstow (A406)          | Contiguous (1.5m piles at 1.7m centres)                                   | Excavated below temporary props spanning underpass, permanent prop below carriageway               | London Clay overlain by 1.5m made ground                   | Carswell, Carder and Gent (1993); Watson and Carder (1994)     |
| Hackney Wick (M11)          | Secant (1.2m piles at 1.03m centres, heavy casing oscillator used)        | Excavated below temporary props spanning underpass, permanent prop below carriageway               | London Clay overlain by 5m made ground and Terrace Gravels | Unpublished TRL data   |
| East of Falloden Way (A406) | Contiguous (1.5m piles at 2m centres), constructed under bentonite slurry | Cantilever   | Glacial Till underlain by London Clay at 23m               | Unpublished TRL data   |
| <b>(b) DIAPHRAGM WALLS</b>  |   |  |  |  |
| A406/A10 Junction           | T-panels (4m x 0.8m front, 2.7m x 0.8m counterfort)                       | Excavated below temporary props spanning underpass, permanent prop below carriageway               | London Clay overlain by 2.4m made ground/sand and gravel   | Carder, Ryley and Symons (1991)                                |
| Walthamstow (A406)          | T-panels (4m x 0.8m front, 3.2m x 1.5m counterfort)                       | Excavated below temporary props spanning underpass, permanent prop below carriageway               | London Clay to surface                                     | Carder, Carswell and Watson (1994)                             |
| Limehouse Link              | Planar panels (4.2m x 1.0m)   | Tunnel portal, cantilever  | London Clay overlain by 6m made ground and Terrace Gravels | Moran and Laimbeer (1994)                                      |
| East of Falloden Way (A406) | Planar panels (5.0m x 1.0m)   | Cut-and-cover tunnel, propped at top by integral roof  | Glacial Till underlain by London Clay at 21m               | Unpublished TRL data   |

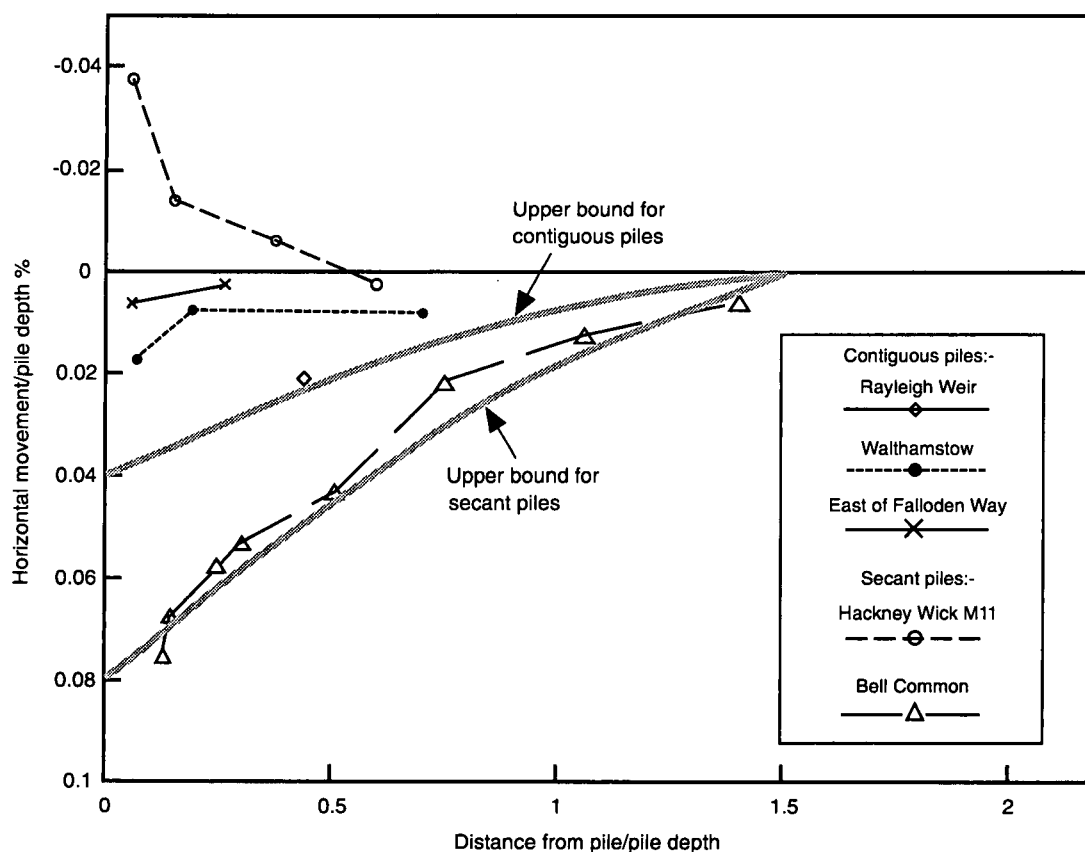


Fig 1. Horizontal surface movement during bored pile wall installation in stiff clay

horizontal movements. This was not surprising as the walls investigated were all founded in stiff over-consolidated clays. A maximum settlement of 0.02% of the pile depth formed an upper bound for the contiguous bored piling techniques, based mainly on data from Rayleigh Weir site. In general, settlements for contiguous bored pile walls fell well within this upper bound and were only just measurable at a distance of about 0.75 times the pile depth. Once again significantly higher movements were recorded due to secant piling at Bell Common with maximum settlements of 0.05% of the pile depth and the zone of movement extending to 1.5 times the pile depth.

### 3.1.2 Diaphragm walls

TRL information on movements caused by diaphragm wall installation was only available from three construction schemes; one of these involved construction using planar wall panels with the other two using counterforted, T-shaped, panels. The data on horizontal ground surface movements are shown non-dimensionally in Fig 3. In the case of the counterforted panels, the distances from the trench have been determined with respect to the edge of the main trench forming the face of the wall. For comparison purposes, the extent of the counterforts have also been indicated in Fig 3.

As would be anticipated the potential zone of movements for the counterforted construction was larger than measured for planar construction and extended to a distance of about 1.0 times the trench depth. Horizontal surface movements for planar walls only extended to a distance of 0.6 times the trench depth, although this finding was based on the results from only one site. Upper bound movements after installation of counterforted walls were 0.11% of the trench depth, whereas movements were below half of this level for planar construction. The larger magnitude and extent of surface movements during installation of counterforted walls was the consequence of the larger volume of soil which had to be excavated and the longer duration therefore for which trenches remained open before concreting occurred.

Fig 4 shows the settlements measured at ground surface at the three diaphragm wall sites. Upper bound movements for the counterforted walls were 0.05% of the trench depth and the possible zone of movement extended to a distance equal to the trench depth. Surface settlements at East of Falloden Way, where the diaphragm walls were planar and the installation was carried out under bentonite, were hardly measurable. Nevertheless, for consistency, an upper bound line has been shown in Fig 4 with the zone of movement being assumed to extend out to 0.6 times the trench depth to conform with that measured for horizontal

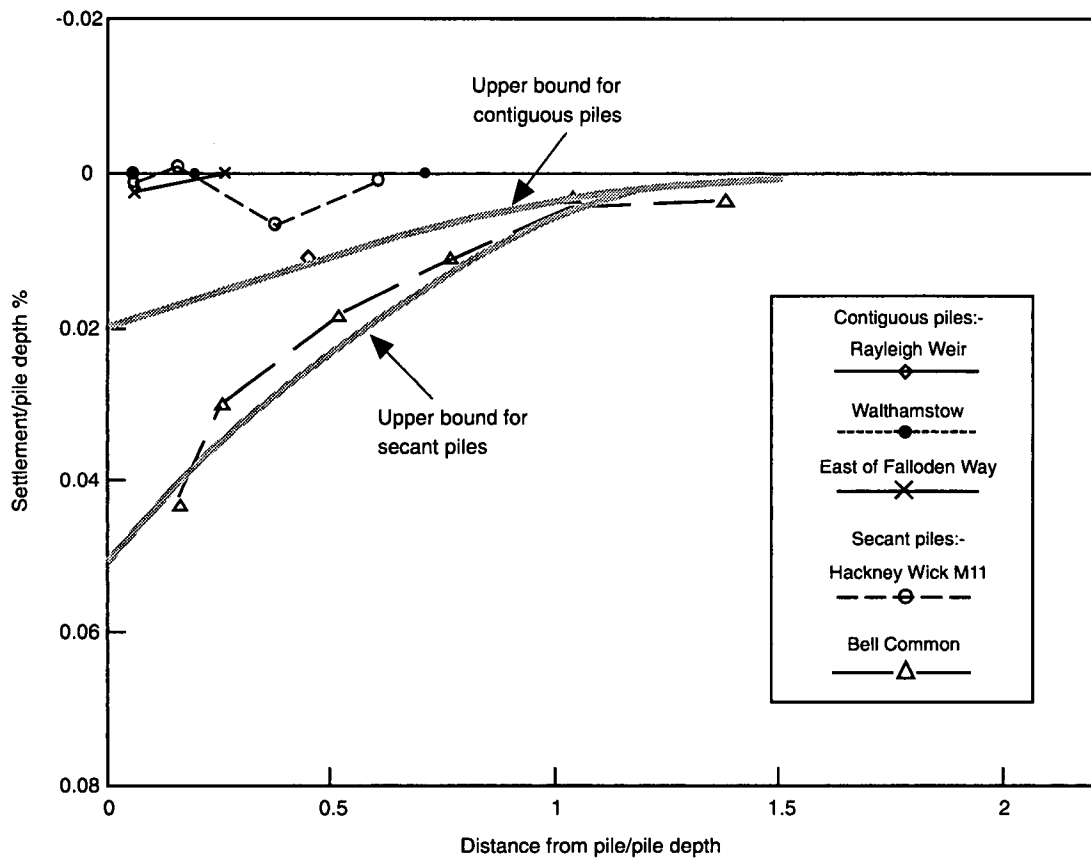


Fig 2. Surface settlement during bored pile wall installation in stiff clay

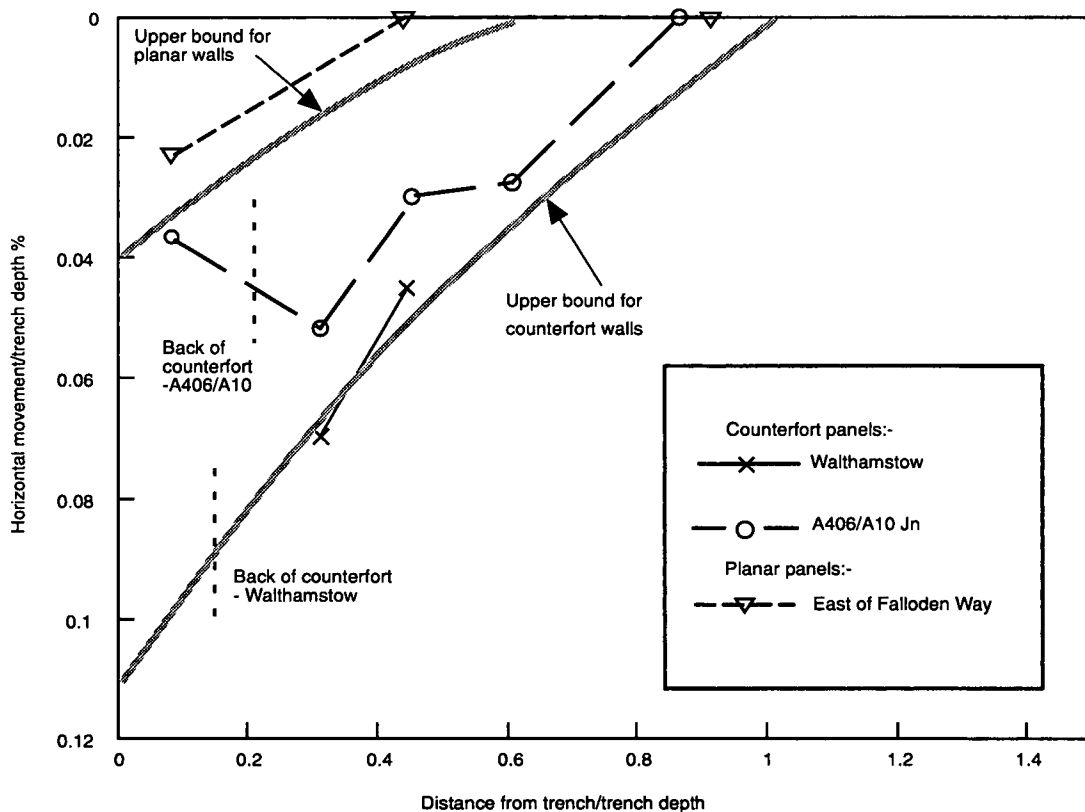


Fig 3. Horizontal surface movement during diaphragm wall installation in stiff clay

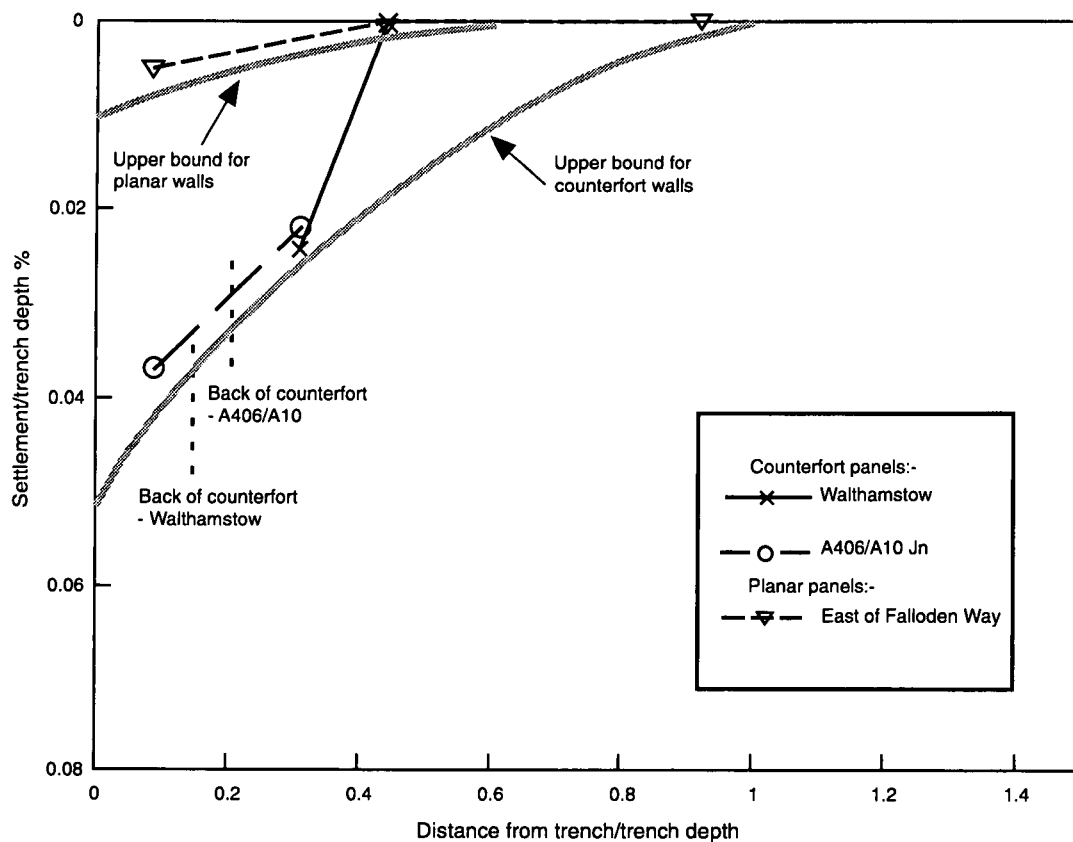


Fig 4. Surface settlement during diaphragm wall installation in stiff clay

movements. Maximum surface settlements of less than 0.01% of the trench depth would be expected.

### 3.2 MOVEMENTS CAUSED BY EXCAVATION IN FRONT OF THE WALL

Measured horizontal movements and settlements at the ground surface caused by underpass/tunnel construction at the TRL sites are shown in Figs 5 and 6 respectively. When the distances from the excavation are zero in these plots, movements actually represent those at the wall top rather than the ground surface. Results are given from datums established after wall installation and for the performance of both bored pile (BP) and diaphragm walls (DW). Some differences in performance might have been expected because of different stress histories resulting from the various wall installation techniques. However other factors such as the nature and effectiveness of any support during bulk excavation and wall stiffness appear to dominate. For example at Walthamstow where the method of temporary support during bulk excavation was nearly identical for the bored pile and diaphragm walls, very little difference in surface horizontal movement is observed in Fig 5.

In Fig 5, an upper bound line has been fitted to describe the behaviour of walls which have moderate stiffness support

during excavation. Included in this category are results from Walthamstow, Hackney Wick M11 and the A406/A10 Junction where high level temporary steel props spanning the underpasses were used, although on their release some rotations occurred about the permanent carriageway props. The results for top of wall movement at Bell Common tunnel are marginally outside the 0.2% limit derived for moderate stiffness support cases and this reflects the construction procedure used. The excavation to 5m depth was unsupported prior to construction of the roof structure and a 75mm thick compressible packing was used between the roof beams and the thrust wall. The large settlements and horizontal movements at Bell Common, at a distance of 0.45 times the excavation depth, were outside the typical range of behaviour and a consequence of temporary works in which sheetpiles were installed and propped against the secant piled wall to support a 3.5m deep excavation close to the wall. As anticipated, movements were well within the upper bound for moderate stiffness support for the top-down cut-and-cover tunnel construction at East of Fallosen Way where the roof slab was integral with the diaphragm walls and provided rigid support minimising horizontal movements at the ground surface and top of the wall. However it was not considered appropriate to estimate a trend for top-down construction, where there is high stiffness support during excavation, on the basis of data from this site alone.

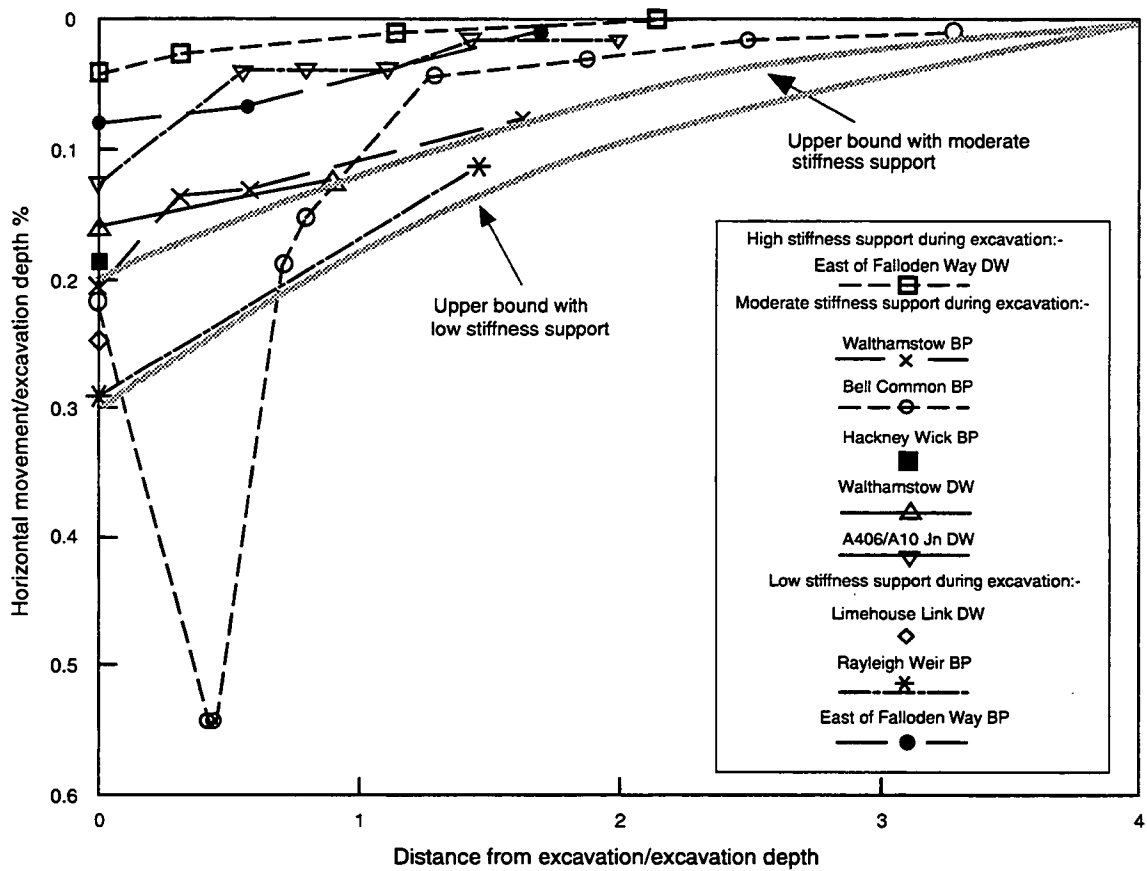


Fig 5. Horizontal surface movement caused by excavation in front of wall (stiff clay)

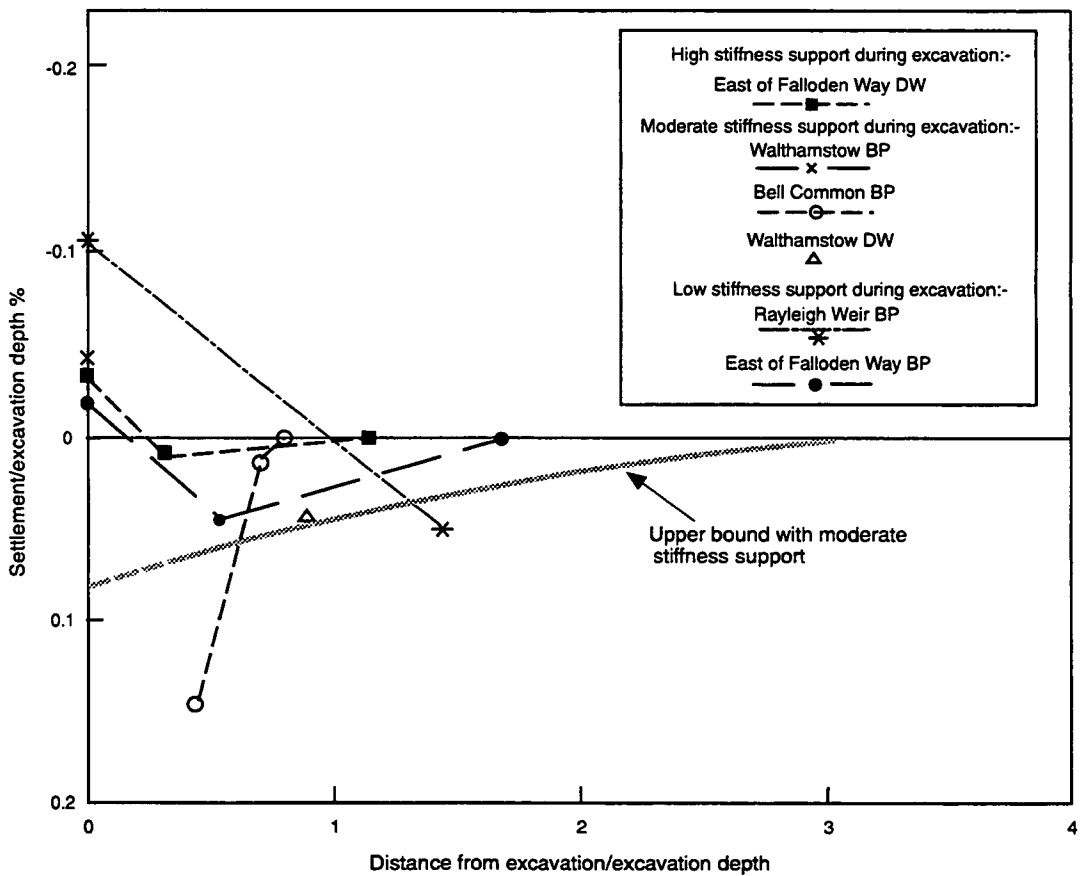


Fig 6. Surface settlement caused by excavation in front of wall (stiff clay)

As shown in Fig 5 a horizontal movement of 0.3% of the excavation depth was established as an upper bound for walls with low stiffness support during excavation. This category includes the diaphragm walls forming the approach to Limehouse Link tunnel and the bored pile wall at East of Falloeden Way (A406) which were constructed as cantilever walls. Results from Rayleigh Weir also fall in this range as the walls were allowed to cantilever out to relieve soil stresses during excavation to about 5m depth: at this stage temporary steel props were installed to provide support during final excavation and construction of the permanent carriageway slab. In all cases the zone of measurable horizontal movements at the ground surface extended out to about 4 times the maximum excavation depth.

Generally, associated settlements of the ground surface were very small as is shown in Fig 6. For walls with moderate stiffness support during bulk excavation, settlements were within an upper limit of 0.075% of the excavation depth and a zone of possible movement extending to 3 times the excavation depth was identified. It was not possible to identify separate trends for walls with high and low stiffness support because of the limited data. However movements at Rayleigh Weir and East of Falloeden Way bored pile schemes, where some cantilever behaviour was expected, were just above and just below the upper bound for moderate stiffness support respectively. Ground surface settlements for the top-down construction at East of Falloeden Way diaphragm wall were hardly measurable. It is worth noting in Fig 6 that measurements at zero distance from the excavation, i.e. at the top of the wall, generally showed small heaves as a consequence of the unloading effect caused by bulk excavation in front of the wall.

## **4. GENERAL EXPERIENCE WITH WALLS FOUNDED IN STIFF CLAY**

A literature search was carried out to identify sites of embedded retaining wall construction where field monitoring had been carried out. The bored pile and diaphragm wall sites which were identified are listed, together with details of the source references, in Table 2. Construction in ground conditions other than stiff clay is dealt with separately in Section 5.

### **4.1 SURFACE GROUND MOVEMENTS CAUSED BY WALL INSTALLATION**

Only two sites were located where surface ground movements were monitored during embedded wall installation; in both cases these involved the construction of planar diaphragm walls. Horizontal movements and settlements

measured at these sites are plotted non-dimensionally in Fig 7. Also shown are the upper bounds of the TRL data for planar walls reproduced from Figs 3 and 4.

Fig 7a shows that, at Reading site, the magnitude of the horizontal ground movements was less than that expected from TRL data. However results from New Palace Yard indicate that the zone of possible movement extended to a greater distance of 1.5 times the trench depth. Surface settlements are shown in Fig 7b. In this case, measurements at Reading were close to the upper bound from TRL data. However once again, the zone of measured movements at New Palace Yard was larger and extended to a distance of 1.5 times the trench depth. Maximum movements were also higher and corresponded to 0.03% of the trench depth. At New Palace Yard, Burland and Hancock (1977) report that ground movements due to wall installation formed a significant part (about 50%) of the total recorded horizontal and vertical movements. This may be due to the 10m depth of fill and gravel overlying the London Clay and the presence of a deep clay layer containing frequent sand and silt partings.

### **4.2 MOVEMENTS CAUSED BY EXCAVATION IN FRONT OF THE WALL**

Nine sites were identified where movement measurements were taken during excavation in front of bored pile or diaphragm walls founded in stiff clay. The data on horizontal movements at ground surface and the top of the wall from these sites are shown in Fig 8.

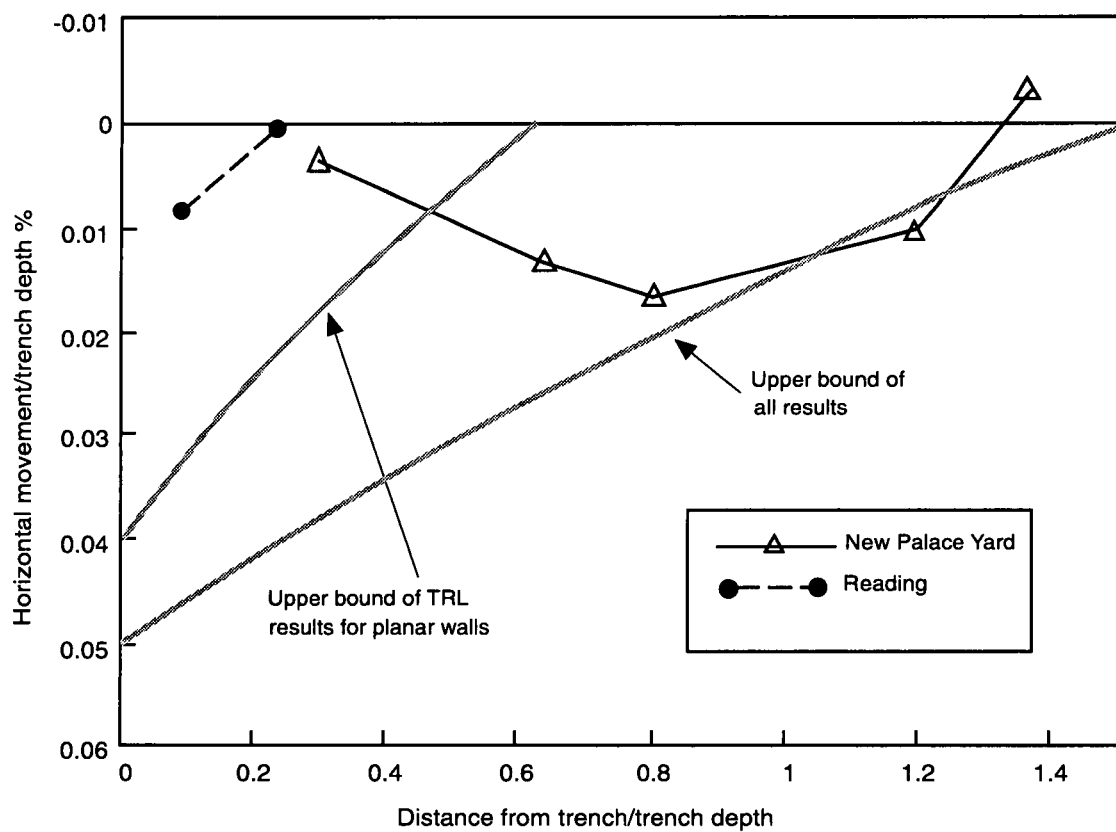
The five sites which are categorised as having high stiffness support during excavation are either top-down constructions for deep basements or are permanently or temporarily strutted near to the wall top during bulk excavation. Generally as shown in Fig 8 the results from these five sites lie within an upper bound with a maximum horizontal movement of 0.125% of the excavation depth and a zone of movement extending to a distance of 4 times the excavation depth. The possible exceptions to this are the movements measured remotely from the walls at New Palace Yard and the YMCA which indicate that the zone of movement may extend beyond 4 times the excavation depth. However at both these sites little change in the magnitude of horizontal movement had occurred between distances of 2 and 4 times the excavation depth away, whereas movements would normally be expected to reduce with increasing distance. For this reason, a revision to the upper bound line to extend the movement zone for excavations with high stiffness support was not considered appropriate.

Excavation at the remaining four sites was carried out with low stiffness support for the walls. At both Britannic House and Waterloo International Terminal, a large central excavation was made with a soil berm left immediately in front

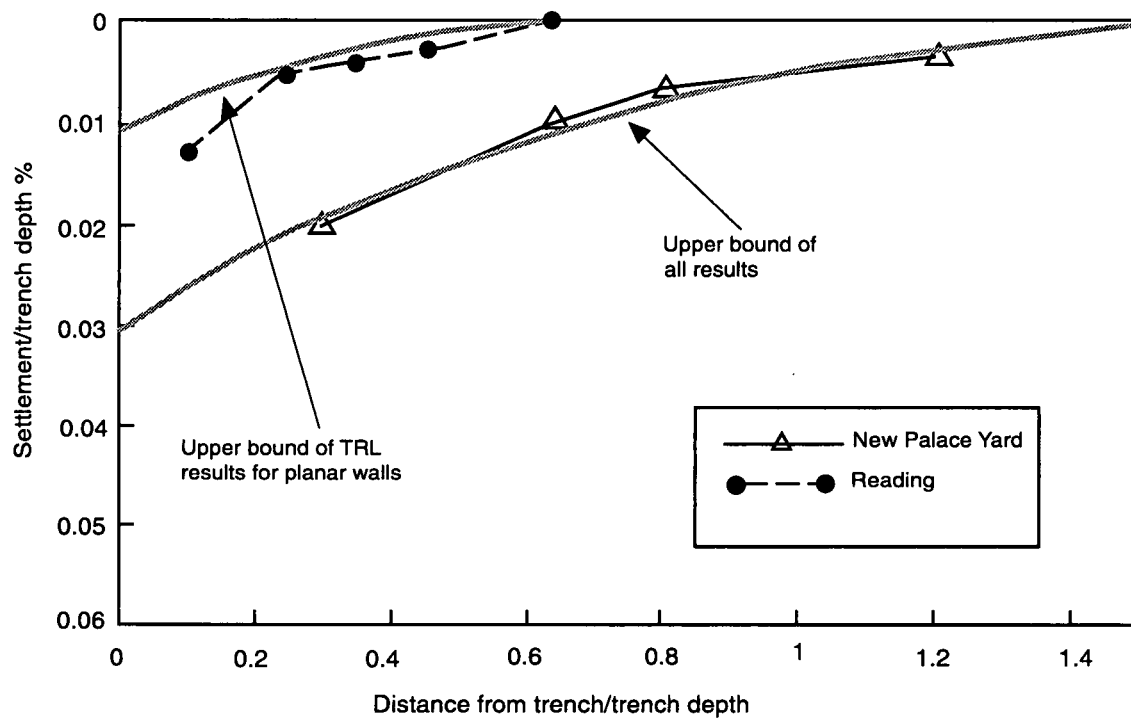
**TABLE 2**

**BORED PILE AND DIAPHRAGM WALLS FOUNDED IN STIFF CLAY (NON-TRL)**

| SITE LOCATION                           | WALL TYPE                              | CONSTRUCTION SEQUENCE   | GROUND CONDITIONS   | SOURCE REFERENCES   |
|---|--|---|---|---|
| <b>(a) BORED PILE WALLS</b>             |  |   |   |   |
| British Library, London                 | Secant (0.9m piles)                    | Top-down construction, multi-propped  | 21m of London Clay overlying Woolwich and Reading Beds          | Loxham, Simpson and Gatenby (1991)  |
| Holborn Bars, London                    | Secant (0.88m piles at 0.755m centres) | Supported by berm during excavation of central area, temporary raked props installed from top of wall whilst permanent slab constructed | London Clay overlain by 3m made ground and 2 to 5m sandy gravel | Ward (1992)   |
| <b>(b) DIAPHRAGM WALLS</b>              |  |   |   |   |
| New Palace Yard, London                 | Planar panels (1.0m thick)             | Top-down construction, multi-propped  | London Clay overlain by 10m made ground/sand and gravel         | Burland and Hancock (1977); St John (1975); Simpson, O'Riordan and Croft (1979)   |
| YMCA, London                            | Planar panels (0.6m thick)             | Supported by ground anchors and multi-propped during excavation   | London Clay overlain by 7.5m made ground and gravel             | St John (1975); Burland, Simpson and St John (1979)   |
| Britannic House, London                 | Planar panels (0.8m thick)             | Supported by berm during excavation of central area, temporary struts then installed followed by casting of strutting floor             | London Clay overlain by 2.5m sand and gravel                    | Cole and Burland (1972); Burland, Simpson and St John (1979)  |
| Waterloo International Terminal, London | Planar panels (0.8m thick)             | Supported by 5m berm during excavation of central area, temporary props then installed followed by casting of permanent prop            | London Clay overlain by 8.5m made ground/alluvial clay/gravel   | Li, Nyirenda and Pickles (1992)   |
| Lion Yard, Cambridge                    | Planar panels (8.5m x 0.6m)            | Top-down construction, multi-propped  | Gault Clay overlain by 3m                                       | Lings, Nash, Ng and Boyce (1991) made ground and gravel   |
| Neasden Lane Underpass                  | Planar panels (4.57m x 0.6m)           | Supported by 4 rows of under-reamed anchors   | London Clay overlain by 0.5m made ground                        | Sills, Burland and Czechowski (1977); Simpson, O'Riordan and Croft (1979); St John (1975); Carswell, Carder and Symons (1991) |
| Reading A329(M)                         | Planar panels (3.66m x 1.22m)          | Cantilever  | London Clay overlain by 3m made ground and Terrace Gravel       | Burland, Simpson and St John (1979); St John (1975); Carder and Symons (1989)   |



(a) Horizontal movement



(b) Settlement

Fig 7. Surface movement during diaphragm wall installation in stiff clay

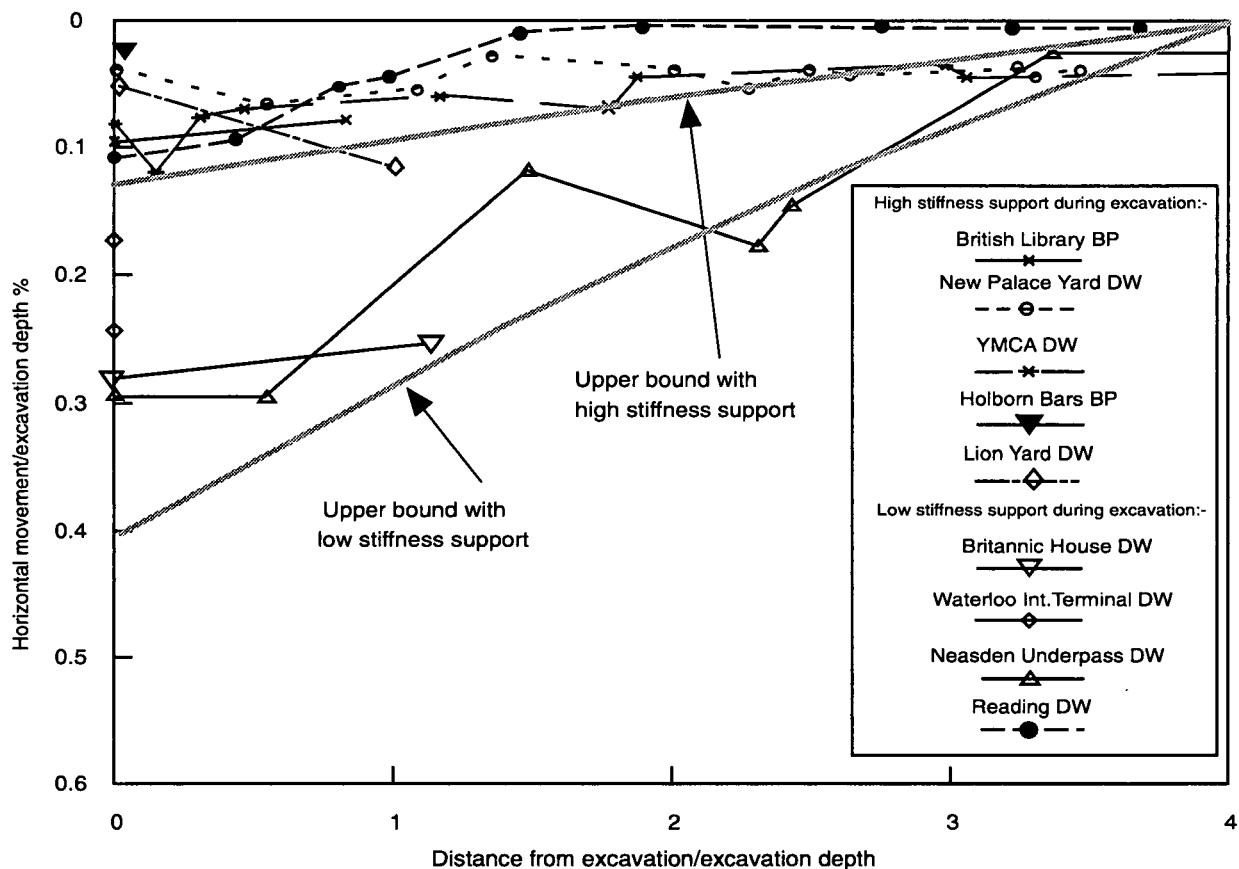


Fig 8. Horizontal surface movement caused by excavation in front of wall (stiff clay)

of the wall whilst a central raft was constructed. Strutting was then installed between the wall and the raft to enable excavation of the berm to take place. On the highway scheme at Neasden Lane, under-reamed ground anchors were progressively installed as bulk excavation proceeded. Burland, Simpson and St. John (1979) recorded horizontal movements beyond the extent of the anchored zone and suggested that some block movement of the ground may have occurred. At Reading, construction of the A329(M) was carried out using cantilever diaphragm walls. Results from these sites can be compared with the upper bound established from TRL data (Fig 5) for walls with low stiffness support during excavation. Generally the TRL data indicate smaller movements: the results in Fig 8 indicate a maximum horizontal movement of 0.4% of the excavation depth rather than 0.3%, although the zone of likely movement extends to the same distance of 4 times this depth.

With high stiffness support during excavation, the maximum horizontal wall movement is not likely to be measured at the wall top. Fig 9 shows the maximum wall movement plotted non-dimensionally against the depth at which it occurs. In addition to the results for the walls founded in stiff clay currently being considered, the TRL data for East of Falloden Way Scheme are also included in

Fig 9 for completeness. This graph demonstrates that for walls with high stiffness support during excavation, e.g. top-down construction, the peak horizontal movement occurs at a depth of between 0.7 to 0.9 times the excavation depth. Individual results for walls which have low stiffness support during excavation plot on the Y-axis as maximum movements are at the top of the wall. Measurements of movement made by TRL on walls with moderate stiffness support during excavation also have maxima at the top of the wall and would plot similarly.

Measurements of surface settlement caused by excavation in front of the wall are given in Fig 10. For the walls with high stiffness support during excavation, a zone of settlement is indicated with a maximum of 0.1% of the excavation depth at the wall top and possible ground surface movements extending to 4 times this depth. The only results which lie outside of this bound are those for Britannic House, Neasden and Lion Yard. The first two of these sites are classified as having low stiffness support during excavation and a zone with maximum settlements of 0.2% of excavation depth is suggested for this category. The anomalous result at Lion Yard was accounted for by cantilever behaviour of the instrumented section of wall during the early phases of excavation prior to grouting of the multi-level props (Lings, Nash, Ng and Boyce, 1991).

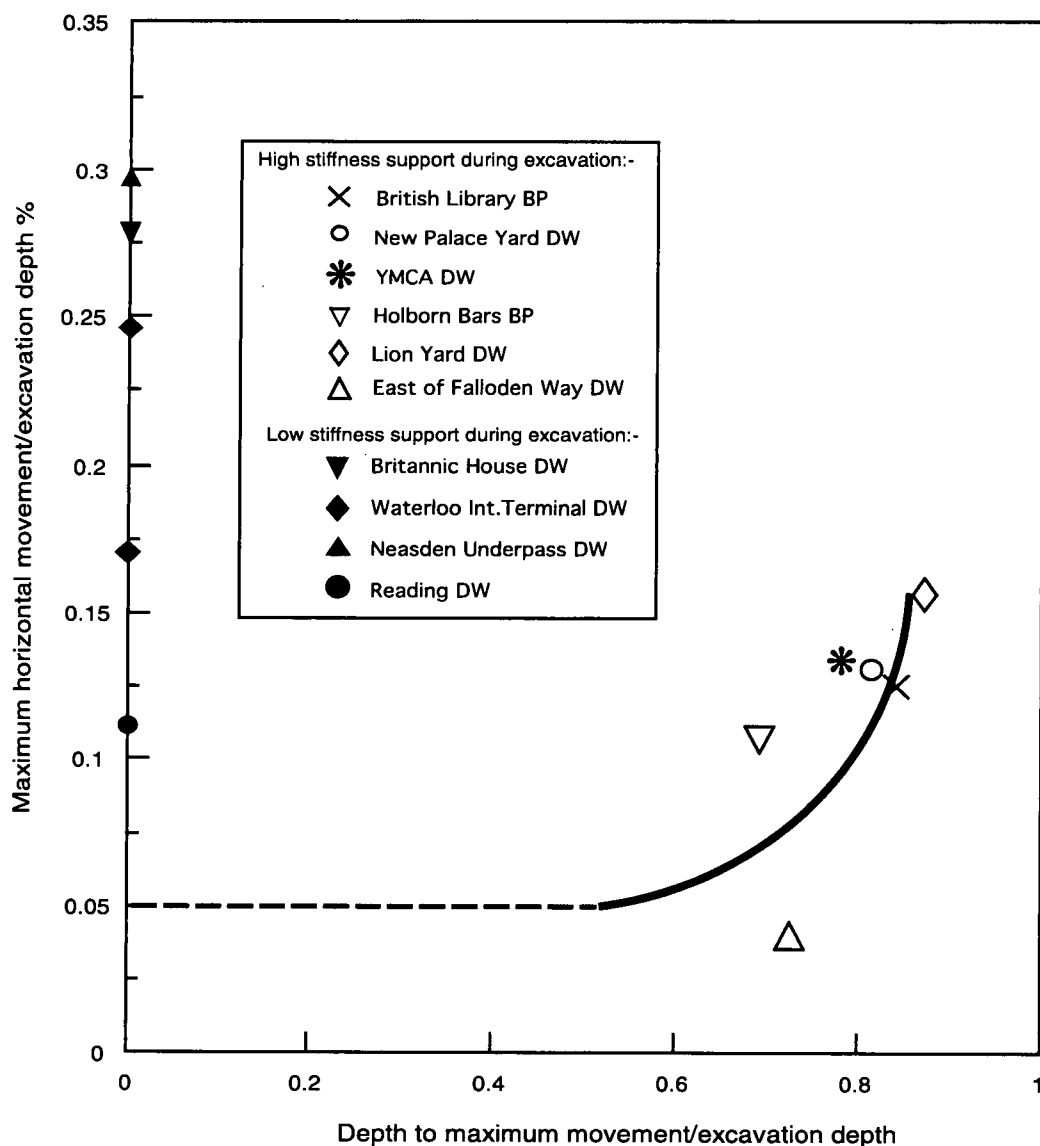


Fig 9. Maximum horizontal wall movements caused by excavation in stiff clay

## 5. GENERAL EXPERIENCE WITH WALLS FOUNDED IN OTHER SOIL TYPES

Sections 3 and 4 have dealt exclusively with measurements on embedded walls founded in stiff clay. Some information was retrieved from construction sites in other ground conditions and this is now considered. The source references and locations of these sites are given in Table 3.

### 5.1 SURFACE GROUND MOVEMENTS CAUSED BY WALL INSTALLATION

No data were found on horizontal or vertical ground surface movements caused by bored pile installation nor on hori-

zontal surface movements caused by diaphragm wall installation. However limited results were available on surface settlements due to planar diaphragm wall installation and these are plotted in Fig 11. The upper bound to the results in stiff clay is also reproduced from Fig 7b for comparative purposes.

Behaviour in other soil types is expected to conform with the broad pattern suggested by Peck (1969) with the zone and magnitude of surface settlements increasing as the strength of the soil decreases. The results in Fig 11 generally support this trend. With the exception of settlement measurements taken in glacial till and during the slurry trench trial in soft clay undertaken by the Norwegian Geotechnical Institute, the other results were outside the upper bound values for stiff clay. Most movement was recorded in the soft alluvial deposits encountered on reclaimed land along the coast of Hong Kong Island and the

**TABLE 3****BORED PILE AND DIAPHRAGM WALLS FOUNDED IN VARIOUS SOILS (NON-TRL)**

| SITE LOCATION                 | WALL TYPE  | CONSTRUCTION SEQUENCE   | GROUND CONDITIONS   | SOURCE REFERENCES  |
|-------------------------------|--|---|---|--|
| <b>(a) BORED PILE WALLS</b>   |  |   |   |  |
| Manchester                    | Contiguous<br>(0.75m piles at 0.9m centres)                | Unsupported excavation to 4m before installing ground anchors and basement slabs    | Up to 4.6m of drift deposits overlying Middle Coal Measures | Curtis and Mirzabaigian (1992)   |
| <b>(b) DIAPHRAGM WALLS</b>    |  |   |   |  |
| Hong Kong (7 sites)           | Planar panels<br>(0.8m to 1.0m thick)                      | Measurements during wall installation only  | Soft alluvial deposits encountered on reclaimed land        | Cowland and Thorley (1985)   |
| Chicago, site E<br>site H     | Planar panels (0.76m thick)<br>Planar panels (0.61m thick) | Braced excavations designed to give high system stiffness                           | Soft silty clays  | Gill and Lucas (1990)  |
| Harvard Square,<br>Boston     | Planar panels (2.7m x 0.91m)                               | Unsupported excavation to 4.6m, anchors then installed progressively                | Glacial soils overlying bedrock                             | Hansmire, Russell, Rawnsley and Abott (1989)   |
| Lyon Subway, France           | Planar panels (0.6m thick)                                 | Supported by two levels of stiff struts during excavation                           | Sandy silt  | Kastner and Ferrand (1992)   |
| Car Park, Holland             | Planar panels (0.8m thick)                                 | Unsupported excavation to 4m followed by installation of prestressed ground anchors | Medium to dense sand  | Kooistra and Beringen (1984)   |
| Chicago (3 sites)             | Planar panels (0.76m thick)                                | Braced excavations  | Soft compressible clay                                      | O'Rourke, Cording and Boscardin (1976)   |
| Post Office Square,<br>Boston | Planar panels (3.0m x 0.9m)                                | Top-down construction, multi-propped  | Soft Boston Clay  | Whitman, Johnson, Abbott and Becker (1991); Whittle and Hashash (1992); Whittle, Hashash, and Whitman (1993) |
| Dartford, A258                | Barrette wall (0.8m thick)                                 | Prestressed ground anchor at top of wall  | Boyne Hill Terrace gravel (9m) overlying Upper Chalk        | Wood, Maynard and Forbes-King (1989)   |
| CNA Center,<br>Chicago        | Planar panels (0.76m thick)                                | Doubly propped during excavation  | Soft Chicago Lake Clay overlain by about 3m made ground     | Cunningham and Fernandez (1972)  |
| NGI Test Wall                 | Planar panels (5.0m x 1.0m)                                | Measurements during wall installation only  | Soft marine clay  | Dibiagio and Myrvoll (1972)  |

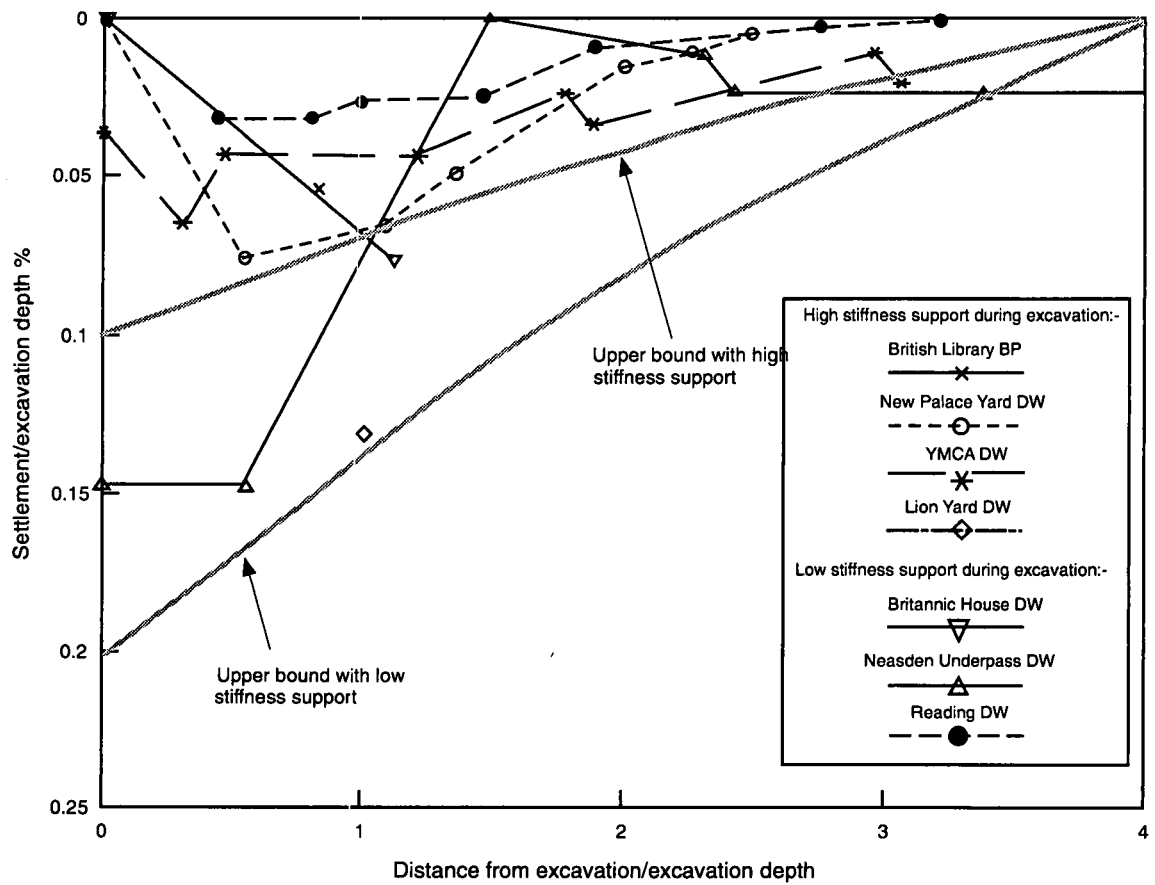


Fig 10. Surface settlement caused by excavation in front of wall (stiff clay)

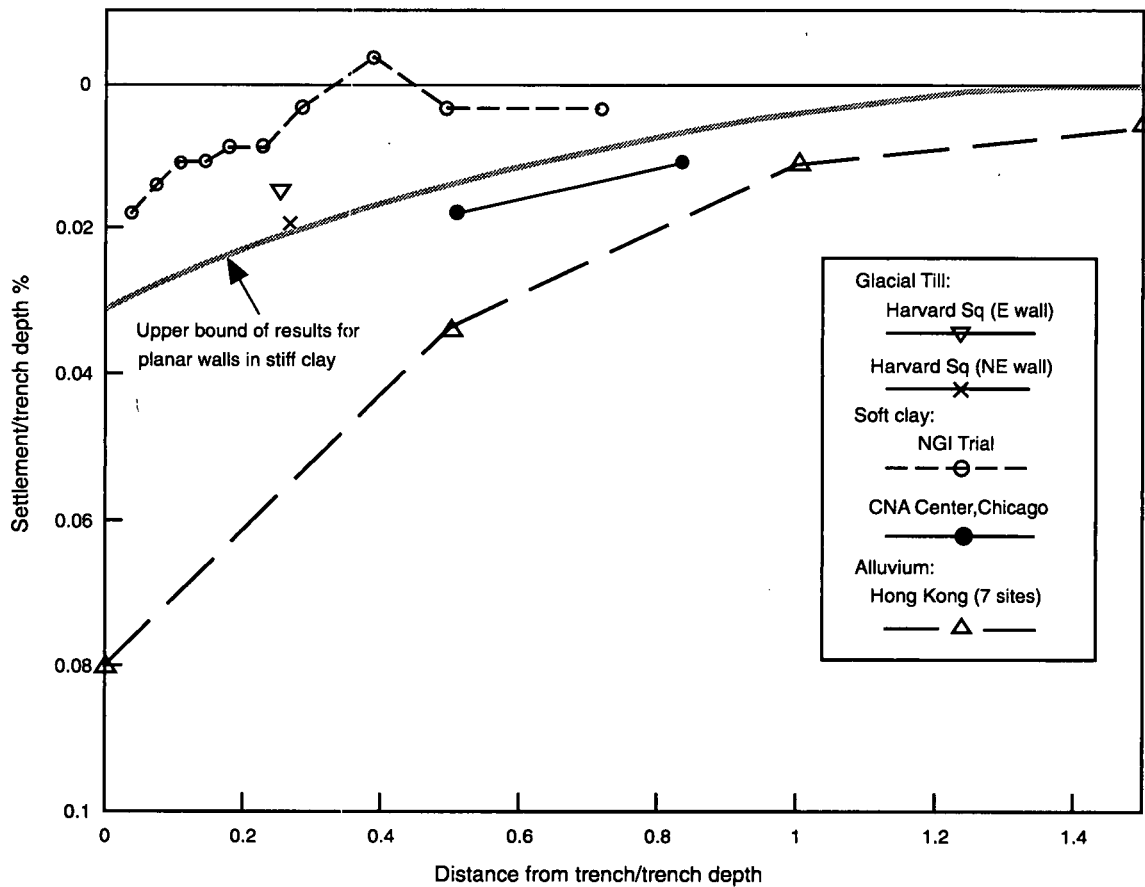


Fig 11. Surface settlement during diaphragm wall installation in various soils

Kowloon Peninsula. Cowland and Thorley (1985) report measurements from seven sites in this region and the mean of their data is shown in Fig 11. On this basis the maximum settlement was 0.08% of the trench depth and the zone of possible movement extended to over 1.5 times the trench depth. If the upper bound of their data is considered the maximum settlement increases to about 0.15% of the trench depth and it is this value that Clough and O'Rourke (1990) have taken in their review. Because of the paucity of data a definitive upper bound for settlement caused by diaphragm wall installation in soils other than stiff clay is not presented in this report.

## 5.2 MOVEMENTS CAUSED BY EXCAVATION IN FRONT OF THE WALL

Although the need to control horizontal wall movement during bulk excavation has meant that these measurements are frequently taken, there is a paucity of data on horizontal movements of the ground surface. For this reason the standard Peck type plot has not been produced, although Fig 12 shows the variation of wall movement for different excavation depths and soil types. Also shown plotted are

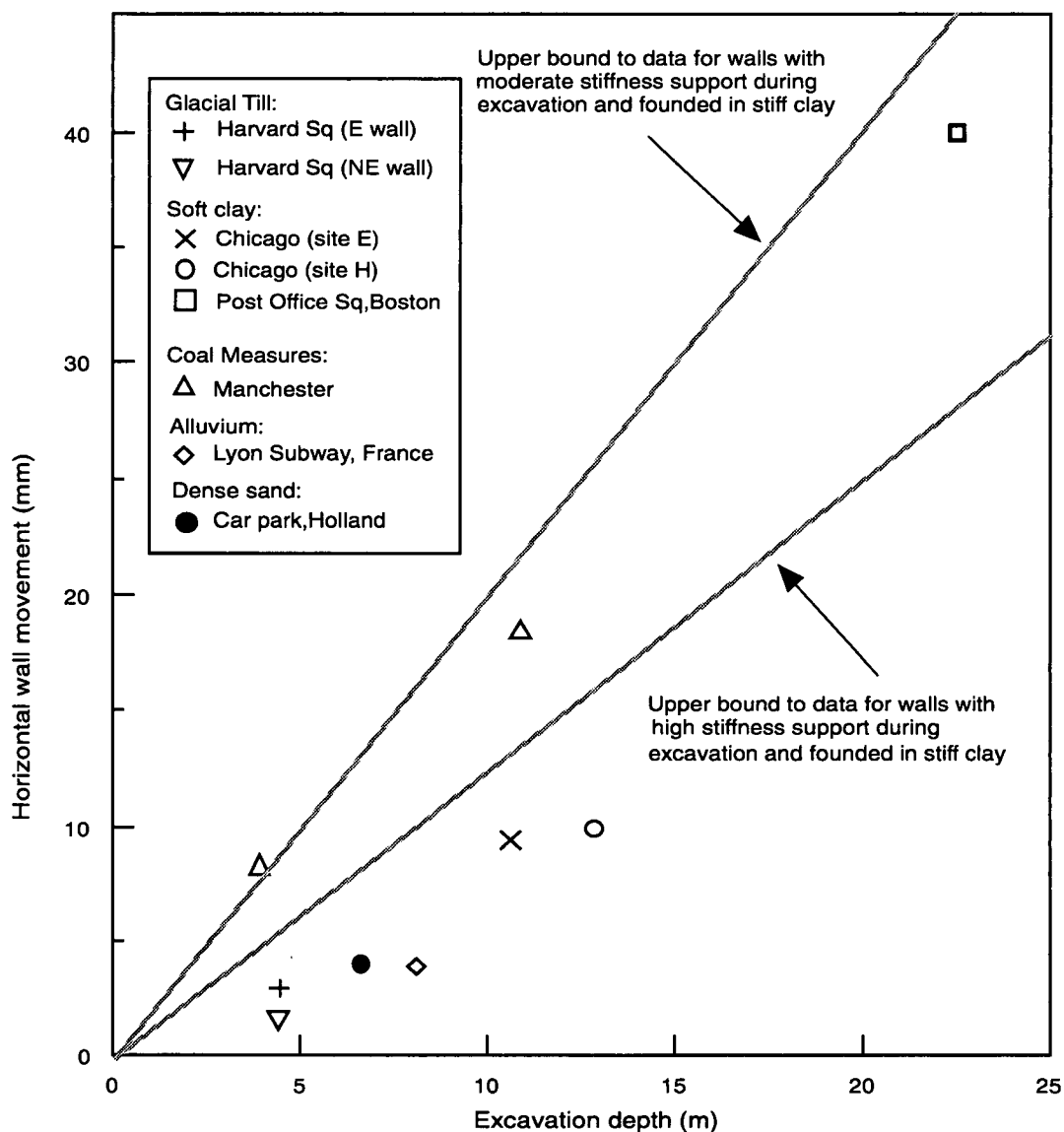


Fig 12. Horizontal wall movements caused by excavation in various soils

the upper bounds to data for walls which are founded in stiff clay with moderate and high stiffness support during excavation in front of the wall, i.e. maximum movements of 0.2% and 0.125% of the excavation depth respectively.

Generally the wall movement developed in the various soil types lies below the upper bound for excavations with moderate stiffness support in stiff clay. The only scheme where movements approach this upper bound is the contiguous bored pile construction of a 10m deep service basement at Manchester where unsupported excavation was permitted to 4m depth prior to installing ground anchors. All the other schemes given in Fig 12 are top down construction of basements where a reasonably high level of support was in operation. The results tend to demonstrate that the magnitude of horizontal movement at the wall top is almost totally dependent on the effectiveness of the support system, although in the cases investigated these had clearly been designed with the ground conditions in mind. It must be noted that, although top of wall movement was controlled, very large variations in horizontal wall movements at depth were recorded with values of up to 1.2% of excavation depth in the soft clays of the Chicago area. Not included in Fig 12 are the

results from a highway scheme on the A258 at Dartford, where an anchored barrette wall was constructed in Boyn Hill Terrace Gravel. In this case, horizontal wall movement into the retained ground was recorded due to the use of prestressed ground anchors. However horizontal movements at the ground surface were towards the wall and were generally about 50% higher than would be expected in stiff clay. Further details of these measurements are reported by Wood, Maynard and Forbes-King (1989).

Although horizontal movements of the wall and hence the retained ground surface can be controlled by use of a suitable support system, the magnitude of the measured settlements is more dependent on the ground conditions and generally above the trend in stiff clay as shown in Fig 13. This was particularly the case for excavations carried out in the soft compressible clay encountered in the Chicago area. All the Chicago cuts show large settlements (up to about 2% of the excavation depth) indicative of large plastic deformations. The same behaviour was recorded for a large number of braced excavations in soft to medium clay where sheetpiles were used; these measurements are comprehensively reported by Clough and O'Rourke (1990).

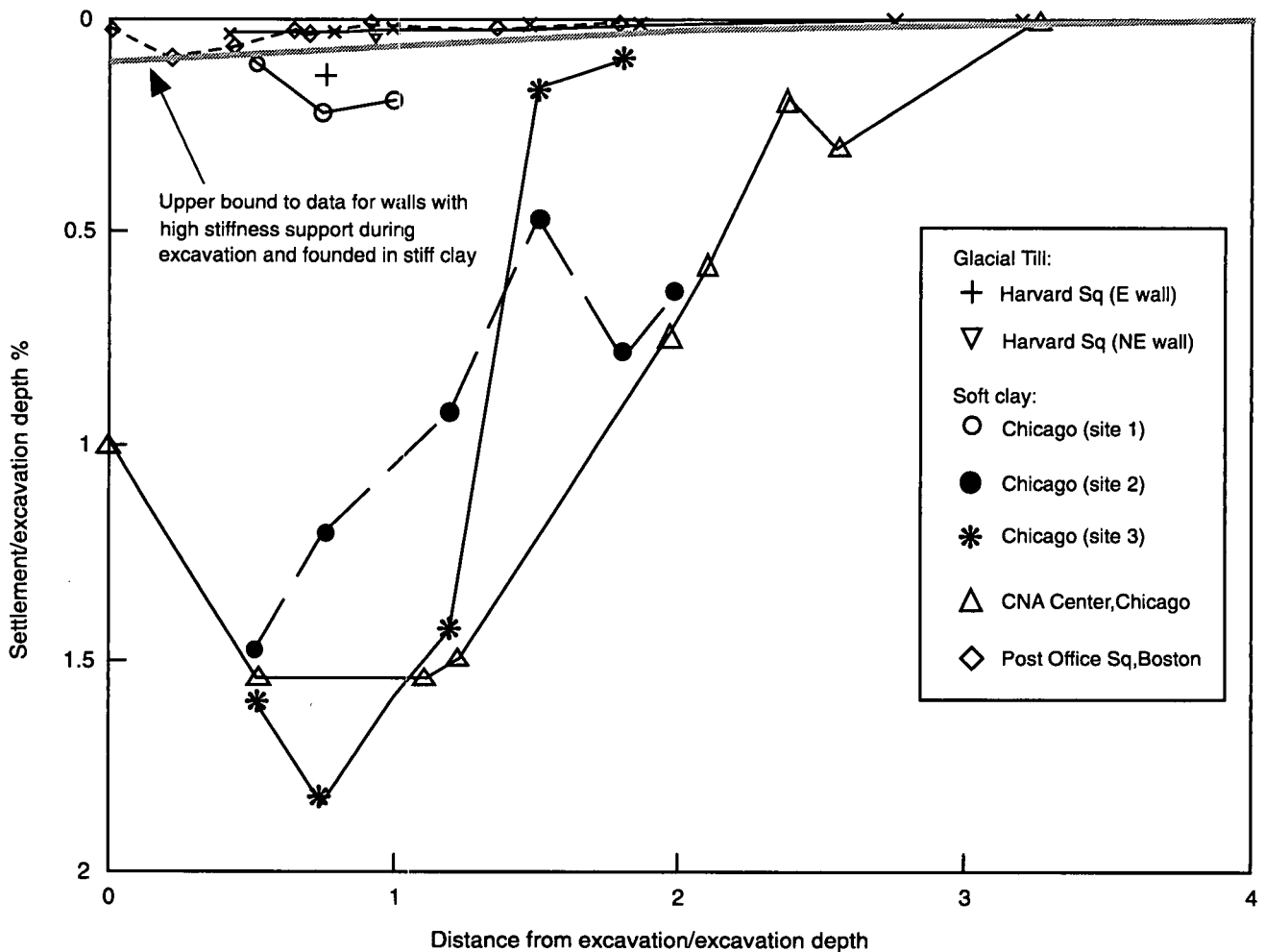


Fig 13. Surface settlement caused by excavation in various soils

## 6. SUMMARY AND CONCLUSIONS

Establishing the most probable wall and surface ground movements, together with acceptable limits, is essential in the use of the Observational Method to control embedded retaining wall construction. It is also important in assessing the effects of the construction on neighbouring buildings and buried services. In this report a database has been established from measurements of movement at sites where retained cuttings, cut-and-cover tunnels and deep basements were being constructed. Movements caused by wall installation and excavation in front of the wall have been separately assessed and total movements can therefore be found by summation of the two effects. The main findings were as follows:

1. Movements of the ground surface due to wall installation in stiff clay varied according to the construction technique employed. Maximum horizontal movements ranged from 0.04% of the pile depth for contiguous piling to 0.11% of the trench depth for counterforted diaphragm walls. Maxima for planar diaphragm walls were 0.05% of trench depth and 0.08% of pile depth for secant piling. The last result was heavily influenced by measurements at Bell Common Tunnel where stiff clay was overlain by 7m of superficial deposits. More data are needed to establish that the normal trend of surface movements for secant piling is below this value. In general, maximum settlements were about half of the horizontal movements and in all cases the zone of possible movement was considered to extend no more than 1.5 times the trench/pile depth.

2. A summary of the magnitude and extent of horizontal and vertical movements at ground surface caused by excavation in front of walls founded in stiff clay is given in Table 4. Final recommended upper bound values of horizontal surface movement were 0.125%, 0.2% and 0.4% of the excavation depth depending on whether high, moderate or low stiffness support was used during bulk excavation. Upper bound values of surface settlement varied between 0.1% and 0.2% of the excavation depth over the same range of support conditions. Generally the extent of possible movements was up to 4 times the excavation depth. Although this extent was slightly larger than recorded by other authors (Clough and O'Rourke, 1990; Burland, Simpson and St. John, 1979), the maximum movements close to the wall were generally smaller. For this reason it is important to calculate the movement profile from the non-dimensional values as the effective zone of influence may be considerably less than 4 times the excavation depth if, for example, movements of less than say 1mm are ignored.

3. With top-down construction using high level props in particular, the maximum horizontal movement of the wall during bulk excavation is not likely to be measured at the

top. In the cases investigated where the walls were founded in stiff clay, the peak movement occurred at depths of between 0.7 to 0.9 times the excavation depth. The magnitude of this movement varied between 0.04% and 0.16% of the excavation depth.

4. Generally horizontal movements at the top of walls founded in various soil types lie below the upper bound for excavations with high stiffness support in stiff clay. This data generally related to top-down construction and demonstrates that the horizontal movement at the wall top can be effectively controlled by using high stiffness support systems during excavation, although large movements (up to 1.2% of excavation depth in the soft compressible clays of Chicago) can occur at depth. The magnitude of measured settlements at the ground surface is more variable and generally above the values for stiff clay. This was particularly the case for excavations in soft clay.

## 7. ACKNOWLEDGEMENTS

The work described in this report forms part of the research programme of the Civil Engineering Resource Centre of TRL and was funded by Bridges Engineering Division of the Highways Agency. The assistance of Dr GB Card (Card Geotechnics Ltd) and Mr P Darley in retrieving, processing and interpreting the data is gratefully acknowledged.

Thanks are also due to the team involved in acquiring the TRL field data which included Mr MD Ryley, Mr GH Alderman, Mr AH Brookes and Mr S Bennett.

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**TABLE 4****ZONES OF MOVEMENT FOR EXCAVATION IN FRONT OF WALLS FOUNDED IN STIFF CLAY**

|                                |            | HIGH STIFFNESS SUPPORT  |        | MODERATE STIFFNESS SUPPORT |        | LOW STIFFNESS SUPPORT   |        |
|--------------------------------|------------|-------------------------|--------|----------------------------|--------|-------------------------|--------|
|                                |            | Max.surface<br>movement | Extent | Max.surface<br>movement    | Extent | Max.surface<br>movement | Extent |
| TRL<br>DATA                    | Horizontal | -                       | -      | 0.2%                       | 4      | 0.3%                    | 4      |
|                                | Vertical   | -                       | -      | 0.075%                     | 3      | -                       | -      |
| GENERAL<br>EXPERIENCE          | Horizontal | 0.125%                  | 4      | -                          | -      | 0.4%                    | 4      |
|                                | Vertical   | 0.1%                    | 4      | -                          | -      | 0.2%                    | 4      |
| FINAL<br>RECOMMENDED<br>VALUES | Horizontal | 0.125%                  | 4      | 0.2%                       | 4      | 0.4%                    | 4      |
|                                | Vertical   | 0.1%                    | 4      | 0.1%                       | 4      | 0.2%                    | 4      |

- Notes:
1. Maximum surface movement occurs close to the wall and is calculated as a percentage of maximum excavation depth in front of the wall.
  2. Extent of movement is calculated non-dimensionally by dividing by the maximum excavation depth.
  3. High stiffness support during excavation includes top-down construction, temporary props prior to permanent props at high level.
  4. Moderate stiffness support during excavation is temporary props of high stiffness prior to permanent props at low level.
  5. Low stiffness support during excavation includes cantilever, temporary props of low stiffness or at low level.
  6. Wall installation effects to be considered separately.

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