Design methodology for retaining walls for deep excavations in London using pseudo finite element methods

Méthodologie de conception pour murs de soutènement pour excavations profondes à Londres par méthodes aux éléments pseudo-finis

P.J. Ingram, A.R. Chodorowski, S.E. Anderson & A.R. Gaba
Arup, London

ABSTRACT
A geotechnical design methodology for horizontal and vertical equilibrium of retaining walls has been developed which considers the wall friction conditions appropriate for the excavation sequence and vertical loading conditions. The methodology is compatible with EC7, builds on the guidance of CIRIA C580, and has been developed from experience on previous large infrastructure projects in the UK, including the Channel Tunnel Rail Link and Crossrail. Recommendations for retaining wall design for the Ultimate Limit State during the excavation stage have been proposed, incorporating compatible wall friction assumptions for both lateral stability and vertical capacity checks. The design methodology also provides guidance for the design of retaining walls to resist upilift actions. The methodology provides a robust design and would be appropriate for the design of retaining walls for deep excavations.

RÉSUMÉ
Une méthodologie de conception géotechnique pour l'équilibre horizontal et vertical de murs de soutènement a été développée. Cette méthode prend en compte les conditions de friction du mur appropriées au déroulement de d'excavation et aux conditions de chargement vertical. Cette méthodologie, compatible avec le code Européen EC7 et les directions de CIRIA C580, est basée sur l'expérience de grands projets d'infrastructure en Grande-Bretagne, tels que le Channel Tunnel Rail Link et Crossrail. Des recommandations sont données pour la conception de murs de soutènement à l'état limite pendant excavation, avec des hypothèses de friction du mur compatibles avec les essais de stabilité latérale et de résistance verticale. Des directions sont aussi données pour la conception des murs de soutènement sous-pression. Cette méthodologie fournit un modèle robuste (et économique) et serait appropriée pour la conception de murs de soutènement pour excavations profondes.

Keywords : Retaining Walls, deep excavations Eurocode design

1 INTRODUCTION

This paper presents a design methodology for embedded retaining walls for deep excavations which considers compatible wall frictions for lateral and vertical loading design. The methodology builds on the guidance of CIRIA C580 (Gaba et al., 2003), and has been developed from experience on large infrastructure projects in the UK, including the Channel Tunnel Rail Link and Crossrail.

The design methodology has been developed in line with the partial factor requirements of EC7 for retaining wall analysis to provide compatibility between horizontal and vertical equilibrium when using pseudo finite element models such as Oasys FREW or Geosolve WALLAP. The method has been developed within the context of London ground conditions and is therefore suitable for excavations in stiff clays such as London Clay as well as the Lambeth Group with stiff clay and sand horizons.

2 GENERAL DESIGN METHODOLOGY FOR DEEP EXCAVATIONS

The design of embedded retaining walls in the UK is often carried out using pseudo-finite element computer programs such as FREW or WALLAP where the designer must select the magnitude and direction of wall friction when determining active and passive earth pressure coefficients.

Typical directions of wall friction adopted for excavations are shown in Figure 1 taken from CIRIA C580 (Gaba et al., 2003) . These assumptions of wall friction are appropriate for excavations where vertical loading of the retaining wall is minor.

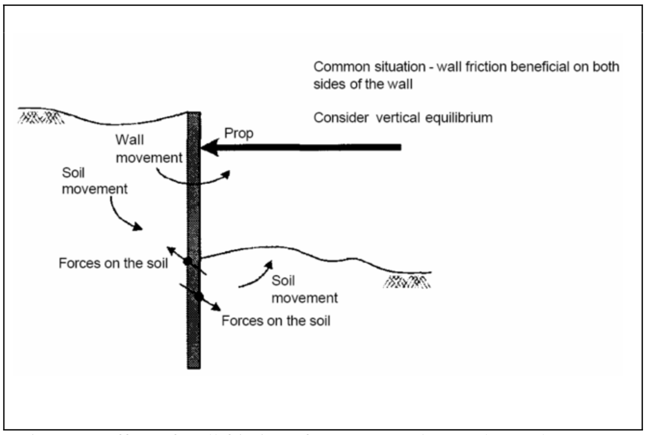

Figure 1. Effect of wall friction after CIRIA C580 (Gaba et al., 2003)

Diaphragm or piled retaining walls for deep excavations, particularly in the top down method of construction or anchored walls, may be subject to significant vertical compressive loading during construction.

For embedded retaining walls, and particularly those subject to significant vertical loading, the critical design condition for determining the toe depth of the wall is at the end of the final excavation and before the ground bearing base slab is constructed. At this stage, the retaining wall in conjunction with any slabs, props and anchors provide lateral support to the sides of the excavation. The retaining wall also carries the

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1437

vertical dead and live loads of the slabs, temporary props or anchors which restrain the wall, any load applied to the top of the wall and the weight of the wall itself from excavation level to ground surface. Typical distributions of movements for retaining walls with significant vertical loading are shown in Figure 2.

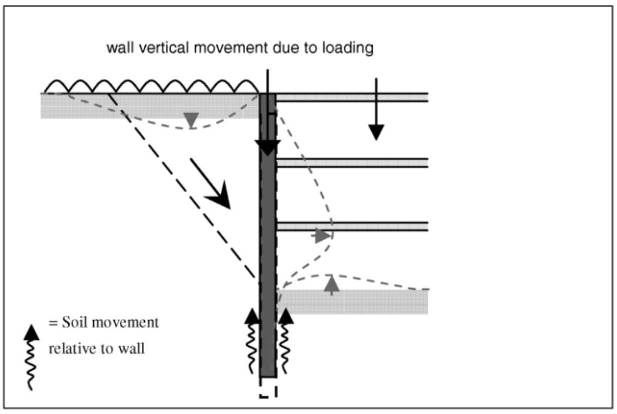

Figure 2. Typical movements around excavations supported by retaining walls with significant vertical loading

The pressure distribution and shear friction acting on the retaining wall will be the result of the complex interaction of relative soil movements adjacent to the wall due to horizontal and vertical loading as well as soil heave within the excavation. This interaction can only be modelled accurately by full soil-structure interaction analysis using non-linear finite element or finite difference methods.

There is little guidance in technical literature and existing codes of practice about the design of embedded retaining walls which are subjected to vertical loading. This paper provides such guidance.

For deep excavations where floor spans and construction loads are large, assumptions about compatible wall friction become increasingly important.

3 HORIZONTAL STABILITY AND VERTICAL EQUILIBRIUM OF RETAINING WALLS

3.1 *Method of analysis*

The direction in which wall friction acts is dependent on the direction of relative movement between soil and wall.

As the direction of wall friction affects both the lateral soil pressure on the wall and its vertical load carrying capacity, it is important that the lateral and vertical analyses are compatible.

Analysis programs such as Oasys FREW and Geosolve WALLAP, are unable to model vertical equilibrium concurently with horizontal calculations. Therefore appropriate design assumptions are required to allow compatibility between lateral and vertical loading and resistance to be achieved.

The proposed method of analysis is intended to bound the behaviour of the wall in terms of the magnitude and direction of wall movement for limiting conditions of horizontal and vertical stability. It adopts slightly different friction assumptions for the vertical and horizontal stability checks such that adopted frictions are more onerous for each of the stability checks and do not overestimate the resistance of the wall system.

Three basic steps need to be considered:

1. Determine length of wall required for horizontal or retaining wall stability
2. Check whether vertical equilibrium conditions are satisfied
3. Increase toe depth if vertical capacity is insufficient.

These steps are carried out for the maximum excavation case during construction, since once the ground bearing base slab has been cast, further capacity will be provided through the slab wall connection.

For top down construction, where the permanent slabs are used as the temporary props, wall loading during excavation is higher than for the equivalent bottom-up construction. More relative movement between the wall and the soil occurs, and the interface wall frictions are less beneficial to the horizontal equilibrium calculations.

It is worth noting, that whilst vertical equilibrium is not traditionally checked for bottom-up walls, it may be an issue where the excavation depth is significant and embedment is relatively small, as the weight of the wall (and temporary props) may overcome the available friction. This is particularly relevant where friction within a stratum appears limited – see Section 4.

The sections below outline the horizontal stability and vertical equilibrium checks, for vertically loaded retaining walls, and show how an increase in toe depth to carry additional vertical load can be determined using the approach.

3.2 *Horizontal or Lateral Wall Stability*

The methodology for retaining wall stability calculations has been developed for use with Eurocode 7 (EC7) Ultimate Limit State (ULS) calculations for Design Approach 1 Combinations 1 and 2 (DA1C1 and DA1C2), which are the design cases adopted by the UK.

Figure 3 shows an idealization of the relative magnitudes of ground movements around a significantly loaded retained excavation.

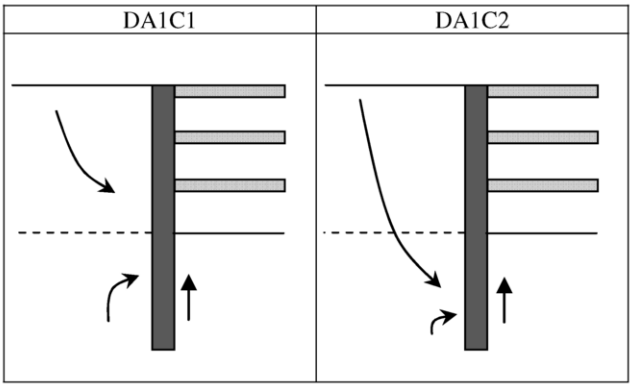

Figure 3. Relative magnitudes of ground movements around significantly loaded excavations

Combination 1 assumes unfactored characteristic soil parameters, and a small partial factor on live loading. Resulting forces and moments are factored to determine ULS values for structural analysis. Wall frictions for this combination assume some downwards movement of the wall relative to the soil, but movements are small as the wall is assumed not to be approaching limiting horizontal equilibrium in this combination.

Combination 2 assumes factored characteristic soil parameters. Under these conditions the wall is approaching limiting horizontal equilibrium, and therefore relative movements are generally greater. Resulting forces and moments are ULS values, and need no further factoring for input into structural calculations.

These assumptions of relative ground movement are consistent with observations made using finite element analyses.

Figure 4 shows suggested appropriate wall friction directions for the EC7 combinations for use in horizontal stability analyses.

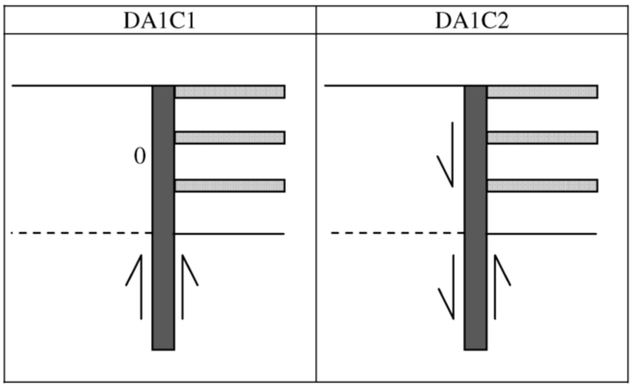

Figure 4. Wall friction directions for FREW or WALLAP analysis – walls with significant vertical loading

Under the DA1C1 conditions, the wall deflection and hence relative movement between the wall and the retained soil will be small and may not be sufficient to generate significant resistance. Therefore where the friction would be beneficial above the excavation level, friction is ignored whereas it is taken into account where it would be unfavorable below the excavation level. For a wall at limiting horizontal equilibrium, i.e. DA1C2, the ground movements will be comparatively large and friction is assumed to be mobilized over the full height of the wall.

3.3 *Vertical Equilibrium*

Retaining walls support vertical loads by means of wall friction together with base reaction (for downward applied loading). It is difficult to accurately estimate the direction of wall friction mobilised on the retained side of an embedded retaining wall. This depends on a number of factors, including:

- The magnitude of vertical loading applied to the wall;
- The action of soil heave beneath the excavation afffecting ground movements outside of the excavation; and
- The magnitude of wall deflection.

The equations shown in Figure 5 have been developed to bound the vertical behaviour of the wall, and assess its load carrying capacity.

Note that wall frictions for DA1C1 vertical equilibrium condition are slightly different from those assumed in the lateral loading analysis. Although the movements between the wall and the retained soil will be small, some extent of downwards wall friction will be generated on the back of the wall. To bound the behavior, downwards wall frictions have been assumed over the full retained height of the wall.

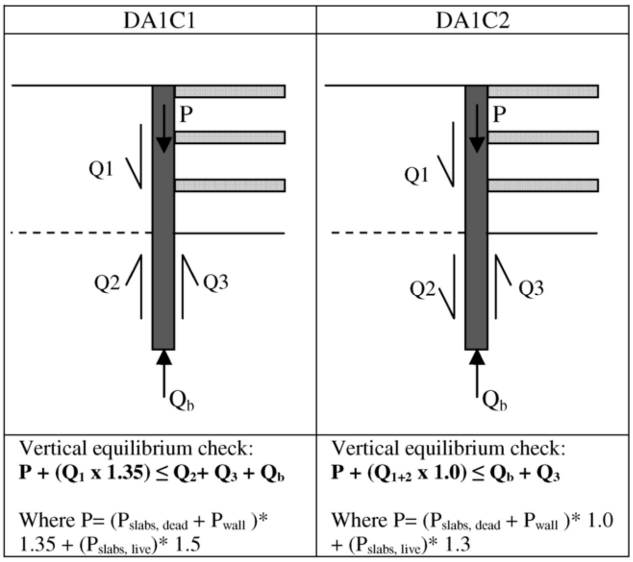

Figure 5. ULS vertical equilibrium check – walls with significant vertical loading

3.4 *Methodology to be used of wall length is insufficient to carry vertical loads*

In the case where vertical equilibrium calculations indicate that the toe depth required for lateral stability does not provide sufficient resistance to support the vertically applied loading, it is necessary to lengthen the wall and make further assumptions as to the direction of wall frictions.

Simply extending the friction regime as outlined in Figure 5 will result in excessively deep walls, as downdrag on the retained side of the wall will increase similarly to the increased capacity on the passive side for DA1C2. For this scenario, it seems unreasonable to assume that additional wall length should be both a help and a hindrance to the vertical load carrying capacity. Therefore it is suggested that a positive contribution to load carrying capacity should be assumed for both sides of the wall as shown in Figure 6.

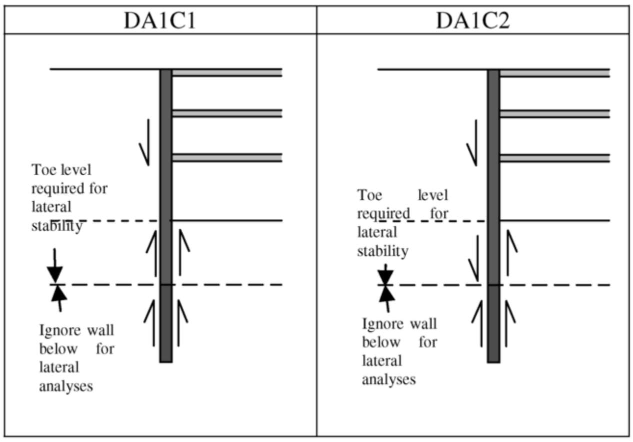

Figure 6. Wall friction assumptions for additional wall to carry vertical loads

The suggested frictions shown in Figure 6 assume that all of the additional wall length is assisting in carrying vertical loads. Since the additional portion of the wall is not required for horizontal stability, there is no requirement to assess the deepened wall for lateral stability. Bending moments and shear forces in the retaining wall along with any prop or anchor forces are determined from the lateral analysis using the toe depth required for lateral stability. Additional toe level to carry the vertical load can be simply assessed in the vertical equilibrium calculations, and added accordingly.

4 INFLUENCE OF WALL FRICTION

It is important in the design of retaining walls to ensure that wall frictions assumed in analysis are compatible with values measured on construction sites where such key parameters as use of driling fuids and the construction duration of the wall can be examined. There is very limited data on friction on diaphragm walls in the UK but a study was carried out to determine an appropriate unit shaft friction for piles constructed within London Clay and the Lambeth Group.

Published data exist for shaft frictions within the London Clay, e.g. Patel (1992). To complement this, data for pile tests within the Lambeth Group were assembled from a selection of previous Arup projects and published papers. This included results of tests on piles constructed using bentonite and left open for periods longer than 24 hours.

Patel's (1992) data show that it would be prudent to adopt a limiting value of average shaft friction of around 100kPa in London Clay.

Figure 7 shows average shaft friction plotted against average vertical effective stress for a variety of pile tests carried out in the Lambeth Group in London.

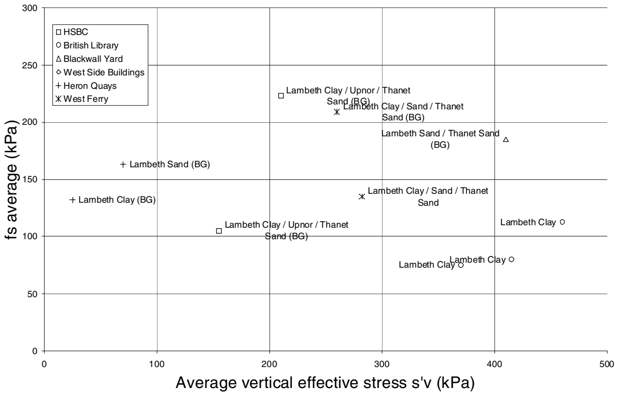

Figure 7. Average shaft friction versus vertical effective stress for pile tests in the Lambeth Group in London

The data appear to show that whilst in these strata strength continues to increase with depth, shaft friction may be limited by other factors. The only data indicating average shaft friction of significantly over 100kPa are from piles which have been base grouted. It would therefore seem prudent to also limit average ultimate shaft friction value in the Lambeth Group to around 100kPa.

In the absence of detailed test measurements for diaphragm walls, the average friction limit of 100kPa could be assumed to apply to walls also.

As noted in Section 3, setting limits on available average wall frictions obviously influences the vertical capacity of the wall element, and it is important to consider this when determining whether vertical loading for a given wall is likely to be significant during construction.

Values of average ultimate shaft friction in dense sands may be higher but these need further assessment. It should also be noted that in the case where base grouting is adopted then the evidence from results of load tests on single piles is that the average unit skin friction is generaly higher than for the equivalent non-grouted piles, perhaps due to grout travelling up the shaft. However, there are no reported case histories of base grouted diaphram wall panels or bored pile walls.

5 EXTENSION TO UPLIFT CONDITIONS

The methodology presented above has focused on the generation of wall frictions during excavation. The same considerations can also be extended to consider long term conditions.

For excavations below the water table or in heaving soils, the retaining wall may become a tension element resisting the upward pressures acting on the underside of the base slab. Under these conditions the friction directions shown in Figure 8 may be applied.

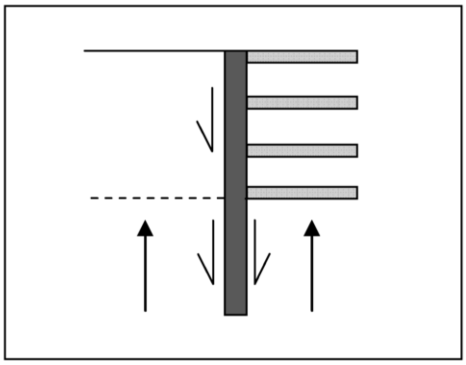

Figure 8. Wall friction directions for FREW or WALLAP analysis – walls subject to uplift conditions

In the long term the lateral resistance of the toe of the wall is supplemented by the propping from the internal slabs. The change in wall frictions caused by uplift conditions will reduce the passive resistance of the wall thereby increasing the load in internal slabs and altering the bending moment and shear force distribution in the retaining wall. This long term condition is often the critical condition for the loading of the base slab.

6 CONCLUSIONS

This paper has discussed the principles of the generation of wall frictions on an embedded retaining wall which may be applied to deep box excavations. A design methodology has been developed which provides a robust analysis for the design of retaining walls considering compatible design assumptions for both lateral and vertical stability. The paper highlights the need to not only consider appropriate vertical equilibrium calculations for top-down boxes, but also for deep bottom-up excavations, where vertical loading from the wall itself, props or anchors may be significant.

ACKNOWLEDGEMENT

The authors are grateful to Mr T.J.P Chapman for his assistance with developing the methodology contained herein.

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