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The design of high performance anchored retaining walls within the Eurocode framework

La conception de haute performance Ancré murs de soutènement dans le cadre Eurocode

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ABSTRACT The design of high performance anchored retaining walls is a complex process that must embrace the elements of efficient design, analysis, execution and validation. The performance of such structures is governed by complex soil-structure interaction phenomena and to derive a satisfactory composite structure the design of the individual elements must be optimised. In this paper the term 'high performance' is defined as a structure where each element's performance is optimised to give a safe and economic solution. The suite of European Standards (the Eurocodes and Euronorms) seek to provide a comprehensive design, execution and testing framework for all civil engineering structures, however a daunting array of documents must be consulted when designing specific structures such as anchored retaining walls. It is therefore helpful to summarise the pertinent elements affecting the design, execution and validation of high performance anchored retaining walls in one document and this paper seeks to do this. The suggest framework for designing high performance anchored retaining walls has been developed from the authors' experience working as practioners within industry and as participants on a number of standards committees including CEN TC288 Execution of Special Geotechnical Work, TC288/WG14 Execution of Special Geotechnical Works – Ground Anchors, TC250/SC7/EG1 Ground Anchors, BSI/B526 Geotechnics, TC341 Anchor Testing and B/526/-/3 – Anchors; BSI's UK Ground Anchors Panel. The paper illustrates the elements of design, execution and testing of high performance anchored retaining walls using the Eurocode suite of standards with the use of a practical example.

RÉSUMÉ La conception de haute performance ancré murs de soutènement est un processus complexe qui doit englober les éléments de conception efficace, d'analyse, d'exécution et de validation. La performance de ces structures est régi par un processus complexe interaction sol-structure phénomènes et d'en tirer un composite satisfaisante structure la conception des différents éléments doit être optimisé. Dans ce document, le terme "haute performance" est pris dans le sens d'une structure où chaque élément de performance est optimisé pour donner un suffisamment sûre mais solution économique. La suite des normes européennes (les Eurocodes et d'Euronormes) cherchent à fournir un programme complet de conception, d'exécution et cadre de test pour toutes les structures de génie civil, cependant une multitude de documents doivent être consultés lors de la conception des structures comme ancré murs de soutènement. Il est donc utile de résumer les éléments pertinents touchant à la conception, l'exécution et la validation des performances élevées ancré murs de soutènement en un document unique, et ce document vise à faire cela. L'avis cadre de conception hautes performances ancré murs de soutènement a été développé par les auteurs de l'expérience de praticiens au sein de l'industrie et comme participants sur un certain nombre de comités de normalisation notamment CEN TC288 L'exécution des travaux géotechniques, TC288/WG14 Exécution spéciale de travaux géotechniques - ancrages de sol, TC250/SC7/EG1 ancrages de sol, BSI/B526 géotechnique, TC341 test d'ancrage et B/ 526/ - /3 - Ancrages; BSI britannique ancrages de sol panneau. Le document illustre les éléments de conception, d'exécution et la mise à l'essai de haute performance ancré murs de soutènement en utilisant l'Eurocode suite de normes avec l'utilisation d'exemples pratiques.

1 INTRODUCTION

The design of high performance anchored retaining walls is a complex process that must embrace the elements of efficient design, analysis, execution and validation. Greatest economy is achieved when the various elements of the structure are combined to perform as efficiently as possible. In 2013 Eurocode 7 (BS EN 1997-1:2004 +A1: 2013) and UK National Annex were amended and now set out the basis for validating the design of all elements of embedded anchored retaining walls. Eurocode 7 (EC7) does not provide guidance on dimensioning an anchor and is only concerned with ensuring (by testing) that the installed anchors provide sufficient restraint to prevent a limit state occurring in the supported structure. When dimensioning anchors reference to BS 8081 should be made.

An anchored embedded retaining wall comprises the embedded wall element (piles or diaphragm wall), grouted ground anchors and capping beam or series of wailings connecting the two elements together. Division of design responsibility is common and the separate roles may be defined as:-

- Wall Designer – responsible for the overall retaining wall design, and the;
- Anchor Designer – usually a specialist (often the contractor) responsible for the design of the anchor elements.

The optimum anchored wall solution will only be realised if the Wall and Anchor Designers are able to communicate in an open and transparent way. Wooland et al (1997) describe the benefit of such close cooperation where the retaining wall was optimised in light of the Anchor Designer's selection of anchor capacity and layout.

Historically the forces imposed on such retaining walls would be derived from limit equilibrium calculations nowadays flexible retaining wall analysis programs and finite element or finite difference programs are used. Whilst these methods have the benefit of modelling stress and strain dependent behaviour their complexity demands a high level of specialist and practical understanding. Lack of understanding of these complex design tools have contributed to significant retaining wall failures (Whittle & Davies, 2006).

2 THE DESIGN PROCESS

Once the need for a retaining wall is established the Wall Designer must assemble the data required for the design, as listed in EC7. This includes:

- Geometry (Clause 9.3.2).
- Proposed dredge levels and construction sequence which may call for sequential excavation and placement of multiple levels of ground anchors. Acknowledgement of excavation control is available via Clause 9.3.2.2(2) by allowing some latitude in the magnitude of unplanned excavation (Δa) to be incorporated in the ultimate limit state (ULS) wall analysis; where justified Δa may equal zero;
- Soil properties, which will include soil stiffness where flexible retaining wall analyses are undertaken;
- Ground water levels (Clause 9.3.2.3);
- External forces (actions) applied to the wall (Clause 9.3.1). Clause (2.4.2(4)) lists actions to be considered including imposed pre-stress in ground anchors or struts. Initially the anchor prestress will be estimated and only finalised after iteration of both the ULS and SLS analyses to determine the optimum anchor value;
- The true anchor stiffness will probably not be known until the anchor is sized to take the required load arising out of the analysis; again design iteration is required to get to the optimum value.

The influence, in retaining wall analysis, of anchor pre-stress and stiffness, on the wall behaviour is illustrated by reference to a completed anchored retaining wall project. In this case the contractor (Keller Ltd) was both the Wall and Anchor Designer. The design discussed here is implemented in accordance with BS EN 1997-1:2004 + A1: 2013 and UK National Annex.

2.1 *Example Project*

Figure 1 shows a section through the anchored retaining wall with a 5.65m retained height formed from 600mm diameter CFA piles constructed in Lias Clay. The wall was designed to support a railhead off-loading slab and a relatively high 50kN/m^2 surcharge from stacked containers. The wall was supported by anchors inclined at 30 degrees from the horizontal and at 4.5m centres through a capping beam at a level of 113.74mOD. The anchors were installed from a temporary berm and locked off at 330kN, before the excavation was completed. The ULS calculations accommodated a 0.5m over-dig allowance. The specified 50kN/m^2 surcharge is unusually high and for comparison purposes the wall behaviour under a reduced surcharge of 10kN/m^2 was also investigated. All analyses are undertaken using WALLAP Retaining wall analysis program (http://www.geosolve.co.uk). Figure 1 shows a section through the wall and Figure 2 shows a photograph taken after the anchors had been installed and locked off but before the wall facing was constructed.

2.2 *Deriving Anchor Loads*

2.2.1 *Wall Design*

To dimension the anchor the Anchor Designer must know from the Wall Designer the resistance the anchors must provide. EC7 Section 9 'Retaining Structures' is the domain of the Wall Designer, out of which the Anchor Designer requires the following forces (see Simpson et al, 2015):-

i. Ultimate Limit State

The Wall Designer must compute the design value of the resistance the anchor must provide to prevent an ultimate limit state occurring in the supported structure, $F_{ULD;d}$.

ii. Serviceability Limit State

The maximum characteristic anchor force, $F_{Serv,k}$, sufficient to prevent the occurrence of a serviceability limit state in the structure is also required. EC 7 defines this as the maximum force the anchor will experience in its lifetime, once it has been stressed and locked off. $F_{Serv;k}$ is obtained from a SLS analysis of the retaining wall. EC7 requires all anchors to be tested to a load higher than $F_{Serv,k}$ prior to being locked-off; the determination of $F_{Serv,k}$ excludes consideration of test loads.

Therefore the Wall Designer must undertake 3 analyses. Firstly at the ULS C1 and C2 analyses to obtain $F_{ULS;d}$, and secondly an SLS analysis to establish $F_{Serv,k}$.

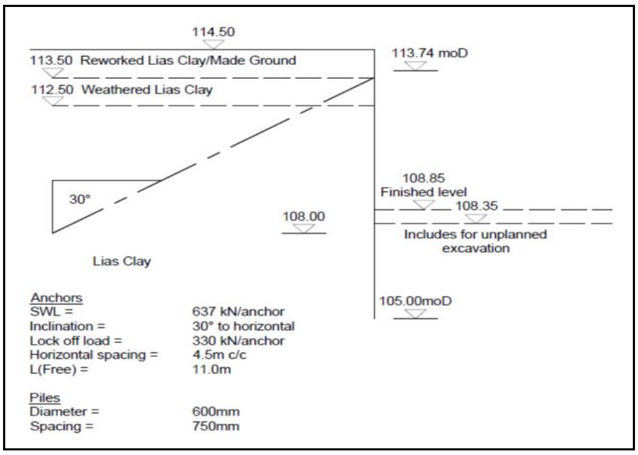

Figure 1 Section through example retaining wall

2.2.2 Anchor Design

EC7 Section 8 'Anchors', is the domain of the Anchor Designer who must take $F_{ULS;d}$ and $F_{Serv;k}$ as given by the Wall Designer to compute the ultimate limit state force to be resisted by the anchor, $E_{ULS,d}$.

$$E_{ULS;d} = max\left(F_{ULS;d}; F_{Serv;d}\right) \tag{1}$$

where

$$F_{Serv;d} = \gamma_{Serv} \times F_{Serv;k} \tag{2}$$

In practice this generates much more complexity than previous UK design demanded.

Figure 2 Retaining wall prior to being faced

2.3 Influence of pre-stress on wall design and anchor loads

Where the wall design is undertaken using a flexible retaining wall or FEA computer program, the selection of the anchor pre-stress load greatly influences the computed anchor load, wall deflection and bending moment. This is illustrated by parametric study of the example project. To avoid obscuring fundamental behaviour by the influence of partial load and material factors the study is based on SLS analyses.

Figure 3 shows the relationship between maximum anchor load and initial pre-stress load. The relationship is non-linear with pre-stress load having less influence on maximum anchor load at low pre-stress, but on reaching a threshold value (approximately 280kN for the 10kN/m^2 surcharge case and 430kN for the 50kN/m2 surcharge case) maximum anchor load increases almost linearly with pre-stress load.

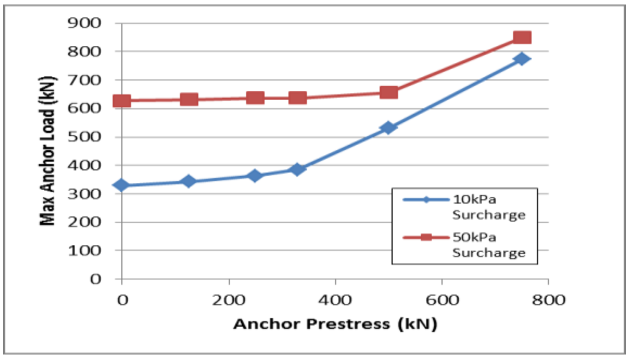

Figure 3 Max anchor load plotted as a function of pre-stress

As would be expected anchor load increases with surcharge load.

Figure 4 shows the relationship between the computed maximum wall deflection and pre-stress load. Again the relationship is non-linear with maximum deflection occurring when pre-stress load is zero. With increasing pre-stress deflection initially reduces sharply until the threshold pre-stress is reached beyond which pre-stress load is less effective in reducing wall displacement.

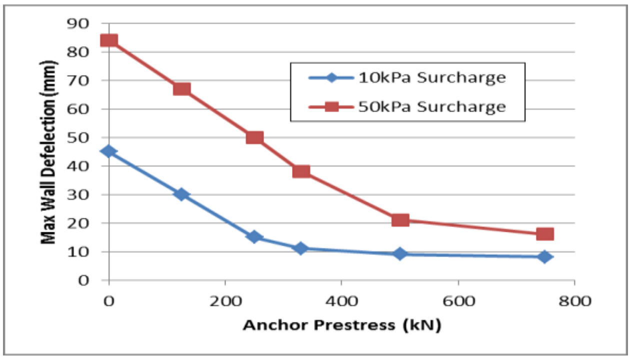

Figure 4 Wall deflection plotted as a function of pre-stress

Figure 5 shows the wall bending moment increasing almost linearly with increasing anchor pre-stress. The increase is more muted with the 50kPa surcharge compared to the 10kPa surcharge.

Thus for practical retaining wall examples, and for a given wall thickness, maximum anchor load can be minimised by minimising pre-stress and this will have a relatively minor effect on wall bending moment. Deflections can be controlled by varying anchor pre-stress but only to a point, beyond which increasing pre-stress has little practical benefit. To further reduce deflections either additional rows of anchors or a stiffer wall must be provided.

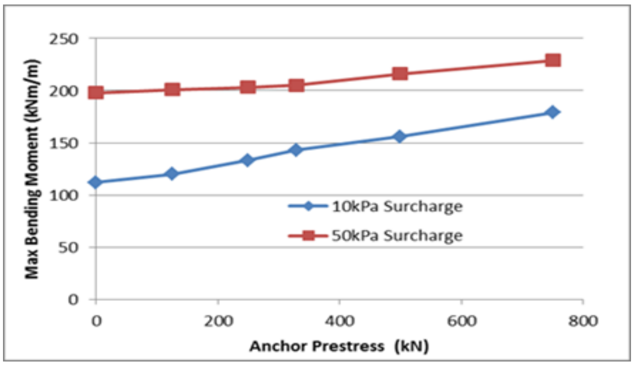

Figure 5 Wall bending moment plotted as a function of pre-stress

2.4 *Selection of anchor stiffness*

In flexible retaining wall analyses the Wall Designer must select the anchor stiffness, k, per meter run of wall. This is a function of the effective length of the anchor, L_e, tendon area, A_t, modulus, E, and spacing S. For practical purposes of estimating stiffness the anchor free length, L_{free} can be taken as the effective length.

$$k = E\frac{E\,A_t}{SL_{Free}} \tag{3}$$

The anchor free length will generally be governed by the need to get the anchor fixed length beyond the active zone behind the wall (for example see BS8081:1989 Figure 39) or down to an appropriate founding stratum, whichever produces the greatest free length.

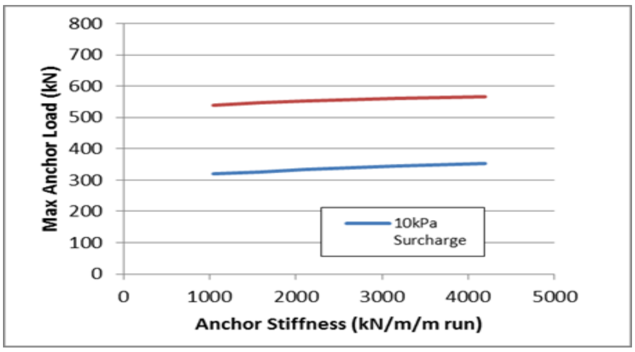

Figure 6 Max anchor load plotted as a function of anchor stiffness

The effects of varying anchor stiffness on maximum anchor load, wall deflection and bending moment are shown in Figures 6 to 8, where the anchors were locked-off at 330kN. Figures 6 and 8 show that the maximum anchor load and bending moment are hardly effected by changes in anchor stiffness.

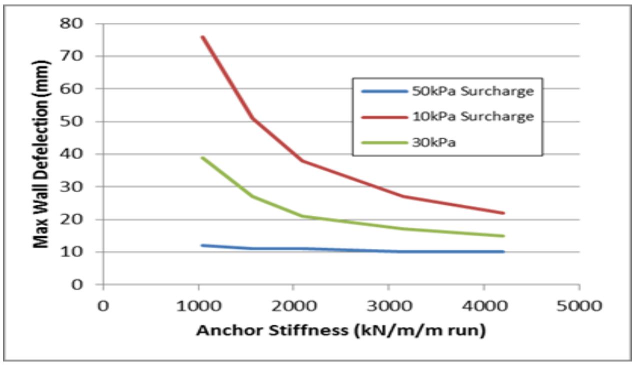

Figure 7 Wall deflection plotted as a function of anchor stiffness

Figure 7 shows that wall deflection is significantly influenced by anchor stiffness at low to medium surcharges. For the 10kPa surcharge case, doubling the stiffness from 1000 to 2000 kN/m/m halves wall deflection, whilst no practical benefit is seen for the 50kPa surcharge case. A 30kPa surcharge case illustrates an intermediate loading case.

In practical applications it is recommended that wall deflection is controlled via anchor pre-stress rather than by attempts to change the anchor stiffness. The Anchor Designer will usually select the size of tendon and anchor spacing to achieve the most economical solution. The Wall Designer should then check their initial assumptions of anchor stiffness to confirm the overall design.

2.5 Designing an Anchor to EC7

Paradoxically EC7 Section 9 provides no guidance to enable the Anchor Designer to dimension an anchor. EC7 is only concerned with validating that the anchor is able to provide sufficient resistance to prevent the occurrence of a limit state in the structure (Simpson et al, 2015).

The UK National Annex mandates the use of Design Approach 1 which necessitates that two ULS design combinations are considered (EC7 2.7.7.3.4.2(1)) as well undertaking an SLS analysis.

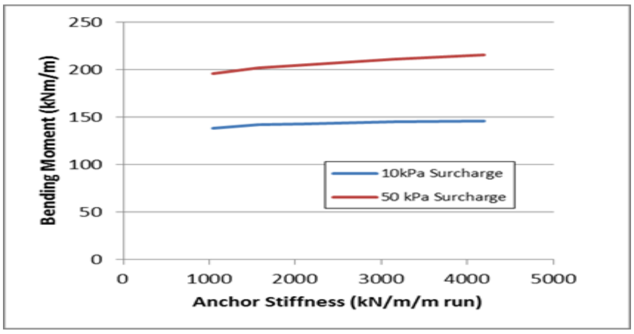

Figure 8 Wall moment plotted as a function of anchor stiffness

In both the Combination 1 (C1) and Combination 2 (C2) analyses anchor pre-stress is considered as a permanent unfavourable action, as it does not vary once applied (EC7 2.4.2(4)). Usual UK practice is to apply the load factor γ_Q, to the effect of permanent actions. In C1 calculations the load factor, γ_G, (1.35) is applied to the resultant C1 anchor load arising from the analysis to give $F_{ULS;d1}$. For C2 calculations , γ_Q, is 1.0, thus the resultant anchor load, $F_{ULS:d2}$, is taken directly from the calculation output.

The ultimate limit state design anchor force, $F_{ULS;d}$ is the maximum of $F_{ULS;d1}$ or $F_{ULS,d2}$. The complexity of Design Approach 1 is such that it is not always clear at the outset of the retaining wall design whether C1 or C2 will govern. Figure 9 shows how the level of pre-stress and magnitude of surcharge load on the wall influences which design combination governs.

To obtain the ultimate limit state force to be resisted by the anchor, $E_{ULS;d}$, (see Eqn 1 above) EC7 also requires the design value of maximum anchor force, $F_{Serv;d}$, to be determined. Figure 10 shows the relationship between $F_{Serv;d}$ and $F_{ULS;d}$. Experience indicates that in all practical designs undertaken to date $F_{ULS;d}$ governs, but this does not remove the need to check this in the design to be fully EC7 compliant.

2.6 Dimensioning the Anchor

To reiterate EC7 does not provide recommendations on how to size the anchor components.

Section 8.5.4 refers the designer to Eurocode 2 and Eurocode 3 for tendon and anchor head design and EC2 and BS EN 1537 for grout/tendon resistance. Neither EC2 or EC3 fully cover the necessary aspects of anchor design and BS 8081 is the preferred source of reference for structural design.

The preferred source of guidance on dimensioning of the fixed anchor length, L_{Fixed}, and in particular ground/grout bond again is BS 8081.

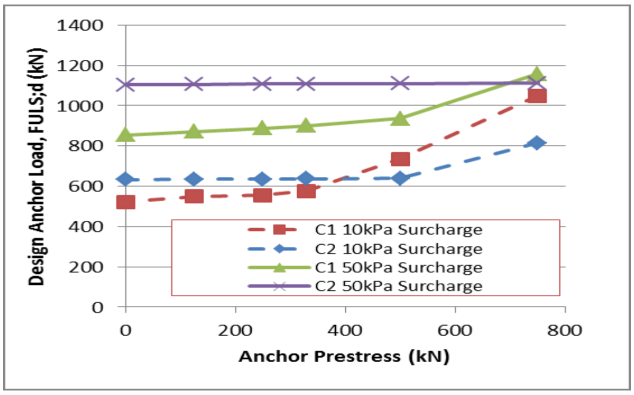

Figure 9 C1 & C2 Design anchor load with varying pre-stress

2.7 *Validating the anchor design*

EC7 Section 8 requires all production anchors are validated by acceptance tests undertaken in accordance with EN ISO 22477-5 Testing of prestressed ground anchors, which is not yet published. In the absence of this standard testing should be undertaken to BS 8081.

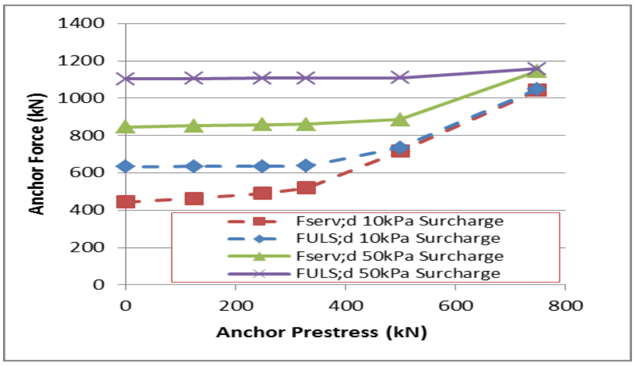

Figure 10 ULS & SLS anchor force as a function of pre-stress

3 CONCLUSIONS

The design of high performance anchored retaining walls requires the combination of practical anchoring experience and detailed knowledge of complex soil structure interaction.

The Anchor Designer must be given the right information by the Wall Designer who must understand the relative influence of various factors affecting the design, particularly the level of anchor-prestress to be used in retaining wall analyses.

The requirements of EC7 and UK NAD to consider two ultimate limit state design combinations in addition to the serviceability limit state adds an additional layer of complexity over an already complex process.

EC7 is only concerned with validating that the resistance of a constructed anchor is sufficient to prevent a limit state occurring in the structure. This is done by mandatory acceptance testing. Until EN ISO 22477-5 is published testing should be undertaken in accordance with BS 8081.

EC7 does not address the dimensioning of ground anchors, therefore BS 8081 should be used for this purpose.

For the retaining wall example used in this paper greatest efficiency in anchor design is achieved by specifying the minimum pre-stress required to minimise wall deflection.

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