New observational method framework and application
Nouveau cadre de la méthode d'observation et d'application

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ABSTRACT: This paper introduces the new holistic Observational Method (OM) framework described in Ciria C760 – the new revision to the Embedded Retaining Wall Design Guide. This new OM framework is described by four approaches and these are explained with reference to case histories. Maximum benefit is achieved by back analyzing case histories in similar ground conditions to derive the most probable soil parameters. These parameters can then be used in an *ab initio* design to maximize saving in the wall thickness, toe embedment, and propping forces. A contingency plan is based on conventional *characteristic* design parameters and this involves additional propping. The term *ipso tempore* is introduced to cover wall redesign after construction starts. This may be to achieve saving in propping where movements are smaller than predicted. Alternatively, additional propping or ground treatment may be required and this is consistent with Peck's 'best way out' approach.

RÉSUMÉ : Cet article présente le nouveau cadre holistique de la Méthode d'Observation (MO) décrit dans la nouvelle révision du Guide Ciria C760 sur la Conception des Murs de Soutènement Encastrés. Quatre approches décrivent cette méthode et sont expliquées avec des études de cas. Le plus grand bénéfice est donné par les analyses en retour des cas historiques dans des conditions similaires de sol qui permettent d'obtenir les paramètres de sol les plus probables. Ces paramètres peuvent ensuite être utilisés dans une conception dès le début (ab initio) pour maximiser les économies dans l'épaisseur de la paroi, l'encastrement de la pointe et les butons. Un plan de contingence est basé sur des paramètres caractéristiques conventionnels pour la conception et implique un renforcement supplémentaire. Le terme ipso tempore est introduit pour désigner la révision de conception du mur de soutènement après le début de la construction. Cela peut consister à réaliser des économies dans les butons lorsque les mouvements sont plus faibles que prévu. Sinon, des butons supplémentaires ou un traitement du sol peut être nécessaire, ce qui est conforme au « best way out » de la méthode de Peck.

KEYWORDS: observational method, retaining wall, deep excavation,

1 INTRODUCTION

The Observational Method (OM) in geotechnical engineering was formulated for the first time by Peck in his Rankine Lecture (Peck 1969). Since the original work by Peck, the method has been revisited on many occsaions (for example Powderham (1994), Nicholson *et al* (1999), Gaba *et al* (2003)). Despite its obvious benefits to the construction industry, the OM has not been adopted widely. The reason for the retisence to adopt the OM may be due to the absence of a Code of Practice for its implimentation, a misconception of increased risk, or perhaps due to the increased fragmentation of the industry.

The Eurocode for geotechnical design (BS EN 1997-1, EC7) is the first design code in the UK that specifically permits the design of geotechnical structures to be undertaken using the OM, although it gives very little guidance or requirements. As part of the update to the CIRIA guide C580 for the design of embedded retaining walls (C760, Gaba *et al*, 2016), a new classification system and approach to the implementation of the OM was introduced. The intention was to bring together the previous work undertaken on the OM in a logical and structured way to allow for its more widespread implementation. The new method is described here with an example of its application in a number of projects, including the Crossrail project recently completed in Central London.

2 BACKGROUND

2 .2 *Peck (1969)*

In his Rankine Lecture, Peck introduced two approaches to the implementation of the OM; *ab initio* where the intention is to use the OM from the start of the project, and *best way out* where construction is not going as planned and some intervention is required to prevent an ultimate limit state (ULS) or serviceability limit state (SLS) failure from occurring.

2.2.1 *Ab initio*

In Peck's original description of *ab initio*, the design of a particular geotechnical structure would be undertaken using *most probable* parameters for the soil and structural behavior of the structure. Separately, a set of contingency measures would be developed that would assure stability of the wall if the behavior tended towards characteristic design (or the equivalent definition of moderately conservative). Depending on the observed behavior, the construction would either continue following the *most probable* behavior or the pre-planned contingency measures would be implemented. In the case of an embedded retaining wall, the wall embedment and structural design would be completed according to the *most probable* design with an alternative construction sequence, likely to include more levels of props, or an alternative excavation sequence would be planned. In the case of embedded retaining walls, it is an obvious but important consideration that once the wall is installed, its embedment length and structural design can't be changed easily, and therefore only the construction sequence and propping structures can be modified.

2.2.2 *Best way out*

In contrast to *ab initio*, the *best way out* is not planned from the start of the project but is implemented during the construction stage when unacceptable, or unexpected movements occur. Rather than offering savings in programme and materials, the *best way out* is used to prevent failure or unacceptable movements. For the case of an embedded retaining wall, the process requires the back analysis of the wall performance to-date and re-calibration of the parameters used to predict the soil and structural behavior. Using the calibrated parameters, the remedial measures required to ensure long term stability of the structure can be designed and implemented.

2 .3 *CIRIA 185, Nicholson et al (1999)*

Nicholson *et al* (1999) provided guidance on the application of the OM to any type of geotechnical structure by building on the initial work of Peck. In describing the *ab initio* approach to the OM, CIRIA 185 makes a significant departure from the original description by Peck; instead of starting with a *most probable* design and having a *characteristic* design as a contingency, C185 proposes starting with a *characteristic* design and having a *most probable* design as a possible modification (i.e. an improvement). It is important to note that the potential savings from this approach are reduced, as the wall embedment and structural design cannot be modified.

3 NEW OM FRAMEWORK

3 .1 *Review of current approaches*

The approaches to *ab initio* proposed by Peck (1969) and Nicholson *et al* (1999) are equally valid but have quite different approaches to the balance between risk and opportunity. Peck's original definition saw the application of contingency measures as a risk mitigation, whereas Nicholson *et al* saw the application of modification as an opportunity. By being more cautious in their approach, the method of *ab initio* proposed by Nicholson *et al* could not maximize the possible savings in cost and programme. If the embedded retaining wall is constructed in accordance with a structural and geotechnical design assuming *characteristic* parameters, the embedment depth, structural thickness and reinforcement requirements will be more onerous than if *most probable* parameters had been assumed, and once constructed, evidently cannot be changed. Economies can therefore only be made by modifications to the excavation sequence and support to the wall. These savings may be significant but can never match the savings possible if *most probable* behavior had been assumed for the design from the start.

The uncertainty in what to assume for the base design assumptions may partially explain why the OM has not gained significant traction in the construction industry since its introduction in Peck's Rankine Lecture.

3 .2 *C760 holistic approach to OM*

To overcome the apparent inconsistencies in the approach to the application of the OM, the authorship team of the new CIRIA guidance on the design of embedded retaining walls, C760, took the opportunity to introduce a new framework that aimed to unify and incorporate all previous definitions. It was hoped that a new consistent framework to the application of the OM to embedded retaining walls would encourage its application, particularly for large infrastructure projects, but also for other types of geotechnical structures.

Under the new system, the OM is divided into two broad categories; *ab initio* in which the application of the OM is planned prior to wall installation, and a new term is introduced *ipso tempore* where the OM is initiated after wall installation has started. The two broad categories are divided into two further sub-categories as described in the following sections.

3.2.1 *Approach A – Ab initio optimistically proactive*

Approach A is akin to *ab initio* as defined by Peck in his Rankine lecture. The geotechnical and structural design of the wall is undertaken assuming *most probable* behavior, and therefore savings in materials are maximized. On the assumption of *most probable* behavior, a fully developed construction sequence is developed. In parallel, an alternative construction sequence is devised that assumes *characteristic* behavior of the ground and the wall. With the geotechnical and structural capacity of the wall defined by the assumption of *most probable* behavior, it is inevitable that an alternative construction sequence will require additional support to the wall to ensure stability and that the structural forces are within the wall and prop capacity. On the basis of serviceability predictions, trigger limits are set to control the behavior of the wall relative to the *characteristic* and *most probable* predictions. Once excavation of the wall has started the observations are compared to the *characteristic* and *most probable* predictions, and a decision is made on which of the defined construction sequences is to be followed.

There are few recent examples of Approach A at the present time because it is not normal practice to design walls based on *most probable* parameters.

3.2.2 *Approach B – Ab initio cautiously proactive*

Approach B is akin to *ab initio* as defined by Nicholson *et al* in the CIRIA guidance document C185. The geotechnical and structural design of the wall is undertaken with *characteristic* assumptions for the ground and the wall behavior. At this stage the design is compliant with the requirements of "design by calculation" as defined in EC7 and monitoring would not be necessary to validate the assumptions. In parallel to the *characteristic* design, a construction sequence is developed with *most probable* behavior assumed for the ground and the wall. Due to the enhanced parameters, it is likely that for this set of assumptions, prop levels could be omitted whilst maintaining the wall stability and structural capacity. It is clear that the material used in the wall construction cannot be optimized at this point, but savings can be made in the construction sequence and the amount of support provided. Trigger limits are then set based on SLS analyses adopting *characteristic* and *most probable* behavior and excavation of the wall started. Depending on how observations develop with respect to the *characteristic* and *most probable* predictions, it can be decided if the modifications assumed in the *most probable* analysis can be implemented or not. The paper by Nicholson *et al* (1998) on Batheaston Bypass is an example of Approach B.

3.2.3 *Choice between approach A and B for ab initio*

The choice between approaches A and B when applying the OM to embedded retaining walls will depend primarily on the familiarity of the project team, and particularly the designer, with the prevailing ground conditions at the site under consideration. If the ground conditions are well known and there are an adequate number of case histories for similar structures in the same ground conditions, back analysis of these can be undertaken to compare with *most probable* parameters derived from site investigation data. The designer may then be confident in using approach A, provided the contractor and client are involved in the process and are actively engaged in its implementation. It would be foolhardy to use approach A when working in unfamiliar ground conditions (where approach B may be more suitable) or when working with a project team that do not understand or are not fully engaged with the OM process (in which case OM should not be used at all).

3.2.4 *Approach C - Ipso tempore proactive to make modifications*

C760 defines *ipso tempore* approach C as the OM being implemented during the construction stage of a project, to proactively make improvements to the construction sequence that have not previously been formally defined. When following approach C, the design of the wall has been completed in accordance with the requirements of the "design by calculation" approach defined in EC7 and is therefore akin to the characteristic design defined in approach B. The significant difference is that when excavation started, there was no intention to implement the OM, and therefore no alternative construction sequence was prepared. At some stage during the construction sequence the design team decide that the wall is performing better than predicted and pro-actively they decide to make improvements to the construction sequence. At this stage it is important that the original designer of the initial construction stages of the wall undertakes a thorough audit of the wall's behavior and the construction sequence that has been followed to allow a rigorous back-analysis of the wall to be undertaken. The audit must include as a minimum the observed wall and ground movements, prop loads, excavation sequence and levels, and surcharges applied to the wall. Once the audit is complete, a rigorous back-analysis of the wall can be completed to re-calibrate the assumed parameters. These re-calibrated parameters can be used to forward-predict the behavior of the wall to completion and to design an improved construction sequence. Associated SLS analyses will be required at this stage using the re-calibrated parameters in order to set trigger limits that ensure the performance of the wall in the subsequent construction stages is in line with the re-calibrated predictions. The benefits in adopting approach C are similar to those defined in *ab initio* approach B.

Despite not previously being formally defined, approach C has been the most commonly adopted. The Crossrail case history at Tottenham Court Road Western Ticket Hall, (Yeow et al, 2014) and Chen et al, 2015) is a recent example.

3.2.5 *Approach D - Ipso tempore reactive to make corrections*

Ipso tempore approach D is akin to the "best way out" defined by Peck. In common with approach C, there was no intention to apply the Observational Method from the start of the project, however movements are larger than predicted and the project team decide to implement the OM to ensure an SLS or ULS failure does not occur. These movements are often associated with wall installation or ground treatment operations. This is in contrast to approach C when the introduction of the OM is implemented because movements are smaller than expected.

Once the decision is made to implement the OM, the process is similar to that described for approach C. The first stage is to undertake an audit of the observations and the construction process to that point and to re-calibrate the analytical model to make a forward prediction to the completion of construction. To prevent an SLS or ULS from developing, it is likely that additional support to the wall, or a revised construction sequence will be needed. An example of Approach D is at Newton Station in Singapore (Gaba 1990) where an unforeseen buried channel infilled with marine clay was encountered during diaphragm wall installation. A jet grout raft was then used to provide additional propping to the wall below formation level, (Gaba, 1990).

3.2.6 *Summary of approaches to the Observational Method*

A thorough discussion on the different approaches to the observational method can be found in CIRIA C760 (Gaba *et al*, 2016). Chen *et at* (2015) and Table 7.2 in C760 give a summary of the key points related to each approach.

4 INTERPRETATION OF SITE INVESTIGATION DATA

4 .1 *Definition of parameters*

One of the principle requirements of EC7 when applying the observational method is that "*the range of possible behavior shall be assessed and it shall be shown that there is an acceptable probability that the actual behavior will be within the acceptable limits*".

In this current framework, the range of possible behaviors is reduced to "*characteristic*" and "*most probable*". The term *characteristic* was introduced with EC7, but for most purposes can be taken as being equivalent to *representative* used in BS8002 (BSI, 1994) and *moderately conservative* used in C580 (Gaba *et al* 2003). Other definitions, such as *worst credible* or *more probable with progressive modification* (Powderham 1994) could be applied within the framework, however, for simplicity only *characteristic* and *most probable* will be discussed here.

It is important to bear in mind that when choosing *characteristic* or *most probable* parameters for the design of an embedded retaining wall, it is not only the selection of soil strength that is important. There are many facets of wall behavior that should also be considered, including wall stiffness, surcharges, ground water level, prop stiffness, undrained versus drained behavior, numerical model and design assumptions etc.

4.1.1 *Characteristic parameters*

Clause 2.4.5.2 of EC7 states that "*the characteristic value of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state*".

The choice of characteristic value for geotechnical design has been controversial and misunderstood since the introduction of the Eurocodes. The choice of a characteristic parameter will depend on the limit state under consideration as well as the geotechnical structure being designed. For an embedded retaining wall at ULS, the volume of material mobilized at failure is large, and therefore the overall strength will be close to the average. On the other hand, an end bearing pile will be more susceptible to local variations in strength and therefore the characteristic strength should be a more cautious estimate. The use of statistics has been proposed by many researchers to provide more rigor in the choice of characteristic strength. BS EN 1990 (EC) defines the characteristic value as the 5% fractile value, although this definition is not considered appropriate for geotechnical design (Bond and Harris, 2008) and shall not be considered further here.

4.1.2 *Most probable*

Nicholson *et al* (1999) defined the *most probable* value of a parameter as being "*a set of parameters that represent the probabilistic mean of all possible sets of conditions. It represents, in general terms, the design condition most likely to occur in practice*".

The *most probable* value may therefore be defined as the arithmetical mean of the available data, or may be defined by back analysis of case history data in the same ground conditions for similar construction. The parameters that result from the back analysis may be higher than the numerical mean of the data from the site investigation data. This process is discussed in more detail for a case history from the Crossrail project in London in the next section of this paper.

5 BACK ANALYSIS OF CASE HISTORIES

The process of back analysis described in this section of the paper could be applied to a completed project with the intention of using the parameters *ab initio* using approaches A or B, or during the early stages of an excavation in order to apply the OM *ipso tempore* using approaches C or D. The principles are the same whatever the approach, however, the time available to complete the exercise might be somewhat different.

5 .1 *Data audit*

To undertake a thorough back analysis of a case history a significant amount of information is required, for example:

excavation details including levels and sequence, wall movements from inclinometers, surveyed capping beam movements, surveyed ground and building movements, the propping layout, stiffness and installation sequence, prop forces from strain gauges, pre-stress in props from jacks and strain gauges, testing records for concrete cubes, levels and description of excavated materials and site use during the works.

One of the most critical aspects of the audit is to tie movements and forces to the corresponding excavation levels. For intermediate excavation levels this can be difficult if the designer does not have a permanent presence on site keeping record of excavation progress. The use of time-lapse photography can help in the process of linking together the cause and effect of excavation on wall movements.

If a published case history is being used for the back analysis, the data available will be limited to that included in the paper if the analyst or their organization were not involved in the project. Should critical aspects be missing from the write-up, it may be advisable to abandon the back analysis and seek other more rigorous examples rather than use partial and potentially misleading information.

5 .2 *The back analysis process*

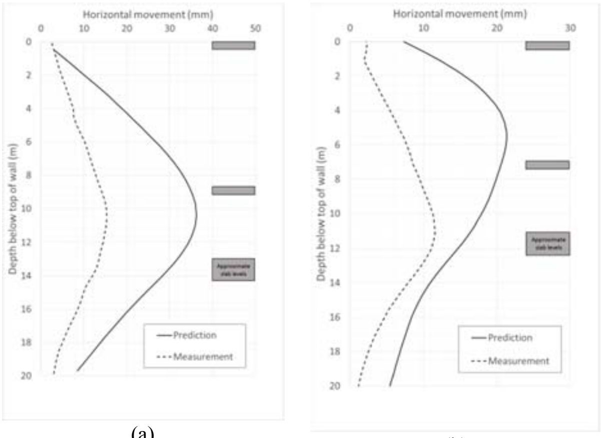
The primary variable that the analyst will be attempting to match during the back analysis process is likely to be the wall deformation. Using the information gathered during the audit phase a systematic approach is required to achieve a reasonable match between the analytical model and field measurements. At each stage significant engineering judgment is required to assess if an analytical result is acceptable or not.

A comparison of predicted and observed wall movements at each available excavation stage should be the first stage of the calibration process. If the deformed shape of the wall is similar but the magnitude of the displacements differ, the strength and the stiffness of the ground, and possibly the stiffness of the wall should be the principle variables for consideration. If the deformed shape of the wall does not resemble predictions then a more fundamental re-appraisal of the wall's construction is probably needed. This should include the excavation and propping sequence and the soil behavior (for example drained versus undrained).

Examples of real data from the same site where some inclinometers gave deformed shapes that correlate well with predictions, but with lower movements and other inclinometers showed significantly different behavior are shown in Figure 1. To recalibrate the prediction model to match the wall movements shown in Figure 1(a), adjustment to the soil and/or structural stiffness parameters should be sufficient. For the example of Figure 1(b), where the deformed shape is significantly different, a reappraisal of the wall behavior might be required. For the example presented in Figure 1(b), the modelling of the top and middle prop could be reassessed, or the excavation sequence up to installation.

The process of matching monitoring data with a recalibrated analysis is inevitably iterative and due to the multitude of possible variables, there will be no unique solution. It is therefore important that the range of variables used in the iterative process are within the feasible range.

An active area of current research is the use of multi-variable stochastic analysis for the analysis of embedded retaining walls. In this approach, each parameter in the retaining wall analysis is systematically varied and its effect on certain output, for example wall movement, is quantified. In this way the relative importance of each parameter on the retaining wall behavior can be quantified and subsequently used to aid the calibration process.



(a)

(b)

Figure 1. Example of (a) good shape but poor predicted magnitude and (b) poor deformed shape prediction

6 CONCLUSIONS

The observational method has been used in construction for centuries and defined in geotechnics for nearly 50 years. Despite the clear benefits in terms of economy, programme, partnering and clear risk allocation, there remains some reticence in the civil engineering profession to employ it widely.

The new CIRIA guidance C760 proposes a new holistic framework for the OM. It identifies four approaches to implementing the OM for embedded retaining walls. It is hoped that the clarity provided by the new guidance will encourage the use of the OM, particularly using the *ab initio* approach A. It is considered that modern instrumentation and rapid back analysis will facilitate this approach.

7 REFERENCES

Bond , A and Harris, A 2008. *Decoding Eurocode 7*, Taylor and Francis, London

Chen Y, Nicholson D, Ingram P, Hardy S, Liong Liew H, Farooq I, Biscontin G, 2015. Application of the observational method on Crossrail projects. *FPS Crossrail Lessons Learnt conference.*

Gaba, A R, Simpson, B, Powrie, W and Beadman, D 2003. *Embedded retaining walls – guidance for economic design*, Report C580, CIRIA, London.

Gaba, A R, Hardy, S., Doughty, L. Selemetas, D and Powrie, W 2016. *Embedded retaining walls – guidance for design*, Report C760, CIRIA, London.

Gaba A, (1990) Jet grouting at Newton Station, 10th SE Asian Geotechncial Conf, Taipei, pp77 – 79.

Nicholson, D.P., Tse, C and Penny, C 1999. *The Observational Method in ground engineering – principles and applications* Report 185, CIRIA, London.

Nicholson D P et al. 1998. Value achieved using the observational method on the retained cutting at the Batheaston/Swainwick bypass, The value of Geotechnics in Construction, pp123-146, Proceedings from the seminar ICE, London.

Peck, R B 1969. Advantages and limitations of the observational method in applied soil mechanics Ninth Rankine Lecture, *Geotechnique*, vol 19, no 2, pp 171–187.

Powderham A.J. 1994. An overview of the observational method: development in cut and cover and bored tunnelling projects *Geotechnique*, vol 44, no 4, pp 619-636

Yeow H. C., Nicholson D. P. & Man C.L. et al. (2014) Application of observational method at Crossrail Tottenham Court Road station, UK, Geotechnical Engineering Vol.167, Issue GE2, pp 182-193